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Built Heritage: Monitoring Conservation Management

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Foreword

The online volume “Built Heritage: Monitoring Conservation Management” has the ambition to offer to the reader an overview of the global challenge of preserving and studying our rich architectural heritage, from different but highly correlated points of view.

Advancing our knowledge of the Built Heritage is today a technological challenge that often requires sophisticated competences and interdisciplinary studies; therefore, we tried to cover the main areas of interest, presenting the research approach on different technologies and exemplar case studies. The topics range from structural monitoring and strengthening, seismic vulnerability, guidelines for the preservation of complex sites, digital survey and multimedia documentation, 3D digitization of museum collections to the development of innovative surface treatments.

To promote dialogue among the researchers in this wide field has been a challenge into the challenge; we all know that scholars, researchers and professionals involved in the conservation and management of historical and valuable complex architecture often come from different education backgrounds and are sometimes distant from each other. This book aims at showing and analysing the different aspects of the entire process, focusing on new and advanced projects and research results. In addition, it highlights the importance of interdisciplinary research in Built Heritage preservation, where insights and methods from different scientific disciplines are integrated and used to investigate a jointly defined research problem.

The book shows how the development of the safeguarding of Architectural Heritage, through the use of innovative technologies, can escape the traditional and artisanal dimension and be a valuable engine of growth.

Lucia Toniolo
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Gabriele Guidi

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Farmhouses in the Phlegrean Fields Between Archaeology and Architectural Palimpsest. A Multi-disciplinary Approach

Renata Picone

Abstract The contribution aims to deepen the study of the rural architectures in Campi Flegrei, with particular reference to the territorial area of Pozzuoli. Country houses, manor houses in the countryside, agricultural and lookout towers, rural outbuildings, farms born on archaeological remains, are the components of a rich architectural heritage strewn over agricultural land of Campi Flegrei; a heritage not yet fully known and cataloged, which pours in a state of apparent abandonment and constitutes an irreproducible repertoire of building traditions, materials and local techniques of undeniable interest. The study, which uses the results of a research, started by a group of scholars of the "Federico II" and funded by Regione Campania for the biennium 2004–2006, is characterized by an interdisciplinary approach, and will address (1) the relationship with the landscape of these settlements, (2) the reuse of ancient and existing buildings highlighting the continuity of use, (3) the technical-constructive and typological aspects and more specifically the architectural and materials ones. Two illustrative case-studies will be chosen, detailed through a careful graphic and stratigraphic relief, as well as through diagnostic surveys: the first one, relative to the area of Via Campana, which consists of a farm built on Roman remains witnessed by the presence of a nymphaeum in opus reticolatum, and the second one related to a home-farm, with a more complex plant, arose ex novo in the eighteenth century for the production of wine. In both cases will be highlighted the recurring conservative critical and the mechanisms of degradation and damage, aimed to the detection of correct methods for the conservation of this 'fragile' heritage.

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Rural dwellings, manor houses, agricultural and lookout towers, and rural farmhouses built on archaeological evidence are the main components of a full palimpsest strewn over the agricultural land of the Phlegrean Fields. This heritage, which is in a state of disuse and abandonment, is not yet fully known and catalogued and constitutes an irreproducible repertoire of local building, material, and technical traditions of undeniable interest.

The close relationship with its landscape, the reuse of ancient and pre-existing constructions, the continuity of use, its typological and more properly architectural technical-constructive specificities, are only some of the aspects that emerge from the analysis of such structures.

In 2006, a research work conducted by a group of scholars of the University of Naples 'Federico II' and funded by Regione Campania[1] compiled an inventory of the farmhouses and rural dwellings located in the area of Pozzuoli, giving rise to a systematic work of knowledge dissemination and protection. This kind of work was urgently needed because of the widespread conditions of degradation of this heritage, or worse, because of the unaware operations being conducted on it.

Setting off from the results of that experience, this paper takes on the study of rural architecture of the Phlegrean Fields, the area west of the city of Naples (Italy) characterised by extraordinary geological and landscape characteristics, by thoroughly analysing all its connoting elements, in view of their conservation and protection.

The Phlegrean Fields consist of many crater belts (Gauro, Astroni, Monte Nuovo, etc.), also transformed into lakes (Lucrino, Agnano, Fusaro, and Miseno) and residual strips of volcanic craters, such as Soccavo, Pianura, and Quartouarto, culminating on the spur of the Hermitage of Camaldoli.

The localization of the largest Phlegrean rural dwellings follows the low-lying areas between the crater belts; these areas are best suited to extensive crops such as vines, which have been historically able to take advantage of the abundant presence of water, as well as of the presence of volcanic slag in the soil, an extraordinary element of fertilization in the entire Campania Felix.

The heritage of rural architecture in the Phlegrean Fields has thus closely followed the structure of its agricultural territory: vine is the main crop, but the presence of fruit trees and woods is historically documented, especially of chestnuts, which provided wood for vine piling. However, in the case of the Phlegrean area, during the classical age historical farmhouses were also built along the routes of the

[1] "*Forma Urbis Flegrea. Catalogazione e Restauro dei Contesti Storico-Ambientali di Pozzuoli e Procida. Proposta di un Codice di Pratica*", Research funded by the Italian Regional Law No. 5, March 28, 2002—financial year 2005; Research group: professors architects Giancarlo Alisio (scientific supervisor), Stella Casiello, Salvatore Di Liello, Andrea Pane, Renata Picone, Pasquale Rossi, Valentina Russo, and Gianluca Vitagliano.

ancient roads of communication of the ager puteolanus, between Rome and Naples: 'via Consolare Campana', Consularis Puteolim Capuam, and 'via Antiniana', Puteolis-Neapolim per colles (Alisio 1995; Annecchino 1996). In the vicinity of these routes—connecting the port of Pozzuoli to Naples and, through Capua and the Via Appia, to Rome—a widespread rural urbanization arose ranging from agricultural warehouses, to cisternae, columbaria, funeral mausoleums, and villae rustiche (Maiuri 1924, p. 48, 1957, p. 37; Quilici 1969; Quilici and Quilici Gigli 1968–1969; Quilici Gigli 1970; Amalfitano et al. 1990).

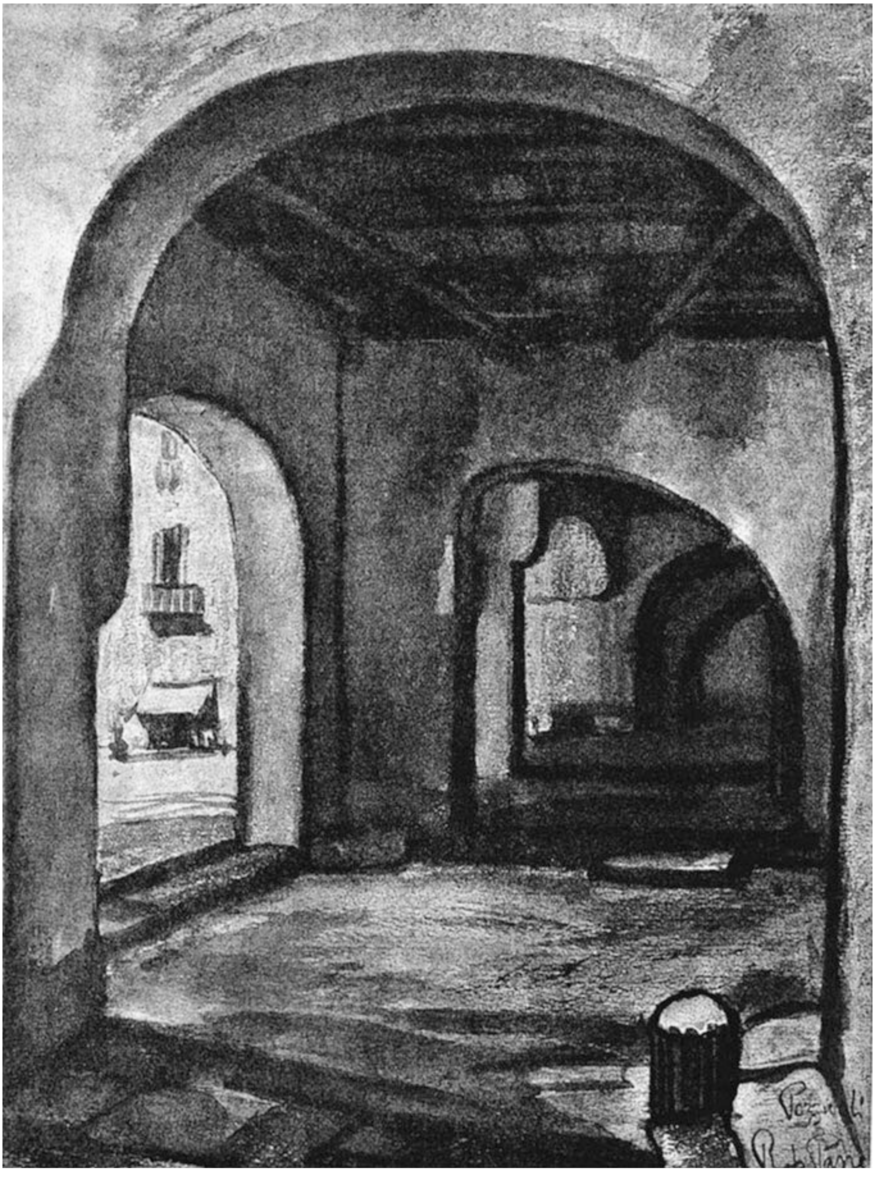
The nuclei of modern hamlets (De Seta 1984a, b) have subsequently been grafted on the Roman ruins of these architectures strictly connected to the purely agricultural vocation of the Ager Campanus. Later, the first structures of the farmhouse complexes were built without formal, material, and functional interruptions (Falcone 2009). They were sometimes complex structures surrounded by a vast cultivated area, as can be seen from the main cartographic maps of the contours of Naples—such as the 'Duca di Noja' map, the 'Rizzi Zannoni' map and the 'Mappa Topografica e Idrografica de' Contorni di Napoli'—drawn between the late eighteenth century and early nineteenth century.[2]

Inside these farmhouses, it is not uncommon to find ruins of Roman nymphs in opus reticulatum reused as cellai (cellars) or inside the ovens, as seen in the case of the Caleo farmhouse in Pozzuoli.

Therefore, it can be argued that the Phlegrean agricultural landscape is characterised not only by the geological naturalistic and agricultural components of the territory, but also by the signs of an ancient and relatively close past, only partially concealed by recent land speculation.

The broad reuse of forms, spaces, and materials of the Roman building tradition (Picone 2008a, pp. 31–61) was often due to economic reasons, as in the case of the use of ancient nymphs as foundations for new rural constructions. As the foundations were the most substantial constructive investment both in economic and technical terms, the reuse of ancient artefacts allowed for an easier and more rapid execution.

[2] Giovanni Carafa Duca di Noja, *Mappa Topografica della Città di Napoli e dè Suoi Contorni*, Napoli 1775; Rizzi Zannoni, *Topografia dell'Agro Napoletano con le Sue Adiacenze,* Napoli 1793; Regio Officio Topografico, *Carta Topografica ed Idrografica dei Contorni di Napoli,* Napoli 1817–'19.



Roberto Pane, Pozzuoli, passage with a porch, in R. Pane, *Tipi di architettura rustica in Napoli e nei Campi Flegrei*, in “Architettura e Arti Decorative”, fasc. 12, agosto 1928

Pozzuoli. farmhouse

However, the ancient spolia continued to be used for purposes similar to those for which they had been originally built, with a functional continuity that recalls the phenomenon defined in the 1960s by Emilio Sereni as "inertia of the agricultural landscape" (Sereni 1961). The expression refers to those centuries-old experiences and lines of cultural continuity for which farmhouses are considered a "deposit of collective memory" (Gravagnuolo 1989), places which hardly undergo any change, where it is possible to read the historical and cultural evolution of a geographic context, through the interpretation of the materials associated with the 'choral' history of the territory.

The close link between the agricultural community and cultivated lands has been the object of many studies conducted on rural houses by scholars belonging to the fields of sociology, ethnography and geography, both in the Italian (Biasutti 1924, 1932; Sereni 1961) and Neapolitan academic community (Fondi et al. 1964).

In the field of architectural historiography, in the period between the two world wars, there has been an in-depth analysis of the legacies of rural tradition led by Rationalist architects such as Giuseppe Pagano, who in 1936 defined this area as a "huge dictionary of the constructive logic of mankind" (Pagano 1935; Pagano and Daniel 1936). Among the Neapolitan academic community, already Roberto Pane's studies on the environment and architecture having a choral value—which followed the studies by Biasutti (1925), Cerio (1922a, b, 1923) and Castaldi (1930)—had outlined (Pane 1928) some interest in the crucial theme of the twentieth century architectural debate in the Campania region. This topic will be repeatedly investigated by Pane, becoming one of the current topics of his reflections (Picone 1988, 2005a, pp. 81–87, 2008b, pp. 312–320). These insights also influenced many architects (Baculo 1979; La Regina 1980; De Seta 1984a, b; Bruno 2001), which have conducted in-depth investigations on the typological aspects of 'rustic architecture' scattered in the Campania region, using the typical tools of the architectural historiography of the second half of the twentieth century.

Convents or large manor houses arose on the crater belts or along the gentle slopes of the Phlegrean hills and were later on transformed into rural settlements. Also the latter were often handed over to the religious orders as a donation, becoming a major source of livelihood for internal use, for maintaining religious men living in city monasteries, and for annuity. Such complexes, agricultural convents sometimes surrounded by towers and walls for protection against robbery attacks, became farms with complex rural services.

In terms of materials, the Phlegrean hills are made of yellow tuff, pozzolana, rare remains of loose lava, pumice, and lapillus: this provided Phlegrean farmers with excellent materials to build the outer walls and the roofs of their houses (Fondi et al. 1964). Quarto, with its quarry at Poggio Spinelli, is one of the main sources of supply for tuff used in vertical masonry—often grafted on archaeological evidence reused as foundations—and for the traditional extrados vaults, with their coating in beaten lapilli, which is one of the key elements of this heritage. Linked to strong anthropological traditions, apart from technical and constructive ones (Cerio 1922a, b; Di Stefano 1967; Aveta 1987), for centuries the beaten lapillus technique enabled waterproofing of the plastic extrados membranes of barrel vaults, trough vaults, cloister vaults, and bohemian vaults, which cover rural houses in Campania, connoting their presence in the agricultural landscape: an architecture without architects, where "yardsticks have been replaced with footsteps, levels and plumb lines were ignored, the shape of the walls is influenced by the same plastic vivacity of a clay object created by a craftsman's hands" (Pane 1936, p. 76).

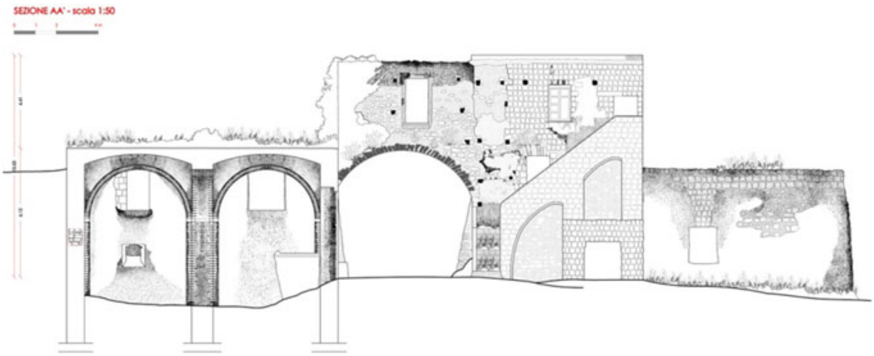
The presence of Phlegrean woods and chestnut fields gave rise to the use of chestnut beams for the horizontal elements of rural houses. The intermediate floors of the farms are made of wooden beams, alternately arranged with respect to the thickness of the section, surmounted by a secondary plank of panconcelle, also known as chiancarelle, which were used to distribute the loads without any further weight increase on the deck and consisted of chestnut bark and a separating boulder made of pumice and lapilli, autochthonous materials easily found in the area. The heads of the beams were supported by a solid brick called 'dormant'.

While the walls, often protected by the thick beaten lapilli, have been kept in an overall good state of preservation, the same cannot be said for the horizontal wood, far more fragile, which over the centuries have been subject to rot, pests, and fires resulting from chimney smoke, and were therefore often replaced with joist floors and vaulted ceilings (in the early twentieth century) or, more recently, with brick and cement floors, which nowadays is one of the major causes of deterioration of these architectures due to the oxidation of their reinforcing bars.

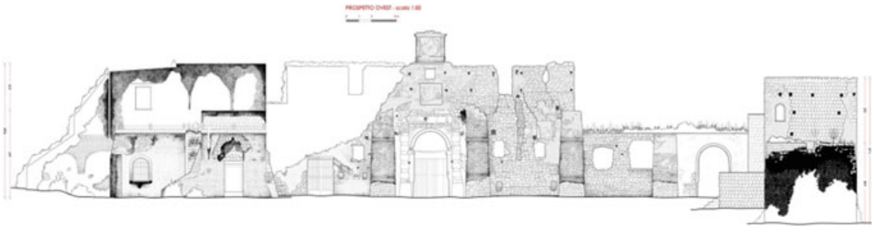
The rainwater regimentation system was particularly complex: starting from the extrados plastic membranes of the covering vaults, water was conveyed to the ground or to a tank by means of exposed gutters made of trapezoidal brick roof tiles that followed the course of the water from the vault and then along the facade, constituting a connoting element of these constructions. In Phlegrean rural houses, bricks were also used as abutments for the vaults of the intermediate floors, as elements of wall reinforcement-the so-called 'chains of bricks', or in the cylindrical elements used for the ventilation of walls, which resemble modern siphons reinforcement-the so-called 'chains of bricks', or in the cylindrical elements used for the ventilation of walls, which resemble modern siphons.

Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Main facade of the manor house

Even the finishing materials of these historical farmhouses were made of products that could be easily found on site. They were also used for the historical plasters consisting of pozzolan mortars slaked on site, traditionally painted with pinkish lime paints that mark the presence of these farms in the natural landscape. As already observed by Pane in his ‘Tipi di architettura rustica a Napoli e nei Campi Flegrei’, all the elements that are made of iron in modern constructions, are made of wood in the historical Phlegrean farmhouses, because the availability of wood was higher: window frames, gates, fences, wooden fences are the main decorative elements of this plastic architecture and they offer greater durability.



Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Materic prospect. University of Naples “Federico II”, Faculty of Architecture, course of restoration laboratory, prof. arch. Renata Picone, student: Antonia De Gattis



Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Manor house, materic prospect. University of Naples “Federico II”, Faculty of Architecture, course of restoration laboratory, prof. arch. Renata Picone, student: Antonia De Gattis

Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Exterior view of the “order to sit”, where the harvest was positioned (note the presence of the wooden elements used instead of the iron for the closing of the compartments-window)

The mild and dry climate of the area has also influenced the ways of living and determined certain specific distribution of the Phlegrean farms, which favour outdoor activities. Thus, social life takes place at the threshing floor or in the farmyard; horizontal and vertical connections are created using ramps and walkways outside the core settlement of rural houses, and sanitary installations are located in independent buildings. External masonry stairwells on rampants with gooseneck arches, balconies in solid masonry jutting out on big shelves or supported by arches and vaults, loggias and rampant arches are the key composition elements of rural architecture.

As already noted, the agricultural structuring of a territory determines the various types of rural architecture: the Phlegrean Fields are poorly covered in grass and livestock farming has historically been affected by this unfavourable soil condition, so much so that rural Phlegrean houses are often deprived of stables, while the prevalence of vineyards has led to the construction of big cellars, often, as mentioned, grafted onto pre-existing Roman columbaria, nymphs in opus reticulatum, or simple agricultural warehouses. In many cases, they are areas used for wine and olive oil processing, with torches, pressing vats, and wine aging barrels. Except for more complex cases, cellars have a rectangular shape and are covered in Lamia, i.e. masonry barrels vaults; they are characterised by a bare prospect on the short side, with an opening in the centre with a rectilinear trabeation surmounted by a square window, enclosed by wooden lattices to ensure internal ventilation. Many rural houses were provided with tanks, an environment under the threshing yard or the outside yard sealed in cocciopesto or lapillus, which, by storing rainwater, ensured the irrigation of appurtenant fields even in periods of low rainfall. This shows how the types of settlements spread around the Phlegrean agricultural land have been influenced by the landscape features of the 'burning fields' (Picone 2005b, pp. 153–159) and by the agricultural use of its soil. However, we should not underestimate the influence that the type of ownership (private or religious) and the sheer size of the estate have had on the conformation of these architectures. Some poor or lofty formal solutions are in fact justifiable on the basis of whether the building belonged to noble families, landowners or to simple peasants. The presence of a private chapel on the farm is usually due to the historical monastic property of the farm where it is located.

Agricultural lands of vast dimensions, usually owned by the feudal nobility or used by religious orders linked to the major monasteries of the capital of the Kingdom, have encouraged the spread of the most complex type of settlement, with a closed court, which borrows its constructive language and composition from the Roman rustic dwellings on which the were often built. The closed court typology of the Frà Vecchia farmhouse in Pozzuoli consists of a main building with two floors where the main rooms were located, a sleeping area on the upper floor accessible from the outside by a brick staircase and through a gallery that serves the various rooms. The main body opens onto the courtyard which is also used as a vegetable garden and is closed on the other sides by low, one floor-areas used for production (stores, warehouses, stables, cellars). The reduction of land ownership resulting from the division of the ancient estates, which occurred between the eighteenth and nineteenth century and then with the agrarian reform, has favoured, conversely, the spread of single or multi-cellular farmhouses, with a square base, consisting of one or more floors, which constitutes the basic settlement model.

Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Front of the farmhouse

Pozzuoli (NA), Frà Vecchia farmhouse (XVIII sec.). Internal view of the cellaio

The increased farming complexity of the Neapolitan area in comparison with other Italian areas is generated by a greater land fractioning (95 % of the agricultural lands do not exceed five hectares), thus Phlegrean rural houses present a great variety of types, even in very small areas.

It must not be forgotten that the fragmentation of large rural dwellings was dictated by the reduction of land property attached to them and, therefore, also by the change in land use and the gradual substitution resulting in extensive cultivation with others requiring a smaller size property. The agrarian structure of the Phlegrean territory changes as crops change, with special adaptation to the climate, altitude, and to the land structure: the land fractionation and the fragmentation of the ancient nuclei increases, as well as the dispersion of rural architecture settlements, which continue to be isolated and to adapt their typology to the main crops, and hence to the agricultural processes that take place within them.

Pozzuoli. Farmhouse on the Averno lake

Nowadays, the Phlegrean farms are in a general state of disuse and abandonment, due not so much to earthquakes or bradyseism as to their progressive abandonment, even by their owners. A heritage that has gradually lost its original function—also due to wild urbanization and ecological conditions that make quality agriculture difficult—is struggling to justify its conservation, although it still preserves its historical-constructive values and also in some cases its landscape value. Consisting of low and compacted buildings with no more than two floors, this heritage has withstood the earthquakes that have historically taken place in the area, but will not stand the lack of maintenance that today is gradually consuming the beaten elements, bringing down the wooden floors, pulverizing the masonry mortars subjected to crushing and deleting the traces of a building tradition that is disappearing because of abandonment.

In compliance with Law N. 378 of 2003 containing "Provisions for the Protection and Enhancement of Rural Architecture", in 2006 the Campania Region issued a draft law "Regulations Regarding the Protection, Preservation and Enhancement of Traditional Rural Architecture", which in the absence of a full awareness of the values and elements necessary to safeguard this heritage, actually encouraged interventions that distorted the technical and anthropological specificities of these architectures, in the name of a misunderstood work of 'enhancement'.

The two case studies chosen are representative of some of the aspects set out above; one, related to the via Consolare Campana, consists of a farmhouse built on pre-existing Roman ruins testified by the presence of a nymph in opus reticulatum, and another, relating to a more complex farm house, was built in the eighteenth century for the production of wine. In both cases, we highlight the conservative issues and the recurrent mechanisms of degradation and damage, to detect the correct methods for the conservation of this 'fragile' asset.

The examples of farmhouses that have been analysed are the 'Capuzzelle' farm in Marano and the rural complex called 'Frà Vecchia' in Pozzuoli. The first example is a two-floor multi-cellular manor farm with a quadrilateral base and an external staircase on a gooseneck arc. The conformation of the farmhouse in Pozzuoli is far more articulated; it has such an extent as to give the name to the toponym of the area, still present in cadastral maps. This type is characterised by an enclosed courtyard: a rural estate belonging to an important noble family, with a large estate attached to it. The complex consists of a two-floor manor house, with a stone portal and a large cellar consisting of two sail-vaulted spaces and two-floor buildings used to house the farmers, with external masonry stairs.

Pozzuoli, Masseria Caleo farmhouse. Remains of the Roman ninfeo reused inside the cellaio and remains of walls in opus reticulatum reused in the structure of the furnace (picture by R. Picone)

Pozzuoli. A farmhouse after the "restoration" works

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Guidelines for Eco-efficiency in the UNESCO Site of Cinque Terre: An Example of Good Practice

Luisa De Marco, Giovanna Franco and Anna Magrini

Abstract The paper discusses the results of a recent research focussed on the formulation of criteria of landscape and architectural compatibility to set up Guidelines to achieve eco-efficiency and install renewable energy source applications for domestic or agricultural use in the rehabilitation of traditional rural buildings within the World Heritage Property of Cinque Terre, Porto Venere and the Islands. The research was commissioned by the Regional Directorate of Liguria to the Universities of Genoa and Pavia and faces a new challenge for this type of sites due to the highly sensitive landscape and heritage values in place. Two factors oriented the research: a continuous passage of scale, from the territorial level to building detail and the continuous exchange among specialists within a trans-disciplinary team. The results of theoretical models of calculation of energetic behaviour and requirements applied by experts in Building Physics have been compared with the evaluation of the actual state of conservation of the buildings, with the local conditions of weather and sun exposure, with the data on relative climatology and on superficial and profound geology, with the possible energetic exigencies and with the reasons for heritage preservation and protection so as to select the possible solutions able to respond to all identified needs.

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1 Guidelines for the Eco-efficiency in Sensitive Historic Contexts: A Path Between Technical Awareness and Cultural Appropriation

The World Heritage property "Cinque Terre, Porto Venere and the Islands Palmaria, Tino and Tinetto", in the extreme eastern Liguria, represents one of most renown examples of protected cultural landscape. Thanks to its morphology, to the relatively difficult accessibility and to a protection policy began well before World War II, the territory was spared from the great transformations of the 20th century which have impacted most part of the Italian countryside (Besio 2003; De Marco 2005; Micoli and Palombi 2006).

Nonetheless, since the 1970s, Cinque Terre assisted to a progressive and rapid abandonment of the agricultural activity which had shaped profoundly this territory and given it its character for which it is appreciated worldwide. In parallel, its notoriety as a tourist destination had continued to grow, inducing, as a consequence, innumerable apparently minor transformations to the rural built heritage to meet new comfort and functional exigencies, or just for taste choices. Although modest in size, these widespread modifications have caused evident changes to villages, hamlets and the landscape, through minor or major maintenance/upgrading interventions, which have escaped an effective govern of the territory, despite the control activity by the bodies responsible for landscape protection. With a view to readdress these trends, in 2001, thanks to a special fund for landscape active safeguard projects, the Regional Directorate of Liguria, in agreement with the competent Soprintendenza, the National Park of Cinque Terre and the Regional Government of Liguria, commissioned a research, which was developed by the University of Genoa (prof. S.F. Musso and G. Franco), aimed at drawing up a Guide for the maintenance and the rehabilitation of rural buildings in the National Park of Cinque Terre, published in 2006 (Musso and Franco 2006; De Marco and Musso 2008). This guide contained already first elements to approach the problem of the energetic supply necessary to any type of consumption, a crucial issue in a context which is only episodically reached by the energetic grids.

In parallel, the growing consciousness of environmental issues and the issuing of laws and norms at the national and regional levels promoting the use of systems to reduce energetic consumption and the exploitation of renewable resources encouraged the adoption of technologies which have caused further modifications to the traditional built heritage and to the landscape of the World Heritage property.

Taking into account the increased number proposals of installation of these devices, aiming at ensuring the protection of the World Heritage site and, at the same time, at exploring possibilities of their insertion in ways compatible with the character of both the traditional rural architecture and of the landscape, the Regional Directorate decided that specific guidelines were needed, first, to increase the awareness on the wide theme of energy supply, saving, efficiency and use of renewable resources in existing traditional buildings and protected setting and then to provide an instrument that can assist owners and professionals in decision-making when facing the technical and architectural problems of energetic upgrading.

These guidelines should be read as a specific follow-up of the above mentioned Guide for the rehabilitation and shall become, along with it and other manuals and guides already elaborated (i.e. the Manual for the construction of the dry stone walls—Guidelines for the maintenance of the terraces of Cinque Terre) or yet to be prepared (i.e. in the agricultural and forest sectors), one of the operational tools of the management plan for the World Heritage property. They may also represent useful orientations for other highly sensitive areas within the region, i.e. regional parks, protected landscapes or areas.

The Regional Directorate of Liguria, therefore, submitted a research project to a call for proposals opened by the Ministry of Cultural Property and Activities to allocate the funds made available by the Law n. 77/2006, promulgated by the Italian State to sustain the protection, management and enhancement of Italian World Heritage Properties. The research was approved and funded (72.000 €) and the Universities of Genoa and Pavia (with the scientific responsibilities of the authors, G. Franco and A. Magrini) have been chosen to develop the research and to verify the real applicability of systems for the eco-efficiency of the buildings and of their compatibility with the landscape values. The outcomes of the research constitute the base for the Guidelines by the Offices of the Regional Directorate of Liguria.

Considering the high visibility of the terraced landscape, mostly exposed towards the south and the sea, the most recurrent exigencies and the legal trends pushing towards a simplification of authorisation regimes for small interventions, the Regional Directorate has reputed strategic focussing on individual buildings, first to improve their energy performances and only then to consider the installation of technical systems for energetic supply.

The scope of the research, therefore, has been limited to individual buildings and has not examined the possibilities and criticalities of larger facilities for energetic production with respect to the features and vocations of the territory. In this regard, it is worth mentioning that the Italian legislation in force only permits to select areas not suitable for the collocation of these installations but does prevent to identify the most convenient ones, thus limiting the possibility to orient the localisation of these equipments. However, wide scale planning, in this sector, remains strategic for an effective energetic policy which takes into consideration the vocations of any territory to the use of these sources, with a view to optimize their positioning and to reduce as much as possible drastic alterations to the historic built heritage and to the landscape (Fig. 1).

The cultural heritage sector, which has been slowly approaching the themes of sustainability and of technological innovation, can contribute to a much needed overturn of the objectives and of the cultural references so far adopted in the field of energy efficiency, underlining heritage safeguard considerations beyond resource saving goals, thus stimulating the search of new forms and levels of compatibility. At the same time, the goals of sustainable development and of energy efficiency may become an opportunity to strengthen and to make more specific the objectives of architectural and landscape preservation.

For these reasons, in addition to a survey of the legal instruments in force at the national and regional levels (Baldesco and Barion 2011; MIBAC 2006), attention

Fig. 1 PV cells already installed in the world heritage property

has been given to the most updated Guides for the sustainable conservation of the historic heritage elaborated in Europe and North America (Advisory Council on Historic Preservation 2011; Canada's Historic Places 2010; U.S. Department of Energy 2011; Grimmer et al. 2011; Changeworks 2008; Advice Series 2010; Vancouver Heritage Foundation 2011). This survey has made clear that laying out criteria for the admissibility of interventions represents a methodological issue which requires be resolved in a clear manner, not in a reductively normative or excessively technical way, but grounded on safeguard principles beyond technical feasibility.

On these bases, the work has been developed following some general principles, already adopted for the above mentioned Guide and articulated as follows:

- managing effectively natural resources (rainwater collecting and water recovery through integrated herbal depuration, wind, sun, biomass) in relation to territorial vocations and to landscape compatibility;
- Conjugating aesthetic perception with scientific research, by setting up reliable calculation methods to assess the real energetic behaviour of the target building, which, by virtue of its status, is not to comply with energetic standards but could undergo energetic rehabilitation interventions;
- Ability to verify/repeat necessary energetic audits for buildings within the WH property or to relate correctly to the representative case studies, so as to help the user read the analytical results;
- Adopting simple methodologies, available on the market and economically sustainable, with regard to costs/benefits ratio and to building/installation integrated systems, explaining the most advantageous conditions so as to orient the choice of different installations, including those exploiting renewable resources;
- Maintaining/repairing rather than substituting, especially when installing new technical devices becomes necessary, and hence assuming the conservation of the edifice and its components as one of the fundamental criteria for the admissibility of the interventions;
- Aspiring to a constructive dialogue between technical innovation and architectural enhancement, focusing on sensitivity and creativity, specific of design, and shifting the vision from the mimetic level to one more deeply linked to the values of architecture and of the landscape.

Specifically, the study has been articulated in the following phases, set up at the intervention level scale, from the territorial up to the architectural detail level. These phases have been developed in parallel and integrated as follows:

1. a systemic landscape analysis has been carried out: environmental resources, territorial vocations and sensitivities, settlement systems and the recurrent building morphologies have been examined in an integrated manner;
2. the thermal characteristics and of the energetic needs of the sparse rural built heritage have been analysed and criticalities due to settlement and constructive features have been identified;
3. the technical operations to improve energetic performance of buildings have been identified and architectural compatibility and non-compatibility criteria have been defined to ensure the respect of traditional building features;
4. energetic savings of the adopted solutions have been evaluated and quantified in a combined manner;
5. landscape compatibility criteria have been defined for the insertion of technologies based on the use of renewable resources.

2 Reading the Landscape as a System. Vocations, Territorial Resources and Architectural Quality of Built Artefacts

On the base of the body of knowledge accumulated along the years through previous studies, the research selected some examples which could be considered highly representative of the territorial system, the settlement morphologies (aggregated houses, rural buildings, isolated structures) and the building technologies.

At the territorial scale and for the different settled areas, resources, vocations and sensitivities (orography, exposition, superficial and profound petrology, land use, presence of terraced systems, accessibility…) were examined in order to select the installation typologies most apt to be integrated with natural resources (water, sun, biomass).

In some sample sites analyses of climatic and geomorphologic conditions aimed at understanding the effective applicability of innovative technologies for individual production and energy consumption (solar panels, photovoltaic panels, geothermal or hydrothermal installations, biomass, heat pumps…). Also at this level, more territorial in nature, the importance of landscape and architectural value was taken into consideration. The improvement of the energy efficiency and production for residential use, agricultural or tourist activities was approached in a systemic manner, pointing out the relations among different systems (geo-morphological, climatic, environmental, constructive, anthropic…) and identifying the possible solutions and the consequences of their application so as to optimize the relation among systems and to achieve the most effective mix of technologies rather than maximizing the use of one in respect to others.

At the territorial scale, the most significant public paths and panoramic views were identified, with special regard to famous or traditional views which have become part of the collective imaginary of these places, so as to assess the visual impacts of the most recurrent interventions on the landscape and to outline criteria for the positioning of new technical installations that ensures an acceptable performance and minimizes the impacts on the landscape and on the built heritage.

3 Thermal Characteristics and Energetic Exigencies of the Sparse Traditional Built Heritage

The calculation of the energy performances of the sample buildings was carried out considering the climatic conditions of the localities in which these are located. With regard to the indoor temperature of the target buildings, as requested by the procedures set up by the technical norm *UNITS 11300 part 1—Determination of the thermal energetic exigencies of the building for its summer and winter air conditioning*, a winter temperature of 20 °C, constant along the 24 h, was adopted as project data.

The first two examples are located in Cacinagora, near Riomaggiore, and feature 1,437 Degree Days, in climatic zone D, corresponding to a heating season of 166 days, from 1st November to 15th April (Figs. 2, 3, 4 and 5).

Fig. 2 Case study n. 1 located in Cacinagora. View of the double-cellular building

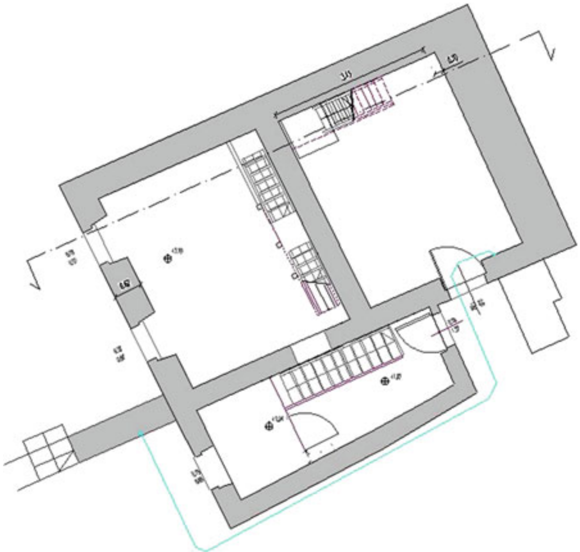

Fig. 3 Case study n. 1 located in Cacinagora. Plan of the double-cellular building

The third case study is situated in La Costa, near Monterosso al Mare, which features a value of 1,321 Degree Days, in climatic zone C, corresponding to a heating season of 137 days, from 15 November to 1st April (Figs. 6 and 7).

For the calculation of the average monthly external temperature, an interpolation has been necessary, as indicated by the norm *UNI 10349—Heating and air conditioning of buildings. Climatic data*, of the data concerning the province of La Spezia, where the municipalities of selected examples are located.

First, the thermal needs were assessed, and it emerged that these are similar for all three cases and depend exclusively from the envelope characteristics, since the three groups of buildings have currently no heating system.

Energy performance index during heating season for building envelope EPHenv [kWh/(m^2 year)] is: in case study n. 1 160,90, in case study n. 2 136,25; in case study n. 3 140,16.

Assuming as hypothesis low-efficiency technical installations, in relation to the examined case studies, the Theoretical global performance index of the buildings has been determined and associated to the energetic class of the building—installation system for winter air conditioning and hot water production, which is presented below with the energy performance index (Table 1).

EPH_{env} energy performance index during heating season for building envelope, it represents the energy needs for the building envelope. EPH energy performance index in the heating season; it represents the primary energy needs of the building-heating system (it does not include the domestic hot water). EPgl global energy performance index (EPH + EPw), it represents the primary energy needs during the heating season for the heating system and for the production of domestic hot water.

Fig. 4 Case study n. 2 located in Cacinagora. View of the multi-cellular building

Fig. 5 Case study n. 2 located in Cacinagora. Plan of the multi-cellular building

Fig. 6 Case study n. 3 located in Monterosso. View of the manor house

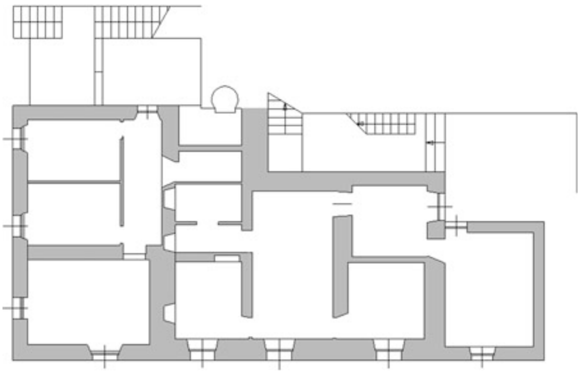

Fig. 7 Case study n. 3 located in Monterosso. Plan of the manor house

Table 1 Energy performance index of the three examined case study. EPHenv Energy Performance of the building envelope; EPH Energy Performance for Heating; EPw Energy Performance for Hot Water; EPgl Global Energy Performance

Energy performance index [kWh/(m^2 year)]					
	EPH_{env}	EPH	EP_w	EP_{gl}	Class
Case study n. 1	160,9	320,5	36,1	356,6	G
Case study n. 2	136,2	251,3	21,8	273,1	
Case study n. 3	140,2	271,8	22,06	293,82	

4 Interventions for the Improvement of the Energetic Performance (Insulation and Technical Installation)

An overview of interventions for thermal improvement was prepared, including the adoptable technical solutions (insulation systems and installations for the production of hot water through solar energy, for the winter/summer air conditioning through heating pumps and biomass, for the production of electric energy and the recycle of rainwater). For these interventions, the impacts on the architectural system—i.e. possible modifications to the constructive system due to the real modalities of application of insulation technologies—were assessed, and their effectiveness, in terms of resource saving, compared to the reduction of volumes and surfaces, caused by insulation systems.

For the critical points of the buildings, source of thermal dispersion and humidity infiltration, the most compatible insulation solutions were indicated and the most suitable technical systems, also in terms of economic sustainability were identified. Alternative combined solutions for the building—installation system were evaluated, through the selection of different types of insulating products and of different thickness (verifying the formation of interstitial condensation and surface mould), and the results were summarised in graphics illustrating, for the alternative solutions, the percentages of improvement for the energetic performance indexes of the envelope.

Departing from an energetic exigencies as high as 300 kWh/(sqm per year), corresponding to an energetic class G, it is possible to achieve very efficient energetic classes if the rehabilitation encompasses integrated actions on the envelope and on the technical systems through the use of renewable energetic resources.

The interventions have a different percentage incidence according to the examined configuration and on the base of its geometric and structural features. In particular, for the multi-cellular configuration (case 2), interventions on the roof result more effective than the solutions foreseeing the insulation of the walls, in relation to the higher bearing of the horizontal surfaces in this type of edifices. On the contrary, for the configurations 1 and 3, the insulation of the walls appears more advantageous, in that they weigh on more on the global envelope surface.

Also in the case of transparent envelopes, substantially different percentage of improvement are registered in relation to the percentage of window surface out of the global building envelope; in particular, substituting the windows with new ones appears more advantageous for configuration 3, which is featured by a window surface wider than the other configurations.

5 Architectural and Landscape Compatibility of New Technical Installations

Finally, the criteria of landscape compatibility for devices fed by renewable energetic resources have been made explicit also through photo-simulation. Compatibility depends on location factors (in respect to the territorial vocations and the panoramic views), quantitative (i.e. if they are isolated or repeatable/aggregated systems, on the base of the covering of the soil or orography) or qualitative factors (i.e. device morphology, its colour, possibilities of visual impact mitigation). The impacts have not been assessed only from a perceptual point of view: also the state of conservation of building materials and systems subject to intervention, and the subsequent possibility to remove decayed traditional materials have been considered, the level of invasiveness of the structure on the ground and on the terraced system. Photo-simulations visualise possible interventions integrating solar technologies with traditional roofing (in case of complete replacement due to advanced structural deficiency, in agricultural or residential service structures, in projecting roofs, in improper existing additions) so as to build the richest picture of possible interventions to be considered admissible, admissible under particular conditions or, on the contrary, unacceptable.

The compatible insertion of innovative technical systems that can be integrated, possibly on added components, rather than on traditional roofs, pose in the foreground the role of creativity, in mimetic, non- mimetic or contrasting forms.

Fig. 8 Photo simulation of the substitution of a plastic shelter with PV glass cells

Creativity can find expression through the design of components that can be easily integrated with traditional architecture, hand in hand with the most recent experiments in the field of new materials, i.e. the production of organic photovoltaic cells, of films or thin wraps that can be transferred on other surfaces through a photographic print process, of photovoltaic elements on flexible membranes, therefore more suitable for the realisation of canvases or added elements (Fig. 8).

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Planning for the Historic Built in Developing Countries: Challenges and Opportunities Through the Case Study of Multan (Pakistan)

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Abstract Since 2010 the Authors have been involved, on behalf of your department, in different tasks of the multidisciplinary project "Sustainable Social Economic and Environmental Revitalization of the historic core Multan City", financed by funds from the Pakistani-Italian Debt for Development Swap Agreement and governed by a Consultancy Services Agreement signed between the Foundation Polytechnic of Milan and the Ministry of Housing and Works of the Islamic Republic of Pakistan. Multan, one of the oldest inhabited cities in the Asian subcontinent and the sixth largest within the boundaries of Pakistan, is a city in the Punjab Province of Pakistan and capital of Multan District with a population of over 3.8 million. The general objective of the project is the promotion of the old town of Multan by valorizing its historical, architectural and cultural heritage. The proposed program aims to develop a pilot model in conservation by urban renewal and infrastructure improvement accepting culture and history as common human heritage and as tool to development based on approach of global and local citizen participation and public and private partnerships. Specifically, the Authors have worked on the tasks of the guidelines for the preservation of historic buildings within the walled city and Musafar Khana Complex at the Musa Pak Complex preservation project, including the Pakistan Italia Resource Centre design. The experiment, with complex objectives and focused on an urban scale and not on single buildings, in fact allowed to make some reflections about the preservation of cultural heritage in developing countries, despite the differences of cultural contexts.

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1 Which Way for the Conservation in Developing Countries? A Short Overview

The territories of developing countries are very complex places, where the process of constant stratification and the different ways of living have left many tangible signs on the urban texture. Here the different issues and problems involved, often with no easy solutions, face with the ethical responsibility and cure required from the historic and cultural heritage: how can we improve the urban quality and the living conditions of the inhabitants and at the same time preserve the unique identity of the places? The first challenge concerns the conflict between the preservation of the identity and the need to implement the necessary transformation: the legacy of the past is too often seen as an obstacle to the future development; a heavy and uncomfortable memory of poverty, oppression, ethnic and religious conflicts. The transfer of specific knowledge is only one of the aspects involved and the goal is not to impose cultural models or advanced techniques.

An active conservation should not impede the transformation but should act in synergy with it. The first step should therefore aim to start repossession processes and awareness of the local cultural heritage, developing the autonomy of the inhabitants and ruling class in the preservation. In this way, through the consciousness of its importance for the history and identity of a nation, the cultural heritage is not an obstacle to development but a resource to promote it.

A first big difficulty to implement these goals concerns a sort of justifiable diffidence towards "foreigners" involved in the preservation of cultural heritage without great economic interests. The international cooperation should not be seen as a kind of cultural colonization but as a mutual enrichment of knowledge (Figs. 1 and 2).

2 Goals of the Project: Ensure a "Right to the City" for All

The historic old center in developing countries, especially in the contemporary global network, doesn't permit simple reading for the great and various issues involved but at the same time the real wealth of these places lies in their variety, multiplicity and diversity, making the complexity a resource.

These are precisely the elements that give vitality to the urban fabric and working in these contexts means first of all face the challenge of "diversity": different cultures, specific climatic and environmental conditions, various building traditions and construction techniques (also due to the colonial processes), variety of materials, different approaches to the historic built, intricate economic, political and social conditions. This requires a new approach and different strategies to look at the city: what are the elements of identity and what responsibilities in respect of them? What are the borders of the concept of cultural heritage? What does it mean to bring the practice of conservation as an alternative to the reconstruction? How is it possible to transform the constraints determined by the context into opportunities

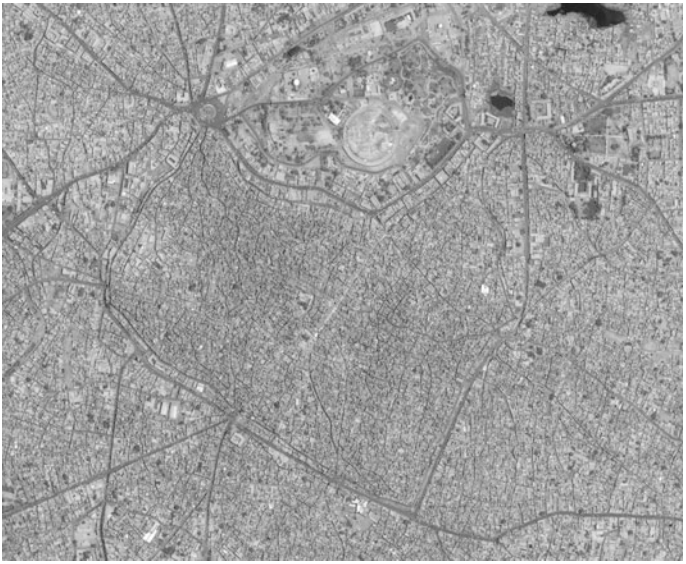

Fig. 1 *Top view* of the Multan Walled City with its complex urban asset

Fig. 2 Multan: views of the Walled City with its rich and stratified existing built

for the project? The Italian experience in historic contexts showed that the answers for an urban regeneration are already in the city itself: the task is to extract this potential through a compatible project, respectful of the stratifications, identities and needs of the people. The project can restart only from the city, by capturing the intrinsic values and by transforming them into strategies, from a structural, architectural, functional, social and economic point of view. Facing the challenges of complexity means protecting the elements for the construction of development.

In a such difficult context, ideas and projects must work starting from the specificities offers by the local culture and must put in place alternative practices of architecture. First of all this is possible through a recognition process of signs and meanings included in the permanences: this reading permit to transform it in a project respectful of the natural inclination to transformation. A second level of action has to search a balance between preservation and transformation, by identifying the limit of possible changes. The final level of action must be capable to activate a process of care, also through the promotion of a "culture of care", which directly involves people in the conservation of sites.

3 Issues and Challenges

Work for the preservation of historic heritage in developing countries means simultaneously addressing problems, at first sight unsolvable, and at the same time enhance our knowledge. All things that are well established and habitual in our research and professional practice applied in European contexts, here should be reconsidered and daily re-calibrated, first of all starting from by theoretical choices.

The preservation of historic element in its material integrity is incomprehensible for a worldwide market that just started to erode traditional craftsmanship: how can be understood the reasons of the irreproducibility of historic heritage if the gap between old and new is not yet perceived?

The theoretical issue drag along a lot of practical issues: difficulty of reading the designed project by skilled workers, development of bill of quantities, unavailability of products commonly used in restoration, lack of skilled workers in conservation, organization of the worksite, durability of products and techniques in particular climatic conditions. For example, if the stones even superficially eroded, are traditionally replaced, why should we read punctually decay phenomena and define appropriate conservation techniques? Or again, why should we identify consolidating or protective products able to resist to weather conditions, different from those where they are normally used? Therefore exists, primarily, a problem related to the conservation techniques and their durability in the weather situation in which have not been specifically tested. Certainly a proper practice would be to check the results with appropriate laboratory tests subsequently verified in situ. The practice of the yard, the timing imposed by the projects and the difficulty awaiting the results of the experimental tests is even more evident in these contexts. It is therefore forced to use materials that, although not tested in these situations, are sufficiently tested and used in other more well-known places that have stood the test of durability. But the difficulties do not end there. The availability on site of products and preservation techniques, widely tested and normally commercially available in our contexts, also due to the low demand that has never stimulated international companies to their import. Then there is the question, very important, of the construction of a common lexicon. Materials and techniques, including traditional, takes, in every context, name and consequent different characteristics. With no little surprise, it was learned how in Pakistani Punjab it is very common the use of "cocciopesto", after realizing that the local word to define it is "Surkhi." The common vocabulary becomes, therefore, the first goal of anyone who wants to work in the field of restoration in non-Western contexts, both as regards the definition of materials that, above all, of the decay.

These are just some examples of the technical challenges faced that provided an important lesson: any work method, although scientifically rigorous and shared by the scientific community, any technique or material, tested and commonly used, cannot be imposed and imported but must be shared and adapted to the local specificities.

4 Three Practical Experiences

4.1 The Pakistan-Italian Resource Centre—the Musafar Khana Complex Preservation Project

The theoretical issues have found an opportunity of practical testing through the project developed for the Pakistan-Italian Resource Centre, besides the Musafar Khana Complex preservation project.

This is a documentation, research and training center, a facility that will be tasked to promote the cultural, economic and social development of the city of Multan. It supports the exchange of knowledge and increasing the productive sectors through relations, trade and finance between Pakistan and other countries, Italy in particular. It will also become the ideal forum for activities aimed at enhancing the urban fabric of Multan and at the same time constitute a sort of commercial/business hub to promote the economy of the walled city and its surrounding productive land. The symbolic, historic and cultural importance of Musa Pak Complex makes it one of the most significant and representative of the historical core of Multan.

The Musa Pak Complex has an intricate genesis. The basic elements of the original urban form are the Shrine of the Saint (connected with the Mosque), the empty space and the Darbar (gate). So, according to history, the beginning of the eleventh (AH)/seventeenth (AD) century, the Musa Pak Complex is reorganized in clear composition, set according to an east-west axis:

- to the east was the gateway to the sacred area, the building of Darbar Musa Pak, designed to accommodate the pilgrims. The door is a key element in the definition of place in general and especially for a holy place;
- the centre was open space, the real pivot around which the whole complex of Musa Pak was organized. It allowed the direct visual relationship between the various monumental buildings, in particular it was organized around the longitudinal axis (east-west) that united the complex and the Darbar Shrine of Musa Pak Shaheed;
- to the west stood the Shrine of Musa Pak Shaheed, in longitudinal position. An entrance was to open towards the court and the axis forming the Darbar and a second entrance facing north, toward the mosque.

This space system was completed to the north of the building curtain, and in particular from the porch of Khanqah Gilani, also part of the sacred place.

The enhancement the Musa Pak Complex must be accompanied by a redevelopment project of the area that may trace relationships between the component parts, define the functions and give importance to the open space around which monuments articulate, a place where a community comes together and is recognized.

The design of the new Resource Centre is an opportunity to reorganize the central courtyard of Musa Pak Complex. Its shape, recognizing the importance of the complex and the court, aligns the axes of the main monuments and the court itself by helping to give a made figure to that portion of public space (Figs. 3, 4 and 5).

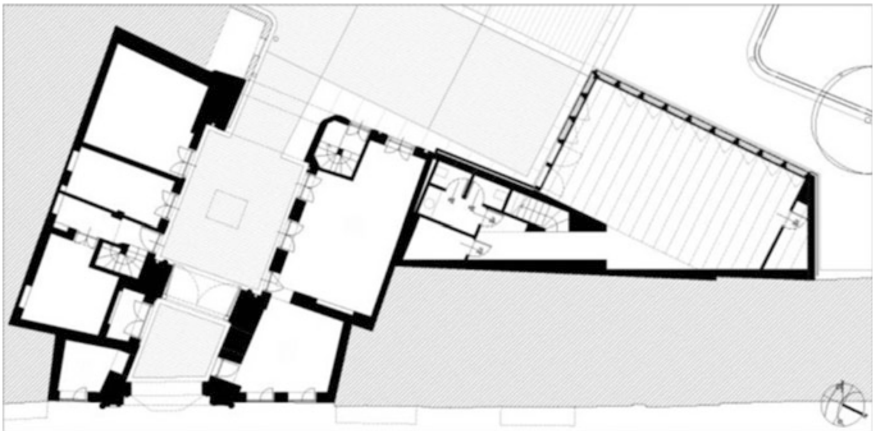

Fig. 3 Ground level: the Musa Pak Courtyard Darbar and P.I.R.C. building planimetric drawing

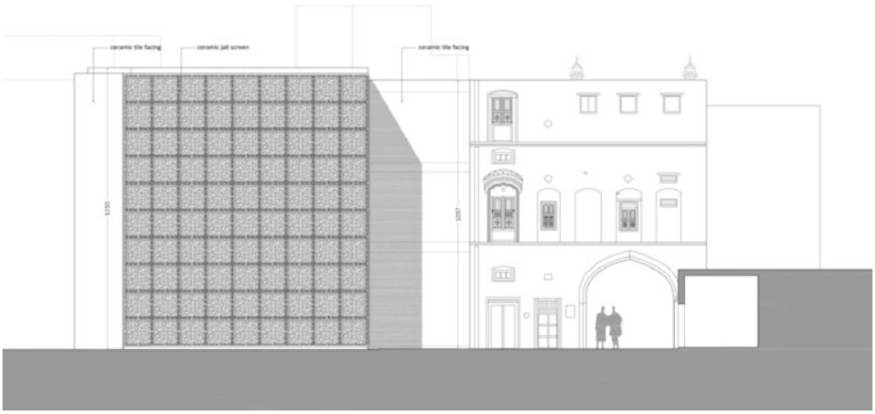

Fig. 4 Front from the Musa Pak Courtyard

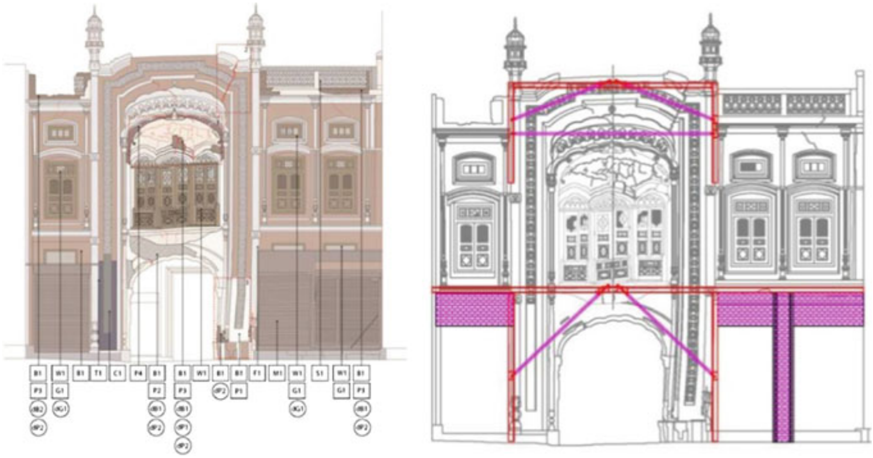

Fig. 5 Musa Pak Darbar building: Sarafa Bazar front survey and diagram of structural intervention

This solution would allow:

- to put a stop to private commercial functions related to the Bazaar, which have eroded over time the space and has changed the shape of Darbar itself and of that of Musa Pak Complex,
- to have a showcase of the Resources Centre on Sarafa Bazaar contributing to the perception of the Resources Centre building as an element belonging both to the complex of Musa Pak and to the rest of the Walled City. It is essential that role of associated element to the economy of the city should be emphasized along with its belonging to the urban fabric,
- to enhance the space of great architectural value of the inner courtyard of the Darbar.

4.2 Guidelines for Maintenance, Conservation and Reuse Works in the Walled City of Multan

One of the tools developed by the research team focused on the setting up of Guidelines for the Walled City of Multan, designed with the aim to suggest and guide different types of users (owners, specialized workers and technicians) to rehabilitation and valorization of the city. The buildings of the Walled City come from different historical ages with important examples of materials, traditional building types and construction techniques: the project wants to preserve this great complexity recognizing it as a resource, and transforming it into an opportunity of urban regeneration.

This implies the need to face with complex issues and problems from different level: luck of proper sanitation and high water, air pollution, interventions carried out without a general project as electrical installations arranged randomly, not designing air condition systems, intricate system of curtains that cover the fronts of historic buildings. The state of preservation of many historic buildings is, in many cases, precarious for natural deterioration, absence of maintenance but also for the execution of wrong interventions, with a general bad housing conditions.

In a such difficult context, the enhancement of the Walled City of Multan should provide synergistic actions for the conservation and rehabilitation of historical heritage (Fig. 6). The Guidelines are just designed as a friendly tool but at the same time a technical guidebook with indications and virtuous suggestions (best and bad practices, technical sheets for interventions, check lists) for different levels of

Fig. 6 Guidelines for maintenance, conservation and reuse works in the Walled city of Multan: the structure of the book

intervention: maintenance, repairs and restoration. An urban regeneration process that starts directly from the main users, the inhabitants, through works realized in self-made: choices easily feasible, economic, easy to implement and capable to give results in short times. The structure of the Guidelines is designed to develop, at first, the knowledge and awareness of designers and inhabitants about the importance of the historical context in which they live: historical research, geometrical survey, materials historically used in the construction of buildings and decay phenomena survey. A *Glossary* of materials decay and structural phenomena observed in the historic buildings of the Walled City helps designers, engineers and inhabitants to recognize if their buildings require urgent actions or are affected by only superficial decays.

The part *Best and bad practices* shows, with an immediate and simple tool, illustrated with the pictures of the major errors, the best and bad practices for the conservation and the reuse of historic buildings. The goal of this tool is to sensitize the inhabitants and to guide them to correct conservation and reuse interventions. The *Technical sheets for maintenance, conservation and reuse works* is dedicated to the description of the main correct interventions, describing, in a simple way with the help of drawings, problems and possible solutions through interventions step by step. At the end of the Guidelines some Check lists for technicians or inhabitants are designed to verify the process and recognize the risks.

4.3 The Conservation Project of Haram Gate

Haram Gate represents an important landmark for the Walled City of Multan. The work has been developed with the aim to test a method on a concrete pilot project starting from a careful knowledge of materials and construction techniques, detailed studies on decay phenomena and set of cracks, to define sustainable, compatible and non-invasiveness strategies. The real challenge of the work has been to transfer the Italian experience to specific needs and problems of the local context (weather, availability of products normally used in restoration, lack of skills for the execution of the works).

The Gate, at the entrance of Haram Bazaar, is formed by two specular towers connected by a bridge and it is built in brickwork. Detailed analysis and researches were performed to understand the characteristics of the object as historical, geometrical, material and decay investigations, punctually mapping the current state of conservation. Parallel to the reading of the decay phenomena macroscopically observable, were carried out and crossed investigations on structural phenomena to understand the structural scheme, the withstanding elements and the possible unbalanced forces (Fig. 7).

The design process has been developed to ensure the maximum preservation of the building with a specific conservation project able to stop the decay phenomena and to guarantee a better performance of the materials from a chemical, physical and mechanical point of view. The interventions are divided into two phases and

Fig. 7 Haram Gate project: 3 dimensional model of the Gate (by Andrea Garzulino)

provide removal, cleaning, consolidation and protection phases. Cleaning works help to remove from the surfaces damaging deposits; consolidation works have to re-establish the mechanical consistency of the materials and the final protection gives unity to all interventions. Finally, the project faces the generation of electric power through a photovoltaic system using the steel strand (provided in the strengthening project) as supports for the light system and the steel plate as supports for the led: in this way the project wants to be as much as possible recognizable, non-invasive and compatible.

In order to contrast the structural weakness of the building, the project provides a series of elements with the purpose of balance the horizontal thrust of the vaults, focusing on the weaker parts such as the holes of the stairs.

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New York City Local Law 11/98: Consequences of Administrative Regulations on the Conservation of Buildings

Mariachiara Faliva

Abstract In 1979 a piece of terra-cotta fell from a 1912 residential building at 115th street and Broadway in New York City and killed Grace Gold, a student from a local college. The Department of Buildings became increasingly concerned about the general aging of the city building stock and the overall lack of maintenance. A city law (Local Law 10/80) was passed soon after that dramatic event: it imposed a requirement on building owners to file a report on the structural soundness of their building facades every five years. Since then, the law has evolved to become increasingly strict in terms of procedures for the inspections and liability for owners, architects and engineers. Currently about 12,000 buildings are affected by the law. The building facades can be placed in three categories based on the severity of the conditions observed during the examination: Safe, Safe with Repair and Maintenance Program (SWARMP) and Unsafe. Defects in the "unsafe" category are supposed to be repaired within 30 days, unless the Buildings Department grants an extension, which typically requires that temporary pedestrian protection must remain in place until the repair is completed. SWARMP conditions must be repaired within the next five-year cycle. Although it is true that sometimes heavy and useless interventions were carried out in the name of public safety, the continuous monitoring and the subsequent repairs have helped to preserve the integrity of many building facades, including those of landmark buildings. Ultimately it has been positively welcomed also by building owners who, after initially lamenting additional costs for the inspections and mandatory repairs, have seen an advantage in doing minor preventative maintenance as opposed to drastic and expensive once-in-30-years restorations. The paper will present the main provisions and requirements of the law, illustrate its evolution, and discuss the consequences for the physical preservation of facades by showing some case studies.

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1 Introduction

In 1979 a piece of terra-cotta fell from a 1912 residential building at 115th street and Broadway in New York City and killed Grace Gold, a student from a local college. The Department of Buildings became increasingly concerned about the general aging of the city's building stock and the overall lack of maintenance. A city law (Local Law 10/80) was passed soon after that dramatic event: it required building owners to file a report on the soundness of their building façades every 5 years for buildings taller than six stories. At the time, this was the second law of this type enacted in the United States: a similar law was passed in Chicago in 1978 after another deadly accident (Weiss 1981). The New York City law required an inspection, or critical examination, to be carried out by registered architects or professional engineers and prescribed intervention if unsafe conditions were uncovered. Observation of façades and appurtenances had to be performed from the street level via binoculars. In its original configuration, the law applied to about 8,000 buildings in all five boroughs, with three-quarters of them in Manhattan (Blair 1990). It required the periodic inspection of exterior walls and appurtenances of buildings more than six stories high and within 25 feet of any sidewalks, plazas or play areas. This essentially limited the object of the examinations, and consequent corrective actions, to walls facing spaces accessible by the public only, in effect excluding all rear walls facing private courtyards or alleys.

Since then, the law has evolved to become increasingly strict in terms of inspection procedures and liability for owners, architects and engineers. The main turning point occurred when in 1998 a section of brick veneer separated from a lateral wall back-up structure on a Madison Avenue office tower and fell on the roof of a lower building next door. The event triggered revisions to the law to require examination of all façades, including rear and lateral elevations. This new law was Local Law 11/98. It also introduced the requirement for "hands-on" examination from scaffolds and platforms, in addition to observations from street level via binoculars. A report describing the outcome of the inspection must be filed with the NYC Department of Buildings, the local authority in charge of reviewing the reports, verifying their compliance, and follow-up if repairs are required. Currently about 12,000 buildings are affected by the law.

The law, and its implementation, was harshly criticised by owners, architects and engineers, and preservationists, all for different reasons. The owners foresaw soaring costs related to the erection of sidewalk sheds and mandatory repairs. Architects and engineers were concerned about the liability they would carry if owners did not perform the remediation of unsafe conditions, or if new unsafe conditions developed between inspections. Preservationists feared that owners would, in the name of public safety, justify removal of historical architectural façade features from buildings not protected by the Landmarks Preservation Commission. Although many of these concerns have dissipated during the 33 years since the law was passed, its provisions and requirements have had a significant impact on the way building maintenance is perceived and implemented, with obvious consequences on the building themselves.

2 Provisions and Requirements of the Current Law

A critical examination of all exterior walls and their appurtenances on buildings that fall under the requirement described in the current version of the law (those buildings that have at least one wall taller than six stories) is carried out and a report is filed every 5 years. In recent years, the five-year cycle was subdivided into sub-cycles, staggered to include certain buildings only. For example, for buildings located on a block ending with the number 4, 5, 6, 9, a report must be filed between February 21, 2010 and February 21, 2012; a second set of locations fell under the sub-cycle running from February 21, 2011 to August 21, 2012; and a third sub-cycle ran from February 21, 2012 to February 21, 2013. This allowed inspections, filing of reports, and completion of repairs for the 12,000 buildings to be spread over a period of 3 years. The change reduced the congestion of construction sites in the streets and paperwork at the NYC Department of Buildings.

Each examination is conducted by, or under the direct supervision of, an architect or engineer who is a Qualified Exterior Wall Inspector (QEWI) retained by the owner. The QEWI "designs an inspection program for the specific building to be inspected, which shall include, but not be limited to, the methods to be employed in the examination. The inspection program shall be based on the considerations of the type of construction of the building's envelope, age of the material components, the façade's specific exposure to environmental conditions and the presence of specific details and appurtenances. Consideration shall be given to the façade's history of maintenance and repairs as described in previous reports and submittals to the department" [Local Law 11_RCNY_103-04]. Although the QEWI is responsible for defining the inspection methodology, which may include selective removals to verify construction characteristics, the law requires that at minimum all façades are visually examined with binoculars (without the use of any other diagnostic instrumentations) from the street level and that one close-up, or "hands-on", inspection—from a suspended platform, pipe scaffold or other device—is to be conducted on every street façade. It is the QEWI's responsibility to select representative areas for the close-up inspections: knowledge of traditional construction techniques and materials, together with experience, become a useful tool in selecting the right number of hands-on observations.

The building façades can be placed in three categories based on the conditions observed during the examination: "safe," "safe with repair and maintenance program" (SWARMP) and "unsafe." If even one condition is classified unsafe, the entire building is deemed unsafe. The report is then filed with the Department of Buildings within the prescribed deadline. No action is expected for those conditions classified as Safe and SWARMP. Defects in the unsafe category must be repaired within 30 days, unless the Department of Buildings grants an extension, which typically requires that temporary pedestrian protection remain in place until the repair is completed. Because many Local Law 11/98 inspections trigger overall building repair campaigns, the time required often exceeds 30 days and extension are common, as long as the repairs are actually carried out and effective pedestrian protection is maintained. SWARMP conditions do not pose an immediate threat to public safety but require some sort of intervention to prevent them from becoming unsafe. They have to be repaired within the next five-year cycle or they will be reported as unsafe by the QEWI, although they may not really be hazardous. Non-compliance with the law—late or missed report filing—results in violation notices and fines for the owner. Falls of façade fragments following a report filing may have harsh outcomes for the professional responsible for the inspection, including fines, license revocation and penal consequences.

3 Consequences for the Physical Conservation of Façades

While the law's main purpose was to protect pedestrians from falling masonry and other façade components, it has undeniably had significant consequences for the conservation of buildings. In its infancy, the law was strongly criticized by preservationists because it allegedly legitimized "façade stripping," the removal ornamental elements, such as terra-cotta cornices, stone balustrades and cast stone balconies. Some notorious cases in the early 1980s, such as the removal of all of the terra-cotta ornamentation from the 1920s Mayflower Hotel on Central Park West and 61st Street because it was deemed "unsafe" and "un-repairable," shook the preservation community. What was conceived as a way to increase the maintenance of buildings and thus improve conservation began to be seen as the cause of many horrific actions against historical buildings. Advocates of the law, however, proved that façade stripping was already occurring before the law had been enforced. An interesting study on this subject was conducted and reported by Christopher Gray in the famous New York Times column "Streetscapes" (Gray 1993). A review of 207 street façades of tall buildings on Broadway, West End Avenue and Riverside Drive, between 70th and 110th Streets, revealed that 46 of them once had cornices, balconies and other protruding ornamentation. A comparison of existing conditions with post-World War II photographs and Local Law 11/98 reports showed that 17 were stripped before the 1980s, 12 between 1980 and 1985, and seven between 1985 and 1993 (when the study was conducted). For 10 buildings it was not possible to pinpoint a precise date when the removals occurred. Although it is true that sometimes heavy-handed and unnecessary interventions were carried out in the name of public safety, the data indicate a decrement in the number of the cases where ornamentation was removed. This may be due to architects and engineers becoming more familiar with the law and its requirements over time and gaining expertise in dealing with historical materials and construction.

In some cases, however, removing the ornamentation may have been the only practical option. Tall buildings began to appear in the New York skyline at the turn of the 20th century, as improvements in the design and construction of steel structures permitted them to grow taller. This new way of building had consequences on the façades: masonry façades and their terra-cotta and stone ornamentation were "applied" to the back-structure through metal cramps, while the steel structure itself was embedded in brick masonry to provide fire protection. Because of lack of experience in using these new construction methods, many details, such as those preventing the ingress of water into the façade, were neglected and their importance underestimated. Over the following decades, corrosion of the steel structure and anchors led to cracking, fracturing and spalling of the masonry elements, sometimes in such a critical manner that repair would be hardly conceivable even by the most passionate preservationist. These extreme conditions were often aggravated by the lack of maintenance in the years preceding the law. Many building façades are not easily accessible because of their height and the density of the surrounding urban fabric; the cost of installing a scaffold or a suspended platform can sometimes be equal to or greater than the cost of repairs.

The constant monitoring required by Local Law 11/98 has undeniable benefits: causes of decay are detected at their first stages; damage is less widespread and less severe; repairs are restricted to localized areas and replacements due to un-reparability are less common. Undoubtedly, conservation of the historic fabric of these buildings has gained from the law. Ultimately, the law has been welcomed by building owners who, after initially lamenting the costs of inspections and mandatory repairs, have seen the benefit of regularly doing minor preventive maintenance instead of drastic and expensive once-in-30-years restorations.

Paradoxically, the law sometimes causes an overabundance of repairs. Because the law requires the architect to report conditions that are not yet unsafe but may become so in the next 5 years (SWARMP), conditions that may not result in problems are often reported as SWARMP. That's the case, for example, of cracks caused by settlement of the structure that have not progressed in years: a cautious architect or engineer would not want to risk liability by not reporting the crack and would specify repairs even if not strictly necessary. This prudent attitude is justified by the fact that the examinations are not thorough enough for the QEWI to fully determine the actual causes of each condition.

But what happens to buildings shorter than 6 stories? A statistical study (Davis and Eschenasy 2009) was conducted in 2009 to assess the safety of the façades of the 40,000 Manhattan and Brooklyn residential buildings built in the 18th century that are not subject to the mandatory periodic inspections of Local Law 11/98. Location, conditions, materials, exposure and height were all factors considered in the study of a statistically selected number of buildings. The research showed that the buildings are generally in fair condition despite the fact that inspections and repairs are left to the will of the owners. The reasons for this are many. They were built with solid brick or stone masonry and wood joist structures instead of steel, so the detrimental effects that corrosion has on masonry does not occur. Their façades are usually very simple, with limited protruding architectural features. Their lower height reduces exposure to weather elements. And maintenance and repairs, when needed, are easier to perform on these buildings.

3.1 Case Studies

The following presents three case studies about terra-cotta and stone façades.

Terra-cotta cladding and ornamentation are among the most critical architectural features that are often subject to careful examinations and subsequent repairs. Terra-cotta elements are hollow blocks serially produced out of molds with the intent to replicate stone. Terra-cotta cornices, balconies, lintels, sills, pinnacles and piers were used by architects to create flamboyantly decorated façades. The blocks were secured to the brick back-up wall with steel anchors and clamps. A significant example is a 14-story Neo-Gothic tower, located on the Upper West Side of Manhattan and built in 1911 (Fig. 1). Originally, the building was entirely clad in detailed high-relief, glazed terra-cotta. During the 1950s most of the ornament and approximately 60 % of the flat ashlar terra-cotta were replaced with brick. A significant amount of terra-cotta remains and the building is still a stand-out on its block in a Historic Landmarked District and is an individual Landmark itself. In 2006,

Fig. 1 The upper west side building façade before the majority of the terra-cotta decoration (*left*) was removed in the 1950s and how it looks today after the repair campaign (*right*)

Thornton Tomasetti was engaged by the owners to perform the Local Law 11/98 critical examination and file the report. The unsafe conditions were many and the building was classified unsafe. The main issues were related to the terra-cotta ornamentation: its close proximity to steel members, a lack of maintenance, and ineffective and improper repairs had caused major cracking and splitting of the terra-cotta elements. In many cases, the cracking and splitting occurred along protruding elements such as sills and vertical piers (Fig. 2). The deterioration was so widespread that the cost for repairing or replacing the terra-cotta (about $1.3 million) amounted to 50 % of the cost to repair the entire street façade. The project goal was to save as much of the original fabric as possible and minimize substitution with new material, but many blocks (about 30 %) had to be replaced because they had broken into too many fragments.

The importance of periodic examination of the New York City buildings is demonstrated by the building located at 230 Park Avenue (Fig. 3). The inspection revealed widespread cracking of extremely large terra-cotta ornamental elements, such as at the three-story tall columns located between the 28th and the 32nd floor, the full-story brackets below them, and the seven-foot (approximately two-meter) tall buffalo heads. Almost all of the terra-cotta was preserved, thanks to a customized anchoring system that re-secured the elements to the structure behind.

Sometimes the five-year periodic inspections prescribed by the law are not sufficient to address all of the conditions developing on a building. In this case, the QEWI recommends more frequent inspections so that no hazardous conditions are left unaddressed, and the cost of repairs can be spread over a longer period of time rather than concentrated before a five-year deadline. This is the case at a downtown Manhattan

Fig. 2 Upper west side building. Fractured terra-cotta sill: cracking propagates along the entire length of the sill and up into the vertical pier (*left*). Extreme deterioration of terra-cotta ashlars due to the corrosion of the steel beam behind them (*right*)

Fig. 3 Fractured terra-cotta bracket (*left*); brackets are located below the three-storey tall columns at the 28th floor of 230 park avenue, New York City (*right*)

Fig. 4 A crack, originated by the corroded steel cramp and exposed by the removal of the adjacent stone unit, is visible at the cut line of the probe but not yet visible on face of the stone (*left*). Limestone façades of the office building (*right*)

office building, which occupies an entire city block, with façades built of large limestone blocks (Fig. 4). The steel cramps used to secure the blocks to the back-up structure were installed so tightly into the stone notches that when corrosion began, the pressure initiated fracture in the surrounding stone. The resulting spalls, however, do not reveal themselves to the observer until they are fully formed and become unsafe conditions. Because of this, more frequent inspections have been recommended.

4 Final Considerations

Although Local Law 11/98 was not conceived with the intent of protecting historical buildings and does not provide any direction in terms of methodology for inspections and repairs, it has had an impact on the building conservation. This impact has been predominantly positive because the periodic inspections have helped to detect detrimental situations at early stages and to address their effects on the historic fabric in time for effective repairs. Nevertheless, the ultimate responsibility for understanding the damage and specifying the proper repairs is left to the QEWI. Unjustified removals of architectural features or improper repairs may still occur if the building is not protected by the Landmarks Preservation Commission, if the owner is uninterested in preserving façade features, or if the architect does not have sufficient knowledge and experience to recommend the proper response. The past 10–15 years have seen more complex and clearly articulated procedures—such as "planned conservation" organized not only around the monitoring and the maintenance of buildings, but also involving large-scale risk assessments and everyday operational activities—have been implemented mostly in the European countries (Della Torre 2003). Local Law 11/98 may have been founded on simple principles to achieve simple targets, but by improving maintenance, it has certainly lengthened the survival of many historical building façades.

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Recovery and Reuse of the Architectural and Urban Heritage of Carbonia, a 20th-Century Company Town. Materials for a Handbook

Antonello Sanna and Giuseppina Monni

Abstract The policies and strategies put in place in 2001 for the requalification of the architectural heritage of the company town of Carbonia, and for the recovery of the "Great Mine of Serbariu" (that won the *Landscape Award of the Council of Europe in* 2010–2011), was based on a close collaboration between a multidisciplinary team of the University of Cagliari and the municipal administration of Carbonia. "The Handbook for the recovery", whose construction is still underway, fits this framework and coincides with an operational tool that regulates action on the built heritage. It does not provide a catalogue of standardized solutions, but merely defines a knowledge base to guide the designers towards the recognition of the buildings' invariant aspects and towards the understanding of the original architectural expression.

The "Handbook for the Recovery" of modernist buildings coincides with a significant stage in a study, still underway, that concerns that branch of research regarding the preservation and recovery of modern heritage and in particular in the renewal of residential buildings in series and its urban fabric. Together with the other close satellite towns, Bacu Abis and Cortoghiana, Carbonia has an architectural and landscape heritage that may be called an "author's product" designed and built with high levels of quality, an emblem of 1930s industrial modernization in Sardinia, but currently invested by specific challenges of recovery and reuse. It is not a matter of specific pin-pointed problems regarding single objects, although relevant, but rather a problem involving the complex urban organism, that requires complex and articulated strategies to deal (Fig. 1).

The reasons for the foundation of Carbonia must be found in the discovery of the massive coal deposits in Serbariu, and more upstream in the desire to build an autarkic coal district able to answer the nationwide issue of energy sources. The salient phase and then the deep crisis affecting the political strategy soon forced Carbonia to confront with the fragility of the urban and industrial programme, not always able to adapt to the new purpose and new collective practices. Following the

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Fig. 1 Carbonia. View of the company town from the north, 1940

Fig. 2 Carbonia. Perspective towards the "Great Mine" of Serbariu. In the foreground the single workers' accommodations

mine's closure, Carbonia has gone from an incredibly rapid growth to an extreme crisis that called into question its very existence and undermined the identity of the foundational phase (Fig. 2).

For this reason, since 2001, the city administration, with the scientific support of a multidisciplinary team of the University of Cagliari, started up a process of

Fig. 3 The "Great Mine" of Serbariu and its infrastructures

sustainable recovery based on the culture's economy and the search for renewable energy. The program focuses primarily on the recovery of the 'Great Mine' of Serbariu that, in the time frame of 10 years, has been turned from a symbol of the industrial modernization into a centre of cultural and technological development. And thanks to the restoration project for this industrial landscape, characterized by its rationalist architecture, Carbonia won the *Landscape Award of the Council of Europe* in 2010–2011. It is then added to the most famous European cases regarding the restoration of a company town, a large development project based on the construction of an integrated industrial landscape (Fig. 3).

The construction of the first-phase project of the coal town, which provides for a population of some 12,000 inhabitants, begins in 1937 and concludes at the end of 1938. Shortly afterwards the inauguration it begins the construction of the second-phase project that is expected to welcome 50,000 residents and will end in the immediate post-war period. The outcome is a company town at the mouth of the mine, formed by the serial repetition of few building types in a hierarchal urban design of high quality landscape.

Called upon to plan it and oversee its construction were Trieste born Gustavo Pulitzer Finali, a fine yacht designer and author of the zoning plan and buildings of Arsia, the coal town of Istria, and two roman professionals, Cesare Valle and Ignazio Guidi, that shortly after will sign the plan of Addis Abeba. They designed a garden city perfectly integrated into the landscape and in direct contact with the mine at the same time. In a second moment the young Eugenio Montuori was added to the team, he drew among others the central single workers' accommodation, known as the Albergo Centrale. Soon after, in 1940, Saverio Muratori will be engaged with the construction of the neighbouring satellite town of Cortoghiana, for which he designs the urban asset, public buildings and most of the residential building types (Fig. 4).

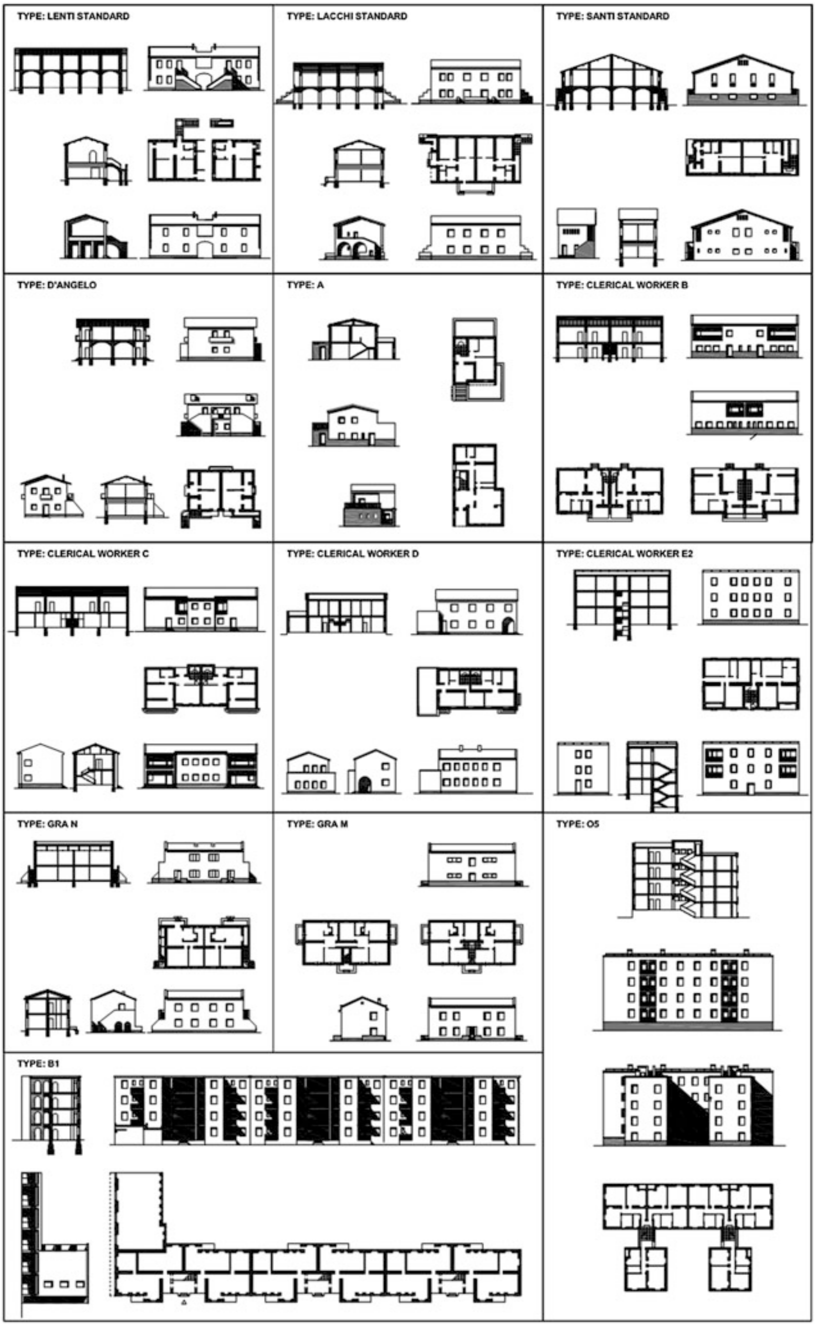

Fig. 4 The abacus of the different residential types that, among other things, illustrates the transition from the arched floor, used during the first phase of construction, to the hollow block floor, introduced essentially in the second phase, and the introduction of the intensive building types

Those young designers, almost all in their early thirties, had then to deal with the need of synthesis between the "modern" requirement of their cultural positions and the limits imposed by autarky, furthermore emphasized by scarcity of the resources and the difficulties in the supply of the materials.

Equally "signed" were the workers' lodging types of the first-phase project, two-storey four-family homes surrounded by a garden and also designed in the forms of "autarkical rationalism". They coincide with a sort of local version of the typical English cottage, a symbol of preindustrial and rural houses. For some precedents of this compromise, we have to refer to the lesson of Muthesius or to Tessenow's "modernity with no avant-garde". And the result may be called a version of "Mediterranean rationalism" that seeks a mediation between the masonry in elevation and the introduction of the reinforced concrete (Fig. 5).

The peculiarity of the "autarkic project" emerges, for example, in the arched floor of the first building types realized with cement bricks produced on site. They form a vault that transmits its load to the trachyte masonry wall through a concrete edge beam or the presence in some "Pistoni", an intensive building type designed by Montuori in the second-phase, of a framed structure within load-bearing masonry. And still in the use, in the second-phase of project, of the more advantageous reinforced concrete floor, "Sap-type" or "Rex-type", both made of prefabricated beams and "weakly armed".

The single workers' accommodations deserve a separate discussion. They constitute a substantial change of scale in relation to the types of the garden cities, their urban dimension is enhanced by their disposition in pairs heading down the main pathways connecting the dwellings with the mine. Those are the only residential building types of Carbonia directly attributable to G. Pulitzer. There he used a reinforced concrete floor, "type-Rex", and a structure of reinforced concrete trusses with a section extremely thin to cover environments with a space 10–12 m wide. That relatively simple grid structure, which Pulitzer also used in the building called *Dopolavoro* (OND), is an interesting element of continuity between the civil construction of Carbonia and the buildings of the "Great Mine" of Serbariu. Although it was a distinctively "technical and industrial" detail used in the "Great Mine," it had been applied on residential buildings types, witnessing the interplay between constructive culture of Carbonia and its mine.

In the division of the roles of autarkic policy, the mine depicts the technological development at the highest level. The large reinforced concrete trusses with their slender section in the workshops and the electrical plant are juxtaposed to the infrastructure of the 'steel castles'. In the Lampisteria (or Lamp room; the hub connecting the town with the galleries in which the miners picked up their headlamps before descending) the barrel vault, realized with a sequence of reinforced concrete arches of great span hidden by an evenly plastered surface, abandoned its orginal meaning of massive formal element. A skylight straights overhead, enclosed in glass blocks, exposes the structural game and helps to emphasize the metaphysical character of this space.

Following the intervention of recovery, mostly financed with European funds, the pavilions of mine have become the nodes in a network of activities oriented to

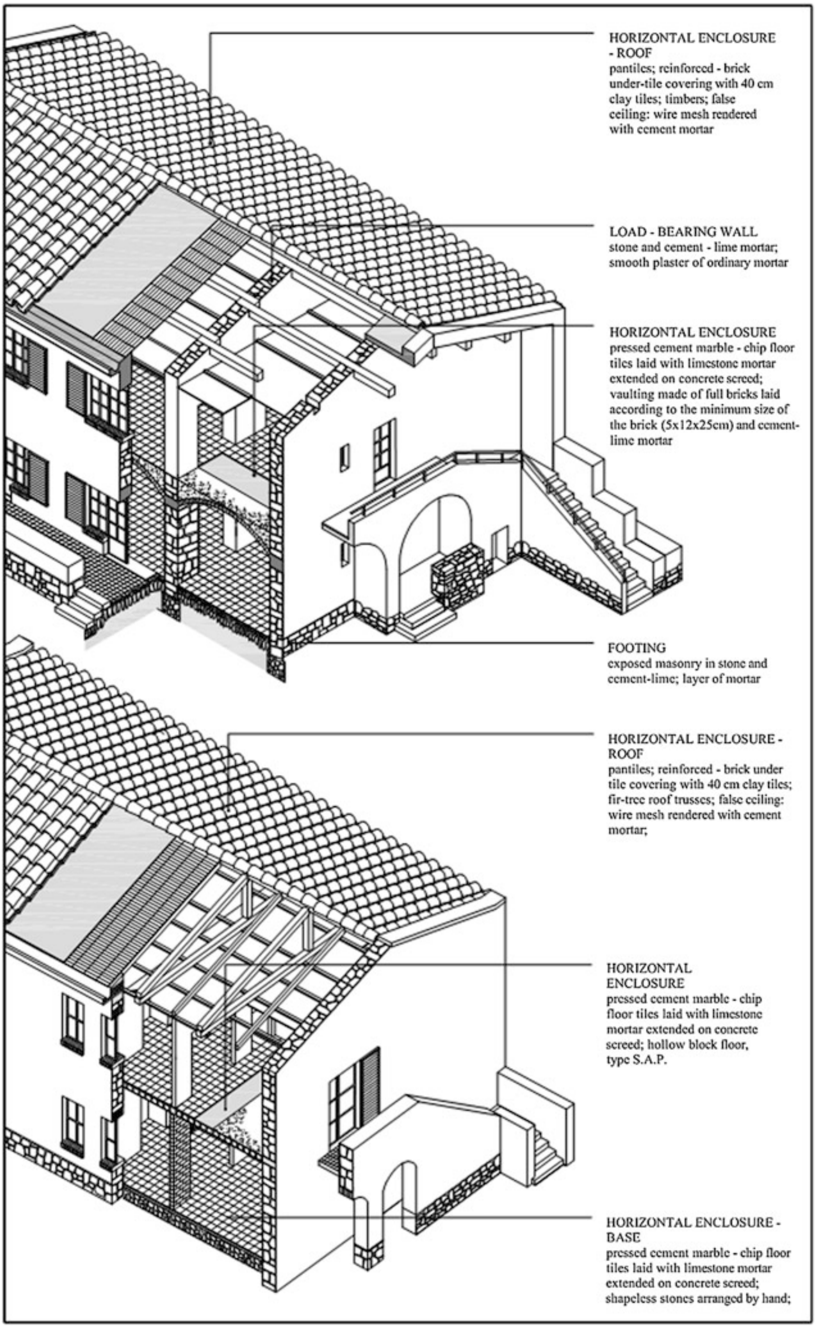

Fig. 5 The comparison between two cut-aways: the "Lacchi" type, realized in the first phase, and the "Gra N" type, that belongs to the second phase of construction

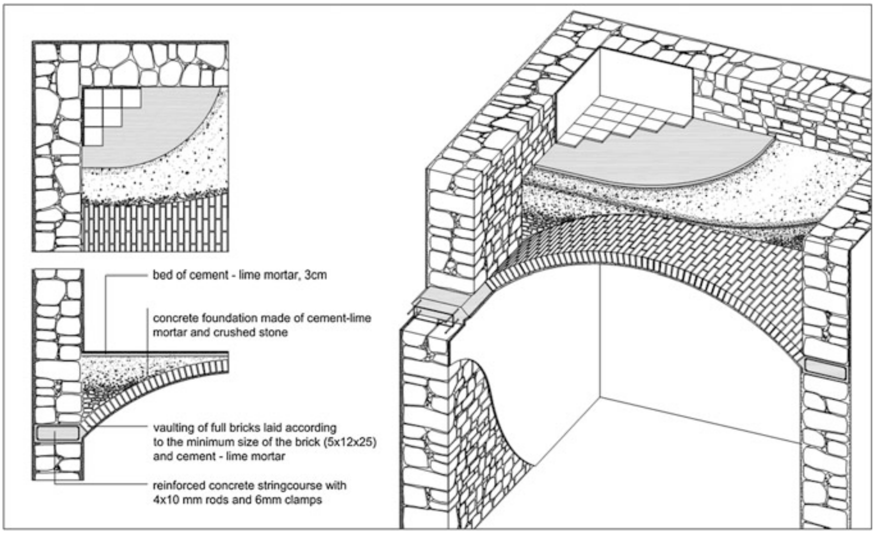

Fig. 6 Datasheets from the "Handbook for the recovery": detail of the arched floor used in the "Lenti standard" type

culture, research and industrial development of sustainability, innovation and energy efficiency. The Lampisteria has been transformed into the Italian Center of Coal Culture (*Centro Italiano della Cultura del Carbone*), a combination scientific and anthropological eco-museum. The original path to fruition of the miners has been reconstituted by the recovery of galleries and wells equipped with elevators. The library and historical archives of the mine and the city are located in the adjacent pavilions, the Officine hosts another scientific museum, the *Museo dei Paleoambienti Sulcitani*. The Tornerie houses a research facility for the University higher education, dedicated to the experimentation of solutions for energy efficiency and alternative energy sources. Another contiguous industrial buildings, serving the mine, hosts the "Sotacarbo", a centre for sustainable energy research and experimentation on the use of coal.

The recovery of the mine is part of a more ambitious goal, represented by the requalification of the entire urban and territorial system of the company town. The intrinsic "permeability" of the garden city has actually made the buildings vulnerable to the corrosion and eased the severe decay of houses, compromising seriously the understanding of the original idea.

The point of departure coincided with the new urban plan that is conceived as a heterogeneous and diversified tool with a series of studies that create a complex strategy and design process. The plan is based on a few key elements. The first expression of the new urban plan is the "Quality Charter", written to function as a summary of previous papers and matrix of coherence for the city's urban and design strategies. The second is an "Urban and Architectural Quality Workshop", the coordination centre for the realisation and design activities for the restoration of

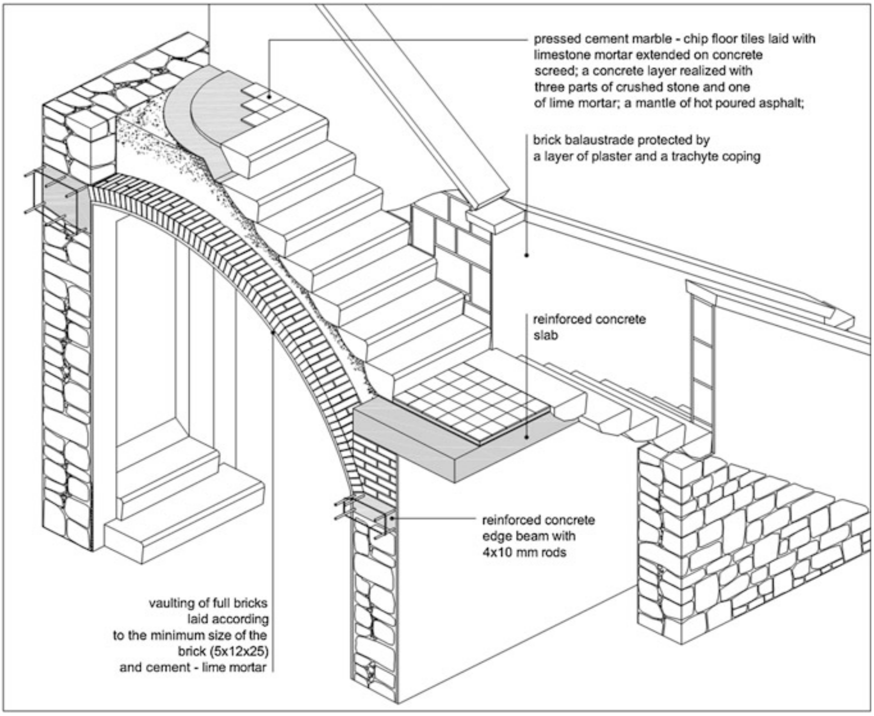

Fig. 7 Datasheets from the "Handbook for the recovery": detail of the stairway used in the "Lenti standard" type

public heritage which scientifically monitors the jobsites. It checks and controls the private sector initiatives that bring about and actually conduct the interventions in the company town, concerning both philological restoration and changes or extensions of residential spaces. It is a research and operation centre that conducts experiments regarding the application of advanced models for the daily management of the city. It is, therefore, perfecting and implementing a complex strategy aimed at flexible restoration policy that deals with problems directly connected to the coexistence between various cultures, their housing tendencies and the original architecture of Carbonia's buildings. The third key element is the "Handbook for the recovery" of modernist buildings, i.e. an operational tool of guidance and support interventions on heritage. In the tension that is generated in the time between continuity and change, the Handbook is designed to ensure the quality of the conservation project: it investigates the traces of the '*how to build*' of the autarkic rationalism, it studies the anatomy of the buildings of the foundation with an effort of critical reconstruction of design and construction cultures, it begins to outline the guidelines for the difficult path between the preservation of witness buildings and the regeneration of its changed urban fabric. It does not provide a catalogue of standardized solutions, but merely defines a knowledge base to guide

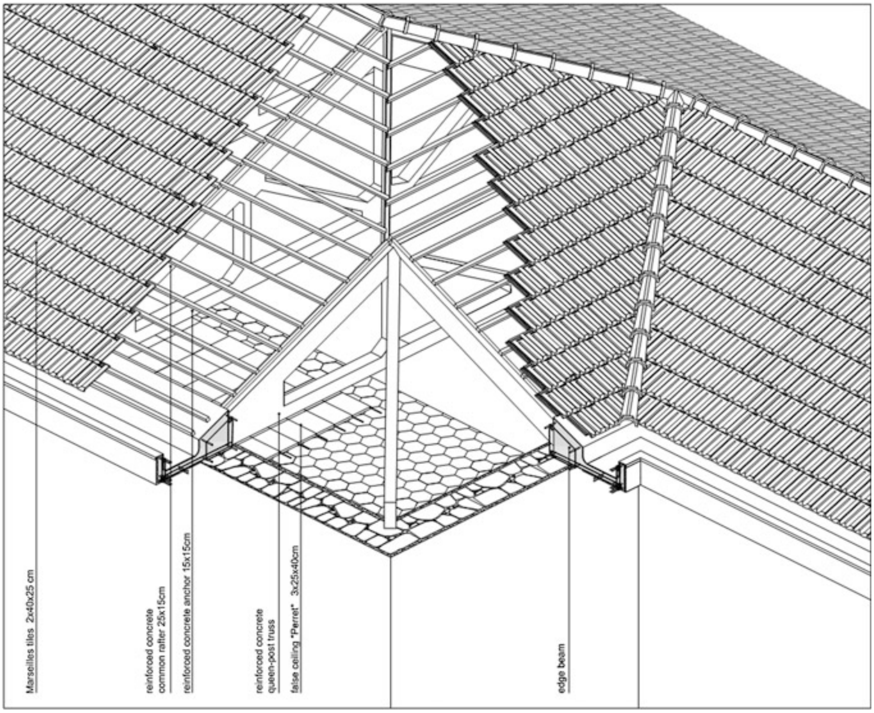

Fig. 8 The design detail of the roof and gutter in the single workers' accommodations, from the "Handbook for the recovery"

the designers towards the recognition of the buildings' invariant aspects and towards the understanding of the original architectural expression. The "Handbook" is emerging as a "Code of Practice": through technologically advanced analysis it identifies features and fundamental performances of building components and identify design methods consistent with the objective of conservation (Figs. 6, 7, 8).

In this regard the "Material Technologies Working Group" has carried out sample surveys on the built heritage of Carbonia with functional objectives for the preparation of the Handbook: assessment of the state of artifacts' conservation, identification of the weathering forms and damage categories; preparation of an atlas of the degradation forms; instrumental checks on materials and technological object of interest, with particular reference to the production technology of the materials most relevant, especially binders, reinforced concrete, bricks. The information gathered from these surveys are the key elements and guidance for proper planning of interventions on the built heritage.

It explores the history of the construction methods of autarkic rationalism also making use of all the documents found in the archives: such as design drawings, historical photographs and especially booklets yard. It reconstructs the anatomy of the early buildings, investigating on the connection between design—construction

Fig. 9 The restoration of the *Dopolavoro* with the design of the gutter

—modification also through careful study of the detail solutions. At the same time, the search path will analyze and discuss the practices of intervention in cases of recovery already made and verified in the field.

Emblematic in this regard is the intervention of conservation and recovery of the industrial building whose specificity has required diversified modes of intervention. The thin sections of the trusses and the thickness too contained of the iron covers, now out of norm, did not give sufficient guarantees against corrosion and in many cases the concrete is absolutely disaggregated and iron completely corroded. Sometimes, recourse was made to complete replacement and reconstruction "as it was where it was", especially in a case in which the great structural skeleton of the roof (which the process of degradation had revealed), is left in sight and used as a container open air, i.e. "an architecture inside the architecture". In the building that hosts the historical archives the iron structure has been recovered with the carbon fibers and the original trusses have been restored in situ. And more in the *Officine*, transformed into the *Museo dei Paleoambienti Sulcitani*, however, the load-bearing masonry has been emptied and the roof, irreversibly collapsed, was reconstructed with steel structures.

An other meaningful intervention, documented and discussed, is the recovery of the *Dopolavoro* (OND) designed by Pulitzer in 1937. Also this operation required different approaches. The high-ceilinged hall, used originally as a local leisure hall, was returned to its initial spatial configuration even if the function has of necessity become the new civic assembly hall, fully compatible with the architectural and spatial features of the *Dopolavoro*.

The existing fixtures and plaster facade of the porch were the subject to "philological" restoration. The recovery of the gutter has posed important problems in terms of method, because of the discrepancies between the original designs and construction, and its technical defects. From the drawings and site documents it emerged that Pulitzer had planned to protrude the gutter and to use a reinforced-concrete floor between trusses. During construction, the projection was reduced to 30 cm and it was preferred to use thin reinforced bricks known as "Perret", which is more fragile and much more breakable. The latter has collapsed because of the extreme slenderness and the iron oxidation so it was replaced in the 1980s with a reinforced concrete floor of greater depth and mass, which, however, has compromised the function of the gutter to the "reduced" extent "with which it was originally performed. Moreover, the investigation of project documents has made it clear that the importance and the strong projection of the gutter was linked to the design role that Pulitzer gives it in his buildings. This aspect emerges with even greater clarity in the single miners' accommodation, where the gutter reaches the eaves, jutting out 60 cm, performing admirably in the protective function that is proper, but at the same time mitigating the "domestic" character of the gabled roof. While retaining the traditional structure, he was able to give the illusion of a "modern" pure volume covered with a terrace from an angular perspective. Thus the restoration has led to the reconstruction of the gutter in compliance with the intent of the original design but with a height compatible with the modifications already undertaken and considered irreversible (Figs. 9 and 10).

Also one of the single workers' accommodations, however, was the subject of an action for recovery. The relatively good state of preservation of this historic architecture has guided the intervention towards a "philological" conservation and with the support of the Material Technologies Working Group it was possible to recover the original plaster and the flooring. However, it was necessary to change the initial function with a compatible use. And so this building currently is a Youth Integrated Education Centre.

The same philosophy is also applied to intervene in the public space. The Handbook, for example, develops an accurate philological reconstruction of the phases of the project and realization of the central square Piazza Roma, where is condensed the architecture of power that gave rise to the company town. There we have the headquarters of the Party (Torre Littoria), its propaganda buildings (Cine-Teatro, Dopolavoro), the Church and, more modest, the City Hall. The square is a huge space, a terrace overlooking the landscape, between the porch of the OND and the parterre of City Hall. Every public building has its "thematic square", with

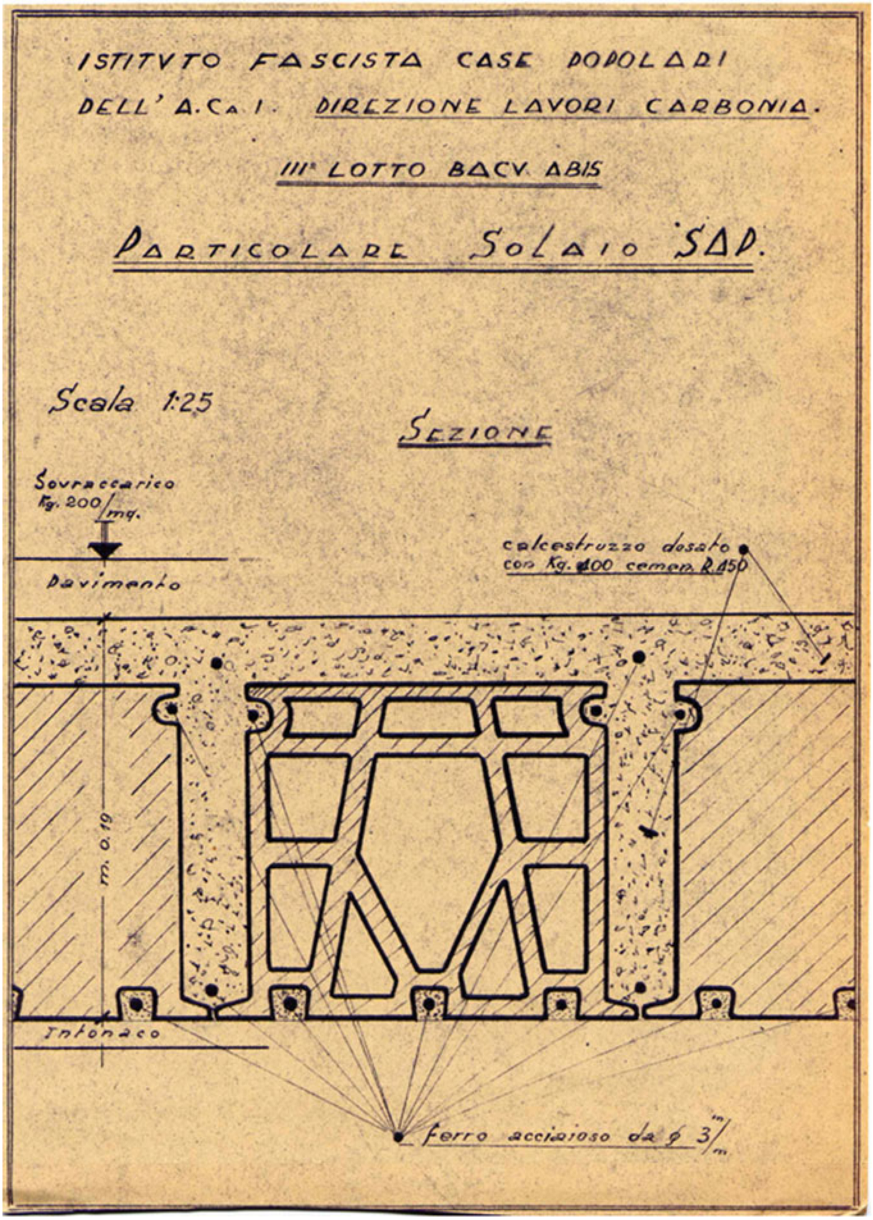

Fig. 10 "Sap" type attic detail, namely a structure of in situ reinforced concrete beams, which not only permits less metal to be used but also does not require the use of wood as it is sufficient to insert a simple beam on the centre—line of the span, (Carbonia, AREA record office)

Fig. 11 Piazza Roma. Restoration of the public space

paved floor and water points, while the rest of the square was once an undifferentiated area covered with dirt, gravel, asphalt, and recently occupied by roads and car parking lots with improper uses and objects.

The urban regeneration project, organized by the City Hall-University Laboratory, has reconstructed the original concept of the central square, transforming it into a pedestrian space with a homogeneous and "abstract" stone surface recovering also the meaning of "metaphysics" of the great urban space and with the inclusion of a 'contemporary work of art, the "empty fragment" by Pomodoro (Fig. 11).

Inventory, Preservation and Valorization of Historic Roads in Lombardy Region (Italy). Current Policies and Future Plans

Alberta Cazzani and Camillo Sangiorgio

Abstract The historic trails form a very interesting architectonic and cultural linear system: not only the traces, but also the road works (walls, bridges, tunnels, drain wells, etc.), the connected buildings (churches, chapels, fortifications, custom-houses, mills, mines, etc.) rose out of ancient religious, military, commercial or industrial functions with a relationship between villages, towns, landscapes. Leaving out the more ancient trails (roman and medieval roads) with a lot of archaeological importance, there are in Italy many XVIII–XIX century roads now transformed or abandoned and decayed. These could be used now as trekking, cultural and museal resources, but it is necessary to preserve and conserve this heritage with specific inventories, analysis and restoration projects. The paper illustrates some recent studies and plans with guidelines for evaluating, preserving, rehabilitating, restoring and managing the Lombardy historic system trail. Particularly the goals of this paper are to: Describe the historic roads inventory that the Politecnico of Milan, connected with Lombardy Region Forestry Agency, made, comparing XIX century military maps with current maps to understand the permanence of the itineraries. Present the analysis and survey work made in some Lombardy areas to check the conservation levels of the inventoried roads and the architectural and landscape features connected to them. Show some detailed surveys of historic road segments analyzing materials, building techniques, decay problems and transformations to define conservation and rehabilitation treatments. Explain the Lombardy historic roads GIS set to organize and join all the gathered and surveyed data and to manage them in the future.

The roads system in Italy is very old: some of the ancient Roman and Medieval itineraries, transformed and modernized, are still in use and they present a lot of archaeological importance. During the XVIII and XIX centuries a modern road system developed in Italy to respond to the traffic needs and to increase the connection

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from North Italy to Europe through the Alps. Many roads were often built to perfectly connect and integrate the natural and cultural landscape around them.

These roads present notable architectonic, technical and cultural values: not only the traces, but also the road works (walls, bridges, tunnels, drain wells, etc.) and the connected buildings that rose out of ancient religious, military, commercial or industrial functions with relationships between villages, towns, landscapes.

These historic roads in Lombardy Region are often still in use, even if increased traffic has led to transformations and modernization, often deleting the old settlement and altering historic architectural features.

Considering historic roads like an architecture, makes necessary to analyze not only typology and dimension, but also constructive techniques, materials, connected features in order to recognize decay and alteration problems and to define preservation treatments (Boriani and Cazzani 2002).

Historic roads characteristics are often joined with traditional way to build and local materials: they have to be studied to delineate specific conservation and recovery projects. It is necessary to preserve and conserve this heritage with specific inventories, analysis and conservation projects focused on cultural, trekking and museum reuse.

With this purpose the Politecnico of Milan, connected with Lombardy Region Forestry Agency, made a historic roads inventory comparing XIX century military maps with current maps to recognize the permanence of the old itineraries and also to understand the social, cultural and political value of the historic roads, studying the national and international importance of them for tourist development and commercial purposes (Boriani et al. 1999c).

Analyzing a historical map of XIX century we can understand how the road system was in the past more spread and diffuse. There were not only the most important commercial, religious and military itineraries, still recognizable and in use, but also many roads and trails built to get accessible different productive places like agricultural areas, woods, mines, farms. The present road system, particularly in mountain zones is less spread because a lot of areas—that historically were productive and important—lost their economic interest. Agricultural groves, mines, mountain pastures, paper mills are now abandoned and fortifications, customs, defensive features are now useless. The old road system, even if is now not used and in decay—is often still readable and represents an important historic and architectural document and also a cultural, touristic and trekking resource (Fig. 1).

The historic route network represents for North Italy—connected with the important economic and political areas of Germany, France, Switzerland and Austria—an important heritage that is threatened by the continuous man-made processes transforming the infrastructure of the territory.

The approach of Lombardy Region Inventory foresees a documented historical study and cartography analysis, the field identification of all the elements related significantly to ancient communication routes with a direct survey of the built remains to define preservation and management criteria (Boriani et al. 1997, 1999a).

Inventories must be considered as the first phase of a more complex policy of landscape preservation and management. They lead to the preparation of a historical

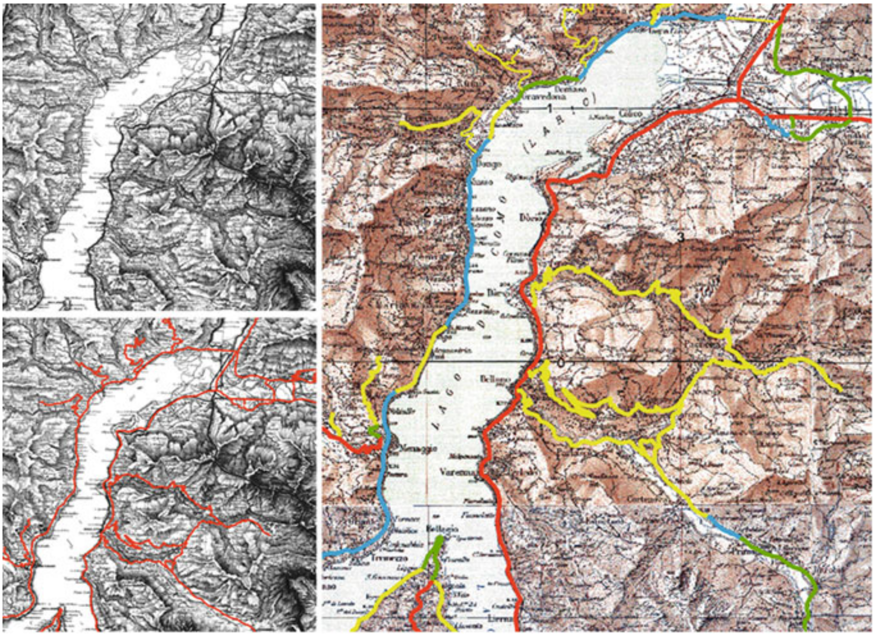

Fig. 1 The first step of the Lombardy historic roads inventory, comparing the very detailed XIX century military maps (*on the left*) with the current map (*on the right*). With different *colors* we *underlined* how the present State and Regional roads were classified in XIX century

and analytical reference map. Starting from this cartographic inventory in some Lombardy areas where a lot of historic roads are still recognizable—particularly in the Alps—Pre Alps zones—a deeper analysis and survey work was made to check the conservation level of the listed roads and to identify the architectural and landscape features connected to them. Detailed surveys of historic road segments were completed, analyzing materials, building techniques, the transformations and their present situation, showing decay and alteration problems, architectural and landscape values, and rehabilitation potential in order to define conservation and management treatments.

The historic trails are not considered only for their traces, but also with respect to the natural and cultural sites and scenic views linked with them. This means that historic trails are preserved and valorized along with a corridor extending sometimes several meters wide, forming a linear park that connects other sites and areas of historical and naturalistic interest (Fig. 2).

The methodology set up by the Politecnico of Milan is, therefore, aimed at counting historic communication routes as a cultural heritage (whose typological, architectural and material features must be analyzed and conserved) that are closely connected (functionally and spatially) to a system of historic sites (customs houses, chapels, boundary stones, taverns, road engineering works, areas of natural and scenic interest, etc.) creating a complex territorial system to be preserved by defining

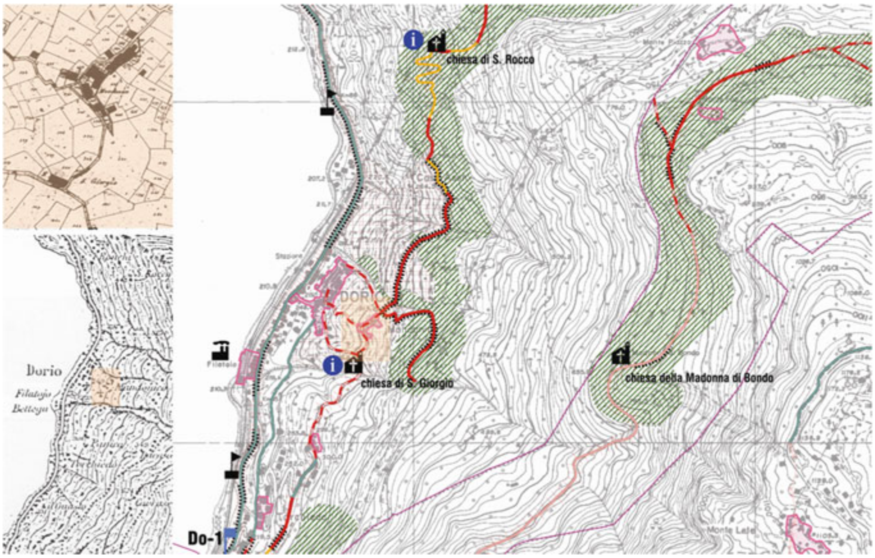

Fig. 2 An example of Lombardy historic roads survey, studying the old maps, considering the conservation level and analyzing the historic roads materials, characteristics and features

landscape planning criteria, identifying necessary conservation treatments and foreseeing plans for rehabilitation and management, in the context of a larger complex of environmental preservation policies.

The goal is to recognize the historic road system network as fundamental settlement of our cultural landscape and a significance component of our heritage: through a first analytical phase carried out by comparing historic maps and studying archive and bibliography documentation and a second subsequent phase with site examinations to deeper investigate the result of the historic research and to identify not documented trails and connected elements.

The results of the surveys are elaborated with the definition at a scale of 1:25,000/1:10,000 of a *Carta del Terreno*, a *Map of Terrain* utilizing the Lombardy Region aero photogrammetric maps and a specific catalogue of conventional symbols: historical roads and trails, joined features and eventual traces and relicts document the structural and morphological elements of the road network.

All the man works and supports that characterize the historic roads (walls, pavement, water system, bridges, etc.) and the connected sites related with the old function of the itineraries, like chapels and churches for religious trails, fortifications and trenches for military roads, mills and factories for commercial roads are identified and geo-referenced on the *Maps of Terrain* (Fig. 3).

The historic roads (divided in segments homogeneous for typology or architectural/material characters) and the connected sites underlined in the *Maps of Terrain* are also carefully analyzed filling out specific forms to organize historic documentation, to describe and to evaluate the present condition. Attached to these

Fig. 3 *Map of Terrain* and *Synthesis Map* legend to survey historic roads analyzing materials, building techniques, decay problems and transformations, to evaluate their level of conservation and permanence to define conservation and rehabilitation treatments

maps is a report that provides detailed information on the historic roads system, underlining values and resources as well as problems and negative impacts.

The forms are useful to describe typological, architectural, material characteristics, conservation level, preservation problems and rehabilitation potentialities. In that way the forms are not only an analysis tool, but also a pre-project useful instrument, able to evidence resources and values, lacks and vocations that must be considered to carry out a good preservation plan.

The historic roads and trails are then classified and evaluate in a final map, the *Carta di Sintesi*, *Synthesis Map* (drafted at a scale of 1:25,000/1:10,000 using specific conventional symbols) according to their importance (national, regional, local) and their level of conservation and permanence (roads/trails with great historic substance, with historic substance, without historic substance).

The *Synthesis Maps* constitute a fundamental reference for planning processes that must consider historic roads and trails as elements of our cultural landscape to be preserved.

To better handle the results of these studies, it was set the Lombardy historic roads GIS to organize and join all the gathered and surveyed data and to manage them in the future (Fig. 4).

Therefore it must be reminded that the historic road inventory and survey are not only useful for a quantitative knowledge, but also for qualitative knowledge, to evaluate the current conditions and to define the criteria needed to preserve and valorize these sites. The *Synthesis Map* can also assume legal and binding value for the regional authorities and it is available to the Provinces and Municipalities as an auxiliary planning tool.

This analysis and survey work allowed to check the conservation levels of the inventoried roads and the architectural and landscape features connected to them.

The research about historic roads demonstrated the exceptionality and peculiarity of this tangible and intangible heritage that requires specific preservation

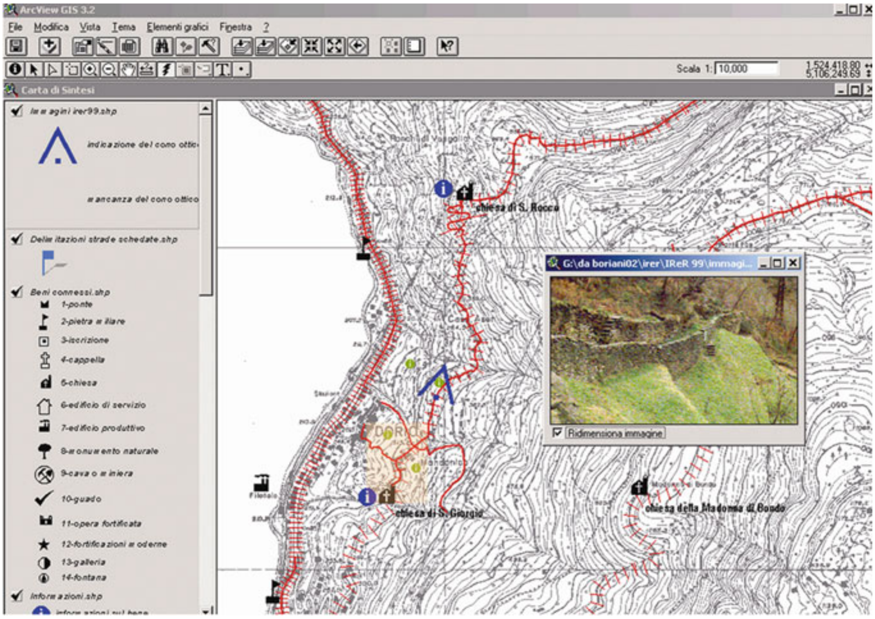

Fig. 4 A detail of Lombardy historic roads GIS set to organize and join all the gathered and surveyed data and to manage them in the future

policies. With this purpose detailed conservation guidelines were issued to describe in a meticulous way historic roads typologies, constructive techniques, traditional materials, architectural characters, typical features and to illustrate a preservation approach.

Particularly the expressed goal of the *Guidelines for preserving historic roads* is retention of the trail's existing form, features and detailing. This may be as simple as basic maintenance of existing materials and features or may involve preparing a historic structure report, undertaking laboratory testing and hiring conservators to perform sensitive work. Protection, maintenance, and repair are emphasized while replacement is minimized (Boriani et al. 1999d) (Fig. 5).

The guidance begins with recommendations to identify the form and detailing of those architectural materials and features that are important in defining the road's historic character and which must be retained in order to preserve that character. The character of a historic road is defined by the form and detailing of materials, by connected features, by spatial relationships, as well as structural systems; and the road's site and setting.

When the physical condition of character-defining materials and features requires additional work, repairing by stabilizing, consolidating, and conserving is recommended. Preservation strives to retain existing or traditional and compatible materials and features while employing little new material as possible. Consequently, guidance for repairing a historic road's component or feature again begins

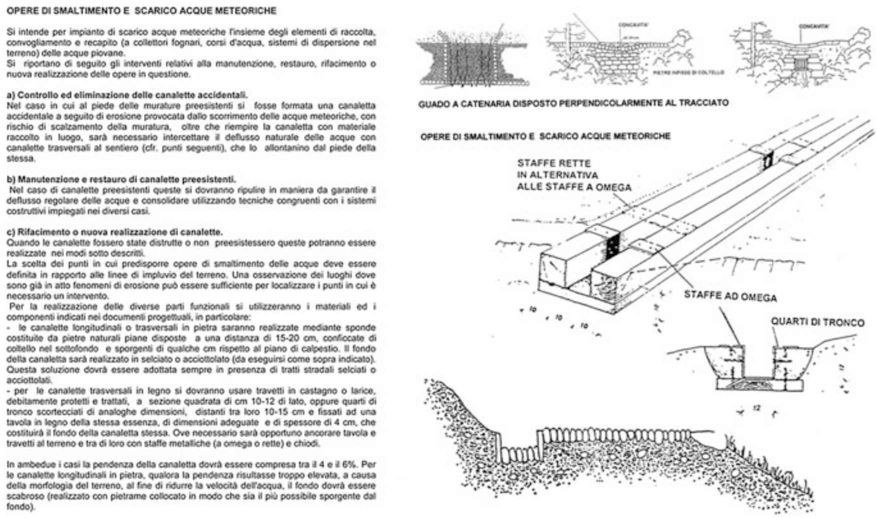

Fig. 5 Guidelines for rehabilitating, conserving and managing the Lombardy historic system roads: a detailed analysis and description of features and components of historic trails allows to define specific preservation and management treatments

with the least degree of intervention possible such as strengthening fragile materials through consolidation. Portions of a historic structural system of the road could be reinforced using contemporary materials. All work should be physically and visually compatible, identifiable upon close inspection and documented for future research.

With the aim of recovering and enhancing historic trails the Lombardy Region with Politecnico of Milano promoted some manage programs through specific plans for long trails the *Giubileo Trail* issued in 2,000 Jubilee to create a long itinerary to connect different sites with religious values and the *Peace Trail*, designed to valorize First World War fortifications, roads and historic sites. These plans analyze resources and conservation/alteration problems in order to define preservation and maintenance treatments to obtain a long itinerary with cultural, landscape and recreational value and to reuse it as an open-air museum.

Particularly the *Jubilee Trail* (Boriani et al. 1999b, e, 2000) is a 450 km itinerary along the West Lombardy Region border that uses different historic traces with the purpose of connecting historic, scenic, cultural and religious sites. It is the result of a detailed survey (delineating the *Maps of Terrain* already described) and *Synthesis Maps* to underline historic significance and conservation levels in order to issue a list of preservation and rehabilitation treatments to make possible the long itinerary use.

The *Peace Trail* (Boriani et al. 2001; Cazzani 2003) is located along the East Lombardy Region boundary, involving the fortification system set up during the First World War beside Italy and Austria border. From Livigno the trail crosses Stelvio National Park, Adamello Regional Park, continuing through Camonica

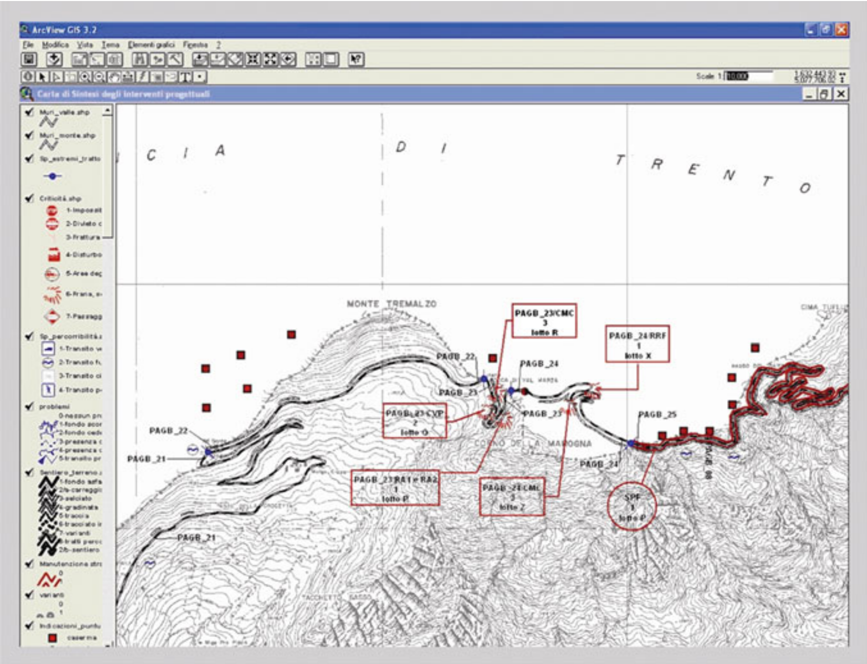

Fig. 6 The *Peace Trail Plan* a detail of the GIS map with architectural and material survey, conservation level, accessibility and modes of transit and the projected conservation and management treatments

Valley, Trompia Valley and Sabbia Valley to arrive to Alto Garda Bresciano Regional Park. The trail is 600 km long and it connects—in Brescia Province—several important scenic and natural areas and a lot of significant historic and cultural sites issued before and during the First World War, like forts, fortifications, trenches, roads, military villages and hospitals. The trail, thanks to military roads and infrastructure system allows to get in a very easy way many places also above 2,000 m., usually accessible only for expert hikers and mountaineers. At the same time the *Peace Trail* gives the opportunity to understand and to appreciate the complex First World War tangible and intangible heritage (Fig. 6).

Also for that trail after a detailed analysis, an executive project was prepared to establish conservation and recovery treatments, defining priorities, costs and management plans. The goal of the project was not only to design rehabilitation and valorization interventions, but also to provide a comprehensive maintenance program. The *Peace Trail* can be considered like a linear park, where it is possible to enjoy fabulous natural and cultural landscapes and—like an open air museum—appreciate First World War historic military architectures and features built at the beginning of XX century with particular, often standardized—constructive techniques and materials.

The Inventory of the Historic Roads of Lombardy Region, *Jubilee Trail* and *Peace Trail* are now included in *Lombardy Region Landscape Plan* (Regione Lombardia 2010). This Plan, established in 2010, underlines the necessity to recognize and valorize the regional historic and scenic road system, including it in the local planning tools.

A specific article of *Lombardy Region Landscape Plan* rule defines the historic roads and the importance of considering them in planning tools. Historic and scenic roads are underlined on specific maps of the regional plan, demonstrating the connection of these roads with modern infrastructures, bicycle and pedestrian trails, protected areas, views and vistas and the necessity to define preservation and planning criteria to improve cultural, natural and recreational values of this significant component of Lombardy landscape (Fig. 7).

With the purpose of providing references and standards for Lombardy infrastructures preservation, construction and management, the Lombardy Region established specific guidelines for local bodies and for professionals (Regione Lombardia 2009). The goals of these guidelines are to consider infrastructure system like a landscape resource, defining recommendations to conserve and rehabilitate historic and scenic roads and trails and to design new roads with compatible materials and constructive techniques with a low impact.

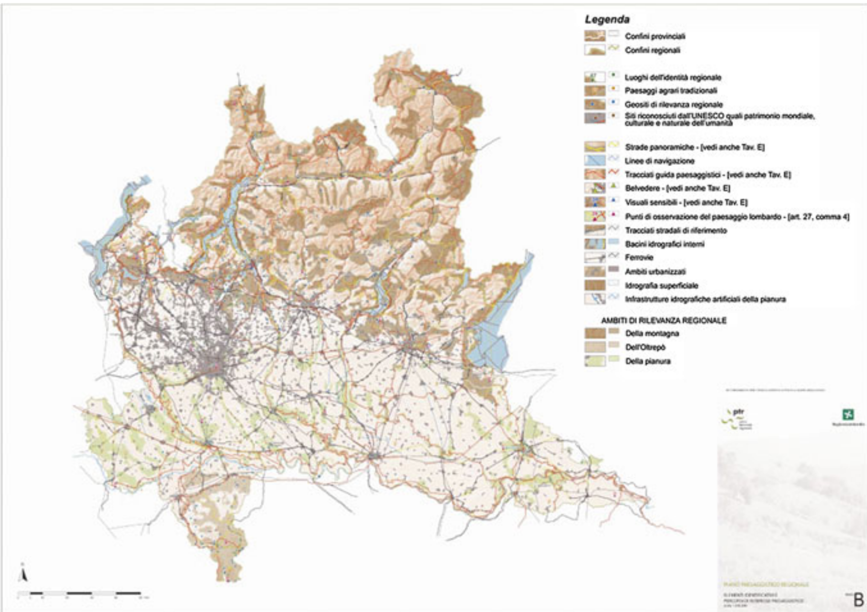

Fig. 7 *Lombardy Region Landscape Plan* historic and scenic roads, views, vistas protected areas, traditional agricultural zones are underlined in this map to define criteria to rehabilitate and to valorize Lombardy landscape

Considering roads like linear landscapes, able to connect several areas and sites with natural, historic, cultural importance means to program preservation and planning policies to increase values, to solve (or almost to control) alteration impacts, to take care of decay problems and to define new plans and projects focused on respect of the context and on landscape integration.

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Part II
Architectural Heritage: Diagnosys, Conservation and Monitoring

Structural Monitoring of Historical Constructions: Increasing Knowledge to Minimize Interventions

Eva Coisson and Federica Ottoni

Abstract In all the fields of restoration, from the artistic to the architectural one, the principle of minimum intervention is always mandatory: no work is allowed if not effectively needed for the perpetuation of the cultural heritage to the future generations. Within the architectural restoration interventions, this approach should be applied also to the structural ones, but often this doesn't happen, in part for safety's sake, in part for the cultural unpreparedness of some technical designers, who work indistinctively on new and old buildings. Increasing the knowledge and the understanding of the ancient monuments structural behaviour is the only method to decrease the uncertainties and in consequence to minimize the interventions, whose effective necessity has to be proven, in line with the theoretical requests. In step with this, the structural monitoring, with its different approaches, represents an important mean to increase this knowledge, investigating what happened to the structure in the past, understanding its present evolution and also controlling it in the future. The aim of this paper is therefore to inspect the role of structural monitoring in the knowledge and also in the conservation process of the built historical heritage, bearing in mind that knowledge and conservation should always go hand in hand.

1 The New Role of Structural Monitoring in the Italian Legal Framework

One of the most interesting, and in some ways innovative, contents in the recent Directive on the seismic protection of cultural heritage (DPCM 2011) is certainly the role ascribed, in the evaluation of the seismic risk, to the observation of the buildings and to their control, and thus to their monitoring.

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The Directive defines the "*regular monitoring of construction*" as "*a practice highly desirable because it is the main instrument for the conscious conservation*". Moreover, it adds that "*in some cases, when the possible collapse mechanism is well understood and safety thresholds can be reliably defined, monitoring can constitute a valid alternative to strengthening interventions*" (DPCM 2011).

The same concept had already been expressed, at the end of the 1980s, by the Commission Ballardini-Gavarini, which emphasized as "*from this data series [monitoring] can derive an indication on the building global behaviour, considering the phenomena that have taken place over time as a direct experimentation, at a real scale, very indicative and conclusive*" (Ballardini and Gavarini 1989).

Indeed, monitoring is not only a matter of understanding what has happened in the past: it can also assume an active role in the conservation of historical buildings. A methodology of slow experimental investigation is particularly suitable for the historic buildings, as it allows to calibrate a reliable model of the structure, which is not only able to understand better its "normal" behaviour but also to simulate responses to various accidental events (earthquakes, wind, temperature variations and changes in structural constraints). This procedure allows not only a continuous evaluation of the cracks and damages, but also short and long term forecasts and simulations on the behaviour of the monument, also assessing the actual effectiveness (or possible recalibration) of proposed interventions.

2 The Different Monitoring Strategies

Too often the structural monitoring is seen only as a sort of alarm system to signal an imminent threat. This is only one of the possible utilities of such an instrument, which has a more general aim: to achieve a better understanding of the monument. In the case of ancient structures, the influence of past events (like traumas and modifications) and the uncertainties about the geometrical and materials characteristics, make it particularly difficult to interpret their structural behaviour. When it is necessary to assess the safety conditions and to define the interventions for its strengthening, monitoring is an important scientific tool to define not only the present mechanical behaviour of an artefact, but also to give hints about its travel through time and to control its future evolution.

Of course, to obtain all these data, structural monitoring should not be seen only as a set of mechanical instruments. Indeed, it would be more correct to talk about "monitorings", in plural, as the possible complementary approaches in this field are numerous, with different purposes, instruments and time-domains. In short, the different strategies of structural monitoring can be summarized in the following broad categories:

- the historical monitoring, which considers the evolution of a structural disorder from age to age;
- the instrumental monitoring, for the understanding of the physiological behaviour of the structure, essentially useful to the calibration process of interpretative models;
- the monitoring for damage evolution and alarm (the one that in the Directive is evoked as possible "alternative intervention");
- the "observational method" for the control of possible proposed (and implemented) intervention.

In all these meanings, monitoring is crucial in the preservation of cultural heritage, not only as means of damage control but as fundamental instrument of knowledge (Ottoni 2012).

2.1 Historical Monitoring

Usually structural monitoring is dealt with only considering instrumental, modern monitoring. Indeed, this type of monitoring only opens a very small window on a centuries-long experiment (Roca 2004), if we consider that the data that can be obtained, although very useful to define the present evolution speed, are very partial and do not give any information on the much longer period which goes from the original construction to the present condition of the examined monument.

To inspect this period—often full of modifications, traumas and deformations—the so-called "historical monitoring" is needed. This method consists of specific researches on historical documents, to be matched with the strict attendance of the monument in order to check the signs that history has left on it. This process allows to reconstruct the evolution of the disorders in time, from the construction to present times, without any technical instrument.

First of all, a careful study of the historical archives has to be carried out. The identification of the traumatic events suffered during centuries (earthquakes, fires, wars, etc.), of the building reaction (collapses and damages) and the dating of consequent restoration works, together with any repair or strengthening intervention, is extremely important, as well as the knowledge of any historical "spy" or historical measurements.

The next step is to enter into the monument and "read" the information it conceals. The deformation of a decorative element, the measurement of a crack on a fresco, the different levels of pavements or the out of plumb of the walls, become as many historical evidences of the path followed by the structure since its construction. Then, if we complete the obtained series of data by those registered by the modern monitoring system, a global graph of the building behaviour—from the past to date—can then be derived (Fig. 1). The results of damage observation, in fact, can be misunderstood if they are not correctly inserted into the long period: indeed, in terms of the monument stability assessment, the alarm aroused by a recent crack is quite different from the danger represented by an ancient one.

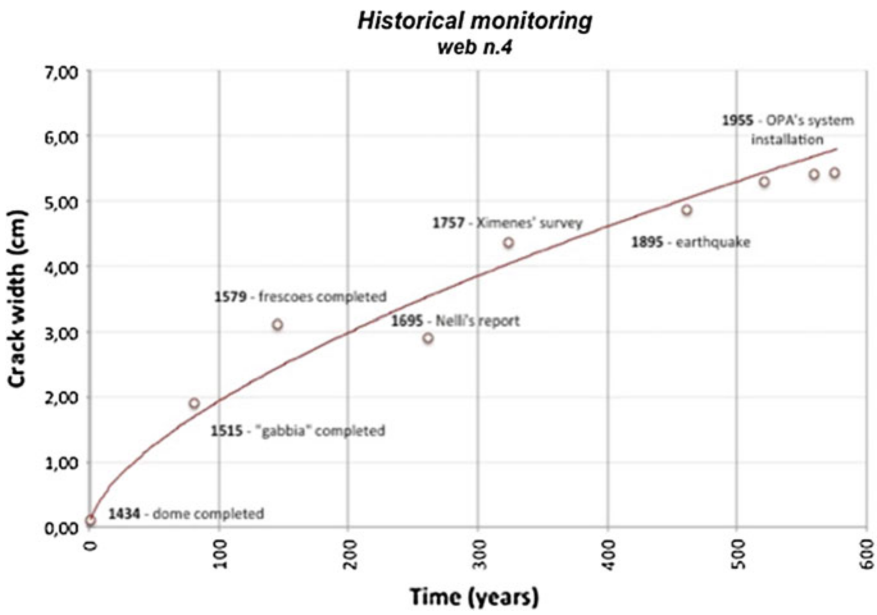

Fig. 1 Evolution of the main crack amplitude in web n. 4, Santa Maria del Fiore dome from the construction to date

Since the 80s, Roberto Di Stefano had pointed out that "*The study of the static behaviour of structures [is] always historical investigation*" (Di Stefano 1981). The information that a careful and focused historical analysis can provide on the static (and seismic) behaviour of historical monuments are in fact many and provide, to those who can read and interpret them, the results of a unique "experiment" in real scale.

For structural experts, this historical approach is not so obvious, but it is crucial in the process of validation and interpretation of the model chosen to calculate the ancient structure's safety: it can measure the similarity of the model to reality.

Conversely, the historical study must be careful to pick the aspects related to structural implications, which are often overlooked.

Numerous examples can be cited to demonstrate the fundamental role of this approach in the definition of the stability conditions of historic buildings: one of all, exceptional for extent of damage and for the amount of information collected over the centuries, is the dome of Santa Maria del Fiore in Florence (Bartoli et al. 1993). Thanks to historical analysis, in the above described meaning, the cracks insisting on the great dome were fully included in their secular evolution (Blasi and Ottoni 2012).

Whatever the measure observed in relation to the damage of the structure, the "historical monitoring" not only follows the evolution of the damage, but also notes the behaviour of the structures and, more, investigates the reasons behind the damage, paving the way for an interpretative model of the building essentially derived from its own history. Therefore, it results clear that in such a process of progressive understanding, the modern systems of instrumental monitoring can be considered only as the last and most recent update of this story of structural behaviour.

2.2 Structural Monitoring and Model Validation

After decades of experience, the scholars had finally to admit that numerical modelling procedures, which can provide with good accuracy the behaviour of structures made of homogeneous and isotropic materials, are not yet capable to fully describe, with an acceptable precision, the seismic response of historical buildings. By contrast, the empirical procedures, traditionally defined as approximate, allow to understand the behaviours and risks of ancient buildings better than the so-called scientific methods.

The application of instrumental monitoring systems for high-precision motion control of abnormalities in the structures is a well-known method to civil engineering, which commonly monitors the great infrastructures (dams, for example) with particularly advanced measuring systems, given the obvious and disastrous consequences that their movement, or worse collapse, would have for the general safety. However, in this case, the purpose of monitoring is to check that the reality actually resembles to the numerical model used to design it: this similarity is in fact the first guarantee of safety for modern structures.

For historic structures, instead, it is the opposite: the problem is to better calibrate the model to reliably interpret reality and therefore to be able to make realistic predictions of ancient structures behaviour. The purpose of monitoring is therefore specular and, in some ways, diametrically opposed.

In the field of ancient structures, static and dynamic monitoring can be used as calibrating methods for the interpretative model chosen to understand and simulate their behaviour: the comparison of some structural parameters registered by instruments with the model results can give a measure of the ability of the model to represent the reality (Aguilar et al. 2009). Indeed, automatic instrumental systems are able to measure both the actions that disturb the buildings (thermal changes, wind, earthquakes, changes in level, changes in groundwater) and their structural consequences, thus allowing a comparison with the input/output of the model (Fig. 2).

In step with this, when a huge amount of data are available, the statistical analysis becomes a tool to analyse the phenomena, to identify the inter-relations between all the components of the system and thus to verify the possible causations —both direct and indirect. Defining a statistical-dynamical model, which fully exploits the measurements obtained through the monitoring system, allows to prepare numerical models able to make predictions on the performance of cracks depending on the possible external actions and, consequently, to calibrate a reliable pattern of behaviour of the structure.

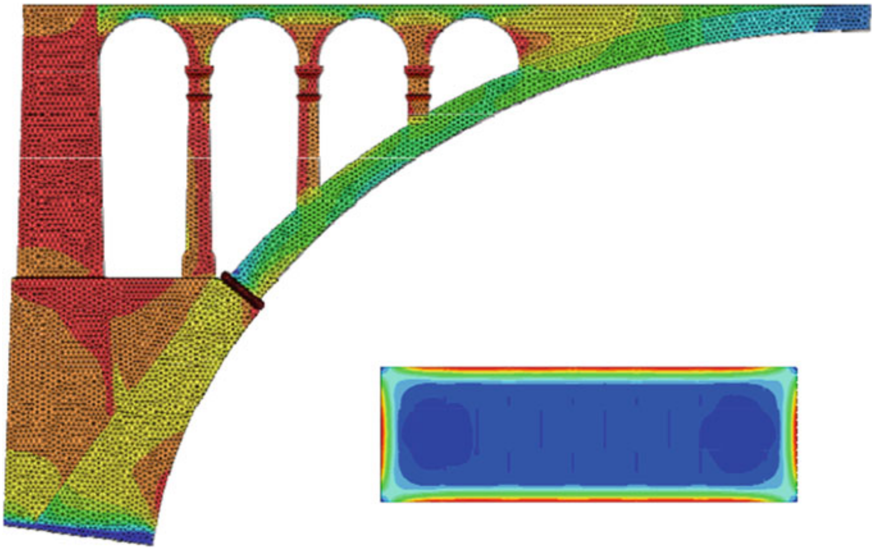

Fig. 2 Environmental and structural monitoring data were used to calibrate a nonlinear numerical model of the Pont Grand Duc Adolphe in Luxembourg, in order to understand its unexpected structural behaviour and thus to minimize the proposed interventions

2.3 Damage Evolution and Alarm

Once the physiological reactions of the building to the external actions has been modelled, also the pathological, irreversible behaviour can be identified and separated from the reversible one. This type of approach is useful both to control the long-time evolution of slow phenomena and the short time reactions to singular events. Once the mechanism is clear and the “normal quantities” are defined, safety thresholds can be fixed, in order to provide alarms if they are exceeded.

Given the long duration of the slow phenomena involving masonry structures (creep, soil settlements, cyclic seasonal loads), it is clear that also the monitoring systems must be designed in order to operate and be reliable for enough time. In general, short time-monitoring is not very useful: in some cases, it can even provide misleading claims. Some years (or better, decades) can be considered as a significant time-span for the monuments monitoring systems, thus they need to be designed for the same duration. They must be seen as means of knowledge which have to be bequeathed to future generations, allowing them to introduce, if necessary, structural improvements on the monuments, to control them in the future and to verify the past interventions. Most of the time, instrumental monitoring can then simply serve to control an evolution of the damage which can be more or less known and risky. Therefore, the installation can follow a sudden alarm, like the onset of new cracks or obvious deformities, or, conversely, can constitute the first intervention for the monument safety. In this process, it is crucial to distinguish the

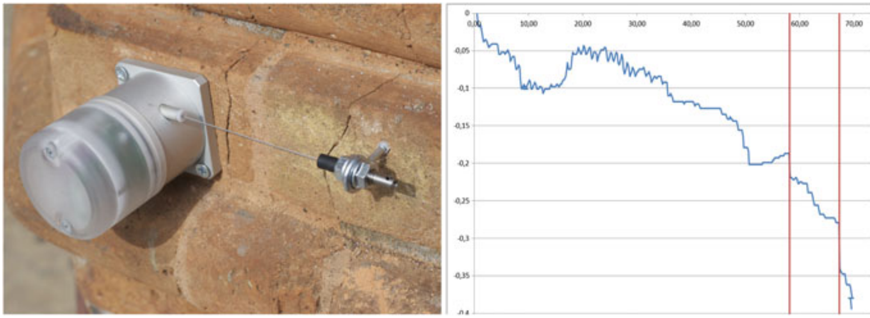

Fig. 3 When the damage mechanism is well understood, even very small, single point instruments (in the picture, one by Fiama srl, Parma) can allow to precisely control the evolution of cracks and to check the reaction of the building in case of singular events (in this case: earthquakes)

quantities to be monitored: the more meaningful ones for the stability of a structure. This process requires not only a previous clear identification of the expected behaviour of the structure, which can only derive from a deep knowledge of the past movements and of the characteristic parameters of the structure, but also, consequently, a critical classification of the detected parameters (crack widths, temperature variations, inclination, levels, etc.). What is clear is then the need, in the design of a monitoring, to organize the information acquired, or rather, their classification in terms of relevance. This classification needs to be assessed in relation to the peculiar history of damage and deformation of the monument. Ultimately, the monitoring system must be designed not only to be complete and exhaustive, but especially targeted, and therefore a minimum, like every intervention (Fig. 3).

2.4 Intervention Control or "Observational Method"

When historical buildings are not subjected to immediate hazards, it is possible to work slowly, making minor changes and controlling them for a long time. Especially for monuments, it is highly desirable to detect in time the effectiveness of restoration and strengthening interventions before making them definitive. The proposed method is far different from the usual one: very frequently, some extensive, costly and irreversible interventions have actually reacted negatively in the long time period, or against earthquakes.

Indeed, recalling the interpretation of a historical building as a non-replicable experiment, in real time and dimension scale, it is possible to gather from this experiment precious information also on the behaviour of its strengthening interventions, to be read by means of an appropriate monitoring (Ottoni 2012).

First of all, as ratified explicitly by the recent Italian seismic law (DPCM 2011), the structural monitoring can be an alternative to the direct intervention. This strategy can be adopted only when the structural problem has been clearly identified and some safety thresholds have been defined, but in these cases the minimum intervention criterion is fully guaranteed. Moreover, monitoring can also have an important role in controlling the interventions, verifying their efficiency and in some cases calibrating their application. More, it can be a real guide for the intervention, since it reliably records—better than any forecasting model (which the monitoring contributes significantly to build and calibrate)—the results of the designed interventions on the building itself, measuring experimentally their effectiveness and even correcting possible errors.

In the case of the Tower of Pisa, for example, monitoring has contributed significantly to the definition and to the implementation, in the 1990s, of the interventions necessary to ensure its stability and conservation. In that case, the monitoring not only has allowed to fully understand the causes of the inclination, but also to perform, consequently, a consistent intervention: the under-excavation of soil from beneath the foundations, whose effects on the tower's inclination was continuously controlled and guided by the monitoring system.

The experience of the tower of Pisa is particularly significant because it highlights another aspect of monitoring, already known in the geotechnical field, which seems particularly appropriate also in the restoration and conservation process of historic buildings, where no reliable tools are present, until now, to predict the real behaviour of structures: the "observational method". This method consists in defining the characteristics of the system, through a prediction model, and to define a series of scenarios, analysed in relation to the possible interventions. This step allows to define which variables have to be controlled, which thresholds have to be defined, or rather the limits within which to proceed with the intervention. The interpretative forecasting model is then adjusted on the basis of the observations made during the implementation of the interventions, guiding the operations on the basis of the measured response: a sort of "dynamic design". This allows the adoption of appropriate and suitably calibrated corrections to the intervention in case of ineffectiveness (or worse, damage). In this way, monitoring becomes an essential part of the design, modified in process.

Sometimes it happens that an intervention and a case study becomes not merely an example from which to learn but a kind of experiment to the truth, fully recovering the concept of empiricism of the ancients. That's what happened with the intervention of strengthening through an encircling system of tie rods in the hexagonal dome of Santa Maria del Quartiere, in Parma. The period of measurement after the intervention is too short to testify its effectiveness on the global, long term crack width trend. Nevertheless, it's interesting to stress that in this case the measurements have allowed to register the effects of post-tensioning operations on the cracks (Fig. 4). Moreover, this intervention does not hinder the natural dome behaviour in response to temperature variations—its "breath" is still evident even after the insertion of the tie rods—while it has already demonstrated to be active against seismic actions. A longer monitoring period will give the final evidence of the efficacy of this intervention and will provide fundamental information to recalibrate it in the future,

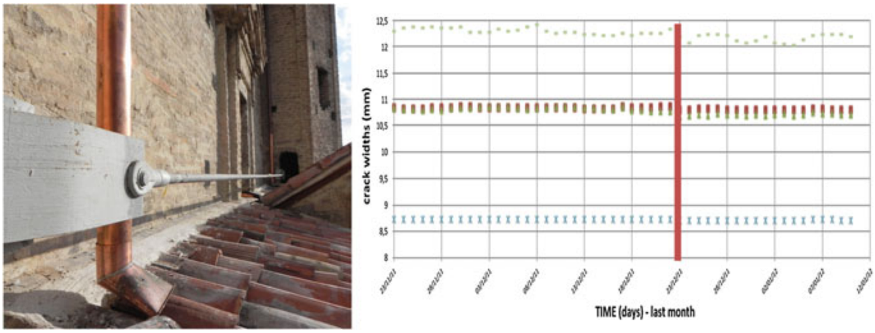

Fig. 4 An application of the observational method to architectural restoration: the crack opening monitoring shows the positive effects of the insertion of tie-rods in the Santa Maria del Quartiere church in Parma, without hindering its physiological movements

if necessary, starting, at the ancient manner, from empiricism and from the observation of damage evolution (Ottoni and Coïsson 2012).

The same approach could be applied also to the well-studied and more complex Brunelleschi's dome, in Florence. Thanks to its imposing monitoring system and its long duration, the physiological behaviour of this great dome is well known and any effect of the possible future intervention can be attentively analysed. Moreover, the comparative analysis between these two structures has already provided the confirmation of a strong similarity in the damage mechanism and maybe also in the strengthening solution, allowing in the future a continuous cross-reference between them. In conclusion, the small cupola of Parma can constitute a monitored experiment, in scale, for the great Brunelleschi's cupola, allowing to assess with certainty the effects in the long run, confirming the validation and forecast model prepared on the basis of the observation in a sort of "test site".

3 Conclusions

The different monitoring strategies shown are all aimed at the achievement of a complete and reliable knowledge of historical heritage. Being knowledge the base of any kind of restoration of historical artefacts, the structural monitoring should always be used in order to define and control the possible strengthening interventions. Indeed, monitoring is based on the most reliable "model" available to date of the real structural behaviour: the real response of the building and its deep observation. Numerical models without comparison with the real measured behaviour cannot produce reliable results, and sometimes even indicate as necessary more interventions than effectively needed. Only a thorough knowledge of the real structural resources of the building, as they have changed in time, can indicate the present deficiencies and suggest the minimum interventions to be carried out.

Monitoring, in its different acceptations, allows to determine both the movements of the structure since its initial situation and the present evolution of its instability: the comparison between them is fundamental to evaluate the safety conditions. The crucial importance of monitoring also in the operative phase is even more clear in the cases in which the intervention does not derive directly from the numerical model of interpretation but it is rather addressed, and if necessary corrected, by the instrumental evidence.

The concept is that only by understanding the possible "error", the modern architect-engineer (or better, restorer) can approach the historic structures, and understand their evolution; the measure of this error, and its variations in time, permits to assess the present stability condition of the ancient monuments and to control the effectiveness of any proposed intervention.

This method, in the end, is not very different from the one used by the ancient master masons who constructed such marvellous structures, by observing the past.

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Monitoring of Cracks in Historic Concrete Structures Using Optical, Thermal and Acoustical Methods

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Abstract Cracks are a major issue in the field of cultural heritage. In order to evaluate the significance of a crack, a long term monitoring of the damaged region is required. However, there is a lack of easy to operate tools for such monitoring measures. Therefore, new or existing methods for other applications have to be optimised for cultural heritage investigation. The paper describes the application of such crack observation methods on a historic concrete sculpture. Beside conventional methods, like mapping by hand and ultrasonic depth profiling, a novel tracking system is presented. Furthermore, the suitability of active thermography for the investigation of cracks was investigated. The results show promising prospects for these non-destructive techniques.

1 Introduction

An efficient and repeatable 3D mapping of damage is urgently required for preservation as well as for assuring the safety and reliability of historic buildings and structures. This enables visualization, monitoring and assessment of temporal changes of damage and deformation. Currently, there exists no systematic and standardised best practice. Conventional 2D methods are based on photos or drawings with the disadvantages of shifts for the 2D projections and the limitations to fixed views, thus in several cases important areas are not visible due to masking. Crack documentation is mostly limited to manual techniques and for monitoring,

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only local crack sensors allow manual or remote recording of crack movement. Furthermore, for the investigation of crack depth, no sufficient state-of-the-art solutions are available.

In this paper, new developments of efficient 3D mapping in combination with crack monitoring by means of a tracking system, active thermography and ultrasonics are presented. With tracking systems, usually the position of moving objects is captured. For crack monitoring, a probe tip was developed which is moved along the track manually while a continuous positioning of the probe is performed. Here, a commercial tracking system is illuminating the probe with infrared radiation and is recording the reflections (Seidl et al. 2012). Active thermography is usually applied to masonry structures for investigating plaster detachments, moisture and masonry structure below plaster (Maierhofer et al. 2010). In the following it is shown that cracks oriented perpendicular to the surface as well as tilted cracks can be visualized by simple heating of the surface. Image processing using pulse phase thermography can increase the contrast. By analysing the thermal contrast systematically, information about crack angle and crack depth might be gained. A more accurate determination of crack depth can be achieved from the travel time of an ultrasonic pulse recorded in a configuration of two transducers positioned on both sides of the crack (EN 2004).

In the following, the development of these methods is described in more detail. The application of these methods is demonstrated as a case study. Here, a sculpture at a historic concrete bridge located in Halle, Germany, has been investigated.

2 Historic Concrete Bridge: Giebichensteinbrücke in Halle

From 1926 to 1928, a new bridge was built over the river Saale, right below the castle ruins Giebichenstein in Halle. On the accompanying icebreakers on both sides of the bridge, two animal sculptures—a cow symbolizing the rural side and a horse on the city side—were mounted. The precise manufacturing procedure of the concrete sculptures is not known. Each consists of a compressed solid body of Portland cement as a binder and an additive mixture of quartz sand, porphyry gravel and copper slag in different size fractions (Müller-Gerberding 1994).

First damage to both the sculptures and the bridge were already detected shortly after completion as crack pattern on the surface. Over the decades, these cracks have widened and deepened to several millimeters.

From 2011 to 2012, the sculptures were restored as part of a research project on conservation practice of concrete funded by the *Deutsche Bundesstiftung Umwelt*. The objective of the restoration project was the reduction of moisture incorporation into the sculptures by filling and closure of the numerous cracks and honeycombs. Within the project and in the process of restoration, 3D mapping of the cracks with the tracking method and with active thermography was applied at selected areas. The results of these studies were compared with manual crack mapping. Such a manual crack map of the cow is shown in Fig. 1. An overall crack length of 222 m

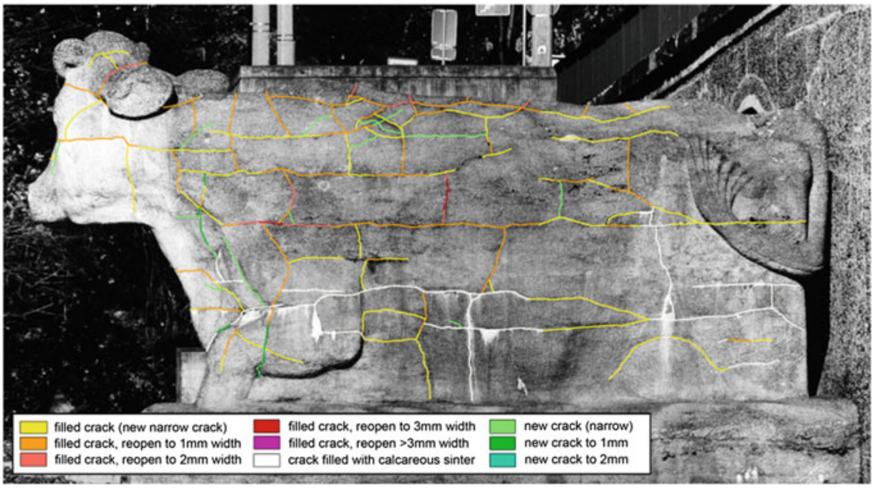

Fig. 1 Manual crack mapping on the cow sculpture situated at the Giebichensteinbrücke in Halle (Saale)

was detected. About 50 % of these cracks have been intended for grouting. The green lines indicate further growing of existing cracks and the development of new cracks within a period of 9 years.

3 Development of Methods for Crack Detection and Characterization

3.1 3D Mapping of Cracks Using a Tracking System

For 3D mapping of cracks directly on the object, a method was developed in which the user runs a measuring tool along the crack, see Fig. 2. The location of the tool is determined by means of an optical tracking system. Tracking means a continuous determination of the position of a recognizable object (here: known arrangement of optical markers). Based on these data the pose, i.e. position and orientation of the tip of the measuring tool in space, see Fig. 2a, can be determined. The recording of data can be done either at individual discrete points or continuously (or in defined range intervals). For position detection of the measurement tool, a commercial infrared tracking system from *NaturalPoint* was used. The usual application of this system is the recording of human movements for Motion Capturing applications. In these applications variations in the positioning of the optical markers can be tolerated in the centimetre range, as in general the data is reworked and corrected afterwards.

The mapping of cracks imposes significantly stricter requirements; i.e. only deviations in the millimetre range can be accepted. Different investigations to find

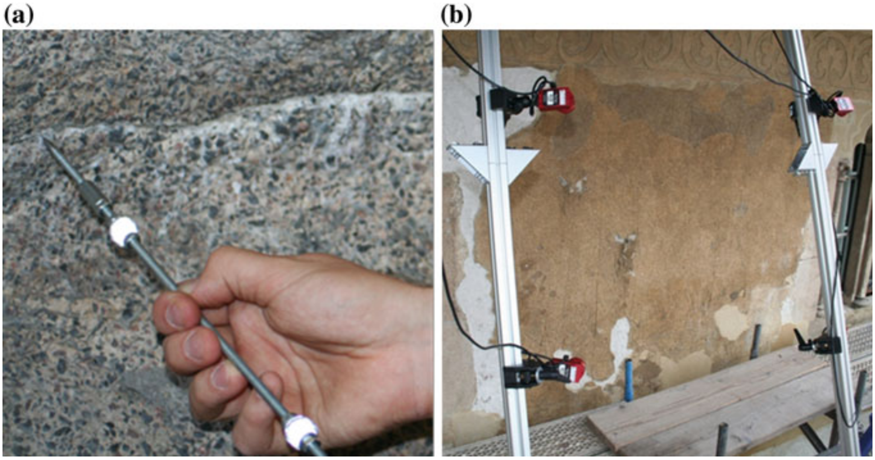

Fig. 2 Set-up of the 3D tracking system. **a** Tracking along the surface of a crack with the measuring tool. **b** On-site application

out the tracking accuracy have shown that a determination of the positions of single markers is possible with a precision of ±0.5 mm. This accuracy can be achieved with a camera set-up as illustrated in Fig. 2b. However, a good calibration of the camera system is essential. For tracking the area of the cow shown in Fig. 6, 41 cracks have been recorded with a total of 4,451 measurement points. For mounting and dismounting the experimental set-up as well as for the measurements, an expenditure of time of about 3 h was required.

3.2 Determination of Crack Depth Using Ultrasonics

Crack depth can be determined with ultrasonics. Here, with an electro-acoustic transducer, an ultrasonic pulse is generated; thereby various types of ultrasonic waves are generated. The most important parameter for ultrasonic measurements is the propagation velocity (v_L) of the longitudinal wave (p-wave). Normally, ultrasonic waves run along the shortest way between two points, but air-filled cavities such as cracks and pores cannot be passed. Instead, the sound is transmitted in a roundabout way, thereby increasing the signal path (EN 2004). The resultant ultrasonic travel time is increased. The knowledge of this fact is used for the determination of crack depths. For crack depth measurement transmitter and receiver must be positioned in approximately the same distance from the crack, see Fig. 3a, and a good coupling of the transducers onto the material surface is required. As coupling agent, commercially available fine chamotte clay is recommended, which can be easily removed from the surface after the measurement. The geometry of transmitter, receiver, and crack tip should correspond approximately to an isosceles triangle.

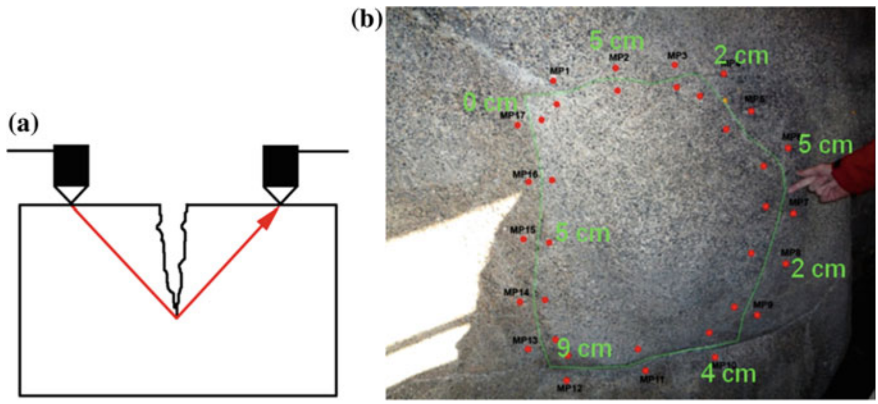

Fig. 3 Determination of crack depth using ultrasonics. **a** Principle of method. **b** Crack *polygon* with marked ultrasonic measurement positions and evaluated crack depths

First of all, the propagation velocity has to be determined in transmission configuration at an appropriated sector, e.g. across the nose of the sculpture. Thereafter, a surface measurement in reflection configuration along undisturbed material has to be performed in order to estimate a geometrical correction factor. After these preparations the measurement system is ready for operation.

For crack depth measurements, first the crack must be identified and understood in its course. Then, appropriate measuring points have to be selected according to length, structure and texture of the crack or a crack polygon. In Fig. 3b, the distribution of measuring points along a crack polygon on the left chest of the cow is shown exemplarily together with the results of crack depth evaluation. These vary between 0 and 9 cm.

3.3 Crack Characterization with Active Thermography

With active thermography methods using global heating, in principal defects located parallel to the surface can be detected well, as these disturb the heat flow in depth direction. Thus, in general cracks oriented perpendicular to the surface are difficult to characterize. However, it is shown in the following how open surface cracks generate thermal signatures.

Various studies on sandstone specimens in laboratory with sawed notches and real cracks have shown that these can be detected easily by a transient heating of the surface of 1 min using infrared radiators. Directly after heating, the crack cannot be recognized clearly, see Fig. 4a. During cooling down, the path of the crack appears warmer but without blurring, as shown in Fig. 4b.

This *afterglow* can be explained by the scheme shown in Fig. 4c, d. Shortly after the excitation only a thin layer of the material parallel to the surface appears warmer. In the further course of time, the heat diffuses into the specimen heating up

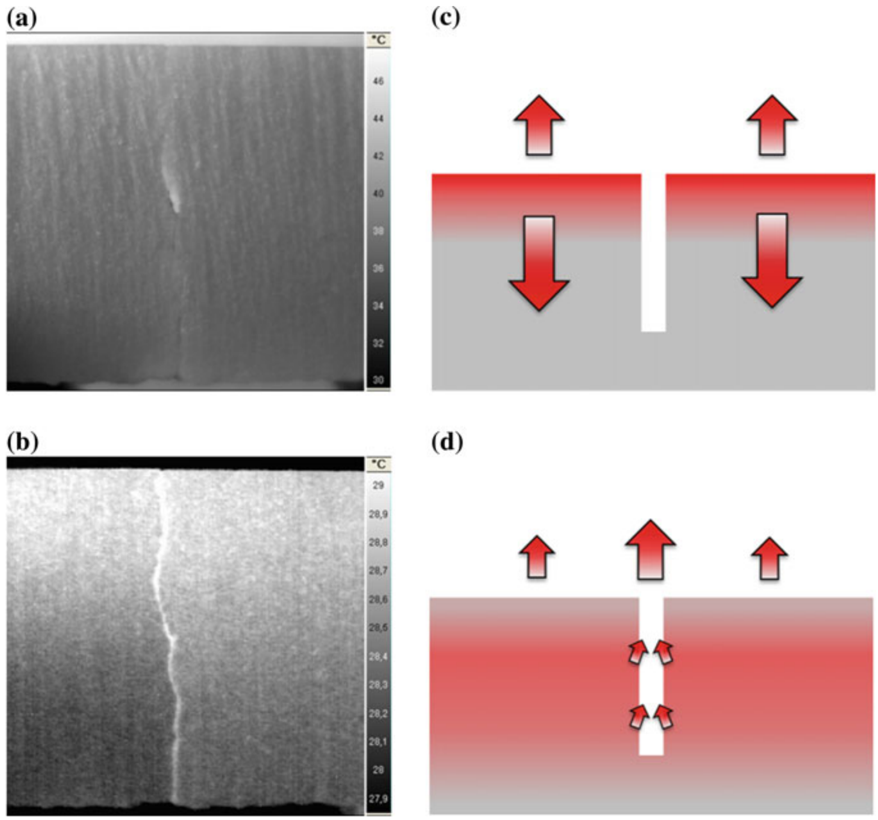

Fig. 4 **a** and **b** Thermograms of Cottaer sandstone specimens with a real crack after 1 min of heating with an infrared radiator (**a**, 30–48 K) and after 4 min of cooling down after heating (**b**, 4.7–25.2 K); **c** and **d** Schematic representation of the thermal contrast development of perpendicular cracks during and after heating. Shortly after heating the surface, the crack appears colder (not shown here). The edges of the crack cool down more slowly than the outer surface, as convection and radiation losses are significantly reduced (**d**). So the crack appears warmer

also the crack edges. During and after external heating, heat losses due to convection and radiation occur at the surface. Both loss processes are significantly reduced at the crack edges. Therefore, the crack edges remain warmer for longer times than the surface.

However, this effect can be observed at cracks which are nearly perpendicular to the surface, but almost vanishes in the case of tilted cracks. Here, the heat conduction into the specimen is reduced by the tilted gap. Thus, the area on the surface above the crack appears warmer as shown in Fig. 5 while the area at the opposite side remains cooler. So, a typical step contrast can be observed across the crack. Depending on the crack angle, different temperature profiles above the crack are formed. This facilitates the localization of cracks and enables an estimation of the crack angle and crack depth by analysing the temperature evolution.

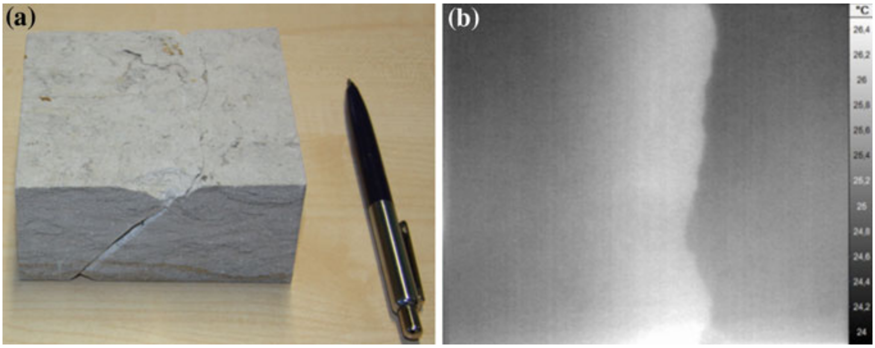

Fig. 5 **a** Tilted crack of a sandstone specimen. **b** Temperature step contrast after thermal excitation above the tilted crack (the two parts of the broken specimen have been reassembled forming the tilted crack)

4 Results

Figure 6a shows a section of the manual crack mapping in the chest area of the cow. Beside the cracks several reference points were also included in the survey, which are marked by colored tiles on the sculpture, so that they are easily visible in photos (not shown here). The result of mapping with the tracking system is a 3D data set as shown in Fig. 6b. The crack structure is in good agreement with the result of

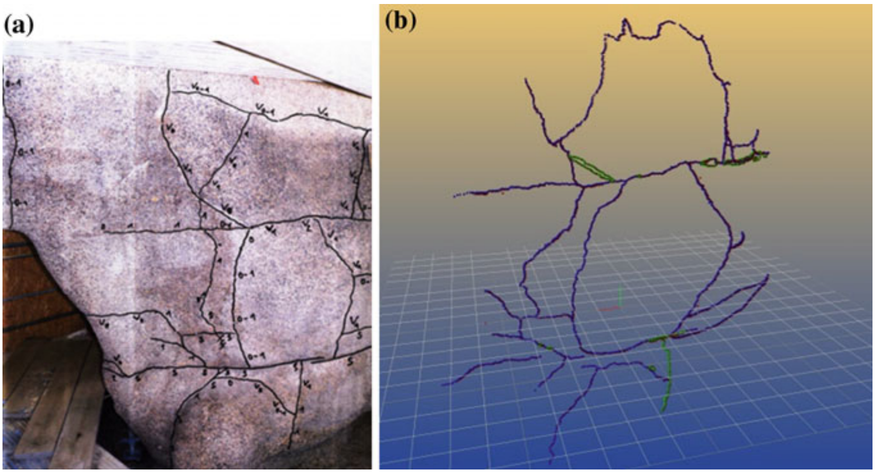

Fig. 6 **a** Manual mapped cracks on the cow sculpture of the Giebichensteinbrücke. **b** 3D visualization of the cracks with the tracking system

manual recording but shows some more details. As the data set is three dimensional, real crack lengths on curved surfaces can be estimated. Further on, it enables the correct fusion to 2D images recorded from different camera positions.

The required heat for active thermography was introduced with an infrared radiator (2.4 kW). This was done by moving it in a distance of 5–15 cm above the surface to be examined. In order to achieve a homogeneous surface temperature the heating process was controlled by simultaneous observation with an infrared camera. However, the highly curved surface complicates a uniform surface heating. Therefore, the cooling sequence was evaluated with pulse phase thermography, a procedure that is typically less sensitive to experimental imperfections like non-uniformly heating (Maldague and Marinetti 1996). Here, the cooling down sequence in time domain of each pixel in the thermogram is analyzed with Fast Fourier Transformation, resulting in amplitude and phase images in frequency domain. Contrasts in phase images are related to different cooling rates.

In Fig. 7a, a thermogram recorded 2 min after heating is shown. The orange arrows are marking some cracks, which show the typical afterglow.

The green arrows are pointing to cracks with a step contrast very similar to the laboratory observations at tilted cracks.

The phase image of the first harmonic of this sequence is shown in Fig. 7b. Here, the cracks can be identified much better than in the thermogram on the left. The cracks can be represented with a similar spatial resolution as obtained by the manual mapping, in which both methods are limited to provide only 2D data. But thermography can be performed automated and objectively. In summary, the most accurate 3D acquisition of the cracks can be performed using the tracking method.

The determination of crack depths along this crack polygon was measured with ultrasonics as shown in Fig. 3b. Crack depths between approx. 0 and 9 cm have

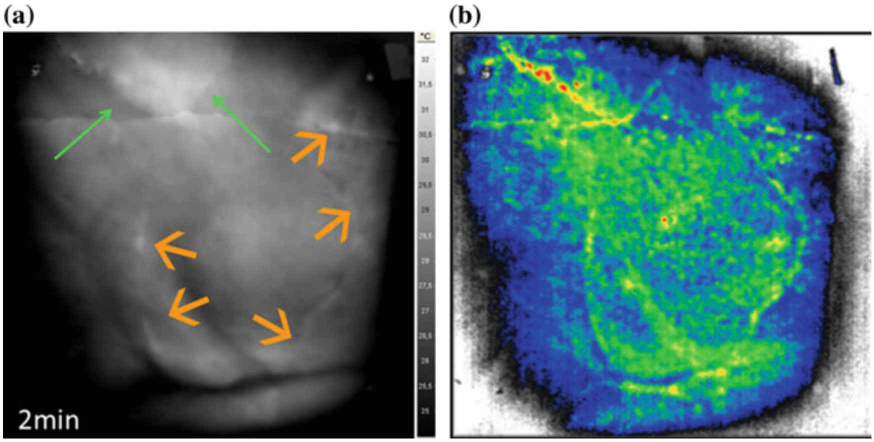

Fig. 7 Investigated area on the back of the cow. **a** Thermogram, recorded 2 min after heating, temperature scale from 2 to 7.8 K related to a thermogram before heating. **b** Phase image of the 1st harmonic of the thermal sequence

been measured; the deepest cracks appear along position 6 (top right) and position 12 (bottom left).

In the phase image in Fig. 7b, the cracks can be clearly detected at these positions, which might be related to the distortion of heat conduction by such deep cracks.

5 Summary

The following methods have been developed and optimized:

- new measurement method for 3D mapping of cracks and crack structures based on a 3D tracking method. Extensive tests concerning accuracy and precision have been performed and new measurement tools have been developed and optimized.
- active thermography for the effective crack mapping, which can distinguish between cracks which are either oriented perpendicular to the surface or tilted. For homogeneous materials, the crack angle could also be estimated.

Together with the crack depth determination using ultrasonics, these methods have been applied on-site for characterising the crack structure of sculptures made of historic concrete. It has been shown that with the 3D tracking method, an efficient and very accurate 3D crack mapping is possible, whereby the cracks are recorded with a higher geometric resolution than manually in 2D. Active thermography enables a fast detection of cracks, even if these are not directly visible on the surface. As the geometric resolution depends on the detector size of the infrared camera and might be influenced by thermal diffusion processes, it is less than for the 3D tracking method. Only with ultrasonics, a determination of the crack depth is possible. Although the experimental effort using all three methods is high, together they enable a comprehensive crack characterisation of the structure.

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Monitoring Noise and Vibration in Santa Clara-a-Velha Monastery

Telmo Dias Pereira and Diogo Mateus

Abstract The generalized increase in noise and vibration emissions in the vicinity of structurally sensitive buildings is a factor of degradation of monuments and built heritage. In extreme conditions those emissions may also pose a risk to life as the result of collapse of constructive and decorative elements. In this paper we present a case study, where we proceeded to vibration monitoring by assessing the impact of excessive noise levels and vibrations on the surroundings and the interior of Monastery of Santa Clara-a-Velha (Coimbra, Portugal).

1 Introduction

The Monastery of Santa Clara-a-Velha (Coimbra, Portugal) is a stone masonry construction, dating from the fourteenth century, threatened over centuries by floods and siltation from the nearby Mondego River.

Some major engineering works (1995–2006) made it possible to keep the Monastery away from phreatic water levels, inside a cofferdam around its perimeter, allowing excavation to the level of the fourteenth century and extensive rehabilitation works (Fig. 1). Recently the detachment and fall of a constructive element of the dome of the church prompted an investigation over the causes of the incident. Vibrations caused by human actions were immediately identified as likely causes. At first sight we learned that a continuous source of environmental noise and vibrations corresponds to nearby road traffic. On the other hand, we figured out that it was also important to assess noise exposure of the monastery to the impact of nearby live music concerts, some of them with very high noise levels. Recently public authorities have taken some measures to minimize noise, however, our

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Fig. 1 The Monastery of Santa Clara-a-Velha in the XX century and nowadays

perception tell us that levels attained are still significant. The effects of fireworks shockwaves from local festivities are also an important source of concerns in this field.

This paper is organized as follows: in the next section we detail the events monitored; in Sect. 3 we refer the documentation and applicable regulations; in Sect. 4 we describe the test conditions and equipment employed; in Sects. 5 and 6 we present the results obtained and discuss its interpretation. Finally, in Sect. 7 we establish prescriptions to this case and similar ones.

2 Events Monitored

In order to fulfill our goals, relevant points of the structure of the church were selected including the central vault, an arch, the top of the high altar and an intermediate level pavement.

Between November 2012 and May 2013 vibrations produced by different types of events were monitored, including: the presence of visitors inside the church; residual vibration from sources like nearby road traffic; outside live concerts (called "nights at the park") located as close as 250 m to the church, sometimes with a strong low frequency component; fireworks over Mondego riverside, blasting at a distance of 400 m from the church.

Other conditions were simulated with repeatable standard sources such as: percussion of the ground floor of the church with a standardized mechanical source (proved not to be relevant to the structure); sound emissions inside the church, with very high sound levels, issued through an omnidirectional sound source (with average values of LAeq approaching 100 dB(A)).

These emissions do not match the traditional sources of dynamic actions on buildings whose propagation occurs mainly through the foundation soil, as in earthquakes or dismantling of rock masses (see Bachmann and Ammann 1987 or Bernardo and Gama 2006).

Among the various types of situations monitored, greater focus was placed on live concerts outside and inside the monastery (the last ones simulated by an omnidirectional sound source). The firsts, despite the distance from the monastery, seems to be determinant to the vibration of its structure, since the emitted sound levels at concerts are extremely high, with values of LAeq exceeding 100 dB(A). Their impact on massive stone buildings can be quite significant as they associate high amplitude with low frequency sound emissions, the natural vibration frequency of this kind of structurally sensitive buildings.

The wind effect was not monitored because the building has small height (25 m) and a massive body. The same does not apply to Gothic cathedrals with slender spiers as in Milan (109 m), Rouen (151 m), Cologne (157 m) or Ulm Minster (162 m).

3 Documentation and Applicable Regulations

With the monitoring operations, peak values and actual values of vibration velocity were obtained. Those values were compared with the limits specified in applicable standards including Portuguese, Italian, German and British standards.

According to NP2074:1983, whatever the transducer used in the measurements, the magnitude of the vibration is characterized by the velocity of vibration. This velocity is measured at the building foundation and expressed by its maximum value (mm/s) during the event. It is obtained over the components of the velocity of vibration in three orthogonal directions by the following expression:

$$\overline{v}_R = \max_t \left| \sqrt{v_x^2(t) + v_y^2(t) + v_z^2(t)} \right|$$

For evaluation purposes, the value of velocity shall not exceed the value of vibration velocity limit, set according to the characteristics of the foundation soil, the type of construction and the average number of daily occurrences (Table 1).

The above standard was unofficially updated introducing maximum velocity limit values when considering situations with more than 100 daily occurrences (Schiappa and Patrício 2001). Those values are approximately half the velocity considered (in Table 1) for 3 or less daily occurrences.

Values were also proposed for continuous vibration, setting up limits for the effective velocity of the vibration (i.e. taking in account its most significant component as shown in Table 2).

Several European countries also adopted standard limits for vibration peak velocity. Examples are Italian UNI 9916:2004, German DIN 4150 (part 1, 2 and 3, from 1999 and 2001), British BS 7385 (part 1 and 2, from 1990 and 1993) and BS 5228-2 (2009).

Table 1 Maximum velocity limit values (in mm/s) of the impulsive vibration at building ground level (NP2074:1983)

Foundation soil / Construction	Loose incoherent or soft coherent soils (c < 1000 m/s)	Compact incoherent or hard coherent soils (1,000 m/s < c < 2,000 m/s)	Very hard coherent soils (c > 2,000 m/s)
Sensitive buildings	1.75–2.5	3.5–5	7–10
Current buildings	3.5–5	7–10	14–20
Concrete reinforced	10.5–12.5	21–30	42–60

First values are suitable for more than 3 daily occurrences and second values are appropriated for 3 or less daily occurrences

Table 2 Proposed limits for the effective velocity (in mm/s) of continuous vibration

Duration of vibration / Type of construction	Less than 1 h/day	More than 1 h/day
Sensitive (monuments and other historical buildings, hospitals, old houses, water reservoirs, masonry chimneys, etc.)	1	0.7
Current (buildings with sound masonry structure, older industrial buildings, etc.)	2	1.8
Reinforced (concrete reinforced buildings recent industrial buildings, etc.)	5	5

Table 3 Limit values of the vibration velocity peak (mm/s) proposed by DIN 4150 and UNI 9916 for sensitive buildings

Situation	From 1 to 10 Hz	From 10 to 50 Hz	>50 Hz	Global
Structural damage induced by short duration vibration	3[a]	3 (10 Hz) to 8 (50 Hz)[a]	8 (50 Hz) to 10 (100 Hz or higher)[a]	8[b]
Structural damage induced by permanent vibration	–	–	–	2.5[c]

Metering points:
[a] Foundations
[b] High locations
[c] All structure

Table 3 shows a summary of the limit values of the vibration velocity peak presented by these standards in the specific case of sensitive buildings (monuments and historic buildings) and considering only the more restrictive limits from DIN 4150 and UNI 9916.

In other way (vibration control applicable to piling operations) BS 5228-4 (1992) standard presents limits intended to avoid aesthetic damage. Should be more severe than the ones in Table 3 but actually they are not.

4 Test Conditions and Equipment Employed

Measurements of ambient noise and vibration in the monastery were obtained between November 2012 and May 2013 using the following equipment: a portable analyzer (01 dB) connected to a PC with data acquisition and processing of measurements using specific software; an ICP type accelerometers (PCB Piezotronics 352B); an integrating averaging sound level meter (brand 01 dB model Solo Premium) with microphone (01 dB MCE212) and preamplifier (01 dB PRE21S).

Airborne high level noise (measured about 3 m from the source) inside the Monastery was simulated by a dodecahedral omnidirectional noise source (DO12 – 01 dB) with two channel amplifier (INTER ML 800) and noise generator (01 dB RD10).

Relevant metering points (V2, V3 and V4) are shown in Fig. 2.

Vibrations were recorded in the form of accelerations in time domain (including audio with 1250 measurement readings per second) and frequency domain. To obtain the corresponding vibration velocities over time from the recorded accelerations, a FFT (fast Fourier transform) algorithm was applied to obtain the frequency response to acceleration, the speed calculated in frequency and finally was applied an IFFT inverse algorithm in order to obtain the time response to the vibration velocity.

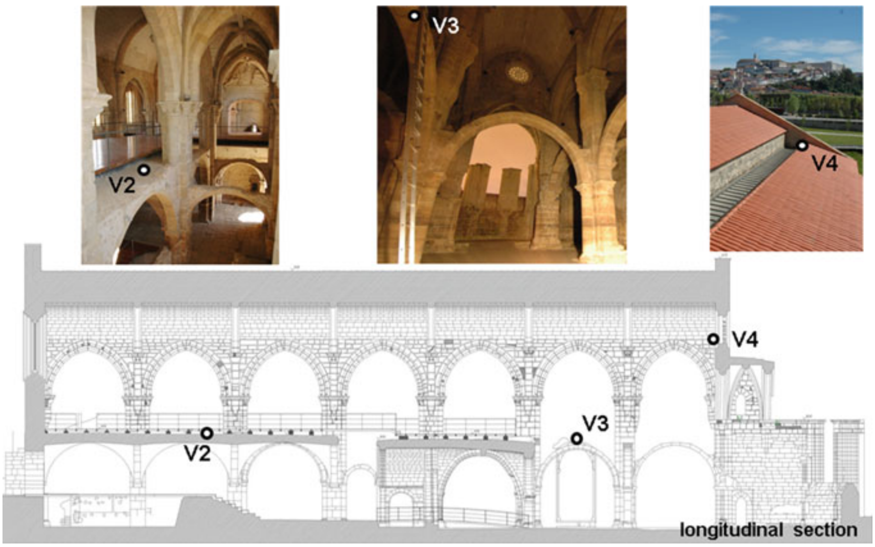

Fig. 2 Relevant data metering points: V2—Intermediate level pavement added during the XVII century to allow nuns escape from progressive flooding; V3—Loose arch; V4—Wall in the top of the high altar

5 Results

The measurements allowed large amounts of information in the time domain and frequency. It is thus possible to perform comprehensive analyzes of the events monitored.

Figure 3 for example shows the average sound levels in the frequency domain and the overall value LAeq in one period of a concert. Note the production of low-frequency sounds that are more critical to structures of this type by being close to its natural frequency of vibration. Shows also average and maximum values registered with the fireworks.

Collected data allowed us to get the vibrations recorded in the form of accelerations in time domain and frequency domain. Figures 4 and 5 shows vibration velocity over time, obtained from the record of such acceleration in a selected time interval. These speeds of vibration were recorded at the point V4, which corresponds to the most sensitive point with respect to outside emissions.

Considering all data and the various situations evaluated at each point of measurement we obtained (Table 4) a maximum peak and average values (for situations of "almost continuous" sound level) of the vibration velocity.

Table 4 also shows global maximum velocity values for the three components (x, y, z), considering a conservative situation with each component x and y equal to the value obtained in the records for the horizontal direction.

In addition to the velocities recorded, the outside metering in time and frequency domain allowed to detect the correspondence of higher values to the use of diffusers (loudspeakers) with very high capacity emission at very low frequencies, as what

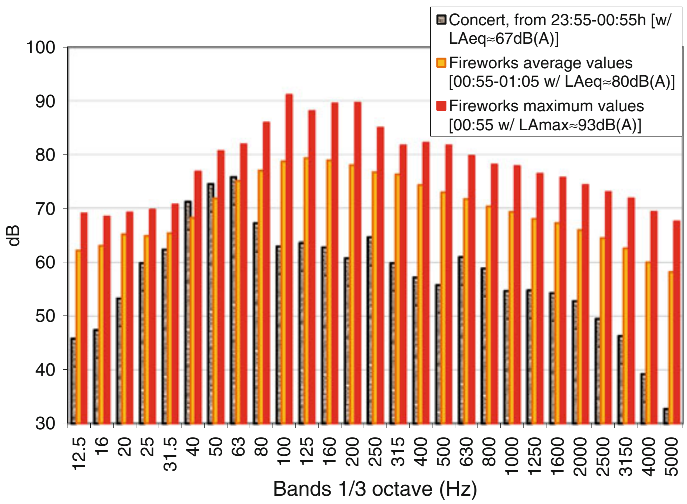

Fig. 3 Sound levels in the frequency domain obtained over the roof of the church

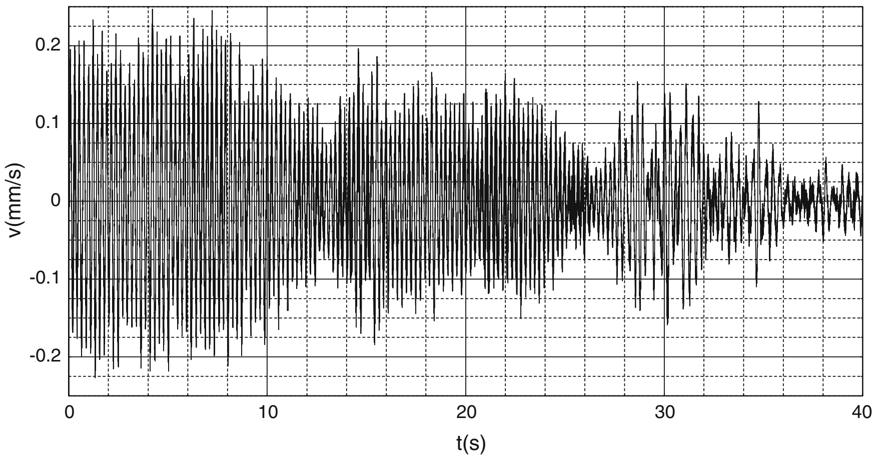

Fig. 4 Instantaneous values of vibration velocity (*horizontal* component) at the point V4 (wall in the *top* of the high altar), 10.05.2013 at 02:55 h, 2nd part of the concert with LAeq ≈ 73 dB (A) in a near point over the roof

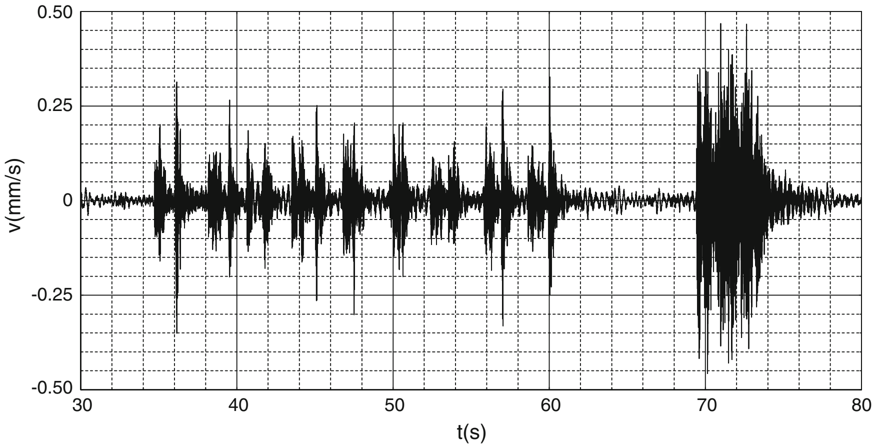

Fig. 5 Instantaneous values of vibration velocity (*horizontal* component) at the point V4 (wall in the *top* of the high altar), 10.05.2013 at 01:04 h, fireworks with LAeq (10 min) ≈ 80 dB (A) and LAeq (max. 10 s) ≈ 93 dB (A) in a near point over the roof

happened in the evening concert from 8 to May 9 May 2013. That night, between 2 and 4 a.m., the equivalent continuous sound level recorded on the coverage of the Monastery was 72 dB (A), which itself is already very high, but with the corresponding value without aggravating the "A" weighting correspond to 87 dB.

Table 4 Peak velocities (in mm/s) and mean values for global (x, y, z) and the most unfavorable component in all relevant situations evaluated

Situation	Vibration velocity type	Point V2	Point V3	Point V4
Residual noise	Maximum peak horizontal velocity	0.03	0.04	0.03
	Maximum peak global velocity (x, y, z)	0.06	0.06	0.05
Omnidirectional noise source (placed inside the church)	Maximum peak horizontal velocity	0.14	0.20	0.05
	Maximum peak global velocity (x, y, z)	0.21	0.30	0.09
	Average horizontal velocity	0.06	0.03	0.01
	Average global velocity (x, y, z)	0.10	0.05	0.02
Most adverse conditions with concert	Maximum peak horizontal velocity	0.10	0.20	0.25
	Maximum peak global velocity (x, y, z)	0.15	0.30	0.36
	Average horizontal velocity	0.03	0.03	0.07
	Average global velocity (x, y, z)	0.05	0.05	0.10
Fireworks show	Maximum peak horizontal velocity	–	–	0.50
	Maximum peak global velocity (x, y, z)	–	–	0.70

6 Results Interpretation

Now we may analyze some of the most important results. Firstly, the amplitude of the vibration velocities is lower than regulatory limits under various structural domain (presented herein) standards. Even the most unfavorable situation for the value of the vibration effective velocity (long duration) was about 10 % of the limit in the case of live concerts, and the value for the situation of fireworks show (short duration) was about 9 % of the stated limit. We must conclude that it is likely these kinds of events probably are not the first cause of detachment and fall of the constructive element of the dome of the church which occurred in October 2012.

Anyway, loose arches (with less structural rigidity and located in a place open to the outside) and the wall most exposed to concerts or fireworks noise are the more sensitive points of the structure to sound from outside sources. Loose arches are also particularly sensitive to sounds produced inside the church (as was the case of omnidirectional source), showing also a significant vertical component of vibration velocity.

Beyond questions of structural stability of the buildings mentioned above, it is noted that this type of vibration accelerates processes of fall of unstable elements.

Stone elements of great slenderness or more prone to buckling (crosses, rosacea ribs) have a non-negligible probability of joint degradation or failure under this kind of actions.

The effect of road traffic (sound emission or induced vibration into the soil) is minimal in terms of peak velocity. This is explained by the distance to the monument, low traffic density and soil characteristics (predominantly clay).

7 Prescriptions

From the data obtained it was possible to establish certain requirements relating to these kinds of actions.

One prescription was the introduction of limits to sound levels inside the church, especially during music shows. Strong amplification using loudspeakers with high power low frequency sounds must be avoided.

As an order of magnitude, it is proposed to limit the sound levels inside the Monastery, with equivalent continuous sound level (3 meters away from the noise) less than 85 dB, and with instantaneous noise levels below 90 dB. Although usually weighted values "A" are used, i.e. in dB(A), which usually lead to substantially lower values than the values recorded in dB, in this case the goal is to grant an effective limit on low frequencies, suggesting a limit without weighting.

Outside the monastery, in live concerts, local authorities must constrain the use of diffusers (loudspeakers) with very high capacity of emission at very low frequencies, as was detected during the night from 8 to 9 of May of 2013. In addition to the vibrations induced in the Monastery this type of noisy environment dramatically affects the well-being of local residents.

Fireworks are widely used in various occasions throughout the year (new year, town festivals, celebrations of the university, etc.). Organization of such events near the monastery must ascertain limits to the average load used per unit of time (for example in Kg/minute of fire) and the maximum load applied to each rocket.

The persistence of festivals with the production of high sound levels inside the monastery and its surroundings leads to the need to carry out inspections in the monastery building elements that are more vulnerable to the action of vibrations.

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Testing and Monitoring for the Control of Strengthening Interventions of Santa Maria Gloriosa Dei Frari in Venice

Alberto Lionello, Christian Rossi and Pier Paolo Rossi

Abstract The Basilica of Santa Maria Gloriosa dei Frari was involved by dangerous horizontal and vertical movements of the bell-tower which induced severe cracks on the supporting structures of the Basilica. After the installation of provisional reinforcing systems, two main works were carried out in order to decrease the movements of the bell-tower and the openings of the cracks in the structures of the Basilica. At first, the consolidation of the soil foundation of the bell-tower was carried out by using the soil-fracturing technique; then a structural joint was created between the bell-tower and the adjacent structures of the Basilica. All the phases of the interventions, which were completed in December 2008, were carefully checked by using an automatic monitoring system able to give in real time precious information on the movements of the structures. This monitoring system, which includes a direct pendulum, several crack-gauges and livellometric measures, is still active and it will continue to operate in the future for a log-term control of the behaviour of the Basilica after the consolidation works. This type of monitoring is able to guarantee the safety of the structure during the works and can be considered as a design tool which allows, through the application of the observational method, to change during the works the design of the strengthening interventions taking into account the real behaviour of the structure.

1 Introduction

The reconstruction of the Frari Basilica started in 1340 and was completed in the second half of the 15th century. The bell-tower was built between 1361 and 1396 and it was designed as a separated body. The bell-tower, 65.00 m high and 9.50 m

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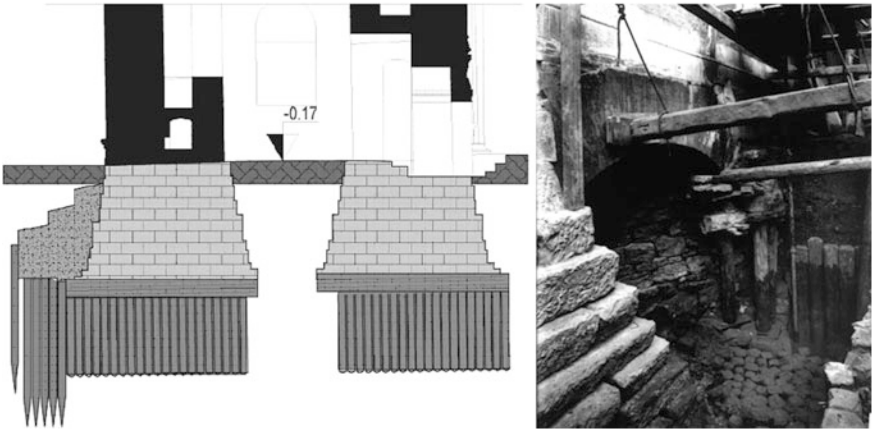

Fig. 1 Strengthening intervention on the foundations of the Frari bell-tower at the beginning of the 20th century

wide, shows a double pipe brick masonry structure, supporting the internal staircase. In 1432, the St Peter's chapel was constructed, leaned against the bell-tower, on its north-east side. The chapel's structure is nevertheless independent from both the bell-tower and the Basilica. The bell-tower showed the first documented signs of movements at the end of the 16th century. Its movements (settlement and tilting) continued progressively and at the end of 19th century it was observed a differential settlement of about 40 cm between the bell-tower and the walls of the Basilica. At that time, the deviation from verticality, measured at a height of 42.50 m, was about 76.50 cm toward outside.

The vertical settlement of the bell-tower induced severe crack pattern in the wall of the Basilica and in the vaults of the St. Peter chapel. In 1904, after the collapse of St. Mark bell-tower, a strengthening intervention was carried out on the bell-tower foundations. This intervention, consisting in widening of the bell-tower foundation base, was carried out only in the external side of the bell-tower and was not extended to the other sides. The strengthening project considered the traditional venetian soil strengthening technique, with the insertion of new timber piles (3.80 m long) covered by a two meters wide concrete bed, parallel to the side of the bell-tower (Fig. 1).

During this intervention phase, the bell-tower and the St. Peter chapel, were strictly connected at the foundation level and at different heights on the perimeter wall. After this intervention on the external side, the bell-tower progressively inverted the tilting effect towards the internal structures of the Basilica. The effect of this movement was a large crack pattern on the wall which connects the bell-tower to the adjacent pillar of the Basilica, as well as in the supporting structures and vault of St. Peter chapel.

After the intervention of 1904, to the end of 20th century, the estimated vertical settlement of the bell-tower was about 100 mm which means about one millimeter per year.

2 Structural Diagnostic Investigation

In 1990, subsequently to an extensive analysis of the structural behaviour of the Venice bell-towers, a diagnostic investigation on the Frari bell-tower started. In September 2000, some signs of structural deterioration appeared: new crack patterns, especially in the St Peter chapel vaults, widening of already existing cracks, falling of small portions of plaster and bricks from the vaults. Emergency interventions were provided to the structures more affected by the deformation processes. In particular, the installation of a timber frame was required to support the stone arch which connects the bell-tower to the adjacent pillar of the Basilica.

In the period 2001–2003, detailed diagnostic investigations were carried out as well as the installation of a monitoring system able to check in real time the deformation behaviour of the structure.

2.1 Crack Pattern Survey

The crack-pattern survey was carried out with the aid of climbing technicians. The opening and the length of the main cracks were checked as well as the extension of the damaged zones, mainly concerning the detachment of the surface layer of the masonry wall. It was observed the presence of several cracks near the corners which is due to local stress concentration. Large areas involved by the detachment of the surface layer were also found, mainly in the pilaster strip.

2.2 Measurement of the State of Stress

Flat-jack testing technique was used to measure the existing state of stress on the masonry structures of the bell-tower and of the adjacent structures of the Basilica (Fig. 2).

At the base of the bell-tower an average value of 1.92 MPa was measured on the external side, while on the inner part a mean value of 1.44 MPa was estimated. Very high values of compressive stress were measured at the top of the column sustaining the propped arch: 1.76 MPa at the external side and 3.20 and 3.04 MPa on the inner side.

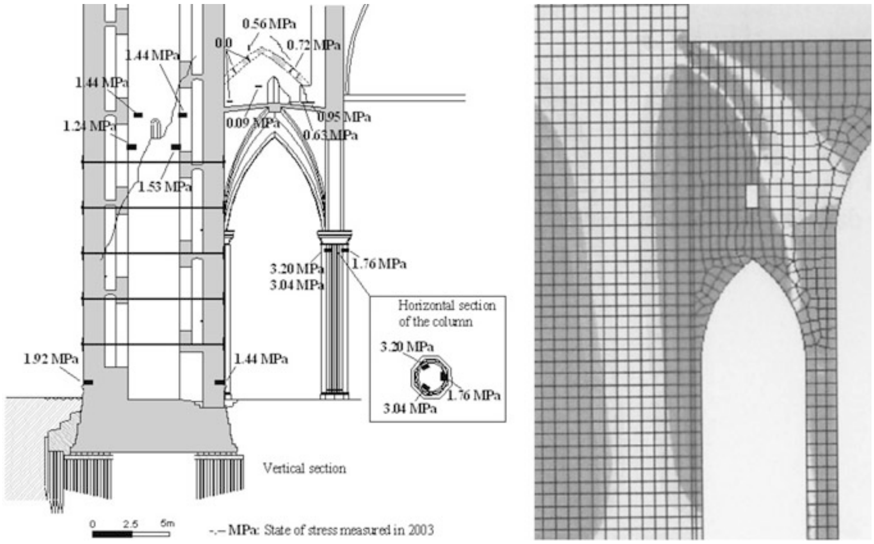

Fig. 2 Values of the state of stress measured by flat-jack test in the supporting structures of the Frari Basilica and bell-tower and comparison with the results of the numerical model

2.3 Geotechnical Investigation

An extensive geotechnical investigation campaign was carried out, including

- continuous vertical and inclined boreholes up to a depth of 25 m
- continuous coring into the foundation masonry
- static penetrometer tests with monitoring of pore water pressure (piezocone tests) up to a depth of 20 m;
- standard Penetration Tests (SPT), in boreholes;
- extraction of several soil and foundation samples, for the evaluation of physical and mechanical properties.

The stratigraphic units are shown in Fig. 3. The results of the geotechnical investigations were used for the numerical model of the soil foundation of the bell-tower.

The foundation of the bell-tower is made up of limestone (Pietra d'Istria) squared blocks, about 0.20–0.40 m thick, in a good state of preservation. Among the blocks, the original mortar was also locally found. Below the foundation blocks there is a wooden floor of squared larch boards, 0.40–0.50 m thick. Under the boarding, a thin layer of clean sand was found, probably used to prepare a uniform bedding plane for the foundation. Below the wooden floor, the typical wooden piles layer is made up of short (from 1.5 to 2.0 m) consolidation piles, pushed into the fully saturated, soft clay, very close each other, often side by side, to make it denser and stronger.

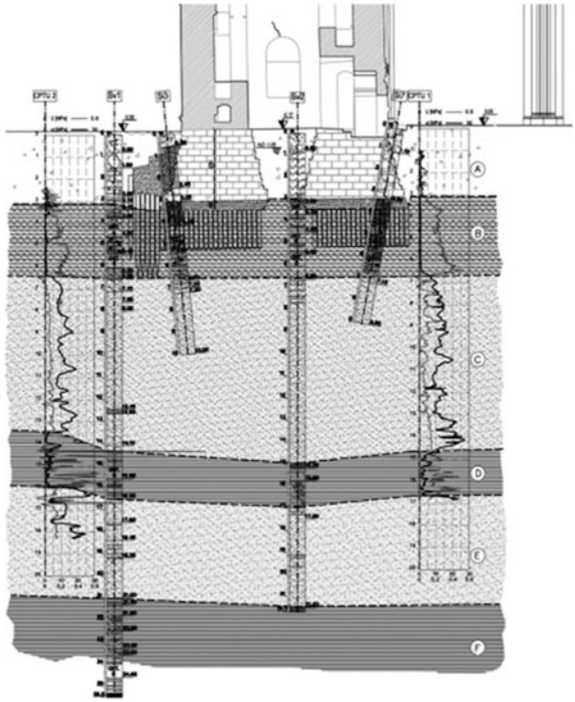

Fig. 3 Stratigraphy of the soil foundation of the Frari bell-tower

2.4 Numerical Model

A structural analysis of the bell-tower and the adjacent parts of Basilica was performed. The aim of the model was the identification, through the historical processes which led to the actual situation, of the masonry structures' present behaviour. The portion of structure which was reproduced in the model, includes the bell-tower and the adjoining parts of the church which were mostly affected by the interaction with the tower. For all the numerical simulations the only loading condition considered is the self weight. The load corresponding to some parts of the real structure not reproduced in the model (timber structure roof of the basilica, belfry), was imposed as external forces. The crossed vaults' filling was included as surface load. The mechanical properties chosen to describe the materials arise from the results of flat jack tests performed on the masonry structures. The material is considered homogeneous and isotropic and the analyses performed are linear elastic. This numerical model was used as a design tool for verifying the different phases of the strengthening interventions.

3 Monitoring System

After the end of the diagnostic investigations, an automatic monitoring system was installed to analyse the deformation behaviour and the structural conditions of the bell-tower and the adjacent portion of the Basilica during all the phases of the strengthening interventions.

The general lay-out of the instruments, includes:

- direct pendulum equipped with automatic telecoordinometer, for the measure of the absolute horizontal movements of the top of the tower.
- crack-gauges and long-base extensometers installed on the main cracks of the masonry walls.
- strain-gauges to measure the deformation of the steel cable installed in the bell-tower.
- thermal-gauges to measure the temperature of the internal and external air, and also inside the masonry at different depths from the outer wall.
- geotechnical instrumentation, installed into the boreholes drilled in the soil foundation, including electrical piezometer multibase extensometers and biaxial inclinometers.

All the instruments are connected to an automatic data acquisition and recording system which is equipped with a modem to transfer the data to a remote controller. This acquisition system was very precious during the phases of the strengthening works because it was able to follow in real time the effect of the works on the structures thus allowing to introduce appropriate variations of the intervention design.

In addition to the instruments connected to the automatic acquisition system, it was considered extremely important to measure the vertical movements of the bell-tower and of the adjacent portion of the Basilica. For this reason an high-precision manual levelling system was installed with several measuring points and the periodical readings were carried out during the most significant phases of the works.

4 The Role of Monitoring During the Strengthening Intervention Phases

Owing to the deep connection between structural and geotechnical aspects, it was clear that, in order to guarantee the safety of the complex Basilica and bell-tower, it should have been necessary to find a suitable technological solution able to realize gradual strengthening interventions with a strict control during the execution of the works, by adopting the so called “Observational Method”. The only way to obtain a strict control during the execution of the works is represented by the structural and geotechnical monitoring system. The complexity of the problems required the set up of an interdisciplinary group of technicians including experts in structural and geotechnical engineering, diagnosis and monitoring, chemistry and wood conservation.

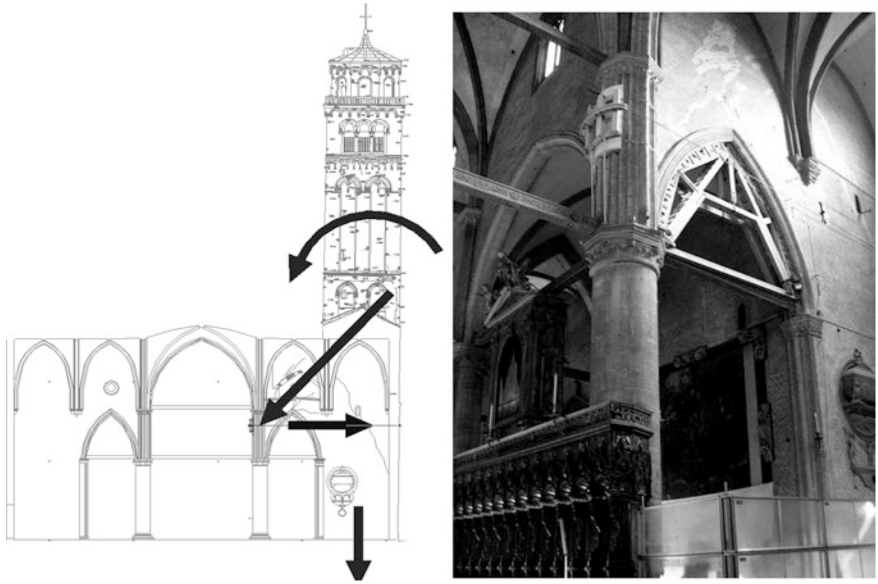

Fig. 4 Temporary intervention with steel cable to support part of the horizontal thrust acting on a column of the Frari Basilica

4.1 Phase A: Temporary Strengthening Intervention

The first intervention was required by the considerable deformation induced on the column of the Basilica by the thrust of the bell-tower. A provisional intervention was carried out in order to guarantee the safety of this portion of the Basilica. A steel cable was positioned connecting the stone ashlars just above the capital of the column to the bell-tower structure at a height of 14.40 m. This steel cable aimed at support part of the horizontal thrust acting on the column. The structural scheme of this intervention is shown in Fig. 4. Two strain-gauges were installed on the steel cable and the tension was continually controlled during the whole intervention period.

4.2 Phase B: Soil-Fracturing Intervention

From the results of the experimental and numerical simulation it emerged that the bell-tower and the interacting structures of the Basilica could not bear, without serious consequences, further differential settlements. It was evident the need of an intervention, at the level of the foundations, aimed at reducing the settlements of the bell-tower thus obtaining that the entity of vertical displacements of the complex basilica/bell-tower should be in the same range. A special technique able to improve the mechanical characteristics of the foundation soil with the respect of all the prescriptions above described, was chosen. An interesting result was obtained by using grout injections with soil-fracturing technique.

The soil-fracturing technique consists in installing special injection tubes in the foundation soil, with valves at different depths. The careful and slow-rate injections of suitable cement and bentonite mixtures is repeated at successive stages, to obtain progressive increments in terms of mechanical characteristics, according to the above-mentioned “observational method”. The final outcome is a reinforced soil, made up of the original material and a mesh of thin layers of injected grout, as can be observed in the particular of Fig. 5.

The soil is confined by these thin layers of injection mortar and subjected to an increased stress state. An increment in terms of deformation modulus of the consolidated soil (with subsequent creep reduction) and an improvement of the soil shear resistance, is obtained.

With the aim of validating and calibrating this rather innovative strengthening method, a full-scale test site was arranged on the northern corner of the bell-tower, inside the Basilica by installing a special monitoring system including several piezometers and multibase extensometers.

After the positive answer of this full-scale test, the soil-fracturing intervention was decided and the scheme of the intervention is shown in Fig. 5 where the planimetry and the cross section of the intervention is shown. Around the foundation basement, 88 injection tubes (length 12 m, diameter 88.9 mm. distance 500 mm) with special valves at a distance of 500 mm each other, were installed in two or three lines. A grouting mortar with pozzolanic cement, water, bentonite and limestone filler, was used with a grouting pressure of about 5 bars in the clay levels and 25 bars in the sand ones. The grouting processes were carried out very slowly through a continuous control of the movements and at the end of the intervention about 100 cubic meters of mortars were injected.

The most useful information for the analysis of the behaviour of the structure during the soil-fracturing works are coming from direct pendulum and from altimetric precision levelling. Also the crack-gauges installed in the arch which connects the bell-tower to the adjacent column, gave precious information concerning the interaction between the two structures. During the soil-fracturing intervention (between April 2005 and March 2006) the monitoring system was used to define the velocity of the intervention phases as well as all the parameters of the grouting procedures (pressure, flow rate, etc.). A notable movement of the bell tower during this intervention phase was observed. The component of movement in x direction shows a movement toward the abse of about 9.0 mm and a movement in y direction of about 5.0 mm toward the Basilica. After the end of the soil-fracturing, the velocity of the bell-tower movement shows a quick reduction, reaching a value which is lower than the one observed before the soil-fracturing intervention. Also the movements of the cracks in the stone arch which connects the bell-tower to the Basilica, show a marked increase during the soil-fracturing and a rapid decrease at the end of the operation.

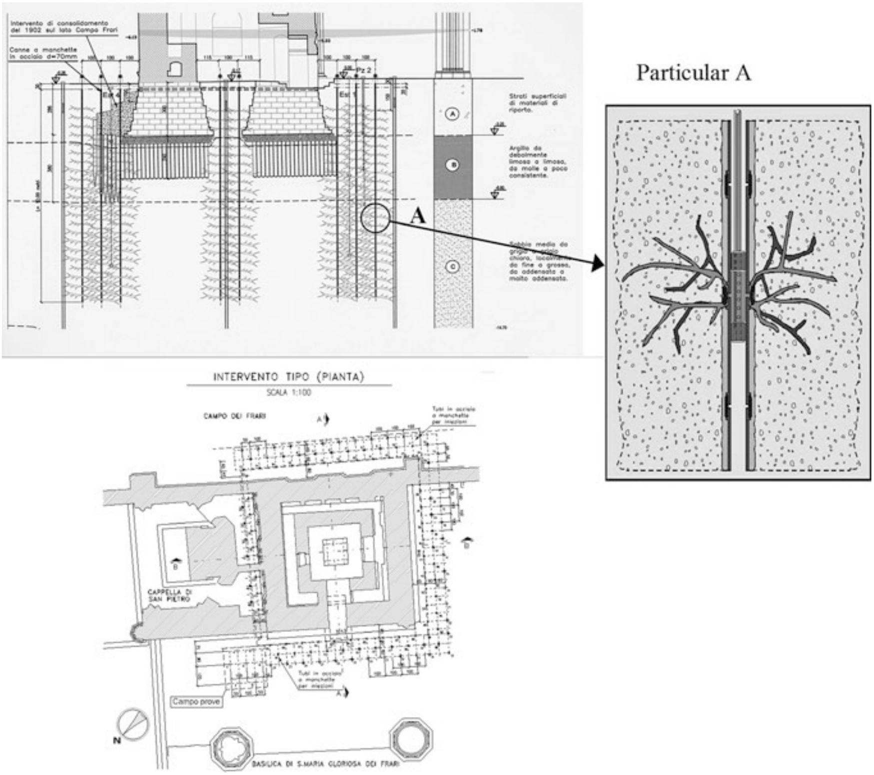

Fig. 5 Scheme of the soil-fracturing technique for the consolidation of the soil foundation of the Frari bell-tower. The position of the full-scale test is also indicated

After the end of the soil-fracturing intervention, the vertical settlements show a marked decrease of the velocity of settlements in comparison with the values measured before the intervention. It was estimated a decrease of this settlement velocity from about 1.0 mm/year to about 0.5 mm/year. This can be considered a very satisfactory result in spite of the temporary movements induced by the soil-fracturing intervention.

4.3 Phase C: Structural Joint Execution

About two years after the end of consolidation works of the soil foundation by soil-fracturing technique, it was decided to introduce a new structural intervention aiming at modifying the boundary conditions of the bell-tower and to reduce as much as possible its interaction with the adjacent structures of the Basilica. At the beginning of June 2008, a structural joint was created between the bell-tower and the Basilica in the position shown in Fig. 6. The effect of this intervention was a marked change of the direction of the thrust applied by the bell-tower to the adjacent column. The direction of this thrust, before and after the execution of the structural joint, is shown in Fig. 6, together with the corresponding numerical models.

The execution of the structural joint was very slow and lasted about 6 months. During this period a detailed analysis of the information obtained by the monitoring system allowed to carry out the different steps of the intervention with a continuous check of the structural behaviour, so avoiding to induce damages to the bell-tower and to the supporting structures of the Basilica.

In order to follow with special care the deformation behaviour during the execution of the structural joint, new crack-gauges were installed as well as new long-base extensometers. In Fig. 7, the lay-out of the deformation sensors is shown, with the values of the deformations measured during the whole structural joint intervention. In the same figure, also the movements measured by the direct pendulum are shown, as well as the settlements of the soil foundation measured by altimetric levelling. It was observed a marked movement of the bell-tower (10.40 mm) in y direction, towards the adjacent column of the Basilica. This movement is only partly related (about 50 %) to the differential settlements of the foundation, while the remaining part is due to deformation processes of the bell-tower itself.

The analysis of the deformations shown in Fig. 7, indicates a closure of the structural joint of 6.72 mm and appreciable movements of the cracks in the masonry wall which connects the bell-tower to the Basilica, while small movements and deformations are observed on the masonry walls of the bell-tower.

In order to follow with particular attention the modification of the thrust between the bell-tower and the Basilica, special flat-jacks were installed. It can be observed a decrease of the state of stress in the upper part of the wall between the bell-tower and the Basilica which is a clear confirmation of the lowering of the thrust applied by the bell-tower.

The complete history of the two components of the movements measured by the direct pendulum is shown in Fig. 8, where the soil-fracture intervention and the structural joint execution are indicated. It can be observed a great influence of the soil-fracturing on the displacement component in x direction, while during the structural joint execution the effect on the component in y direction is more evident. After the end of the structural joint execution and after the complete removal of the temporary steel cables and of the timber prop system, the deformation behaviour was observed during a period of about 3 year During the period of three years after the end of the structural joint execution, the average differential settlement of the bell-tower relative to the Basilica was about 0.40 mm/year. This value is considerable reduced in comparison with the value of about 1.0 mm/year which was

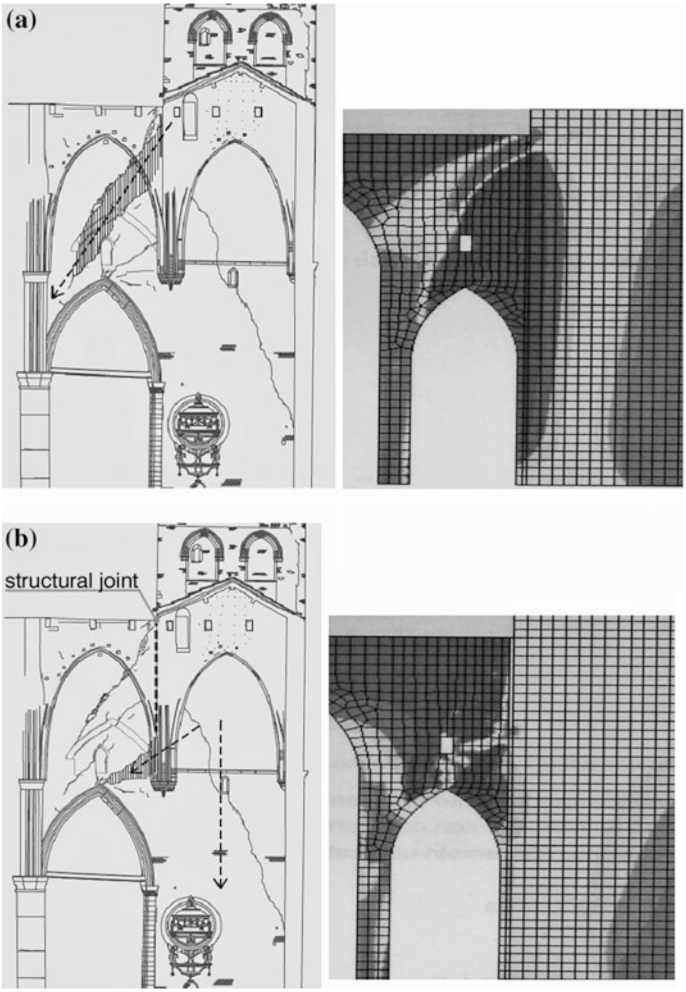

Fig. 6 Direction of the thrust between the bell-tower and the Basilica and comparison with the numerical model results: **a** before the structural joint execution, **b** after the structural joint execution

measured before the interventions. The actual rate of the differential settlement of the bell-tower must be carefully controlled in the future in order to analyse its evolution during the time.

It can also be observed that the presence of the structural joint between the bell-tower and the Basilica reduces the interaction between the two structures with consequent reduction of the risk of cracks under static or seismic loads.

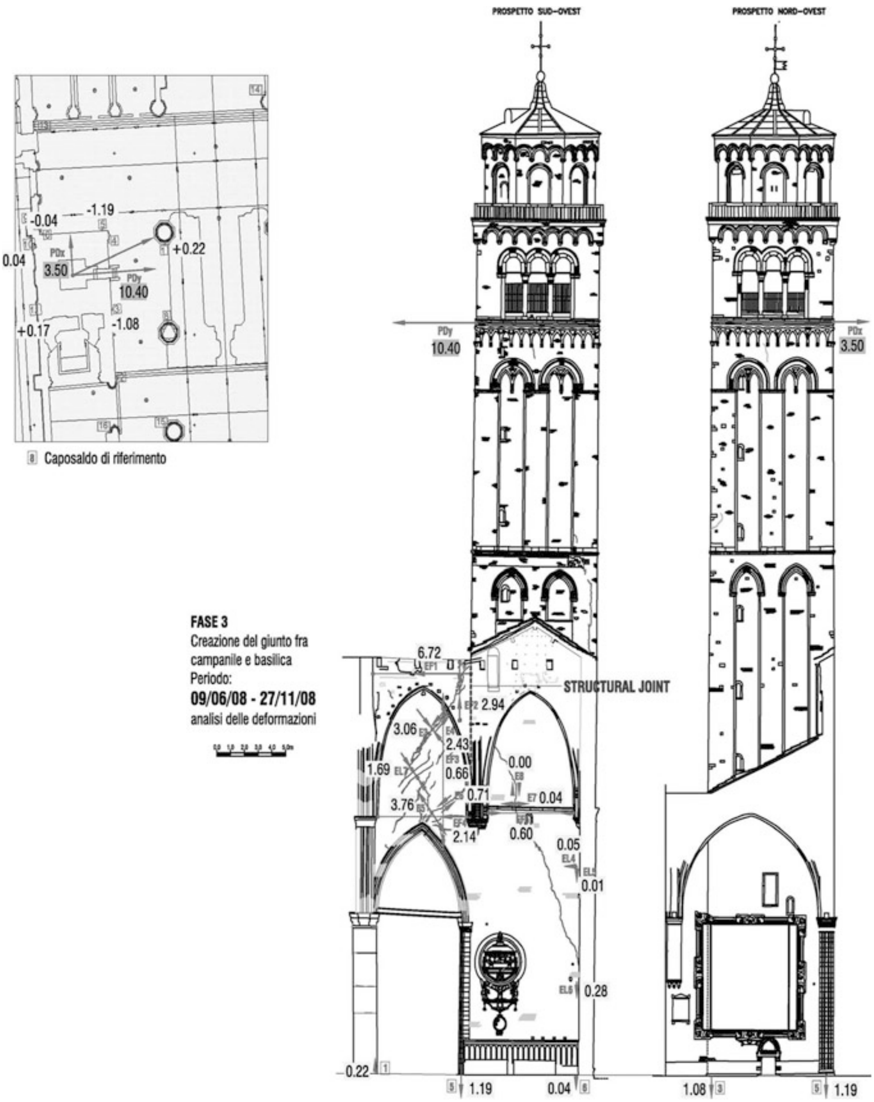

Fig. 7 Analysis of the deformations induced by the structural joint execution

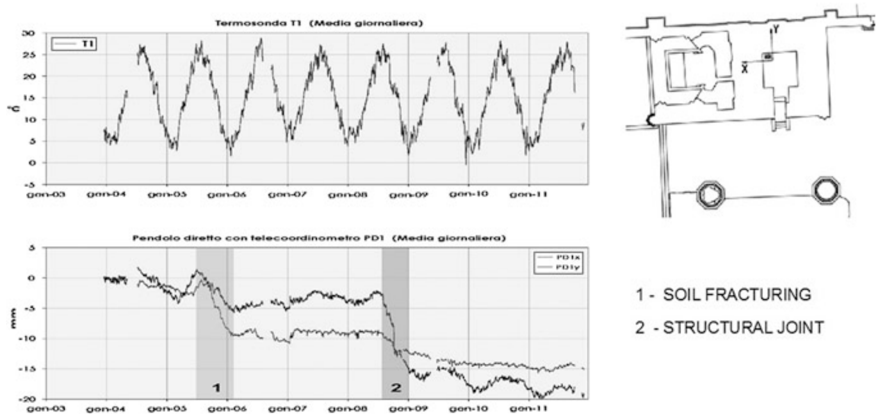

Fig. 8 Complete history of the displacement components measured by the direct pendulum with the indication of the intervention phases (soil-fracturing and structural joint execution)

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Guidelines for the Evaluation of the Load-Bearing Masonry Quality in Built Heritage

Giuliana Cardani and Luigia Binda

Abstract Historic buildings rarely show themselves as they were to their origins, with the same shape and materials The signs of local repairs, but also modifications and expansions are reported on the building as indelible scars that need to be recognized and interpreted. It is important to read these signs, especially in load-bearing structures. One of the first steps for this study is the correct analysis and classification of the quality of the load-bearing masonry, with the help of both an accurate visual inspection and a diagnostic investigation. The classification of the correct masonry typology is now requested also by the last Italian seismic code (NTC 14.01.2008 and annexes), that supplies different mechanical parameters useful for the structural evaluation, according to the masonry typology. Serious mistakes can be made in the structural evaluation of a historic stone masonry if the definition of the masonry typology is incorrect. In several cases there is no coincidence between the visible masonry texture and the transversal cross section. There are different levels of approaching this matter, starting from a description based on a visual inspection, that can be carried out with the help of a template, till the parameters definition achieved by in situ investigation tests. Several parameters may be important to be determined in order to evaluate properly a masonry. The results of the experimental investigation (with a comparison between NDT and MDT tests) and a methodology for the analysis of the masonry quality, according to the standard suggestions for the knowledge levels, reporting all the pros and cons of all methods, are here presented.

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1 Introduction

Historic masonry buildings present different masonry textures according to their typology and consequently their use. Thus, according to the importance of the building, a masonry typology built with a different and suitable constructive technique, can be observed in each historical construction. In addition, historical masonry buildings may have experienced a constructive evolution over time, with the addition of volumes or with partial reconstructions, that led to an additional number of masonry.

The term “masonry”, a non-homogenous material made of mortar and stones or bricks, describes an extremely differentiated system not only in terms of the component materials but of the constructive technique according to the historic period of construction, the geographical area location, the economic conditions and the building function (Giuffre 2000).

The contemporary relevance of a study on stone masonry is linked to the possibility of re-appropriation of the knowledge of the heritage “practice”, once widely spread, but now forgotten in the construction practice and still not yet studied in theoretical framework. One of the first steps for this study is the correct analysis and classification of the load-bearing masonry quality, with the help of both an accurate visual inspection and a diagnostic investigation.

The latest Italian standard on constructions (NTC 2008) has recently acknowledged this necessity, supplying guidelines for masonry investigation with different levels of knowledge (LC1, −2 and −3); there are also tables with some general mechanical parameters, referred to a list of masonry typology classes, to be used for the seismic evaluation in case of a poor level of knowledge (LC1).

Serious mistakes can be made in the structural evaluation of a historic stone masonry if the definition of the masonry typology is incorrect. In several cases a multiple leaf wall can appear externally regular while the cross section is poor with non-connected leaves. On the contrary, the masonry texture appears irregular from the prospect with small irregular stones of different dimensions while the cross section shows a well interlocked masonry with long stones (“diatoni”) used for connection among the leaves.

This last example is the case of the 19th century ex-hospital of Savona, a three storey masonry building, where diagnostic tests showed a reliable mechanical behaviour despite the appearance of the masonry texture.

The research developed by the authors within the frame of the RELUIS project (Reluis-DPC 2009), has the aim of giving guidelines to characterize the masonry quality at different levels of investigation with the elaboration of a special proposed template for the on-site survey. The suggested survey procedure requires the masonry qualification at a first level of investigation through visual survey and local geometrical measurements, while at a further level requires on site non-destructive or slightly destructive tests. Some results of the experimental investigation (with a comparison between NDT and MDT tests), reporting all the pros and cons of all methods, are here presented.

2 Stone Masonry Features: Basic Parameters

The study of the effects of earthquakes that struck Umbria, Marche ad Abruzzo regions, showed how several retrofitting carried out in the 70's and 80's and still in the 90's, mainly consisted in invasive interventions (substitutions of timber floors and roofs with r.c. structures, jacketing of walls, etc.) and caused unforeseen and serious damages, especially due to out-of-plane loads (large collapses, local expulsions). These damages are due to the "hybrid" behaviour activated from the new and the old structures.

It was also clear that the main cause, which led to inappropriate choices of intervention techniques, was due to: (i) the lack of knowledge of masonry and of structural behaviour of the type of construction used in the past centuries for historic buildings, (ii) the use of structural models too far from their real behaviour, (iii) the lack of control on the applicability of the retrofitting techniques.

There is a real difficulty in applying some intervention techniques to some type of stone masonry (Binda et al. 2003). For example, a direct inspection can show if a masonry wall is not injectable or injectable with great difficulties, observing if the voids inside the masonry do not exceed a minimum percentage (around 4 %) and are not vertically connected. The injections are effective where cracks are present, but, in other cases, it is practically impossible to inject the mortar even if it is highly porous and weak.

In case of stone masonry, the load bearing capacity depends strictly on the deficiency of the constructive details, which may be the cause of a local mechanism. The observation of only the facing masonry texture is not enough to reveal how the masonry is constituted in each parts.

In some cases also the analysis of the eventually present crack pattern survey can be of help in defining the masonry quality. The number and the shape of the cracks can indicate the stiffness and the compactness of a masonry wall: a single large crack that splits a masonry wall in two rigid elements shows a better masonry quality than a series of smaller diffused cracks in non-homogenous masonry wall, considering the same loads action (Fig. 1).

Data can be collected in a dedicated survey form (Fig. 2) (Binda et al. 2009a; Binda and Cardani 2011) following, in general, a procedure developed for the definition of the masonry quality that should start from the choice of the most representative areas of the masonry walls. The stratigraphic method allows subdivision of the building into homogeneous blocks characterised by relative chronological relationships. Any block corresponds to a unique building phase, recognized by the observation of constructive details. This identification will help in choosing the most representative masonry walls.

After the selection (it could be necessary to remove a portion of the plaster 1 × 1 m), the survey of the masonry texture has to report the following descriptions:

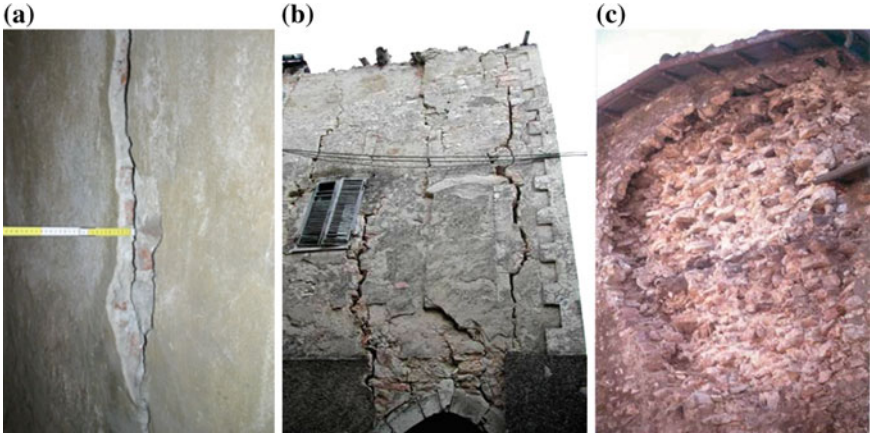

Fig. 1 Different crack patterns observed in masonry walls: **a** example of homogeneous and compact masonry, **b** and **c** example of non-homogenous weak masonry

- the type of masonry units: brickwork, stonework, mix of stone and brick masonry;
- the shape of the stone elements: regular or irregular. The average stones dimension. The type of manufacturing: cut sides and sharp edges, split sides, non-manufactured sides, round pebbles, and so on;
- the thickness of the horizontal mortar joint, realized with different types of binder, aggregates and aggregates dimensions; general description of the mortar consistence;
- the horizontality of the courses (masonry can show horizontal courses, sub-horizontal courses or irregular courses), the stagger of the vertical joints (respected, partially respected or non-respected), the presence of wedges and levelling of other materials.
- the type of cross section of the masonry wall (Binda 2000): one or multiple leaf, well interlocked or not (Fig. 3), the presence of transversal connecting elements (diatoni).

The correct survey of the masonry texture should refer to an area of $1 \times 1\ m^2$ of dimension.

If no large cracks or collapsed portions are visible, and so when it is impossible to observe directly masonry sections, a small masonry disassembling can be carried out, not larger than $40 \times 40/50$ cm (depending on the stones dimension) and ¾ of the section deep. This should be realised in the same wall portion after the diagnostic investigations, so to verify the correspondence with the higher or lower values of the sonic pulse velocity tests.

The example here showed (Figs. 4 and 5) is referred to the masonry of the St. Paul Hospital in Savona, where there was no correspondence between the prospect texture and the cross section of the masonry walls (Cardani et al. 2012). The 19th century.

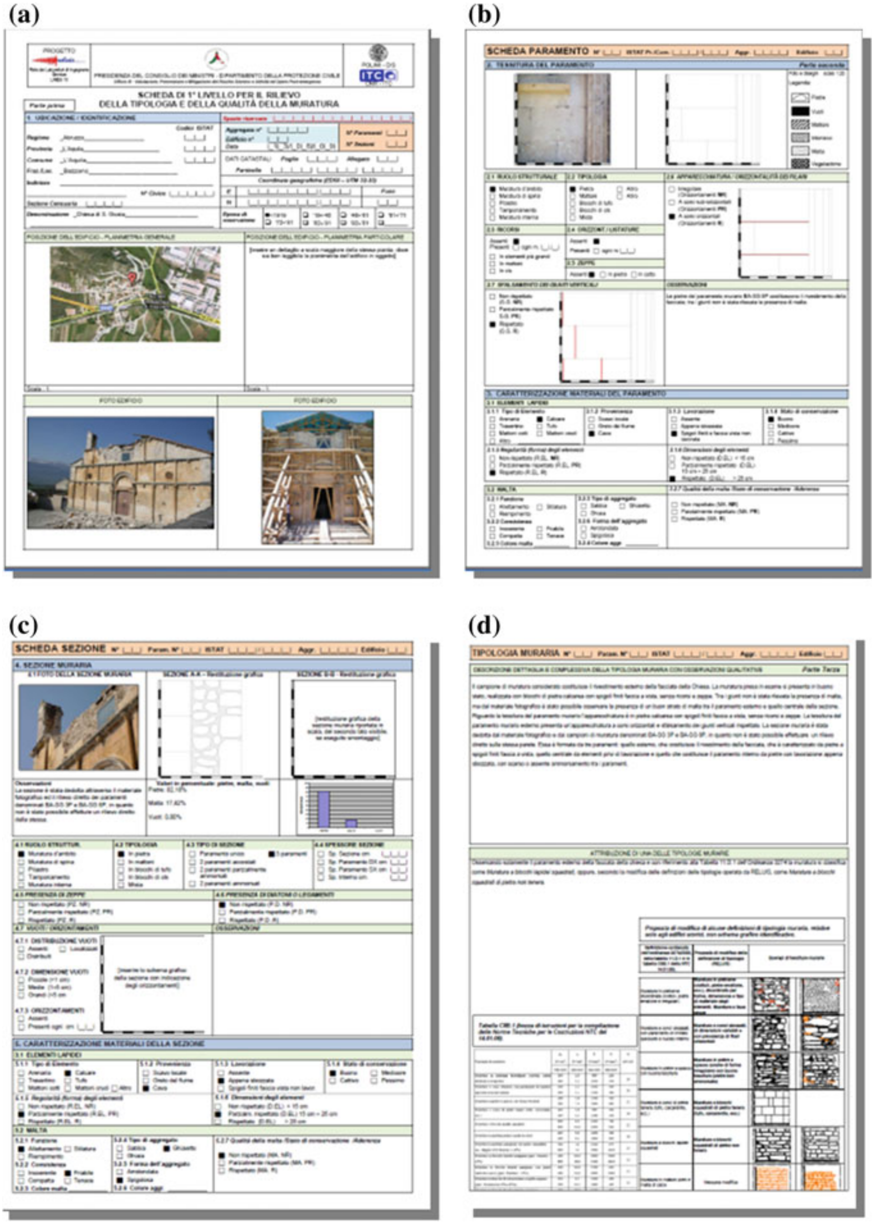

Fig. 2 a–d: Part of the template for the evaluation of the masonry quality; reduced version for LC1 (used after the L'Aquila earthquake of 2009)

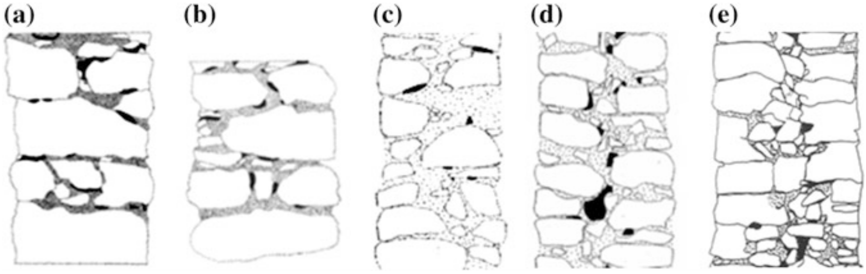

Fig. 3 Examples of masonry cross sections: **a** one single leaf; **b** 2 leaves well interlocked (with one "diatono"); **c** 2 leaves partially interlocked; **d** 2 leaves not interlocked; **e** 3 leaves or multiple leaf

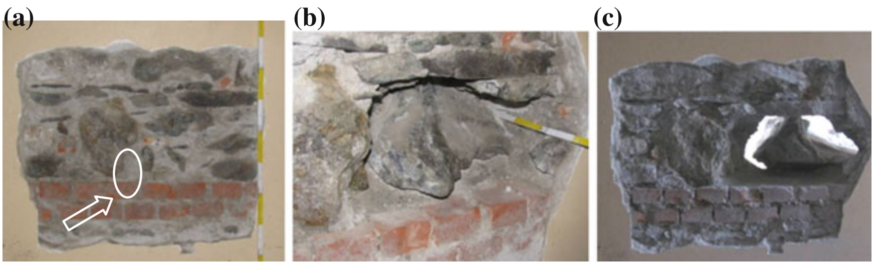

Fig. 4 Inspection HSP- I5-6 at the first floor: three phases of the removal of a large stone used as a transversal connecting element ("diatono")

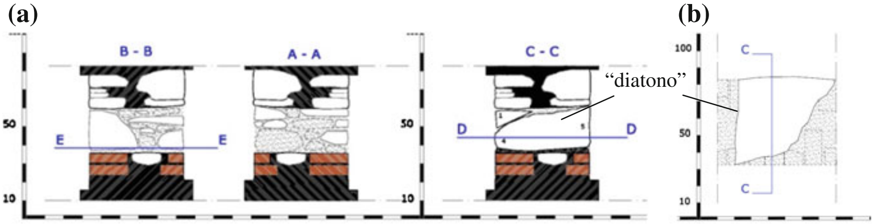

Fig. 5 Inspection at First floor (HSP-I5-6): **a** *right* and *left* vertical cross section; **b** *C–C* vertical cross section considering the removed stones; **c** *D–D* horizontal cross section showing the upper façade of the "diatono"

ex-hospital of Savona (Italy) is a three storey masonry building, built in 1860, that has gone out of use since many years, waiting for repair strengthening and functional reconversion. The building is characterized by an irregular stone masonry walls.

The prospect of the masonry showed an irregular distribution of roughly cut stones of variable dimension (larger than 30 cm), bricks and wedges, with a grey lime mortar of a good quality. Smaller stones during the disassembling revealed to be larger in the depth and well stuck, showing two layers well interlocked with no voids. In several cases some "Diatoni" were found in half of the sections inspected (Figs. 4 and 5).

The stone masonry resulted, following the table given by the present Italian code, as the one with the poorest quality. On the contrary, this masonry cross section can guarantee a monolithic behaviour under vertical and horizontal loads.

As a matter of fact, the ND- and MD-tests carried out on this masonry revealed a compact and dense masonry, still within the elastic behaviour, despite the high vertical stresses measured. In general, no cracks were visible before carrying out the tests. The diagonal compression tests, carried out by the University of Padua in the same places, also gave good results, with values of shear strength above those given by the national standard (Circular n. 617 2009).

Therefore it is so important to achieve this information about the masonry typology without only observing the façade of a wall.

A wide number of historic masonry buildings (both palaces, churches and minor buildings) of some historic centres of the Abruzzo region shows in general a masonry of a rather poor quality, made by round pebble stones and a high quantity of mortar (sometimes of a very good quality as in the church of St. Biagio Amiterno in L'Aquila), rather low values of sonic pulse velocity and high vertical and horizontal deformation.

The visual inspection and the local survey during the disassembling phase show the typology of some masonry cross sections, mainly with three leaves, with a low adhesion among the materials and limited or no interlocking among the stone units (Fig. 6).

According to the experimental results, indicating a low quality of the masonry, it turned out that the structural units in the historical centres of Abruzzo region, if subjected to seismic action, show a low out of plane response, demonstrating a rather high vulnerability, due to their cross-section. Furthermore during the double flat jack tests unexpected displacements distribution (and so tension), due to the rotation of stones, was observed in the masonry. Comparing this aspect with the historical one (many heavy seismic events in the same buildings over centuries) teaches us to consider other aspects, such as the presence of an intrinsic ductility of that poor masonry.

3 The Role of Diagnostic Investigation with Non- and Minor Destructive Tests

The evaluation of the masonry quality may assume quantitative values if the survey is followed by some in situ diagnostic tests, aimed to define the physical and mechanical masonry properties.

The in situ diagnostic investigation allows to reach the level of knowledge L2 required by the Italian National code (NTC 2008). But it is important to remark that here the proposed investigation tests, based on NDTs and MDTs, are not able to

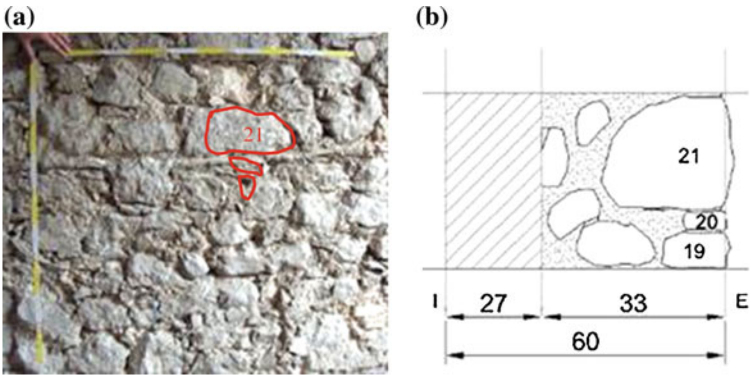

Fig. 6 Masonry texture and its three-leaf section after small disassembling in one of the residential palaces of the historic centre of Sulmona (L'Aquila) (Binda et al. 2009b)

supply the shear strength; they allow to identify more precisely the masonry typology (as table C8B.1 in (NTC 2008) for the most recurrent typologies) and some important parameters as the Young Modulus, the transversal dilation coefficient, the stress value at the onset of cracking under compression.

The investigation phases were designed in order to give an answer to the questions put by the surveyed damages. In fact NDTs always need to be appropriately used in order to solve known specific problems, taking into account also the high costs and the difficulties in the interpretation of the results.

The suggested tests for the masonry quality evaluation, to be carried out on a unique selected area, are: (a) sonic pulse velocity test by direct transmission on a grid of about 1 × 1 m with a graphical elaboration of the results represented on the drawn area through the calculation of the velocity distribution; (b) single flat jack test to define the masonry local vertical state of compressive stress, (d) double flat jack test and elaboration of the stress-strain behaviour indicating also the measured local state of compressive stress.

The NDT sonic pulse velocity test is based on the generation of elastic waves in the frequency range of sound (20 Hz–20 kHz), by means of mechanical impulses at a point of the structure. In the case of masonry, due to its heterogeneity, the pulse velocity represents a qualitative characteristic of the masonry. The velocity is influenced by the composition of the masonry as well as by the presence of inhomogeneities, voids and deteriorated areas, as well as the number of intersected mortar joints. A velocity reduction corresponds to an increase of mortar joints or voids or to cracks presence. Higher velocity peaks states higher density of the materials and in stone masonry could represent the presence of a "diaton" (Fig. 7). It is better to carry out the test by direct transmission on a grid of measurements points that covers the area analysed later on with the double flat jack test (Fig. 8).

The test was codified by ASTM in 1991, recommended by RILEM later and in Italy, as part of the on site and laboratory investigation on existing masonry buildings, is also recommended by the new Italian Seismic Code since 2003. The

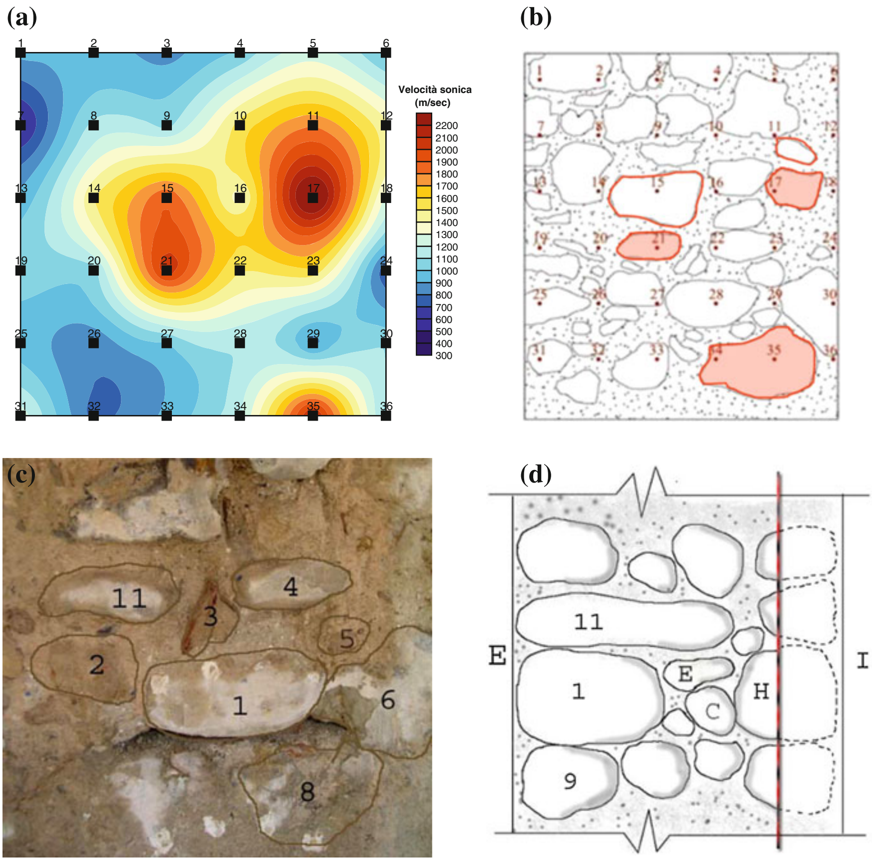

Fig. 7 **a** and **b** Presence of transversal connecting elements visible through the sonic pulse velocity test by direct transmission and confirmed by **c** a subsequent small dismantling of the masonry portion that shows a partial connecting element, a “semi-diatono”, in the stone number 11 of the **d** cross vertical left side section, (Binda et al. 2009b)

authors have carried out more than hundred tests on different types of Italian and European masonry structure usually coupling the flat-jack test with the sonic test and with the observation of the masonry section by sampling. The accumulated experience allows to define not only the limits and advantages of the test, but also to show that the flat jack when coupled with sonic tests is useful to classify different types of masonry (solid, multiple leaf, stone, brick masonry, etc.).

In Fig. 8 the results of the tests with single and double flat jack carried out on some sample buildings of Campi di Norcia (Perugia, Italy) are reported, where the masonry materials were always the same, while the texture was different. Results pointed out the differences in behaviour of masonry belonging to important buildings or complex structures (church or the bell tower) in comparison with

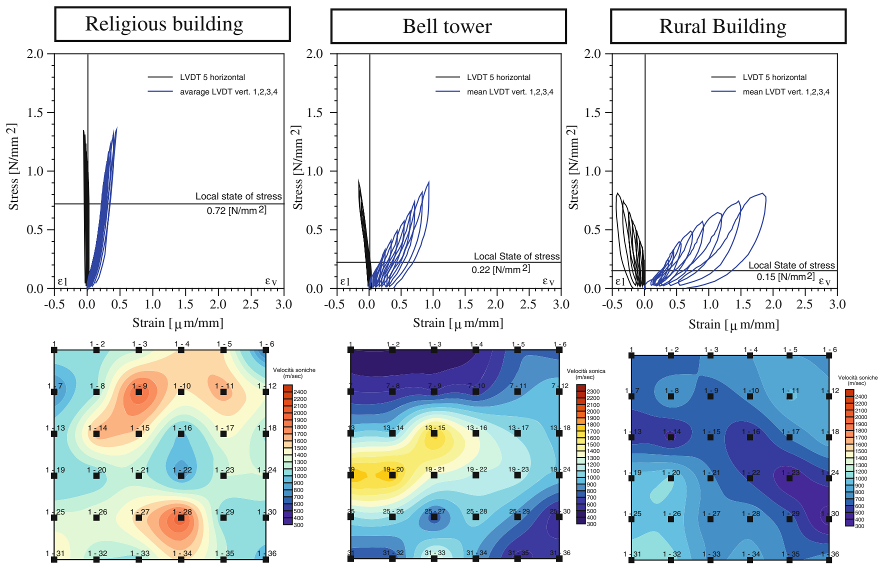

Fig. 8 Results of double flat jack tests and sonic pulse velocity tests carried out on a same stone masonry (same materials) but of different building typologies of Campi Alto di Norcia (Perugia) (Cardani 2004)

private buildings. In particular, it is possible to see that both sonic velocity and flat jack results are in agreement.

Flat jack tests are sometimes difficult to carry out on poor quality stone masonry with small round pebbles as units. The relative displacements measured by linear vertical transducers (L.V.D.T.) and consequently the achieved stress/strain plots are sometimes difficult to evaluate. In order to understand better the mechanical behaviour of an irregular stone masonry walls a new system could be applied during the standard double flat jack test: an optical method able to follow all the movements of the specimen points by referring them to an initial X, Y system (Cucchi et al. 2012).

A high resolution monochrome video camera is directly connected to a personal computer interface and the video signal is analysed in real time. The principle is based on tracking markers fixed to the specimen surface. Each analysed frame gives information about the position X, Y of the markers respect to an origin fixed on the first frame. A dedicate software allows viewing: captured images and graphs, absolute displacements X and Y, relative displacements between points selected and vectors displacements for each reference markers. With the help of this optical system, the double flat-jack test is able to show in real time the distribution of the forces in the irregular masonry specimen, showing stones rotation and where tensile stress are higher and so cracks are forming (Fig. 9).

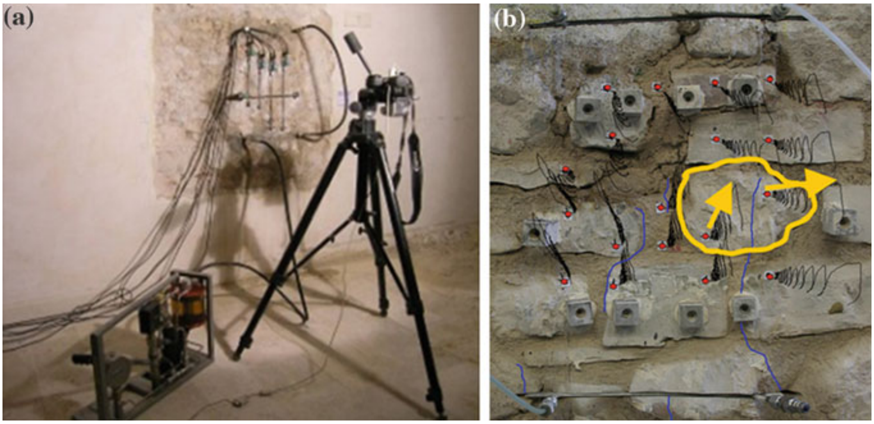

Fig. 9 The optical system applied during a double flat jack test on an irregular masonry: **a** the camera placed at a fixed distance; **b** the amplified trajectories of markers and a stone subjected to tensile tension (Cucchi et al. 2012)

4 Conclusions

The here proposed investigation procedure refers to the qualification of load-bearing masonry by means of surveys and local inspections, according to the knowledge level L1 and by means of sampling, laboratory and in situ tests according to the knowledge level L2 of the Italian Code, in order to better understand the characteristics of a masonry typology and to choose the most compatible repairing materials. The data should be collected in a dedicated survey form following, in general, a procedure developed for the definition of the masonry quality that should have its steps in the following order: (a) choice of the most representative masonry areas to be investigated in a building, (b) survey of the masonry texture; (c) description of the visible masonry texture and try to refer to the masonry class typology reported in the national code NTC08; (d) sonic pulse velocity test by direct transmission on a grid of about 1 × 1 m; (e) single flat jack and double flat jack test with the elaboration of the results; (f) local disassembling till ¾ of the masonry cross section thickness with removal of some stones or brick (it is suggested to start the disassembling in correspondence of one of the highest sonic pulse velocities in order to verify the presence of transversal connection elements); (g) graphical representation of the excavation survey and recognition of the masonry section. After this point, a second check should be made with the masonry class typology of the code selected during point c), to confirm or change the first selection; (h) sampling, during disassembling, of mortar and stones for their characterisation and numerical modelling; (i) restoring of the analysed area, replacing the sampled stones/bricks with compatible mortar.

Attention should be paid to verify the correspondence between the visible masonry texture and its cross section before defining the quality of the masonry structure.

In conclusion, it should be remarked that the visual inspection of the texture only has some limits in the masonry quality evaluation. Investigation through boroscope supplies only a very local stratigraphy without constructive characteristics. The masonry properties can be detected only experimentally in situ and in laboratory, as well as the mortar properties can be deduced only from samples taken out from the core of a masonry wall and not from the surface wall, where past re-pointing mortar or decay can be found. The physical and mechanical characteristics of the masonry elements do not supply directly or indirectly the mechanical characteristics of a masonry as a whole when dealing with historic masonry. In the end, before choosing an intervention technique, which should be able to improve the efficiency of weak masonry walls, it is necessary to recognise the properties that helped them to arrive up to our time, despite the numerous small seismic events of the last centuries, such as the one surveyed in Abruzzo region.

Sometimes one wonders if it is really necessary to alter radically these structures with invasive interventions in order to reach a working level that they have never had. Secondarily when a new intervention typology is found, laboratory tests should previously be carried out, before applying them directly on cultural heritage, in order to verify their effectiveness on the peculiar masonry.

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Dynamic and Seismic Assessment of the Gabbia Tower in Mantua, Italy

Antonella Saisi, Carmelo Gentile, Marco Guidobaldi and Lorenzo Cantini

Abstract The paper describes the experimental procedures applied to assess the structural condition and the seismic vulnerability of the Gabbia tower in Mantua, after the seismic sequence of Spring 2012. An extensive research program was planned and carried out to support the future preservation actions, including direct survey and historic and documentary research, several experimental and numerical tasks. The paper summarizes the results provided by a wide multi-disciplinary investigation and especially focuses on the key role of direct local inspection and dynamic testing in the seismic assessment of the historic building.

1 Introduction

The international debate concerning the assessment of historic structures and the possible following interventions, define a series of requirements or criteria oriented to ascertain the efficiency of the solution together with its compliance with recognized conservation principles. Critical issues to be addressed in the structural assessment of the historic structures are the lack of information about the construction techniques, the changes over time and about the effects of the decay and local damages, even if detailed mapped. Masonry quality is highly dependent on manufacturing practice with considerable variation in the mechanic properties and with limited opportunities of sampling and testing. In addition, the discussion on the correlation between the results of local tests and quantitative parameters to build up global structural capacity models is still open. Further uncertainties are related to the structure evolution, damages and subsequent repairs, all aspects affecting the actual structural condition. Within this context, ambient vibration testing of the structure could have a key role, due to either the non destructive way of testing,

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performed by measuring only the response under ambient excitation of the structure in service, or the global nature of the modal parameters (i.e. natural frequencies and mode shapes) extracted from the responses. These parameters, describing the global behavior of the structure in terms of characteristics of the key vibration modes, effectively assess the structural state of preservation. The effectiveness of such testing technique is improved by a systematic comparison with the outcomes of on site inspection and direct survey. Furthermore, the procedure could be considered the starting point of a continuous monitoring, when the results of the dynamic tests reveals anomalous behavior to be checked in their time evolution.

The paper presents the results of a recent post-earthquake assessment of a masonry tower applied the above procedure. The investigated tower (Fig. 1), about 54.0 m high and dating back to the 12th century, is known as *Gabbia Tower* (Zuccoli 1988) and is the major historic tower in Mantua, Italy.

After the earthquake of May 29th, 2012 an extensive research program was planned and performed to evaluate the structural condition of the tower. The first part of the research included: (a) historic and documentary research; (b) geometric survey and visual inspection of the bearing walls; (c) on-site survey of the crack pattern and structural discontinuities; (d) non-destructive and slightly destructive tests of materials on site (i.e. sonic pulse velocity tests and flat-jack tests); (e) dynamic tests in operational conditions; (f) FE modelling and prediction of the seismic performance.

Visual inspection and the stratigraphic reconstruction of all main bearing walls (Saisi et al. 2013) clearly indicated that the upper part of the tower is characterized by the presence of several discontinuities due to the historic evolution of the building, local lack of connection and extensive masonry decay, factors which affect the structural behaviour particularly under seismic actions. The poor state of preservation of the same region was confirmed by the observed dynamic characteristics (Saisi et al. 2013) and one local mode involving the upper part of the tower was clearly identified by applying different output-only techniques to the response data collected for more than 24 h on the historic building.

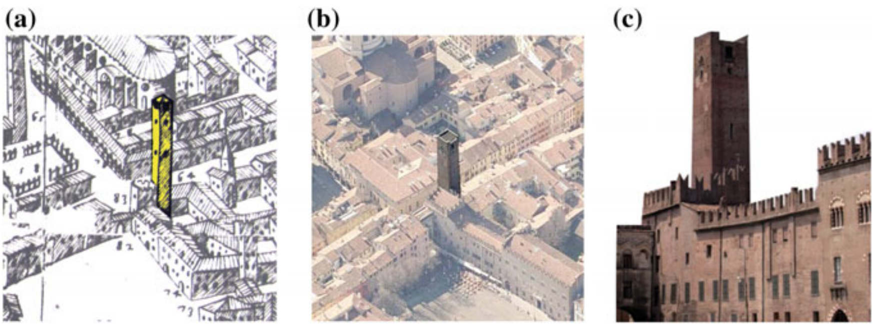

Fig. 1 Views of the Gabbia tower and the surroundings: (**a**) view of the 17th century (Bertazzolo 1628); (**b**)–(**c**) from East

These results clearly highlighted the critical situation of the upper part of the tower, pointing out the need for structural interventions to be carried out. With this motivation, and in order to allow better indoor inspection of the tower bearing walls, a metal scaffolding and a light wooden roof have been installed inside the tower. Hence, a second dynamic test was performed—aimed at checking the possible effects of scaffolding and wooden roof on the modal characteristics of the structure—and a simple permanent dynamic monitoring system (including three highly sensitive accelerometers and one temperature sensor) was installed in the tower, with structural health monitoring and seismic early warning purposes.

After a brief description of the Gabbia tower, the paper summarizes the information and the results provided by the execution of visual inspection and two campaigns of dynamic tests.

2 Description of the Tower and on Site Inspections

The *Gabbia Tower* is the tallest tower in Mantua, overlooking the historic centre listed within the UNESCO Heritage (Figs. 1 and 2). According to recent research, the tower dates back to XII century. The tower, about 54.0 m high, is built in solid masonry bricks and has an almost squared plan; the load bearing walls are about 2.4 m thick up to the upper levels (Fig. 2) where the thickness of the masonry cross-section decreases to about 0.7 m. The top part of the building has a two level lodge, which hosted in 19th century the observation and telegraph post. A wooden staircase reached the lodge but it is no more practicable since several years due to

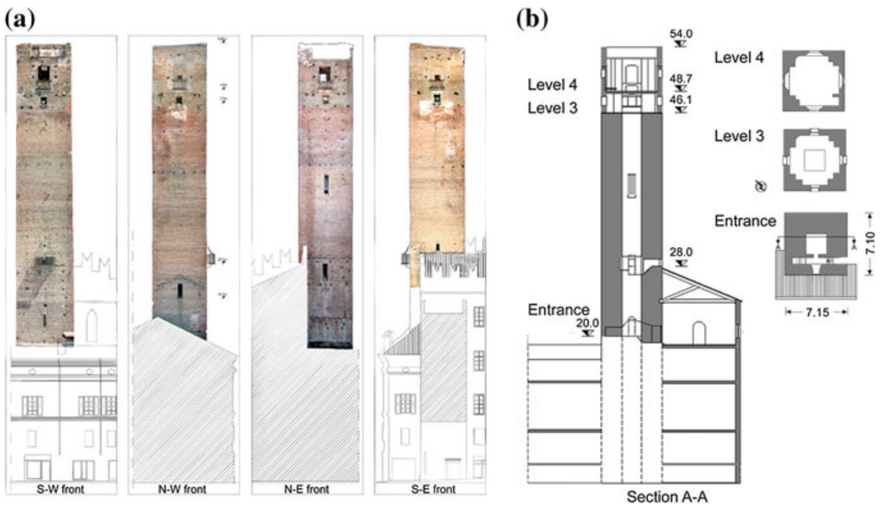

Fig. 2 Fronts and section of the Gabbia Tower

the lack of maintenance. The inner access to the tower was re-established recently (October 2012) through provisional scaffoldings.

The original layout of the surrounding structures is unknown. At present the tower is part of an important palace, evolved since the 13th century (Zuccoli 1988), complicating the geometry of the structure and the mutual links. In general, the load bearing walls of the palace are not effectively linked but just drawn to the tower's masonry walls.

Few historic documents are available on the past interventions on the tower but the observation and the stratigraphic survey of the masonry reveals passing-through discontinuities in the upper region, that are conceivably related to the tower evolution (Figs. 3 and 4). Traces of past structures are visible on all fronts (Fig. 4) and the presence of merlon-shaped discontinuities (Fig. 5a, b) suggests modifications and further adding at the top of the tower reconstructed by the stratigraphic principles. Moreover, at about 8.0 m from the top, a clear change of the brick surface workmanship (the bricks of the lower part are superficially scratched) could reveal a first addition (Fig. 5e); in the same region concentrated changes of the masonry texture reveal local repair.

A first hypothesis, based on the surface discontinuity survey, could recognise six main building phases (Figs. 3 and 4): (i) erection of the main building (probably concluded in 1,227) up to about 46.0 m; (iii) subsequent addition, up to the crenellation level; (iv) adding of 4 corner piers supporting a four side roof; (v) opening infilling and construction of the windows, crowning and the new roof; (vi); repair of the South corner.

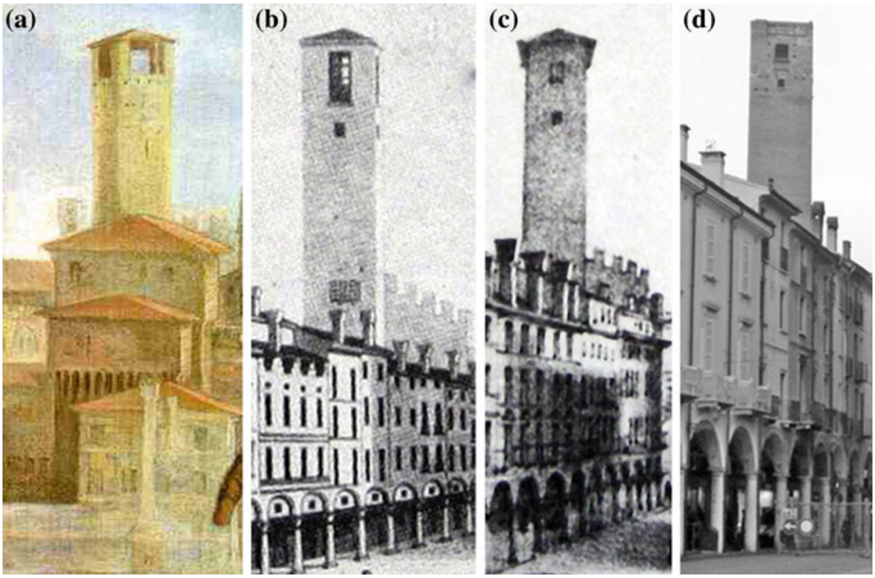

Fig. 3 Views of tower in 17th (**a**), 18th (**b**), 19th (**c**) and 20th (**d**) century

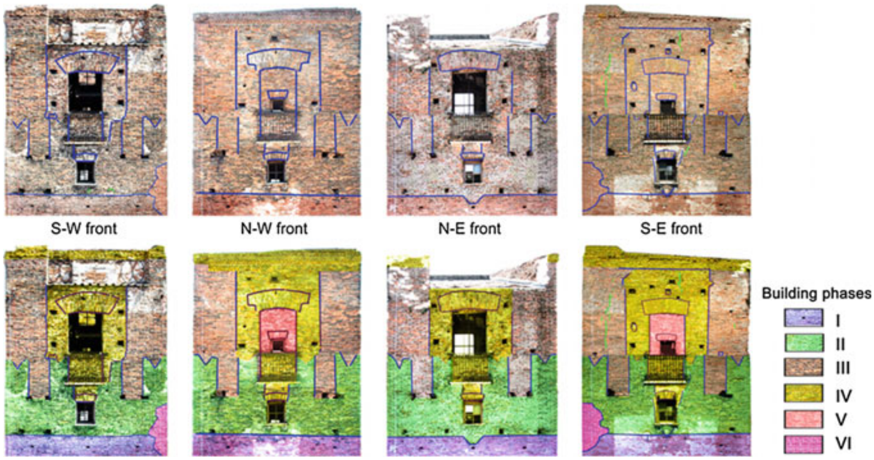

Fig. 4 Map of the structural discontinuities and of the supposed building phases

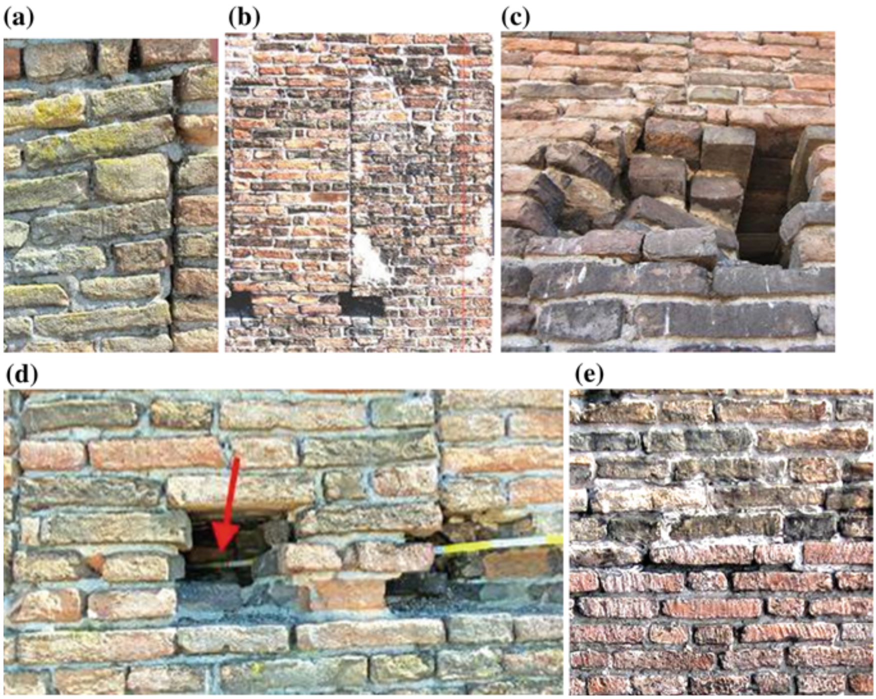

Fig. 5 **a** Typical discontinuities and lack of horizontality of the courses on top of the tower; **b** typical infillings between the supposed merlons; **c–d** critical layout of the scaffolding holes; **e** change of the surface workmanship at about 8.0 m from the *top* (the bricks of the lower portion are superficially scratched)

An accurate on-site survey of all fronts of the tower was firstly performed using a mobile platform. This preliminary survey was aimed at providing details on the geometry of the structure and identifying critical areas and irregularities, where more refined inspections were carried out. In the meantime, the historical evolution of the structure should be better investigated and understood to explain the observed signs of damage. In fact, excepting the upper part of the tower (i.e. a portion about 8.0 m high, Figs. 4 and 5e), visual inspection did not reveal evident structural damage but only superficial decay of the materials (mainly mortar joint erosion, due to the natural ageing and the lack of maintenance). Subsequent pulse sonic tests, double flat jacks and laboratory tests on sampled mortars and bricks confirm the soundness and the compactness of the masonry until the height of about 46.0 m. On the contrary, in the upper 8.0 m of the tower (Fig. 4) significant damages were observed, related to the abovementioned detachment of the several construction phases and worsened by the natural decay. More specifically, critical areas are the infillings between the merlons (Fig. 4a, c, d), supported only by few courses of thin masonry due to the unusual layout of the scaffolding holes.

Moreover, the stratigraphic survey and the accurate mapping of the structural discontinuities allowed to support some concerns on the seismic behaviour of such portions. Because of the lack of effective links except the friction, some unrestrained portions could overturn for the twinned actions of the earthquake and of the roof thrust. Low intensity actions, like after-shocks or far-field earthquakes could slightly move such weakly restrained elements decreasing the adhesion and accentuating the boundaries.

Figure 6 shows an example of the detailed survey of the masonry textures aimed at recognising the structural discontinuities and the boundaries of the weakly restrained portions. Based on this investigation, the first evaluation of out-of-plane seismic behaviour for each recognised masonry portion not effectively linked was carried out (Fig. 6c). This procedure, implemented according the most recent technical literature and the Italian seismic code, gives an overview of the seismic vulnerability related to the building transformation over time and the effect of local damage.

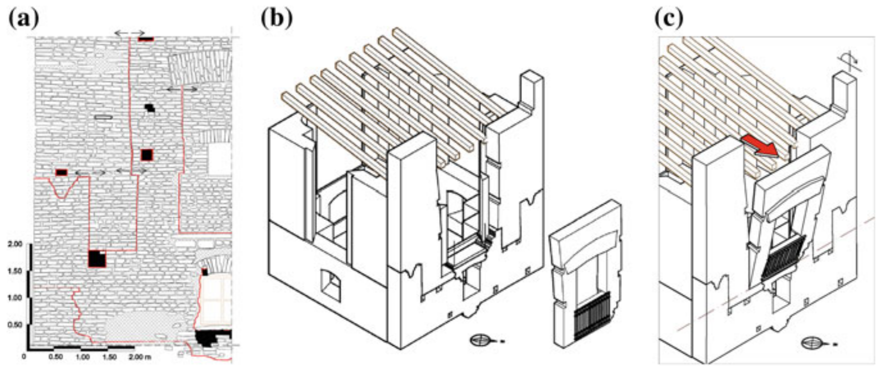

Fig. 6 **a** Map of the structural discontinuities; **b** recognizing of the weakly restrained masonry portions and **c** of the possible overturning mechanisms due to seismic actions

3 Ambient Vibration Tests

The assessment of the structural integrity and of the load-bearing capacity of a building requires firstly careful inspection and on-site investigation and subsequently modelling and numerical analysis; all the collected information could be articulated within a synergistic process where methodologies flow from several disciplines, that are related to the reconstruction of the building evolution, the materials and construction techniques and the possible state of decay. The geometric survey, accompanied by the crack pattern survey, provides valuable information on the structural state of preservation, highlights problems and allows reconstructing the building phases through the stratigraphy of the fronts, supported by further historic research.

In general, the knowledge of building phases allows to detect structural discontinuities (very relevant for the seismic response of the building) and to identify differences in the construction techniques and in the properties of the materials. Hence, knowledge of the construction phases triggers the programming of the subsequent tests of the materials, both on site and in laboratory; such investigations are strictly local and can be hardly extended to the structure as a whole, due to the variety of construction techniques and the different state of preservation of the various parts.

Critical step of the above procedure is the merging of all collected information to assess the global state of preservation.

A possible practice to settle these issues is to employ ambient vibration testing in the diagnostic program and monitoring. These experimental methods are based on measuring the dynamic response of the structure to ambient excitation and extracting from the measured data the modal parameters (i.e. natural frequencies and mode shapes). The experimental technique is especially suitable for historic structures and the identified modal parameters are representative of the global structural behaviour.

In general the vibration responses due to micro-tremors, wind, swinging of bells (in the case of bell-towers) and other sources of ambient excitation are measured; subsequently, the modal parameters are estimated using output-only modal analysis techniques and the identified quantities can then be used as diagnostic parameters to assess the global state of preservation but also the presence of local damages. Furthermore, the natural frequencies might be sensitive to environmental effects, such as the temperature, but a relatively short training period is generally sufficient to understand the effects of temperature.

Beyond the sustainability of the testing procedure and monitoring, other advantages are related to the absolute non destructive way of testing, the moderate costs, the sensitivity to structural changes, the possibility of long-term monitoring (that might be temporarily interrupted and subsequently resumed with different equipments) or to repeat periodically the test.

3.1 Testing Procedures and Modal Identification

Two ambient vibration tests (AVTs) were conducted on the tower: between 31/07/2012 and 02/08/2012, and on 27/11/2012. The first test, jointed to the direct visual inspection and survey, could be considered as a prompt structural control after the earthquake. It is worth recalling that the second test was performed after the installation of a metal scaffolding and a wooden roof inside the tower in order to check the possible effects of those additions on the dynamic characteristics of the structure and to define a starting condition for the following installed monitoring system.

The response of the tower was measured in 12 selected points, belonging to 4 different cross-sections along the height of the building, according to the sensor layout shown in Fig. 7a. Figure 7b refers to the first AVT and shows two accelerometers mounted on the corner of the lower instrumented cross-section. It should be noticed that the positioning of the accelerometers at the upper levels was aimed at checking whether the change of masonry texture detected by visual inspection (and the decrease of thickness in the load bearing walls, see Figs. 2 and 7a) affects the dynamic characteristics of the tower.

It is worth noting that the same cross-sections of the first test were instrumented also in the second one, with the accelerometers being placed on the inner side of load bearing walls (Fig. 7a). In both tests, the excitation was provided only by wind and micro-tremors. In the first test, acceleration data were acquired for 28 h: between 16:00 and 23:00 of 31/07/2012 and from 9:00 of 01/08/2012 to 6:00 of 02/08/2012. Figure 7c shows a sample of the acceleration recorded at the upper

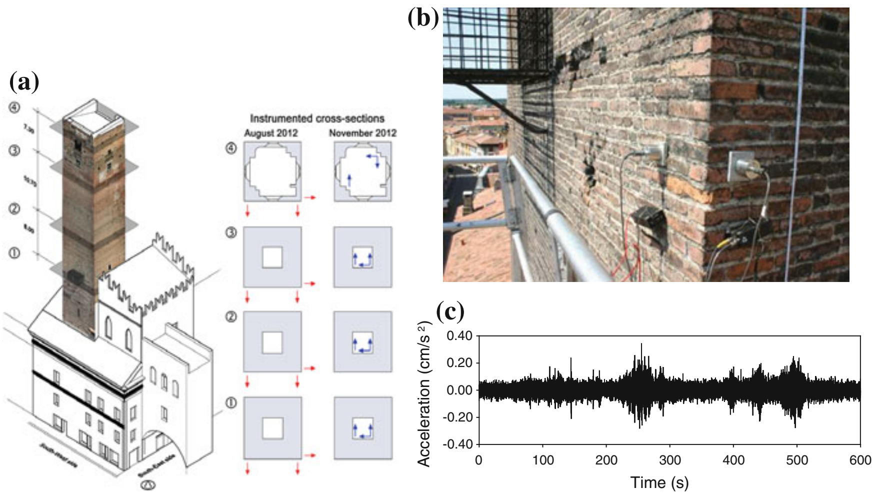

Fig. 7 **a** Instrumented cross-sections and sensors layout during the dynamic tests performed on August and November 2012; **b** typical mounting of accelerometers; **c** sample of acceleration recorded at the *top* of the tower

instrumented level and highlights that a very low level of ambient excitation existed during the tests, with the maximum recorded acceleration being constantly lower than 0.4 cm/s^2. The amplitude of responses was very similar in the second test, as well.

During the first AVT, a second acquisition system was used to measure the temperature in three different points of the tower: on the S–W front both indoor and outdoor temperatures were measured, whereas only the outdoor temperature was measured on the S-E front. It is worth mentioning that the changes of outdoor temperature were very significant, ranging between 25 and 55 °C, whereas slight variations were measured by the indoor sensor (29–30 °C), due to the high thermal inertia of the load bearing walls.

The modal identification was performed using 3600s long time windows and applying the data driven Stochastic Subspace Identification method SSI-data (van Overschee et al. 1996) available in the commercial software ARTeMIS (SVS 2012).

3.2 Dynamic Characteristics of the Tower: 31 July/2 August 2012

Notwithstanding the very low level of ambient excitation (Fig. 7c) that characterized the tests, the application of the SSI-data technique to all data sets generally allowed to identify 5 vibration modes. Typical results in terms of natural frequencies and mode shapes are shown in Fig. 8 and allow the following comments:

1. two closely spaced modes were identified around 1.0 Hz. These modes (Fig. 8a, b) are dominant bending (B) and involve flexure in the two main planes of the tower, respectively;
2. the third mode (Fig. 8c) involves dominant bending in the N–E/S–W plane with slight components also in the orthogonal N–W/S–E plane;
3. just one torsion mode (T) was identified (Fig. 8d);
4. the last identified mode is local (L) and only involves deflections of the upper portion of the tower (Fig. 8e). The mode shape looks dominant bending, with significant components along the two main planes of the structure. The presence of this local vibration mode provides further evidence of the structural effect of the change in the masonry quality and morphology observed on top of the tower during the visual inspection. On the other hand, both visual inspection and operational modal analysis confirm the concerns about the seismic vulnerability of the building and explain the fall of small masonry pieces from the upper part of the tower, reported during the earthquake of May 29th 2012.

Statistics of the modal frequencies identified between 31/07/2012 and 02/08/2012 are summarized in columns (2)–(5) of Table 1 through the mean value, the standard deviation and the extreme values of each modal frequency. It should be noticed that the natural frequencies of all modes exhibit slight but clear variation, with the standard deviation ranging between 0.011 Hz (mode B2) and 0.037 Hz (mode L1).

Table 1 Natural frequencies identified (SSI) in the AVTs

Mode	31/07/2012–02/08/2012				27/11/2012
	f_{ave} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)	f (Hz)
(1)	(2)	(3)	(4)	(5)	(6)
1 (B1)	0.981	0.018	0.957	1.014	0.918
2 (B2)	1.026	0.011	1.006	1.052	0.986
3 (B3)	3.891	0.025	3.857	3.936	3.887
4 (T1)	4.763	0.022	4.714	4.802	4.648
5 (L1)	6.925	0.037	6.849	6.987	–
6 (L1′)	–	–	–	–	9.893

B bending mode; *T* torsion mode; *L* local mode

The correlation analysis performed to investigate the possible relationships between natural frequencies and temperature (Saisi et al. 2013) clearly indicated that:

1. the natural frequencies of the global modes B1–B3 and T1 increase with increased temperature. This behaviour, observed also in past experiences on masonry towers (Ramos et al. 2010; Gentile et al. 2012), can be explained through the closure of superficial cracks, minor masonry discontinuities or mortar gaps induced by the thermal expansion of materials. Hence, the temporary "compacting" of the materials induces a temporary increase of stiffness and modal frequencies, as well;
2. unlike the global modes, the natural frequency of the local mode L1 (Fig. 8e) decreases as the temperature increases. Hence, the thermal expansion of materials in a very inhomogeneous area of the structure causes a general worsening

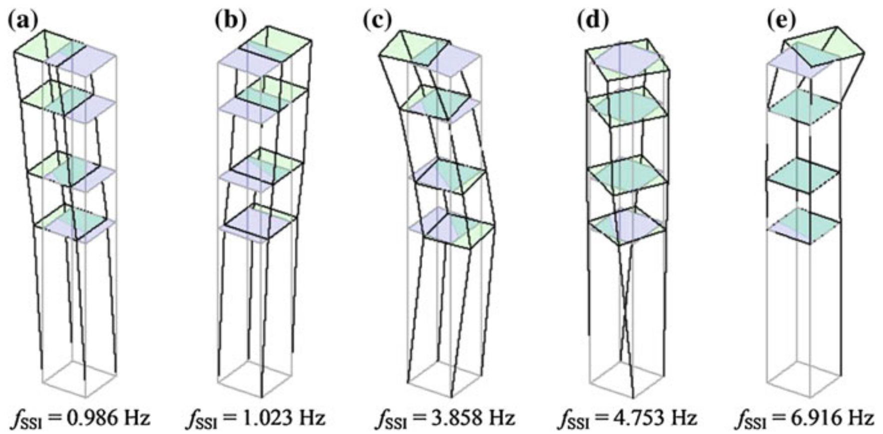

Fig. 8 Vibration modes generally identified during the first AVT (SSI-data, 31/07/2012, 21:00-22:00) **a** Mode B1 **b** Mode B2 **c** Mode B3 **d** Mode T1 **e** Mode L1

of the connection between the masonry portions. This evidence, again in agreement with the main observation of the visual inspection and the presence of the local mode L1, confirms the poor state of preservation and the high seismic vulnerability of the upper part of the building.

3.3 Dynamic Characteristics of the Tower: 27 November 2012

As previously stated, the possible effects of scaffolding and wooden roof on the dynamic characteristics of the tower were evaluated in a second AVT, performed on 27 November 2012 with the outdoor temperature being almost constant (10–11 °C). The results of this investigation in terms of identified natural frequencies main and mode shapes are shown in Fig. 9 and can be summarised as follows:

1. beyond the difference in terms of natural frequency (that are conceivably related to the temperature effects), the mode shapes of bending modes B1–B3 did not exhibit significant changes (see Fig. 9a–c). Hence, the metal scaffolding and the wooden roof practically do not affect those modes;
2. on the contrary, the mode shape T1 (Fig. 9d) now involves both torsion and bending. The identified frequency did not change appreciably with respect to the first dynamic survey, but the mode shape looks significantly different. The torsion component is still dominant in the lower portion of the structure, while the upper part is characterized by dominant bending with significant components along the two main planes of the tower. In other words, after the

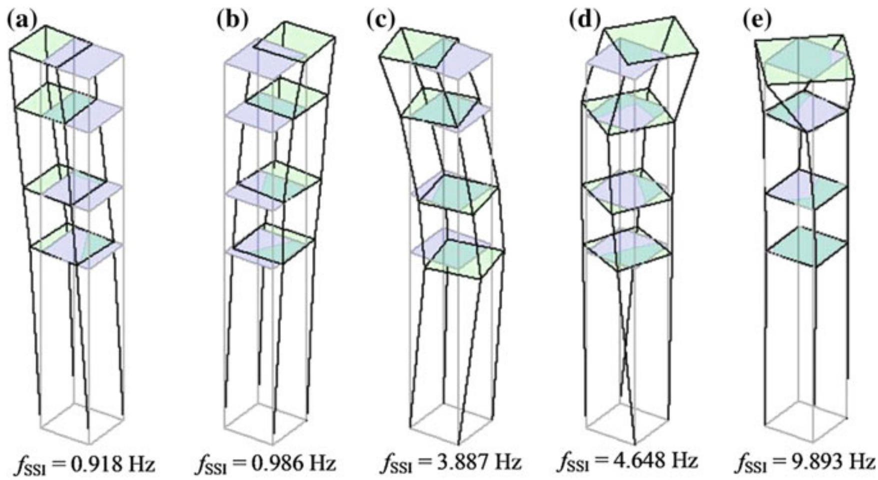

Fig. 9 Vibration modes identified in the second AVT (SSI-data, 27/11/2012) **a** Mode B1 **b** Mode B2 **c** Mode B3 **d** Mode T1 **e** Mode L1′

installation of the wooden roof the deformed shape of mode T1 becomes a sort of superposition of previous modes T1 (Fig. 6d, lower part of the structure) and L1 (Fig. 6e, upper part of the structure). Furthermore, the previous mode L1 was no more detected;

3. the previous local mode L1 (Fig. 6e) has been “replaced” by another local mode, with higher frequency of 9.89 Hz and involving torsion of the upper part of the tower (Fig. 7e). This local mode, not identified in the first AVT, is probably related to the increase of connection between the masonry walls of the upper part of the tower induced by the new covering.

As a further comment, it seems that especially the wooden roof, even if very light, affects the dynamic characteristics of the upper part of the building. The effect is two-fold: on one hand, the roof acts as a mass added in a vulnerable area (so that a possible decrease of the natural frequency of previous local mode is generated) whereas, on the other hand, the roof has binding effect on the dismantled masonry characterizing the upper part of the tower.

4 Conclusions

The paper focuses on the post-earthquake assessment of a historic masonry tower and summarizes the results of visual inspection, ambient vibration tests and long-term dynamic monitoring of the building.

Visual inspection and the stratigraphic survey of all main bearing walls clearly indicated that the upper part of the tower is characterized by the presence of several discontinuities due to the historic evolution of the building, local lack of connection and extensive masonry decay. The poor state of preservation of the same region was confirmed by the observed dynamic characteristics and one local mode, involving the upper part of the tower, was clearly identified by applying the SSI-data technique to the ambient response data collected for more than 24 h on the historic structure. Furthermore, the natural frequency of this local mode tends to decrease as temperature increases, suggesting that the thermal expansion of materials in a very inhomogeneous area of the tower, causes a general decrease of the connection between the masonry portions.

These results highlighted the need for preservation actions to be carried out. For this reason, a light wooden roof and a metal scaffolding were installed in the tower. To check the effect of both wooden roof and scaffolding on the dynamic behavior of the building, a second dynamic survey was carried out. The comparison between normal modes identified in the two dynamic tests provided the following evidences:

1. the mode shape of the lower normal modes is practically unchanged;
2. the first torsion mode changed its mode shape in the upper part of the building. More specifically, the torsion component is dominant in the lower part of the tower, whereas a local bending component prevails in the upper region;
3. a new local mode was identified, involving torsion of the upper part of the tower.

Few weeks after the second dynamic survey, a simple dynamic monitoring system was installed at the crowning level of the tower. The description of the system and the first results are reported in (Gentile et al. 2013).

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Integrated Measurement Techniques for the Monitoring of the Ancient Walls of Ferrara

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Abstract The ancient walls surrounding the historic center of Ferrara for 9 km almost uninterrupted, create one of the most impressive defensive systems of the Middle Ages and the Renaissance. The earthquakes of May 2012 increased the instability of the bastion of "Sant'Antonio" in the south walls, in fact, existing lesions are evidently grown. In order to preserve this historical and artistic heritage a complex monitoring system, based on the integration of various surveying techniques was realized. At the base of the structure a high precision geometric leveling network has been materialized to determine the vertical component of displacements, indeed on the top have been set up targets to determine by total station the planimetric component of displacements. Finally, we used TLS (Terrestrial Laser Scanner) to rate global variations of wall shape and some crack gauges to monitoring the main lesions. From the first repetitions of surveying with the described techniques, we remark a progressive increase of the framework deformation and an interesting agreement of the results.

1 Introduction: Ferrara's City Walls and the Bastion of "Sant'Antonio"

Ferrara is considered by historians to be the "first modern city" in Europe and in 1995 Unesco declared it City of the Renaissance, a World Heritage Site. This award is primarily due to the city's Herculean Addition, the urban renewal plan commissioned by Ercole I d'Este to the architect Biagio Rossetti (1484), and also to the nine kilometres long city walls that surround Ferrara's historical centre. Originally built in the Middle Ages, the defensive walls have been altered through the centuries in order to keep up with progress in military technology. The last decades have seen the city walls being the subject of a significant urban renewal project,

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Fig. 1 Ferrara's historical center and the bastion of "Sant'Antonio" of the ancient walls

which brought cycling and pedestrian routes on the external perimeter, along with restoration of the brickwork where the masonry was seriously damaged. The paper focuses on the bastion of "Sant'Antonio" (Figs. 1 and 2), which has the characteristic shape of a "spike". The outer wall of the bastion presents a remarkable slope, a height between 7 and 10 m and has a constant thickness of 85 cm. The wall was originally leaning against numerous counterforts, placed at regular intervals within the structure. Because of the action of the ground and the settlement of foundations, the wall is now detached from the counterforts, which have lost their function of support. The static situation of the bastion is further aggravated by the presence of tunnels that were dug during the Second World War to protect the population by aerial bombing (Fig. 3). Moreover two major near-vertical cracks are present on the wall in correspondence of the tip of the bastion (Fig. 2b, c) and other diffuse lesions were observed on the internal counterforts. The geological survey of the ground showed a fairly homogeneous stratigraphy compatible with the presence of the ancient riverbed of a branch of the Po river, which in the past centuries supplied water to the moat of the city walls.

The Municipality of Ferrara, worried by the extent of the main cracks, found it useful to assess their progress by the installation of four mechanical crack gauges. Measurements were correlated to the outside temperature and to the groundwater level, simultaneously detected in four piezometers located close to the bastion.

The graph of Fig. 4 indicates the enlargement of the cracks over time with a consequent possible detachment of the tip from the rest of the bastion, with a maximum speed of 2 cm/year at the top of the south side (B2).

On May 2012 two major earthquakes occurred in the Po river valley (Scognamiglio et al. 2012; Pellegrinelli et al. 2014), causing serious damages in many buildings in Ferrara and in the surrounding area. As a consequence of the seismic events the cracks of the bastion visibly increased and other minor ones took place. In order to

Fig. 2 **a** The tip of the bastion of Sant'Antonio and **b**, **c** detail of one of the major cracks

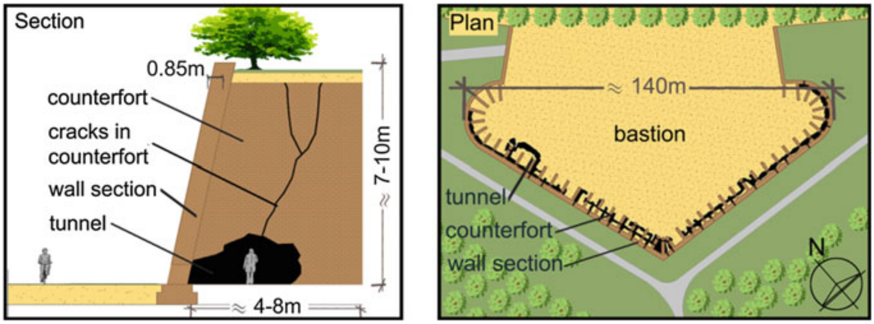

Fig. 3 *Horizontal* and *vertical* section of the Bastion

prevent the collapse of the structure, the Engineering Department of the University of Ferrara was commissioned to design and realize a new monitoring system, able to determine the kinematic of the structure, by the integration of the crack-gauges measurements with geodetic ones.

The installation of the system has been terminated at the end of 2012 and today various measurements campaigns have been performed. In this paper we present the monitoring system of the monument highlighting the contribution of the individual techniques employed and showing the consistency of the results in interpreting the complex behaviour of the structure.

2 The Monitoring System

A monitoring system is constituted by control points on the object to be monitored, external reference points, appropriate measuring instruments and operating modes and a processing method of the results of measurements. There are several geomatics techniques that can be used for the measurements. By precise digital

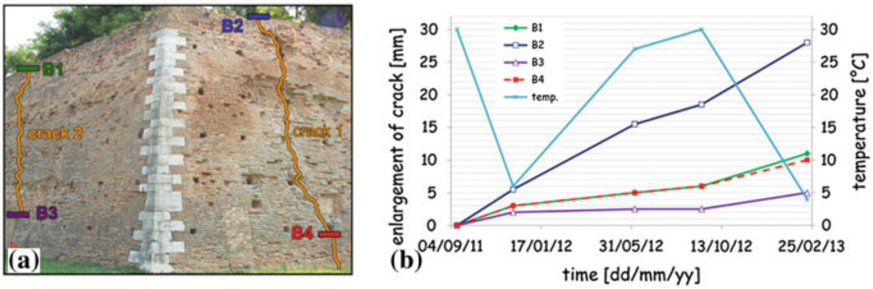

Fig. 4 **a** Position of the four crack-gauges (*B1*, *B2*, *B3* and *B4*) on the two main cracks; **b** enlargement of cracks from September 2011 to February 2013 and trend of the average temperature

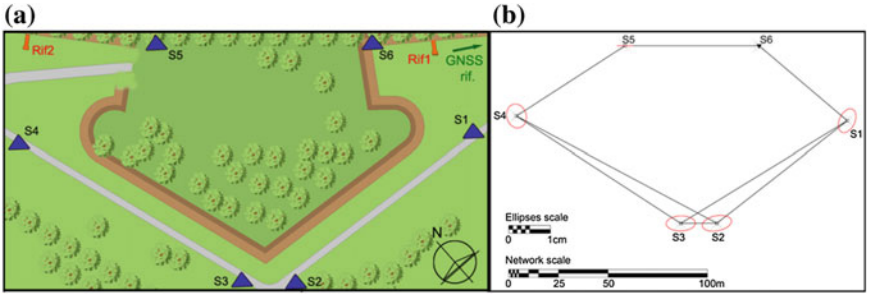

Fig. 5 **a** Rif1 and Rif2 reference benchmarks for levelling network, 2D network (*S1–S6*), approximate position of GNSS reference point; **b** error ellipses of the adjusted coordinates of the 2D network

levelling, 3D total station or GNSS (Pellegrinelli et al. 2013), the deformations are obtained by repeating the measurements over time and determining the changes of the positions in space of a finite set of control points. By Terrestrial Laser Scanning (TLS) (Beraldin 2004) or Digital Photogrammetry (Beraldin 2004; Guarnieri et al. 2013; Park et al. 2007) it is instead possible to detect the movements of a large number of points so that to allow to reconstruct the deformation of surfaces with continuity. The new monitoring of the bastion is performed by four different techniques: digital leveling and a 2D total station surveying for the detection of the vertical as well as of the horizontal components of the movements of a finite number of control points; 3D Laser scanning for an overall assessment of the morphological changes of the outer surface of the wall and GNSS for a fast and more frequent 3D monitoring of few control points on the top of the bastion.

With regard to the reference system, two benchmarks were materialized on the walls for the leveling network, far from the bastion (Rif1 and RIF 2 in Fig. 5a). For the total station and the laser scanner measurements, a reference network of 6 vertices (S1–S6, in Fig. 5a) was established in the ground surrounding the bastion. The adjustment of the network, surveyed by a Leica TCR 802, pointed out a

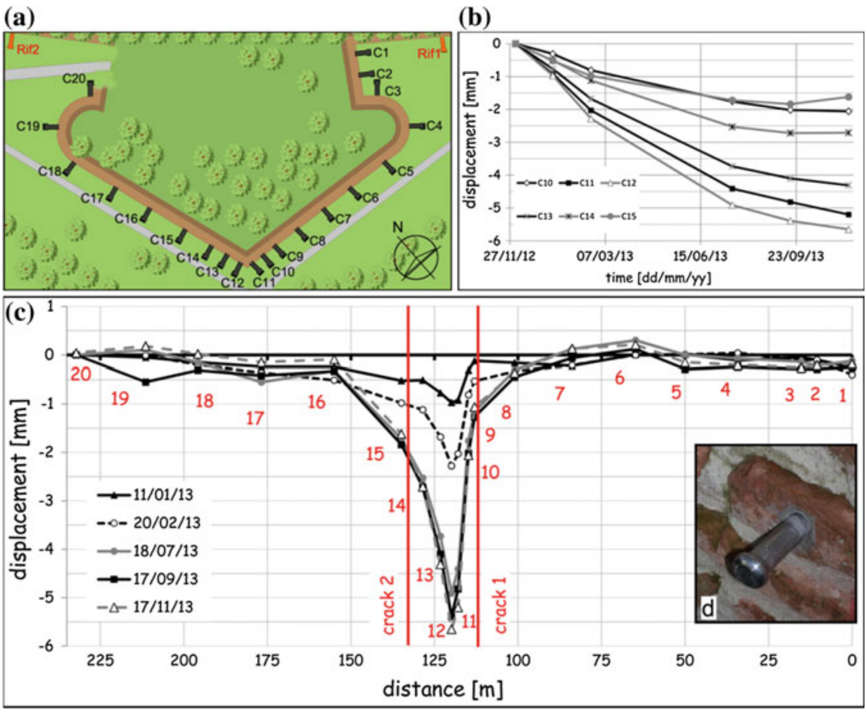

Fig. 6 **a** Levelling network *C1–C20* with Rif1 and Rif2 reference benchmarks; **b** displacement/time only for benchmark *C9–C14* between cracks; **c** displacement profile for each benchmark in the six campaigns; **d** example of benchmark at 0.5 m from the ground

maximum value of the standard deviation of the horizontal coordinates less the 3 mm (see Fig. 5b). Finally, the national geodetic reference frame RDN-ETRF2000 (2008.0) was used for static GNSS.

3 Results of Measurements

The leveling network consists of 20 control points (from C1 to C20 in Fig. 6a), in addition to the two reference benchmarks. Six measurement campaigns were carried out between December 2012 and January 2014, using an automatic digital level Topcon DL101C with INVAR rods. The adjustment of the observations pointed out a maximum standard deviation of the adjusted heights less than 0.45 mm (significance level 95 %).

The comparison between the six series of measures has allowed to determine the vertical component of displacements showed in Fig. 6b, c. The 2D network, aimed at the determination of the horizontal component of the displacement of the bastion, consists of 14 vertical sections of the wall (see Fig. 7a), each composed by two targets,

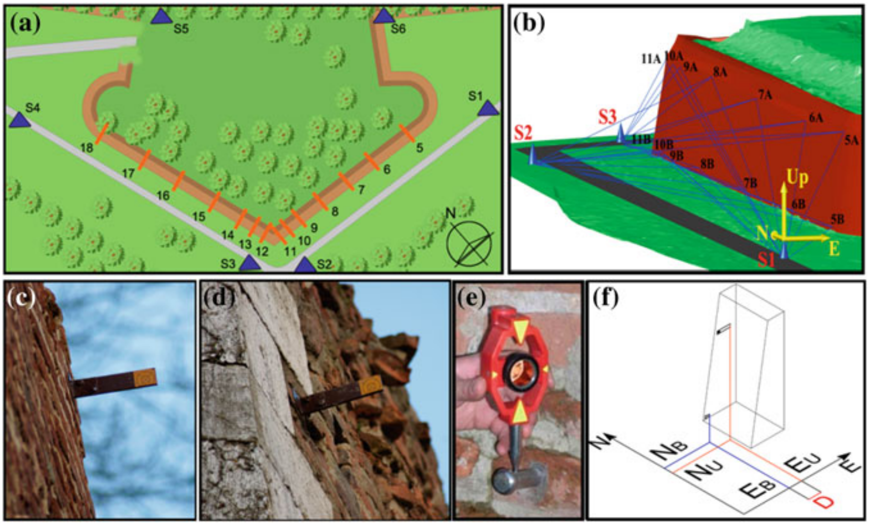

Fig. 7 **a** Plan of the 2D network (6 vertices and 14 sections); **b** local reference system and scheme of measure for the South wall; **c**, **d** target bounds masonry by a steel plate at 5 m from the ground; e marked benchmark at 0.5 m from the ground; f computation of the segment D, difference between the East coordinates of the targets on the South wall

respectively at 0.5 and 5 m from the ground. The higher targets are inserted in the masonry by means of steel plates (see Fig. 7c), placed on the vertical of some of the leveling benchmarks, specially marked to place a mini prism on them (see Fig. 7e).

The survey of the targets was performed by measuring angles and distances from at least two vertices of the network for each of them, acquiring a very high number of observations, adjusted using the method of least squares. To simplify the analysis, a local reference system for each façade having one axis parallel to the wall was created (see Fig. 7b): the movement of the targets was so computed as a displacement perpendicular to the wall (see Fig. 7f): this value is represented by the segment *D*, difference between the coordinates of the two targets of each section; its variation related to the four measurement campaigns (done between December 2012 and December 2013) is shown in Fig. 8.

The laser scanning survey was repeated once a year since December 2011 using the vertices of the reference network in order to keep a constant reference system (see Fig. 5a). The goal was the evaluation of significant morphological changes of the wall. To do this, many vertical sections were made in the three final point clouds cutting them with planes perpendicular to the walls (see Fig. 9b): the comparison of the deriving contours shows that the rotation of the tip is clear (see Fig. 10b), while the noise of the clouds, together with the irregularity of the walls, carry to insignificant change of the grade of the remaining walls. In addition, two horizontal section were extracted in correspondence to the two targets used for the 2D network in order to evaluate if the roto-traslation is visible: the comparison between the three surveys shows that the bottom sections are almost coinciding, while in the top a

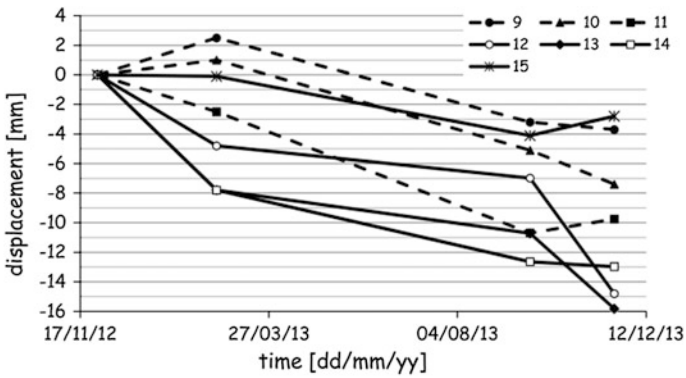

Fig. 8 Variation of length/time graph of the segment D for the seven sections on the tip of the bastion obtained with the 2D network

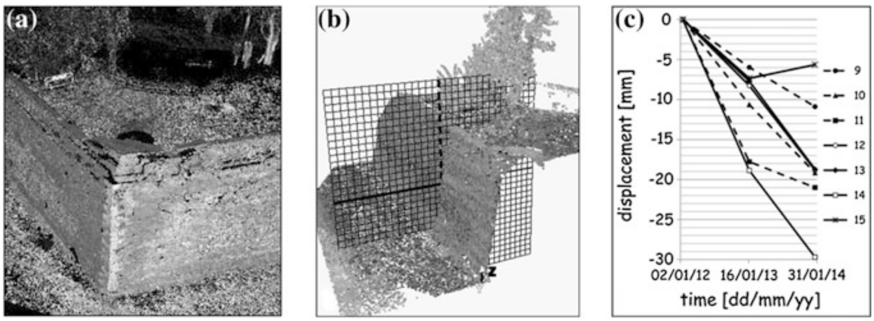

Fig. 9 **a** The tip of the bastion acquired by terrestrial laser scanning; **b** slice of the point cloud and plane perpendicular to the wall used to extract the sections; **c** variation of length/time graph of the segment D (see Fig. 7f) for the seven sections on the tip of the bastion after three campaigns

difference of about 2.5 cm is visible between the first and the last survey, with a very slight movement towards a West direction.

To assess the precision of these results, we computed the variation of the out of plumb between the three surveys for the section corresponding to the targets of the 2D monitoring (see Fig. 9c). Table 1 show the comparison of these values with the ones of the D segments described before: very good results were obtained also with laser scanning, even if the decrease of the out of plumb is a bit underestimated.

Finally, a first test with GNSS was made with a static survey. A receiver was set up on an external reference point, while the other one logged data for 30 min on each of four control points (P1, P2, P3 and P4 in Fig. 11a). The post processing of the data, carried out using also a reference permanent GNSS station, pointed out that the horizontal distances between each couple of surveyed points were in very good agreement with the same distances measured by total station (see Table 2).

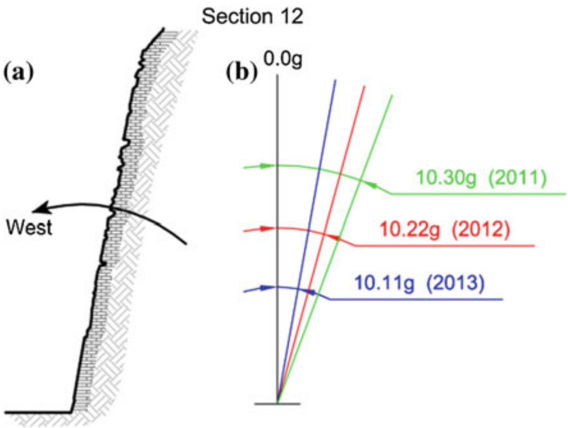

Fig. 10 Section 12 **a** contour; **b** comparison between the slope of the three surveys: the angle, used to evaluate the out of plumb of the wall is quoted starting from the vertical, (the rotation of the three lines has been exaggerated in order to make the small variations visible)

Table 1 Variation of length in mm of the segment D for the seven sections on the tip of the bastion occurred during the last year: comparison between 2D network and laser scanning surveys

Technique	S9	S10	S11	S12	S13	S14	S15
2D network	−3.7	−7.4	−9.7	−14.8	−15.8	−13.0	−2.8
Laser scanning	−4.9	−8.5	−3.2	−10.6	−11.0	−10.8	1.7

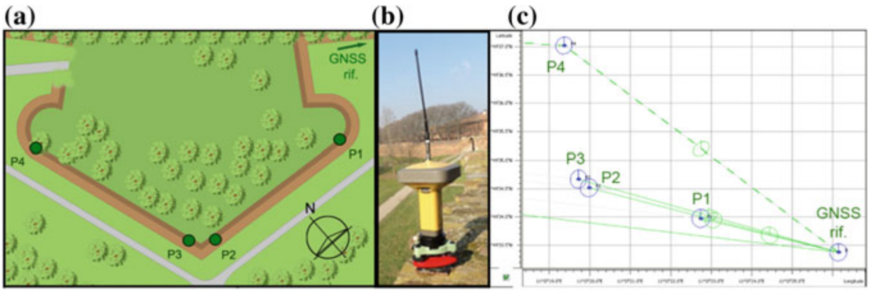

Fig. 11 **a** Position of the four GNSS control point (*P1*, *P2*, *P3* and *P4*) and approximate position of the external reference point; **b** GNSS receiver logging data; **c** plot detail of the processed network with baseline and ellipses error (only the RDN permanent station, 2 km far from the bastion, is not visible)

Table 2 Comparison of the horizontal distances between the control points obtained by GNSS or Total station survey

Distance	GNSS		Total station		ΔD [m]	σ [mm]
	D [m]	σ [mm]	D [m]	σ [mm]		
P1-P2	62.941	2.8	62.939	1.3	0.002	3
P2-P3	7.446	2.2	7.449	1.5	−0.003	2.7
P3-P4	72.998	0.3	72.997	0.9	0.001	0.9

4 Discussion and Conclusions

The analysis of digital leveling shows that the south side of the bastion has no significant shifts until the lesion (from C1 to C9) and the same is true for the west side (from C16 to C20). A remarkable differential subsidence of the tip of the bastion is instead occurring (from C10 to C15) with a maximum value of the trend of about 6 mm/year. On the other hand, the 2D network points out a significant horizontal movement toward the external of the wall of the top of the same part of the bastion and this result is confirmed by the laser scanning survey. The magnitude and direction of the horizontal movements detected by both methods are in good agreement with the crack gauges measurements, and explains the enlargement of cracks determined by the direct monitoring. As regard the test with GNSS, the results demonstrate that this technique is suitable for a fast monitoring of only the planimetric movements of the top of the bastion with a good accuracy.

The analysis of the results obtained with four different monitoring techniques, leveling, 2D network, laser scanning and crack gauges leads to the belief that the terminal part of the rampart has a movement of roto-translation due to a differential settlement of the foundation structures. This movement fully justifies the formation of significant lesions on the outer wall and confirms the hypothesis that the wall is detaching from the inner counterforts at the extreme tip of the structure.

The integrated use of different techniques, in conclusion, has allowed us to highlight the behavior of a very articulate monumental complex, which would not have been possible by limiting the investigation to only monitoring the lesions. Anyway, the use of a single individual of these techniques would not be sufficient to reconstruct the kinematic behavior of the structure.

To conclude, a monitoring system, based on the integration of various direct and geomatic techniques, is recommended to be applied to other monumental assets that have an important crack pattern, so as to provide structural engineers elements to evaluate the mechanical behavior of the structure.

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Constructive Features and Seismic Vulnerability of Historic Centres Through the Rapid Assessment of Historic Building Stocks. The Experience of Ferrara, Italy

M. Dolce, E. Speranza, R. Dalla Negra, M. Zuppiroli and F. Bocchi

Abstract During the earthquake emergency which involved Emilia Romagna Region (Italy) since 20th of May 2012, the Italian Civil Protection Department (DPC) undertook, with prevention purposes, an extensive survey on the ordinary buildings of the historic centre of the town of Ferrara, around 30 km far from the epicentral area. The activity, carried out in close cooperation with local authorities, was aimed at enhancing the seismic emergency response of the town in case of a possible further seismic event, as well as collecting technical information on the structural characteristics of the buildings, to be elaborated and hence used for further prevention purposes. Innovative element of the project was the use of two joint survey operative tools, consisting of the AeDES form used by DPC for post-earthquake usability assessments (2007) and AS form (specific for historical building blocks) which have been experimentally combined in this occasion. Activities were coordinated by DPC and carried out in collaboration with the Architecture Department of the University of Ferrara, which provided an operative and scientific support in the whole development of the work.

1 Introduction

The town of Ferrara, located in Emilia Romagna, few kilometres far from the epicentral area, was moderately involved in the events of the 20th and the 29th of May (Fig. 1). Nevertheless, the official statement from the Italian High Risks Commission of the 7th of June, outlined a high risk associated with this area, of possible further events with magnitude comparable to the previous earthquakes. This risk, combined with the high exposure of the city in terms of population,

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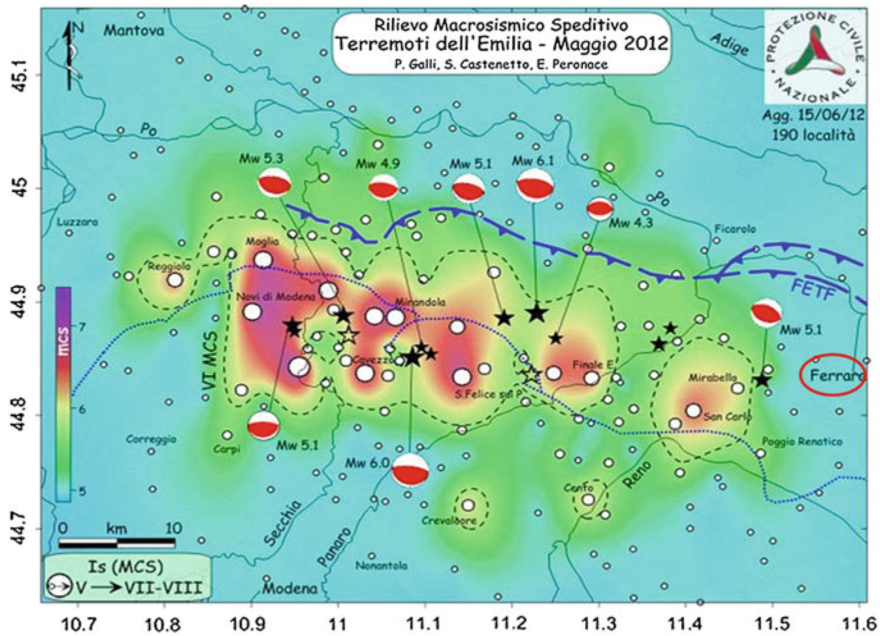

Fig. 1 Macroseismic survey of the Emilia earthquake: on the right hand, the town of Ferrara, outside from the epicentral area

buildings and dwellings (respectively 130.992 inhabitants, 19.718 buildings, 63.175 dwellings), determined the need by Italian Civil Protection Department to carry out a specific prevention activity in this area and specifically to concentrate its prevention efforts on this town.

In particular it was agreed, in coordination with local institutions, to focus on the historic centre of the town, potentially characterized by a higher vulnerability of buildings.

The urgency dictated by the emergency imposed two main features for the development of this activity: the maximum optimisation of data collection time in order to speed up the on-site surveys as well as reducing the impact on the population, already emotionally stressed by the on-going earthquake sequence.

The main objectives of the survey campaign were represented by:

- Improve the effectiveness in terms of civil protection response, through the optimization of the usability post earthquake inspection phase, needed in case of a real emergency.
- Check and assess the emergency response of the town, with particular reference to the historic centre, relatively to those buildings strategic for the management of the emergency as far as to emergency road system;

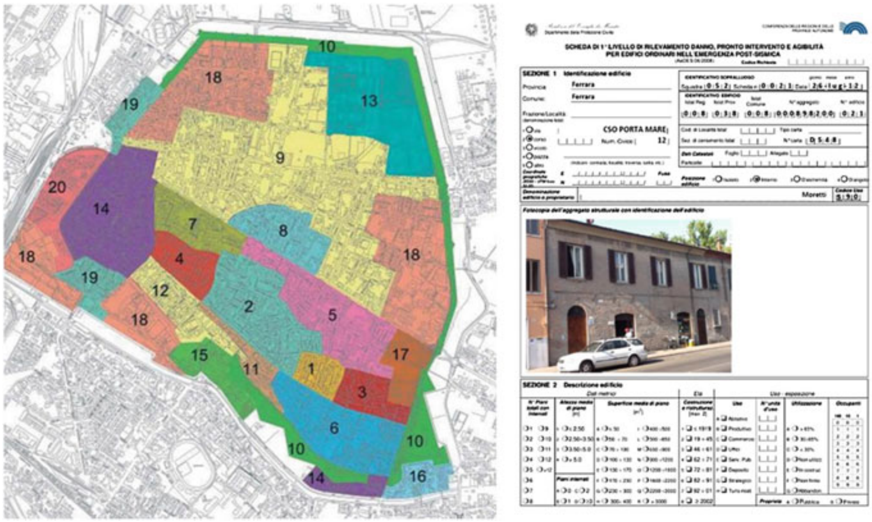

Fig. 2 *Left* Subdivision of the historic centre in zones homogenous for structural characteristics. *Right* Example of AeDES form of a structural unit in the historic centre of Ferrara

- Set up an informative system geographically referenced (GIS) to be provided to the Town Council and local authorities including identification, metrical and structural characteristics of the whole building stock surveyed, representing a basis for enhancing and orienting further prevention activities such as risk mitigation and/or emergency planning.

2 Inspection Tools

The data collection tool used for the entire historic centre, was represented by the mentioned AeDES form, officially used by Italian Civil Protection Department for evaluating the usability of buildings following a seismic event. This form is specific for individual buildings which are defined as autonomous and homogeneous structural units from ground to top.

In order to speed up the survey phase, inspections were carried from the outside of the buildings, and AeDES forms, in absence of seismic damage, were only partially filled as far as structural and constructive characteristics of the buildings. Information concerning the internal, as horizontal structures or data related to the masonry fabric quality were previously provided to surveyors, on information collected in previous research work by University of Ferrara (Dalla Negra et al. 2011), and associated with different zones of the historic centre. Figure 2 left shows the map of the historic centre split in different homogeneous zones to which generalized information on the constructive techniques were provided to surveyors during investigation. Figure 2 right, shows an example of the AeDES form (first two sections).

Being the AeDES related to individual structural units, it implicitly requires a preliminary subdivision of the building block in different structural units in order the object of investigations to be clearly identified. When carried out during an emergency, this process can involve inaccuracy especially when more inspections are not made at the same time within buildings of the same block.

In order to accurately plan the investigations and enhance the subdivision in structural units, also providing an organic and homogenous framework of the building consistency of the historic centre, a preliminary survey tool was experimentally used in association with the AeDES survey campaign.

The Building Block form (AS) is a novelty, derived by a recent Italian Government normative tool (Ordinance 4007 7/3/2012, in appliance of art. 11, code 77 of 24/06/2009) and originally conceived for the evaluation of Emergency capacity response of a town together with a set of 4 more inspection tools (Emergency Limit Condition). When specifically looking at one historic centre in its whole, the advantage of this form is that it collects additional data, beyond those commonly collected and related to individual buildings, highlighting further seismic vulnerability elements which greatly can influence the seismic performance of a series of adjacent buildings, very common in Italian historic centres.

The experimental combination of AeDES and AS forms enabled the achievement of two different purposes: specific characterization of each structural unit as well as description of the mutual relationship between adjacent buildings within the same historic block. As "motherboard" of a collection of individual AeDES forms, the Building Block form provides a clear and detailed framework of how individual structural units are each other mutually related, focusing on the major structural irregularities deriving from their spontaneous growth over the time (main result of the typological process). Information like structural heterogeneity, discontinuities in the roof or floors alignment, irregularities in the opening layout and so on can provide an overview of possible vulnerability factors of the building block which might increase the seismic damage, beyond the vulnerability of each individual building. Figure 3 shows an example of AS form filled for one of the blocks of Ferrara, it can be noted the complexity of the block, the building number of which, in Ferrara, was averagely of 50 structural units. Besides ordinary building, inspections were carried out on strategic buildings for the emergency and emergency road system, located within the historic centre, defined by the Emergency Limit Condition analysis, as defined in the mentioned Ordinance.

3 Survey Planning and Results Achieved

The survey campaign, coordinated by Civil Protection Department with the technical and scientific support of Architecture Department of University of Ferrara, began June 21st, 2012, and lasted for 6 consecutive weeks. Surveys were carried

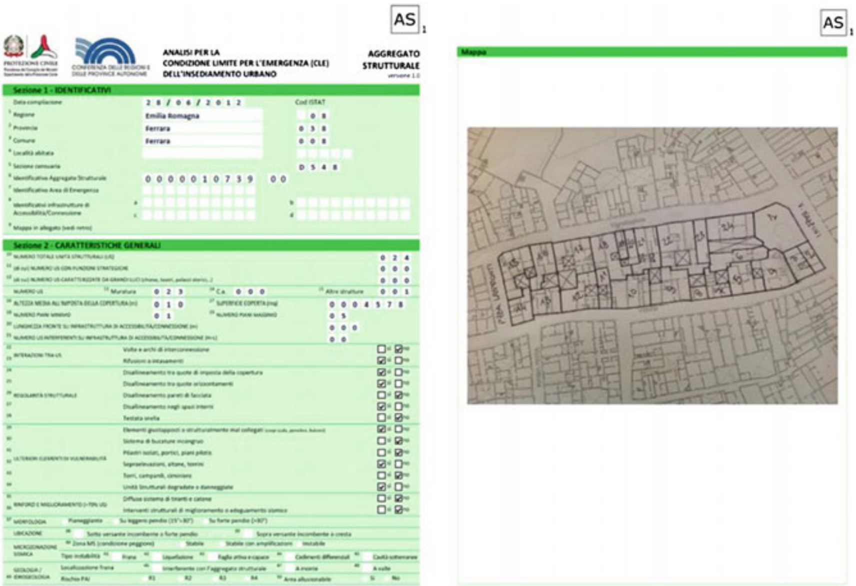

Fig. 3 Example of building block from of a structural block in the historic centre of Ferrara

out through instrumental equipment consisting in an iPad®, provided by Groma Ltd, in which the two electronic forms were implemented. They were carried out by technicians operating on a voluntary basis during the emergency, also for ordinary post-earthquake usability inspections on the epicentral areas. Technicians were joined with trainees in mixed teams, and previously trained on the specific features of the survey at the beginning of each week. At the end of the 6 weeks 3416 buildings and 439 building stock were inspected. A further implementation of the surveys carried out in the further weeks by University of Ferrara, yielded to the total amount of 3795 buildings and 485 building block inspected.

4 Constructive Features of Ordinary Buildings

One first significant result of the survey campaign was a geo-referenced database of the whole historic centre which, was provided to local authorities for further possible prevention initiatives together with the stock of partially filled usability forms. Figure 4 illustrates an overview of the whole historic centre highlighting in red the perimeter of building blocks and in blue (see detail on the left hand corner of the figure) the perimeter of each individual structural unit identified within the block. Information collected over the entire building stock of the historic centre, enable some early considerations about the generalized constructive and structural quality of ordinary buildings.

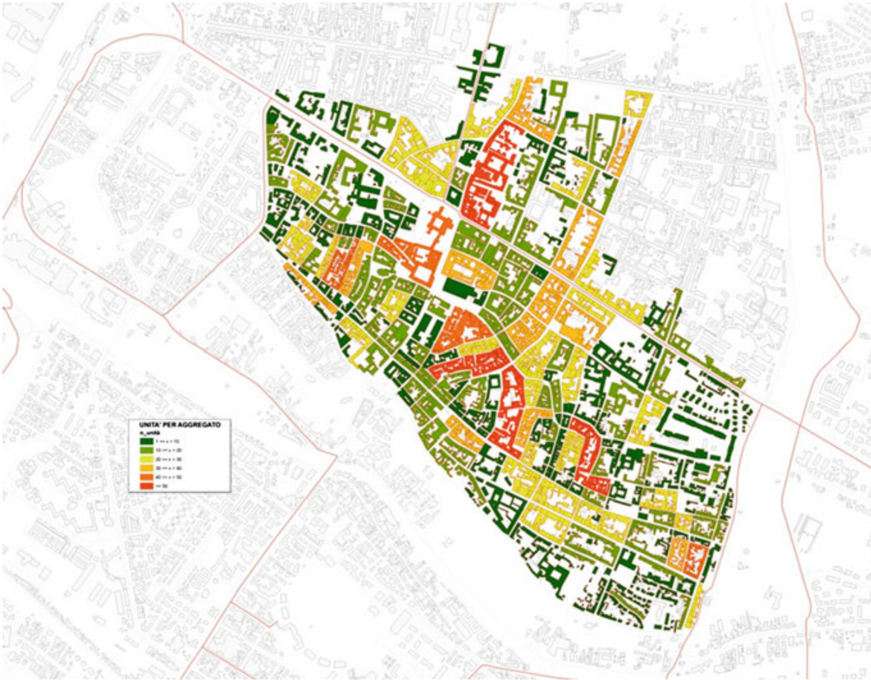

Fig. 4 Division of Ferrara building stock into individual structural units

The population of buildings is realized by 92 % of masonry and the remaining percentage by r.c. and mixed structures. The number of storeys is averagely low, in fact 83 % of structural unites are characterized by less than 3 storeys; although not uniformly distributed in relation to the different constructive "addition" of the city centre carried out by the Estense dynasty, occurred from the end of 14th until 19th century.

Notwithstanding the generalized used of brickwork, commonly associated to a good masonry fabric, in the case under exam its double-leaf layout outlines a bad structural performance. In addition to this, the use of strengthening devices like metallic ties or ring beam is little used: the histogram of (Fig. 5, left) highlights like around 50 % of masonry buildings are associated with bad masonry without any strengthening device, the 5 % of which is also featured by a number of storeys greater than 3. In the same diagram 35 % is featured by bad masonry with metallic ties, while the very low remaining percentages describes good masonry fabrics.

Notwithstanding some notable difference in the distribution of constructive techniques in the different zones of the city centre, horizontal structures are realized in the majority of cases by wooden structures (in total 53 %) and by iron and lightweight tiles structures (around 40 %). One can also observe the very little percentage of slabs as well as the absence of vaulted structures (Fig. 5, right).

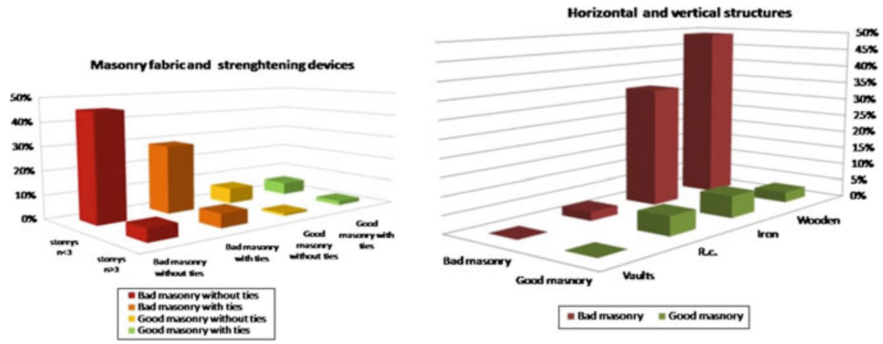

Fig. 5 *Left* masonry fabric and strengthening devices. *Right* Horizontal and vertical structures

The overview on the constructive techniques, based on the features of individual buildings, outlines rather week structural systems, and hence a sensible susceptibility to seismic damage.

5 Seismic Vulnerability

Similarly to previous works carried out by the authors (Dolce et al. 2012), the seismic vulnerability of buildings has been assessed through classes provided by EMS 98 scale (Grunthal 1998). The adoption of this simplified criterion is due to the limited consistency of data collected for each structural unit, consisting in few metrical data and a short description of the structural system.

According to EMS approach, macro vulnerability classes, universally valid in order to describe the worldwide population of ordinary buildings, can be defined basically through the type and quality of the vertical structure. Since '90 it was recognised by the scientific literature on the topic the unsuitability for describing the peculiarities of the Italian building population, so that the original formulation of EMS classes was later enhanced in order to better fit the Italian ordinary buildings assortment.

The method here proposed, shown in Table 1, and recently adopted in similar applications by the authors (Dolce et al. 2012), is an upgrade of previous methods (Dolce et al. 2000) specifically focused on the Italian building inventory. The table provides a mutual association between vertical and horizontal structures the combination of which univocally brings to find out the corresponding vulnerability class.

The criterion is also based on the construction period, this information together with the year of seismic classification of the municipality in which the building is located, allows to determine whether the building has been designed according to seismic regulations or not. In the specific case of Ferrara, being its seismic

Table 1 Vulnerability classes of building typologies

				Bad quality masonry			Bad quality masonry			Mixed (R.C. + Masonry)			R.C.	
Horizontal structures	Builded£1982 (or > 1982 for sismically unclassified municipalities)	Vulnerability classes	Not identified	N storeys ≤ 3		N storeys ≤ 3	N storeys ≤ 3		N storeys ≤ 3	N storeys ≤ 3			Irregular plan and layout	Regular plan and layout
				W/0 tie rods or tie beams	With tie rods or tie beams		W/0 tie rods or tie beams	With tie rods or tie beams		G1 º G2	G3	N storeys > 3		
		Not identified	–	–	–		–	–	–	–	–	–	–	–
		Vaults w/o tie rods and/or light pushing roof	–	A	A	A	A	B	A	A	A	A	–	–
		Vaults with tie rods and/ or heavy pushing roof	–	A	B	A	B	B	A	A	B	A	–	–
		Flexible floors	–	A	B	A	B	C`	B	A	B	A	–	–
		Semi-rigid floors	–	B	C1	B	C1	D1	C1	B	C1	B	–	–
		Rigid floors	–	B	C1	B	C1	D1	C1	B	C1	B	B	C2
	Builded > 1982 (for sismically classified muni-cipial ities)		–	C1	D1	C1	D1	D1	D1	C1	C1	C1	C2	D2

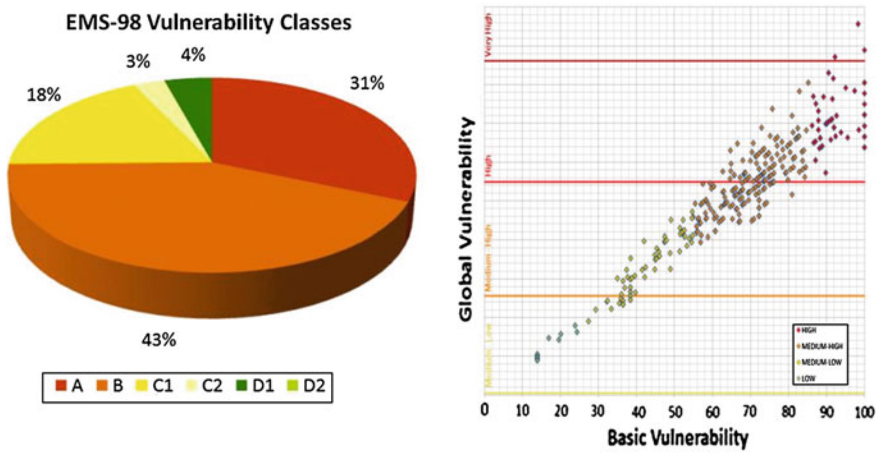

Fig. 6 *Left* Distribution of building vulnerability classes in historic centre of Ferrara. *Right* Global vulnerability of the historic centre of Ferrara

classification date late (2003), most of the building stock were unclassified and hence without any anti seismic device.

Masonry buildings are associated with classes from A to D1, with decreasing vulnerability. Class C and D of EMS 98 scale are split into C1 and C2 and D1 and D2 in order to be specifically related to masonry and r.c. structures.

The seismic vulnerability of r.c. structures also depend on the structural regularity, so that in case of very irregular structures without any anti seismic design, it is assumed a vulnerability class B, comparable to a vulnerable masonry structure.

At present, the CPD is checking the above criterion of Table 1, in occasion of a research work in progress on data set of the l'Aquila 2009 earthquake.

Following the association between building types and vulnerability classes, the building population of the historic centre of Ferrara have been hence associated, on the basis of their constructive features obtained through the AeDES data set, with the classes provided by Table 1.

Figure 6 left shows the vulnerability distribution obtained over the whole historic centre.

One can note a seismic vulnerability averagely high, consisting in 31 % of buildings in class A; 43 % in class B, 18 % in C1 and remaining percentage distributed in other classes (Fig. 6 left).

One innovative aspect of the present application is represented by the attempt to define a criterion in order to keep into account the vulnerability of an entire building block, starting from the vulnerability of the individual building, as above illustrated.

Moving the focus from one building, featured by its intrinsic vulnerability class, to the entire building block consisting of (i) structural units, one first step is the formulation of a "average basic vulnerability" Bvj for an entire building block j, defined by the average among the i vulnerability classes of buildings, weighted on the volumes of each structural unit included in the block. The basic vulnerability is described by different linguistic levels from "Low" to "Very High".

Consequently, the possible interaction among structural units of the same block have been taken into exam, starting from the information on structural irregularities, collected in the AS form. In particular 13 irregularity types of the building block have been considered as possible variables influencing the vulnerability of individual buildings included in the block and hence the overall vulnerability of the block itself.

The vulnerability factor Vf, when applied to the "average basic vulnerability" of the block produces an increase of the overall vulnerability of the block, finally determining its "global vulnerability" Gvj, taking into account the structural irregularities due to the structural units adjacent to each other, as well as from their intrinsic vulnerability. As a function of the number of block factors occurring at the same time, the basic vulnerability value is subjected to increase, and it can or cannot overcome the threshold associated with a higher vulnerability level. Figure 6 (right) illustrates the global vulnerability as a function of the number of block vulnerability factors in the historic centre of Ferrara. One can note that while in the basic vulnerability, depending on individual vulnerabilities of structural units, the medium/high level is prevailing (congruently with the distribution of Fig. 6 left), when taking into account block irregularities the vulnerability distribution sensibly increases, reaching in many cases the "Very high" level.

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A Multidisciplinary Approach for the Assessment of Great Historical Structures: Ties of "Duomo di Milano"

Mira Vasic, Dario Coronelli and Carlo Poggi

Abstract An investigation methodology, based on a scientific approach for historical structures, has been applied to the case study of the Duomo di Milano. In particular, a continuous process of data acquisition, analysis of structural behaviour, diagnosis and safety evaluation is followed with the aim of assessing metallic ties present in the Cathedral. Different techniques and fields of expertise were used for data acquisition: historical investigation gave important information on the ties origin, their structural purpose and the construction process of the Cathedral; the wide experimental campaign included visual inspection, material characterization, and dynamic tests on the original ties and contributed to the understanding of the structural system. The main results and considerations from such a multidisciplinary investigation are presented in the paper, providing a reference from a real case-study. Relevant aspects for the study of the Cathedral's structural behaviour are addressed, various approaches to be used are proposed, such as limit analysis or Finite Element Modelling (FEM) and their benefits are outlined. These models, once validated through the prediction of past and present states of the structure, will be used during diagnosis and safety evaluation to predict the future behaviour, or identify potential causes of eventual observed damage, as well as to evaluate the current state of the stress in ties measured with a more refined Non-destructive testing (NDT) approach.

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1 Introduction

In historical masonry structures, particularly in Gothic cathedrals, metallic or wooden ties were extensively used during the construction (Fitchen 1961) or later on during interventions, such as seismic improvement. Considering the life time of these structures, lasting several centuries, the issue of the durability of these structural elements is relevant. While dealing with the Cathedral of Milan (further in the text as “Duomo di Milano”), besides its imposing dimensions and the complexity of its structural system, another challenge is the big amount of unknown characteristics, the features of the used materials and of the structural elements. Despite the existence of big archives collection regarding the Duomo di Milano and its life, several issues appeared during this research and require to be investigated using a multidisciplinary approach presented in this paper. In particular, due to the appearance of metallic ties present in the Cathedral under the arches of all five naves (Fig. 1) and no existing data on their maintenance or structural investigation during the past, it was necessary to assess their current state.

Taking into account that the ties in the Duomo di Milano are active in balancing the lateral thrusts—as indicated by the static theory and the test measurements detailed in the following—the assessment of the conditions of such members is of high value for the future life of the Cathedral. Therefore the origins, structural role and present health stage of the ties were investigated, combining historical research, on-site diagnosis by means of visual inspection and dynamic Non-destructive tests (NDT). Main motivations for the future use of modern computer aided simulations, such as taking into account non-linear material properties, long-term damage, different constructive phases, soil settlement and local overstressing are described in this work. Results obtained numerically could be later on compared to the damage observed during performed visual inspection and displacements measured by a monitoring system in Duomo di Milano.

2 Diagnosis

2.1 Historical Investigation

When dealing with an existing structure, and in particular a historical one such as the Duomo di Milano is, it is essential to understand its original design, evolution of the construction and the damage during the time, so as to list mayor events in the past (seismic events, structural failures, previous restoration works, etc.…). Historical investigation was done during the present work within this scope and included: a review of the relevant literature (the *Annali* of the Duomo, previous structural analysis, documentation on the past restorations, Dizionario storico artistico e religioso (Majo and Vigini 1986)), study of the historical “technical” drawings and comparison with the on-site inspection, analysis of the photos and

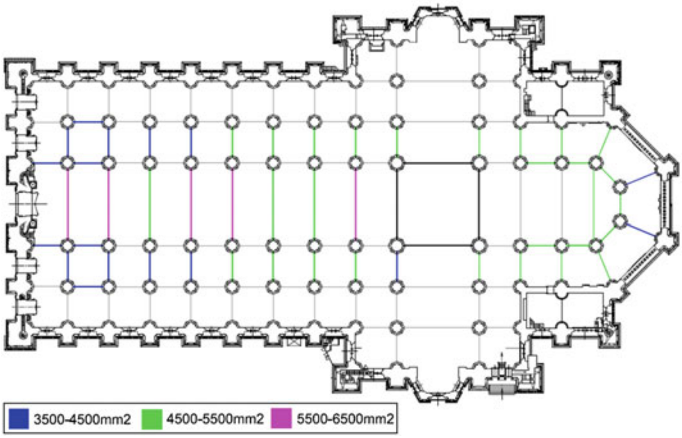

Fig. 1 Ties of the Duomo di Milano with position and average cross sectional area of inspected ties (*coloured*) and ties under the tiburcio replaced in the 20th century (*bold*)

Table 1 Comparison of Gothic cathedrals

Cathedral	Date	Free span of the main nave/choir	Height of the main nave/choir
		m	m
Amiens	1220	14.60	42.30
Palma	1357	17.80	44.00
Milano	1386	16.65	45.22

drawings from the archive of the Veneranda Fabbrica del Duomo. It was complementary to the performed visual inspection for producing a refined constructive phases map and the calendar of mayor structural events of the Cathedral. In some cases the constructive joints may present a weak point in the construction or the place where the structure might exhibit different behavior due to the long interruptions in the erection of the building.

The construction of the Cathedral started in 1386, designed partly in a Gothic style and compared with other cathedrals of the same period (Table 1) had the highest main nave at that time. Moreover, the cathedrals listed here have the system of massive buttressing walls and flying arches which carry lateral forces, differently from the Duomo which is the only one having metallic ties as permanent part of the structure after it has been completed. In other cathedrals these elements may have been used during their construction, but later on were removed (Fitchen 1961). Since the beginning of its construction, European building masters were invited during the time to examine the quality of the design and give their opinion. Such was Mignot from Paris, who within a long list of remarks and issues expressed concern regarding the stability of the structural scheme and the members he observed at the end of the 14th century. In the response of Duomo's engineers to his

Fig. 2 Typical appearance of ties in the Cathedral of Milano

remarks (Brigola 1877, pp. 203) it is said: "…and also the aforesaid masters want to put above the capitals the great iron ties, which connect a pillar with each other, and so should be done for the whole church …".[1] This confirms that the ties were used during the Cathedral's construction and most of them are still the original ones. The erection of the Cathedral started in the 14th century from the East by constructing the apse and chapels next to it, further constructing the crossing towards the West and finalizing the five nave structure in the 16th and the façade in the 18th century (Fig. 5) (detailed history of the structural evolution is given in Coronelli et al. 2014). Therefore, the original ties of the Duomo were made and placed over a period of almost 200 years and are clamped into the masonry in different ways (Fig. 2), made of wrought iron with probably different characteristics, being man-made elements which once more gives importance to the constructive phases map.

One of the important historical events is the excessive water draining from the soil under the Duomo di Milano by industrial companies during 1960s which caused a global lowering of the water table of about 20 m with respect to the 19th century (Niccolai 1967). This caused differential settlement under the piers of the Cathedral and probably was one of the factors influencing the high stress concentration in Gothic arches' voussoirs which were replaced in the past and at the present are visible as new stones. Moreover, it accelerated the long-term damage in piers under the tiburio present at that time and finally led to a big structural intervention in the final decades of the 20th century. Damage of the four piers under the tiburio originates from the 15th century (Coronelli et al. 2014) when the hidden arches were constructed to support the structure above (the tiburio and the dome) eccentrically with respect to the piers under. This caused a break of the ties connecting them in 1470 and remained for 500 years until the restoration in the last century when they were connected with a system of steel ties and most columns of the tiburio and choir columns were restored (1980–1984). Although the zone of Milano is a non-seismic zone, the underground train is running under the Duomo

[1] "…et ulterius praedicti magistri volunt super capitellis ponere ferrous seu strictores ferri magnos qui inclavent unum pilonem cum altero et ita fiat ubique per totam ecclesiam…" (Brigola 1877, pp. 203).

since 1964 and until the present no research using modern numerical tool has been done on its vibration effect to the Cathedral.

2.2 On-Site Inspection

2.2.1 Visual Inspection

During the on-site inspection, 51 ties were examined visually, building up a photographic database and measuring their average cross sectional and length dimensions (Fig. 1, Table 2). Based on the results, three types of tie anchorage into the gothic arches under the vaults were distinguished: Fig. 2 shows typical anchorages of the inner lateral nave (Fig. 2a, b) and the main nave (Fig. 2c) with the visible part of the clamping inside the masonry structure. These different types give valuable indications regarding the construction period, since types in Fig. 2a, b are observed in two different parts of the structure, representing possibly two different construction periods. Moreover, on one of the historical photos provided by the archive of Fabbrica del Duomo (Fig. 3) two different parts can be distinguished in zone of the main nave vaults; possibly corresponding to different construction periods. As for the appearance of the ties, their cross section is rectangular and oriented vertically, covered with a layer of rust—typical for the wrought iron (Fig. 2).

2.2.2 Dynamic Identification of Ties

Identification of axial load in ties existing under arches or vaults is sometimes a crucial issue in diagnosis and safety evaluation or design of an intervention. Both in the case when they have been used as a construction tool, or later on inserted as a part of structural intervention, a successful diagnosis is of great value for their effectiveness and health condition. In addition, when investigating on a large-scale historical structure, it is of interest to adopt a simple, easily feasible, fast and precise enough solution. One of the methods is dynamic investigation, widely used by several scientists (Lagomarsino and Calderini 2005; Tullini and Laudiero 2008; Amabili et al. 2010) and especially interesting when dealing with historical structures. Being a fully non-destructive, it represents a valuable tool for testing these kinds of structures, giving the possibility to estimate different element properties, such as axial load, boundary conditions or damage level; based on the dynamic properties of the examined tie.

In the present work, dynamic testing was used during the preliminary analysis as a first approach which can give the information about the tie global behavior in terms of axial force existence, and afterwards to be developed as a NDT technique. It should be noted that most of the procedures existing in the literature have been calibrated and verified or only in the laboratory conditions, or on a real-case ties in

Table 2 Dynamic testing results

Tie	L	b	h	$f_{p\text{-}p}$	$f_{c\text{-}c}$	f_{exp}
	m	mm	mm	Hz	Hz	Hz
N92_S67	15.08	92	62	0.63	1.43	3.05
N62_S92	6.50	74	51	2.81	6.32	8.60
N67_S33	6.54	77	44	2.39	5.38	8.48

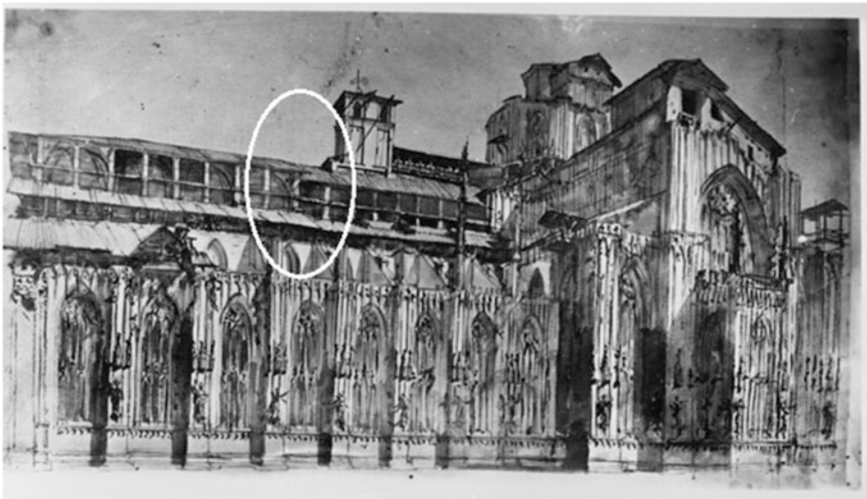

Fig. 3 Duomo di Milano (*middle* 18th century, courtesy of Fabbrica del Duomo)

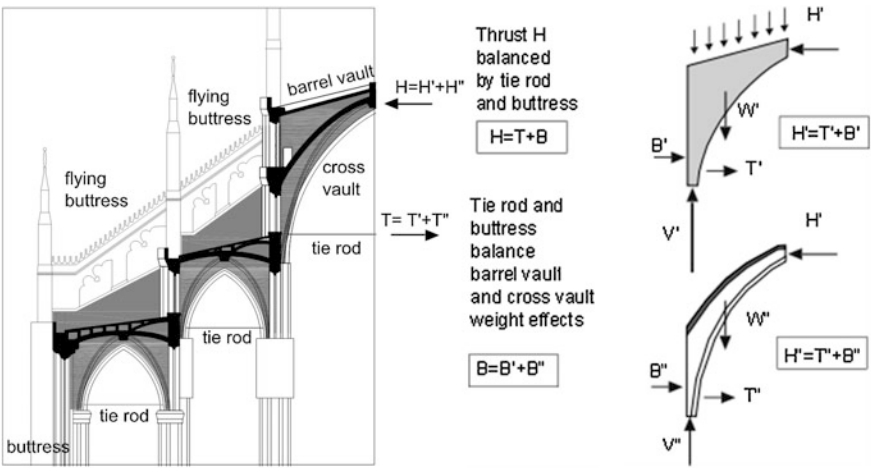

Fig. 4 Structural system of Milan's cathedral

historical structures, having much lower bending stiffness to length ratio than the one in the Duomo di Milano. Therefore, further research towards an adequate technique in this particular case is necessary.

As mention earlier, in this very first approach, on-site dynamic tests were performed on ties present in the Duomo di Milano (rectangular cross section), and in this work results are given for the three ties belonging to one representative bay: N92_S67 (main nave), N62_S92 (inner lateral north nave), N67_S33 (inner lateral south nave). Their dimensions and first natural frequencies are given in Table 2, where L is length of the tie between the anchorages, b and h are the cross section dimensions and f_{exp} is the measured frequency.

In order to verify that the ties are active members, carrying partially the lateral thrust in the structure, a theoretical solution for the first natural frequency estimation in two limit cases (pinned and fully clamped beam) for vibrating member having no axial force have been estimated. For a beam with uniform section, uniformly distributed load and linear density μ (Baldacci et al. 1971):

$$f_1 = \alpha^2 \pi / 2 \left(EI / \mu L^4 \right)$$

Where α has the value 1 and 1.5 for pined and fully clamped boundary conditions, respectively. Values of the first natural frequency neglecting existence of axial force are given in Table 2 as $f_{p\text{-}p}$ and $f_{c\text{-}c}$ for pined and fully clamped boundary conditions, respectively. Comparing these values with measured frequencies, it is obvious that the axial force is present in the ties having measured values higher than theoretically possible in case of a fully clamped unloaded beam. Therefore, further investigation is necessary for the estimation of the axial tension load, boundary conditions and eventual presence of damage, taking into account the high bending stiffness and rectangular cross section, but still adopting a simple, easily feasible, fast and enough precise solution suitable for a large-scale historical structure.

3 Structural Models

Structural behaviour of historical structures can be analysed using different approaches regarding the level of refinement, and several scientists (Roca et al. 2010; D'Ambrisi et al. 2012) underlined the importance of a precise and enough accurate approach. Certainly as a first approach, simplified methods based on equilibrium, within the framework of limit analysis provide useful interpretations (Heyman 1995). As mentioned before, the structural system of the Duomo di Milano is unique when compared to the other Gothic cathedrals due to the use of tension ties in the whole building. Preliminary analyses by Coronelli et al. (2014) suggest that these members are active in resisting the lateral thrusts from the vaults and arches. Another peculiarity of this system is the presence of double vault

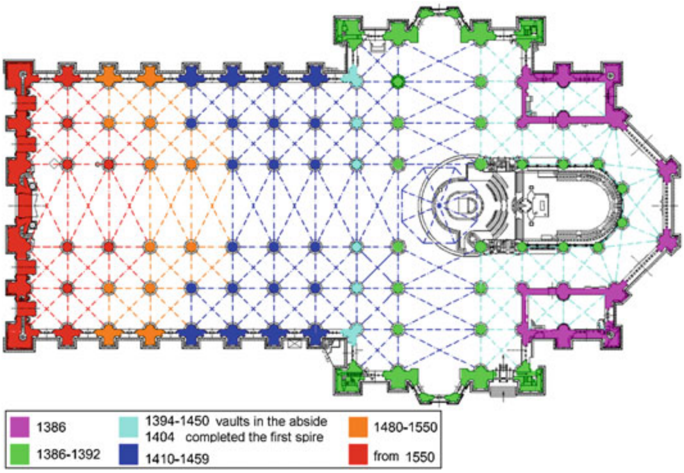

Fig. 5 Constructive phases based on the present research

system in all five naves of the Cathedral. In Fig. 4, the structural system of the naves is shown, with metallic ties and lateral walls above the Gothic arches which in combined action take the lateral thrust from the vaults. One relevant question posed to the structural analysis is what portion of the lateral thrust of the vaults and arches is resisted by the ties and what by the lateral walls.

Taking into account the complexity of its structural system, the long-term effect and soil settlement (Niccolai 1967) evidenced also by the monitoring tools, a more detailed and refined analysis would be beneficial in the future work. In last two decades, lost knowledge on historical structures has been partially recovered and accompanied with rapid development of software for structural analysis, nowadays enables accurate simulation of reality. Many efforts have been made towards the development of sophisticated models which making use of Finite Element Method (FEM) reproduce structural response to seismic loads (D'Ambrisi et al. 2012; Cagnan 2012), settlement analysis (Teomete and Aktas 2010) or construction process and long term deformation (Roca et al. 2013). However, in order to obtain the input data necessary for these kinds of analysis, a large amount of parameters (usually unknown when dealing with historical structures) need to be provided. In case of the Duomo di Milano, performing a sophisticated, FEM based analysis certainly may clarify what portion of the lateral thrust of the vaults and arches is resisted by the ties and what by the lateral walls. It should also explain the damage observed in the structure during the visual inspection, and is it a consequence of different effects emphasised during this research, such as soil settlement, different constructive phases and long-term damage of the material. Once the numerical model is verified by comparing to the present stage of the structure, including damage, big deformations and stress level in ties, it can be used to predict future possible lacks and vulnerable parts of the structure. Therefore, it is necessary to obtain the in-depth knowledge on its geometry, structural features, material's properties and present damage which in case of such a great heritage structure requires a multidisciplinary approach.

4 Conclusion

As shown in the present paper, assessment of the Duomo di Milano and its structural parts is a complex and challenging task. Effects of soil settlement, long-term damage, constructive phases, big deformations and vibration induced by the underground train should be taken into account for making adequate structural analysis. In order to obtain the reliable results, it is necessary to combine different fields of expertise and investigation techniques. In the present research, historical investigation was done analysing historical diaries, drawings and photos of the Cathedral; combined with the results of visual inspection this enabled the proposal of more refined construction phases map (Fig. 5). Non-destructive testing by means of dynamic identification has shown that the ties present in the Duomo di Milano are active members in carrying lateral loads and require special attention in the future research, which is valuable information on the structural behaviour of the Cathedral and together with preliminary static analysis makes the input for future advanced numerical analysis and maintenance plans. In this way, making use of a multidisciplinary approach enables to develop an in-depth knowledge about the structure and its past, so as to predict its future behaviour.

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MOdihMA at Sforza Castle in Milano: Innovative Techniques for MOisture Detection in Historical Masonry

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Abstract The research line MOdihMA (MOisture detection in historical MAsonry) proposes to improve the innovative techniques recently developed to measure different parameters related to water content in masonry, that has an important role in the damage of historical buildings. The first objective of this project is to compare the effectiveness of the different methods in understanding how the quantitative data obtained are directly related to water content. The second objective of the MOdhiMa project is to compare the ability of the different techniques to map water as a function of its location and depth within the masonry structure, both on macro and micro-scale. A selection of these innovative techniques recently had an application on the "Sala delle Asse" in the Sforza Castle in Milan. The hall is famous for the decoration of the vault and the monochrome on the northwest wall, attributed to Leonardo. Recently Milano Municipality defined the plan of diagnostics for detecting the causes of the increasing damage on the painting and the poor conditions of conservation of the vault. Unilateral NMR, SUSI, IR Thermography, gravimetric and chemical tests were applied for mapping the moisture distribution in the bottom of the northwest wall. The comparison with the results of the standardized techniques confirmed the low moisture content distributed in the masonry.

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1 Introduction

The historical documents of Sforza Family report that Leonardo had the task to decorate the so called Tower Hall in April 1498; this was the name of *Sala delle Asse* at that time (in the following of the paper Asse Hall). Currently, it is not known if the artist accomplished the task alone or if somebody else completed the decoration.

Luca Beltrami, the Chief of Register Office for protection of Historical Building at the turn of 19–20 century, discovered the ornamental paintings in 1893, during the restoration of the Sforza Castle, while removing the whitewash with the Paul Müller-Walde plaster sampling, although Betrami did not document the remains of the decoration that was appearing underneath the whitewash.

Eight years after, the painter Ernesto Rusca had the task to integrate and repaint the remains, finishing in 1902. Beltrami and he did not recognized Leonardo's monochrome painting remnants on the two walls. In 1954–1956, Ottemi Della Rotta removed most of the Rusca's over-paintings with the aim to show better the layers underneath; cleaning methods, unfortunately, were very invasive, and furthermore not well documented.

In 2006 a first survey was carried out by Sforza Castle conservators together with the florentine *Opificio delle Pietre Dure* (Fiorio et al. 2007); on that basis the following targets have been focused:

1. Gather all the historical documents about the Asse Hall; unfortunately the scarce sources are not easily readable, and there is not any documentation available regarding the 1893 and 1902–1904 conservation works. Few images remain the only evidence of the restoration accomplished in 1954–1956.
2. The monochrome decoration on the north-western and north-eastern walls, certainly painted by Leonardo, requires urgent works: soluble salts efflorescences whitened the surface, altering the pictures and endangering the plaster cohesion.
3. Some structure and micro-climate parameters of the Asse Hall and the nearby rooms require monitoring. Although the Politecnico of Milano first investigations did not detect worrying rising damp in the walls, nevertheless the masonry of the hall and the nearby rooms shows some structural cracks probably due to changes in the water table level. A further investigation of the masonry/vaults pattern is required to assess the real condition of the structures.

The final results will support the complex project of restoration of the vault's and *lunette* decoration. The restoration has the aim to preserve the surface, remove the efflorescences that smooth the colors sharpness. Moreover, the most updated and not-invasive diagnostic technologies will help distinguishing the part of decoration painted by Leonardo, respect to the other further accomplishments over-paintings and it will also help to assess the overall conservation conditions. A pilot intervention will lead the researchers to solve the main issues (Figs. 1 and 2).

Fig. 1 Sforza Castle, Milan. The monochrome painting in Asse Hall

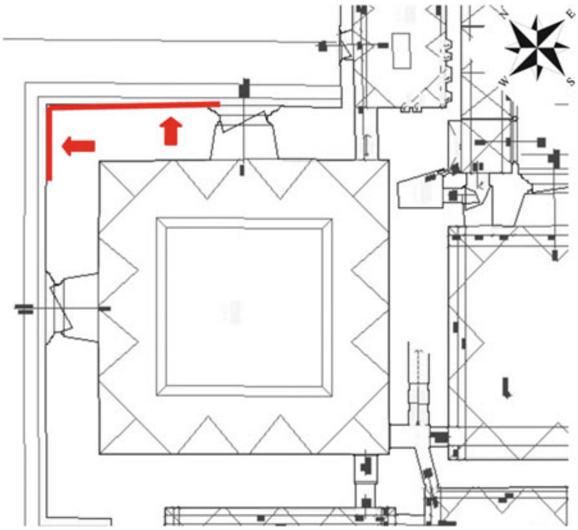

Fig. 2 Sforza Castle, Milan. Plan of the tower where the monochrome is. The *arrows* indicate the areas of investigation

2 Diagnostic Techniques and Results

The paper shows the application of two innovative techniques for measuring the water content in ancient masonry, that are described in the following. The research line MOdihMA (MOisture detection in historical MAsonry) is the framework in which these techniques has been improved since 2009 with periodical comparison and a common tests field (Materials Evaluation 2011).

MOdihMA network involves experts from many research laboratories. The first aim of the project is to compare the effectiveness of different measure methods in understanding how the quantitative data obtained are directly related to water content. The second objective is to compare the ability of the different techniques to map water as a function of its location and depth within the masonry structure, both on macro and micro-scale (Materials Evaluation 2011). The research is on-going, and the first results merged in the proposal for a EU standard dealing with moisture content measurements, currently under the final discussion.

With the aim to check the effectiveness of the innovative techniques, the authors used also some steady techniques, as gravimetric tests; X-ray Diffraction has been used in order to characterise soluble salts (see Sect 2.3). In addition, a preliminary IR Thermography scanning of the masonry has been performed in order to detect any thermal anomaly of the surface that could indicate the presence of moisture (Rosina 2006) (Fig. 3).

2.1 Unilateral NMR

Unilateral NMR[1] is a fully portable instrument allowing to measure the water content of materials, on site and in a totally non destructive way, without taking any sample, fully preserving the integrity and the dimension of the object to be investigated (Blümich 2008; Mitchell 2006). On the contrary, the conventional unmovable NMR instruments require sampling the object for the laboratory test. Portable NMR allows one to assess the state of conservation of wall paintings (Proietti 2005; Proietti 2007) and to quantitatively map the moisture distribution (Capitani 2009; Di Tullio 2010) in the outer layers of a wall painting as well as in historical masonry. The probe head of the instrument is a U-shaped magnet assembled with two permanent magnets mounted on an iron yoke and including a radio-frequency resonator. The probe head detects the hydrogen signal of moisture at a selected depth inside the wall. The intensity of the detected signal is directly proportional to the water content. With a proper calibration of the integral of the recorded signal, each area of the map is related to an amount of moisture accurately measured. The magnetic field penetrating the object is inhomogeneous and decreases with the distance from the magnetic surface. Measurements at different

[1] NMR instrument Bruker Biospin.

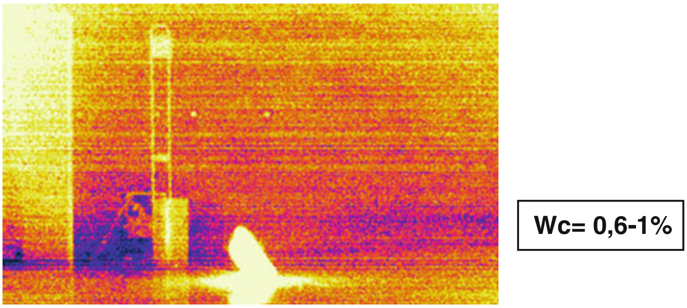

Fig. 3 IR Thermogram of the Northwest wall, range of temperature 22.3–23.5 °C, emissivity 0.92; air T 24.5 °C. Location of sample n. 1 of gravimetric test, resulting 0.6–1 % water content

depths inside the object are carried out by changing the resonance frequency. A recent development of portable NMR is able to scan depths up to 2.5 cm producing depth profiles with micrometric spatial resolution. The application of these sensors allows to obtain a NMR stratigraphy of the material. NMR measurements were performed with a portable NMR instrument, at 17 MHz, at a depth between 0.25 and 0.35 cm from the surface, fully disregarding the signal from the surface. Measurements were carried out on the northwest and northeast walls of Asse Hall along a matrix of 25 points for each wall, each point being labelled with (x, y) coordinates. Each measured point corresponds to an area of 10 cm square, which is the area that the probe head detects (Fig. 4).

Each measurement took about 600 s. The collected data were processed to obtain a contour plot where x and y were the coordinates of the measured area and z was the integral area of the NMR signal. Figure 5 shows the resulting maps of the moisture distribution at a depth of 0.3 cm. In these maps differences in moisture content are shown as colour gradients, red indicating a very low water content, while dark blue—violet indicates a very high moisture content. At a preliminary screening, maps showed a very low moisture content. Cement mortar specimens were used to calibrate the NMR signal. The calibration was obtained by measuring the dried material as well as the water-saturated material. According to this calibration procedure (Capitani 2009; Di Tullio 2010), the maximum value of the integral of the NMR echo signal measured on the northwest and northeast walls respectively corresponded to about 1.5 and 1 % of moisture content. The error was lower than 10 % of the nominal value.

2.2 *SUSI: An Instrument Based on Evanescent Field Dielectrometry*

Evanescent Field Dielectrometry (EFD) is a technique deriving from dielectric spectroscopy (Olmi 2006). The SUSI instrument (SUSI is the Italian acronym for *integrated sensor for measuring humidity and salinity*) works at microwave

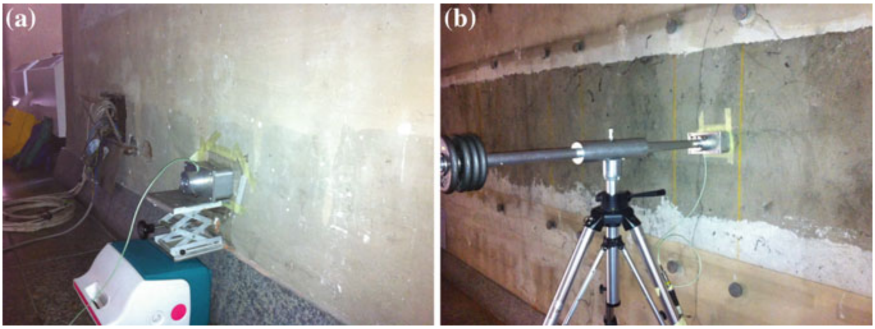

Fig. 4 (**a**) and (**b**), two probe heads of the portable NMR device

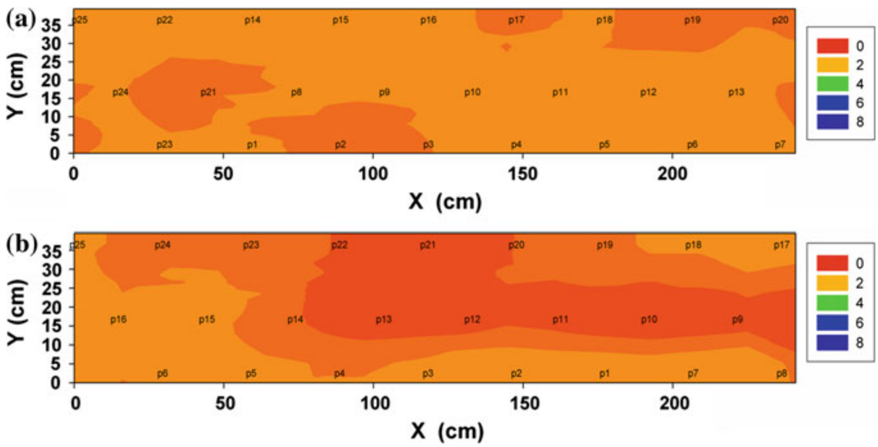

Fig. 5 **a** The graphic representation of NMR results on the North-Western (NW) and **b** North-Eastern (NE) walls: the distance from the window in the walls is marked on the *x* axe, the height from the floor is on the *y* axe. The scale of values ranges between 0 (*colour red, totally dry*) and 8 (*colour blue-violet, totally wet*)

frequencies (1–1.5 GHz), it is portable, battery-operated and totally safe for the operator. It has been developed by the Institute of Applied Physics of the National Research Council (CNR), and it is patented in Italy, in the EU and in the USA (Bini 2009).

The moisture content (MC) of the porous materials constituting a wall (mortar, bricks, stone) is measured because of the dielectric contrast between water and the dry host material (Olmi 2008).

SUSI uses a scalar network analyzer and a resonant probe, allowing to measure and elaborate in real time the sub-surface moisture content (MC) of a wall and to detect the presence of soluble salts in it. The main uses are monitoring and diagnostics of walls of artistic interest—mainly frescoes and mural paintings. Its low-weight allows

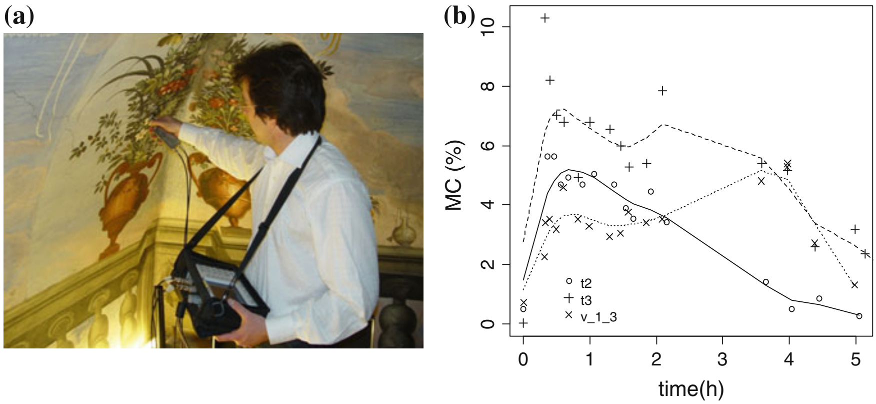

Fig. 6 **a** The SUSI instrument, **b** Water diffusion dynamics curves

an easy portability also in "difficult" environments such as scaffolds. Data are acquired by a general purpose net-book computer, with a friendly application running in Microsoft Windows (XP, Vista, Windows 7). The EFD instrument has the following technical characteristics: the measurable MC (on wet basis) is in the range: 0–20 %; salts are detected in terms of a *Salinity Index* (SI) which ranges between 0 and about 10 (from no-salt to saturated salt conditions (Di Tullio 2010). Direct contact, non-invasive measurements concern the sub-superficial region (up to a couple of cm in depth): the affected volume is about semi-spherical with a radius of 2 cm. SUSI is mainly used for: (1) seasonal monitoring, (2) diagnostics of water content, (3) detection of soluble salts, (4) water diffusion dynamics studies. The instrument has been extensively used for measuring MC and SI on frescoes and walls of artistic interest, in several churches and museums. Although operating point-wise (the measured MC is an average on a volume of about 15 cubic cm), the instrument easily allows to obtain 2-D maps through a post-processing procedure. False-colours distributions help to evaluate the "health" conditions of a wall. Moreover, the real-time operation allows to follow the time behaviour of a material after wetting and to determine its drying time constant, helping restorers to plan conservative treatments.

Figure 6a shows the application of SUSI instrument. Figure 6b shows an example of water diffusion dynamics curves obtained on three positions on the fresco. This approach requires to wet the surface by means of a small sponge and to follow its drying behaviour for a time sufficient to restore the equilibrium with the environment.

SUSI has been recently applied in the Asse Hall for determining the moisture content and the salt distribution in selected areas. A specific calibration has been performed on site, saturating with de-ionized water a dry region and measuring the water content of a small sample by the gravimetric method. Figure 7 shows the MC map on the NW wall: the sub-superficial moisture content is always below 1 %.

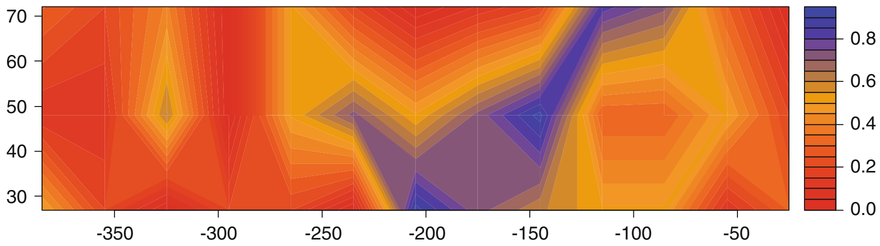

Fig. 7 False-colour MC map on the NW wall. The negative abscissa values are distances from the corner of the wall

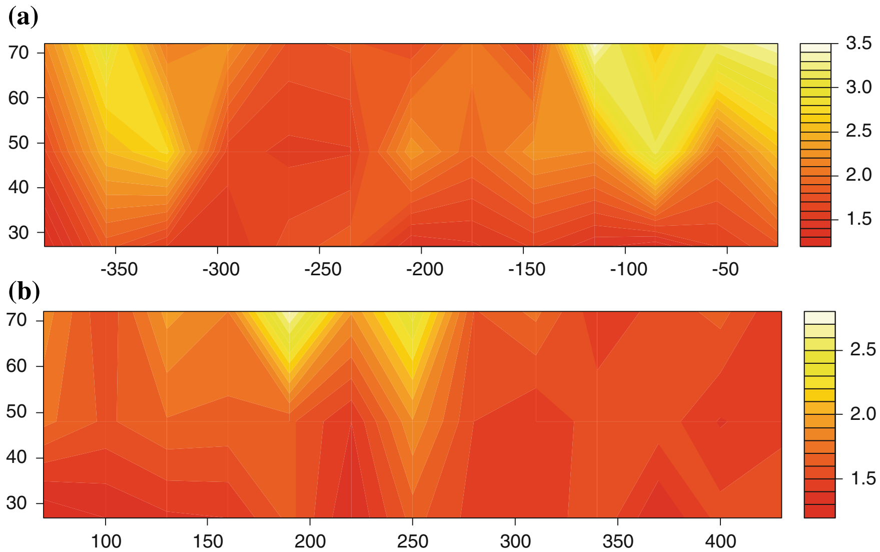

Fig. 8 Maps of SI on the NW (**a**) and NE (**b**) walls

The salinity index of the investigated walls is rather low. The SI distribution on the NW and NE walls is shown in Fig. 8. Also at low MC regimes, as in the present case, an SI value higher than 3 suggests a not negligible presence of salts. The NW wall appears with a slightly more amount of salts than the NE one.

2.3 The Validation of Visual Analysis and X-ray Diffraction

On the monochrome wall (NW wall) four samples have been collected by light brushing on the plaster surface. The decay morphology corresponds to micro blistering and white efflorescences as it is possible to see in Figs. 9 and 10.

Fig. 9 White efflorescences are concentrated alongside the border of a patch which is composed by a different cement mix respect to the surrounding matrix

Fig. 10 White efflorescences are spread all over the surface but the patches

Efflorescences are mostly localized close to recent cement plastering. On the plaster surface it is possible to observe also some patches probably composed by a different cement mixture. The white efflorescences are concentrated alongside the border of the patches described above, most probably due to a difference in the porosity distribution in between the matrix cement plaster and the cement patch (see Fig. 10). The same decay pattern is visible where the original white plaster is still present. These salt formations have been sampled and analysed by means of X-ray Diffraction (X Panalytical X'Pert PRO). The results are showed in Table 1. It is possible to see that the main soluble salts responsible of the micro-blistering are nitratine ($NaNO_3$) and gypsum ($CaSO_4$ $2H_2O$); it is possible to hypothesize that nitratine is coming from the cement matrix.

Table 1 X-ray Diffraction results on 4 sample taken form the Monochrome wall

	Calcite	Quartz	Plagioclase	Horneblende	Gypsum	Nitratine	Baryte
1	xx	–	–	–	tr	xxx	tr
2	x	–	–	tr	tr	xxx	tr
3	xx	x	tr	–	xx	xxx	–
4	xx	xx	tr	tr	xxx	xxx	–

Xxx main component; *xx* secondary component; *xx* minority component *tr* trace component

3 Conclusions

The comparison between steady and innovative techniques for moisture detection on ancient masonry resulted with a good agreement among the used techniques: the lack of rising damp was the main result, as well as the high accuracy that the innovative techniques showed on testing area that was damped by the researchers as reference test.

Regarding the study case: the first part of the diagnostic survey provided these results: the development of the damage on the monochrome is not due to water infiltration (or pipe leakage), but it is more probably caused by the microclimate unbalances and the diffusion of soluble salts. The salts could come from the cement mortars and plasters applied to the masonry during the last restoration intervention; otherwise the salts possibly could come from the cleaning products that the restorers used. Actually, also the location of the most severe and fast damage, close to the eastern window, indicates that further investigation should be accomplished to ascertain the lack of tightness of the window frame and the effects of the further exchange of air.

The next diagnostics will support the project of a prototype for mitigating the exchange with the outdoor climate without intervention on the masonry and the windows, together with the innovative application of NMR for the investigation of the vaults plasters.

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The Chapel of the Blessed Virgin of Miracles: A Multidisciplinary Approach for the Project of Conservation and Reuse

Elisabetta Ciocchini, Aldo Maiocchi and Fabio Zangheri

Abstract From the date of its construction the chapel of the Blessed Virgin of Miracles is an important reference for the devotional Milanese population. It is so significant that the funding for its construction are raised thanks to the offerings of the faithful people visiting the church of S. Maria alla Porta, attached to which the chapel was built in 1705 to preserve the image of a Madonna and Child found—by chance—in the same church during some maintenance works carried out in 1651. During the XVIII and XIX centuries the chapel and the painting acquire an increasing importance and affection that will continue to grow until the tragic events of the World War II and, in particular, the bombings of 1943, which destroyed the chapel, saving only the wall adjacent to the church even if severely disfigured. The project of conservation and reuse aims to give back the building and its values to the city, valorizing the two crucial aspects that have characterized, and still characterize, the chapel. The one linked to the devotion to the Virgin and the other connected to the memory of the wounds caused by the war. Despite the small size of the ruins, the approach to the conservation project has been set on a strong multidisciplinary approach which allowed to reach excellent results in terms of knowledge of the status quo of the remains from both morphological/material and historical/documentary points of view.

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1 Indirect Research: Historical and Documentary Research

Historical and documentary research,[1] first step to build a wider knowledge framework, have focused predominantly in the archives of the Parish of S. Maria alla Porta,[2] which houses documents and drawings useful to reconstruct some fragments of the history of the building. In support of this documentation and to seek for more information most of the more traditional eighteenth and nineteenth centuries Milanese history manuals have been investigated in which the chroniclers describe, with some coloring of local folklore, city's particularly significant buildings and habits.

At the same time was carried out a research using mapping registers and historic city plans that would allowed to reconstruct the evolution of the building and of the church.

In particular the Teresiano, the Lombardo Veneto and the Cessato registers were investigated, by integrating data from those plans with cartographic information from more recent years using the documentation provided by the City Council that is directly accessible online via a web-based GIS system.[3]

Whether from a documentary and cartographic point of view it has therefore been possible to reconstruct with good approximation the evolution of the building, from the iconographic point of view the retrieval of the material has been well below expectations, with very few images found to show the appearance of the chapel before the bombing of 1943 (Fig. 1).

Thus, despite being this a church of primary importance, research has not allowed to collect a significant *corpus* of documentation in terms of quantity, but to create a correct reconstruction of the building stages and gave access to a purely informative kind of information that will prove very valuable during the next project phase and help to determine meanings and values of which it must be interpreter.

This refers, in particular, to the anecdotal regarding the circumstance under which the painting depicting the Madonna and Child has been discovered and to the chain of events that this fortuitous discovery have made possible and whose culmination is the construction of the chapel decades later.[4]

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[1] With the collaboration of Arch. Ilaria Lelii.

[2] Parish Archives of Santa Maria alla Porta: Disegni, C5; Fondo Fabbriceria, Cartella 43/4 fascicolo 3–4, Cartella 43/8 fascicolo 2-4-5-6, Cartella 53/1fascicolo 1, Cartella 53/2, fascicolo 2; Fondo Parrocchia, Cartella 53/3, fascicolo 3. Were also investigated the Fondo Catasto 3563 e 518 in the State Archive of Milan and the Fondo Chiese at the City Photographic Archive in the Sforzesco Castel.

[3] "Portale Cartografico del Comune di Milano"—www.comune.milano.it/sit2006/sit2006/ot/home/homesit.asp.

[4] When, in 1651, began the restoration of the Church operated by Francesco Maria Richini, a mason removing the old plasters discovered "a picture of Our Lady with the Holy Child in her womb, tempera painted over a semicircular small door, he was already in the act of throwing the hammer onto the sacred effigy, when a person passing by advised him to desist, finding that face

2 Geometric Survey

Given the state of the chapel it was decided to carry out the geometric survey using the laser scanner technology[5] because it is up to now the most effective methodology to acquire the large amount of geometric information that the knowledge of an architectural ruin implies. A more traditional topographic survey would have not allowed, in a reasonable short time, to capture the amount of data required to give back such a complexity. Given the small size of the ruins, it was decided to go with only two stations, one near the wall in conjunction with the church, near the center of the chapel—which allows to work with medium resolution which results in an high density points cloud, given the proximity to the building—and one which is about 20 m away useful for detecting, at a lower resolution, also the surrounding buildings which are nonetheless essential to redraw the geometrical information of the context.

The morphology of the ruins, which presents numerous overhangs and recesses, has made necessary the execution of three other close scans useful to complete the points cloud in correspondence of the shadow cones produced by the projections mentioned above.

An ICP[6] algorithm without topographical references was subsequently employed for the registration of the five clouds. This recalculated cloud was then used, through the extraction of significant profiles, to produce standard planimetric and elevation drawings—plans, elevations and sections—and to create a three-dimensional semi-automatically calculated model by generating a triangular mesh starting from the points that make up the cloud (Fig. 2).

The three-dimensional model has proved itself necessary for two different purposes: to provide a realistic model of the existing building helpful for the subsequent project phases and to provide a continuous surface—unlike the points cloud that is, by its nature, discontinuous—to apply a photomosaic for the generation of the main façade complete photoplan.

In fact, for this project it has been choose to realize the photoplan for the subsequent materials, conditions and interventions mapping steps not by using the

(Footnote 4 continued)
very beautiful and devout. The mason wiped the dust with his apron and discovered the loveliness of the Image, taken from instant horror, held the shot, and reverently worshiped the image. Indeed there are some proven memories asserting that being the mason lame since long time, driven by devotion exclaimed: "Blessed Virgin straight me up", and that was enough, because he instantly felt his legs firmer and stepped down from the scaffolding with the grace perfectly obtained". A portion of the apron of the mason was preserved in a small pouch inside the glass that protects the image and venerated by the faithful. The original description of the story can be found in the Parish Archives (Fabbriceria, cart. 43/4 fasc. 4).

[5] The instrument used was the laser scanner Topcon GLS 1000, for data elaboration it has been used the Topcon Scanmaster software and the Trimble Realworks software. Scanning was performed by Diego Vanotti.

[6] ICP—Iterative Closest Point is an algorithm employed to minimize the difference between two points clouds during the registration phase.

Fig. 1 The church of Santa maria alla porta and, on the *right side*, the Chapel before the 1943 bombings (Parish Archive of Santa Maria alla Porta)

Fig. 2 3D Model with application of the photomosaic for the generation of the main façade photoplan

photo-rectification on topographic bases technique but rather by working directly with the data coming from the three-dimensional points cloud.

The small size of the ruin turned out to be a suitable field test to verify this possibility that produced different outcomes.

In particular, if the photoplan serves as a high-resolution base for information mapping—as in this case—it will require the execution of a surfaces three-dimensional model onto which associate the photographic images and from which, subsequently, extract the orthophoto. If the goal of the photoplan is, instead, to provide a medium to low resolution support, experimentation has revealed that it is possible to work directly with the geometrical and colorimetric information associated with the individual dots that build up the cloud since the gap between each point is not visible.

This technique has been employed in the second surveying phase, after the first stages of the intervention have brought to light the remains of the floor of the chapel which were covered by a concrete slab presumably made after the war during a safety measure operation which has not, however, shown up during the archive research activities.

Also in this case the supplementary geometric survey was performed with laser scanner technology[7] setting up just two scan stations with the instrument positioned respectively to the right and left of the center of the chapel so as to cover—with two readings—the respective shadow cones under the tripod (Fig. 3).

Because a high-resolution photoplan is not required and the information acquired is to be used solely to redraw geometries, we have not proceeded with the creation of three-dimensional model but we worked directly with the points cloud colored with the images taken by the instrument that was used to draw the complex geometries of the floor. The instrument was set up to acquire with a medium to high density resolution—equal to a scanning speed of approximately 122,000 points per second compared to approximately 1 million allowed by the instrument—which results in a resolution of about 6 mm at a distance of 10 m. Considering that the distance between the scanner and the flooring is maximum 5 m the resulting effective resolution is approximately one point every 3 mm.

3 Chemical and Physical Analysis

The aspects of prior knowledge necessary to build a comprehensive framework, propaedeutic to the drafting of the conservation project, have been completed with the execution of the chemical, physical and stratigraphic analysis aimed to clearly identify the materials of the painting depicting the Madonna and Child as well as the state of impregnation, and the possible presence of salts in solution, in the substrate on which the painting is placed.

[7] The instrument used was the laser scanner Faro Focus 3D, data were processed with the Faro Scene software.

Fig. 3 Axonometric view of the point cloud, *in light grey* lack of data caused by the position of the scanner

The investigation, carried out by a team consisting of one restorer[8] and one chemist,[9] has initially focused on the painting so as to ensure the painting technique and, most importantly, to validate what is reported in a document of the archives about an heavy reconstruction undergone in recent years.

The restorer has sampled five cleaning zones in the most compromised areas or otherwise subject to repainting to verify the persistence of pigments stratification, the real extension of the accumulated painted layers and to understand how these recent interventions have altered both chromatically and figuratively the composition.

Cleaning tests have been carried out to sample surface dirt removal, they have been carried out using both dry and wet methods, with Wishab sponges the first and with water and mild detergent in low percentage the latter. These tests have proven ineffective for the removal of surface deposit that was particularly tenacious due to the long exposure to atmospheric agents.

Other tests have been carried out using a saturated solution of ammonium carbonate to verify the type of residues present on the surface of the painting and to evaluate the response of the materials. The samples were carried applying the cleaning agent with a brush on the surface with interposition of Japanese paper. The application duration lasted a few seconds after which the surface was immediately rinsed with deionized water to stop the process.

8 Annalisa Belloni, restorer (for Teknelitos Restauro e conservazione S.r.l).

9 Prof. Luigi Soroldoni (Consulting and diagnostic investigations for the restoration and conservation of works of art—Castano Primo).

The samples have shown the effectiveness of the test, removing surface dirt settled on the painting, also colors have regained some of their original intonations. Tests also pointed out the necessity to work with different products on some portions of the image that showed low resistance to this type of intervention.

It was also performed a stratigraphic test to check the composition of the support and also to ascertain the presence of other more ancient layers of paint. The stratigraphic sample was performed with the aid of a small chisel, removing the finishing layer of plaster and the plaster body down to the brick. Survey made visible two states of matter of different thickness and composition.

The contribution of chemical investigation has focused on the characterization of the mortars that provide support to the painting, on the characterization of paint layers and on the measure of the moisture in the masonry.

In particular, chemical analysis were carried out on the mortars aimed at ascertaining the content of soluble salts—made with gravimetric method[10], the determination of carbonate and hydraulic binder and other investigations in order to identify the nature of the aggregate used in the plasters (Fig. 4).

To investigate the structural composition the chemist have instead worked with polished cross sections on intact fragments—resin embedded and properly cut and polished—observing with an optical microscope the presence of crusts and paint layers, cracks and micro-porosities and operating a visual estimation of the relationship between aggregates in the limestone matrix.

The characterization of the paint layers, carried out on four samples, made use of micro-stratigraphic polished thin sections observations, aimed at the identification of the constituent materials (pigments, inorganic fillers and organic binders), at the recognition of the painting technique and at the detection of any repaintings, dirt layers and degradation products. Analysis have been carried out by means of a microscopic observations with visible and ultraviolet optical source and with microanalysis in the electron microscope equipped with microprobe (SEM-EDS).

The measures of moisture in the masonry, made in two points at two different heights, were carried out with the method of weight, sampling the material with a low number of revolutions microdriller and determining the moisture percentage as a weight loss starting at 105 °C till constant weight.[11]

Samples for this investigation were extracted both from the external layer (about 10 mm) and deeper in the masonry structure (120–150 mm).

As for the painting, all the samples showed twentieth-century painting technique and materials without traces of ancient paint layers, thus confirming the information provided by archival research.

In particular, on the sample that includes the skin of the Child, where the thickness of the material is consistent, it was possible to do an analysis with microspectrophotometer that returned a spectrum with bands attributable to calcite, yellow ocher and milk, while on the surface of the sample which includes the

[10] NORMAL 13/83.

[11] NORMAL 40/93, 41/93 o UNI 11085:2003.

Fig. 4 Thin section performed on the skin of the child

Madonna's red mantle the analysis was performed using micro FT-IR spectroscopy that showed the presence of an acrylic resin like the Paraloid B72 which led to the conclusion that the painting undergone a twentieth-century intervention to consolidate paint layers.

4 Conservation Status and Intervention Project Mapping

Research, surveys and investigations carried out on the ruins and on its materials have contributed to outline a framework of knowledge that has allowed setting up a plan of action tailored to the real needs of the building.

Even primarily it was necessary to prepare a document able to gather the entire corpus of the collected information into a smart and efficient management tool. This goal has been reached by building a set of papers—using as a base map the photo-rectification made during the survey campaign—in which are condensed information on materials and pathologies that characterize the chapel, along with the information on the causes generating that pathological status.

This graphic representation has been made by overlapping the photographic image with colored patterns associating the color to the type of material and the weaving of the pattern to the pathology, using short textual references to report information about causes and types of each architectural element. These data were

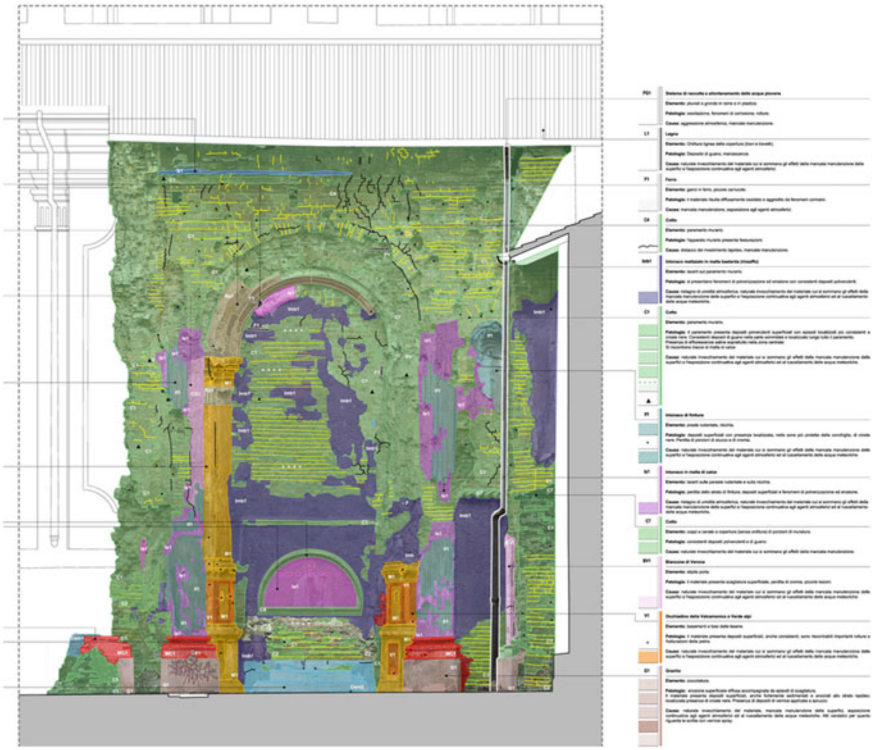

Fig. 5 Main façade: mappings of the intervention project, each color identifies the type of intervention

subsequently graphically linked to diagnostic tests data to have the possibility to read the data both ways (Fig. 5).

Likewise, the information contained into the conservation project has been organized using a similar technique. Specifically, by using a B&W version of the photo-rectification as a base map, the mapping of the interventions has been carried out associating the color to the type of each restoration procedure and the pattern to the extension of each intervention.

Even in this case, to make the drawings more understandable and comprehensive there have been used textual references providing insight on the work phases to be adopted for each intervention, splitting generic from specific and selective operations. To produce an even more exhaustive paper were also included references to the bill of quantities in order to ensure, even in this case, a bidirectional reading between the various components of the project (Figs. 6 and 7).

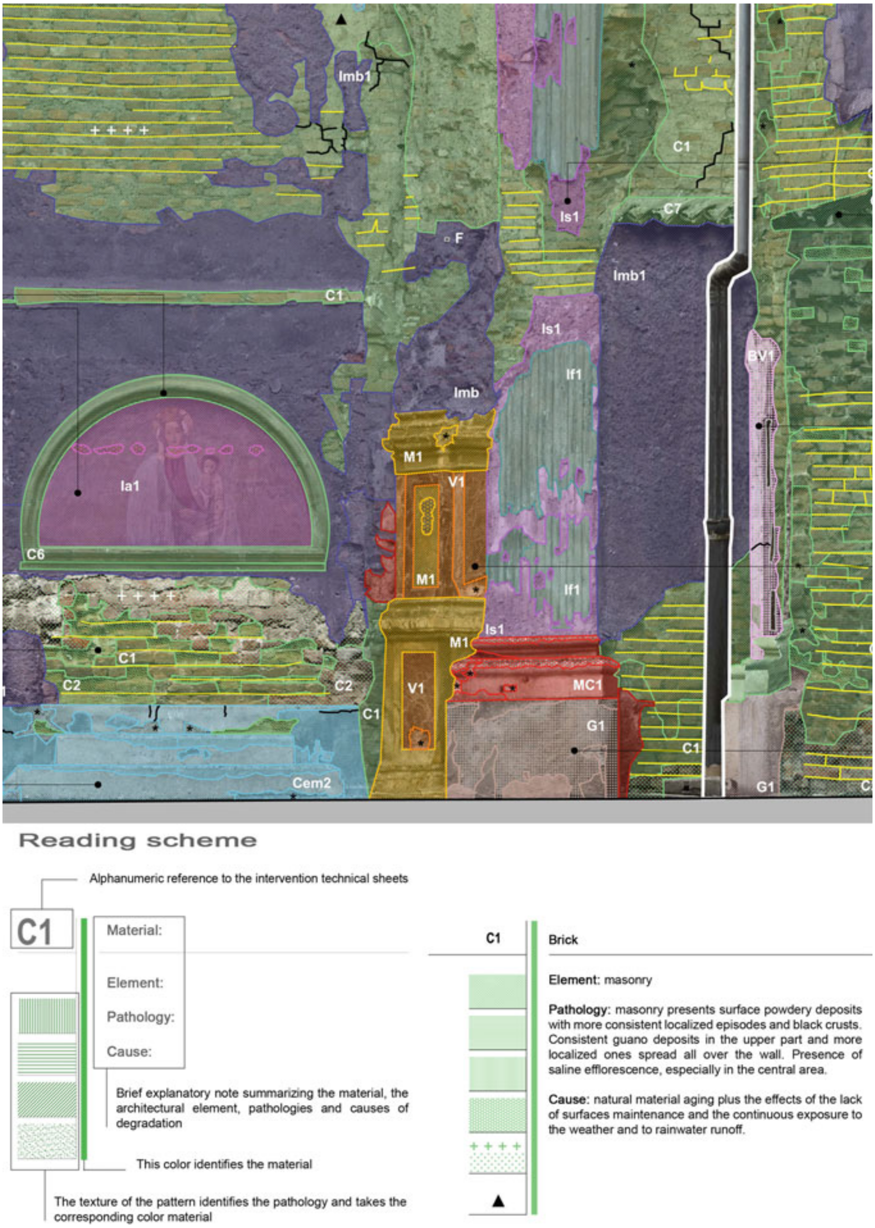

Fig. 6 Extract from material-pathological drawing. On the *left* the reading scheme of the references present in the drawing; on the *right* the reference to "masonry" element, made of bricks (*C1*). In addition to the alphanumeric code and the textual descriptions you can see the *four squares* of the same color but different weaving, which specify widespread pathologies present on the element—in this case superficial deposits, consistent deposits, black crusts and guano deposits—plus two others *boxes* indicating the punctual pathologies—saline efflorescence (*the pluses*) and localized tears (*the black triangle*)

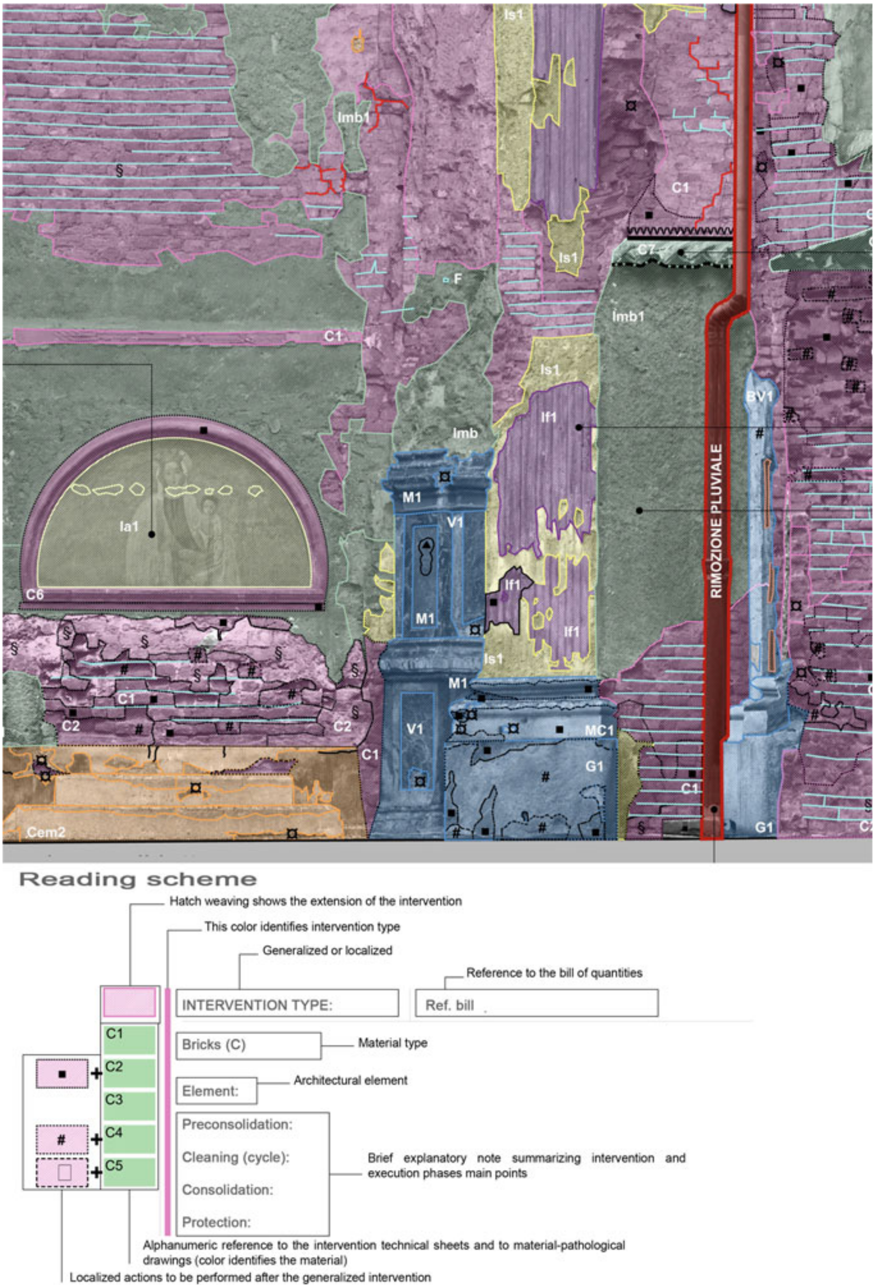

Fig. 7 Extract from the conservation project. The reading scheme shows the complexity of information that are reported in the drawing as well as references to material-pathological analysis and to the items for the bill of quantities

5 Conclusion

The approach adopted since the early stages of analysis was characterized by the contribution of different professionals, some more focused on technical issues, some others on more humanistic topics. Thanks to this multidisciplinary approach it has been possible not only to acquire key information to develop the strategies of the conservation project—focused on physical and structural restoration of the authentic material still in place—but also to establish a straight relationship with the building itself through which derive the guidelines for its future reuse.

Specifically it has become clear the dual significance of the ruin and the necessity for the reuse project to work on two different reading levels: on the one hand the devotional aspect, related to the discovery of the painting and to the subsequent act of construction of the chapel, on the other hand the aspect linked to the memory of the tragic events of the war and the destruction of the chapel in August 1943 whose current restoration has concurrently started the rehabilitation and valorization of an urban space to be returned to the city of Milan.

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Past, Present and Future of the Forgotten Places in the Ancient "Ospedale Maggiore" (Ca' Granda) in Milan: Studies, Surveys, Analysis, Prospects and Projects

Mariangela Carlessi and Alessandra Kluzer

Abstract During the last 10 years an inter-disciplinary campaign of surveys, researches and analysis has been undertaken on the buildings of the historical Archive and the church of the B.V. Annunciata in the *Ospedale Maggiore* in Milan, dubbed from the milanese the *Ca' Granda*. The campaign was urgently appointed in 2002 by the Cultural Heritage Service of the Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico, as a consequence of the worrisome structural conditions, the clear suffering signals displayed by the places and the severe environmental conditions. Moreover it had to be taken into consideration the vulnerability of the valuable multimaterial cultural heritage (manuscripts, paintings, wood libraries, sculptures etc.) that has been hosted here for centuries. We could count on a rare disposal of financial resources and time that made it possible to improve and to refine through the years the steps, the methods, the tools, and the goals themselves, given the priority to the going on of the original and historical function inside the places. It should be stressed that despite the well known importance of the places, as far as the history of architecture and of restoration are concerned, the progress of the researches and the multidisciplinary approach led to a true rediscovery of the identity, the role, the specific history, the material features and the artistic arrangement of some hidden and forgotten places of the Ca' Granda, such as the crypt and the sepulchres below the church of S. Maria Annunciata. We were given the opportunity to set up and coordinate a well cooperative team that has followed the different steps of the work, including the researches on the archive sources, the geometrical survey, the stratigraphic survey, the detailed description of the building features and conditions, done room by room, and a broad campaign of diagnostic tests and analysis on the structures, on the materials and on the micro-climate. A thorough knowledge was gradually increased during the years, thanks to

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the disposal of new resources, with the primary aim to permit a well planned program of interventions for the maintenance and for the conservation of these once forgotten places, giving the priority to the strengthening of structures.

1 Releasing a Glorious Past from a Recent Forgetfulness

The "Ospedale Maggiore", founded in 1456, has always been considered one of the main "monuments" of Milan, well known for its architectural features, which perfectly matched the most in the vanguard criteria of efficiency in the care and treatment of those in need, as the main guides to the city of Milan prove through the centuries. It soon became a model and its peculiar plan—with the two "crociere" separated by a courtyard—gained the role of a proto-type, described in the most important treatises on architecture and proposed again in other european hospitals.[1] The functionality of the Ospedale's plan has even overcome the complex events of the construction, that went on for almost four centuries, following the main issues of Filarete's "original" idea (see Fig. 1).

The buildings we have worked on are the seat of the Archive, once the monumental *Capitolo d'Estate* and the smaller *Capitolo d'Inverno*—where the hospital's administrators used to gather until 1796—and the adjoining places, together with the church of the SS. Annunciata. These places belong to the second phase of the hospital's construction, which took place from the end of the 1620s for over 20 years, thanks to the generosity of Giovanni Pietro Carcano, who made it possible to build the main central courtyard and the corresponding buildings along the Naviglio, according to the plan of Francesco Maria Richini.[2] The *sale capitolari* and the church were actually the most representative places of the hospital, in a time when architecture was strictly connected to the ceremonial's requests, as their location in respect to the whole complex and the layout of the walks-through clearly show. The quality of the architecture is disclosed by its constructive and ornamental features as well, together with the magnificent fixed furniture that has enriched these places, such as the XVIIth Century valuable oak shelving of the *Capitolo d'Inverno*.

Even more, what actually characterizes these places is the continuation through time of their functional destination, so that the various adjustments—made especially between the XVIIIth and the XIXth Centuries—are the consequence of the

[1] The bibliography on the Ospedale Maggiore is conspicuous, the main references might be found in Carlessi and Kluzer (2011), Il cuore dell'antico Ospedale Maggiore di Milano. I luoghi dell'Archivio e la Chiesa della Beata Vergine Annunciata, Silvana Editoriale, Cinisello Balsamo, Milan.

[2] Richini, thus preserving Filarete's general layout, enlarged the main courtyard and placed the Church between the courtyard and the Naviglio, with its entrance along the main axis, corresponding, on the opposite side, to the new monumental entrance to the Ospedale.

Fig. 1 The Capitolo d'Estate in a photo of the 1930s, with the Gonfalone designed by Gio Ponti (*Archive* Ospedale Maggiore of Milan)

need to go along with the progressive increasing of the archive heritage and the recurring changes in the organization of the hospital's administrative functions. The Church has undergone interventions related to its peculiar function, such as the addition of the apse in the middle of the XIXth Century, the new decorations between XIXth and XXth Centuries, and the adjustment of the crypt—one of the ancient cemeteries inside the Ospedale—as the shrine of the fallen during the 1,848 uprisings (see Fig. 2).

Until the beginning of the XXth Century, the role of the Archive and of the Church was unaltered, actually enhanced, for example, by the studies and the reorganization promoted by the archivist Pio Pecchiai.[3]

Afterwards, the destiny of the Ospedale was determined by the tragic consequences of the bombings that took place in 1942 and in 1943. While most part of the Ca' Granda was assigned to the Università degli Studi, giving the opportunity for one of the most cultured and praised post war intervention of re-use and restoration—thanks to a composite professional team, under the guide of Ambrogio Annoni first and of his scholar Liliana Grassi later -, the buildings left to the Ospedale Maggiore as the headquarters of the administration and the parish church of the hospital, underwent quite a different destiny. The intricate border line

[3] On the Church of the Annunciata and its crypt see also Carlessi and Kluzer (2013) Storia e identità del *sepulcrum magnum sub ecclesia annuntiationis* (1636–1696). I documenti e la lettura della fabbrica. In: Vaglienti F, Cattaneo C La popolazione di Milano dal Rinascimento, Edizioni Biblioteca Francescana, Milan, p 83–136.

Fig. 2 The same place, today

between the Ospedale and the Università clearly shows how factitious the separation between the two parts was, and the reinforced concrete structures that violently cut the ancient brick masonry in the crypt and in the attic, mark a final physical detachment (see Fig. 3).

The Archive and its adjacent rooms, slightly damaged by the bombings, were progressively "forgotten" and marginalized in a sort of boundary area, with a separated entrance on the back of the building. Post war interventions were made on the timber roofs, while the great vault of the *Capitolo d'Estate*, decorated in 1637 by the painter Pietro Antonio de Maestri (called "Volpino"), was left mutilated and weakened, with the central area of the plaster pulled down as it was unsound. The Church, whose narthex was totally destroyed by the bombings, underwent a restoration intervention which turned the once richly decorated places in a simple geometric, "neutral" appearance, lost its predominant role, and was left for the fearful prayers of the students before the exams. The underneath crypt was used as a lost deposit, and it gradually fell in abandonment conditions (see Fig. 4).

As far as the Archive is concerned, the worsening of the places conditions, more and more inadequate both for the office requirements (it is still a "living" archive) and for the opening to the public, led to their inaccessibility, and were gradually taken away from the scholars and, inevitably, from the memory of the city. At the

Fig. 3 The buildings of the Archive and the apse of the Church along the Naviglio, before its covering (*Archive* Ospedale Maggiore of Milan)

Fig. 4 The courtyard and the church just after the bombings

same time, the prosecution of the archive function has led to sporadic and sometimes inappropriate works of maintenance and refurbishment, such as the interventions made to adapt the upper rooms on the *Capitolo d'Inverno* to be used as offices (see Fig. 5).

Fig. 5 The central part of the crypt (the "sacello") before the intervention

2 Getting to Know a Rich and Complex Present

Since 2002 a renewed interest by the Cultural Heritage Service of the Fondazione, oriented primarily to the safeness and the conservation of both the "contents" and the "container", which are closely related, and aimed at the prosecution and valorization of the Archive, has made it possible to set forth to an articulated knowledge phase. This has been conceived since the beginning as a base for every future choice, both in terms of prevention for the ongoing functions and for the planning of maintenance and restoration interventions. First of all it must be taken into consideration the extraordinary richness of the Hospital's cultural heritage, which is extremely meaningful not just for the history of health assistance and care in Lombardy during the last millennium, but for social, art, economy, and landscape history as well. In effect, the Hospital's heritage gathers different but strictly connected collections: the precious historical archive, the celebrated collection of the benefactors portraits (a tradition that began in 1602 and is still living), the photographic archive, more than 100.000 volumes of the historic medicine library, the historic medical and surgical equipment collection, the majolica apothecary vases, etc. In particular, what makes this cultural heritage unique and extraordinary is the contiguity of the different collections inside the building itself, and the possibility of studying and understanding them altogether, drawing the attention of scholars specialized in the different historical fields (see Fig. 6).

Since the first surveys we were struck by the complexity of the places, amplified by the contrast between the anonymous image given by the facades along via Francesco Sforza (corresponding to the flow of the ancient Naviglio, covered in 1929), characterized by plasters and interventions made during the 1960s, and the abundance of solicitation offered from the inside, where the sedimentation of furniture, objects and works of art was left intact, and still clearly testifies the long life of these places, where neither the absence nor the inadequacy of the recent maintenance interventions diminish the high dignity of the architecture (see Fig. 7).

The bad conservation conditions were firstly denounced by the evidence of the structural vulnerability, by the large lacuna in the vault of the Capitolo d'Estate, by

Fig. 6 The “navazzone”, below the narthex, after the intervention, with the “totems” for the lights, the new gates, and the new cocciopesto pavement

Fig. 7 The video endoscopy for the investigation of the features of the vaults between the basement and the Capitolo d’Estate

the deformations of the brackets of the wood shelving built in 1808 along its walls, by the wear and tear of the floors, by the plasters deterioration, chiefly caused by moisture. Furthermore it emerged the chaotic net of the systems, whose paths weren’t documented at all (see Fig. 8).

Moreover, walking through the different rooms it was also possible to perceive the microclimatic conditions as one of the main risk factors for the cultural heritage hedged in, mainly for the precious documents. It was displayed quite a worrying picture of the places’ general conditions, which, *in primis*, had to be discerned in order to allow an effective analytic process (see Fig. 9).

Fig. 8 The double flat jack tests on the outer front of the Capitolo d'Estate

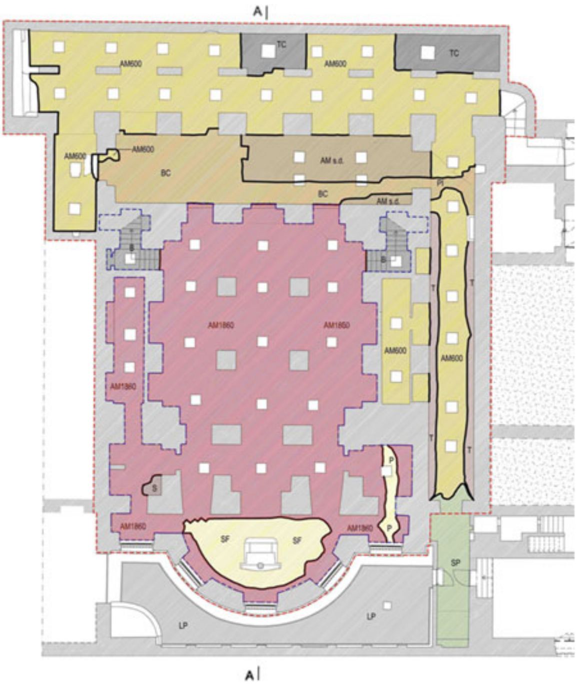

Fig. 9 The survey of the different types of flooring of the crypt

2.1 *Through Studies, Surveys and the Diagnosis Campaign: Questions and Steps*

2.1.1 The "Sale Capitolari" (2002–2008)

The features of the Ospedale's cultural heritage, heterogeneous by matter, and the suffering conditions of the places themselves, together with the awareness of the overlapping of different risk and vulnerability factors, demanded a gradual cognitive approach, through a step by step directing and deepening of the knowledge.

The urgency conditions requested to acquire data on the places' consistency and conditions that could made it possible to recognize the critical situations in terms of safeness and to identify the processes, the causes and the extent of decay. This, having to avoid interruptions in the Archive activities and having no basic documentation at all, not even the boundary delimitation of the places (see Fig. 10).

The Office's availability has made it possible to plan the different phases counting on large enough time resources, and to gradually refine the scheduling of the studies and of the analysis, so that it was even possible the backwards check of the data that had been acquired.

The first phase was concentrated on the reconstruction both of the building and reform events and of the usage layouts through time, on the precise examination of the building features, on the recording of the signs of structural weakness and of the materials' suffering.

Fig. 10 The inspection and survey of the sepulchers that still keep the human remains, leaning inside with the chest

Moreover, the rare chance to freely consult the documents inside the place that is being studied itself, and to immediately verify their contents through the direct observation, has made it possible to precisely follow the "life" of the buildings and to record on synoptic plans the sequence of the masonries modifications undertaken through time. This has pointed out meaningful correspondences with the cracks and deformations survey, facilitating the structural diagnosis, committed to Lorenzo Jurina.

2.1.2 The Pre-diagnosis

The pre-diagnosis report has pointed out the critical cruxes according to which an articulated inter-disciplinary campaign of in-depth instrument analysis was planned, beginning in 2004. The priority was assigned to a reliable geometrical survey, to the detailed identification of the reinforcement interventions done after World War II, to the acquisition of fundamental data about the features of foundations, masonries, floors and vaults and about the cracks behavior through time (thanks to a long time monitoring and to in situ and laboratory tests), to an accurate survey of the timber roofs (with the identification of the woods species and of the reparations done after the War, the inspection of the defects, the faultiness and of the degradation of the wooden elements, etc.), to the identification of the wall finishes (beginning with the original XVIIth century plasters, the fresco covering the vault of the Capitolo d'Estate, the decorations hidden by later interventions, etc.), to the accurate survey of the wooden shelvings, to the recording of all the millworks, which were extremely various in type and age.

Part of the analysis were set aside for the check of the environmental conditions —in particular the pollution—that affect the conservation of the artistic and documentary heritage, through the chemical, physical and bacteriological tests on the indoor and outdoor air, together with the monitoring of the hygrothermal conditions of the rooms and the measuring of the water and Salts content inside the masonries.

2.1.3 The Structural Issue

The almost dramatic patency of the structural decay has first of all drown our attention to the evaluation of the structural conditions, starting with the in situ close observation of the cracks and their survey, and the research of documents dealing with the interventions done in the past; it was possible to make the first hypothesis on the causes of the structural imbalance—which, it was soon clear, began just during the construction site, mainly as a consequence of the particular conditions of the soil related to the foundation system. The diagnosis, undertaken under the control of professor Lorenzo Jurina, was improved thanks to the in situ tests: flat-jack tests, the dynamic tests on the ties, the monitoring of the cracks, and the dynamic test on the extrados of the *Capitolo d'Estate* vault. Thanks to this data, a

Finite Element Model was created, through which the real vulnerability of the vault and its structural behavior in case of a seismic event were evaluated.

The results of the tests and of the monitoring (undertaken for 15 months) were comforting with respect to the absence of forthcoming risks and made it possible to point out some hypothesis on the intervention methodologies. The interventions should conceivably consist in "punctual" reinforcements, auxiliary to the existing structures; the interventions should be reversible, as far as possible, and oriented to giving back the continuity to the masonries and the vaults, re-establishing the box action between the masonries. New metal snares and a structural reinforcement at the extrados of the vault of the Capitolo d'Estate, using Fiber Reinforced Polymers or the so called "reinforced arch" technique, might be used. On the contrary, given the specific conditions, it is far more complicated to opt for underpinning interventions that are nevertheless necessary especially under the masonries of the ex poarch and of the building's edge along Via Sforza, towards the B.V. Annunciata Church.

2.1.4 The Church of the B.V. Annunciata, Its Crypt and Sepulchres (2009–2011)

In 2009 a new funding has permitted to extend the studies to the church of the B.V. Annunciata and on the adjoining places: the ancient cemetery below—that was actually rediscovered—and the upper floors (the "Rettore's flat"). Once again, the goals and the steps were planned on the specificities that came to light during the preliminary phases of inspection and the studying of the archive documents. Soon two main topics emerged: the intricate history of the crypt and of its cemetery, and the events of the post-war period reconstruction.

The evidence of the structural weaknesses, even if apparently less serious compared to the Sale Capitolari, has suggested different types of inspections such as several digs for the foundations survey (starting from the sepulchres' floor level), the flat-jack tests, and the cracks monitoring, particularly in the large dome of the church and in the lowered vault of the apse, at the crypt level. The diagnostic campaign was assigned to engineer Riccardo Sonzogni. Video endoscopies were also done to investigate the construction features of the post-war floors. The results were useful for a new Numerical Modeling, mainly oriented to estimate the seismic risk and to foresee the structures' useful life. Stratigraphic tests were done on the wall surfaces inside the church, to search for the remains of the original decorations and of those of the early Twentieth Century. Nevertheless, most of the analysis were done in the crypt and inside the sepulchral rooms: places forgotten long ago, yet of great importance and interest, and deserving of being rediscovered. Places that at the same time still keep untouched some vulnerable elements of the XVIIth Century arrangement that have required particular care and caution even in doing the surveys. Take, for instance, the presence of human remains in most of the sepulchres (9 out of 14), or the extremely precarious conditions of the wall paintings fragments and of the original flooring.

3 Giving a Chance for the Future

3.1 The Intervention Priorities for the Archive

Since the first phases of our researches, the main goal has been the possibility to obtain the appropriate information to orient priority actions for the safeguard and the care of these buildings. The conditions that had been ascertained, imposed great caution in the usage of the places, even in the absence of imminent structural risks. It was immediately clear the need of an overall assessment, the urgency of an articulated conservation project, that could consider all the main issues: the overriding topics of the functional and distributional reorganization and of the architectural crucial issues (such as the connection between the different floors, the need of new toilets, the lay-out of the emergency ways, and so on), the structural urgencies in order to reinstate the continuity of the structural system and to guarantee anti-seismic security, the taking care of the finishes and the interventions for the preservation of the decorative surfaces and elements, the project for a new wiring and a new microclimate control systems (designed on the features of the different rooms and on the specific type of the cultural heritage inside them), the accurate design of the lighting system and of each new element that will be necessary for the new museographic plan which should consider the increasing of the collections (such as the valuable benefactors portraits, the Apothecary Museum, the anatomical-pathology Mangiagalli collection, and so on).

The Ospedale Maggiore is therefore an excellent study-case, both as an inexhaustible source for the deepening of the knowledge, and for the didactic experiences on the topics of the preservation project, as the workshops attended since 2009 by the students of the Politecnico of Milan clearly show Della Torre and Giustina (1993).

In conclusion, it’s important to remark that the information acquired offer good basis for the starting of the project procedures, which can’t be further delayed: diagnosis are essential, but the value of their results is obviously limited in time.

3.2 First Preservation Interventions in the Ancient Cemetery Below the Church

The studies, the surveys and the researches done on the church of the B.V. Annunciata have given back to our memory the complex history and the identity of the two levels existing under the church: the crypt (the “scurolo”), that was originally painted with macabre subjects by the already mentioned Pietro Antonio de’ Maestri, part of the underground net of places and walks through, that was fundamental for the hospital’s everyday organization, and the underneath level, the *sepulchrum magnum*, that is to say the cemetery consisting of fifteen underground rooms, where the deaths were laid from 1637 to the end of the same century. After a long time abandonment, some of the sepulchres were opened again to bury those who died during the Cinque Giornate uprisings, in 1848. In 1860, the central part of the crypt received a new architectural and decorative arrangement, becoming the sacred shrine of the fallen, and was connected to the church thanks to two new staircases. At the end of the XIXth Century, the remains were moved to a new monument in Piazza Cinque Giornate, and the crypt was soon abandoned again. The bombings in 1942–1943 partly destroyed the structures below the narthex, and after the reconstruction the crypt was reduced to a storage, indiscriminately crossed by the wiring and the heating systems.

At the time of our first inspections, in 2003, the crypt seemed a dark and hostile place, apparently without relations with the rest of the building, full of every kind of objects, where all the surfaces were covered by dust, by the remains of the chalking of plasters and by efflorescence. A suggestive mess that has soon required attention and a painstaking decipherment, starting from the identification of the stone manholes which mark, on the floor, the presence of the burial chambers below. An articulated program of researches was planned, proceeding from the studying of the documents, the stratigraphic survey and the exploration of the sepulchral level, having care not to “bother” the human remains. Some analysis were done to know the foundations features, the quality of the different mortars (through the chemical analysis and the petrographic study), the sequence and the features of the wall painting layers (stratigraphic analysis), the entity and the nature of the processes of decay (such as the analysis of the biological growth and the measuring of the content of soluble salts). All that in relation with the severe microclimate conditions and with an important presence of rising dampness inside the masonries, which was also measured and monitored (the measurement of water content in the masonries, the microenvironmental analysis for the measuring of the temperature and of the relative humidity of air).

Above all, these places also gave the chance to apply the knowledge that had been gained in a first conservation project, carried out between 2012 and 2013, with the priority goal to give appropriate conditions for access and usage, although controlled and limited, both to visitors and to the researchers who will be engaged in the examination of the remains and, moreover, to ensure the best chance of duration to the structures and materials, having care not to delete the delicate and the specific identity of this place.[4]

It was a very cautious intervention, yet well distinguishable: it consisted in the minimum reinforcement interventions, which were necessary to ensure the continuity between the main building and the apse—added in 1852—and in the cleaning and the consolidation of the plasters and of the remains of the wall paintings. The same interventions were made on the brick-tile pavement, whose lacunae were integrated with a new mortar floor, made using natural hydraulic lime and

[4] Project: Lussignoli Associati s.r.l. Brescia, with the consulting of M. Carlessi and A. Kluzer, together with Davide Pini for the structural reinforcement. Works superintendence: M. Carlessi, A. Kluzer, D. Pini, with the consulting of the Cooperativa per il Restauro s.c.a.r.l., Milano, for the interventions on the decorative surfaces.

cocciopesto, suitably developed in situ. A new wiring has been made, completely external to the walls, in which the cables and the lights are hosted in new elements ("totems") made in steel and copper, expressly designed to emphasize the different nature of the places (the shrine, the places under the narthex and under the porch, the apse). New gates with a sober design were set in order to suggest the original perimeter of the shrine (where the walls were destroyed by the bombings), and to separate the shrine from the adjoining places; a new lapidario in dark brown steel was designed for the exhibition of the statues and of the commemorative stones that are stored in the crypt.

The conservative principles has thus led to opt for additions, excluding demolitions or other invasive actions on the stratified matter of the crypt. The same criteria of caution have suggested to postpone the installation of an air treatment system, for the control of the humidity and of the chemical quality of the indoor; so to consent a longer monitoring of the microclimate, and, as a consequence, a more conscious thinking, in collaboration with experts in the field of the physics applied to the cultural heritage.

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Part III
Architectural Heritage: Case Studies

Grancia of Cuna: From the Complexity of the Historical Building to a Composed Knowledge for the Project

Silvia Dandria, Fabio Gabbrielli, Marco Giamello, Elisabetta Giorgi, Andrea Magrini, Elena Manzoni and Fausto Randazzo

Abstract First results on the knowledge of the stratified complex of Grancia of Cuna derived from interdisciplinary researches and from works of preservation in progress. Methods of analysis and interrelation of the contributions derived from various professionals involved in the project of conservation and re-functionality.

1 Historical Background: Granges of Santa Maria Della Scala and the Role of the Grange of Cuna

Between the end of the 13th and early 14th century, the hospital of Santa Maria della Scala in Siena initiated the organization of its landed property, which extends over vast areas of southern Tuscany, on farms called granges. For almost five centuries, until the end of the 18th century, they represented the very foundations of the of the hospital's economic activities (Epstein 1986).

The term granges also indicates the administrative headquarters of these farms, that is the fortified building complexes where grangers resided, and where agricultural commodities were stored before being transported to the urban cities.

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Fig. 1 Aerial view of Grange of Cuna (foto di F. Pericci, Lap&t, Univ. degli Studi di Siena)

The grange of Cuna, remembered as such since the early 14th century (Banchi 1877: 40), located south of Siena, on Via Francigena, was the largest and most productive grange of Santa Maria della Scala. Even today the entire building structure is one of the most significant examples of a maufacturing structure from the Italian Middle Ages (Fig. 1).

Since the early 1990s, the farming activities have been permanently discontinued and many of its areas completely abandoned. The residential area of the building complex, divided into many properties, is still inhabited but the communal accesses have endured the same rapid degradation of the larger storehouses. Recently, the municipality of Monteroni d'Arbia had acquired a portion of the building complex in order to locate the resources necessary for addressing its research and restoration (Fig. 2).

Because of the partial collapse of several roofings, it then became necessary to initiate the restoration of its roofs before the conclusion of the cognitive studies. The overlapping of the two phases requires a continuous exchange of data between the supervision of the construction works and the research team.

2 A Multidisciplinary Project of Knowledge

The complexity of the building structure and rare studies (Coscarella and Franchi 1982) have brought forth the creation of a multidisciplinary working group that would occupy itself with the entire complex as well. The objective of the group is to establish a knowledge base that can be integrated and broadened in the future. The group consists of:

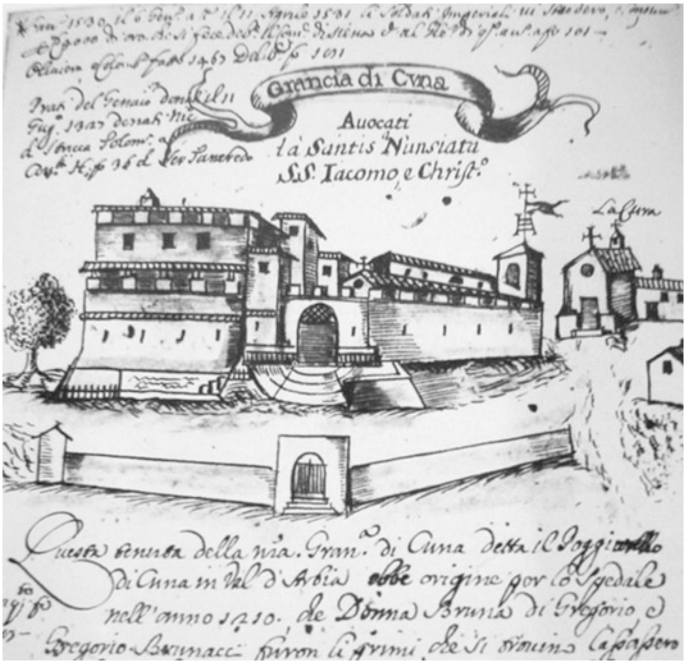

Fig. 2 Drawing about Cuna of G. Macchi, 1720 (Coscarella-Franchi (1982): original drawing in ASS,Ospedale MS D 113, c. 68v)

- Architects; for the general coordination, architectural survey and relations with the ongoing construction of the roofings
- Archaeologist; for the cross analysis of written sources (archival and bibliographic research) and material culture, allowing a better reading of stratigraphic data
- Medievalist historian of architecture; for investigating visually the stratigraphy of the buildings and determining the relative and (with historical information) absolute chronologies
- Petrographer; for the analysis of the materials and mortars to report with the theories on the construction phases
- Geologist; for the determination of the stratigraphy of the subsoil, its technical characteristics, seismic response and system of subsurface waters
- Engineer; for the compilation of a diagnostics plan aimed at the characterization of the structures, definition of loads, identification of vulnerabilities and damage mechanisms.

The first step was a survey obtained by laser scanner technology, which provided the basis for the in situ analysis, the instrument for the comprehension and measurement of the spatial complexity of the Grange. In the first phase five horizontal sections were realized, along with twenty-four vertical sections and several details in reduced scale (Fig. 3).

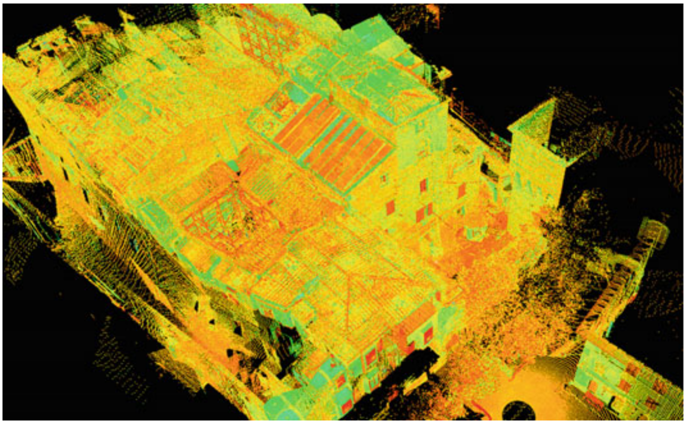

Fig. 3 Laser scanner survey: the point cloud (Ianus soc. coop.va)

A system of shared rules had been established for the exchange of data and in order to facilitate the joint work of the group and the exchange of data in accordance with the distinctive features of each individual discipline. The focus of the work method lies in the joint inspections in order to take advantage of the knowledge of the locations of the coordinators, in the comparative meetings and in the continuous exchange of data.

The inspections have allowed for the immediate exchange of knowledge and perceptions which, after the appropriate re-elaborated versions, were shared by video conferencing systems and carried out through cloud computing systems.

The ongoing construction site had granted access to almost all of the areas, internal and external, and to obtain ulterior data on the wooden structures and masonry, contributing greatly to the knowledge of the construction details and the relations among the groups.

In the initial stages of the construction work there was available data obtained from archival research, the construction site and geological surveys, which were added to the initial surveys.

Later on, the first stratigraphic considerations, analyses and structural assays were developed. At this point an iterative process had begun: **data comparison—in-depth analysis of survey data—inspections—processing of new data** that continued until coherent and documented positions were achieved. At this phase the role of the coordination in receiving incitements, organizing and enhancing them to all the members of the research team became fundamental.

The results of the completed surveys had addressed the project of the diagnostics of the structures. The identification of the phases that had followed in the construction of the complex and the determination of the borders have allowed for the defining of the homogenous areas for the expansion of the results of the tests to be carried out and to limit their number.

3 Examples of Interdisciplinary Work

3.1 The Original Core

The stratigraphic examinations of the masonry structures made it possible to identify the original center of the grange, dating as far back as the early 14th century, or at least the oldest structure which still remains visible.[1] It is therefore a building structure located near the east perimeter wall of the complex, which is rectangular and strongly developed in height.

Compared to the other bodies of the building, its anteriority is readily identifiable at all levels, both for the presence of windows and portals buffered by other structures and for their stratigraphic relations with the adjacent walls. What must be pointed out, on the three sides of the top floor, are the ruins of the original crowning, consisting of a brick cornice which served the purpose of a drip, decorative sections in brick and overlying and later buffered battlements.

Important and essential clues of the original portal were also preserved at the ground floor. Its surviving structures, as has been found in other Siena cases of the early 14th century (Palazzo Pubblico and Palazzo Petroni: Gabbrielli 2010; Droghini et al. 2010), have been incorporated and hidden by the walls of modern age as demonstrated by a buffering of thin bricks laid out in a sheet. Laboratory tests indicate that, in an unknown era at the time being, the bricks were painted red and white in order to give off the impression of a sort of standard curtain in brick.

The considerations that emerged during the construction site works of the roofings are extremely interesting from the point of view of a structural engineer. The features and characteristics of the masonry curtain wall are clearly inferior to those of a monolithic wall of the same thickness. Their discovery brings about the necessity to verify if a similar technique had been used in other elements in the same construction stage or in elements with the same function in different historical periods. Therefore, for the project of the diagnostics of the structure, endoscopies had to be included for the other battlements and wall surfaces of the same period. The results were to be shared with the team so that the considerations implemented on the datings may be confirmed or bring about new considerations (Fig. 4).

[1] The existence of an installation that existed prior to the Grange on the hill of Cuna is well documented in archival sources that speak of a 'small castle' that goes back to the year 1295 (ASS, Ospedale 1404, c. 35v: *Ristoro di Giunta Menchi vende allo spedale ogni qualunque possessione posto in contrada di Cuna […] il poggio detto il Castelluccio di Cuna con casamento e case e fonte overo pozzo d'acqua che sono li*), while an undocumented historiographical tradition would vouch for the construction of the 'palace' of the grange in the year 1314 (Merlotti 1995: 174–175).

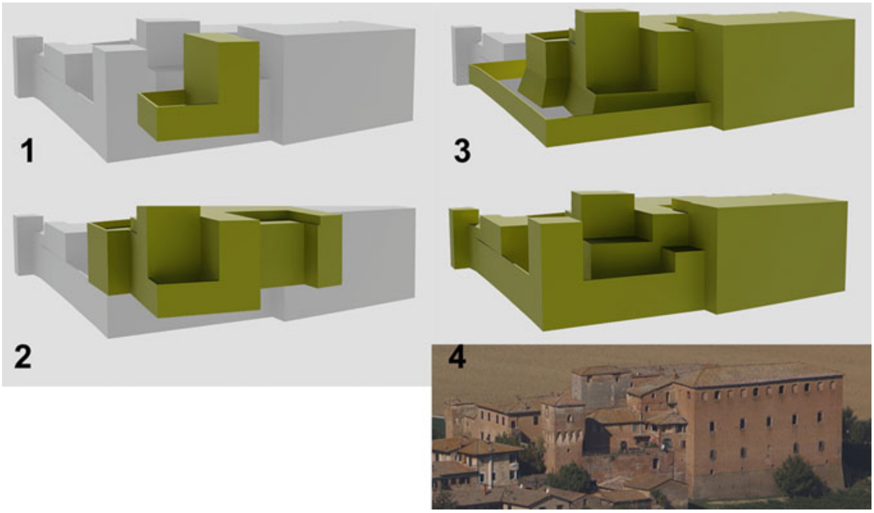

Fig. 4 Hypothetical reconstruction of the building phases on the basis of current knowledge (foto di F. Pericci, Lap&t, Univ. degli Studi di Siena)

3.2 The Granary and Surrounding Walls

3.2.1 Northwest Corner (Granary and First Surrounding Wall)

Research had resulted in the identification of three surrounding walls within the entire complex, the last of which is dated around the middle of the 15th century. The stratigraphic relations illustrate that the first wall was devoid of scarp. This evidence may be referred to an earlier fortification of the grange dating between 1367 and 1370.[2]

Since 1379, Hospital Capitolo allows an annual expenditure for the construction of *barbacane,*[3] recognizable in the powerful scarp that characterizes the entire perimeter of the building structure (Fig. 5).

The stratigraphic relation between the northern front of the surrounding wall and the granary—the largest and most monumental building structure of the grange of an undefined date—is particularly significant. The granary leans (and is therefore

[2] Regarding this intervention, we have several findings from the documentary sources; in fact, in 1366 the inhabitants of the Isola, Tressa and Cuna had requested that a fortress be built in Cuna (ASS, Consiglio Generale 174, c. 63r), while shortly after, the spending of 500 florins for the purchase of more than 90,000 bricks was annotated (ASS, Ospedale 516, cc. 231v, 248v, 262v); in the same context, in 1369 the reinforcement of the portal of the Grange had taken place (ASS, 516 Ospedale, c. 236v).

[3] ASS, Ospedale 20, c. 12v: *che si spenda ogn'anno per lo spedale CC fiorini d'oro nel barbachane della fortezza di cuna e nello aconcime che si fa col detto barbachane per afforzare la detta fortezza*.

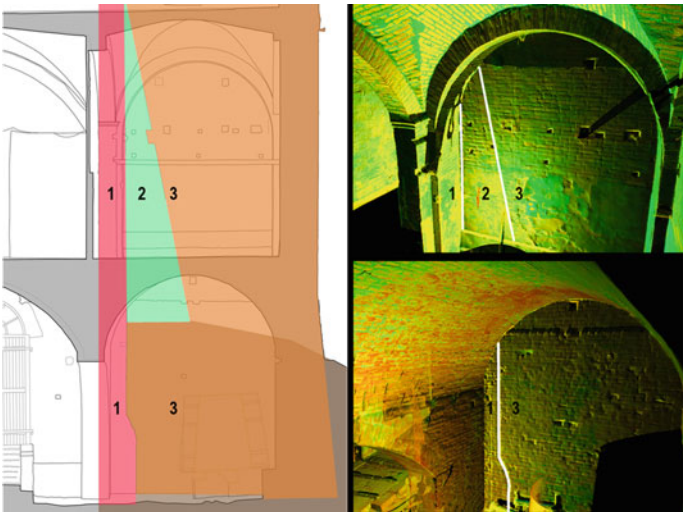

Fig. 5 Section and views of the point cloud of the northwest corner: the first phase may be an earlier fortification of the grange dating between 1367 and 1370; the second phase is the construction of a *barbacane*; the third is the building of the granary

successive) on the scarp, which in turn rests on the surrounding wall. The diagnostics of the structures should examine the overlap among the surrounding walls, verifying the bricklaying technique of the two facings and the installation method of the thickening. This can be performed with endoscopic surveys or controlled dismantling.

Another point of considerable interest is the joint between the surrounding walls and the granary. Particular attention should be paid to the surveys on the joint, even on the ground. From assays performed on the foundations, pre-existing bottom grounds on which the granary was built may be brought to light.

3.2.2 Southeast Corner (Granary and Second Surrounding Wall)

Towards the end of the 14th century or early 15th century, the second surrounding wall was built, perhaps due to the works documented by the decision taken by the Capitolo in 1386 for the construction of *buttresses* in Cuna.[4]

The stratigraphic data indicates that the second surrounding wall was built at the same time as the granary; in which case the scarps, such as the granary as well as

[4] ASS, Ospedale 21, c. 156r: *si murj ciò e che sopra al muro incominciato il quale palazzo si facciano speroni sofficienti e anco si muri sopra il palazzo principiato.*

the surrounding wall, are coeval with the respective walls. At the present moment there is a lack of timely archival claims of the construction of the granary, even though it seems entirely legitimate to relate it to the construction of a *palace* documented between 1379 and 1390.[5]

The new surrounding wall was later fortified with the raising of the curtain and the realization of a new crenellation. The stratigraphic sequence is clearly documented in relation to the granary: the raising leans against the wall of the granary and is therefore located next to it. The study of the map cracking at the connecting point between the raising of the surrounding wall and the granary can supply important indications on the definition of the homogeneous parts in bricklaying.

3.3 The Ramps

The access ramp to the granaries, built between 1709 and 1712,[6] is the unifying element of the entire Grange; it has a hairpin structure with inclined ramps that have courses in stone or bricks (at regular and rather short intervals) that were used to facilitate the boarding of animals laden with cereals.

3.3.1 The Preexistence of the Cellar

Written sources attest for the construction of the cellar in 1612, which was realized in the embankment.[7]

In 1709, the cantina is affected by several functional interventions in the construction of the access ramp to the different levels of the granary and, in particular,

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[5] ASS, Hospital, 21, cc. 222v, 228r.

[6] ASS, Ospedale 1431, c. 24r: *Il signor Dottor Gabriele Bucci… vedendo quei poveri contadini e vetturali che da diverse Grancie, portando quantità di biadumi lì conveniva, sul dorso a salirvi alli granari superiori, onde mosso a pietà si voltò col pensiero a riflettere a far disegno di fabbricare una dolce et agevole salita alli detti granari e da questi alla grande stanza della campana, conforme presentemente si vede il detto suo disegno passato in opera con l'aiuto del buon gusto et intelligenza del già Signor Anzano Farnesi allora granciere e ministro di Cuna… quale fu da maestro Bartolomeo Farinelli muratore principiata il dì 14 Ottobre 1709 e terminata il 26 Marzo 1712.*

[7] ASS, Ospedale 184, c. 308 r: *Nel corpo della Grancia si è fatta per prima una cantina nuova cavata per la maggior parte nel terra pieno con rifondare da ogni parte le muraglie e farvi la volta e situata nel corpo della fabbrica e con essere esposta al caldo quanto meno si è potuto in quel luogo con farvi da piedi la sua finestra e la porta che riesce nel tinaio quale insieme con detta cantina si può praticare con le bestie da soma. Nel principio vi si è fatta la porta principale facendo più a dietro la scarpa del Palazzo acciò non l'impedisse.*

of the creation of eight supporting arches[8]; the materials used and the cost required to purchase them for these works are annotated.[9]

The study of the structures' geometry confirms that the concept of space of the cantina and ramps did not occur in a unified manner. The overlapping of diagrams at various levels confirms the presence of wall elevations that were distributed according to a spatial pattern that appears to be due more to the necessity of adapting to existing spaces rather than to optimize the structural behavior.

4 Medieval Facade of the Building of the Ramps

The stratigraphic studies conducted thus far on the ramp were focused only on the east wall of the structure, facing the exposed section. Much evidence has proven that the exterior front of an older building structure was reutilized for the realization of the ramp, in which its original volume is still yet to be identified. The facade, which has been cropped in most of its areas from 18th century openings, appeared characterized by a stringcourse-drip, now completely smoothed, and from a series of decorative brick belt courses, with characteristics similar to those of the grange's original construction and therefore referable to the early 14th century.

5 Conclusion

The Grancia of Cuna is an exceptional annex, with several interrelated functions: the maintenance of the individual sections cannot be separated from the conservation of the entire building complex. The refunctionalization of its productive spaces and preservation of the residential property, along with scheduled maintenance of the complex, is the only way to prevent further deterioration and abandonment from occurring. Therefore, the results of this study and others must be rendered entirely available to support any present and future choices for preservation design and functional projects. We are completing a database that can be consulted from the website www.granciadicuna.it (with the aid of an internal search engine, accessible by license), which will contain historical reports, drawings, analyses, projects and chronicles of building construction sites.

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[8] ASS, Ospedale 1801, c. 82r: *Lavoro consumato in muramenti questo anno: nel mese di ottobre in Grancia a principiare la nuova salita cioè li primi archi in cantina; nel mese di novembre in Grancia archi in cantina e fuori per la nuova salita.* ASS, Ospedale 1801, 82v: *Lavoro del legnaiolo […] per servitio della nuova salita per far centini per li 8 archi fatti di nuovo in cantina e per tutte le volticine che si sono fatte per detta salita.*

[9] ASS, Ospedale 1801, cc. 115v, 125r; Ospedale 1373, c. 3r.

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Earthquake and Enhancement: An Opportunity to Preserve the Medieval Castle of Fossa (L'Aquila, Italy)

Caterina F. Carocci, Fabrizia Campisi and Irene Tranchina

Abstract Can a seismic event be seen as an opportunity for the conservation of architectural heritage? This question was the starting point for the discussions that were held during the feedback from the cognitive analysis which was in turn preliminary to the formation of the Reconstruction Plan of Fossa, one of the many small historic settlements heavily damaged by the L'Aquila earthquake in 2009. In this study, the medieval castle which characterizes the historic centre, becomes the paradigm to show that, if the post-earthquake reconstruction is tackled with a perspective that focuses on sustainability and preservation of the building fabric, the monuments, which are at its heart, will inevitably be involved in a new phase, that recognizes in their historical nature the profound meaning of their beauty.

1 Introduction

Originating in the larger preliminary cognitive framework carried out on the urban fabric following the seismic event of 2009, the fact-finding analysis centred on the medieval castle was directed both at underlining the extent of its damage, its construction and historical features and also at appraising its role in the context of the whole urban settlement. The results obtained clarified that the castle could represent one of the keystones for the reactivation of the historical settlement, which was heavily damaged and for this reason evacuated after the earthquake.

Taking these considerations into account, the post-seismic reconstruction plan of Fossa is formulated on the basis of a strategy in which the physical reconstruction of the buildings accompanies the rethinking of the quality of civic life that takes place in the houses as well as in the public buildings and spaces.

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In this context, the pilot project developed for the castle is an example of the approach promoted in the development of the plan and, at the same time, of the method of analysis which prepares for the defining of the intervention to safeguard and preserve the built heritage. The design for the castle (presented here in some detail) and the post-seismic reconstruction plan are complementary parts of a tool specifically directed at the physical and socio-economic reactivation of the historical settlement of Fossa and its territory (Andreani and Carocci 2013).

2 The Urban Settlement, the Castle and the Earthquake

The Fossa settlement is part of the system of ancient centres which look down on the valley of the river Aterno and which contributed in the twelfth century to the building of the city of L'Aquila. Identified as part of the Roman city of Aveia Vestinorum at the end of the seventeenth century, Fossa was mentioned for the first time in 1204 in a Pope Innocent III Bull (Martella and Medin 1988). Nevertheless, its designation derives from its position next to the sinkhole located in the lower side of Mount Circolo. The urban structure has developed longitudinally—without overlapping except partially the ruins of the Roman city[1]—along the old road connecting the two Benedictine Monasteries of Santo Spirito and Sant'Angelo in the area immediately below the Castle (D'Antonio 2003). The position of the castle with respect to the settlement makes it a point of reference for the surrounding countryside and an essential element in the panorama that includes the overlooking Castle of Ocre and the above-mentioned Benedictine Monasteries (Fig. 1).

Like most of the castles located in the Abruzzo mountain territory, the Castle of Fossa is situated on a steep incline and consists of a trapezoidal walled enclosure surrounding an area of about 1.7 m^2 in which three quadrangular towers are located (Martella and Medin 1988).[2] There are various constructions located in the inner area which vary in their age and usage: a circular look-out tower situated close to the highest level area and a certain number of ordinary residential buildings some of which are erected against the lower portion of the defensive wall and have merged with the quadrangular towers. Additional constructions are located in the eastern part of the enclosure just below the north quadrangular tower and hide with their masonry structure a portion of the defensive wall. The main entrance—an ogive-shaped gate—is located in the lowest side of the enclosure, while a secondary access, used to reach the entrances to the inner houses, is placed in the inclined southern side of the walled enclosure and is accessible via a flight of steps.

[1] The University of Naples "L'Orientale" (scientific responsible Prof. F. Pesando) is in charge for the excavation of Aveia-Fossa from 2007).

[2] The building of the Castle was due to 'incastellamento', a process with both defensive and territorial aims that was pursued by the monastic and lay feudal Lords in the large mountain areas of Abruzzo.

Fig. 1 Relationship of Fossa historical centre, the castle and the surroundings

The strong physical relationship between the castle and the settlement, which can also be seen in the spatial connection with the urban residential block located immediately below (Fig. 2), meant that both of them suffered in an analogous way from the effects of the earthquake of 2009. In spite of the quite good level of conservation of the elements that identify its original defensive system, the castle complex was characterised, even before the earthquake, by an advanced level of degradation due, above all, to abandonment of both the parts in private hands (the residential buildings) and the public property (the enclosing walls, the circular tower and the internal areas which have not been built on). In this context, the effects of the seismic action merely highlighted the weakest parts by causing their collapse or provoking important crack patterns. On the other hand, although the historical centre was marked by a substantially integral general appearance, it had been in decline during the decades before the seismic event; its permanent population had decreased (mainly due to the attraction of the main town and the standard of living offered by it). This produced a corresponding decrease in the maintenance of both private buildings and public spaces. The result of this neglect and the consequent pre-existing weaknesses appeared clearly in the damage caused by the main shock of April 6th and the consequent landslide on the slopes of Mount Circolo. The already vulnerable urban structure was heavily hit making the evacuation of the inhabitants of the entire historical centre unavoidable (Piano di Ricostruzione di Fossa 2012).

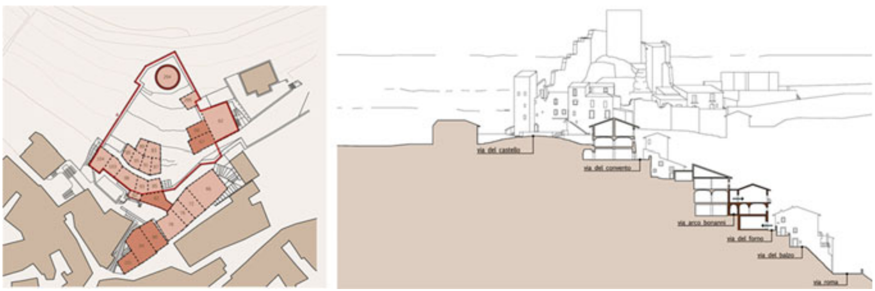

Fig. 2 The castle and the ancient urban fabric

3 The Post-seismic Reconstruction Plan and the Castle

The historical and environmental importance of the Fossa settlement lies in the urban fabric and the construction features of blocks and buildings considered as a whole. This is the core idea that the post-seismic reconstruction plan contains and it provides the starting point for the methodology applied.

Although the primary goal for the reconstruction was identified as the preservation of physical identity, at the same time, a tangible improvement of the housing and urban quality was recognised as an essential design task in order to reactivate the currently suspended civic life. To this purpose an in-depth, systematic fact-finding investigation was extended to all the urban fabric and collected data on several aspects related to the preservation and improvement of design, such as: typological analysis of the evolutionary process of houses and blocks; construction techniques and architectural vocabulary; damage and degradation.[3]

Supported by this significant set of data, the plan introduces transformational models, which are compatible with the types of historical building while allowing the possibility of their sustainable renewal with regards to their architectural and constructional qualities. Nevertheless, the responsibility for safeguarding the urban and architectural history of Fossa during the extensive repair and restoration process is too big to be faced without more consistent tools, which are able to control and suggest suitable design procedures in terms of both private interventions and urban pilot projects, these last having the precise role of driving the whole reactivation process.

In this framework, the so-called 'cores of urban renewal' constitute the basis of the Fossa Reconstruction Plan strategy since they truly represent the public interest project that will determine to a large extent the success of the reconstruction. The most important of these "cores" is certainly that dedicated to the Castle as the plan recognizes its value as a monument as well as a symbol of Fossa's history. In conformity with the 'Reconstruction Plan Implementation Standard' mandatory rules for developing the 'Castle—core of urban renewal' project—strictly directed at the conservation of the monumental portion and the recovery of the residential buildings with possible partial changes in their usage to include public functions—a pilot project has been elaborated in order to provide the Municipality with a more detailed tool to be used as the keystone in the reconstruction process since it expresses both the methodology and the results achieved.

[3] Post-earthquake analyses were accompanied by a documental investigation—both in the L'Aquila State Archives and in the Municipality Historic Archives—that provided a completion of knowing on historic transformation referring to nineteenth and twentieth centuries.

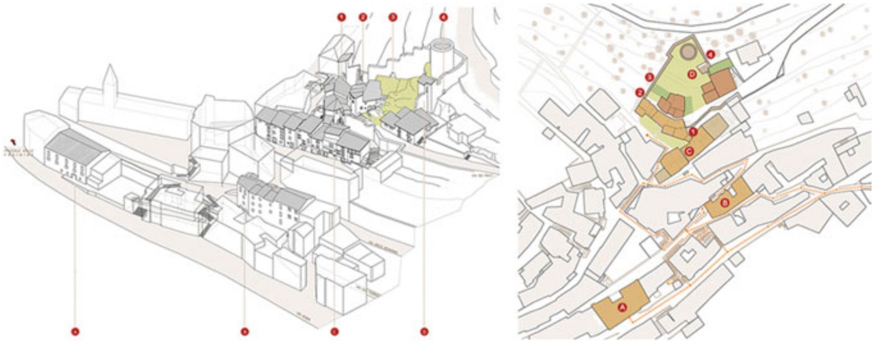

Fig. 3 An overall view of the strategic enhancement project

4 The Castle as a Strategic Enhancement Project

The subject identified in the "Castle—core of urban renewal" project is developed in the pilot project by including a larger part of the urban context. This choice comes from the conviction that the Castle—thanks to its position, conformation and size—can become the centre of the requalification of the value-system present in the territory by becoming the headquarters of an organization, which manages the sites of cultural interest across a number of Municipalities (di Marco 1963).[4] For this reason a preliminary analysis is devoted both to listing the sites of interest and to identifying the activities already operating in the area and which can be included in the enhancement circuit outlined by the project for the creation of a cultural and nature tourist network. In this framework, the project confirms wherever possible the location of the activities involved—if they are placed in the historical settlement —or rethinks their location based on the results of the architectural analyses carried out in the Reconstruction Plan framework. The buildings that were unused before the earthquake or those in which the previous functions will not continue (e.g. the Town Hall that will be moved to a different building) will be chosen to house the offices of the aforementioned network. In this way, the project combines a privately-managed reconstruction of the residential structure with a public reconstruction under the auspices of the Municipality, for which it anticipates the uses, management and maintenance of the architectural heritage over time. In this framework, it is clear that the project gives the Castle complex (it will be entirely dedicated to public use) a crucial role in exploiting the cultural sites present in the area and restarting life in the historical centre (Fig. 3).[5]

[4] A list of important cultural sites in the territory includes the Santa Maria ad Cryptas (built on the remains of a Roman-Byzantine hypogeum), the Vestina Necropolis (over 5000 m², where about 6000 tombs dating from the ninth to the first centuries BC have been found); and the remains of the Roman city of Aveja.

[5] The project rethinks the castle accesses (1, 2, 3, 4) and some buildings functions (A, B, C, D).

5 The Methodology: Knowledge-Interpretation-Project

A three-step methodology was used to carry out the Castle pilot project, specifically as regards restoration interventions on the monumental complex.

The first step included both the carrying out of the geometric-architectural on-site survey and data research based on historical documents from published works and archives. On the bases of the first set of results, a subsequent interpretation step was performed. This last aimed to outline: (i) the principal evolutionary phases of the monument by identifying—through a second on-site investigation—the signs and traces of historical or recent transformations; (ii) the weaknesses or critical points of the masonry complex (e.g. structural vulnerabilities or damage) as well as its favourable aspects (e.g. its historical value, but also positive constructional features) by reading systematically the results of the analyses. The aim of this 'critical reading' is to establish a concise but robust cognitive base to be placed at the heart of the project and to which the last step of the methodology is devoted. In so doing, a close link between the actual state of the masonry complex and the definition of the design criteria is stated. A significant part of the on-site work was dedicated to surveying the entire fortified monument and the buildings included within its defensive walls, including the linear block situated immediately below the Castle, considered a particularly good case study as regards the typology and aggregation of its buildings (Fig. 4).

The survey of the whole complex was mapped at scale 1:100 in order to have good basic maps with which to proceed to the interpretation phase through the above-mentioned 'critical reading'. This last was carried out as a comprehensive interpretation both of the indirect information taken from the sources and the more detailed information taken from the monument itself by examining construction arrangement, masonry texture, lintel inscriptions, evidence of transformation and identified traces. In this context, a comparison with other nearby castle structures (specifically the castles of Barisciano and San Pio delle Camere) was carried out as

Fig. 4 The lateral view of the wall enclosure and section through the look-out tower

they belong to the same fortified-enclosure typology and contain a set of analogies concerning both the general layout and the construction system adopted (Perogalli 1975). Furthermore, special attention was paid to the identification of the areas of change, disrepair, and incongruous transformations both in the defensive structures and the residential buildings. In the first case, important reconstruction work carried out in the 1980s on the enclosure walls (parts of which had probably collapsed) and the cylindrical wall of the look-out tower was identified.[6] Furthermore a number of violent private transformations were observed, such as that carried out on the external side of the defensive wall, which represents part of the houses' walls (addition of reinforced concrete stairs, concrete plaster finishing, etc.). The large amount of data collected led to various interpretations concerning different aspects of the construction complex and related to defining the content of the last step which was dedicated to conservational intervention criteria. The most significant results are related to the castle construction system; its evolutionary process, as well as the level of damage. On this last issue, the analysis showed that—in terms of conservation needs and with regard to the overall condition—the present situation was not substantially different from the situation before the earthquake. However, the detailed analysis highlighted how in some cases existing problems became critical (series of cracks which became more serious, the collapse of already crumbling elements etc.) and in others worsened significantly (e.g. the collapse of the upper quadrangular tower).

6 The Reconstruction of the Evolutionary Process

Following the source analysis and the comparisons with the data from the survey, the evolutionary process was reconstructed with the aim of facilitating operative remarks finalised in the design choices. The main elements used in the identification procedure were the physical traces found on the buildings and walls (e.g. inscriptions on lintels and cornerstones), masonry work techniques (e.g. different masonry textures), as well as constraint devices (e.g. different shapes and materials of tie rod anchor plates). The result of the interpretation was the reconstruction (in some parts hypothetical) of the construction history of the castle starting from the erection of the first walled enclosure to the current situation.

The construction of the defensive enclosure, which exploits the natural slope, and the round look-out tower represents the first layout of the fortified structure (twelfth to thirteenth centuries) to which the main and isolated square tower was later added against a part of the defensive wall (Fig. 5).

The transformation of the lower towers into houses (fourteenth to fifteenth centuries) represents an important evolution, as it starts the erection of the group of

[6] Chiarizia G. (1985), Progetto per la salvaguardia della parte alta del paese e consolidamento delle mura del castello. Archivio Soprintendenza BAP, L'Aquila.

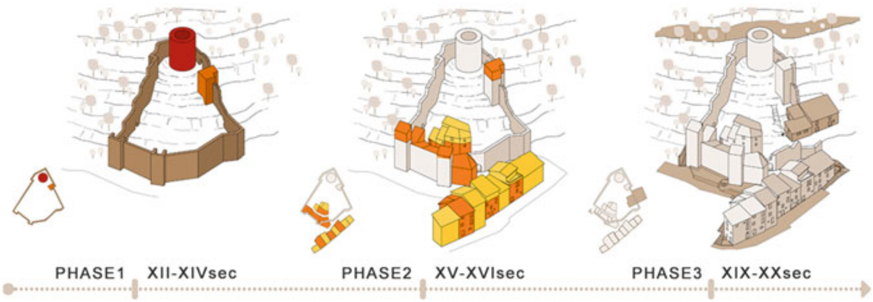

Fig. 5 The castle evolutionary process carried out from the cognitive analyses

buildings located inside the defensive enclosure, from which the opening of a new entrance into the fortified wall also derives. At the same time, the construction of the block located just below the castle area was taking place.

The most recent variations are represented by the addition of upper-storey levels and adjacent volumes to the already existing buildings, and the erection of two new buildings (incorporating a portion of the fortified wall) near the area cleared by the demolition of part of the enclosure.

7 The Restoration Project for the Castle Complex

The project proposal includes both the architectural restoration of the masonry structures of the Castle, which has the aim of ensuring the conservation of its parts (the enclosing wall and the towers, the old residential buildings which back onto the walls, the terraces etc.), and the recovery of the buildings situated in the block immediately below which will host new public functions.

The key points of the project are identifiable in the choice of compatible functions, in the improvement of access and extent of use of the sites, and in the definition of criteria for conservation work based on the specific conditions of the buildings.

Within the overall framework for the system of cultural tourism proposed by the strategic project, the protected buildings, which are included in the fortified enclosure, become a museum with the realisation of a tour and will include the areas without buildings, which will become a garden.

The circular tower in particular will again be a lookout point on the valley with the introduction of an internal staircase. The buildings which back onto the lowest part of the walls will house public services connected to the system of cultural sites across the area: specifically, the headquarters of an association which manages the sites and a small 'Castle Museum'.

The quadrangular tower and the buildings, which back onto the northwest part of the walls, will become guestrooms with a small restaurant, which can periodically use the garden in front.

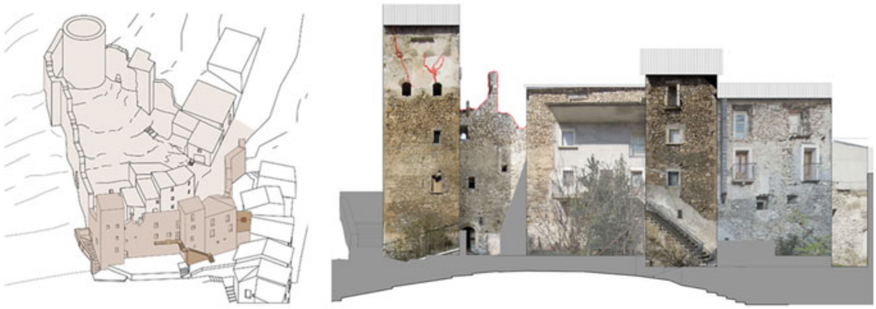

Fig. 6 Conservational and maintenance problems affecting the monument

Finally, some of the buildings in the block will be residential while others (in a different position with respect to the tour of the historical centre) will be public and linked to cultural tourism (location of the Tourist Office and an already existing local periodical magazine). An important part of the project is dedicated to rethinking the access and external routes to the Castle either on foot from the historical centre or using the road above, which provides access to emergency vehicles and disabled car parking. The project also includes the recovery of the Castle's oldest access points (which are currently inaccessible) by providing paths and steps, which are able to overcome the steep incline.

The work criteria adopted by the restoration project are defined with reference to the state and configuration of the buildings as precisely identified in the fact-finding and interpretation phases. In this framework, the results on the level of damage and on the weaknesses, which are due mainly to recent transformations assumed a particular importance. The design choices were based on the interpretation of the critical points highlighted including the consistent techniques aimed at minimizing the extent of works, and emphasising the historical construction process of the current palimpsest (Fig. 6).

The most important interventions involve the rebuilding of collapsed portions of walls and horizontal elements (in the northern quadrangular tower and some buildings), the strengthening of the unsafe structures, the removal of the incongruous elements (such as the external RC stairs and plaster finishing), and the preservation work on masonry surfaces and tops of the walls.

The project also outlines the technical work to be done on the free areas inside the enclosure, in the organisation of a small public garden. Specifically, it calls for the renovation of the pre-existing masonry terraces, which are still identifiable, and the creation of small pathways, in order to link the various different levels and so permit a comfortable visit of the complex.

8 Conclusions

The synergy of both the town planning provisions in the Reconstruction Plan for the historical centre of Fossa and the detailed analysis of the castle is intended to conserve and enhance the area of the buildings and the wider territory of which it is a part.

In this context, the Fossa castle restoration project is one of the key points for the recovery of the historical centre and in particular for the return of the inhabitants who were evacuated after the earthquake in April 2009.

In fact, the experience of various post-earthquake reconstructions has shown that the successful completion of the Reconstruction Plan cannot be based solely on projects of recovery and anti-seismic improvements for the groups of private buildings. The Plan must be part of a wider and more cogent process of work on the buildings and the socio-economic activities in the area.

The study and the pilot project of the castle implies this very vision: it aspires to reactivate the functioning of activities and initiatives which already existed before the earthquake and to favour the beginning of new activities within a sustainability framework for both the natural and man-made environments of which Fossa and its Castle are essential elements.[7]

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[7] This paper is the results of an extended collaboration among the Authors during the elaboration of the Fossa Post Earthquake Reconstruction Plan, carried out during 2011 and 2012. In particular, Caterina F. Carocci wrote the parts devoted to the methodological approaches both of the plan and the castle analyses, while Fabrizia Campisi and Irene Tranchina those describing the results of the fact-finding analysis and the castle project.

Safety and Preservation of Saint Agata Church in Tussillo (L'Aquila, Italy)

Caterina F. Carocci and Anna Scudero

Abstract Starting from the damage condition of the small Saint Agata church affected by 2009 L'Aquila earthquake, a procedure of carrying out the restoration project is presented. It pursues dual design goals that bring together seismic safety and conservation of the monument establishing a rigorous correlation between the different phases of the design process. The methodology assigns particular importance to the cognitive analysis, both on the monument and historical sources, and to the interpretations of the investigation results as they allow the identification of the vulnerabilities which characterized the building at the moment of the earthquake. Specific observations on the evolution of the church and the current deterioration (both structural and superficial) reveal the crucial features, which help to explain the damage suffered and become an essential part in the definition of a consistent restoration program. The close link established between the cognitive analyses and interpretation becomes essential for the outlining of the criteria and the correct strategies for the project definition.

1 Introduction

Saint Agata church is a small church situated in the historical settlement of Tussillo which was badly affected by 2009 L'Aquila earthquake. In spite of the large number of collapses in the ordinary urban fabric, the church, isolated on the higher edge of the settlement next to the wood, suffered no collapsing except in the vaulting over a span of the left side aisle. However, it did suffer a heavy and composite crack pattern. The occasion to carry out the study of the church was the signing of an

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agreement between the Municipality and the University of Catania with the aim of elaborating a Post-Seismic Reconstruction Plan. When the preliminary analyses started, in the spring of 2010, the most dangerous parts of the church had already been made safe by the fire brigade in the first moments of the emergency. This situation allowed the execution of in-depth and comprehensive on-site analyses of the church that included an accurate survey, observation of construction techniques and careful documentation of the damage and the degradation of materials. A special part of the church analysis was devoted to investigating historical sources where the data were also analysed from a technical point of view in order to underline eventual links with the recent seismic behaviour of the church. The purpose of the study was to make coherent proposals for the preservation and improvement of seismic safety of the monument by following a methodology, which closely links the preliminary investigation phase to the definition of the intervention criteria. The used methodology assigns particular importance to the interpretations of the investigation results as they allow the identification of the vulnerabilities which characterized the church at the moment of the earthquake and which help to explain the structural behaviour and damage suffered.

2 The Fact-Finding Analysis

The investigative phase was carried out through (i) the specific observation of the current situation (geometric and architectural surveys, investigation of the construction techniques, study of the decorative elements, analysis of instability and degradation), (ii) the study of historical bibliographical and archival sources, and comparisons between the building and other churches of the same type which are to be found in the area. The information produced by these analyses (which included, for example, the extent of the seismic damage and the identification of stratigraphic signs) was then used both to put forward a number of hypotheses on the evolutionary phases of the church and also to highlight certain constructional vulnerabilities and architectural peculiarities which should be correlated to the behaviour of the church during the earthquake of 2009.

Survey: A precise geometric and architectural survey was carried out on the church and its graphic presentation at scales 1:50 and 1:20 permitted the elaboration of a comprehensive record of both the architectural and material aspects, and the state of preservation with particular reference to the seismic damage.

The church has total dimensions of around 16 m by 20 m and the layout is of three naves with a slightly raised chancel and a flat-ended choir, to which has been added two quadrangular volumes used as a vestry (Fig. 1).

The right-hand wall alongside the chancel, which is next to an alley, has a bow, which is visible in both wall surfaces. The central nave is characterised by two walls with rounded arches supported by square pillars, which are in square-shaped stone with big well-fitting blocks with sections of perforated brick to complete the surface. They did not suffer strain during the earthquake. The imposts of the arches are

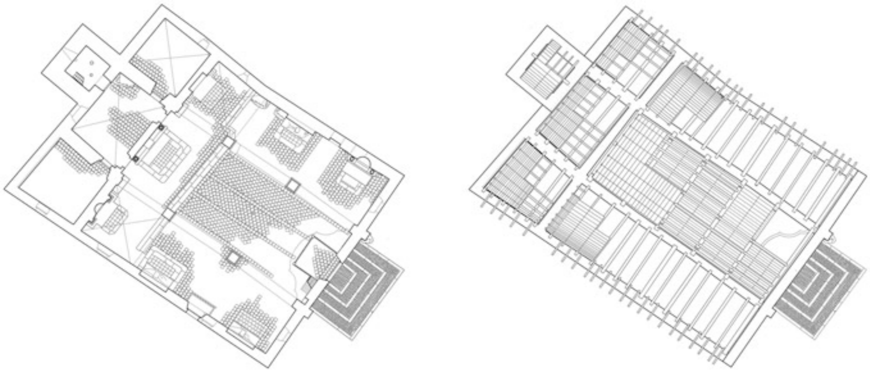

Fig. 1 Floor and roof wooden structure (originally 1:50 scale)

of four different types of salvaged capital. Alongside the chancel, the side naves have brickwork groin vaults. The main façade, which is the result of seventeenth- and eighteenth-century work, is partially placed on bare rock and finishes in a tympanum. The bell-tower is against the north-west side of the building and is characterised by bare stonework.

The decorative elements were analysed specifically and reproduced graphically at scale 1:20; these elements include a wooden ambon, plaster or stone altars and wall frescos or secco paintings. These paintings, which come from a period extending from the end of the fifteenth to the seventeenth century, were given particular attention both as regards their creation and the information they provide on the relative and absolute dating of the evolution of the church building (Fig. 2).

Historical Analysis: From the point of view of historical research, an initial bibliographic study was designed to frame the church within the ecclesiastical constructions of Abruzzo, while a second made comparisons with other churches of the same type in the area, and a survey of the most recent archive sources aimed to gather information on the work done on the building in the last 2 centuries. From the first 20 years of the thirteenth century until the second decade of the fifteenth

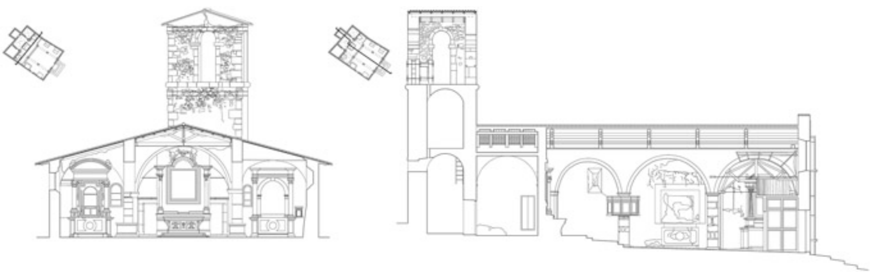

Fig. 2 Longitudinal and transversal sections (originally 1:50 scale)

century, the single-nave model is the main type of traditional Franciscan construction brought to Abruzzo by the mendicant orders (Franciscan but also Dominicans and Augustinians). Besides this type, there is also a *three-nave basilica model* from the Lombard-Benedictine tradition, which is particularly characteristic of the Romanesque phase in Abruzzo between the eleventh and twelfth centuries. Of these typological references, the three-nave layout of the church of Saint Agata could still be attributed to the Franciscan model with a subsequent evolution from the original smaller single-nave model to a three-nave church. One piece of evidence, which leads to this conclusion, is the position of the oldest fresco in the church, the *Madonna di Loreto tra i Francescani*. This dates from the end of the fifteenth century (a period still influenced by the unrest of the Franciscan Reform) and could represent the decoration of the first single-nave building. This hypothesis, as will be demonstrated below, seems to be supported by the observations made of the other decorative and constructional elements, such as the position and craftsmanship of the altars and the Baroque-era murals. An important restoration of the church is documented in the phase following the earthquake of 1703, and the construction of the two buttresses in the façade and the insertion of the main altar, which closes the quadrangular choir, can be attributed to this work. Judging from the stonework decoration of the main door, the sloping façade and the main door could also be the result of work carried out in the eighteenth century (Bartolini Salimbeni 1998). A sun between two barrels (*barili*) is sculpted on the architrave above the side door and shows that Tussillo belonged to the Barili lordship until the end of the fifteenth century (Vittorini 1999). A close examination of the archival sources produced information on the conditions of the church in the period between the start of nineteenth century and the 1930s (ACS L'Aquila). The reports of the *master builders* are dated 1825, 1846 and 1851 and denounce the terrible conditions of the building while indicating the work necessary to repair the paving, the roofing and the fixtures, and maintain the decorative elements. The documents which refer to the years after the Avezzano earthquake of 1915 are a rich source of information on the repairs carried out on the damaged parish churches; work is also done on the Saint Agata church to repair the damage caused by that earthquake, such as the collapse of the groin vault in the vestry and the roofing of the bell-tower.

Finally, an investigation of the churches in the area, which are of the same type concerning the overall layout, allowed further reflections, particularly on themes relevant to the constructional evolution of the examined building (Antonini 2005; Donatelli 2010). In fact, the current layout of many churches is due to significant transformations: the addition of side aisles alongside the original volume, the walls of which are opened with arches to create a new nave-and-side-aisles layout like at Saint Andrea a Stiffe; or the enlargement of a single-naved church by inserting arched internal walls which produced a three-nave building like at Saint Michele a Villa Sant'Angelo.

3 The Interpretation of the Research Data

As has been mentioned, the results produced by the research phase were used instrumentally to achieve two explicit goals: (i) the hypothetical reconstruction of the history of the transformations which the church has undergone since its construction (Doglioni 1997); (ii) the identification of the church's reaction to the earthquake using deductions drawn from the damage which occurred and which is interpreted in terms of mechanisms working on the various constitutive macro-elements.

Evolution of the church. The most obvious signs of the church's constructional history are the position of the two oldest frescos (*Madonna di Loreto tra martiri francescani* and *Santo Vescovo* from the late fifteenth or early sixteenth centuries) on what is now the counterfaçade, and the Baroque stone altars which are placed against the outside walls, partially obscuring pre-existing murals (Fig. 3).

However, other rather less striking pieces of evidence for the stratification were identified during the direct-analysis phase: blocked openings; various overlapping layers of painting; the juxtaposition of walls. Interpreted together and checked against the information taken from the historical sources, these elements permit the elaboration of a relative chronology. For example, the niche fresco *Santo Vescovo* is partially hidden by the last pillar of the arches and this highlights the chronological break between the two elements while at the same time demonstrating that the current three-nave layout was created through transformation.

In this way, cross-evaluating the information produced by the various research activities—surveying, examining the stratigraphic signs, historical research, typological comparisons—a number of hypotheses were formulated about the evolution of the building. Those which were incompatible with the research data were then excluded as was the case, for example, for the hypothesis of a single-nave layout with proportions that match those of other Franciscan churches in Abruzzo (about 1:3) and which was transformed into a three-nave layout through a symmetrical widening, cutting the arches into the walls of the old nave. This was incompatible with two pieces of data, which were taken directly from the building: the longitudinal arched

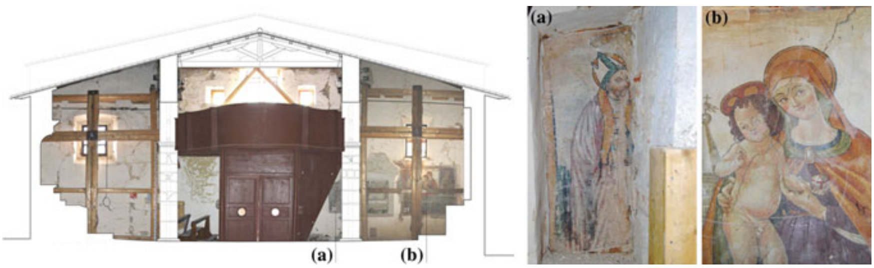

Fig. 3 Frescos located in the internal side of the main façade; **a** figure of a *Santo Vescovo*; **b** *Madonna di Loreto tra martiri francescani*

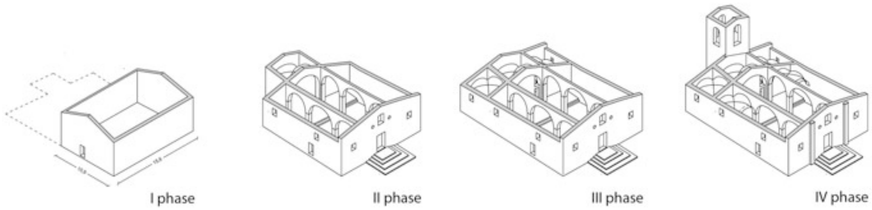

Fig. 4 The evolutionary process reconstruction deriving from sources data and on field analysis

walls which are not built into the façade (as can also be seen from the deep cracks caused by the earthquake); the position of the two old frescos on the inside of the main façade.

The most plausible evolution hypothesis is that of an original twelfth-century building without an apse and with a single nave running east-west with access from the current side door. Towards the middle of the sixteenth century this layout was extended to include side naves through the construction of the arches and the quadrangular choir; as a consequence the axis of the church was rotated. In subsequent phases, the two quadrangular volumes were apparently placed alongside the choir and the bell-tower against the back wall. This hypothesis is consistent with the information acquired and validated by the similar construction process at the church of Saint Michele in Villa Sant'Angelo (Fig. 4).

Damage: interpretation of mechanisms. By dividing the church building into macro-elements and bearing in mind the information on the evolutionary process, the damage mechanisms activated by the earthquake were identified in order to proceed to the critical interpretation of the series of cracks and deformities which were observed (Doglioni et al. 1994). There follows a concise description of the macro-elements and the related mechanisms (Figs. 5 and 6).

Main façade: even before the 2009 earthquake, the main façade was the site of significant bowing and warping due to past earthquakes—in particular the earthquake of 1703. The pressure of the internal arches—amplified during the dynamic action—can explain the signs of this older damage on the façade. This weakness in

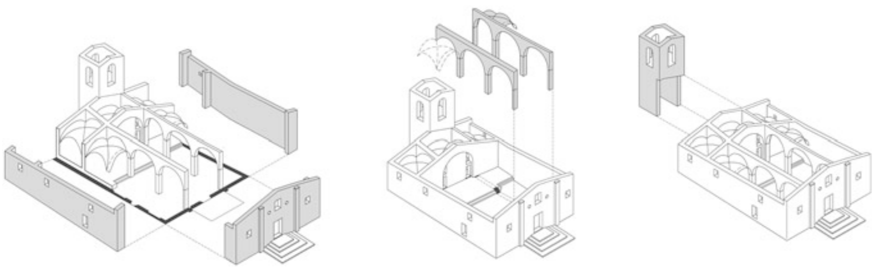

Fig. 5 Macro-elements: main and side façades, the walls of the nave, the bell-tower

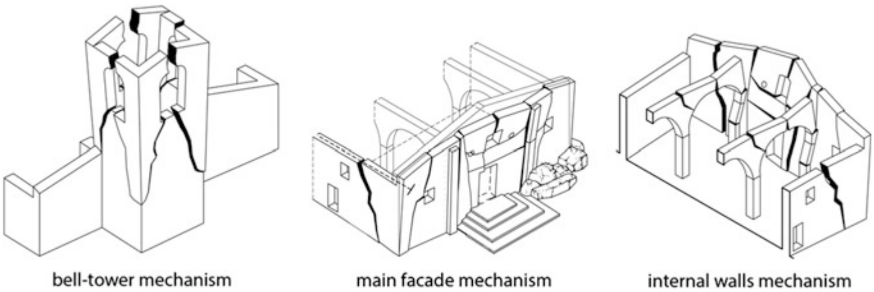

Fig. 6 The main seismic mechanisms identified on the church

the configuration also re-emerged during the last earthquake and highlighted the inadequacy of the nineteenth-century tie-rods, which were fitted to counteract the overturning of the façade. The present effects show how the right-hand arches have transferred a greater horizontal force and produced an asymmetrical rotation in the façade. This is presumably also due to other factors such as the presence of old openings which have been closed and included in the most recent arrangement of the façade, and the local scarf joint defect between the pre-existing wall and the added buttress. The mechanism in the highest part of the tympanum is also visible in the formation of cylindrical, horizontal hinges.

Side façades: the external side walls contributed to the mechanisms that were activated in the main façade by limiting or increasing its movement during the earthquake. In one case particularly—in the left-hand wall where a slanting crack is visible near the main façade—the good scarf joint of the cornerstone worked together with the longitudinal chain to stabilize the rotation of the façade. However, in the right-hand wall, where the two walls converge in the corner, there is a division crack—a sign of the activation of a simple overturning mechanism for the main façade and in a similar way for the part next to the side façade. In this case, the positive contributions of both the corner scarf joint and the chains do not seem to have manifested themselves. In terms of movement out of plane in the side walls, it is noted that only the right-hand wall is partially affected by an overturning mechanism next to the aforementioned cornerstone with the façade. The rest of its line does not present any signs of instability probably because of the contrasting action performed by the church's series of cross-chains.

The walls of the nave: as has already been mentioned, the arches at the end near the main façade have undergone a rotational translation, which is due to the movement towards the direct bearing next to the wall. This translation activated a flexing mechanism in the arches, which resulted in the transmission of a horizontal force concentrated on the wall of the façade. The current instability is shown in the separation of the elements, which were previously in contact, and makes clear the lack of a scarf joint between the longitudinal walls and the façade. This confirms the hypothesis of the construction chronology.

The bell-tower: it represents the element of the building which is at greatest risk. Despite the presence of a recently-built wooden covering and good-quality stonework, the seismic action caused the formation of cracks which reached a significant size in the upper parts of the tower as is shown by the loosening of the keystone in one of the four bell-tower arches. The damage can be summarised in an overturning mechanism, which affects the separated sections of the cells.

4 The Preservation and Seismic Improvement Project

The investigative and interpretative analyses permitted the outlining of a comprehensive framework of the necessities of the church both in terms of the damage caused by the earthquake of 2009 and the previous lack of maintenance. In particular, the interpretation of the seismic effects as damage mechanisms is directly aimed at defining the preservation project criteria which are in general finalised at strictly minimal, necessary interventions (Giuffrè, 2006; Carocci and Tocci 2009). Furthermore, the project supports a vision of this small church as a monument containing important historical and cultural values and—for this reason—it looks for the purpose of a whole preservation also taking into account the material history that the church itself tells throughout the stratifications (Fig. 7). In this way, the actual operations designed can be divided into two categories: (i) those which aim at repairing the seismic damage, recomposing the architectural structure, and improving its ability to react to earthquakes; (ii) those which aim at eliminating the degradation of both the internal and external surfaces and restoring and re-presenting the decorative elements.

As regards seismic improvement and repair work, the project pays particular attention to increasing the connections between the constituent parts of the building—a congenital weakness of historic brick buildings that was well known to past builders, above all in earthquake-prone areas. The reconstruction of the unified behaviour of the building is obtained through the use of a system of cross- and longitudinal chains, which substitutes the present, inadequate system, and the building of a masonry tie rod at the top of the walls.

These general interventions are accompanied by a series of localised operations, which together contribute to the reduction of the weaknesses identified in the church. For example, the disassembly of the wooden roof (which is necessary for the construction of the masonry tie rod)—will allow both the checking of the conditions of the wooden elements and the addition of a system of metal bracing. Also the connection between finishing elements and the wall support—for example, in the partial re-composition of the stone cornice of the window on the main façade—is part of the general strategy of the project, the aim of which is to avoid detachment during a possible future earthquake.

In the case of the collapsed brick vault, the project proposes its reconstruction in order to reconfigure the consolidated internal space of the church. This reconstruction will be executed with the same traditional techniques and in part using salvaged bricks. However, the supporting width of the vault is doubled. The symmetrical vault, which escaped collapse but was severely damaged, will be strengthened by increasing its supporting section.

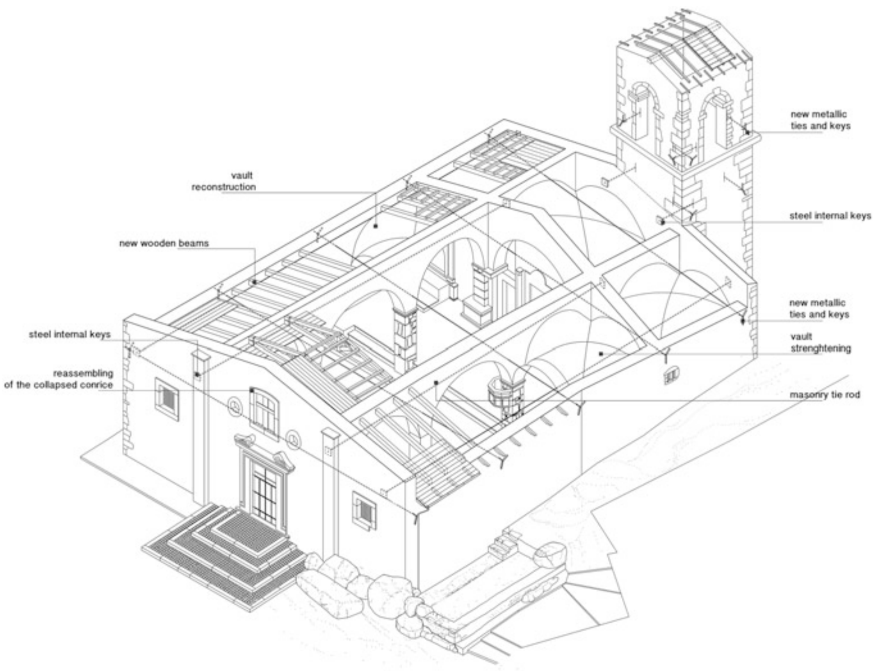

Fig. 7 Synthesis of the design intervention

In terms of the technical aspects of the operation, the project chooses masonry techniques both for their mechanical compatibility and to preserve the construction process that is characteristic of masonry buildings. Regarding interventions designed to preserve surfaces, the project aims to combat the state of neglect of the external and internal surfaces by starting from a close examination of information on the structures and the materials (plaster, stone jambs, stucco), and also the analysis of the murals and frescos (Doglioni 2008).

These permitted the specific definition of the nature (cleaning, removal, strengthening, and integration) and extent of the conservation work on the plaster surfaces and stone elements of the decorative apparatus. The project pays special attention to the frescoed and painted internal surfaces as well as the altars, in its final goal of both preserving them and permitting the legibility of the historical stratification of the church.

5 Conclusions

The methodology used in the study of the church of Saint Agata in Tussillo pursues dual design goals that bring together seismic safety and conservation of the monument. The characteristic feature of this procedure resides in the establishment of a rigorous correlation between the different phases of the process, from the cognitive to the design, and in their formulation through a specific construction language, the masonry technique. In so doing, specific observations on the evolution of the church and the current deterioration (both structural and superficial) reveal the crucial features, which cause seismic vulnerability. The results of the investigations carried out on the actual masonry structure become an essential part in the definition of a consistent restoration program.

One can infer from the aforementioned study method that the phase of direct analysis of the building (geometric and architectural surveys, interpretation of the stratigraphic signs and the damage mechanisms), accompanied by historical research (bibliographic and archival sources) is essential for the outlining of the criteria and the correct strategies for the project definition. This project aims to eliminate the weaknesses highlighted by the effects of the earthquake but in a design framework which has at its centre the architecture of the church as an historical masonry structure. In this way, the customary, old-fashioned formula that sees the division between structural and architectural elements reflected in the project is superseded by the observation that in historical masonry architecture the line between these aspects, which today we assign to different disciplines, is difficult to distinguish.

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Promoting a Nineteenth-Century Italian Technology: The Crystal Skies of Milan Gallery “Vittorio Emanuele II”

Iva Stoyanova, Ornella Selvafolta and Amedeo Bellini

Abstract The nineteenth-century technological revolution gave birth to a brand-new kind of monumental architecture—the secular “cathedrals” of the bourgeois called commercial galleries. They reached their ultimate incarnation as such in the Italian case of “Vittorio Emanuele II” counterpointing the sacred Milanese cathedral over a common square. Cathedrals were those “books of stone” that once embodied building codes of monumental architecture. Innovation became necessary with newly-developed typologies and materials. It was exactly the iron-glass covering that revolutionary element of the “gallery” typology which bridged architecture and advanced technologies. The Milanese one was a “book of bricks, metal and glass” encoding spatially genuine Italian concepts and practical knowledge on bonding traditional materials with modern ones. Demanding immediate attention is their adequate profiling and translating into practical guidelines. Even though “Vittorio Emanuele II” was thoroughly researched, its iron-glass structure offers field for further investigation on innovation. The initial aim is two-fold: first, to unveil the complex of creative ideas enclosed in the crystal skies of the Milanese gallery and the technical decisions behind them; second, to trace those which survived the numerous restorations and the adoption of advanced techniques in resolving the variety of problems verified over the years. As far as creative ideas and technical solutions are concerned, there are three main examples which could be highlighted. The first one regards the 15-m span of the coverage designed deliberately without visible reinforcing rods. The second intriguing aspect was a perspective effect in the glass cladding achieved by the glass plates’ overlapping. The third technical solution of interest concerns the glazing bars and their expediency in the effective resolving of the famous water-leakage problem. The fate of all the original design ideas and technical solutions changed on a number of occasions of ordinary and

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special maintenance and occasional replacements. In the rich history of interventions in the roof, its partial reconstruction after the Second World War occupies a central place. In it, the cross-like section of the glazing bars along with the spatial configuration of the glass plates were consciously observed criteria for their substitution in order to assure the fruition of the perspective effect by future generations. Another case of preservation in the post-war intervention was the profile of the new main metal arches replacing the severely destroyed original ones. Each new arch was composed by segments instead of being produced as a whole piece. Moreover, the diversity of problems began right after the completion of the cover in 1868 and continues to the present day. Multiple disciplines are involved in the search of their solution: from history of architecture for an efficient archival investigation to material chemistry and physics for preventing damages in the contact zones of bricks, iron or pig-iron and glass, caused by their different thermal expansion coefficients; from brittleness of the nineteenth-century metal structures, accompanied by severe corrosion in the metal joints, to the structural-engineering issue of instability of the lantern bodies. The very challenge before the required multidisciplinary approach is to invent advanced solutions respecting the genuine concept behind the original ones. The ultimate objective is not only to trace nineteenth-century ideas and their technical solutions but also to introduce them as future-intervention guidelines for the purposes of sustainable preservation.

1 Introduction

"Cathedrals of material culture" or "secular cathedrals of glass and steel" (Mayer 1981, p. 11) are often attributed to the 19th-century commercial arcades which are claimed to have their ultimate incarnation as such in the Milanese gallery "Vittorio Emanuele II". It was inaugurated on the 15th September 1867 after the larger part of its construction was completed in the period of two and a half years.[1] The project could be attributed with the significance of an international undertaking since it employed the foreign financial resources of the English Society "The City of Milan Improvements Company, Ltd." which relied on the iron production of the French Company of Henry Joret. Moreover, the Gallery brought to life new concepts of urban architecture especially due to the profound devotion of its creator Giuseppe Mengoni. Thus, not only did it overcome the economic and industrial difficulties of the complex Milanese historical reality, but it developed the common understandings of architecture and urbanism.

[1] The ceremony for the official posing of the first stone which could be retained as the start of the construction was on 7th March 1865. However, it is to be noted that even though the larger part of the Gallery was completed for about 2 years, it actually took an additional decade until 1877 in order to finish the triumphal arch for the entrance from the Piazza del Duomo.

The iron-glass cover was often referred to as "skies of glass" or "crystal skies" which in itself already suggests how significant its contribution was for the overall spatial impact of the Milanese arcade. One of its basic dimensions was monumentality—a feature that was only touched on in the concepts of the already constructed at that time galleries. Presumably, all of these followed the basic matrix of a covered shopping street beginning from the highly representative French passages created for the newly-born bourgeoisie, then passing through the Victorian dome-covered British arcades and arriving at the Brussels Galeries Royales Saint-Hubert as an instrument of urban renewal. Still, it was "Vittorio Emanuele II" that managed to convey the idea of the gallery to the whole new conceptual level of monumental architecture and thus, to generate the hidden potential of commercial streets as an urban form of monumentality. In this way, the Milan gallery seems to have offered the age of industry and the epoch of rising bourgeoisie its matching form of monumentality: employing pioneering materials in service of the secular.[2]

At the light of this specific profile of the Gallery, its iron-glass cover, especially celebrated for the dimensions and impact of the cupola, merits a more profound investigation in terms of creative concepts and technology.

2 The Milanese Iron-Glass Cover as a Book of Practical Guidance

Adopting the famous interpretation of the archdeacon's words in *Notre-Dame de Paris* by Victor Hugo:

> The archdeacon gazed at the gigantic edifice for some time in silence, then extending his right hand, with a sigh, towards the printed book which lay open on the table, and his left towards Notre-Dame, and turning a sad glance from the book to the church,—'Alas,' he said, 'this will kill that'.[3]

Cathedrals could be interpreted as books of stone encoding conventional building practices of monumental architecture. Applied to the gallery "Vittorio Emanuele II" as an edifice of monumental scale, such a definition might offer an interesting point of view towards its building technology. The challenge before the latter was not only the accord between Italian building tradition in masonry and modern technology employing iron and glass. It also had to provide for such grand proportions inherent to monumental architecture. As a result, a hybrid structure[4]

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[2] In the support of the idea that the "urban" is a category that suited best 19th-century bourgeois monumentality see Benjamin (2002), p. 11.

[3] The translation in English is from a contemporary edition of the book: Hugo (2013) Notre-Dame de Paris. Hapgood, Isabell (translated by), Book V, Chap. 2, Madison: Circket House Books, p. 174.

[4] "The system integrated the building traditions in masonry with those of the modern construction in metal in a hybrid between tradition and innovation."—Translation by the author. Original text:

was developed which employed masonry, pig-iron and wrought iron in the main load-bearing elements, as well as glass in the covering plates. These materials collaborated exclusively in the building technology adopted for the crystal skies of the gallery "Vittorio Emanuele II". In this sense, it might be interpreted as a "book of bricks, iron and glass" which encoded genuine Italian practices on meeting the constructive and representative challenges in the second half of the 19th-century.

Thus, the Milanese cover can be featured as the element bridging monumental architecture with engineering, building traditions with advanced technologies, modern celebrative concepts with confirmed aesthetical criteria. As such, it might be approached from a new point of view: as a marker of spatial identity. In this sense, it could be explored as a complex of creative ideas that were translated into a system of certain technical decisions.

Today, an interesting question appears to be which of these were retained valuable and survived the numerous interventions over the years.

3 On the Track of Creative Ideas and the Technical Decisions Behind Them

As far as creative ideas and innovative technical decisions are concerned, three main examples could be traced looking into archives and into previous research on the Gallery.

3.1 Avoidance of Reinforcing Rods or Ties in the Spans of the Wings and the Cupola

In the first place, this was the concept of spatial immensity as a prerequisite for monumental impact. The feeling of vastness inside the Gallery depended above all on the sufficient width of the wings and the cupola along with the unobstructed perception of their interior space. In order to ensure statically the larger spans required on this account also in the base of the glazed roof horizontal reinforcing iron rods were usually employed as a reasonable technical solution in the building practice of that time. However, their use was rejected as inappropriate for the case of the Gallery since they would have compromised the monumental impact of its interior space.[5] Moreover, it appears that visible horizontal rods would have separated sharply the iron-

(Footnote 4 continued)
"Il sistema integrava le consuetudini della costruzione in laterizio con quelle della moderna costruzione metallica, in un ibrido fra tradizione e innovazione…" Selvafolta (1983), p. 241.

[5] "…in order to avoid the use of chains or horizontal ties not allowed in a monument of that kind…"—Translation by the author. Original text: "…allo scopo di evitare l'impiego di catene o tiranti orizzontali non consentiti in un simile monumento…" Chizzolini and Poggi (1885), p. 217.

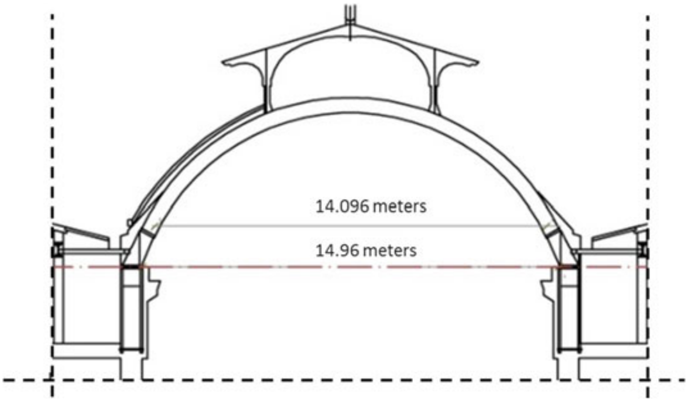

Fig. 1 Transversal section elaborated by the author on basis of table III from the graphic attachments to the Expertise on the iron-glass roof conducted in 1868. It displays a transversal section of the iron-glass roof in the main wing leading to Piazza della Scala. Here can be observed the roof span of 14.56 m free of horizontal reinforcing rods

glass cover from the space underneath and as a result would have hindered the holistic spatial perception of the visitor in the perspective of the wings.

Being an essential factor, the avoidance of reinforcing rods was adopted as a condition in the contract between the Municipality of Milan and the English Society "The City of Milan Improvements Company, Ltd".[6] Technically, it challenged the collaboration of iron with masonry in the walls supporting the iron arches of the cover (Fig. 1).

The fundamental problem was the lateral thrust at their foot caused above all by the movement of the arches themselves in case of iron expansion. Gerolamo Chizzolini who was the head of the Construction Works Department and collaborated with Giuseppe Mengoni came up with a technical solution which was once criticized as an excessive and expensive precaution measure but that might have guaranteed the stability of the cover over the centuries surviving even the Second World War.[7] He employed a secondary system of vertical and horizontal iron elements which eliminated the horizontal force in question. The vertical elements (Fig. 2a) were 4 m iron ties which anchored into the masonry a granite block. To the latter was rigidly bolted the foot of each arch made from a double-T profile. The horizontal elements (Fig. 2b) were double-T profiles in the plane of each arch which were perpendicular to a longitudinal double-T profile. It practically ran along the periphery of the wings, hence of the adjacent to the Gallery buildings.

According to Chizzolini's words, the conventional decision at the time allowed free expansion of the iron arches which practically meant a hinge joint permitting slight movement in the connection between the foot of the arch and the granite

[6] On the clauses of the contract between the Supervision of Construction Works of the Gallery and the Parisian Company Joret , see Saldini (1885)

[7] On the reinforcing system see Chizzolini and Poggi (1885), p. 217.

block.[8] On the contrary, in Chizzolini's decision not only did the bolts fix a rigid connection, but the ties further stiffened it engaging a significant block of masonry. In this way, in case of expansion the iron arches would move prevalently up-words, towards their summit, while any horizontal force left would be transmitted to the surrounding edifice through the horizontal system of perpendicular and longitudinal profiles. Thus, this secondary system offered an alternative to the iron rods in which a significant role played this particular kind of reinforced masonry—a very clear illustration of the hybrid between traditional building materials and technology, on one hand and the new ones, on the other.

It is intriguing to explore if the vertical and horizontal iron elements of this secondary system could be found in place today. There is a very high possibility since there is not any official documentation available on interventions in the masonry under the foot of the cover. Furthermore, both kinds of secondary iron elements appear to have been entirely integrated into the surrounding edifices which would have impeded their removal unless it was the case of a high-scale intervention. The most significant one of this kind was the reconstruction of the Gallery and especially of its glazed roof after the destructions in the Second World War. On that occasion, a sliding constraint was introduced in the connection between the foot of the arches and the granite blocks underneath during the intervention which was designed and conducted by engineer Giovanni Magnaghi.[9] Such a mechanism actually allowed for slight sliding of the foot in case of expansion of the whole arch. It was retained as necessary since the upward movement of the arches imposed by the previous rigid bolted connection actually resulted in the often breakages of the glass plates. Their often fracturing was further predetermined by the different dilatation coefficient of glass and iron. It was verified as a serious reoccurring problem only later during the numerous interventions for glass plates' substitution.

On one hand, it is to be noted that the logic of the sliding constraint mechanism is exactly the opposite of the rigid connection provided by Chizzolini's bolt junction. On the other, it was indicative to discover that the same sliding solution was already quite popular at the time of the Gallery's construction. This proves that the question of different dilatation coefficients of materials was considered to

[8] "It might be of interest to know that to the contrary of what was used until then, the arches of the roof (of the Gallery "Vittorio Emanuele") were not left free to the dilatation through the sliding along one of the wings of the buildings…"—Translation by the author. Original text: "Può interessare il sapere che al contrario di quanto fino ad allora si usava, le centine della tettoia non furono lasciate libere alla dilatazione collo scorrimento lungo uno dei bracci dei fabbricati…", Chizzolini and Poggi (1885), p. 217.

[9] "…the grafts of the vaults onto the surrounding buildings were particularly studied in order to ensure that the different dilatations do not cause, as it was in the past, very dangerous cases of glass-plate falling. The problem was solved by equipping each graft with a sliding constraint." —Translation by the author. Original text: "gli innesti delle navate sui fabbricati terminali sono stati particolarmente studiati per far sì che le differenti dilatazioni non provocassero come nel passato, pericolosissime cadute dei vetri. Si è risolto il problema dotando i singoli correnti terminali di fissaggio a scorrimento." See Carpinelli (1949), p. 58.

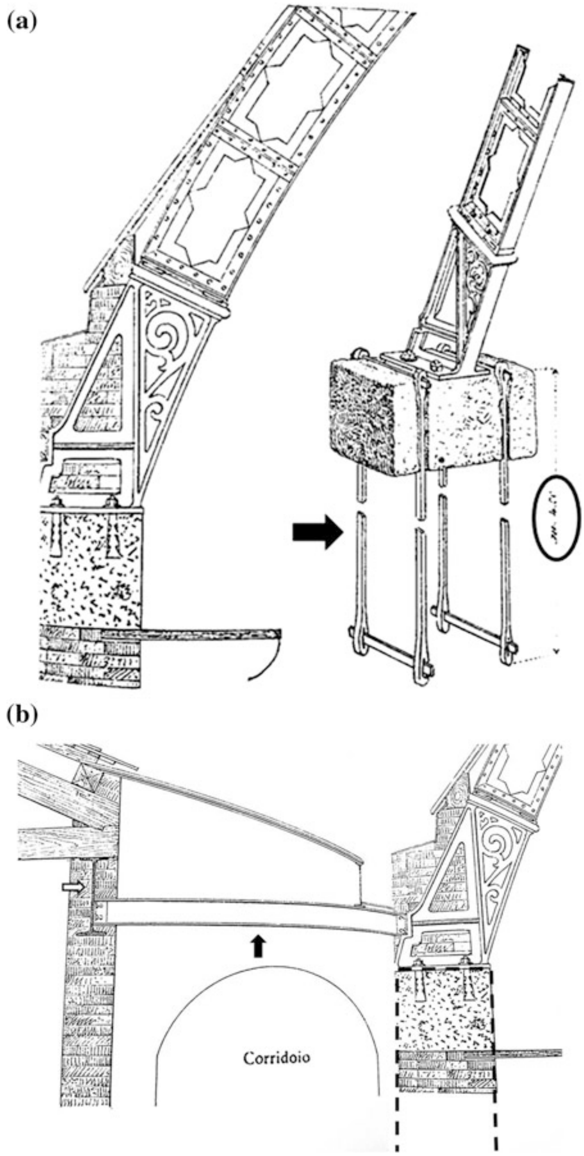

Fig. 2 Detail of the foot of the metal arches and their connection with the supporting walls in the Gallery wings. **a** Vertical elements—4 m high (*black ellipse*) iron ties (*black arrow*), **b** Horizontal elements—transversal double-T iron beam (*black arrow*), longitudinal double-T iron beam (*white arrow*) and the supposed position of the vertical ties (*dashed line*), Ghizzolini and Poggi (1885), pp. 216–217

some extent in the 19th-century, yet not in the case of the masonry-iron connection in the cover of the Gallery. For this reason, the creative touch of Chizzolini's technical decision should be sought above all in the employment of iron vertical ties and horizontal iron beams. Thus, the pioneering material was profited as a secondary system in order to reinforce and improve the efficiency of traditional masonry.

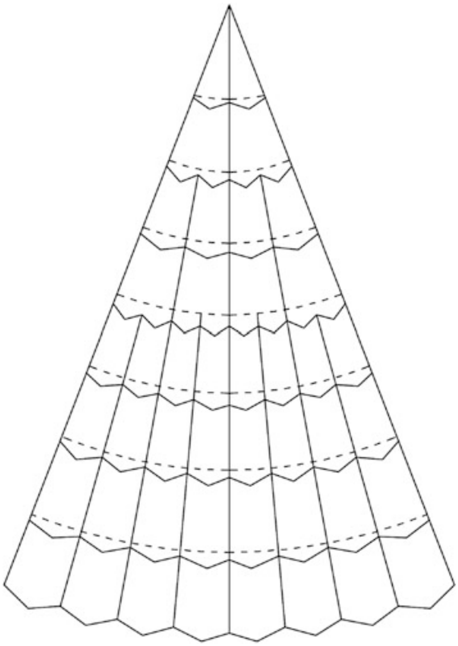

Fig. 3 Drawing of a segment from the cupola lantern with the triangular drips of the glass plates (hypothesis elaborated by the author on the basis of Milan Municipality glazing schemes)

3.2 Dimensions, Overlapping and Triangular Drip of the Glass Plates

A second example of creativity refers to the spatial disposition of the glass plates. Surprisingly, it is once again the documentation on the intervention after the Second World War which mentions three leading features of the glass plates that were adopted as conscious restoration criteria: their dimensions (which varied in length from 0.85 to 2.15 m but were usually about 0.60 m in width), their gradual overlapping and the triangular form of the drip[10] (Fig. 3). The creative idea behind their superposition is claimed to have been a certain perspective effect for the visitor when observing the cover, an effect conceived by Mengoni probably in his search of monumental aesthetics. To it further contributed the scale of the plates set by their measurements along with their decorative triangular ending in the dripping part. What should be noted is that the overlapping here further obtains an aesthetical value which was once considered to be just as important as the technical water-draining and ventilation advantages gained by the superimposition of the glass plates.

[10] These three conditions are described in a letter dating 20 April 1948 from the Archive of the "Superintendence for the architectural and landscape assets of Milan", Folder 6613 and subfolders.

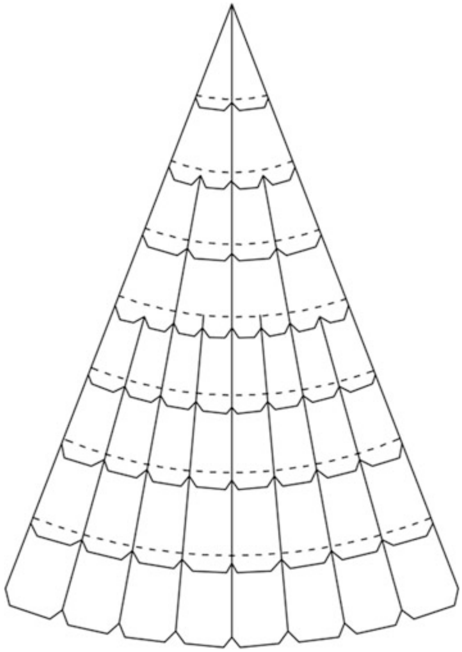

Fig. 4 Drawing of a segment from the cupola lantern with the trapezoidal drips of the glass plates (hypothesis elaborated by the author on the basis of Milan Municipality glazing schemes)

In-situ inspection of the modern plates could verify their general compliance to these technical criteria: the dimensions are similar; the overlapping is present; only a trapezoidal drip has been introduced in the place of the triangular one (Fig. 4). Most probably such a modification was motivated by the necessity to avoid the concentration of the rainwater stream in the middle of the glass plates since it favoured dust and dirt deposit concentration in the center of the plate. A trapezoidal rain drip appears to provide for the more uniform dispersion of rainwater and pollution yet it still managed to keep the water away from the periphery of each glass plate. Therefore, it did not subject the iron-glass joints to the malicious repercussions of the direct contact with rainwater.

3.3 The Cross-like Section of the Glazing Bars

Undoubtedly, the technical solution of the iron-glass joint constituted a question of leading importance in the case of glazed roofs and proved to have been a major preoccupation of the 19th-century iron-and-glass architecture in general. Above all, the iron-glass joint solution had to prevent from water-leakage. Bitter experience had already shared the Crystal Palace, constructed before the Milanese gallery as well as the Neapolitan gallery "Umberto I" projected 20 years later. A research dating right back to the period of construction of the Milanese gallery[11] outlines the solution adopted in its cover as a very successful one. Its efficiency was attributed to the y-like shape of the canal formed in section by the pieces supporting the edge of the plates. It conducted water easily and rendered putty unnecessary in these connection points.[12]

A proper verification of this innovative aspect could be searched in technical drawings from the construction period of the roof of the Gallery or immediately after it. As far as the iron-glass detail in the cover is concerned, there are two main historical sources: the volume "L'architettura del ferro: raccolta di motivi per costruzioni civili, ferroviarie ed artistiche compilata col concorso dei migliori ingegneri, architetti e costruttori italiani" (Fig. 5) which dates back from 20 years after the glazed roof was completed and a drawing focusing on the cupola lantern (Fig. 6) which belongs to the construction period of the roof. In the first case, the object is the glazing bar employed in the cupola that clearly represents an inverted "T" in section. The hypothetical sketch (Fig. 7), elaborated on the basis of the transversal and longitudinal section of the detail, explores its perspective view and illustrates a y-like structure formed by the pair of metal wires. However, these contribute mainly to holding the inclined upper glass plates in the edge and, as a result they prevent any risk of falling.

What acts as drainage but can be hardly attributed with the shape of an epsilon are the two indentations on the horizontal part of the glass-bearing profile. In the case of the drawing, only the glazing bar is present and it constitutes a cross in section. Therefore, a y-shaped piece is hardly traceable neither in the glazing bar, nor in the glass stoppers.

As a matter of fact, the "T" profile in the cupola is mentioned also in the 1892-technical magazine "L'Edilizia moderna" in an article by engineer A.F. Jorini while to a cross-like glazing bar alludes the information on the restoration after the Second World War. According to it, all the glazing bars were substituted and the new profiles did not differ substantially from the previous ones which were elaborated before 1880 and constituted a cross in section.

The confrontation between these technical drawings raises the very intriguing question if different glazing bars were employed in the main morphological parts of the cover: the cupola, the vaults and the lanterns.

[11] The document in question is "Il ferro nelle costruzioni. Dissertazione per ottenere la laurea in Ingegneria" by Quintino Tarantino, dating back to1868.

[12] "…the pieces which support the plates in their edge, have the shape of the cross section as an Y, the two branches of which serve as supports and the internal space they form as a water drain. With this form, being excluded the use of putty in the connections; it is not subject to water infiltration and continuous damages."—Translation by the author. Original text: "…i pezzi che sostengono le lastre nel loro orlo, hanno la forma della sezione trasversale come un Y, i due rami del quale servono d'appoggio ed il loro interno da condotti dell'acqua. Con questa forma, essendo escluso l'impiego di mastice nelle connessure, non si è soggetti ad infiltrazioni d'acqua ed a continui risarcimenti." Tarantino (1868), p. 23.

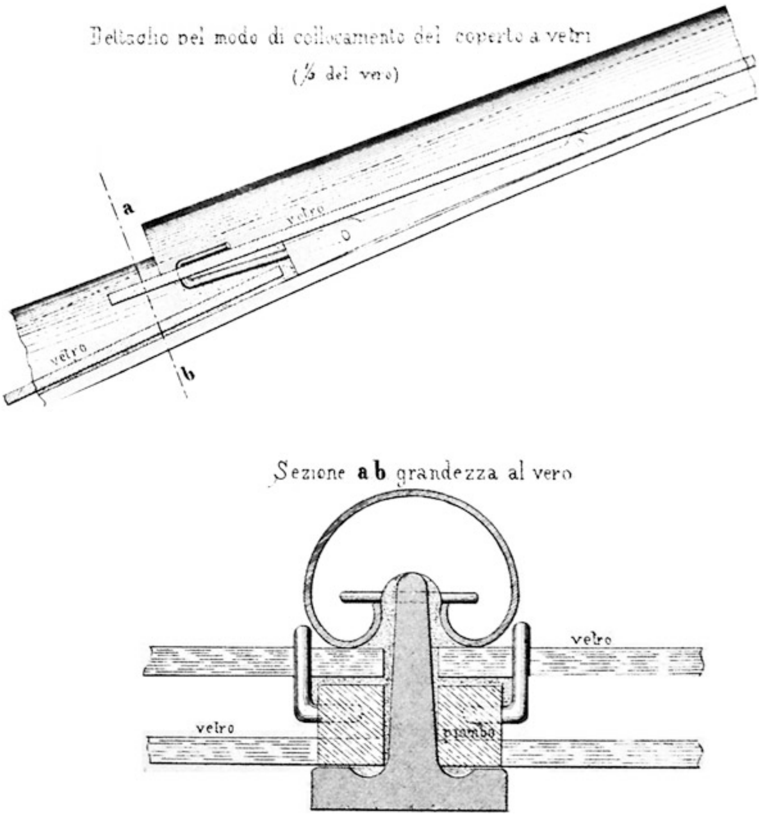

Fig. 5 Detail in the cupola of the inverted-"T" glazing bar with the glass plates in their overlapping zone, Saldini (1885)

What appears certain is that the cross-section glazing bars were originally adopted in some parts of the cover, and then, in the restoration after the Second World War, their geometric parameters were retained valuable as conscious criteria and as a standard for all the new glazing bars in the different parts of the cover (Fig. 8).

4 Concepts and Solutions Which Survived Maintenance Interventions and the Adoption of Advanced Techniques

The case of the iron-glass junction raises also the question what happened to the creative 19th-century technical solutions during the 148 year history of the Gallery. As for the iron-brick reinforcing system, it remains unclear to what extent its

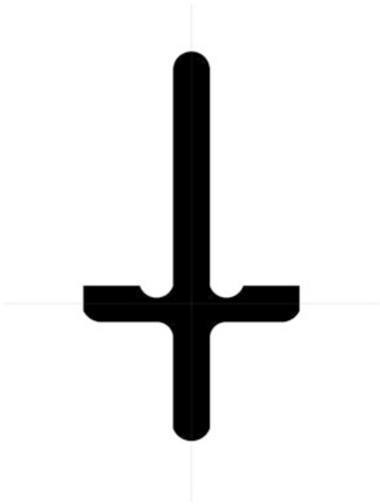

Fig. 6 Detail in the cupola lantern which displays a cross-like glazing bar (hypothesis elaborated by the author on the basis of original technical drawings from the construction period)

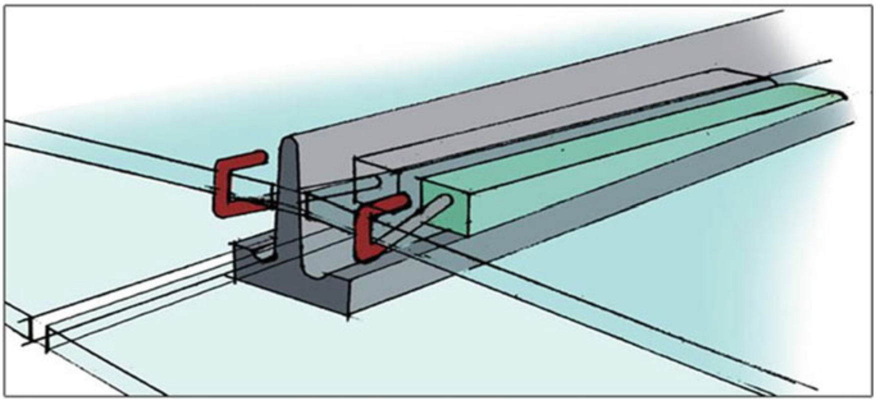

Fig. 7 Hypothetical axonometric sketch exploring the detail in the cupola of the inverted-"T" glazing bar with the glass plates in their overlapping zone

innovative touch was appreciated and respected consciously in the intervention after the Second World War. On the contrary, the glass-plates case is an illustration of continuity which assured the perception of the perspective effect for the sake of future generations.

Another similar example which is traceable through the documentation on the post-war reconstruction concerns the longitudinal profile of the main load-bearing metal

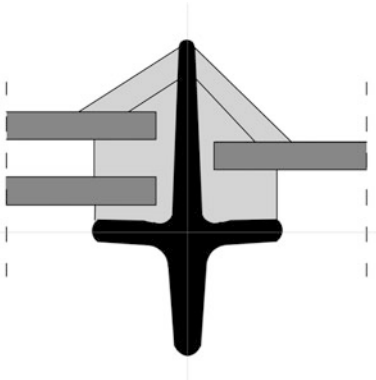

Fig. 8 The contemporary detail of cross-section glazing bars with glass plates from the 1985 (hypothesis elaborated by the author on the basis of Milan Municipality glazing schemes)

arches in the roof structure. Although monolith metal pieces could have been introduced, the new arches were consciously composed of segments just as the original ones in order to guarantee the overall architectural appearance of the cover. Last but not least could, it is to be underlined that the case of the cross-section glazing bar is another illustration of continuity in the history of interventions in the cover.

5 Diversity of Conservation Problems

The examples discussed reveal as a possible threat to the 19th-century cover technology the adoption of advanced techniques. Their main advantage is the efficiency of the technical solutions they suggest for the variety of problems affecting the cover. A glimpse on these issues can be caught in the documentation on the numerous cases of ordinary and extraordinary maintenance which began right after the construction had been completed. It seems that the first problems documented concerned above all the glass components of the cover compromised by their fragility and exposure to atmospheric pollution and rusty water left-overs. Consequently, the metal elements were affected by oxidization. Then, the different thermal expansion coefficients are another example which reveals the co-existence of iron and glass as the main prerequisite for the occurrence of problems. Another group of issues was reported in 1985 by the engineer Arrigo Vallata in his evaluation of the present state of the cover commissioned by the Municipality. On-site visits confirmed severe corrosion in the metal joints.[13] Furthermore, laboratory examination of 19th-century metal samples proved brittleness of the structures. Last but not least, testing calculation of the allowable stresses revealed certain instability of the lantern bodies.

[13] On the examination and laboratory testing of the metal structures, see Vallatta (1981a, b)[1].

6 Conclusion

These few examples of the problems in the cover show that their complexity is due to the coexistence of different materials and of structures belonging to different historical periods since the majority of interventions were replacements of damaged parts with their copies. The principle difficulty in addressing such a wide number of issues is the attention and collaboration of different disciplines: from history of architecture to material chemistry and physics; from material conservation to structural engineering.

As a result, the real the challenge that arises before the required multidisciplinary approach is to come up with advanced solutions, yet respecting the genuine concept behind the original ones. Thus, the nineteenth-century creative ideas would be not only traced in the documentary history, but also promoted practically by introducing them as practical future-intervention guidelines for the purposes of sustainable preservation.

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Gekko-den Case Study: The Process Surrounding the Preservation of Historical Wooden Architecture in Japan

Tanya L. Park

Abstract Architectural preservation in Japan is discussed through the study and observation of Gekko-den pavilion at Gokoku-ji Temple in Central Tokyo. Gekko-den's importance lies in its affiliation with Onjo-ji Temple, founded in early Heian Period, 672, a designated National Treasure of Japan and head temple of the Tendaijimon Buddhist sect. Preservation of Gekko-den began in November 2008 and continued through to October 2013. Through the process of preservation at Gekko-den pavilion, current issues are brought to the fore, namely access to preservation materials necessary for repair and maintenance, access to a skilled knowledge base of craftsmen who hold the understanding and expertise pertaining not only to the material, but also the intricate and complex designs surrounding large Japanese wooden heritage structures. A fundamental understanding of how the material works within the intricate structure is two sides of the coin. Often intangible skills are held up as being necessary to the survival of preservation. This is unequivocally true in wooden preservation where the importance lies in a deep understanding of the wooden material and the way it works and an understanding of the structure. Analysis of the administration that functions to oversee the protection and preservation of cultural properties is examined, together with training and access to available necessary materials for the preservation.

1 Gekko-den Pavilion at Gokoku-ji Temple as a Case Study

Gekko-den pavilion at Gokoku-ji temple dates from the Edo epoch, constructed in early 1600s. The function and purpose includes a guest room for Nikko-inn being a subsidiary temple of Onjo-ji in Shiga Prefecture. The main hall (*hondō*) was built in

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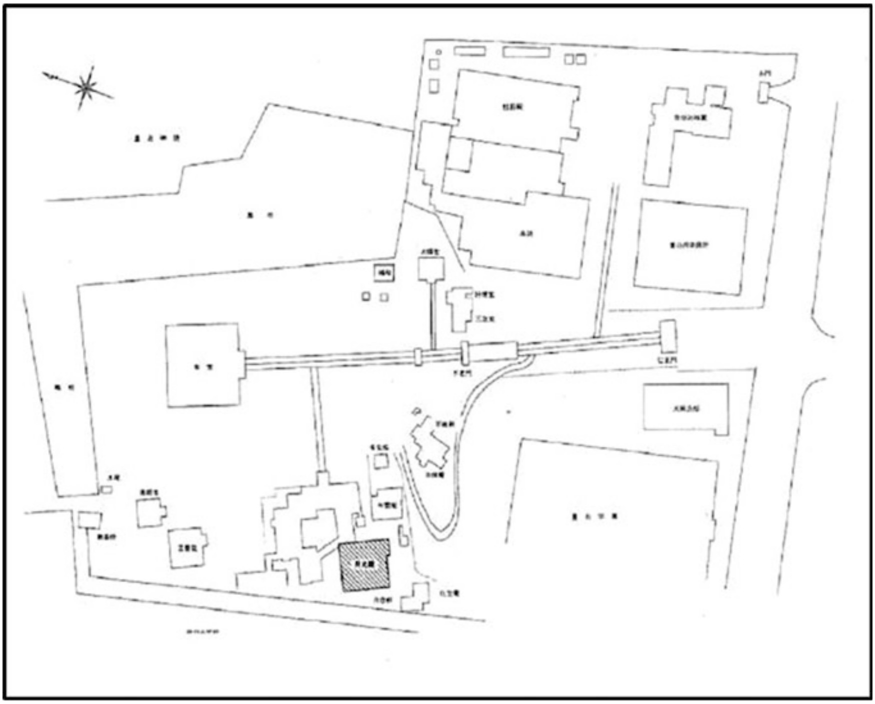

Fig. 1 Map of Gokoku-ji confines, shaded region is Gekko-den pavilion. Due to rapid industrialization of twentieth century Tokyo, temple grounds have significantly reduced (Courtesy of ACA Agency for Cultural Affairs)

1697, the consecration ceremony (*rakkei nyūbutso*) transpired during the month of August in 1697.

In 1894 the building was purchased by a businessman named Hara Rokuro and moved to his private residence in Shinagawa, Goten-yama. Hara-sans interests in the building lay primarily in the screen door paintings in the interior of the building and upon purchase of the building Hara-san removed the paintings and they were prepared into a scroll for the alcove known as *tokonomo.* There are numerous examples of cases where buildings have been transported to different sites, or significantly remodeled due to adaptation of usage and purpose. Katsura palace, in Kyoto, is one such example where traces of such change are evident (Sekino 1983). Through the negotiations of Takahashi-san in 1928 the building was moved to the grounds of Gokoku-ji Temple and renamed Gekko-den (Moonlight pavilion). Gokoku-ji temple is in Bunkyo ward, central Tokyo (Fig. 1).

During the 80 years following the move of Gekko-den to its current site, the structural members had begun to show obvious weakening. Depression of the ground under the flooring system was extensive and deformation and sinking of the structure had become significant. It was due to these contributing factors that the decision for full dismantlement was made (Fig 2).

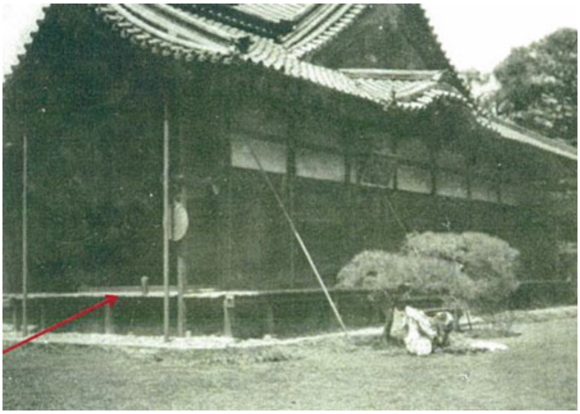

Fig. 2 Historical photograph prior to transportation to Gokoku-ji grounds

1.1 Building Assessment and Preservation Decisions

Procedures deployed in the preservation process in Japan include both partial and full dismantlement. In essence the building is dismantled from the roof down, examined, the structurally deficient parts are fixed or replaced and then the building is reassembled. Nobuo Ito has commented that the roof and its immediate supporting members are typically dismantled about every 150 years and full dismantlement of the building occurs about every 300 years in the life-span of the building (Ito 2007). However, it is important to note that although this is a general time-frame applicable to wooden preservation throughout Japan, there is no intent to maintain buildings at fixed intervals, but to preserve them when deemed necessary; such is the case of Gekko-den Pavilion (Fig. 3).

Meticulous analysis of Gekkoden pavilion during the dismantlement process revealed evidence of previous maintenance and preservation employed. Post structural analysis and during full dismantlement, an analysis was made of preceding maintenance and preservation of the structure and this was formulated in chronological order. In 1622 partial repair of the structure was noted, according to the calligraphy discovered on the arch beam of middle gate south balcony. In 1744 the structure underwent re-roofing, again according to calligraphy discovered on bamboo supporting the decorative roof on the west side of the main building. In 1940, 1959 and 1973 partial roof repairs were undertaken. In 2008 repair for preservation began again, the building was disassembled and repaired.

The process of preservation at Gekko-den pavilion was seen as an opportunity to study and acquire knowledge about the structure, as is the case with any full dismantlement project within Japan.

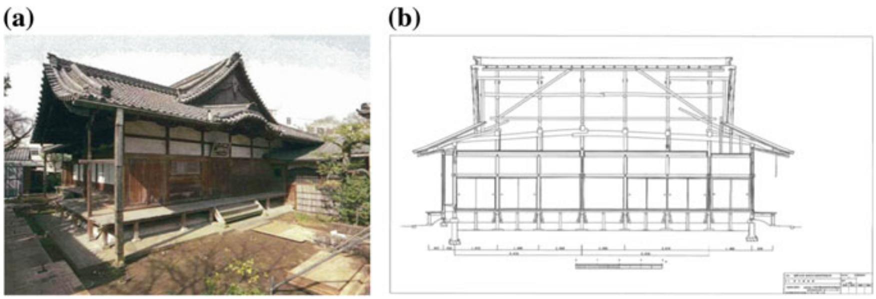

Fig. 3 (**a**, **b**) Gekkoden photograph and architectural cross section elevation illustration prior to the commencement of preservation. (Courtesy of Agency for Cultural Affairs (ACA), Tokyo)

1.2 Misconception of Japanese Preservation Process

Misunderstanding exists regarding the ceremonial dismantlement of all heritage structures throughout Japan at set intervals. The term "*Shikinen Sengu*" is the Japanese term used regarding the complete reconstruction of a structure at set intervals and is exclusively a religious Shinto ritual. Smallness of scale of the structure, common in Shinto, renders the rebuilding comparatively straight- forward. *Shikinen Sengu* is exclusively a primitive Shinto ritual and is performed on a singular shrine considered of great importance, namely the Ise shrine (Adams 1998). Building the replica (every twenty years) of the new shrine materializes on an adjacent site next to the old, each rebuilding alternates between the two sites. This ensures exact replication of the older structure, all wooden members are of clean Hinoki and all materials utilized are new and original. Additional importance lies with Ise's connection to the Japanese Imperial family and the high priest or priestess of Ise Shrine must be a descendent of the Imperial family. All parts of the structure are retained and moved to another site. In 2013 the Ise shrine was rebuilt for the 62nd time.

1.3 Commonality of Procedure

Whilst each wooden structure is unique in design and composition, there are commonalities between the aging of the structure and certain areas in which replacement occurs. In general in conservation work on Japanese important architectural monuments involving the replacement of original members, most of replaced parts are around the exposed perimeter of the structure, close to the ground, is often a place where moisture damage occurs. It is not common to replace the structural frame members which results that most of the more important material components of the building remaining original, even after full dismantlement preservation work. Gekkoden is a typical example of this commonality.

Furthermore, the weight of roof tiles can cause permanent deformation of the wooden beams and the declination of the angle of eaves under heavy constant loadings. This was also evident at Gekko-den pavilion. The weight of the tiles and the overall roof loading is further compounded with the traditional practice of heavy mud beds beneath the roofing tiles. It is possible to reduce weight by reducing the mud thickness. Roofs utilizing organic thatch and cypress result in even further reduced loading. In the case of Gekko-den the original cypress tile roofing has been re-installed, replacing the heavy ceramic tiles, common amongst Japanese buildings.

1.4 Detail of Gekko-den Preservation

Gekko-den is a single story structure with a side of roofing that extends out and up from each side of the rectangular structure. Partway up two of the shorter opposite sides stop and the remaining two continue to the top where they are joined. The Irimoya-style roof was considered the most elegant of the Edo period; the Irimoya roof style was employed in the highest level of castles design. The main structure has a carriage porch and an inner gate which is reflective of the Shuden-zukuri style in Muromachi Period (1338). According to the building method or typological study, Gekko- den is distinctive because it is considered to be built at the beginning of Edo Period, similar to Kojo-in (sub-temple of Onjo-ji Temple) and Kangaku-in Kyakuden (Nishi and Hozumi 1983).

The design is post and beam construction where joints are used to combine pieces of wood in straight longitudinal direction or angles, such as the curved ends of the eaves. The traditional wood jointing system deployed throughout connects wooden members with specialized joints, for which Japanese architecture is venerated and renowned. The underlying principle behind such construction is that the building is held together with a complex jointing arrangement. It is this complex design, so integral and fundamental to Japanese architecture, that over hundreds of years, due to the natural properties of wood, structural loading, climatic wind loadings and seismic action, causes the connections and joints loosen and weaken structural strength. The tightness of the interlocking of the jointing system becomes weakened and needs partial, or full, replacement. The excellence of Japanese carpentry practice comes to the fore, with a strong correlation between the skill of carpentry and the beauty and strength of the building where strong, precise jointing can significantly prolong the life-span of the structure.

Gekko-den was constructed during the Edo period. What is known of the construction techniques and associated carpentry tools during the Edo period? Very few of the actual tools used by the carpenters during this period remain and historical documentation and illustrations are an important source of information. One of the best compilations is the Sino-Japanese illustrated Encyclopedia from 1713, which gives pictures of contemporary carpenters tools together with explanations. Most of the tools depicted have changed very little in their basic construction and

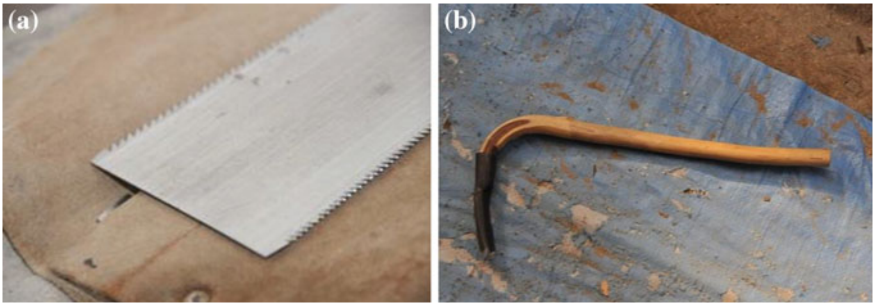

Fig. 4 (**a**, **b**) The hand saw has two different types of teeth, cutting on the pull, the other side cutting with both pulling and pushing movement (Photographs by author)

shape during subsequent centuries and continue to be used, with minor improvements, by carpenters today. What is understood through the historical texts is the significant skill and labour involved by the craftsmen who worked on such structures of the Edo period, and periods prior.

At Gekko-den a combination of contemporary and traditional tools are used. Electric tools are used primarily for the cutting, but traditional hand tools are used for the final finishes and shaping. The traditional Japanese saw *(nokogiri)* cuts the wood on the pull stroke, unlike western saws which cut on the push stroke. The saw, shown in Fig. 4, is known as *ryoba*, meaning dual edged. The rip edged is called *yoko noko-giri* and the crosscut called *tate-noko-gin.* The blades are very thin, which allow exact cutting. An additional saw of significance at Gekko-den pavilion is *osae-biki* which is used for flush cutting such as cutting pegs to a surface without damaging the woods surface.

The adze (Fig. 4b) is used to skim off the outer molecular surface of the wood which creates a barrier. It is well documented that the use of the adze gives a smooth finish, ensuring the longevity of the wood due to its superior resistance to moisture. Due to the adze being a traditional tool the timber has a finish matching other timbers, ensuring aesthetic and similar aging. Hand used adzes consisted of wooden curved handle and a steel blade. For optimal operation of the adze the handle is meant to be curved to fit perfectly the individual user's body, ensuring optimal angle (Suzuki 2012) (Fig. 5).

Diagnosis is the most important phase in the conservation of timber structures. Determining the condition of the structure and its components is essential in the process. Perhaps more importantly there is increasing difficulty associated with obtaining materials necessary for wooden preservation throughout Japan, in particular dimensions of large diameter and of sufficient length. In 2006 the Government established an initiative called "Forests for Heritage" with the primary aim of securing the necessary materials for preservation. One of the underlying principles

Fig. 5 (**a**, **b**) Wooden members of larger dimensions need minimal replacement. An Adze is used to seal the surface of the wood, ensuring resistance to moisture penetration and absorption (Photographs by author)

Table 1 Ten identified material types (Courtesy of ACA, Agency for Cultural Affairs)

1.	Cypress
2.	Red pine
3.	Cedar
4.	Sawara (cypress)
5.	Cypress bark
6.	Thatch
7.	Ramie shell
8.	Lacquer
9.	Rush grass
10.	Shichito rush grass

for the creation of Forests for Heritage is the securing of the necessary organic materials necessary in the preservation of historic buildings across Japan. The raising of the public awareness associated with the preservation of historic wooden structures throughout Japan aids in securing the materials necessary for the preservation process and additionally the crucial Intangible technical skills associated.

Maintaining cypress bark roofing of designated national treasures, or important cultural assets, requires over 157 tons of cypress bark annually, equivalent to the bark of 42,000 trees, furthermore, the trees must be at least 80 years old before the bark can be harvested. In total, 30 areas within 19 prefectures, have been designated as Forests for Heritage. Ten material types have been identified necessary of securing for the preservation of Japanese Heritage structures (Table 1, Yamato 2012).

Newly selected areas for Forests for Heritage, designated on the 22nd April 2010 include: (Courtesy of Yamato, ACA Agency for Cultural Affairs).

Material	Location in Japan
Thatch	Ishinomaki city, Miyagi Prefecture
Ramie shell	Kanuma city, Tochigi Prefecture
Hinoki Cedar	Hadano city, Kanagawa Prefecture
Cypress Bark	Koshu city, Yamanashi Prefecture
Hinoki Cedar	Kameyama City, Mie Prefecture
Cedar, Hinoki	Chizu-cho, Tottori Prefecture
Rush grass	Fukuyama city, Hiroshima Prefecture
Rush grass	Yatsushiro city, Hikawa-cho Kumamoto Prefecture Shichito Rush Grass Kunisaki City, Oita Prefecture

Gekkoden as a case study for the process of preservation across Japanese sites provides opportunities to study the actual methods employed during the overall process. The practicalities of the dismantlement are seen from the categorizing and detailed inspection of singular wooden members. Traditional methods and tools employed by carpenters such as the *nokogiri* and adze which is also applied on other wooden preservation sites, such as sites in Norway. The complexities are soon identified when discussing with carpenters the re-working of very old original wood, its brittleness and its union with new wood of similar quality, such as Japanese Hinoki. The replacement of the tile roofing with original construction of Cypress barking again highlighted the complexities of traditional roofing methods. Cypress bark roofing and bark harvesting are recognized as being important certified techniques and are protected by Japanese Law. Individuals are recognized as holders of the techniques and asked to transfer their knowledge and transmit to subsequent generations (Fig. 6).

Understanding of wooden preservation of important cultural properties in Japan is incomplete without at least a minimal look at the intangible process and the training of practitioners. Training of carpenters and specialists is given great importance and carefully administered throughout Japan.

2 Training

2.1 Agencies Involved

In 1968 the Council for the Protection of Cultural Properties was established. The Agency for Cultural Affairs (ACA) was established and comes under the governmental umbrella of the Minister of Education, Culture and Sports, Science and Technology (MEXT). The ACA has three main tasks:

Fig. 6 (**a-d**) Cypress bark roof installation at Gekkoden pavilion. Hiwada contractors, specialised in cypress bark roofing, work in a team of four to five, commencing with the layering from the base of the roof line moving towards the top. Singular cypress strips are secured with small galvanised steel nails (*photographs* by author)

- Promotion and dissemination of culture
- Execution of administrative affairs of the state concerning religion
- The preservation and utilization of cultural properties

In the Cultural Properties Department, there is a sub-department called "Architecture and Other Structures Division". This Department, according to the Law for the Protection of Cultural Properties, manages the preservation of buildings (Important Cultural Properties) and designated districts (Important Preservation Districts for Groups of Historic Buildings).

The Architecture and Other Structures Division is also in charge of the preparation of proposals for new designations. The Investigative Committee of Specialists gives advice on the designation of Important Cultural Properties or National Treasures, the repair and proposals for return to an earlier design state, usually of original design concept, of cultural properties, and the recognition of holders of designated traditional conservation techniques. The council is comprised of learned individuals who have extensive knowledge of heritage architecture.

2.2 Protection of Traditional Techniques

A significant legal date, as it pertains to the recognition and protection of architectural cultural properties and associated intangible knowledge and skills, is 1975. Amendments, three of importance, were:

- expansion of the system for Folk Cultural Properties (former 1954 amendment to the 1950 enactment)
- establishment of system for designation of important Tangible Folk Cultural Properties and Important Intangible Folk Cultural Properties
- establishment of system for protection of Conservation Techniques for Cultural Properties

The 1975 legal amendments enabled the national government to designate traditional techniques or crafts which are essential for the protection of cultural properties in any field, and officially recognise the possessors or practitioners of those techniques, either individual persons or preservation organizations. The introduction of selected conservation techniques ensures the traditional techniques associated with the preservation of cultural properties. The Protection of Conservation Techniques for Cultural Properties is an important step in acknowledging the skills and techniques associated with preservation as being an essential part of preservation (Park 2003).

The protection of traditional techniques as they relate to architectural preservation consist of; architectural conservation work management, wood carpentry, architectural geometric proportioning, architectural painting and coloration, cypress-bark and wood roof shingling, miscanthus thatching, and the production of clay roof tiles. Among these protected techniques, conservation management holds the highest position in the conservation field and this role includes responsibility for such tasks as investigation design, supervision, documentation, and the publishing of reports (Table 3).

As at September 2013 4,468 structures are designated as National Treasure and Important Cultural Properties. Shinto shrines and Buddhist temples are Japanese religious structures and account for about half of the designated properties (Watanabe 2013).

2.3 Transmission of Knowledge and Skills Historically

Historically the training, essentially the transmission of knowledge, was conducted separately within each cultural group and the methods of transference of knowledge were apprenticeship and live-in discipline. This historic system, dating back hundreds of years, started to decline after the Meiji era (1868–1912) and neared collapse post World War II. Industrialisation similarly played a significant role in the transfer of knowledge and techniques association with historical wooden

Table 2 Certified techniques held by individuals (Courtesy of Yamato ACA, Agency for Cultural Affairs)

Certified techniques held by individuals
Stereotomy (modern stereotomy) wooden construction
Tiled roof (original tile)
Cypress bark harvesting Cypress bark roofing Persimmon roof thatched
Plaster (painted plaster) joinery production casting production
Gold printed paper manufacture plaster (Kyoto traditional wall) metal joinery blacksmith tatami production
Stone tablet roof
Certified techniques owned by associations
Monuments repair; The Japanese Association for Conservation of Architectural Monuments *Monuments woodwork;* as above, Traditional Japanese Architecture Technology Preservation Society
Coloured monuments; Nikko Cultural Assets Association for the Preservation of Shrines and Temples
Tiled roof (original tile); Preservation Society of Japanese Traditional Tile Technology
Bark roof, persimmon roof, thatched roof; Company National Preservation Society of Shrines and Temples Roofing Technical Work
Plasterer (Japanese wall); National Cultural Heritage Preservation Association of wall technologies
Joinery manufacture; National Preservation Society of Joinery techniques
Monuments decoration; Japan Association for Historical Art and Architecture
Cultural Heritage Preservation Association of Tatami
Cultural heritage preservation association of stone walls techniques

preservation. Decline in rural population occurred as youth moved in large numbers to the cities of Osaka and Tokyo. One of the reasons behind such significant social changes was industrialisation (experienced world-wide). Industrialisation brought about significant differences between modern and traditional construction methods and materials. In Japan the introduction of building techniques and materials utilising brick, stone, steel and ferro-concrete, was a significant contributor to the shift in traditional skills and the associated losses attached to traditional wooded structures. Moreover, during the Second World War, fire was one of the foremost causes of building loss. Post war saw extensive rebuilding in a bid to make cities more resilient to the threats of fire and earthquakes and the use of wood was prohibited by law. If a traditional construction was to be built, special permission had to be obtained, which was still the case until 1986.

2.4 Transfer of Knowledge Today

Modern day governmental institutions were created and have taken over of the role of training. In 1971, the Japanese Association for the Conservation of Architectural Monuments (JACAM) was established under the guidance of the Agency for Cultural Affairs. JACAM has two main purposes; maintain the necessary number of architect conservators, and to employ new people each year and train accordingly. JACAM organises annual training courses for beginning and middle career conservators and study meetings for chief conservators and supervisors.

Training courses for architectural conservation work management are conducted over three levels (Inaba 1986); Junior level course totaling 600 h bi-annually, Advanced level course for mid-level managers, 2 days annually; Advanced level course for senior level managers, 1 day annually. Training courses in wood carpentry are similarly provided annually with 50 h training per year, over 2 years. Apart part from the knowledge gained during training, networks and relationships are formed and provide additional support and information after the training courses.

JACAM is also in charge of the investigation and research involved in dismantling architectural monuments, associated historical techniques. It provides advice for construction based on traditional techniques and is responsible also for the preparation of records such as drawings and photographs and the writing and compiling of reports of preservation projects.

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Anthropology of Design: How Traditional Korean Architecture Expands the Terms of Conservation, Collaboration, and Sustainable Management

Pablo N. Barrera and Peter E. Bartholomew

Abstract This project examines South Korean preservation practices applied to *hanok*: vernacular wooden structures built during the Joseon (Chosŏn) Dynasty (1392–1910) through the first half of the twentieth Century. The analysis will evaluate preservation policies, practices and methodologies as products of relationships between heritage management institutions, communities inhabiting architectural heritage sites, vested interests' land development projects, varying levels of awareness of heritage building values, and the understudied features of *hanok* architecture. The project illustrates the analytical and evaluative issues with case studies that reveal architectural design driven by sophisticated, yet under-stated aesthetics, interwoven with multi-disciplinary intellectual and multi-faceted scientific factors to an extent unique in East Asian architecture. The preservation zones selected to further illustrate this project offer unique case studies of architecture intrinsically tied to people in ways that are distinct in the cache of world heritage sites. This research expands on institutional definitions regarding proper preservation methods or policy by reintroducing traditional techniques that have evolved over centuries for maintaining the structure: technologies largely neglected in current preservation policies and procedures.

1 The State of Cultural Heritage Management

Hanok, one of the few remaining examples of a uniquely Korean style of architecture developed during the pre-modern period, has been selected by the South Korean government as one of several traditional elements to embody Korean cultural identity. *Hanok*-related projects have received notable, though narrowly

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targeted funding from municipal governments (e.g. for "Bukchon" in Seoul: 84 million USD) and corporate grant programs (Samsung Foundation for Arts and Culture) since 2002 (Bukchon Traditional Culture Center (BTCC) 2009). Designated *hanok* preservation areas outside of Seoul, such as the villages of Hahoe and Yangdong, as well as individual buildings nation-wide of deemed historical value, also receive financial support from the 문화재청 (Cultural Heritage Administration, National Government) and provincial/regional government agencies.

Other support for the study and preservation of *hanok* is illustrated by Seoul National University sponsored *hanok* projects in 2008, which provided 10,000 USD in grants, and the National Trust of Korea's first overseas *hanok* exhibit that travelled to several countries in the fall of that year. In December 2008, the Seoul Metropolitan Government issued the *Hanok Declaration* to expand preservation sites, increasing its preservation budget to 370 million USD for the next 10 years (Seoul Metropolitan Government (SMG) 2008). In January 2009, the Presidential Council on National Branding was officially launched, highlighting *hanok* preservation efforts in relation to tourism (Markessinis 2009). Concurrently in Seoul, however, *hanok* are continually being demolished by their owners as part of city development programs that favor construction of multi-stories concrete structures. Clearly there is a "disconnect" between these *hanok* preservation policies and the realities of on-going disappearance of the few remaining *hanok* neighborhoods.

While this investment in cultural heritage, preservation, and international publicity is admirable, there has been little academic research about *hanok's* cultural provenance. Due to the effects of the Japanese colonization (1910–1945), the Korean War, and economic development thereafter, most *hanok* nation-wide have been destroyed, and little scholarship has been thoroughly carried out (Palais 1995). Debate continues among preservationists, scholars, and government officials on how to preserve *hanok* and on how they relate to Korean cultural heritage. This dichotomy also will be addressed.

1.1 Preservation Sites

Hahoe Hanok Village, and Bukchon Hanok Village feature as contrasting case studies of intervention. Preservation committees have praised both sites, but an evaluation of preservation performance in these two locations will demonstrate how Bukchon's inability to maintain satisfactory levels of preservation speaks to improper policy, while Hahoe stands out as a unique success.

In the Gahoe-dong, Bukchon area at the heart of historic Seoul, *hanok* from the late Joseon Dynasty (1392–1910) through the Japanese "Annexation" period (1910–1945) fell under the auspices of an officially protected zone (Fig. 1). Recently, UNESCO recognized this "preservation zone" for their efforts at preservation and for raising awareness of *hanok* as cultural heritage. However, much of the original community that imbued these structures and preserved them with understanding of their forms, traditional use and, thus, the deep meaning behind

Fig. 1 Bukchon Hanok preservation zone in Seoul

Fig. 2 Elevated view of Hahoe Hanok village

functional design elements, have since moved on, and been replaced by wealthy Seoul residents or foreigners making second homes. Furthermore, Bukchon has also been criticized for the extent of massive renovations, total demolitions, and new constructions that have occurred despite claims of careful and accurate preservation (Kwon 2010).

In Andong, Korea, Hahoe Village remains a uniquely preserved community that not only has retained its traditional architecture, but also possesses meticulously documented records about their village and continues to practice the customs and rituals affiliated with these vernacular structures from as far back as the fourteenth Century (Fig. 2). The degree of preservation is such that Hahoe was designated a World Heritage Site by UNESCO in 2010 for both tangible and intangible heritage (UNESCO 2010).

The Seoul Municipal Government controls Bukchon's *hanok* preservation planning and management. Their preservation methodology has resulted in consecutive failures leading to demolitions of original *hanok* with new ersatz construction or, at best, complete evisceration of the structures' original materials, components, and forms, resulting in total remodeling of all aspects of the buildings, thus, negating all cultural heritage value of the structures. Hahoe, on the other hand, conducted preservation of meaningful, historic sites with minimal government intervention. In addition, cases in which "standard" preservation practices were disobeyed, the community tactics at Hahoe proved to be superior to official methods.

1.2 Top Down Approach Versus Bottom up Approach

This project research argues that the local Hahoe village community's direct involvement in the preservation of the village's architecture has been instrumental in achieving such a high state of conservation. Hahoe's systems of preservation evolved in tandem with the techno-static aspects of timber-frame architecture as a response to environmental conditions specific to the Korean peninsula. Equally important to the technical execution methodology for preservation in Hahoe is the maintenance of original building forms. These forms are well preserved through periodic preservation programs due primarily to the local community's understanding and appreciation of the cultural values and, thus, the criticality to maintain them. In Bukchon, these systems have been ignored or undervalued in conservation practices, along with an almost complete disregard within policy for the original structures' design, layout and unique components. As a result, the heritage values of the Bukchon *hanok* are irretrievably damaged or completely obliterated.

2 Hanok Definitions Versus Preservation Strategies

Hahoe stands in contrast to Bukchon as a highly organized community that has tenaciously passed down knowledge of the significance of their *hanok* across generations (Slote 2007). Hahoe provides excellent case-study examples of centuries-old systems of maintenance and preservation of the structures' original forms of layout, design, and traditional interior detailed refinements. These strategies can be divided into two categories: techno-static (materiality and structural integrity) and anthropogenic (environmental or cultural design interventions). Through a cross-disciplinary approach combining architectural history, engineering, and community anthropology, these categories will be examined, demonstrating how preservation was addressed in the pre-modern period into the first half of the twentieth Century. Careful study of these systems will make clear the preservation potential of these factors when applied to contemporary efforts at heritage asset management.

2.1 Hanok Techno-static Features

Residences architecturally categorized as *hanok* (韓屋,한옥) refers to a vernacular style of home built prior to and during the Joseon Dynasty and continually through the first half of the twentieth Century (Fig. 3). Structurally, *hanok* are built on a raised platform encompassed by granite stonework upon which are placed the stone foundations for vertical pillars bearing the heavy timber frame. The walls between pillars are made of wattle-mud/clay coated with a type of plaster, latticed and papered wooden doors/windows, and either thatched or ceramic tiled roofs (Fig. 4).[1] While the fundamental timber-frame design concept was based on the Chinese-derived design of parallel-weight distribution (Lee and Peter 1997), *hanok* (and all other Korean wooden buildings) are differentiated by technological innovations and aesthetics that evolved during the past two millennia to create the sophisticated, multi-dimensional forms unique to Korea.

Hanok spatial arrangements are built based upon a modular system of units/bays. These bays are combined to make up quarters, such as the *anbang* (안방), which are the inner/family quarters, the *sarangbang* (舍廊, 사랑방)[2] known as the "male quarters" where guests would be received, and the *haengnangchae* (行廊, 행랑채) that served as the servants' quarters and housing for visiting guests and travelers.[3] Upper-class residences would usually have the ancestral shrine (memorial hall) stand as a separate building on the residential grounds, but other quarters, such as warehouses, granaries and libraries, could also be built on site depending on preference (Choi et al. 2007).

One of the most significantly unique design aspect of traditional Korean architecture is a floor heating system known as *ondol* (温突, 온돌). All rooms used for sleeping in cold weather are equipped with *ondol*, which incorporates horizontal, wood-fired stone channels/flues capped with flat heat-absorbing stones that heat the entire floor area, providing warmth in the winter and efficient under-floor ventilation to avoid accumulation of moisture in the humid summer months. Wooden floored rooms called *maru* (마루) are used as living spaces in warm weather, and are designed to facilitate air flow underneath the wooden floor in order to keep cool while controlling moisture. This relationship between heat and airflow factors into space usage; utility and aesthetic preference determine spatial organization. Heat

1 This initial definition of hanok and the subsequent discussion of its various architectural and structural elements is knowledge that the authors compiled through on-site field surveys and interviews in South Korea.

2 The term 사랑 (舍廊) actually refers to the management of activities. Since men were most commonly in charge of households, the term "male quarters" has remained popular in defining the space. However, one must not discount the possibility of women using the space for management of affairs as well. For more information on the role of women and property management, please consult: Martina Deuchler 1992. The Confucian Transformation of Korea: A Study of Society and Ideology. Cambridge: Council on East Asian Studies, Harvard University.

3 Variations depend on the "class" of the resident family: an important aspect not fully understood is the use of rooms (i.e. divided by "person" rather than by function).

Fig. 3 Yangjindang, in Hahoe (*Source* http://www.orientalarchitecture.com/koreasouth/hahoe/yangjindang.php)

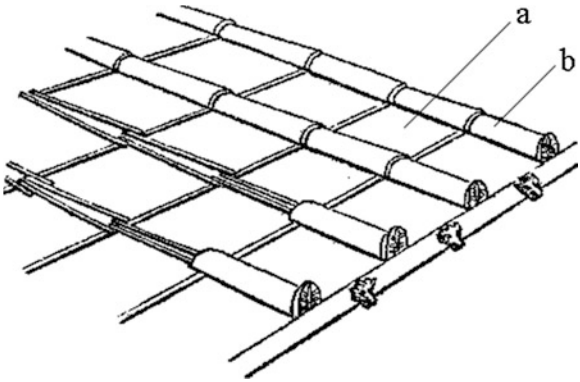

Fig. 4 Imbrex (**a**) and tegula (**b**) components of a tile roof (Reproduced from http://penelope.uchicago.edu/Thayer/E/Roman/Texts/secondary/SMIGRA*/Tegula.html)

absorption in the *ondol* floor and subsequent convection flow within the rooms was incredibly sophisticated, and best demonstrates the scientific value and uniqueness of "pre-modern" technologies in Korean architecture that will be discussed.

2.2 Preservation Technologies

Design elements and construction techniques address usage and preservation concerns that have evolved during at least the past 600 years. The structures were designed to combat environmental stresses caused by wind, precipitation, humidity, and extreme temperature ranges common to the Korean peninsula. Also, *Hanok's* significance regarding lineage and cultural activity further motivated maintenance. The goal was to have a structure that could last several generations as the locus of cultural and genealogical relevance. Familiarity with these subtle design innovations and understanding of their cultural /historical significance could vastly improve preservation methods today.

2.2.1 Pre-construction Preventative Measures

Site selection was the essential first step to assuring a structures' viability and longevity; sites were selected following extensive site surveys for soil moisture, suitability for foundation construction, watershed during heavy rains, prevailing winds, and both the short and long term weather patterns. This process of site selection was known as *poongsu* (風水,풍수), whose complex preservation merits will be discussed later at length (Sect. 2.3.1).

Once a site was deemed suitable, the entire timber-frame structure was set atop a stone-encompassed (retaining-wall type) platform. Foundations were originally composed of pounded soil mixed with salt to prevent uncontrolled vegetation near the structure as well as unwanted insects. Built-up substructures of small-to-larger rough stone were assembled, finally topped with cut, dressed foundation stones for horizontal pillars. Korean buildings' posts/columns were always set on square foundation stones raised significantly above the floor of the overall platform so that moisture in the soil would not egress into the structural wood components. For monumental structures, the lower structural beams themselves were usually "brined" in ocean water so that the salt could prolong the longevity of wooden elements. As a final assurance for protection against rot and insects, all posts/columns benefitted from the practice of carving out a shallow area in the bottom of each post (where the stone and wood meet), and packing it with salt.

Currently, Bukchon preservation methods do not consider the beneficial use of salt, nor otherwise provide alternative remedial measures to properly account for these "problem areas" of timber-frame architecture highlighted by the above-described traditional methods. A closer examination of traditional methods alerts us to inherent issues that could be remedied with modern materials or chemicals able to perform the same functions. These issues are not yet featured in preservation methodologies for heritage structures or in designs and methodologies for new construction of traditional-styled *hanok*. Application of such modern methodologies should be considered only when they do not damage or remove the originality of the structure and, thus, its cultural value.

2.2.2 Design Features

The roof deserves special attention, as it is the most exposed and abused line of defense for protecting the integrity of a *hanok,* and, aesthetically, the most immediately salient. While the novelty of a thatched roof may be appealing to some, the far superior design of a tiled roof merits better study and care. Basically, the *hanok* roof is composed of ceramic tiles arranged in the *imbrex* and *tegula* style (Fig. 4). The tiles sit atop a layer of low-grade clay that holds the tiles in place, facilitates the aesthetic "moulding" of the roof's convex and end-to-end curve depths, and insulates the structure against both the cold and the heat.

The overhanging roof eaves were designed to ensure that rain water always falls outside of the stone platform such that there would be no splatter on to any wooden components of the structure. Angle, height, and curvature are critical factors regarding snow accumulation and optimal watershed. Design of the comparative dimensional proportions of the roof is key when determining all aspects of the rooflines, especially the length of roof extension outside the walls and angle of the overhang. These elements also determine the overall footprint height, length and width of the structure itself and, thus, are the key to the building's overall aesthetic balance and harmony.

Currently, the wooden structural components of Bukchon *hanok* suffer from overexposure to rainfall due to diminished overhang and inadequate angle coverage: the result of contemporary renovations aimed at making structures wider and taller, but unable to increase overhang due to space restrictions and property lines. While the damage is somewhat mitigated by the addition of metal rain gutters and downspouts, without knowledge of the multi-interdependent, integral relationship between roof and bay dimensions, and the multi-faceted traditional design execution measures impacted by these issues, wood becomes more vulnerable to elements and deteriorates far faster than expected, increasing the frequency of intervention. These traditional roof design elements of the *hanok*, again, are both sophisticated and unique and should feature in policy restrictions regarding the extent of "renovation" allowable.

2.2.3 Ondol

Ondol (温突)[4] are an exclusively Korean floor heating system. Archeological remains of *ondol* floor systems have been found dating back more then 1,800 years. As mentioned previously (Sect. 2.1) *ondol* technology best demonstrates the scientific architectural innovations responsible for the longevity of *hanok* prior to less-successful modern interventions.

The *ondol* design takes advantage of thermodynamic flow vortexes so that heat flows under the floor of each room horizontally with nuanced control. Knowledge of the heat absorption/retention properties of clay and stone ensure even heat distribution. Arranged channels under the floor are separated by a structure of stone

[4] An alternate way to write ondol is 温炕, where the second character (炕: literally "heatable brick bed") refers to the materials used. "突" (dash, move forward quickly, suddenly, abruptly) refers to the system of flues utilized and is pronounced dol 돌, the indigenous Korean word for stone or rock. The dissonance in definition and pronunciation of either character accounts for the creation of alternate spellings, but "突" captures the complex functions of the system.

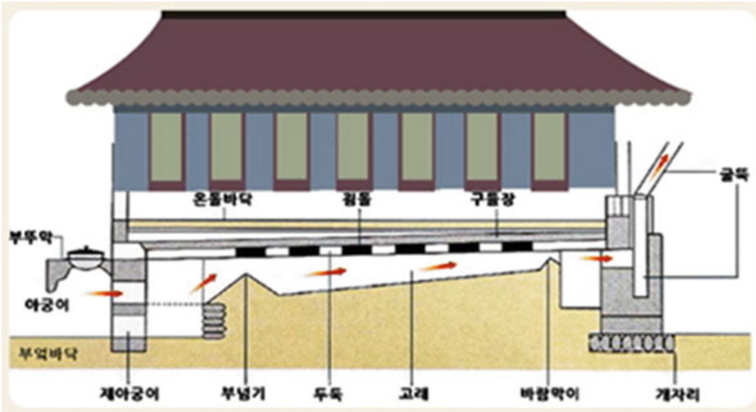

Fig. 5 Ondol system, *side view*

and high viscosity clay. Large, flat stones cap these channels, are covered with clay to form the floor surface, and the final floor covering is a strong paper oiled or lacquered to resist heating and protect the integrity of the clay layer integral to the system. A small, wood burning fireplace at one end of the room provided the heat source; heated air is drawn through the channels leading from the fireplace, exiting through a chimney structure set a distance from the wall at the opposite end of the room (Figs. 5 and 6). The further out from the building that the chimney was placed, the more even the velocity of the heated air flowed throughout channels, ensuring uniform heat across the entire floor surface. The mass of combined clay and stone in this subfloor *ondol* system absorbs and retains the heat long after the fire has extinguished. The fireplace could double as cooking heat, thus, impacting kitchen design/placement, but *ondol* technology went beyond the residential, such as making cold-weather greenhouses possible (Sim 2007, p. 17).

Ondol's most ingenious, yet overlooked use, was during humid summer months: *ondol* served to draw out moisture during the heavy rainy season, preserving the wood of the structure. Normally, the wooden-floored rooms of a *hanok* functioned as cooler rooms with increased ventilation options by design (doors, windows, etc.). By extending the stone channels of an *ondol* under the wooden floors as well, scheduled firing of the *ondol* systems could be used to dry the timber throughout the entire structure when the wood was most vulnerable. Additionally, small openings near the base of columns of the wooden floor rooms helped to both ventilate and dry out these extremely vulnerable portions of the structure. Clearly, the bases of columns were the most exposed part of the timber structure. More care was given to these locations, such as salt in between the post and the stone base, as well as increased heat exposure for preserving the wood, but, also, the soot from

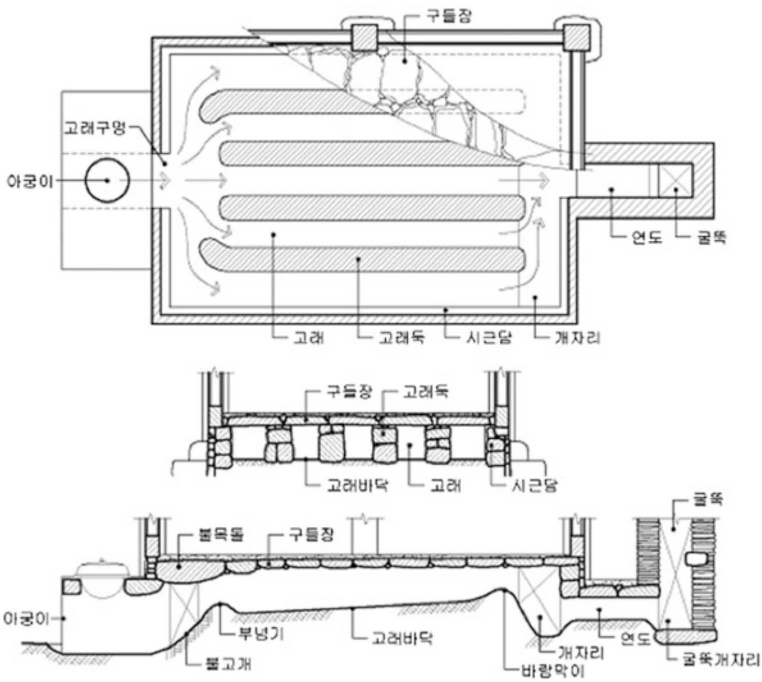

Fig. 6 Ondol system, *top view* (Images Reproduced from: http://www.dprk-tour.com/sub03/02.php)

smoke seeping out from the sides of the *ondol* would fill in any cracks or imperfections in the wood, increasing its lifespan as a usable structural component.

Hahoe continues this practice, and surrounding *hanok* in the area follow suit. Unfortunately, the *ondol* is one of the first elements torn out during "renovations" in places like Bukchon, destroying one of the most scientifically important and unique cultural values of the original *hanok*. A concrete slab with a pipe system of heated water usually replaces the mass of clay and stone: the problem with this system is cracked pipes during freezing weather and water damage to vulnerable wooden elements. It is understandable that fire poses a risk of damage, but certainly the full benefits of the *ondol* system can be safely replicated.

2.3 Preservation Technologies: Anthropogenic

The original design of traditional *hanok* addressed major issues of exposure to environmental elements, but thereafter the human component served to micromanage the endlessly variable degrees in which those elements affected wooden structures. Seasonal conditions and the control of light, ventilation, and heating gave birth to careful study and recording of how these phenomena related to space, place, and architecture, resulting in strategies designed to keep the structure intact over generations. When reexamined as an anthropogenic activity, new, minimally invasive preservation methodologies emerge.

2.3.1 Geomancy

Korean geomancy, *poongsu* (Chinese: *feng shui,* 風水) illustrates how the built environment is carefully selected following detailed evaluation of geological and climactic features in a scientifically rigorous way (Introduced: Sect. 2.2.1). Pragmatic responses in architectural design to wind, water, and soil conditions evolved over time, relying on the data results of geomantic evaluation of each site. These practices are remarkably similar in form and general content to modern site survey procedures for construction projects. Over time, relationships between climactic conditions and topographical features, such as mountains, streams, and cardinal directions, were discerned, establishing the basis of all siting mechanisms (Fig. 7). Codified, yet flexible templates for building design, location, elevation and axis were developed. These diagrams are what remain, but fail to convey relevance in our conception of *poongsu*.

If *poongsu* is viewed merely along the metaphysical elements recognized in historic texts, one would conclude that design features were motivated by auspicious association to non-physically recordable "energies" or "spiritual" elements. This historic analysis of the texts and their associated decorative elements surely speak to a philosophy that, when studied deeply, augments our understanding of intellectual culture and history. However, when archaeological evidence is viewed through the lens of landscape archeology and cultural anthropology, the study of traditional buildings from the pre-modern period indicate that design was just as much driven by scientific analysis of the site's climactic specifics. The degree of sophistication and the amount of information required to properly perform *poongsu* went beyond a lay understanding, and eventually became a career with its own set of examinations and competing schools aimed at certifying qualified practitioners during the Joseon (Chosŏn) Dynasty (Yoon 2006). Properly executed *poongsu* was crucial for both construction and conservation, and, therefore, merits serious study aimed at preservation.

2.3.2 Natural Systems

Poongsu was crucial for determining the location for new, stable construction projects, but the data it produced was used for more than the fundamental layout design of foundations and architectural components. *Poongsu* evaluations went beyond land surveys of the site by incorporating terrain features with the alignment and shape of the *hanok* structure.

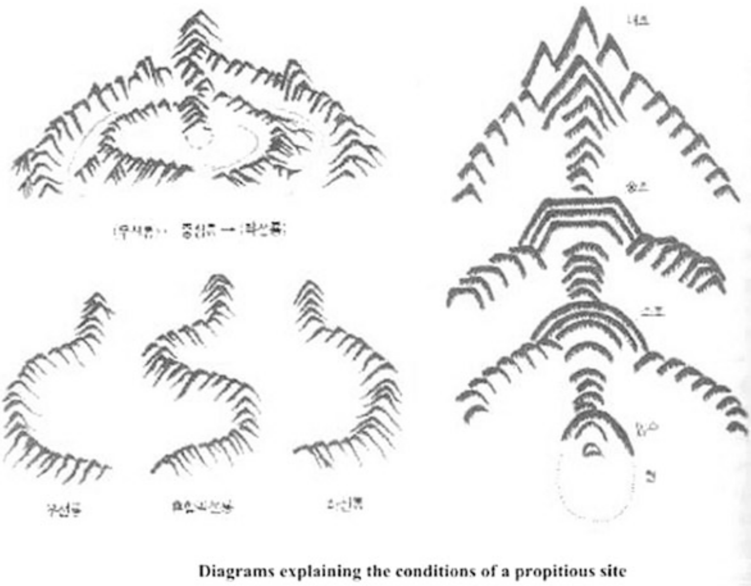

Fig. 7 *Poongsu* diagrams (Reproduced from the Encyclopedia of Korean Culture, online)

The typical feature of most *hanok* sites is that they are positioned to be slightly elevated at the foot of a hill with other hills or mountains behind them, facing a body of running water some distance away. Cool air coming off of streams guided by the contours of the terrain kept moisture from stagnating in the summer. The same terrain served to block cold winds from the north during the winter. In some cases, gravel used in the courtyard created a heat-sink in the summer months. The roof's shape worked together with posterior elevation and the heat-sink formed by sun-warmed stones to generate airflow. Strategically placed windows in the structure's rear worked with open doors in front to vacuum air through the structure (Figs. 8 and 9). Vegetation present on the hill/incline behind a *hanok* worked as a "swamp-cooler" using the natural moisture of vegetation to dramatically drop the air temperature as it rushed through it into the *hanok*.

While not all *hanok* can enjoy such ideal conditions, the very concept of design and terrain working together to promote improved conditions for wooden architecture is an important and valuable area of study that can be woven into policy aimed at the preservation of entire communities of structures. Brush growth and wind patterns aided in strategically vacuuming air through and around the *hanok*, driving out moisture, cooling the space, and mitigating the impact of precipitation on building wooden members during all predictable weather conditions. Currently, renovations in Bukchon alter the height, width, and pitch of roofs, working counterproductively with already established airflow patterns beneficial for the control of ventilation and moisture in the entire community.

Fig. 8 Interior of *Hanjeongdang* showing papered, clay floor with the doors/windows opened

Fig. 9 Interior of *Hanjeongdang* showing papered, clay floor with the doors/windows closed

3 Community Anthropology Methods Aimed at Preservation Efficacy

There is a school of thought among some administrators of heritage buildings that heritage sites should be quarantined of humans, or at the very least, human engagement with historic sites should be severely restricted or controlled. This has been an increasingly prevalent policy in Korea. However, the very nature of timber-frame architecture design necessitates continual human interaction for effective maintenance. The steady presence of people ensures that roof leaks are immediately identified, drafts sealed, and the first indications of any rot attended to before serious damage occurs. The *ondol* floors must be fired periodically to keep the structure free of accumulated moisture.

Including a human component challenges UNESCO-defined preservation policy to think creatively about enforcement and education. The human component is often neglected in conservation programs due to the risk involved in incorporating non-professionals into preservation practices. It is a problem, but also, an opportunity to reexamine architectural theory and preservation techniques in the face of ever expanding and increasingly nuanced definitions for "heritage site."

3.1 Education Versus Rhetoric

The history of preservation innovations tailored to the structures has been passed over for more familiar techniques applicable to modern building methodologies. This neglect is owed to the fact that little research has taken place prior to implementing preservation techniques, Furthermore, local strategies appear novel and lack the formal auspices of "expert" opinion. In many cases, the individuals in charge of heritage building maintenance, preservation and restoration simply are not aware of the important design factors of the original structures, or, if they are aware, feel that these are not of value and should be defaced in favor of total make-over conversion of the structure into a new form.

In many cases, preservation methodology does not include maintenance of the aforementioned features, opting for "renovations" that destroy entire traditional systems. Bukchon best exemplifies the consequences of misguided preservation techniques: *hanok* that recently underwent massive reconstructions or were totally newly built do not adhere to the typical design due to four major factors:

(1) The zone is in the capital: a high-density urban setting vying for the space occupied by *hanok*.[5]
(2) Despite being built by Koreans, the *hanok* were built during Japanese occupation, placing them at odds with national sentiment.[6] A misguided understanding of their relationship to history encouraged the disparaging attitude towards the structures begun by Japanese denigration.
(3) Since the 1960s Korea experienced an obsession with modernization as defined through industrialization, copying modern Western forms of concrete and steel construction to demonstrate "development." Traditional elements were associated with "backwardness." The misunderstanding or unawareness

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[5] Furthermore, this relationship between the center and the strong sense of regionalism during the majority of Korea's history is a recent exploration among academics, and has yet to be fully developed within scholarship.

[6] During this time the architecture may have been influenced by Japanese elements, but more importantly, the fascination and incorporation of Western elements begin to take on a decidedly Korean "flavor." Again, this period of architectural history is woefully understudied.

of the sophisticated aesthetic and "literati" elements inherently embodied in *hanok* design has led to renovations that destroy/obscure the features of *hanok,* or result in their demolition in favor of high-rise construction or low-rise apartments (Anderson 1991).[7]

(4) The dearth in serious architectural history research leaves government officials at a disadvantage in making applicable, appropriate policy regarding preservation. Also, lack of education generally in modern Korean society hinders the ability of communities invested in preserving *hanok* to effectively understand and articulate the values they see in their traditional homes (Knapp and Ashmore 1999, pp. 17–22).[8]

The result has been a dramatic decrease in *hanok* structures that still have their original design, layout and materials in place. The dominant, yet unsuccessful, examples of "sustainable" preservation practice feature either drastic sacrifices to original features in favor of less problematic material, or complete demolition of the original structure to construct a new building with no heritage value whatsoever. For this reason, the preservation approach of Hahoe Village in terms of not just architecture, but art, aesthetics, philosophy, ritual practice, and social customs, provide crucial ground for firmer analysis of similar features found in sites like Bukchon.

4 Research Directions

Hanok are scientifically designed to combat environmental stresses caused by wind, moisture, and extreme temperature ranges. *Hanok's* role in cultural heritage engaged human agents; design evolved to facilitate maintenance. The above are but some examples of how the human component should be included in the preservation methodology.

Through surveys, we sought to consolidate the historical context of *hanok,* investigate the cultural value of *hanok* in relation to its historical legacy, and explore its re-appropriation through South Korean heritage management institutions. Similar architectural surveys are currently underway in other villages in South Korea and China, where residential complexes have survived. Projects are being undertaken in which locally preserved villages and structures feature prominently in conjunction with research,[9] pointing at more case studies that would serve

[7] The rhetoric surrounding the perception of hanok as irreparably "primitive," and the vested interests that benefit from such an attitude has thwarted both the study of hanok, its preservation, and intelligent development of adaptive reuse regarding hanok features.

[8] This is not the case for historic villages like Yangdong and Hahoe, however, it must be noted that the elder residents in Bukchon contrast with the current generation in terms of depth of knowledge and adherence to conservation principles inherent in the structures' original design.

[9] Please refer to Harvard University's Chinese Local History database: http://sites.fas.harvard.edu/~chnlocal/.

as a comparative base for conservation practices and techniques outside of standardized procedures. By recognizing these behaviors as preservation pedagogy, and formalizing these tactics through a hybrid syncretism with modern techniques, these methods can apply to lesser-known sites currently at risk of degradation, driving the state of architectural preservation in East Asia to unprecedented levels.[10]

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[10] The lack of Korean sources is the result of a paucity of research in Korean useful for the paper's aim. We have been unable to identify Korean sources that professionally deal with preservation/conservation of *hanok,* other than those works that touch on rebuilding or promoting new construction projects. There is a proposal and report from City Hall to the Korean UNESCO Committee advocating for the recognition of the Bukchon area as a preservation success, however, the document is not available to the public in its entirety; this paper addresses some of the contradictions that the proposal/report claims as they appear in piecemeal fashion in select news articles. For these reasons, we endeavored to write on the topic of "*hanok*" with an emphasis on how the study of these structures can augment knowledge useful for their conservation when the focus of research is directed away from agendas that privilege new construction, tourism, and/or branding, and, instead, concentrates on achieving an academic exploration of the structures.

Part IV
2D and 3D Digitization for Visual Presentation and Monitoring

Spherical Photogrammetry for Cultural Heritage Metric Documentation: A Critical Review

Gabriele Fangi

Abstract In addition to the well established standard photogrammetric techniques, another type of photogrammetry has been proposed by the Author, the so-called PSP (Panoramic Spherical Photogrammetry). This photogrammetric technique is particularly suitable for architectural surveys. Multi-image spherical panoramas are used which are partly overlapping digital images taken from the same point in order to obtain an all-round 360° cartographic representation of the sphere. There are many advantages: the speed of execution, the drastic reduction of traditional photogrammetric models, the completeness of the documentation, the FOV can be 360° wide, the absence of distortion, and most importantly the low-cost, thereby allowing a photogrammetric survey to be carried out which is, fast, complete, accurate and inexpensive. After a description of the principles of the PSP technique, a few examples are shown. Up to now some 500 projects have been run, ranging from the very initial phase of taking photographs, to the final rendered model. The procedure is very quick in the first phase while, on the contrary, it is time consuming in the orientation phase and above all in restitution, as it is still fully manual. Although only a few projects have been finished, this is precisely the rationale behind the technique: to build up an archive of oriented images (panoramas) which can be retrieved, observed, and used when required.

1 Introduction

A promising technique for architectural surveys is the so-called Spherical Photogrammetry, from now on referred to as PSP (Panoramic Spherical Photogrammetry). The details have already been thoroughly described by Fangi (2007, 2009, 2010), Cingolani and Fangi (2011), Fangi and Pierdicca (2012). Multi-image spherical

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panoramas are used which are the cartographic projection of a series of photographs taken from the same point over 360°, downloaded onto the computer and then assembled using any stitching software (Realviz Stitcher, PTgui, Autopano, etc.).

There are many advantages to this technique: the speed of taking shots, the completeness of the documentation, the width of the FOV (Field Of View) up to 360°, the absence of photographic distortion, which is estimated and corrected by the stitching software itself. The stitching technique for digital images was introduced for Apple computers in the 1990s by Shum and Szeliski (2000), with the aim to improve the poor (by that time) resolution of existing digital cameras.

However the use of the Spherical Photogrammetry technique is still limited owing to a lack of commercial products and distribution.

1.1 The Requirements of the Spherical Photogrammetry Technique

To enable as many potential users as possible to adopt this technique, in order to try to resolve the dramatic problem of Cultural Heritage and Architectural documentation, the main requirement that has to be met is a low-cost technique.

The equipment should cost less than $1,000–2,000. There is no need for expensive tools such as theodolites, total stations, satellite receivers. No signalization or monumentations is involved, as already recommended by the CIPA (the International Committee for the Documentation of Cultural Heritage) because of their temporary nature. The technique must be fast in the shot taking phase and must produce a complete documentation. The only tools required are the camera, the tripod, the spherical head, a longimeter, the computer, the stitching software and software for the orientation of spherical panoramas. All these specifications have been successfully met, as can be seen in Sect. 2.4.1, Table 1, except the easiness of use for non-expert operators.

1.2 Short Description of the Technique

The restitution of the surveyed object takes place by intersecting the projective straight lines coming from oriented panoramas. There are six parameters of orientation for a panorama: the three coordinates of the panorama center, and three

Table 1 Test on the accuracy of the adjustment

Sigma-naught (radiants)	$\alpha_x = \alpha_y = 0$	$\alpha_x \neq \alpha_y \neq 0$
89 control points	0.002384	0.001302
3 control points	0.002195	0.001250

an-gular directions, one of which, around the Z axis, is the horizontal bearing, or station constant. Two rotation angles around the horizontal X and Y axes must be estimated to correct the not perfect verticality of the Z axis (α_x and α_y). In order to facilitate orientation the two correction angles must be small and for this reason the suitable panoramas should be quasi-horizontal. The estimation of the two an-gular corrections must be carried out in two steps, first by setting them equal to 0, and subsequently, only when all the unknown points and parameters have been estimated, by computing the correction angles, leading to a meaningful improvement (see Table 1 in Sect. 2.4.1). Note that the stitching software can estimate and correct the camera lens distortion. The accuracy of the technique is typical of monoscopic photogrammetric systems of between 1/1000 and 1/5000 of the camera-object distance. Compared to traditional photogrammetry there is a drastic reduction in the photogrammetric images and models. The limits of the technique are, up to now, the absence of stereoscopy and the lack of automation in the orientation and plotting phases and the difficult orientation.

1.3 The Improvements Introduced

Some improvements have been introduced over time, and they are briefly described here: block bundle adjustment (with 4 or 6 parameters per panorama), double stations, geometric constraints, monoplotting, combined use of panoramas with non-metric cameras, photo-modeling, the combination with point clouds produced by the Structure from Motion algorithm.

1.3.1 Double-Taking Station Technique

Panoramas shot with short focal length lenses are easy to orient and have a strong geometry, but poor resolution. On the contrary, panoramas with telephoto lenses have greater resolution, a larger average scale, and provide excellent information, but they are difficult to orient and have very unstable geometry. Therefore, an attempt was made to merge the two types of panoramas to combine the advantages of both while at the same time eliminating their defects. Two different panoramas are taken from the same point, one with a wide angle and the other with a telephoto lenses. The coordinates of the projection center of the wide-angle pano are the same as those of the narrow lens panorama and they can be input in the adjustment. Orientation is carried out with the first type of panorama while restitution is performed with the second.

Fig. 1 Cagli, Italy, the façade of the city hall, the rectified photomosaic as a background of the line plot (*orange*), where many details are derived from monoplotting (restitution L. Piermattei)

1.3.2 Geometric Constraints

To obtain the orientation of a block of panoramas the minimum requirement is one fixed point, one direction, one distance to fix the scale of the model and at least one geometric constraint on the verticality or horizontality of a line.

1.3.3 Monoplotting

Due to the lack of stereoscopy, complicated details cannot be plotted. If the details lay on a plane or on a surface with a known geometry, it is possible to plot them by intersecting the projective rays coming from one panorama with the known surface (monoplotting) (Fig. 1).

1.3.4 In Combination with Non-metric Cameras

The joint orientation and plotting of spherical panoramas and non-metric photographs allows the potential of the technique to be improved. For example, in the restitution of internal domes, the image provided by spherical panoramas can be somewhat difficult. A better image is given by zenithal views that can also be the photo-mosaics obtained with the same photographs used for the spherical panorama: the control points needed for the orientation of the non-metric cameras are obtained from the panorama orientation and used as input for the orientation of non-metric cameras with Direct Linear Transformation.

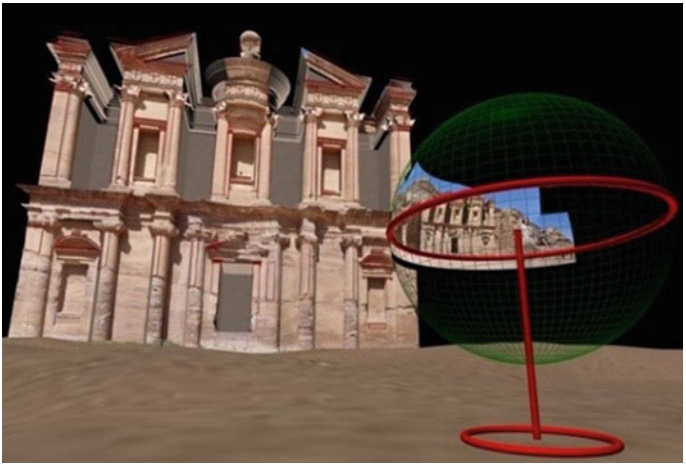

Fig. 2 Petra, Jordan, Ad-Deir—The orientated panoramas were projected over the rough model produced by PSP, enabling the editing

1.3.5 Photomodeling

The oriented panoramas are imported to a CAD environment (like 3D Studio). The known orientation parameters can be input so that the user can:

1. build a rough model
2. project the panorama over the rough model
3. edit, modify and improve the model until the best fit with the panorama projection is obtained (Fig. 2).

1.3.6 In Combination with Structure from Motion

As an alternative to photomodeling there is the possibility to produce point clouds using existing web-services like Photosynth by Microsoft. The user must first register and send the images and in return receives the point cloud, with an unknown scale and orientation. A better solution is to download a stand-alone software package like PMVS2 by Furukawa which can be used to orient the bulk of the photographs and produce the point cloud. The point cloud, with an unknown scale and orientation, can be rotated, translated and scaled over the wire-frame model produced using PSP by means of some common points. (See an example of this in Sect. 2.4 Notre Dame du Haut).

2 Some Examples of Projects

After some unsuccessful experiments using this survey technique, some satisfactory results have finally been obtained. At first, 6 years ago, the image coordinates were determined manually, written on paper and later transferred to the computer. When the method seemed to work, a professional software house was commissioned to create a program for data collection.

Up to now some 500 architectural emergencies have been documented. Unfortunately, the application of PSP for archeology has had little success: in almost all the surveys great difficulty was encountered with orientation.

Some of the attempts included a segment of the Great Wall of China in Badalin, the Manlio Bridge in Cagli, Italy and the Roman Baths in Vininacium (Bosnia). These difficulties are due to the lack of easily identifiable points in the different views, as a result of uneven surfaces. In the case of the Great Wall of China, an additional problem was the extremely difficult accessibility of the sites.

Nevertheless, there are some successful archaeological projects, such as the ancient Roman Theater of Sabratha and Leptis Magna, Libya, and in Bosra, Syria, although in these cases the objects being surveyed are more similar to architectural projects than to archaeological ones.

2.1 Elmina Castle, Ghana, the Block Adjustment with the Largest Number of Panoramas

A survey of Elmina castle in Ghana was carried out on behalf of Irvine California University. Elmina castle is the most noticeable of the many castles built, for trading purposes, by the Portuguese between the sixteenth and the eighteenth century along the coastline of Africa (Fig. 3).

The survey was carried out on June 5–6, 2011. A Canon 60D was used, equipped with 28 and 50 mm lenses, a tripod and a spherical head. For the distance measurements a Disto Leica distantiometer was adopted. In order to be able to depict any possible point of the castle from at least two panoramas more than 100

Fig. 3 Ghana, Elmina castle

Fig. 4 The solid model of the Castle (restitution by I. Pasqualini, S. Morgiani, S. Falasconi, M.P. Sparvieri)

panoramas were taken. The set of panoramas was subdivided into one main network and 4 sub-projects. The main network comprises the exterior traverse and the panoramas connecting the exterior traverse with the inner main courtyard. The restitution consists in the construction of the wire-frame of the model, including, points, lines, and primitives, such as arcs, circles, and so on. Using the wire-frame, the solid model was built (Fig. 4).

2.2 The Largest Project: The Vietnam Cham Towers

The Università Politecnica delle Marche, Ancona, Italy, is carrying out research on the Cham towers in Vietnam. The kingdom of Champa existed from the second to the seventeenth century A.D. and it was located near the coast in the southern part of the country.

The ancient Cham people had a highly developed culture, expressed in the architecture of the so-called towers, which were Buddhist temples (Fig. 5).

2.3 The Most Ambitious Project: The Bahia Project

The Università Politecnica delle Marche, Italy and UFBA, the Universidade Federal de Bahia, carried out a joint research project for the metric documentation of the Cultural Heritage of Bahia. Some examples of the quick metric documentation of Bahia CH are presented here.

The surveys were performed on two separate occasions in 2012. The aim was to build up an archive of historic houses, buildings, architectural emergencies, and churches (Figs. 6 and 7).

Fig. 5 Vietnam, Hoa Lai Tower (restitution by M. Ripanti, Veronica, Sara, Miranda)

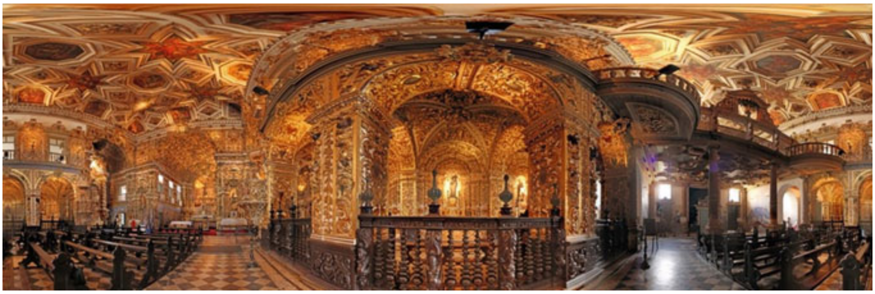

Fig. 6 Salvador do Bahia—Igreja de Sao Francisco, A 360° wide panorama of the interior

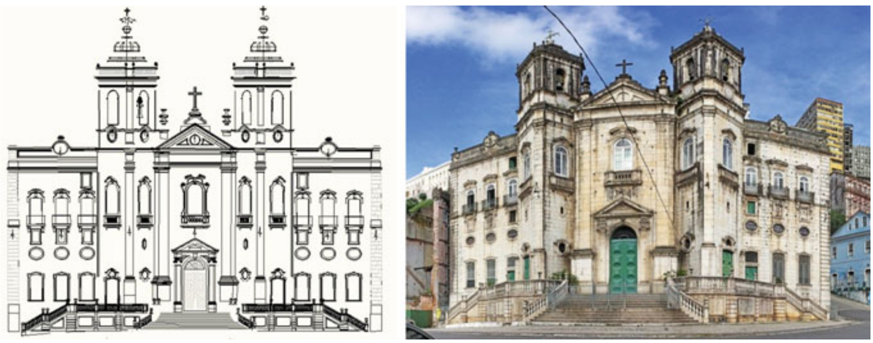

Fig. 7 Salvador do Bahia, Igreja de Nossa Senhora da Conceição da Praia. the restitution of the façade (*left*), the central of three panoramas (*right*)

Fig. 8 Notre Dame du Haut, the rendered model

2.4 Notre Dame du Haut, Ronchamp, France

The church of Notre Dame du Haut is an example of Contemporary Architecture, designed by Le Corbusier in 1950 and built in 1954. It is perhaps Le Corbusier's most important project. The most difficult part to plot is undoubtedly the shell-shaped roof; its strange profile made the survey a challenging test. Thirty seven panoramas of the exterior and nine of the interior of the church were performed during a field trip to Ronchamp in May 2011. A topographic control network of about 100 natural points was already available, created by Fangi in the 1990s. Therefore the photogrammetric models were oriented using this control network, achieving centimeter accuracy. This phase of the work ended with the restitution of all the recognizable points of the buildings that allowed a wire model to be created (Fig. 8).

2.4.1 Quality Control

From the block adjustment the estimated correction angles α_x and α_y have values of up to almost 2 gon.

A set of distances was also measured using a disto laser device and these were compared with the same distances obtained through photogrammetric restitution.

The differences are in the order of centimetres. Due to the large number of available control points, the following test was also carried out: in the global adjustment only the control points 101, 102, 116 placed at the limit of the network were considered as fixed points. The values of the adjusted coordinates of all the other points were compared with the already known coordinates, which in practice were check points. The average module of the differences in the three directions is 0.014 mm of 86 check points. There is probably a gross error for point 114 in elevation. Table 1 shows the results of the bundle adjustment with 89 Control Points and the results of the adjustment with only 3 Control Points.

In both cases $\alpha_x = \alpha_y = 0$ and $\alpha_x \neq \alpha_y \neq 0$.

It is evident that:

- there is a very good improvement when the corrections of the verticality of the pano-sphere axis are enabled ($\alpha_x \neq \alpha_y \neq 0$)
- the number of control points is completely irrelevant for the final result, and therefore the control points network can be limited to three points as has already been done in many projects. This result is very important. In fact it means that, in order to reach the best accuracy, there is no need to use sophisticated and expensive instruments like theodolites and total stations, as men-tioned in the requirements listed in Sect. 1.2.

3 Conclusions

A constant focus of my research has always been on allowing a metrically correct architectural survey to be carried out, in any location and using simple and cheap means. PSP seems to achieve this task. Some conclusions can be drawn from all these projects. Up to now, 6 years after the introduction of PSP, some 500 small or large projects have been run. Buildings, façades, churches have been totally or partially documented using this technique, which is particularly suitable for architecture. Laser scanning is undoubtedly the ideal technique for archaeological surveys. It is however to be regretted that all the PSP projects were carried out by the laboratory in our department and that hardly any other users have adopted the technique, despite the fact that the software has been distributed to many university laboratories. The problem of this limited diffusion can be traced back to several causes: the introduction of the laser scanner, which has greatly reduced the interest in photogrammetry, and consequently in PSP, the lack of automation in the orientation and restitution processes, and above all the absence, to date, of a commercial product.

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The Piacenza Cathedral, from the Digital Survey to a Complete Multimedia Documentation

Giorgio Verdiani, Alessandro Peruzzi and Massimo Gualandi

Abstract The survey work of the Piacenza Cathedral was an extended, articulated and involving operation. Being the survey of such a complex building it took time and attention to produce a correct and complete documentation and a full and judicious coverage of all the exterior and interior parts of the whole church. The whole survey was a digitally born work, based on the use of both time of flight and phase shift technologies to allow a good, reliable, and easy to manage dataset. All the models were completely textured from the data gathered in an extended and specific photographic campaign. Even if a meaningful part of the data post processing was aimed to the creation of classic 2D drawings, the digital survey was also the base for the developing of multimedia presentations, while the 3D digital model was developed according to a logic aimed to produce a good and versatile base, capable to be reused for further BIM usage while for certain specific parts there was the testing of innovative visualization solution, like direct point cloud visualization inside a rendering software based on the voxelization of the points. In general the work on this large building was guided to produce a "state of the art" work, careful about the architectural language, useful for documentation, monitoring and visualization and in its own way a "summa" of all the good procedure such a Built Heritage monument was worth to deserve for a contemporary and well working documentation.

1 Introduction

The Piacenza Cathedral is a classic, solid and evident example of ancient and rich architecture, it shows the work of man in an extended timeline, with all the evolutions, the junctures, and all the possible twists of fate a building yard developed across ten centuries can encounter.

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From what is possible to see today, the image of this monument is composed by a various set of constructive phases, all of which are coordinated to a wise plot of harmonization, but clearly executed in different periods and with different methods.

That said, any intervention needs to start from a deep knowledge of the building, from a clear recognition of the base plot behind the architecture. If the main elements show clearly the presence of multiple phases, the inner part of the buildings, the non public and not easily reachable spaces, will contain even more clear signs of different construction layers. Therefore it is worth saying that if the more visible and clear parts of the cathedral require a deep knowledge of correct approaches in restoration and management, the inner parts make this need even more demanding. Because of their meaningful appearance, the most "in deep" details and inner parts are at the same time linked to the "life" of the building itself, while they form the base of its structural and environmental wealth.

For these reasons any serious documentation process extended to the building as a whole, should only be an integral one, with the maximal and most accurate coverage. For these reasons, the survey work of the Piacenza Cathedral was an extended, articulated, challenging and engaging operation. Being that the survey revolves around such a complex building it took time and attention to produce a correct and complete documentation. The time needed for planning and for the effective survey operation was calibrated according to the will to produce a full and judicious coverage of all the exterior and interior parts of the whole church.

One of the most important decision had to do with the optimization of the entire survey work, developing a survey plan based on the logic of the "minimal effort/ maximum result" that should be the base of any graphical, design and architectural procedure.

2 The Story so Far

To understand how rich and articulated the structures that compose the Piacenza cathedral are, it is useful to look back at some short notes about their main historical phases. According to the main studies done on this building and on the Piacenza urban settlement, the area of the actual church was the place of many transformations since the Roman period (Marini Calvani 1985). The first Piacenza cathedral, probably a quite simple building, was destroyed during the barbarian incursions operated by Totila in the VI Century (Ottolenghi 1947). The following new church, dedicated to St. Giustina, was probably built in a poor way and was later destroyed by an earthquake in 1117 (Tagliaferri 1964). This disaster signed an opportunity to start planning a new cathedral with meaningful characteristics, a building suitable to the increased needs of the renewed Piacenza. The yard started in 1122. Probably because the condition to develop its construction in between the previous buildings, the development of the church was planned starting from the façade. The choice to give the church a double-level design was adopted since the first project, with a quite large crypt dedicated to St. Giustina, characterized by the presence of 104 columns displaying capitols richly decorated with floral and vegetal patterns. The Cathedral has a Latin cross plan, with the central nave larger and higher than the lateral ones. All of the naves are characterized by round arches supporting cross vaults with ogival arches in the central one and round arches in the aisle. The head of the cross terminates with a complex structure composed by the crypt and the triple transept dedicated to St. Maria. This space is well connected and in perfect continuity with all the other spaces. The nave crossing is surmounted by a high octagonal tambour, enriched by a gallery which gives access the outer gallery that passes all along the external structures of the tambour and accesses the attic space between the vault and its roof. The presence of a system of galleries to inspect the whole building is a typical feature found in this type of churches. In Piacenza it becomes a very characteristic element because of its articulation, allowing to move continuously from the inside to the outside and into numerous remote spaces. The most active period of the ancient yard goes from the 1122 to the 1160, with the completion of the crypt, of the transept and of the lateral naves. It is worth to say that in these same period the Gothic architectures starts to spread around Europe. This can be seen either as a as new movement continuing and evolving the Romanesque architecture, or it is possible to consider it as an opponent of the previous architectural language (Von Simson 2001). However, the Piacenza yard continued with the aim to bring on a mainly Romanesque structure. There is more than one hypothesis on the completion of the cathedral, but it is possible to associate its final phase to before the end of the XII Century, because of the numerous intervention of enrichment that happened until the second half of the XIII Century. This way, Piacenza cathedral can be included in the same time range with the other northern cathedrals, like that of Modena and Parma. Together with them, Piacenza gave its contribution to the definition of the "Padan Romanesque" architectural language, characterized by its severe and solid aspect, one integrated by meaningful narrations defined by statues, symbols, stone patterns and a sophisticated use of materials. The main façade of the Piacenza cathedral is based on a quite flat surface, formed by continuous planes, where the prominent entrances and the carved loggias gain an even more robust importance. The material used for the whole cathedral is mainly the local sandstone, While the lower part of the façade is enriched with Verona's pink marble. The front of the cathedral faces the main square in the town. Placed almost in one of its corner, the cathedral influences the whole urban tissue and the square. The square itself is said to be derived from the first Roman plot. During time it received a large number of transformations, but starting from the realization of the cathedral, the most of them were aimed to enhance and improve the relationship with this main front. In 1333 the bell tower was completed, it has a narrow and massive structure made of bricks, with a light sequence of arches and columns opening the bell cell immediately beneath the high conic roof. The square shaped base is founded over one of the cathedral bay, defining in this way an evident enlargement of its walls. The cone shaped roof is completed with a golden copper statue, representing an angel, called Angil dal Dom (the angel of the cathedral). A curious element in this bell tower is the presence of a large cage, hanged to the masonry almost forty meters over the ground, and realized according to the will of Ludovico il Moro to be used as a punishment for people condemned for heinous crimes.

3 The Survey Campaigns

Any good survey works has two main steps: the planning and the campaign: this obvious consideration was at the base of the Piacenza cathedral survey. The whole work was made possible thanks to the collaboration between the "Facoltà di Architettura" (now Dipartimento di Architettura) in Firenze and Area3D s.r.l. Livorno. The survey was a digitally generated work, based on the use of both time of flight and phase shift 3D laser scanner technologies to achieve a good, reliable, and easy to manage dataset, all the survey work was integrated by a general topographical network and by an accurate photographical documentation. The survey phases were divided in two main sessions, each with a duration of 7 days. In this way it was possible to have a good control on the quality of the gathered data and an optimal organization of all the operators involved in the survey. The first survey session has been conducted by six operators divided in three groups. The first group has operated using a phase shift 3D laser scanner (a Cam/2 Faro LS880), used in all the internal spaces of the church (Fig. 1).

The second group has operated using a Time of Flight 3D laser scanner (Leica ScanStation), used to cover the fronts and to operate along the roofs and from the streets around and the building surrounding the cathedral. The second survey session has been operated by five operators divided in three units. This time the 3D laser scanners were both based on phase shift technology (a Cam/2 Faro LS880 and a Cam/2 Faro Photon 120), used to complete the internal spaces and the external galleries of the church. The third unit was involved in the photographic documentation, aimed to produce highly detailed orthophotos and to document all the useful reference details for the further drawing and surface model creations. A complete topographic network was developed to allow the full integration of all the scans. The total station (Leica TCR 705) was operated by two surveyors, gathering a main network of points all over the 3D laser scanner targets and a secondary network based on geometrical features recognized around the cathedral, this secondary network was used as a sort of backup to resolve any later point cloud alignment issue. The overall time needed for the topographical survey was about 7 days. The topographical network has covered all the external fronts, has passed by the main external galleries and was developed across the roofs and the bell tower. It has of course crossed all the main internal spaces from the crypt to the attic, to allow a well consolidated and closed network some station points were taken from the frontal square, targeting the attic and the galleries across the openings in the main façade. With all the 3D scans aligned on the topographical network, it was easy to optimize the overall survey work, because, as it is well known, such a condition allows a well working reference system with better and faster alignment with a lower number of scanning operations and a substantial reduction of the need for large overlapping between one scan and the following one. To get a general idea about the extension of the surveyed building it can be useful to list its quantitative data: the total accessible floor surface is about 3,312 m^2; the accessible floor surface beneath the roofs is about 2,332 m^2; the total length of all the external galleries is

Fig. 1 The two 3D laser scanners at work during the first survey campaign

about 299 m; the overall length of the staircases is about 240 m; the whole building has a length of 85.66 m from the main entrance to the external wall of the apses; its main largeness its 70.47 m along the transept, the height of the tower bell is 67.09 m from its juncture to the ground to the statue at its top; the internal height of the main dome its 38.33 m. The numbers for the results of the digital survey are the following: the final aligned point cloud composed by the various 3D scans it's made of about 1,660 millions points, gathered from 317 scanning stations, the topographical stations operated to build the whole network are 88. The survey work started in 2008 but the final post processing was completed in all of its 2D and 3D products only in the late 2010. Overall it is worth to say that the quality and richness of the dataset can be considered as a work in progress as new and specific data treatments are still going on starting from the original point clouds.

4 Post Processing of the Cathedral Dataset

The main task in the 2008–2010 plans was the realization of a complete 2D set of drawings, aimed to produce clear, detailed and great looking images of the state of the cathedral, with a full architectural detail about every meaningful elements. So, after the organization of the whole amount of gathered data, a long operation of data treatment started to produce more and more detailed representation of the cathedral. The first step was the alignment of all the scans according to the Topographical network. This was done using Cam/2 Faro Scene software and Gexcel 3D Reconstructor. The following processing was aimed to extract traditional drawing and the photo plan imaging combined with the vectors coming from the drawings. In this way it was possible to produce a complete and easy to use set of descriptive vector drawings in a fully compliant condition towards any CAD software. This kind of representation is referred to the common and well consolidated representation standards, but it's also for these reasons that the most easily employable by any kind of users today, is also the one with the better changes to survive data

Fig. 2 The plan looking towards the vaults of the Piacenza Cathedral

obsolescence in the long run. So the whole set of drawing was archived in DWG and PDF format, to allow a better efficiency in further preservation and dissemination of this documentation.

For this same reason the pointcloud dataset was archived in the original formats: FLS for the Cam/2 Faro units and IMP for the Leica Scanstation, but also exported into a PTX format and archived.

The set of 2D drawings were organized to present the whole building in all its richness, a special attention was reserved to creating drawings with full usable features for archiving the state of the cathedral and creating a correct base for any further restoration action. This set of drawings was organized in the following thematic graphic groups: one ground floor plan; one crypt plan; three plans of the attics; one plan of the roofs; 20 sections; four fronts; one horizontal section looking towards the vaults (Fig. 2); four fronts with photographic textures applied (Fig. 3). To complete the documentation of the Cathedral "as it is" there were produced a set of drawings with axonometric representations of the building with transparencies and some removed parts to allow an even more clear reading of the whole architectonic apparatus. These type of drawings might seem more popular than technical ones, but are in fact quite useful to better communicate the organizational structure of the spatial layout of the building (Fig. 4).

All the drawing were realized with the target to obtain a 1:50 representation scale and all the details were calibrated to this aim. This way, all the main needs related to the creation of a comparison with further drawings, as well as to the use of these drawings as a base for any restoration purpose, are entirely satisfied. At the same time there was the creation of a full set of 3D surface models, dedicated to

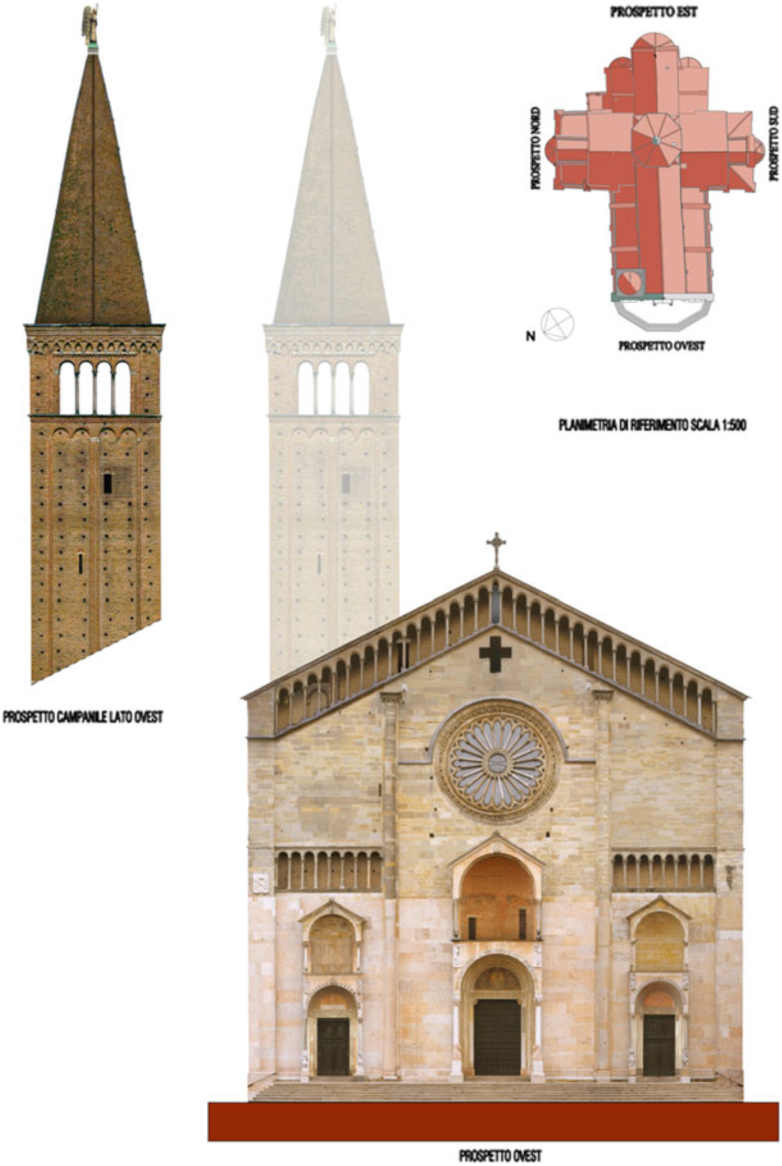

Fig. 3 The main front with photographic texture of the Piacenza Cathedral

developing a digital animation for multimedia dissemination of this important monument. All the models were completely textured from the data gathered in an extended and specific photographic campaign. Meanwhile the 3D digital model was developed according to a logic aimed to produce a good and versatile base, capable

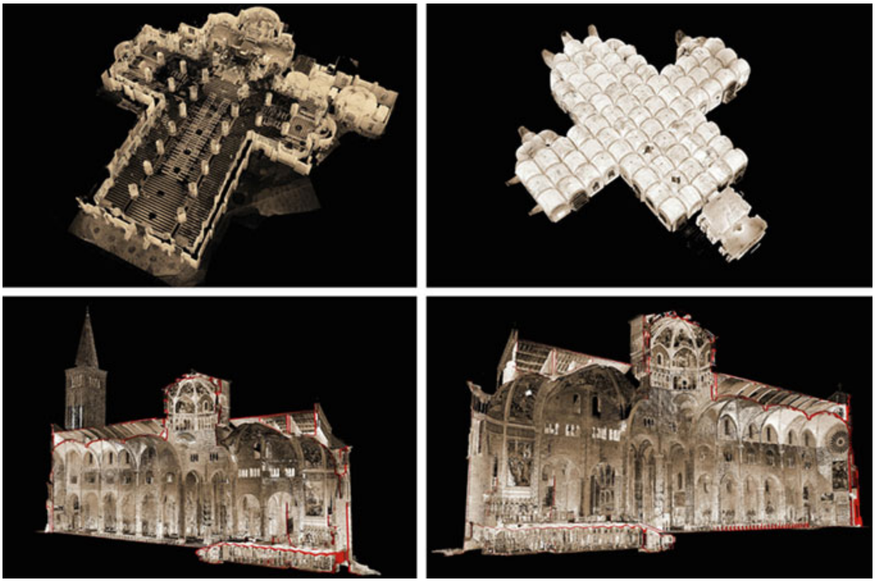

Fig. 4 A selection of views from the aligned point cloud model of the Piacenza Cathedral

to be reused for further BIM usage while for certain specific parts there was the testing of innovative visualization solution, like direct point cloud visualization based on the voxelization of the points inside a rendering software. This last solution was specifically used for the animation sequence inside the crypt, giving back a very good quality and a well convincing effect of that space. In general the work on this large building was guided to produce a "state of the art" work, attentive about the architectural language, inspired by the great survey of the past, useful for documentation, monitoring and visualization and in its own way a "summa" of all the good procedure a Built Heritage monument like such is worth deserving for a contemporary and well working documentation.

Acknowledgments The Survey of the Piacenza cathedral was operated in two separate campaigns, the group participating to the first one was composed by: M. Gualandi, A. Peruzzi, G. Verdiani, S. di Tondo, F. Tioli, E. Carli. The Second one was composed by: A. Peruzzi, G. Verdiani, F. Gualandi, M. Tiefenthaler, F. Tioli and E. Carli. The photographic survey was done by A. Peruzzi, G. Verdiani and F. Piras. The data treatments, drawing preparations, modeling and post processing were done by: A. Peruzzi, M. Gualandi, D. Fedeli, R. Crosara, F. Piras, M. Sahugon, V. Palandri. A special thanks to arch. Manuel Ferrari for the support and the generous collaboration.

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Documenting Lost Heritage: The Experience of the Survey of Architectures Damaged by the Earthquake in the Emilia Area, Italy

Anna Maria Manferdini

Abstract Two years ago, the earthquake that devastated a wide architectural heritage in the Emilia area, in Northern Italy, gave rise to a series of surveys and investigations aimed at both documenting a lost or seriously compromised heritage and at recording information that can be used by different operators (i.e. fire departments, civil protection, engineers, architects, urban planners) and for different uses in different times, concerning the development of safety, recovery, restoration or demolition programs. The aim of this contribution is to show how digital technologies and in particular non-contact 3D survey methodologies can be used as an indispensable practice in order to rapidly and safely produce graphic documentation about an architectural heritage that has been destroyed or severely damaged by a natural disaster. The presented case studies belong to a repertoire that ranges from single buildings to wider complexes that were selected for their historical and cultural importance and for the urgency of the development of intervention plans.

1 Introduction

The earthquake that devastated the Emilia area in Northern Italy on May, 2012 gave impulse to intense survey campaigns conducted in order to collect information about the damages reported by a wide built heritage and to plan intervention programs. In particular, soon after that event, this area has become the field of investigation for different operators that change through time, such as, for example, fire departments, civil protection, engineers, architects, urban planners and institutions that are called to develop safety, recovery, restoration or demolition programs.

The urgency of these investigations and the complexity of this vulnerable territory privileged the adoption of survey methodologies and technologies that fully benefit

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from the potentialities offered by recent advancements in the digital technologies field. 3D reality-based techniques, for example, that allow to directly acquire the spatial characteristics of artifacts and sites, when combined with GIS or 3D databases designed to collect, to link and to exchange different kinds of information, are actually offering great benefits to the deepening, sharing and widening of knowledge. Among these approaches and techniques, non-contact measurement systems of latest generation, such as terrestrial 3d laser scanning and high definition photogrammetry (Pirotti et al. 2013; Remondino 2011; Manferdini and Remondino 2010; Remondino and El-Hakim 2006; Böhler and Marbs 2004; Blais 2004), are particularly useful within emergency contexts (Fratus de Balestrini et al. 2013; Manferdini 2013; Olsen and Kayen 2012).

In case of large scale investigations on wide areas damaged by natural disasters, airborne laser scanning and photogrammetry are actually intensively adopted (Uprety et al. 2013; Brunner et al. 2010; Yamazaki et al. 2004), as well as mobile laser scanning systems that combine the ability of directly acquiring metric information at large distances with rapidity (Kaartinen et al. 2012; Graham 2010; Barber et al. 2008; Tao and Li 2007). In contexts where the damaged heritage cannot be accessed and its documentation consists of photographs, image-based technologies represent a precious solutions, since they can provide 3D information based, for example, on amateur or archive material (Grün et al. 2004). When the only source of documentation is represented by a single image, such as a painting or a drawing, reconstruction through one single image is the only solution that can be adopted (El-Hakim et al. 2001; Crimisi and Zimmerman 2000).

2 Post Earthquake Digitization of Damages in the Emilia Area

After the earthquake that devastated the Emilia area in 2012, one of the first problems related to documentation of damaged heritage was, in many cases, the inaccessibility of archives, whether land registries, historical or private collections.

As a consequence, the impossibility to rapidly recover the previously acquired documentation or its unavailability gave rise to extensive survey campaigns and digitization.

In case studies that needed to be documented at an architectural scale, terrestrial laser scanning was selected as a privileged technique, since it allows to easily and safely conduct survey campaigns.

One of the most important advantages offered by these technologies is the possibility to quickly acquire huge amount of data that are very versatile, since their visualization can be filtered, customized and therefore can be used for different purposes that can change through time. On the other hand, the management of these complex data requires specific skills and expertise that can reduce the possibilities to re-use them.

As far as investigations performed at wider scales is concerned, besides the urgency of developing safety programs and seismic retrofits, in some cases, these survey campaigns were also motivated by the purpose of collecting information on heritages that share common architectural composition and structural characteristics and therefore belong to specific building typologies. These kinds of investigations are particularly useful in case studies such as, for example, rural buildings, that were not previously accurately documented in detail.

In other cases, large scale documentation was mandatory in order to conduct a census of specific heritages, such as, for example, worship buildings, and locate them on the territory, in order to plan their reconstruction, demolition or restoration based on actual needs and real possibilities of intervention.

2.1 Case Studies and Results

The aim of this contribution is to show how the potentialities offered by high resolution digital methodologies and technologies were efficiently used to produce graphic documentation about the architectural heritage that has been severely damaged by the earthquake in Emilia.

The presented case studies range from single buildings to wider complexes that were selected for their historical and cultural importance and for the urgency of the development of intervention plans. In all case studies, the aim of surveys was to collect the most detailed and accurate information compatibly with the reduced possibility to access to unsafe buildings. In particular, most of them have been surveyed just from the outside, using fast and non contact survey methodologies, while documentation of inside spaces was collected through photographic repertoires, pre-existing documentation or specific targeted investigations. In some cases, documentation was also integrated and completed thanks to accurate descriptions that were reported by people who lived those spaces.

All case studies were mainly acquired using laser scanners, since these technologies can actually ensure greater reliability of information with respect to other approaches. When survey conditions are particularly strict, high resolution photogrammetry, for example, cannot often guarantee the check of the quality, level of detail and coverage of collected data directly on field. This is a crucial aspect to consider, when surveyed information can no longer be integrated on field. In some cases, when accuracy and definition were not priority tasks, the indirect measurement approach supported by orthophotos was adopted instead of a range-based one.

2.1.1 Natività Della Vergine Oratory in Crevalcore, Bologna

Worship buildings damaged by the earthquake in Emilia present peculiarities and critical aspects mainly related to their artistic and religious values, to their effective actual use and to the lack of a single tool, such as a GIS or a 3D database, dedicated to collect graphic documentation on the heritage that is administered by all single diocese of a territory.

Our investigations on the small Natività della Vergine Oratory in Crevalcore were therefore undertaken with the double purpose of collecting metric information about damages that interest its outer surface, but also to restore a graphic representation of its inner space, since this building is still inaccessible and no graphic documentation on it is nowadays available.[1] This lack is mainly due to the history of this building that was passed down from different private properties, until it was donated to the Municipality of Crevalcore in 1985 and to the Crevalcore Parish the following year.

This small[2] oratory, commonly known as "La Rotonda", was built between 1765 and 1768 and was erected at the behest of the Countess Maria Vittoria Caprara in recognition of the grace received by her husband who escaped unscathed from an incident in 1764.

The building is located in an estate that belonged to the Counts Caprara from 1501 for three hundred years.

The design of the church is attributed to Petronius Fancelli, a disciple of Mauro Tesi, who is more known as painter of quadrature rather than as an architect.

The apparent simplicity of its inner space corresponds to a complex organization allowed by the presence of furniture and separation elements that permit its flexible use in different situations and at the same time highlight symbolic meanings due to their spatial location that follows precise composition rules.

The central and symmetrical plan of the oratory is enriched by the sinuous shape of the choir that subdivides the inner space into two levels and meanwhile hides private spaces from the public ones.

The decorative apparatus of "La Rotonda" is characterized by the use of peculiar paintings that entirely cover its inner surfaces and reproduce a brocade that seem to belong to the repertoire of the manufactures of Lyon.

This wonderful oratory was severely damaged by the earthquake, as its masonry walls are completely affected by deep diagonal cracks; some of them cross the whole thickness of the outer bearing wall. Despite these damages, the compact shape of the oratory preserved it from the collapse.

Our aim of investigating its outer damages and inner consistency determined the organization of survey campaign into two different moments.

The outer survey of "La Rotonda" was conducted using a Leica ScanStation C5 ToF laser scanner. The minimum detail of the outer surface of the building (1 cm) and the purpose of acquiring additional information on the particular natural landscape in which it is situated, required the location of 7 station positions, each one setting a grid of 1 × 1 cm at 10 m distance, that allowed to finally acquire the location of 50 million points (Fig. 1).

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1 With the exception of a small and synthetic scheme (Cassoli 1979).

2 The diameter of the oratory measures 9 meters.

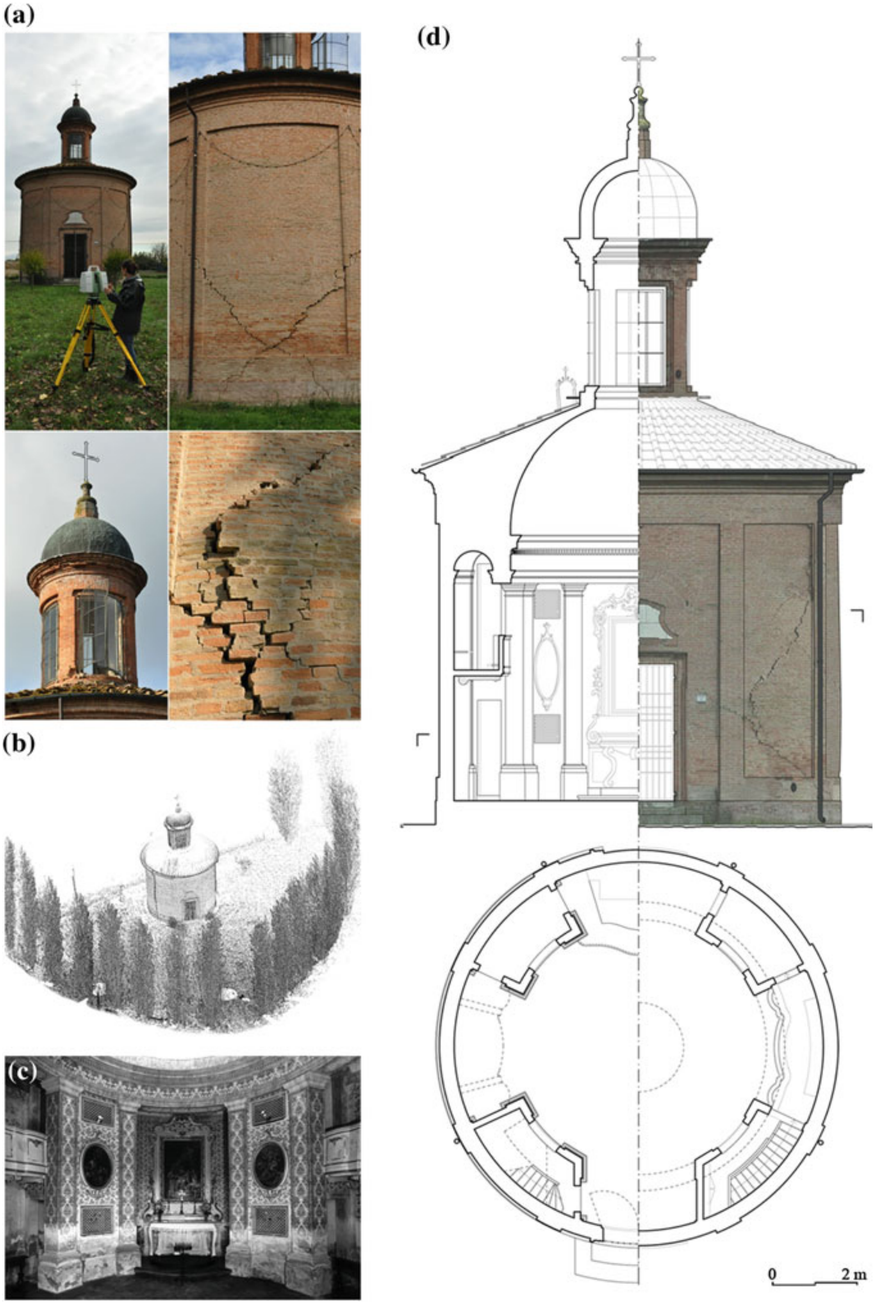

Fig. 1 Natività della Vergine Oratory in Crevalcore. In **a** survey campaign; **b** derived point cloud; **c** image of the inner space collected by the A.I.R. Accademia Indifferenti Risoluti of Crevalcore; **d** example of 2D representations

The reconstruction of the inner space of "La Rotonda" required evaluations based on a photographic campaign conducted in 1986, on some amateur photographs and on images available on the web (Retrieved January 2014).

2.1.2 The Canonical and the Oratory of the Conversione Di San Paolo Apostolo Church in Concordia Sul Secchia, Modena

The integrity of this sixteenth century church has been seriously compromised after the two earthquakes in May 2012. As a matter of fact the coverage of its main nave collapsed and significant damages interested the entire complex facing the adjacent Via Garibaldi, that was located in the border with the canonical and with the oratory, and that was therefore immediately completely demolished.

The canonical and the oratory were less damaged than the adjacent spaces, so that the possibility to recover them was investigated by structural engineers.

In addition to this aspect, the canonical presents a portico that insists on Via della Pace, the main road that crosses the historical center of Cavezzo; the reinforcement of its structure using temporary shoring was therefore an urgent task to assure safety works along the whole road.

This survey was conducted using a Leica ScanStation C5 ToF laser scanner in order to quickly acquire the outer surfaces of the complex. The entire complex was captured through the placement of 6 station positions, each one setting a grid of 1×1 cm at 10 m distance.

As far as its inner spaces are concerned, the relatively safe conditions of the whole structure allowed to conduct indirect measurements and photographic campaign, as well as visual surveys and an in situ cataloguing of the main damages.

These acquisitions were turned into 2D technical drawings and cataloguing sheets that were used by structural engineers and by the fire department to design and build structures with the purpose to ensure secure bearing of damaged areas (Fig. 2).

2.1.3 Villa Delfini in Cavezzo, Modena

This eighteenth century architectonical complex located in Cavezzo, represents a typical courtyard mansion of the countryside of Modena and is enriched by the presence of Villa Delfini, a manor house that belonged to the family of the writer Antonio Delfini (1907–1963) for more than two centuries. During the nineteenth century, Villa Delfini was surrounded by other three buildings that were mainly built and used as stables and housing for servants.

This complex is actually private, but given its artistic relevance, in some occasions it hosts cultural events and is therefore opened to the public.

The survey of the entire complex of Villa Delfini was required in order to provide an updated documentation on its consistency and on the damages that it reported after the earthquake, in order to technically and economically evaluate the possibilities of restoration or partial demolition interventions (Fig. 3).

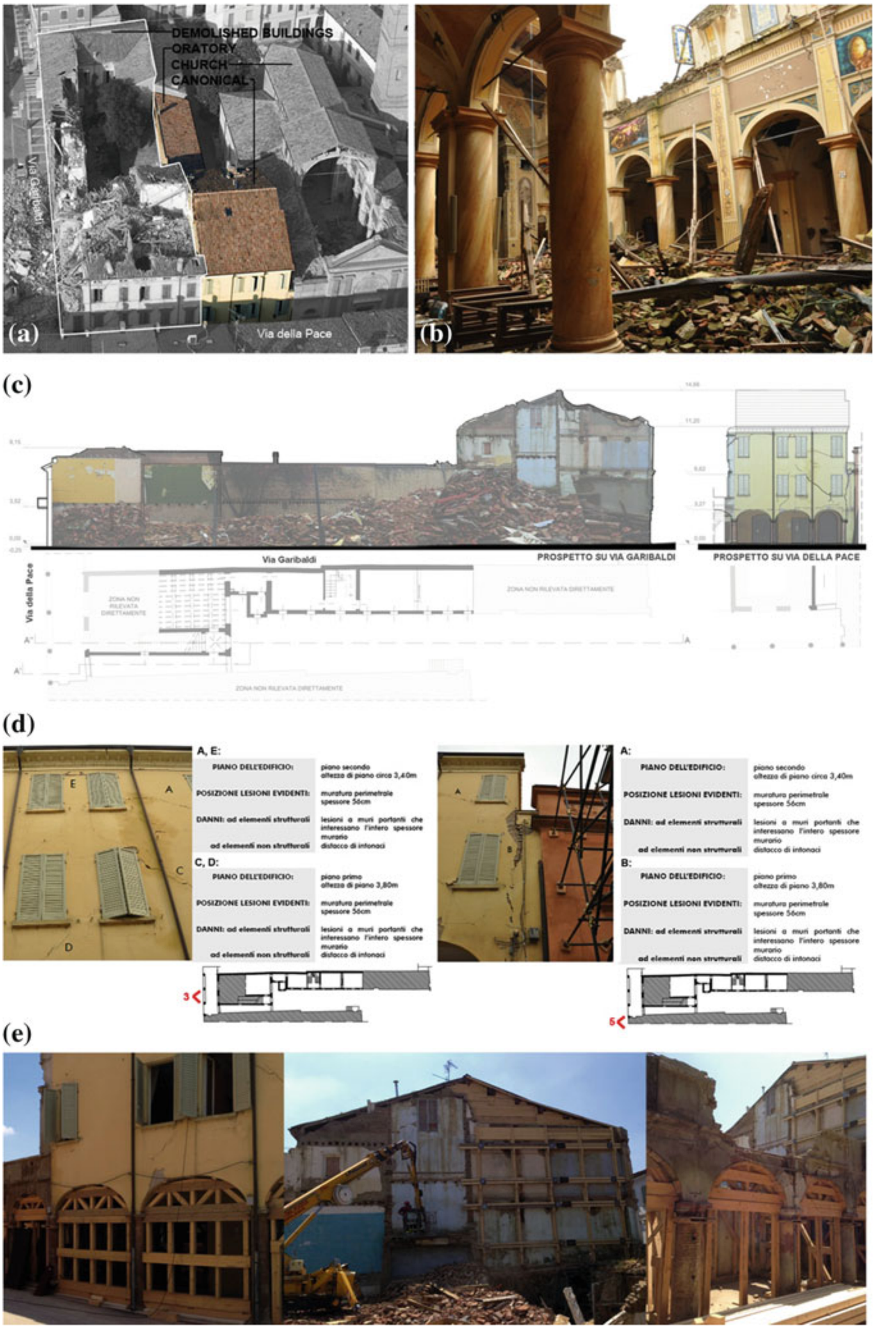

Fig. 2 Conversione di San Paolo Apostolo Church in Concordia sul Secchia. In **a** aerial photographs; **b** view of the main naïve of the church; **c** example of 2D projections derived by laser scanner and indirect measurements; **d** examples of cataloguing of damages; **e** preparation of temporary shoring to bring the building to safety

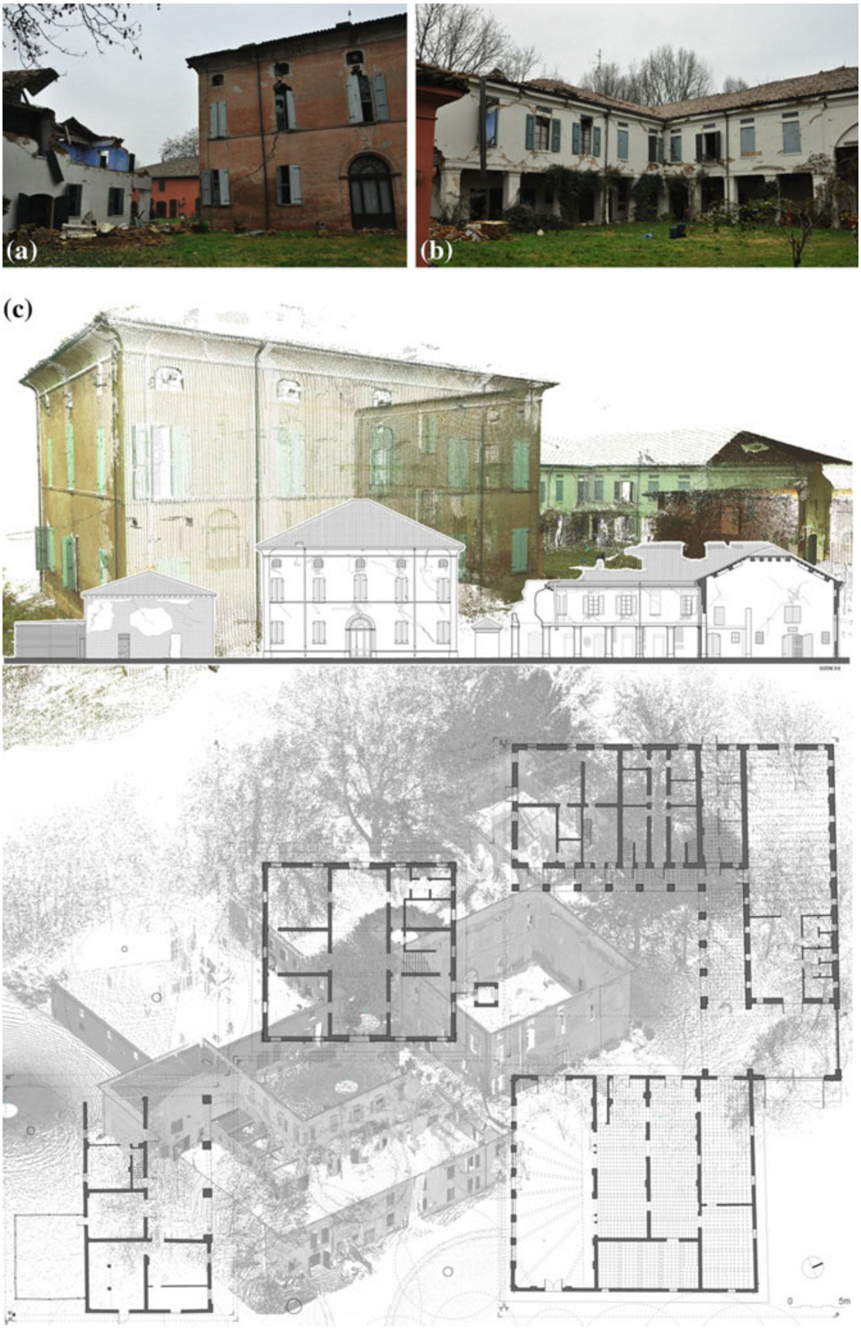

Fig. 3 Villa Delfini in Cavezzo, Modena. In **a**, **b** images of the main damages; **c** point cloud of the whole complex and example of the derived 2D drawings

Investigations were conducted using both a Leica ScanStation C5 laser scanner and photographs. In particular, laser scanner was used in order to recover metric information on the outside of the buildings that are entirely affected by cracks, bulging of walls and, in some cases, wide collapses.

The articulated shape of the complex required the location of 14 station positions, each one setting a grid of 1 × 1 cm at 10 m distance. The alignment of the single point clouds using the ICP algorithm allowed to restore the whole 2D plan of the complex on which more detailed representations of single artifacts were located.

As far as the representation of inner spaces of the buildings is concerned, photographs captured on limited areas and metric evaluations based on schematic archival planar documentation were the only sources of information.

3 Conclusions

This contribution presents the results of the digitization project of case studies that were selected within the Emilia territory devastated by the earthquake on May 2012 for their artistic relevance and lack of documentation.

The main aim of each investigation was to restore graphic representations that can help the preparation of temporary shoring projects, in order to bring buildings to safety and to evaluate the technical and economical convenience of restoration or partial demolition interventions.

All case studies report damages that allowed survey campaigns for limited periods of times.

The planning of survey was therefore a preliminary task to face, in order to limit investigations to few hours and reduce the risks for operators. These requirements and the contemporary need to acquire information whose detail was compatible with the dimensions and localization of damages, as well as with the aims of documentation, defined the methodology and the technology to adopt, as well as the detail of acquisitions and representations.

In all case studies range-based technologies were selected as the best solution to safely acquire huge amount of information in short periods of time. Each case study involved 2/3 operators for half to one day of survey campaign.

The rapidity of these acquisitions required particular attention in the alignment of point clouds during post processing of data, in order to reduce errors that could compromise the detection of small scale details and therefore the reliability of the whole survey. In addition, post processing of data required particular expertise in the filtering of data and in the selection of information to restore following different representation needs. During the drawing of 2D representations, for example, the definition and location of reference points was indispensible in order to fix alignments, evaluate out of plumb walls and therefore define single tolerances for each scale of representation.

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Massive 3D Digitization of Museum Contents

Gabriele Guidi, Sara Gonizzi Barsanti, Laura Loredana Micoli and Michele Russo

Abstract The goal of the 3D-ICONS European Project is to provide EUROPEANA (www.europeana.eu) with accurate 3D models of architectural and archaeological monuments and buildings of remarkable cultural importance. The purpose of this paper is to describe the specific processing pipeline that has been set for digitizing a significant part of the Civic Archaeological Museum in Milan (Italy). All the technical and logistic aspects needed for capturing 3D models in a Museum environment, the implication with IPR, and the metadata acquisition, are covered. The main issue is generating a good result by the technical point of view, minimizing the impact on the usual Museum activity during the 3D capturing operations, shortening in the meantime the processing time to the minimal allowed by the different applicable techniques. This condition has led different choices related to the survey technologies (laser scanning and image based modeling) and the related data processing. Both technical and descriptive metadata have been collected for each item acquired, for generating a record of data searchable on EUROPEANA, with the addition of new metadata not defined in the minimal record, for making traceable the path leading to the generated digital content. The paper gives a general discussion of such issues with some specific examples referred to the large set of 3D objects digitized within the 3D-ICONS project.

1 Introduction

3D-ICONS (3D Digitisation of Icons of European Architectural and Archaeological Heritage), is a project funded by the European Commission's ICT Policy Support Programme (Pilot Type B—CIP-ICT-PSP-PB, CIP5—Theme 2, Digital content.

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Grant agreement 297194), aiming at providing Europeana with 3D models of architectural and archaeological monuments of remarkable cultural importance. The project will end in February 2015, bringing together 16 partners with relevant expertise in 3D digitization, from 11 different European countries.

The main purpose of this project is to produce around 3,000 accurate 3D models that have to be generated both as detailed 3D content, for the sake of completeness, and in simplified form, in order to be visualized on low-end personal computers connected to a 3D repository through the web. To reach this goal a suitable workflow for digitizing the Cultural Heritage assets and the related information, has been outlined.

The Politecnico di Milano unit (POLIMI), the authors of this paper belong to, worked on the massive digitization of the archaeological items conserved in the Civic Archaeological Museum of Milan (MAM). This museum runs on different sections, each dedicated to different periods and areas of interest. The major section is the Roman one, dedicated to *Mediolanum,* the ancient roman city that used to be capital of the Western Roman Empire for more than one century (from 286 to 402 A.D.) and evolved to what is nowadays known as Milan. The MAM museum has been built on the remains of the Roman circus, dated back to the IV century A.D., and the city walls, two towers of which are still visible today. In addition to the Roman section four other sections cover different historical periods (Egyptian, Greek, Etruscan and Medieval), totaling more than 1,000 archaeological objects organized in thematic rooms for each period, grouped by artifact typology: epigraphs, statues, mosaics, furniture and pottery. Very important pieces are included, such as the "Diatreta" (a type of glass cup, only one intact piece left in the world) and the "Patera di Parabiago" (a silver dish finely decorated with bass-reliefs, used for ritual purposes).

Given the unusual large scale of this 3D digitization, it was organized taking inspiration from some large digital conversions carried out in past years by important Cultural Heritage institutions on different types of materials, such as books or other 2D items in the framework of the so called "Digital Libraries".

2 A Metadata Driven Process

In any digital library development, the first step is the creation of a set of bibliographic records, representing the digital version of the library cards, whose role is describing, with a short set of data (Title, Author, Publisher, etc.), the digital content represented by the corresponding digitized books. Technically, such description represents some metadata of the book (i.e. data describing other data), which is often used as starting point for designing the digitization process, allowing among other things to estimate the amount of work needed for completing the job (how many volumes, how many pages, etc.).

Once the process is started each item is converted from paper to digital form and another set of metadata are generally collected, often indicated with the term

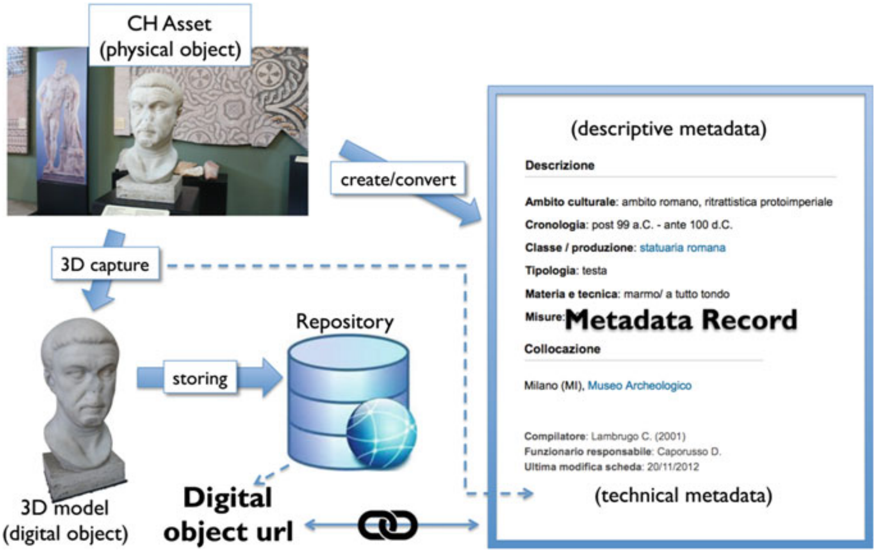

Fig. 1 Creation of a 3D digital resource and the related metadata. The descriptive part of the metadata gives information about the original cultural heritage asset, while the technical ones describe the 3D capturing process and the digital object originated by such process

paradata, representing the technical description of the process and the equipment used to digitize the book (e.g. type of scanner, resolution, bit/pixel, etc.). The whole set of descriptive and technical metadata are usually standardized by rules and terms, defined in the framework of the so-called “Dublin Core” Initiative. “Dublin” refers to Dublin, Ohio, USA, where the first metadata schema originated during the 1995 OCLC/NCSA Metadata Workshop, hosted by the Online Computer Library Center (OCLC), a library consortium based in Dublin, and the National Center for Supercomputing Applications (NCSA). “Core” refers to the metadata terms as “broad and generic being usable for describing a wide range of resources”, such as web resources (video, images, web pages, etc.), as well as physical resources such as books or CDs. The Dublin Core Metadata Element Set are nowadays endorsed in the main standards for cataloguing documents (e.g. IETF RFC 5013, ISO Standard 15836-2009, NISO Standard Z39.85).

In order to implement a Digital Library, that provides users access to large, organized repository of knowledge, a database of searchable descriptive records is needed. Each one represents the access point to the actual digital object (e.g. a scanned book) that is be somehow linked to it.

When the concept of Digital Library is extended to a collection of different materials such as museum artifacts, the set of metadata suitable for describing them has to be adapted to their specific features, but the process remains conceptually very similar, as summarized in Fig. 1.

A major contribution in the development of novel metadata schemas for describing CH assets and the related digital objects, has been done by CARARE, a best practice network funded by the European Commission’s ICT Policy Support Programme (www.carare.eu) in the period 2010–2013. The 3D-ICONS metadata schema is based on the CARARE schema for the descriptive part of the record, trying to enhance the technical 3D capture and modeling description, not much developed in CARARE.

In the framework of the 3D-ICONS project the POLIMI unit contributes with the production of 527 3D models of artifacts and architectural structures (i.e. more than 1/6 of the whole project), most of which (472) are generated from objects belonging to the MAM museum. The motivation of referring so much to a specific CH assets provider is twofold. On the one hand the roman period of Milan is rich of remains that, differently from Rome, are in large majority hidden in the underground and not accessible. The only visible structures are some portions of the building where the MAM has been arranged and a few structures nearby, in addition to the many objects visible inside the Museum. The possibility to enhance the visibility of such valuable assets—not much known by the common public—, in addition to the other non-Roman collections here shown, convinced the MAM administration to cooperate with great enthusiasm and availability to the 3D-ICONS initiative. On the other hand the POLIMI unit found extremely useful to start from CH assets belonging to a structure like MAM, involved by several years in cataloguing its patrimony adding the related records to a specific Data Base named SIRBEC, managed by the local Regional Authority. SIRBEC records are arranged according to a data schema compliant with CARARE, and can be used as primary source for collecting the descriptive metadata for 3D-ICONS, whose creation from scratch would be so time-consuming to be not sustainable for the whole project.

For this reason, as shown by the block diagram in Fig. 2, the POLIMI unit, with the help of the museum direction, identified the 600 most significant pieces of the MAM within those already having a description in the SIRBEC data base. Starting from this first set, a second selection was made, based on 3D acquisition and modeling feasibility. This second selection eliminated all the items whose 3D digitization would have involved an effort not sustainable for the tight 3D-ICONS time schedule, leaving the 472 most interesting objects. This short list was then used for querying the SIRBEC data base, that provided in this way the descriptive metadata of the 472 chosen items, exported in xml format.

On the other hand the unit provided to digitize the actual artifacts, selecting the most suitable technology for each type of asset: (a) automatic photogrammetry based on Structure From Motion (SFM) and dense image matching for small textured museum objects (Jebara et al. 1999; Pollefeys et al. 2000); (b) active range sensing based on triangulation for small untextured museum objects; (c) active range sensing based on Time of Flight (TOF) or Phase Shift (PS) detection for architectural structures. The motivations of this choices and the optimization needed to make them compliant with the technical and logistic constraints of the project will be discussed in the next section. However the technical data about the technique used for generating the 3D digital resource are recorded at this stage, and

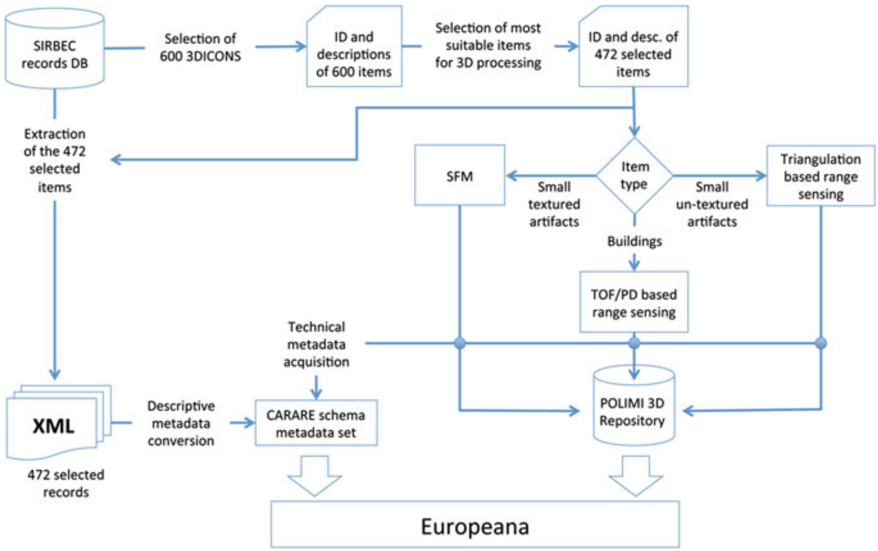

Fig. 2 Workflow implemented by the POLIMI unit within the 3D-ICONS project. The 3D repository is accessible on line and the metadata record contains a link to the corresponding 3D digital resource(s), becoming searchable through Europeana

used as input of a metadata generation procedure developed in the framework of the 3D-ICONS project that provides the functionalities for packing in a single record the descriptive metadata and the corresponding paradata (i.e. the technical descriptions of the process and the equipment used for obtaining that particular digital content).

As a result, at the end of this process, each Cultural Heritage asset has its own 3D model, a 512 × 512 thumbnail represented by a small rendering of the model in jpg format, and the corresponding metadata record. The latter two items are those actually delivered to Europeana, representing the access point to the actual high resolution 3D content, conserved in a specific repository managed by the 3D-ICONS project.

3 Technological Choices for Massive 3D Digitization

The 472 items selected with the process described above were preliminary classified in order to identify the best 3D technology for capturing them. As a result we obtained: (a) 9 % of buildings and large structures; (b) 14 % of small un-texturized museum artifacts; (c) 77 % of small texturized museum artifacts.

It was chosen to 3D digitize the first type of objects with TOF/PS laser scanning for its capability to give a metric 3D output independently of targets and other references to be attached on the monumental surfaces. In addition the architectural complex to be surveyed is the result of the superposition between ancient elements (such as the polygonal tower, the square tower and part of the roman city walls), with modern buildings made by flat regular surfaces. Therefore, while the ancient parts are richly texturized and could be easily surveyed with SFM, the same condition does not hold for the modern ones that should be integrated afterwards. For these reasons and for the relatively limited size of the buildings involved, the device used was a FARO Focus 3D laser scanner implementing range sensing based on phase shift detection.

For the second category of objects (small un-texturized museum artifacts) the most suitable method was triangulation-based range sensing. Actually the first attempt was to use a photogrammetric approach for its intrinsic efficiency, but after a few tests it was clear the lack of readable textures, capable to generate recognizable patterns to be matched on different views, gave unsatisfactory results. A standard triangulation device (both based on laser and patterns projection) in this conditions works nicely without generating artifacts. In addition no texture re-projection is required in this case, making the 3D model generation a rather straightforward process.

The latter category of objects (small texturized museum artifacts), resulted suitable to be digitized with an automatic photogrammetric approach (SFM/Image Matching) for two main reasons: (i) a triangulation based device generates geometrical artifacts in correspondence of highly contrasted textures over the 3D shape, involving a manual post processing for eliminating them with the risk of loosing important geometric details; (ii) the typical 3D acquisition pipeline involving 3D scanning, alignment, merge, mesh editing/optimization and texturing (Bernardini and Rushmeier 2002), requires a considerable amount of manual work in some of these steps, with special emphasis on alignment, mesh editing and texturing. On the other hand the SFM based approach, once the image set is acquired with a proper protocol, is fully automatic, providing directly a textured 3D mesh as final output. Here a moderate residual editing might be still needed, but the extent of the editing work results generally smaller than for scanned models. This seems to be due to the original scanned 3D data, suffering in some cases of larger lacks due to shading effects produced by the fixed baseline typical of triangulation-based range devices, baseline that in SFM is dynamically changed by the operator if a proper image set is chosen. In addition the high quality and high resolution texture that the SFM process generates automatically, has to be re-created from images on a 3D scanned model, finding out the orientation of each texturing image with respect to the model and projecting them on the mesh portions visible from the corresponding point of view, blending possible exposure or color temperature unbalance on adjacent images. As a result the generation of a texturized mesh model resulted to be far more time consuming with an active device, texturing the mesh with photos in a post-processing phase, rather than with SFM. This results, obtained by our preliminary lab tests has also been confirmed in the literature (Fassi et al. 2013).

4 Equipment and Processing

Since a large majority of objects (77 %) was 3D captured with image based techniques, we developed some optimizations and best practices for speeding up this massive 3D digitization, specifically referred to the SFM/image-matching process. Several variants of this process have been implemented as Open Source packages (e.g. Bundler/PMVS; Apero/MicMac; VisualSFM); commercial on-line services (e.g. Microsoft Photosynth, Autodesk 123D catch; Autodesk Recap); or locally installable commercial packages (e.g. Agisoft Photoscan; Eos Systems PhotoModeler Scanner).

Although several test have been made for comparing the performances of those different implementations of the SFM/Image matching process, revealing some stronger competitors (Remondino et al. 2012), it is clear that the process has been conceived as strongly automatic with little or no possibility for the operator to intervene on the single steps for adjusting the final result. This means that the only inputs that the operator can really control are basically: (i) the distribution in the 3D space of the single shots; (ii) the photographic quality of the various images; (iii) some constraints on the estimation of the exterior camera orientation depending on the type of shape to be captured; (iv) density of the final 3D cloud originated by this process; (v) filtering on the 3D cloud based on the type of shape to be captured; (vi) mesh adjustments based on topological considerations.

However, the first two points resulted dominant on the following post-processing adjustments. A single wrong image (both in terms of sharpness or orientation) in a set of several good ones might cause the failure of the whole 3D model generation, producing a considerable waste of time. This is why the optimization described here are mainly referred to these aspects.

First of all in order to improve the image sharpness, the quality of the cameras has been carefully considered. Two DSLR (Digital Single Lens Reflex) cameras have been used by the POLIMI unit: a Canon 5D Mark II with a 22 MPixel full frame sensor (36 × 24 mm) and a Canon 60D equipped with a 18 Mpixel APS-C sensor (22.3 × 14.9 mm). Depending on the object to digitize, and the camera-object distance imposed by the architectural constraints, the lenses used were: a Canon EF 50 mm f/2.5 Macro; a Canon EF 20 mm f/2.8 USM and a Canon EF-S 60 mm f/2.8 Macro USM (the latter usable on the APS-C sensor only). In addition a mirrorless Sony Alpha Nex-6 with APS-C sensor was used, equipped with an aspheric Carl Zeiss Sonnar T* E 24 mm f/1.8 lens.

A proper focal field was maintained by generally using small apertures (f11 to f32), specially in the most critical cases such as at short camera-object distances.

Manual focusing on zoomed areas of the artifacts was used in the most critical conditions, avoiding possible undesired blurring due to uncontrollable autofocus errors.

The ISO level as been kept at level compliant with small apertures and the normal illumination conditions of museum, avoiding to install—unless strictly needed—special illumination devices. In case of insufficient light it has been

Fig. 3 Typical shooting scenarios: **a** indoor. The window behind the operator is shielded with a movable black panel. The subject is shoot with a reflective panel for brightening the shadowed parts; **b** outdoor. In winter days with no sun the light is much more uniform and no special aids are needed. In both cases a black background and a metric target on the support plane were used

preferred the use of a tripod for increasing the shooting time with no movement blurring.

Rooms illumination is based on spotlights pointed directly on the artifacts; the ground floor is illuminated by some skylights and a big glass wall closing the room on one side. The light illuminating the displayed objects is therefore a superposition of natural light entering from the windows and artificial lights impinging over the archaeological artifacts, giving a significant mix in its color temperature. Using—as we choose in this project—an Automatic White Balance (AWB) mode, the result of this mixed light might be a bluish halo determined by the external light if the main light influencing the AWB is artificial, or some reddish areas corresponding to artificial light spots, when the main light contribution influencing the AWB is given by the external light. Therefore, for those object not movable from their position two opposite choices were adopted depending on their distance from the windowed walls: (i) switching on all the artificial lights using a black panel for shielding the exterior light, with White Balance set on the artificial light temperature; (ii) switching off all the artificial lights using a white panel as reflector to lighten the shadowed areas of the object, with White Balance set on the exterior light temperature. In this way set of images reasonably uniform in terms of color balance could be acquired for each object (Fig. 3).

The main camera/lens parameters (some of them rather obvious for a skilled photographer but anyway not always considered by 3D operators) can be therefore summarized as follows.

Focal length. As indicated in the list of equipment reported above no zoom lenses have been used in this project for avoiding variations of a calibrated parameter as the focal length.

Operating mode. Automatic with Aperture priority (A or Av depending on the manufacturer) because distortions—and particularly radial distortion—are very much influenced by the aperture size. The most suitable f value has to be chosen according to the desired depth of field. Due to the relatively large depth of field needed, most if the times f values in the range 16–32 were used.

White balance. Even if more sophisticate choices can be done for best artistic results, automatic white balance (AWB) resulted to be OK for avoiding color dominants in the images where the illuminating light might vary considerably in terms of color temperature. Despite this automatism sometimes residual reddish dominants were still present. In these cases a qualitative manual correction based on a neutral element of the scene (the black background or the white metric target), was made.

Image format. Although jpeg is the only format Photoscan is able to process, the shooting was made with raw images in order to have a dynamic range greater than the 8 bit per channel allowed by the jpeg format, useful for work color or exposure corrections in post processing, without losing useful information.

ISO. A sensitivity level not too low for avoiding long shooting times that in a freehand image capture can produce "movement" blurring, but not too high for avoiding noise grain superimposed on the image that may reduce accuracy of the 3D measurement. Working outdoor in normal daylight in general enough light is available, and ISO can be just close to the minimum (100/200), providing therefore the minimal grain. In indoor photogrammetry the amount of light available might be dramatically lower, therefore the ISO level has to be increased. The rule of the thumb for avoiding too much grain is to check the maximum and use two steps below than that.

Shutter speed. Actually in "A" mode the camera decides autonomously the exposure time, given the amount of light on the scene, the lens aperture and the sensor ISO level. However, if images are taken with freehand photography, the automatically evaluated shutter speed has to be checked being anyway shorter than a certain threshold for avoiding movement blurring. When the maximum usable ISO level lead to a sufficiently short shooting time, using a tripod solves any problem, even if a slightly longer set-up time is needed.

The data processing was then carried out with Agisoft Photoscan, a semi-automatic software package in which both the camera orientation and the internal calibration are made automatically, allowing a little interaction to the user. The software implements image orientation and mesh generation through SFM and dense multi-view stereo-matching algorithms.

According to the functions available on this tool, the images were acquired in such way to be easily processed. For this reason in most shots a black background was used to isolate the object from the contest. On the one hand this eliminate possible background details potentially useful for orienting the images, but, if the subject has an adequate surface characterization the image alignment is equally good. On the other hand the uniform background (black or white) can be automatically selected with a Photoshop-like function implemented in Photoscan. This allows to add masks for generating a clean 3D output with little or no need of further 3D post-processing.

At least a couple of images with length references where acquired in each photo set in order to scale the 3D measurements to metric values. Most of the time a

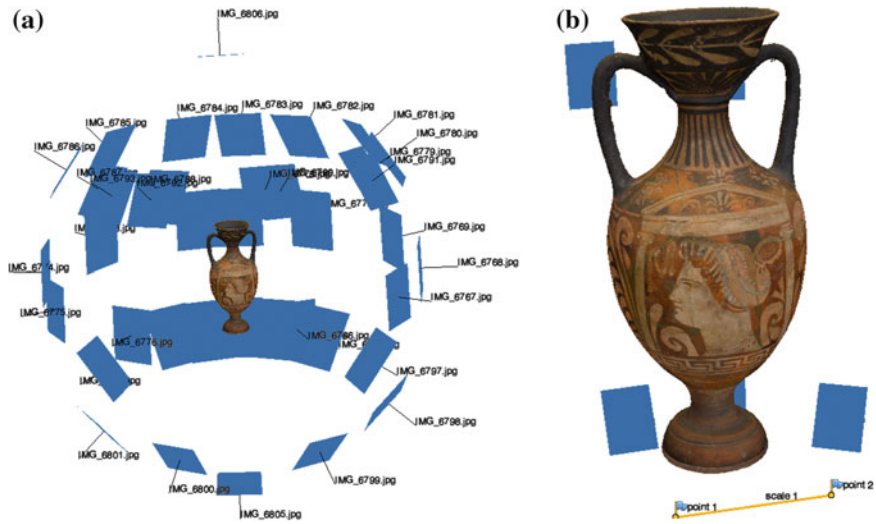

Fig. 4 SFM-based 3D modeling: **a** alignment of a set of images taken all around the object; **b** scaling of the texturized 3D model according with a calibrated reference

reference made with two coded targets at known distance was added on the scene for metrically scaling the model, as shown in Fig. 4.

The Museum conserves several kind of objects of different shape, measures and materials, therefore several potentially critical situations may occur. Since the final goal of the project is to produce an high number of models in a short period, one of the main factor was to identify the best pipeline in terms of a reasonable tradeoff between processing time and accuracy. Hence, several test on different types of objects were done for deciding a reasonable setting of the meshing parameters listed below.

Object type can be set as "Arbitrary", indicating a 3D free form or "Height Field", intending a 2.5D surface like a DTM. For the archaeological objects acquired we always set this parameter to "Arbitrary".

Geometry type specifies how to create the mesh from the acquired data. It can be set as "Sharp", leading to more accurate reconstruction results but no extra geometry like hole filling "patches", or "Smooth, producing slightly less accurate models but watertight meshes. Most of 3D-ICONS models have been generated in "Smooth" mode for the far better mesh topology attainable, as shown in the example of Fig. 5. Here the un-texturized sharp model (Fig. 5b) shows gaps and irregularities above the head and on a side, due to insufficient exposure of those areas in the corresponding images. Contrarily, the mesh generated in "Smooth" mode (Fig. 5d) appears more regular even with a slight smoothing of the geometrical details that is anyway less evident in the textured version (Fig. 5c). A metric comparison between the two models of the example gave a deviation included in the range ±0.5 mm, that resulted to be just slightly larger of the intrinsic 3D method uncertainty. The "Smooth" version was therefore accepted as a reasonable tradeoff for the much better topology of the resulting mesh.

Fig. 5 Comparison between Photoscan “sharp” and “smooth” mode while generating the digital model of the roman “Stele of Geminus” (1st century AD): **a** sharp texturized; **b** sharp un-texturized; **c** smooth texturized; **d** smooth un-texturized

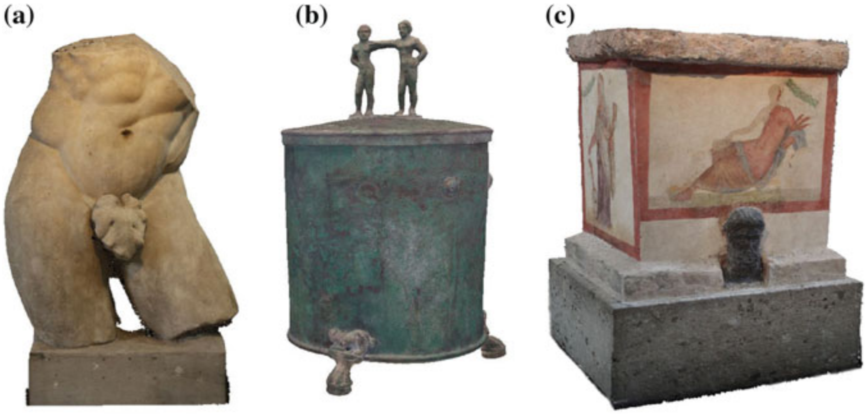

Fig. 6 Some examples of the 3D models generated with the optimized process described in the article: **a** fragment of a Roman statue representing Hercules (II AD); **b** Etruscan Cista (casket used for example to hold unguents or jewels) decorated with human figures (IV BC); **c** Roman decorated altar (III AD)

Target quality specifies the desired reconstruction quality. It is valid with for Smooth processing only: higher quality settings can be used to obtain more detailed and accurate geometry, but require longer time for processing.

Face count is the maximum number of polygons of the final mesh. Considering the actual size of the different objects, in the 3DICONS project the size of the final model was set to a tradeoff level of 2 million of polygons.

Filter threshold specifies the percentage of small connected components to be removed after surface reconstruction.

The 3D resolution of the process was set-up differently for each specific object depending on its size and level of detail. For all the MAM models the GSD (Ground

Sampling Distance, i.e. the spacing on the object surface between two adjacent pixel) ranges from 0.1 to 0.5 mm.

In Fig. 6 some examples of the final results are shown.

Although the project is still in progress a set of more than 350 3D models have been produced till now, with an average rate higher than 25 new 3D models per month, corresponding to 300 items/year, which is compliant with the massive 3D digitization operation needed in the framework of this project.

5 Conclusions

The 3D-ICONS project is allowing to experiment a quick 3D acquisition and modeling approach based on the SFM technique, on different objects and materials. Having the necessity to produce a high number of models in 3 years, it was essential to organize the work in a strict workflow that allowed to avoid time consuming operations.

The preliminary results of a massive 3D digitization project have been shown. Metadata conversion from preexisting sources has been fundamental for generating a set of Europeana-compliant 3D contents in a relatively short time. SFM is also a key technology for shortening 3D digitization to a sustainable level. However no many interventions are possible on SFM, the only actual action is improving image quality. For this reason proper image acquisition protocols have been set-up for increasing the 3D model quality and the success rate, in possible bad environmental conditions like those of a museum.

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Documentation and Analysis of 3D Mappings for Monument Diagnosys

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Abstract The restoration and preservation of built cultural heritage requires a good knowledge of its history and its current state of conservation. Heritage con-servation professionals are used to perform mappings to record and disseminate data relative to the monument. Data to be collected are heterogeneous, starting from the oldest sources (such as archives or iconographic manuscript) up to field observations. This study is applied to the documentation and analysis of the state of conservation of the East tower in the castle of Chambord. The produced map-pings concern the dating of stonework, the nature and origin of each stone, and the distribution of degradation patterns on the outer walls. To enable the graphical drawing and viewing of the different mappings, it is necessary to produce a suitable digital medium. In this study, the medium is a textured 3D model as a mean to characterize accurately and actually all surfaces, including those that cannot be viewed on a 2D projection. This 3D model is associated to the NUBES database to store and analyse all collected data. NUBES is a web-based open source platform for the representation, documentation and analysis of architectural elements. This information system has been specifically developed to include an interface dedicated to the drawing vector mappings and to their organization into hierarchical layers. Results of this study can be used to improve the monument diagnosis and our knowledge of weathering processes.

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1 Introduction

As part of the SACRE project (Degradation monitoring, characterization and restoration of limestone monuments), the castle of Chambord has been studied using various approaches, whether historical or scientific. The aim of this project is to achieve a better understanding of the building and to be part of its preservation.

The East tower of the castle has been selected as the main subject of the study with the aim of creating a digital health record of this tower. Steps of this process, including the definition of dating, nature, origin as well as degradation of stones, have been identified in previous works (Janvier-Badosa et al. 2013; Janvier-Badosa 2012).

Today, digital archiving in databases can constitute an innovative solution in order to classify this heterogeneous corpus of data, to compare these data and extract useful information for professionals of heritage conservation.

The existing NUBES system was used. Developed by the MAP-GAMSAU laboratory (Marseille, France), NUBES is a web-based open source platform for the representation, documentation and analysis of architectural features (De Luca et al. 2011). NUBES is based on a database in which are inserted architectural 3D representations. This interface allows the storage of heterogeneous data, the real time manipulation of three-dimensional geometric representations, as well as the online access and management of data. Originally, NUBES did not include the necessary features for the creation of a digital health record on the state of conservation of buildings, and therefore it has been adapted to match the needs of the SACRE project (Stefani et al. 2013; Brunetaud et al. 2012b).

This article is structured in the following way. The first part describes the different methodological steps of a digital health record creation using NUBES system. The second part of this paper describes a practical application of this methodology on a span of the East tower, in order to illustrate the adopted method and demonstrate the possibilities to improve decisions by cross-referencing data. Finally, limitations and future prospects of this approach will be discussed.

2 Methodology and Features of NUBES

2.1 The 3D Model

The first step to create the health record of a building is its graphical representation. In the field of conservation and valorisation of cultural heritage, many techniques for acquiring three-dimensional digital models have been developed.

In this study, the graphical representation should satisfy various requirements: it should be convenient to achieve, scientifically accurate and precise, and of acceptable image quality to ensure a correct visualization of the smallest required component: a stone. So, photomodeling technique has been adopted (Brunetaud et al. 2012a). After the acquisition of geo-referenced points using a tachometer, we took pictures on a regular basis all around the tower. The ImageModeler software has been used to calibrate and orient photographs to each other. The building volumes were then defined as precisely as possible by the juxtaposition of geometric shapes. Textures, extracted from oriented photographs, have been applied to the faces of the 3D model. Finally, the building was divided into coherent architectural entities (windows, spans pilasters, capitals…). This division is necessary for the 3D model of the tower in order to insert it into the NUBES Information System. This step consists in manually upload 3D elements on a server by means of the user interface, and includes the storage of the x, y and z coordinates of the barycentre of each 3D entity, as well as the upload of each texture in the database. Once all entities are registered, it is possible to navigate through the 3D model, and to select an entity whose unfolded texture can be displayed in a 2D interface for semantic annotation purposes (Fig. 1). Photomodeling allowed to obtain unfolded 2D textures: even if textures are distorted, readability of textures is optimised and this techniques permits to display all faces of architectural elements, including the hidden parts. The size of the drawing interface is flexible and can be increased or reduced in height as needed, resulting in the reduction or expansion of the 3D interface.

2.2 Graphical Representation of Data

2.2.1 Conventions of Representations

The basis of an architectural study is the representation of data for critical and analytical thinking (Núñez Andrés and Buill Pozuelo 2009). The realization of mapping, from drawings or photographs, is a common approach for many professionals in heritage conservation but the type of mappings varies according to the field and the purpose of the work: archaeologists or architects in charge of the heritage with historical data (Reveyron 2002; Bryant 2000), especially different phases of construction or restoration, at different scales and with several levels of accuracy. As matter of example, these representations can be applied to a complex of buildings (Stefani et al. 2009) or to a neighbourhood, where the smallest unit is the scale of the building (Saygi and Hamamcıoğlu-Turan 2009), or simply to a facade where the smallest unit is the scale of the stone (Akbaylar and Hamamcıoğlu-Turan 2007), as in our case.

Geologists working in conservation of historical monuments most often practice stone by stone mapping indicating the nature and origins of each stone (Montel 2007; Rautureau 2001), and conservation scientists generally produce graphical representations of the different kinds of degradation, in the context of degradation monument diagnosis (Janvier-Badosa et al. 2013; Akbaylar and Hamamcıoğlu-Turan 2007; Fitzner et al. 2002).

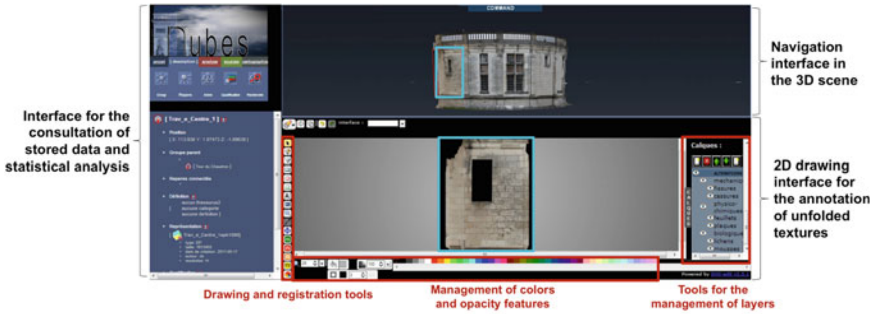

Fig. 1 Graphical user interface of NUBES

2.2.2 Mappings in NUBES

The realization of mappings was not originally an existing tool in NUBES. The platform has been adapted to match the needs of the SACRE project (Stefani et al. 2013). Now, it is possible to select an entity of the 3D model, to display its unfolded texture in 2D, and to produce the mappings on this 2D image. In order to accomplish this task, a vector graphics editor was adapted and integrated into the NUBES platform to draw/edit mappings using hierarchical layers.

A colour corresponds to each layer: colours enable to identify easily annotations that are drawn and projected onto the 3D model. Before drawing the shape, the user selects the layer corresponding to the item he wishes to map. Mappings are made on each 3D entity, one after the other, when they are developed in the 2D drawing interface. The result of the drawing of mapping is a complex juxtaposition of polygons that can be of two types (Fig. 2):

- Free shapes, for example following the contours of the damage. Depending on the case, the degradation can cover several stones and mortar joints, or a stone—or part of a stone—, with the exception of mortar joints.
- Shapes which strictly follow the contour of stones without mortar, called "stone by stone" contour. These contours are drawn on a layer called "matrix". They are duplicated in other layers to keep geometric coherence. These layers correspond to the known information for each stone (dating and origin of stones).

2.3 Display and Data Processing

Mappings are then stored in the database and shown on the 3D model (Fig. 3). NUBES allows the cross-referencing of mappings in real time in the 3D scene. In the 3D interface, the user consults mappings by selecting the layers to be simultaneously displayed. Among mapping features, a statistical analysis tool allows the

Fig. 2 Drawing method of the two types of mappings

automatic calculation of areas concerning drawn surfaces. Percentage is computed as the ratio between the areas obtained for each class of analysis and the total area of the unfolded entity.

2.4 Archiving of Associated Data

NUBES allows data storage, including written and iconographic historical archives that constituted the basis for the creation of mappings. The 3D model can display specific points (reference marks), which correspond to files stored in the database. Formats and types can be various and include details of photographs, reports of restoration, ancient texts, plans, point clouds of specific areas, as well as to descriptions, reports or analysis of samples. These documents can refer to the entire building as well as to a specific component. The main advantages are their free on-line consultation and the easy visualisation of their position in the 3D scene. Moreover, they are consulted online.

3 Practical Application

3.1 Implementation of Mapping and Statistical Analysis

By means of in situ observations and the study of historical archives, we defined the semantic structure of mapping data. The semantic structure is based on hierarchical layers of terms related to the domain of conservation. These layers are created in a dynamic way, according to the list of terms stored in the database. In this study, various mappings were made (Fig. 4): the mapping of date of the stones, the mapping of origin and nature of the stones, and the mapping of the distribution of damages (Janvier-Badosa et al. 2013).

Fig. 3 Display of mappings of damage on the 3D model and statistical analysis of weathered surfaces

3.1.1 Mapping of Degradations

The deterioration measured in the castle of Chambord belongs to three categories. Material losses under the form of breaks have been found on relieves. These are limited and irregular alterations, whose origin is often anthropogenic. Biological colonizations have also been studied, mainly mosses and lichens from different species. Finally, detachments were identified: scaling of stones. These last ones have two forms: spalling and flaking. Each of these aspects is structured in layers and sub-layers recorded in NUBES. To draw a particular degradation, it is necessary to be positioned on the corresponding layer, and to draw its contour on the 2D unfolded texture. The mappings produced in the first span of the East tower are representative of the rest of the tower (Fig. 3). Biological colonizations are the most extensive change since they affect 55 % of the wall surface of the span. However, they constitute the least damaging degradation, since they are relatively superficial and reversible. On the contrary, spalling (3.8 %) and flaking (0.2 %), although not extensive, are extremely destructive because they lead to an irreversible loss of material.

3.1.2 Mappings of Dating and Origin of Stones

Dating of stones identified on the castle of Chambord varies from the 16th to 21st century. Dates correspond to the ones of construction of the castle, as well as to the various stages of restoration. Some stones are easy to date because they present lapidary signs, traced by stonecutters only during the 16th century. For other stones, information is provided by in situ observations coupled with the study of historical archives, and dates are suggested with different degrees of certainty. For this reason, in the mapping of dating, there are specific dates (concerning specific years) as well

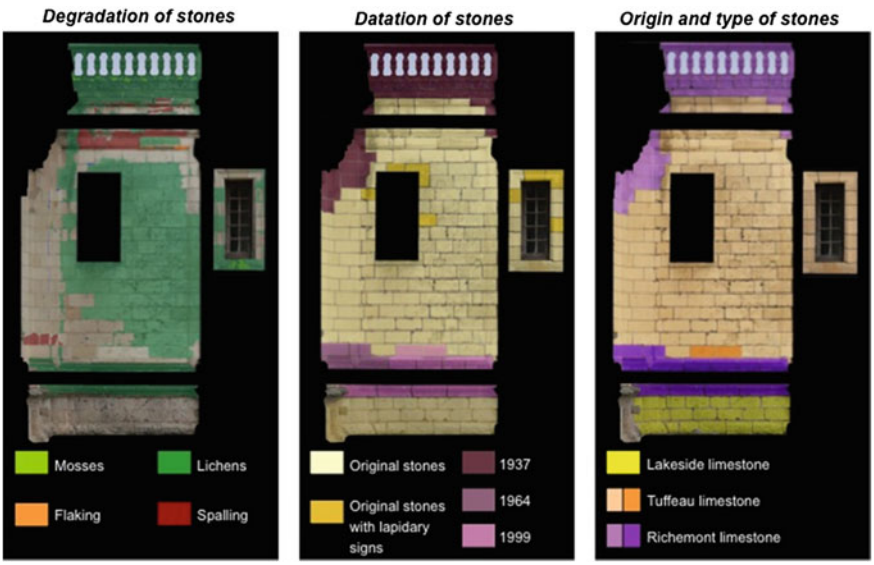

Fig. 4 The three types of mapping applied to the first span of the tower

as great ranges (concerning centuries). For the first span of the tower, the replacement stones (18 %) correspond to three dates: 1937 for the upper parts, and 1964 and 1999 for the lower parts. The remaining stones of the span are supposed to be original (16th century), except for four stones on the window frame, with lapidary signs, therefore being without a doubt from the 16th century.

These same sources (observations and archives) provide indications on the types of stones. They point out that the castle was built with tuffeau, a porous and soft limestone extracted locally. The basements are lakeside limestone, whose properties allow the preservation of tuffeau, limiting capillary rise from the ground. Documents also show that most of the 20th century restorations were made with Richemont limestone, less porous and more resistant than tuffeau. In some cases, quarries from these stones can be identified.

The stones are drawn one by one, on the layer called matrix described above (Fig. 2). The contours of these stones are then copied and pasted into different layers of dating and nature of the stone, according to their characteristics. In addition, stone by stone drawing allows to visualize accurately the morphology of mortar joints, the production technique (large and irregular, or fine and straight), providing information also on its date of installation, and by extension, the date of installation of adjacent stones.

3.2 Contribution of This Methodology

3.2.1 Application to Various Disciplines

Considered individually, these recorded and mapped data can help in understanding the building's history and its present state. In addition to the purely statistical aspect, these maps provide also other information.

For example, the mapping of degradation on a three-dimensional model allows to visualize the distribution of damage, depending on the location or orientation (near reliefs or not, upper or lower part, preferentially at the north, south…) and thus to deduce recurring factors that could cause degradation. In Fig. 3, the mapping of degradation of the first span shows a preferential localization of spalling in the upper and lower parts of the building, near the reliefs (mouldings). In addition, we know that the forms of degradation observed in the castle of Chambord gradually spread over time. The ability to draw at regular time intervals new contours of degradation allows to identify its evolution and to evaluate the kinetics of its development.

The mapping of dates and origin of the stones can provide new information of interest to historians and archaeologists. The "economy of construction" is an emerging discipline of history, still waiting for quantitative accurate numerical data. The count of stones, the position of the lapidary signs or putlog holes, can give indications about construction techniques, the progress of work in the 16th century, or later reworking. The use of different types of stones depending on the period, or the location of different types of stones on the building (structural role, technical, aesthetic…) are clues of interest for archaeologists and historians, especially if they are related with a 3D representation of the building.

3.2.2 Crossing Data and Application to the Heritage Conservation

The NUBES database enables to save a huge amount of data in the fields of archaeology, history, scientific preservation, etc. But its main contribution is the capability of cross-referencing these data, usually treated separately, in each discipline.

For example, by cross-referencing the mapping of damage with the layer of matrix stone by stone, it is possible to know if a specific degradation concerns only stones, or both stones and mortar joints. By combining mappings of degradation with mappings of nature of stones, it is also possible to observe the relation of degradation, with one or more types of stones. Finally, crossing mappings of degradation with mappings of stone dating allows to know if the damage preferentially affects old or recent stones. Data cross-referencing can then be quantified through statistical analysis tools. In the first span of the tower, as well as in the entire castle, biological colonization affects all kinds of stones and are independent from the date of stones. Flaking is not based on the stone dating, but affects only the fine-grained limestone (tuffeau limestone and Richemont limestone). Finally, spallings only affect original tuffeau limestone.

After the recording and processing of cartographic aspects, the future step would be the simulation of the evolution of damages. Indeed, in the mappings, contour degradation is reproduced in vector drawing. As geometric features can be extracted from its shape, a possibility is to apply to this form, automatic transformations, that would follow several criteria defined by the observation of physical aspects. As matter of example, it would be possible to increase the weathered surface, while limiting or slowing down the expansion when the degradation lies near a mortar joint or a stone of another nature. By defining the position of the mortars, the stone by stone drawing is a key element to illustrate this evolution. It is necessary to integrate a temporal concept to these evolutionary patterns, however, for now it is still difficult to define, without (the contribution of the) experimental and numerical simulations.

Finally, the system of data storage in NUBES allows to associate items to mappings and to locate them precisely: this is the case for sampling and analysis results of degraded stones, or restoration reports showing the date of replacement of stone and the quarry exploited for restoration.

Once adapted to the needs, the NUBES platform represents an entirely digital health record of the state of conservation of buildings. NUBES is primarily a system associated with a dynamic and therefore progressive database: unlike written reports or database on CD-Rom, data can be upgraded, extended, and shared via online interface. In this way, results are available to all professionals of heritage preservation concerned with the history and the conservation of the castle of Chambord.

4 Conclusion

A better comprehension of the past of a monument is possible through the study of historical archives and in situ observation. In this specific case, several years of research contributed to bring to light the history of stones of the castle of Chambord, by knowing their dating, type, origin, and state of degradation. All these elements contribute to the establishment of the health record of the monument.

The 3D model of the tower provides support to the collected data. It was necessary to combine the 3D model with a database to store the collected data, to cross them for analyse them. NUBES system was used. In addition to the navigation in the 3D scene, an interface allows the vector drawing on the elements of the facade. Drawn information is structured in layers of hierarchical levels. Each layer corresponds to a colour code to locate on the facade, the areas covered by a layer. The mapped information can then be projected onto the 3D model to visualize its spatial distribution. Statistical analyses can be performed to precisely quantify the area proportion for each layer. Moreover, the most interesting application is to cross the different layers to statistically test spatial correlations. This latest application can be useful to produce quantification of hypothesis, like the particular sensitivity of a stone to a specific degradation, or the typical age of stones subjected to a type of degradation. This digital health record allows to combine all these accumulated data, to confront them and extract useful information to different professional people of heritage preservation.

Future researches related to the use of a multi-dimensional database for the preservation of cultural heritage are various. Infrared thermography for example is a method of non-destructive diagnosis widely used in the study of monuments, and the intersection of these data with visible data already mapped is a prospect of work. Similarly, for the moment, this system allows the recording of data related to the past and the present state of a monument. The prospect of include temporal data in connection with the future evolution of damage over time, for example, constitutes a major interest for curators to predict risk areas and organize restoration operations of the monument.

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Onna Project: A Natural Interaction Installation and Mobile Solution for Cultural Heritage

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Abstract This paper describes the design and development of Onna—Past, Present and Future, a multimedia installation for the museum of Onna (L'Aquila, Italy), a space dedicated to the memory of the town affected by the earthquake in April 2009. Our work consists of a natural interaction system, a user profiling system and a mobile application integrated together in order to provide visitors of the museum a multi-modal experience of the events related to the disaster. Tourists and citizens of Onna are for first invited to visit the interactive installation in which multimedia assets about history, architecture and life of the town are presented. User activity is recorded by a profiling system in order to extract a profile of interest for each visitor. In a second stage of the experience users leave the museum and visit the town. They can start the application on their smartphone, which connects to the indoor profiling system via an Internet connection and then shows suggested personalized and geo-located in-depth information based on the actions performed during the session with the interactive exhibit in the museum.

1 Introduction

In the last years art curators have become more and more aware of the need to provide visitors with an augmented experience while visiting exhibitions and museums. New models of art installations have been proposed via the adoption of advanced digital technologies, like multimedia environments, touchscreen systems and mobile applications. In this paper we present Onna—Past, Present and Future, a multimedia installation and a mobile solution designed and implemented for the museum of Onna, a small town close to L'Aquila (Italy), which was completely destroyed during the earthquake in 2009.

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The whole community of Onna has been working since many years not only to physically reconstruct the town, but also to give local citizens and visitors a clear and strong message of hope for the future. To address this issue the non-profit organization Onna Onlus has built a museum in which the life of Onna before the terrible earthquake is described and presented to visitors. A special area of the museum, called Infobox, is equipped with multimedia technologies and interactive systems with the aim to properly show the past events and raise awareness of the efforts invested in the work of reconstruction. In this environment visitors of the museum can interact with a natural interface system and then discover information about the history of the earthquake via digital content. A large collection of information is showed in audio/video format to tell the stories of these last years: interviews with people who directly lived those dramatic moments, images of Onna before and after the disaster, maps visualizing the altered geography of some places in the area all around the town. While interacting with the system, the activity of each visitor is recorded by a profiling system, which extracts a dedicated profile of interest. At the end of the visit of the Infobox an additional experience is offered to the visitors of the 'real' town using their mobile devices. They have the chance to activate a dedicated application properly installed on their smartphone, which communicates via Internet to the indoor profiling system and shows suggested personalized and geo-located in-depth information based on the actions performed during the session with the interactive exhibit.

This paper is organized as follows: in the next section we explain the indoor system in detail; in Sect. 3 we describe the solution implemented for the outdoor experience. Finally, in Sect. 4 we discuss conclusions of our work.

2 The Indoor System

The indoor system consists of an immersive space composed of a natural interaction system (Fig. 1), which allows visitors to interact with multimedia contents, and a user profiling system, which records the actions of visitors in order to create a bag of information to be used by the outdoor system through the mobile application. Currently the user profiling system is in an experimental state and is being tested in order to be installed soon in the Infobox.

2.1 Natural Interaction System

Natural interactivity permits to display the village situation during the days immediately after the earthquake. Users can touch onto zones of the village and view how they were before the tragedy and watch related multimedia materials, with interviews and stories. In this way an emotional drive is provoked in the visitor so that he/she can emotionally participate to the event: a small touching gesture that can metaphorically restore life from rubble.

Fig. 1 The installation is composed of a central interactive rear-projected screen and two lateral screens used for displaying non-interactive multimedia contents

The village area is divided into 8 different zones. As one of them is selected, the multimedia items that are referred to that zone are displayed in a vertical interactive carousel. Items are displayed video clips and have been realized in collaboration with RAI (the italian TV network) and N-TV (a german TV network).

100 different video clips have been developed: 32 include images with local sentences taken from literature, local traditions, poetry, 6 videos taken before the earthquake, 10 collections of scenes recording first assistance and rescue immediately after the earthquake, 4 interviews with technicians and 7 with engineers in charge of the reconstruction, 2 press records, 33 interviews with local citizens. Finally, 6 video clips have been also included that report the official visits of the Holy Father Benedetto XVI, the President of the Italian Republic Giorgio Napolitano, and the Chancellor of German Republic Angela Merkel with the Ambassador Michael Steiner.

The system is composed of a central large display made with a slab of opaque plexiglass and a short throw projector illuminating it from behind. At the two sides of the main screen, are positioned two opaque panels illuminated by two projectors installed in their upper part, in order to have two lateral displays. A stereoscopic camera placed behind the central display captures the interaction in the front area in real-time, recognizing gestures and then processing them through a Computer Vision module based on diffused illumination technique (Baraldi et al. 2009). In order to make vision sensing reliable and robust to light changes in the environment, the cameras works in the near infrared spectrum and the scene is illuminated with NIR lights.

Fig. 2 The user interface of the installation presents an aerial view of the town after the earthquake. Visitors can move the hand close to a zone of the town and visualize the pre-earthquake status. For each selected zone a carousel of images is shown, which can be activated with the same gesture in order to start the playing of video stories on the lateral screens

The natural interface presents the post-earthquake map of Onna visualizing pre-earthquake areas when the hands of the visitor are close to the surface of the main screen (Fig. 2). For each selected zone the interface shows a carousel of images as thumbnails, which can be activated via gestures by the visitor in order to start the play of multimedia contents on the lateral displays. These contents consist of videos and texts reporting the history of the town through testimonies, interviews and institutional events.

The software module supporting user interactivity with the display has been developed as a Rich Internet Application in Adobe AIR technology. The user interface was build with Adobe Flash Builder, using Action Script 3.0 programming language. Multimedia assets are composed of full HD videos encoded in the H.264 compression format and are streamed locally via progressive download technique.

2.2 User Profiling System

The system features a profiling layer that fulfills two main goals through specific modules: (1) to identify where the user is located with respect to the two areas that comprise the interactive environment (with an experimental position detection module, not yet used in the current installation), (2) to record the interactive session for each detected user (natural interaction module) in order to build a user profile of interest. This profile of interest is used for content filtering and interests targeting in the mobile application developed as part of the outdoor system.

The position detection module exploits RFID technology. Each visitor of the Infobox will be equipped with an RFID passive tag (two solution were experimented: a badge attached to a collar around the neck or mounted horizontally on headphones).

Two antennas positioned at the sides of the installation detect if users are interacting with the right or the left area of the interface through an SVM classifier. The module estimates the distance reasoning on data readings from the antennas and uses as primary input the Received Signal Strength Indicator (RSSI) (Zhao et al. 2006).

The detection of the users position in front of the natural interface is used to associate their identities to the interactive sessions. Data of the interactions are extracted through collaborative filtering techniques (Resnick et al. 1994). These techniques are essential for the filtering and customization of content in multimedia systems. They work through building a database of user preferences for content items. User preferences are exploited to identify other users with similar behavior in a user based recommendation scenario, or to compute relationships between pairs of items through a co-occurrence matrix in an item based recommendation system. In this way new items can be recommended to the current user as he probably will be interested. In the Onna project the profiling module utilizes an hybrid CF in the sense that the module combines a memory based approach, which uses an item based recommender, with a model based one that analyzes the common features among the contents selected by a visitor. The hybrid CF doesn't use explicit ratings data to compute similarity between items but the data are implicitly inferred by the system observing user behaviors during their interactive sessions with the user interface.

User profiles computed by the hybrid CF module are then used by the outdoor system in the process of content generation to recommend personalized multimedia content and real-world points of interest to people using the mobile application.

3 The Outdoor System

In order to enrich the visitors experience during their outdoor exploration of the town, a cross-platform mobile application was developed with the aim to suggest points of interest and offer additional related multimedia contents.

The application proposes some real-world itineraries and geo-localized points of interest, suggesting some itineraries based on the user's interest profile. When a visitor approaches one of the proposed geo-localized point of interest, the mobile application notifies it and provides multimedia contents and some associated in-depth contents. In this way we offer visitors multi-modal ways to enrich their experience.

3.1 Mobile Application

A location-based service paradigm was exploited, using geographical information from mobile devices via GPS. The GPS module of the modern smartphones (Zhao 2002) allows the application to detect the user's latitude and longitude with a certain accuracy, that may change due to the device capabilities or the strength of the signal received.

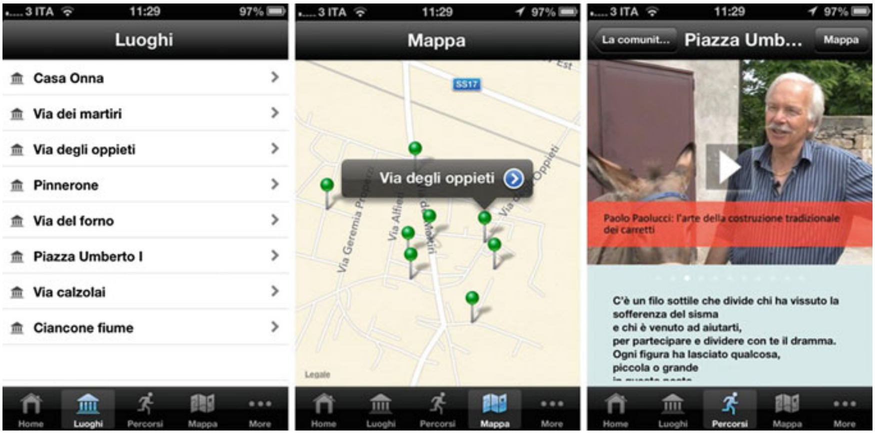

Fig. 3 The mobile application proposes a collection of points of interest displayed as list (on the *left*) or as a map (on the *center*). For each POI a gallery of multimedia contents is provided. (on the *right*)

The app provides a collection of places inside Onna that can be visualized both as a list ordered by distance from the user or as a map (Fig. 3). For each point of interest contained in the collection, users can browse a gallery of related multimedia contents, such as pictures, historical videos or interviews, and future plans of reconstruction. Places are also organized in routes, that can be both pre-defined or dynamically generated by the recommendation module. Predefined routes have been created along with Onna Onlus in order to create thematic visits through the town. Personalized routes can also be generated exploiting the profiling layer, feature that has not yet been added in the real installation. Users can associate their RFID-enabled ticket to the mobile app (e.g. using an unique ID). The application retrieves from a web server a list of geo-referenced points of interest based on the user profile. Then, using the Google Maps API direction service, a personalized walking itinerary is proposed to the user together with in-depth related multimedia content. In this way the system can use the interaction history of the user in order to create and suggest itineraries through the town.

The app was developed using the Titanium Appcelerator framework and the Javascript programming language, and can therefore be deployed for Apple iOS devices and for Android smartphones.

4 Conclusions

In this paper a proposal to enhance the experience of visitors in a museum environment was presented. Our solution consists of an interactive installation based on a natural interaction paradigm, a system to estimate each visitor interest during the interaction with the installation and an outdoor system based on a mobile application. Thus a visitor can live a multisensory, cross-modal and multi-located experience discovering the history of a dramatic event which caused some years ago the devastation of the small town of Onna in Italy. On April 6th 2013 the system was installed in the Infobox space in the new museum of Onna, at the presence of the mayor of L'Aquila and other institutional representatives.

Acknowledgments The work project was developed in collaboration with Onna Onlus and RAI. The authors would like to thank Gabriele Corsinovi for his contribution to the development of the mobile application and Nikrooz Hosseini for the selection and organization of multimedia assets.

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Digital Storytelling for Cultural Heritage: A Modular, Multi-channel, Multi-scenario Approach

Michela Negrini and Nicoletta Di Blas

Abstract Digital Storytelling is emerging as "the" way to engage cultural heritage institutions' visitors, both virtual and real. The wide spreading of media and devices have made stories the most expected way to talk about culture: a "traditional" webpage is distractedly read on the screen or (in the best of cases) printed for later reading; a multimedia story, instead, can be listened to in various situations: in front of a PC at home but also in the street, on a train, sitting at a café, while visiting cultural venues, etc. This paper introduces a specific approach to digital storytelling that is modular (in the sense that the various content elements can be combined in different ways), multi-channel (in the sense that the "stories" can be delivered online and off-line, over all modern channels and devices) and multi-scenario (in the sense that various user scenarios can be covered). All of this at a reasonable cost/effort. This approach is supported by a tool, developed by HOC-LAB of Politecnico di Milano in cooperation with TEC-Lab, Università della Svizzera italiana, named "1001 stories". 1001 stories has been used to produce more than 30 professional stories, mainly in the field of cultural heritage.

1 Introduction

Communication to the broad public is not always felt by museums professionals as a core issue; others are the issues that—rightly or not—pressure curators more. One of these is preservation (at least in countries like Italy); indeed, the very word "curator" literally means "the one who takes care". Sometimes this cumbersome task, made more challenging by a chronic lack of resources, makes those who "take care" forget

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that artifacts and objects are not being preserved for their own sake, but for the sake of someone who may enjoy them, marvel at them, learn from them, etc.: the large public. It is for them, that culture is preserved and it is to them that, first and foremost, cultural heritage professionals should address their communication.

However, today cultural heritage communication appears instead as follows: scholars, researchers and curators alike tend to interpret “scientific communication” as the best, for all different audiences; cataloguing is considered as a necessity while valorization is felt as the “son of a lesser God”, maybe due to its argumentative nature (it must “persuade” people who are not experts that what they are seeing is valuable) that makes it akin to marketing (something perceived as definitely “not proper” for culture) (Table 1).

This paper argues that the hierarchy of relevance should be changed and that valorization should be felt as a primary concern for museum professionals. Valorization means to “generate value” for the addressee; it means making efforts so as people who are not aware of the cultural value of an object, venue, collection, place… begin (1) being aware of (2) appreciating (3) understanding (4) caring for and (5) wishing to get into contact with what is being communicated: a museum, an archeological park, a monument, a church, a cultural institution, specific objects, specific collections, an exhibition, …. This increased value-perception cannot but be beneficial to all: to people’s life-long education through art and culture and to the institutions themselves that become more known to the community at large who may thus start to “take care” of it.

But how can a cultural institution effectively convey its value?

Digital storytelling is emerging as an effective and feasible way to answer this need. Digital storytelling is a vast field, spanning various domains, from sociology (e.g. for memories’ preservation) to education. It has recently witnessed a boom of interest in the field of cultural heritage (see section on “state of the art”).

Stories are by their nature what we are most keen on listening to, like McKee said: “Story is not only our most prolific art form but rivals all activities—work, play, eating, exercise—for our waking hours. We tell and take stories as much as we sleep —and even then we dream. Why? Why is so much of our life spent inside stories? Because, as Kenneth Burke tells us, stories are equipment for living.” (McKee 1997).

Table 1 Different kinds of communication for cultural heritage

Context of communication	Target	Topic	Style
Research	Experts	Scientific data (about analysis, diagnostics, excavations, studies, comparisons…)	Scientific and objective (detached)
Management	Ministry, authorities	Data about management (e.g. cataloguing data)	“Administrative”: objective and detached
Valorization	Large public	Interpretation of the cultural value	Warm, subjective and involving

In this paper, we present our approach to digital storytelling for cultural heritage: an approach that goes with a tool (1001 stories) allowing the creation of multimedia, multi-channel stories in a reasonable time, with a reasonable effort and without requiring specific technical competences. First, we will go through the basics of literature about digital storytelling for cultural heritage; then, we will describe our approach, the 1001 stories tool (requirements, design and implementation) and a case-study of use. Eventually, we will draw our conclusions in the last paragraph.

2 State of the Art

Digital storytelling is only recently emerging in the cultural heritage field as a powerful way to engage visitors, with two main interpretations: first, it is conceived as a better-channeled form of "user-generated content" (which was extremely popular 6–7 years ago). Visitors, instead of being asked to generally express their opinion or comments, are asked to tell a story about something (e.g. an object of their own or an object on display in the museum). The second interpretation sees curators and experts "telling stories" about cultural topics in a web 2.0 way (i.e. in a somehow "improvised", relaxed style). Let us see some examples of both.

"Object stories" was launched in March 2010 by the Portland Art Museum. Object Stories invites visitors to record their own narratives about personal objects —whether a piece of clothing, a cherished record album, or a family heirloom. The stated goal is "to demystify the Museum, making it more accessible, welcoming, and meaningful to a greater diversity of communities—while continuing to highlight the inherent relationship between people and things". Nearly one thousand people from throughout Portland have participated as storytellers in this project. There is also a more professional version of the project, since the Museum has also produced a series of Object Stories that brings out personal perspectives on selected objects in the permanent collection, from the museum staff, local artists, and cultural partners. People have to bring an object they care for to the museum, enter a recording booth and tell the story of what the object is and why they care for it, answering a predefined set of simple questions. As they do so, pictures of them are taken: the final story is thus made up of the audio plus a slideshow of snapshots (Burns and Murawski 2013).

"100 toys" is a story-collecting project by the Children's Museum of Indianapolis. The Children's Museum searched its collection and chose 100 of the most iconic objects of American childhood in the last century. After over 24,000 votes, the online visitors chose a list of "Top 20 toys" that define childhood. In the fall and winter of 2012–2013, these 20 toys were featured in a special display at the museum, alongside selected stories from the over 600 submissions received (www.childrensmuseum.org/100toys).

ArtBabble, the cloud-based, international art video partnership, is an example of professional storytelling. It was initiated and administered by the Indianapolis Museum of Art. It hosts hundreds of videos and additional materials about art in a wide sense. At the time of writing, it brings together 54 international partners and has evolved towards a model that can accommodate even further growth. The partners can manage their own content, and add external video by embedding video from other sources (Painter and Fauconnier 2013).

Storyscope is another example of professional storytelling. Storyscope is a web-based environment for the construction of museum narratives, which links a final narrative to the underlying story and plot, thus allowing end-users the ability to see the thought-processes of the curator and to develop their own personalised narratives. Storyscope supports a narrative author in story building by proposing additional events, and relations between events, for developing a plot of the story (Wolff et al. 2013a, b).

3 Our Approach to Digital Storytelling

Our approach to digital storytelling was developed in 2006 and has evolved since then. It was driven by both cultural and practical requirements. From a cultural point of view, it had to support:

- pleasurable and light-weight approach to cultural topics
- quick reaction to needs (e.g. an exhibition, a special event)
- focus on niche target and content (e.g. “children”, “foreign visitors”)
- easy update of new content
- easy elimination of obsolete content
- From a practical point of view, it had to allow:
- efficient use of a limited budget
- scalable use of budget (low budget –> few productions; high budget –> more production)
- fine-tuning with new trends and technologies.

The result was called “Instant Multimedia” (Di Blas et al. 2007; Campione et al. 2011) to stress the similarity with the instant books phenomenon and the distance between this new kind of production with respect to traditional, long term productions like catalogues and standard websites. At the core of the Instant Multimedia approach stands a tool developed by HOC-LAB at Politecnico di Milano in cooperation with TEC-LAB of Università della Svizzera Italiana called “1001 stories”, described in the next paragraph.

3.1 The 1001 Stories Tool

1001 stories is an authoring, generation and delivery tool that supports the production of multimedia, multi-channel “stories”. 1001 stories was first developed in 2006 and has evolved since then; a new version is bound to be released in September 2013.

Fig. 1 A multimedia story over an interactive table (*left*); a multimedia story over smartphone, used as interactive guide in an exhibition (*right*)

Ideally, 1001 stories has 3 main components:

an authoring environment (which was previously written in PHP and Java Script and is now being rewritten from scratch using Python and web2py) where the various pieces of content are authored;

a generation engine that generates the proper information architecture, organizing the content items in a structure suitable for the final delivery. The information architecture is described via a number of JSON files, according to the various versions envisioned;

a delivery engine, implementing the various interactive formats over various platforms (audio guide, multimedia guide, web version, web for smartphone, app, etc.—see Figs. 1 and 2). The delivery engine is conceptually separated from the generation engine, though "physically" it is a part of it.

While the technical environment is complex, the user interface is quite basic: 1001 stories is also used at school (at all levels) to create multimedia narratives (more than 1,000 created so far), and the average time for mastering the tool is 20–30 min (Di Blas and Paolini 2013).

The stories done with 1001 stories are delivered over various channels and devices, both online and off-line: web for PC, web for mobile, podcasts, iPad (and tablets in general), multi-touch tables, YouTube, standard phone (with audio-only content), paper (brochures and posters), etc. Thus, the stories can support diversified user scenarios.

The stories are composed by visual, audio and textual content. The visual component can be either a slideshow of images, a video or an animation. The audio is a cultural comment about a given topic. The text is typically the audio's transcript, visible on demand. Each story is composed by a number of content items, of reasonable length: the audio for each element lasts between 1 and 2 min at most.

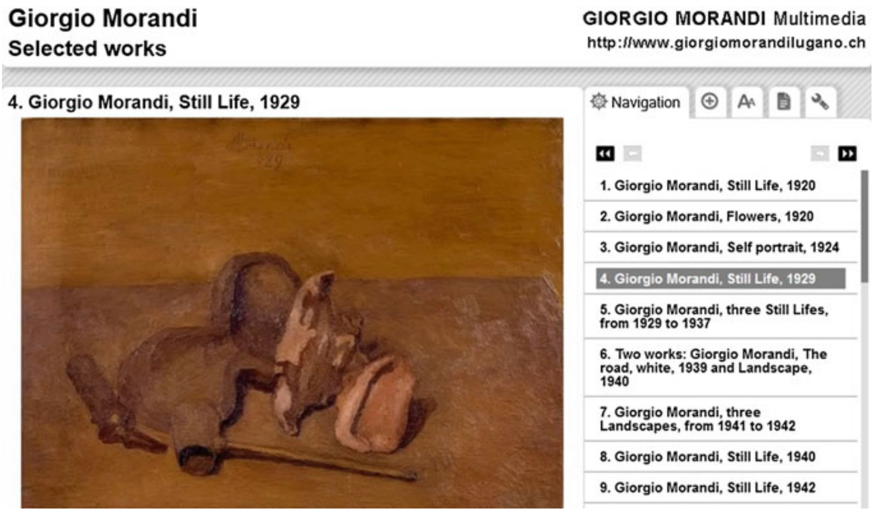

Fig. 2 A multimedia story featuring an art exhibition's catalogue

The final result is an interactive story composed by light-weight, interesting "chunks" among which the user can navigate.

3.2 Content Production and Re-use

The second element of the "instant multimedia" approach regards content production: the starting point for gathering content are interviews to the experts (curators, historians, artists…) that are then transcribed and boiled down to their essence. The overall transcript is divided into specific content items the text of which gets refined to adapt it for oral and interactive performance and fruition (e.g.: syntax gets simplified, each element is made semantically "independent" from the others, etc.). This method has a number of advantages:

- experts are much more pleasurable and easy to understand when they talk in a relaxed dialogue with an interviewer than when they are asked to write;
- the oral style of the initial interview fits the multimedia format (where fruition is oral) much better than a written text;
- it takes less time to interview an expert, revise the text and ask for her assent than asking the expert to write a text about a given topic;
- A 2–3 h interview can provide the bulk of a medium-sized story: production can thus move on in quick time.

Content items are conceived as building blocks pieces that can be combined to support a number of user scenarios (going with different devices/channels) without the need of sitting down and re-creating the content from scratch. For example, from a story about an exhibition the multimedia guide can easily be created by just adding information on how to move from one piece to another: the main pieces of content (comments about the exhibition's themes, descriptions of the works of art…) are done once and for all, all that is needed is just adding new pieces. This makes the approach quite sustainable and at the same time very modern, since it allows an effective delivery over various channels without any loss in communication quality.

4 An Example

More than 30 stories have been developed in the round of 7 years, mostly about cultural heritage. We shall recall here one example: a multimedia story developed in 2012 on "Giorgio Morandi", an exhibition held at Museo Cantonale d'Arte and Museo d'Arte in Lugan (Switzerland), from March 10th to July 1st, 2012. The exhibition, throughout a corpus of approximately one hundred works, traced a line along the most significant moments of Morandi's production. Three interlaced "stories" were created to introduce visitors to the exhibition: one about the exhibition's themes, one about the techniques used by the artist and a "catalogue" with the works of art on display (Fig. 2).

The Morandi story is a good example of re-use of content for different scenarios: the content items about the works of art were re-used to create a virtual tour about the exhibition (Fig. 3).

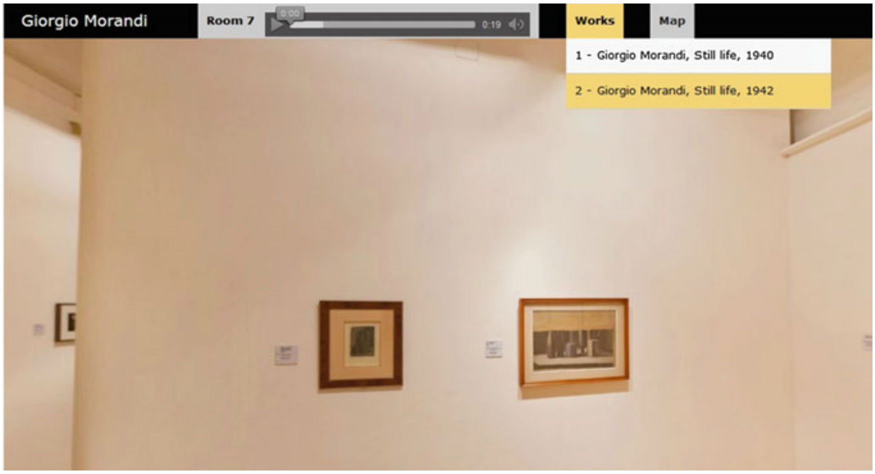

Fig. 3 The multimedia stories (accessible through the links under "work") are re-used in a virtual tour

5 Conclusions

It is our opinion that, at a time of crisis as the one we are facing, cultural institutions should not give up the task of communicating the value of what they preserve, rather, they should enhance it. There are feasible ways to do so, even with a small budget: 1001 stories is one of them. Communication will endear cultural heritage to people and ultimately, and hopefully, lead them to care about the institutions and support them, as is common practice in many countries around the world.

Our future work includes the creation of a set of narratives around Leonardo Da Vinci and the Sforza Castle, where he conceived and painted an incredible fake green room, the so-called "Sala delle Asse". A lot of mystery surrounds this masterpiece, for centuries covered by white painting, where pained trees grows up to the ceiling, entangled with leaves, berries and knotted ropes. We are already gathering very compelling stories from the experts involved in the restoration. In addition, on the technical side, we are about to release version 2 of the tool: it will be even more flexible into supporting people with very basic technical background into creating multimedia and multi-channel stories fitting various scenarios of use. The releases is foreseen for September 2013.

Acknowledgments The authors warmly thank all the people in their labs: HOC-LAB (Milan) and TEC-Lab (Lugano) and especially Paolo Paolini, scientific coordinator of both labs, who conceived the approach and the tool.

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Part V
Development and Testing of Conservation Treatments

Consolidation of Carrara Marble by Hydroxyapatite and Behaviour After Thermal Ageing

Enrico Sassoni and Elisa Franzoni

Abstract In this study, the use of hydroxyapatite (HAP), recently proposed for limestone consolidation, was investigated on unweathered and artificially weathered Carrara marble and the behaviour of HAP-treated samples towards thermal weathering was evaluated, by means of an accelerated thermal weathering test. The results of the study indicate that HAP is a very promising consolidant for marble, able to significantly improve mechanical properties without substantially altering pore size distribution and to provide some mitigation against thermal weathering.

1 Introduction

Architectural elements and sculptures made of marble are threatened by several weathering processes that can severely affect marble durability. These weathering processes can be distinguished in (Amoroso and Fassina 1983; Fassina et al. 2002; Malaga-Starzec et al. 2006):

- *Physical weathering*: calcite crystals are characterized by a strong anisotropic behaviour when subjected to a thermal variation, expanding parallel and contracting perpendicular to crystallographic c-axis (Siegesmund et al. 2000). Consequently, repeated thermal excursions can induce stress inside marble, resulting in micro-cracks formation and porosity increase (Siegesmund et al. 2008). Thermal weathering is responsible for phenomena such as grain decohesion and detachment, leading to the so-called "sugaring" of marble (Fig. 1), and bowing of marble slabs (Siegesmund et al. 2000; Siegesmund et al. 2008; Royer-Carfagni 1999; Luque 2010).

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Fig. 1 Sugaring marble elements in the monumental cemetery in Bologna (Italy, 19th century)

- *Chemical weathering*: after micro-cracks opening and porosity increase induced by thermal weathering, marble exhibits a higher water absorption, which exposes marble to the degradation effects of clean and acid rain, as well as gaseous pollutants, which can penetrate deep into the stone through the developed intergranular spaces (Franzoni and Sassoni 2011; Charola et al. 2010).

For reestablishing cohesion between calcite grains and hence restore marble mechanical properties, several consolidants have been tested through the years. Organic consolidants, such as acrylic and epoxy resins, although rather effective in improving marble compactness, are generally regarded as unsuitable because of compatibility and durability issues (Accardo et al. 1981; Wheeler et al. 1992). Consequently, research has recently focused mainly on inorganic consolidants. Alkoxysilanes, such as TEOS, have been found to be quite effective in stabilizing sugaring marble, as they deposit silica gel in the fissures between calcite grains, so that grain movement is impeded (Wheeler 2005). However, silicate consolidants have the limitation of not bonding chemically to the calcitic substrate (Wheeler 2005) and were found to lose their efficacy when consolidated marble samples were subjected to artificial weathering tests (Verges-Belmin et al. 1992), so that silicate consolidants are currently regarded as not fully suitable for marble consolidation (Charola et al. 2010). Ammonium oxalate has recently been used for consolidating sugaring marble, however it was found to offer insufficient long-term protection, which led to apply a lime shelter coat over ammonium oxalate-consolidated marble (Charola et al. 2010). From the experiences briefly described above it comes out that a fully satisfying treatment for marble consolidation is not currently available, therefore in this study hydroxyapatite was investigated as a possible new consolidant for marble.

Hydroxyapatite (HAP, $Ca_{10}(PO_4)_6(OH)_2$), which is the constituent of human bones and teeth, can be formed inside stone by impregnating it with an aqueous solution of diammonium hydrogen phosphate (DAP, $(NH_4)_2HPO_4$), which reacts with the calcitic substrate forming HAP (Sassoni et al. 2011). Thanks to HAP formation inside pores, resulting in a more effective bonding of calcite grains, remarkable improvements have been obtained in mechanical properties of several different substrates, including porous limestones and sandstones (Sassoni et al. 2013; Matteini et al. 2011; Yang et al. 2011; Naidu et al. 2011). Compared to ethyl silicate, frequently used for consolidation of carbonate stones, HAP proved to have the advantage of being effective after a much shorter curing time and causing no substantial alteration in stone porosity and water transport properties (Sassoni et al. 2011, 2013). In the case of marble, HAP has been investigated as a protecting treatment against corrosion in acid rain (Naidu and Scherer 2012; Liu and Zhang 2011). Given the good compatibility of calcite and HAP in terms of crystal structure and lattice parameters, as well as the much lower solubility and slower dissolution rate of HAP, compared to calcite, forming a coating of HAP over marble surface was identified as a possible effective method for reducing its solubility in rain, as confirmed by the first experimental results (Naidu and Scherer 2012; Liu and Zhang 2011).

In this paper, HAP was investigated as a possible consolidant for marble and its effects were evaluated on both freshly quarried marble samples and previously deteriorated samples. Moreover, considering that marble durability is firstly threatened by thermal weathering, the behavior of HAP-treated samples when subjected to accelerated thermal weathering was investigated.

2 Materials and Methods

2.1 Freshly Quarried Marble

Because of its wide use in historical architecture and sculpture and its high sensitivity to weathering processes, Carrara marble (CM) was selected for this study. As the largest part of studies reported in the literature actually made use of CM (Siegesmund et al. 2008; Accardo et al. 1981; Wheeler et al. 1992; Verges-Belmin et al. 1992), the choice of this lithotype also allowed a comparison with previously obtained results. Prismatic samples ($30 \times 30 \times 10$ mm^3) of CM with a calcite content of 99.3 wt% were cut from a slab provided by Roncato s.r.l. (Italy).

2.2 Artificially Weathered Marble

Since results obtained on unweathered marble are not necessarily representative of those obtained on weathered one (Wheeler et al. 1992; Sassoni and Franzoni 2014), half of the samples was preliminarily weathered by heating at 400 °C for 1 h, according to a previously developed methodology (Sassoni and Franzoni 2014; Franzoni et al. 2013). In this way, HAP effects could be evaluated on marble samples with characteristics as close as possible to those of naturally weathered marble. The complete set of samples used in the study is illustrated in Fig. 2.

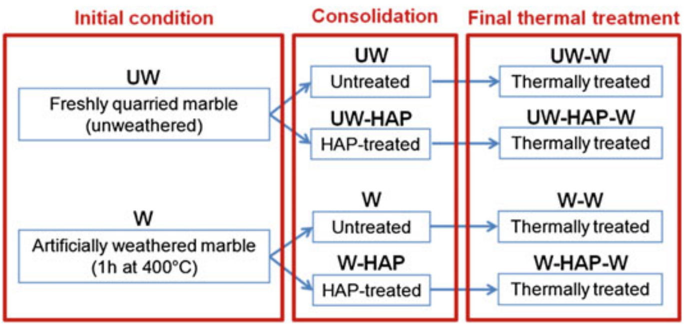

Fig. 2 Scheme illustrating samples and treatments (and respective labels) used in this study

2.3 Consolidation

The HAP-based treatment was applied to freshly quarried samples and artificially weathered samples (Fig. 2) according to the following methodology:

- Firstly, samples were partially immersed in a 3.0 M DAP solution for 48 h, then washed with de-ionized water and dried in room conditions (T = 20 ± 2 °C, RH = 50 ± 5 %) until constant weight (i.e. weight change after 24 h < 0.1 %).
- Secondly, samples were treated with a saturated solution of calcium hydroxide (limewater) applied by poultice (weight ratio between dry poultice and limewater 1:6), evaporation being impeded by wrapping in a plastic film. After 24 h, the samples were unwrapped and the poultice left to dry in contact with the sample, so that possible unreacted DAP inside the sample could be removed during the drying phase. Finally, the poultice was removed, the samples rinsed with de-ionized water and then dried at room temperature until constant weight.

2.4 Accelerated Thermal Treatment

For evaluating the behaviour of HAP-treated samples when subjected to thermal weathering, the same weathering procedure as above (heating at 400 °C for 1 h) was applied to both untreated and HAP-treated samples (Fig. 2).

2.5 Characterization Techniques

The treatments effects were evaluated in terms of modifications in ultrasonic pulse velocity (UPV), which in marble has a strong correlation with compressive strength (Verges-Belmin et al. 1992; Weiss et al. 2002; Pamplona et al. 2012) and is a non destructive test, that can be repeated on exactly the same sample after artificial weathering or consolidation, and in terms of pore size distribution determined by mercury intrusion porosimetry (MIP). UPV was measured on prismatic samples by transmission method, using a Matest instrument with 55 kHz transducers. MIP was performed on fractured samples obtained from the same samples as the UPV test, using a Fisons Macropore Unit 120 and Porosimeter 2000 Carlo Erba. Sample microstructure was observed on fractured samples by scanning electron microscope (SEM), Zeiss EVO 50EP, equipped with energy dispersive spectrometry (EDS), Microprobe Oxford Inca Energy 350. The newly formed phases were characterized by SEM/EDS and by Fourier transform infrared spectroscopy (FT-IR), using a Perkin–Elmer Spectrum One FT-IR Spectrometer. FT-IR was carried out using the KBr pellets method on samples taken by chisel from depths of 0–1 mm (“surface”) and 4–5 mm (“inner”, corresponding to the centre of sample volume) from the treated surface and then ground.

3 Results and Discussion

3.1 Effects of Artificial Weathering

The variations in UPV after heating are reported in Fig. 3. A dramatic decrease (−63 %) was found for weathered marbles, which, according to (Pamplona et al. 2012), passed from the “fresh” condition to the “danger of breakdown” condition. As can be observed in Fig. 4, this was caused by micro-cracks that opened in heated samples as a consequence of the anisotropic behaviour of calcite crystals subjected to thermal variations (Siegesmund et al. 2000). Cracks observed by SEM have an average width of ∼1 μm, in good agreement with results found by MIP, i.e. a shift of the average pore size from ∼0.1 to ∼1 μm (Fig. 5a) and an open porosity increase from 0.3 to 1.3 %. Such alterations closely resemble those exhibited by naturally weathered marbles (Siegesmund et al. 2008), which confirms the suitability of the adopted artificial weathering method.

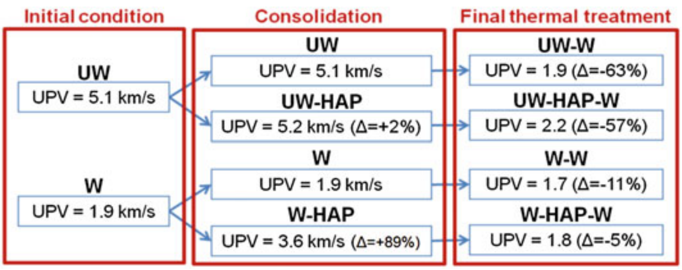

Fig. 3 UPV of the samples and UPV variations (Δ) referred to the relevant initial condition

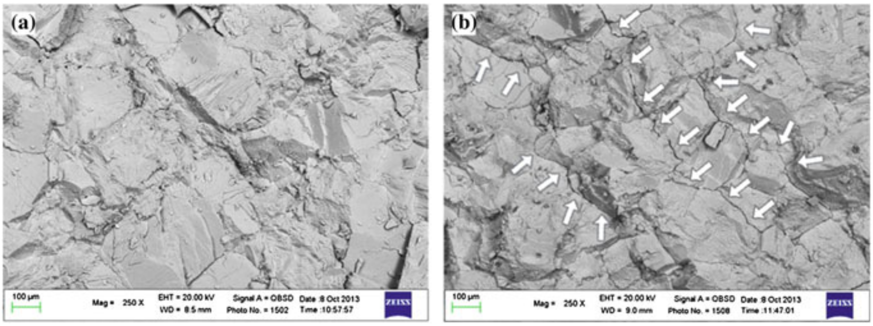

Fig. 4 SEM images of unweathered (**a**) and artificially weathered (**b**) samples (*white arrows* in **b**) indicate micro-cracks opened after heating)

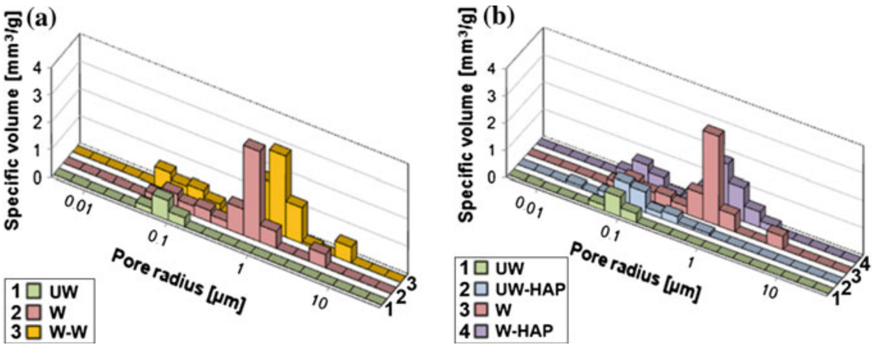

Fig. 5 Modifications in pore size distribution as a consequence of artificial weathering by heating (**a**) and consolidation by HAP on unweathered and weathered samples (**b**)

After heating for the first time, reheating at the same temperature caused no significant additional modifications in UPV (Fig. 3) and pore size distribution (Fig. 5a). This is due to fact that, after the first heating, micro-cracks developed in the sample, so that calcite crystal deformation can be partly accommodated in the new voids, resulting in reduced stress and reduced additional micro-cracks (Sassoni and Franzoni 2014).

3.2 *Effects of Consolidation*

The effects of consolidation by HAP are reported in Figs. 3 and 5b.

In the case of the unweathered samples, a very limited increase in UPV was found, because the very dense microstructure of unweathered CM (open porosity = 0.3 %) did not allow the DAP solution to penetrate deep into the samples.

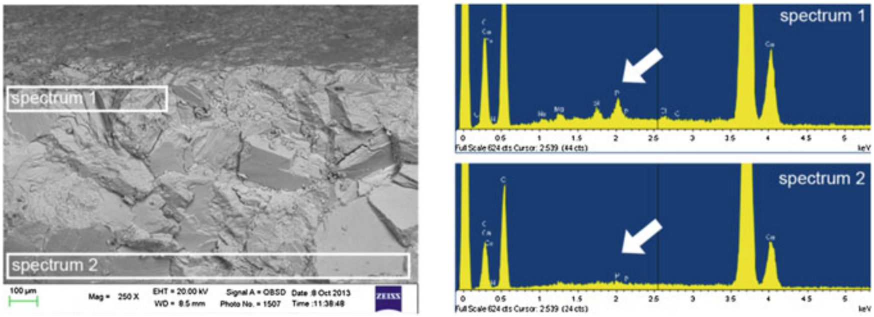

Fig. 6 SEM image of an unweathered, HAP-treated sample and EDS spectra collected in the areas indicated in the SEM picture (*white arrows* indicate the phosphorus peak)

Accordingly, SEM/EDS analysis detected phosphorus peak near sample surface but not at a higher depth (Fig. 6). As a matter of fact, unweathered CM basically needs no consolidation and consolidant penetration is hence hindered (as found also for silicic acid ester applied on unweathered CM (Leroux et al. 2000)). This confirms the importance of testing stone consolidants on suitable weathered samples.

On the contrary, in the case of the preliminarily weathered samples, HAP caused a remarkable increase in UPV (+89 %) (Fig. 3). According to the classification reported in (Pamplona et al. 2012), HAP-treated samples returned to the "increasing porosity" condition, which is the lowest level of marble alteration. Such consolidation effect was possible since, in the cracked microstructure of the weathered samples, the DAP solution could penetrate deeper into the stone and, after reaction with the calcite grains, the newly formed HAP could bind the calcite grains. As illustrated in Fig. 7, in the case of the weathered substrate phosphorus peaks were found both near the surface and down to a depth of more than 600 μm. In terms of pore size distribution, no significant alteration was detected after the HAP treatment, as illustrated in Fig. 5b, which is in agreement with results obtained in the case of limestones and sandstone treated with HAP (Sassoni et al. 2011; Sassoni et al. 2013).

In all the samples, the only calcium phosphate phase detected by FT-IR was HAP, as indicated by the bands at 566 and 602 cm^{-1}, owing to P–O bonds of HAP (Fig. 8) (Maravelaki-Kalaitzaki 2005). While definite bands were found for the "surface" samples (depth of 0–1 mm), no trace was found for the "inner" samples (depth of 4–5 mm), which is consistent with the results of SEM/EDS analysis, i.e. a penetration depth of HAP of about 600 μm for the preliminarily weathered samples.

3.3 *Effects of Accelerated Thermal Weathering*

The variations in UPV after the final thermal treatment are reported in Fig. 3. On both unweathered and weathered samples HAP provided some mitigation of the damaging effects of heating, which may be attributed to a stronger bonding between

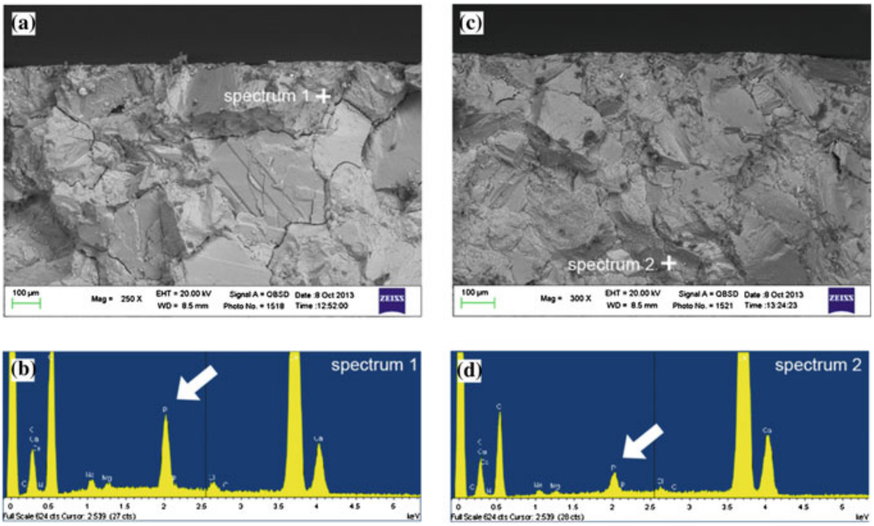

Fig. 7 SEM images of artificially weathered, HAP-treated samples (**a**, **c**) and respective EDS spectra (**b**, **d**) (*white arrows* indicate the phosphorus peak)

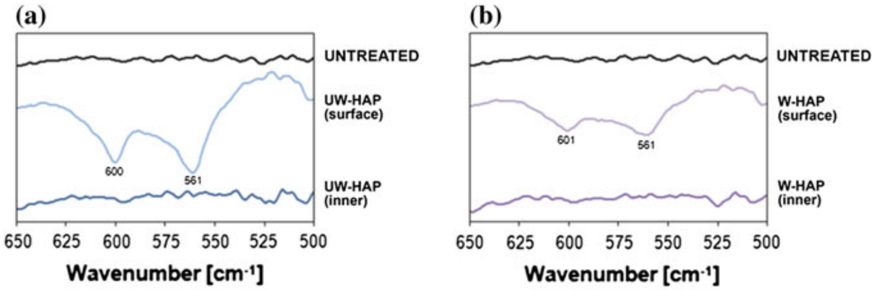

Fig. 8 FT-IR spectra of unweathered, HAP-treated samples (**a**) and artificially weathered, HAP-treated samples (**b**), compared to the untreated reference. Samples labelled as "surface" and "inner" refer to samples taken at a depth of 0–1 and 4–5 mm, respectively

grains promoted by HAP. After heating, modification in pore size distribution of HAP-treated samples was comparable to that of untreated samples (Fig. 9).

Although limited, the mitigation effect of HAP is in line with results reported for other consolidants applied on CM (Malaga-Starzec et al. 2006). Notably, some consolidating treatments were reported to even worsen the behaviour of marble subjected to thermal weathering, as in the case of CM consolidated with polymethylmethacrylate dissolved in xylenes, for which a residual strain higher than that of the untreated references was found after thermal cycling (Ruedrich et al. 2002). Considering that the presence of micro-cracks and voids in stones can partly accommodate calcite crystal deformation upon heating (Sassoni and Franzoni 2014),

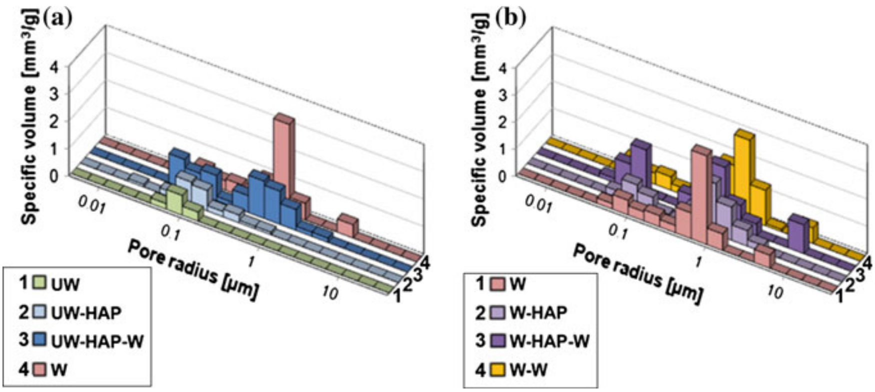

Fig. 9 Pore size distribution of unweathered (**a**) and artificially weathered samples (**b**), both untreated and HAP-treated, after the final thermal treatment

consolidants that significantly occlude porosity may be responsible for a worsening of marble behaviour towards heating. This seems to be not the case of HAP, as it causes no dramatic pore occlusion in treated stone (Fig. 5b).

However, in real field conditions the HAP mitigation effect may be higher than measured in this study. In fact, it should be considered that: (i) HAP and calcite have different thermal expansion coefficients (α_t) (Siegesmund et al. 2000; Hoepfner and Case 2004); (ii) in most calcitic marbles, α_t is non-linear and depends on the temperature interval considered (Siegesmund et al. 2000; Luque et al. 2010); (iii) stress arising at grain boundaries when marble is heated is directly proportional to the temperature variation. Therefore, heating at 400 °C generates high stress inside untreated marble, which is a suitable way for producing samples with characteristics similar to the naturally weathered ones. However, heating HAP-treated samples at 400 °C might exasperate possible α_t mismatch between calcite and HAP, which would not be experienced in the field. Therefore, additional tests adopting temperature cycles closer to the natural ones (e.g. maximum temperature of 80–90 °C (Malaga-Starzec et al. 2006; Ruedrich et al. 2002)) are currently in progress to evaluate the behaviour of HAP-treated samples (in terms of UPV, flexural and tensile strength, resistance to abrasion and tendency to bow) in a more realistic way.

In addition to the possible mitigation of thermal weathering, the HAP-treatment was however found to be very effective in enhancing stone cohesion, which is fundamental for increasing marble durability to other weathering processes, such as salt crystallization, and is expected to substantially increase marble durability to dissolution in rain, which is a further important advantage of this treatment.

4 Conclusions

HAP proved to be effective in improving the UPV of artificially weathered samples (+89 %), without significantly altering porosity and pore size distribution. This is important for increasing marble resistance to weathering processes such as salt crystallization. In addition, HAP formation over marble surface is expected to increase marble durability against dissolution in rain. Encouraging results were also found in terms of behaviour after thermal ageing. Indeed, thanks to its binding action and limited pore occlusion, HAP provides some mitigation effect when HAP-treated samples are subjected to accelerated thermal weathering. Further tests involving temperature cycles closer to those in the field are in progress.

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Characterization of a Newly Synthesized Calcium Oxalate-Silica Nanocomposite and Evaluation of Its Consolidation Effect on Limestones

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Abstract A novel biomimetic nanocomposite was synthesized by the sol gel process in order to reduce the main drawbacks of tetraethoxysilane (TEOS)-based consolidants, such as crack formation upon the drying process and insufficient bonding to carbonaceous substrates. The reaction route involves the addition of a colloidal solution of synthesized nano-calcium oxalate to TEOS producing a crack-free mesoporous xerogel with pore radius of approximately 15 nm, with application to stone conservation. Calcium oxalate which is the main component found on the patinas, was synthesized by the reaction of calcium hydroxide with oxalic acid in the presence of isopropanol. Finally, n-octylamine was added to the mixture, as surfactant. The effectiveness of the new consolidant was evaluated on bioclastic limestones, which are frequently found in historic and modern architectural structures in the Mediterranean basin. The hygric properties and tensile strength of treated samples were improved without affecting either microstructural characteristics or causing phenomena of overstrengthening.

1 Introduction

Over the last few decades, the increase in environmental pollution demanded particular interventions on the building materials of architectural structures and monuments in order to prevent further decay. In this direction, a substantial amount of research has been carried out towards the production of tetraethoxysilane

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(TEOS)-based polymeric resins, to be used as strengthening and protective agents for the porous building materials. This family of materials exhibits many advantages but also several disadvantages such as cracking and insufficient bonding to carbonaceous substrates. To minimize these drawbacks, metal salts, metal colloidal oxides and alkoxides (SiO_2, Al_2O_3, TiO_2) or non-ionic surfactants (n-octylamine) were added to the TEOS-based polymeric resins producing composites with controlled properties (Scherer 1990; Zendri et al. 2007; Miliani et al. 2007; Escalante et al. 2002). The surfactant reduced the surface tension of the solvent and produced a mesoporous matrix with uniform size, thus the capillary pressure was drastically reduced and the cracks during drying were avoided (Mosquera et al. 2008a, b).

The consolidants based on nano-lime dissolved in alcohol offered several theoretical advantages over traditional lime-washes and the desired chemical affinity between product and carbonaceous substrate (Doehne and Price 2010). The presence of alcohol, rather than water, should also limit premature carbonation of the particles and theoretically allow for a greater deposition of material prior to carbonation (D'Armada and Hirst 2012).

Furthermore, the use of calcium alkoxides as an alternative class of compounds to conventional consolidant materials was recently proposed (Ossola et al. 2012). Calcium alkoxides are easily hydrolyzed by atmospheric moisture, leading to formation of amorphous $CaCO_3$ and at higher humidity levels to vaterite and calcite (Favaro et al. 2008). Another inorganic treatment with hydroxyapatite has recently been proposed as a consolidating material for porous limestones and sandstones, where it proved to be effective in binding grain boundaries and improving stone mechanical properties (Sassoni et al. 2011). However, the majority of these new classes of materials refer to laboratory synthesized products; therefore, their performance was limited to the relative case studies. Among the advantages of silicon based materials, what should be emphasized is the adequate penetration depth of TEOS-based resins, as opposed to a series of inorganic products often proposed for stone conservation.

In an attempt to improve the performance of TEOS based materials, a novel nanocomposite consolidant (SiOx) was designed and synthesized based on the modification of TEOS. This modification was derived by incorporating nano-particles of calcium oxalate monohydrate into the silica matrix. Calcium oxalate was selected on the grounds of the remarkable weathering resistance of calcium oxalate layers mixed with silica compounds, often encountered on monuments as patina. In addition, the formation of a stable component, consisting of calcium oxalate and silica, is a well established process occurring in plant biomineralization.

2 Experimental

2.1 *Materials and Synthesis of the Nanocomposite Consolidant*

TEOS, n-octylamine and isopropanol (ISP, puriss. p.a.) were supplied by Sigma-Aldrich, calcium hydroxide (CH) by Fluka and oxalic acid dihydrate (Oxac) by Panreac. Calcium oxalate monohydrate (COM) purchased by LECO, was used for comparison purposes.

The synthesis of the new nanocomposite denoted as SiOx is presented in Fig. 1. This route comprises two steps: (a) the synthesis of a colloidal solution of COM by the chemical reaction of CH and Oxac, in stoichiometric proportions in ISP; (b) the addition of TEOS and n-octylamine into the colloidal solution of COM. The CH and Oxac were dispersed into ISP and separately stirred for 10 min; then mixed and agitated under ultrasonication for 12 h. The ongoing chemical reaction was completed after 36 h in laboratory conditions, yielding a colloidal solution (CaOx−s) of COM nano-crystals (Maravelaki and Verganelaki 2011). Afterwards, commercial TEOS and the surfactant n-octylamine (Mosquera et al. 2010) were added to the CaOx−s under sonication for 2 h. The hydrolysis of TEOS was initiated with the presence of water which had already been produced during the synthesis of CaOx−s. The presence of ISP facilitated the hydrolysis, because water and alkoxides are immiscible, and therefore ISP functions as a homogenizing agent. The mole ratios of the final colloidal solution TEOS/COM/H_2O/ISP/n-octylamine were equal to 0.5/0.03/0.09/7.15/0.05.

The final colloidal solution defined as SiOx−s was stirred for about 3 h, at room temperature. After each step of synthesis, both the yield and product morphology were determined with specific analytical techniques.

The SiOx−s was casted into transparent molds, the top of which was sealed by a moldable film. The mold was kept under laboratory conditions to dry (RH = 60 ± 5 %, T = 20 ± 2 °C). After polymerization and drying processes, a crack-free gel was produced in a period of 35–40 days.

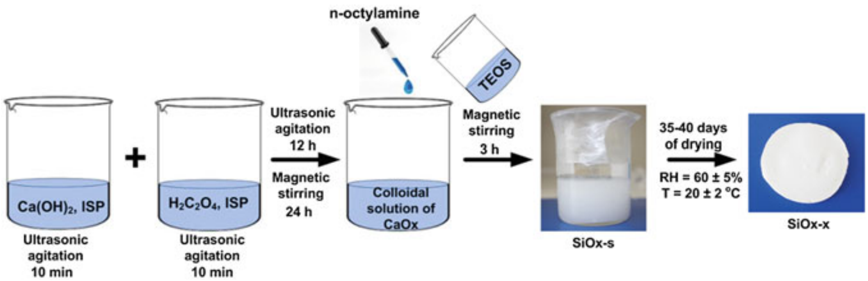

Fig. 1 Experimental procedure for the synthesis of the SiOx nanocomposite

For purposes of comparison, two further sols were synthesized. The first one, was a sol containing TEOS, ethanol (EtOH) and water in a molar ratio TEOS/EtOH/H_2O (1/4/16), while the second one was a sol containing TEOS and synthesized CaOx−p in the same molar ratio as that of SiOx−s (TEOS/CaOx−p = 0.5/0.03). These sols were compared with SiOx−s, aiming to verify both the embodiment of CaOx within the silica matrix and the formation of a mesoporous structure.

2.2 Characterization

The viscosity of the SiOx−s was measured with a Brokkfield DV-II + Pro spindle: S18 viscometer. The physico-chemical stability of the designed nanocomposite SiOx was evaluated before its application as consolidant on porous limestones. The crystallinity of the CaOx−p, was carried out by X-ray powder diffraction analysis (XRD) on a Bruker D8 Advance Diffractometer, using Ni-filtered Cu Kα radiation (35 kV 35 mA) and a Bruker Lynx Eye strip silicon detector. The quantitative XRD analysis was performed by the RIETVELD method. FTIR analysis was carried out in a FTIR Perkin-Elmer 1000 spectrometer in the spectral range of 400–4,000 cm^{-1} for characterizing powders from commercial COM, synthesized CaOx−p, SiOx−x at various curing time and finally for the determination of the reaction time between CH and Oxac. For comparison purposes a xerogel containing TEOS and CaOx−p was also studied by the Fourier Transform Infrared Spectroscopy (FTIR). Textural characterization of the xerogels was performed by using isothermal nitrogen adsorption-desorption at 77 K in an automatic device, NOVA-2200 Version 1.20 (Quantachrome Corp.). Adsorption isotherms of N_2 at −196 °C were performed in an automated volumetric system (AUTOSORB 1, by Quantachrome). The samples were outgassed under high vacuum ($<1.3 \times 10^{-6}$ Pa) for 72 h at 50 °C. The surface morphology of fractured specimens of both CaOx−p and SiOx−x, was examined under scanning electron microscopy (SEM) using a FEI—Quanta Inspect D8334 instrument operating at 25 kV.

2.3 Assessment of SiOx Consolidation

In this study the consolidation effect of the new nanocomposite was investigated in two porous stones, similar to those frequently found in historic and modern architectural structures in the Mediterranean basin. More specifically, aiming to evaluate the performance of SiOx in stones species with different porosity, a bioclastic limestone (defined as Alfas) and a calcareous sandstone (defined as PRC) were selected. Both types of stones were mainly composed of calcium carbonate and low amounts of quartz. The porosity of the bioclastic limestone was measured 32.7 %, while the calcareous sandstone had a total porosity of approximately 47.4 %.

Cylindrical test specimens of approximately 50 mm in diameter and with a height of approximately 27.5 mm were washed with de-ionized water, dried in the oven set at 80 °C for 3 days and then cooled to ambient temperature in a desiccator. In this study, two different treatment procedures were followed: (a) treatment with capillary absorption and (b) brushing treatment. As it is known, the consolidation effectiveness depends on the choice of consolidation procedure, which in turn is related on the type and properties of stone, such as chemical constituents, porosity etc. (Ferreira Pinto and Delgado Rodrigues 2008). The samples of bioclastic limestone were treated with the obtained SiOx sol by capillarity for 24 h, under laboratory conditions and the product uptake was measured. The samples of sandstone were treated with SiOx−s by brushing. After treatment, the test specimens were allowed to dry until they reached a constant weight, taking about a month. The amount of the dry matter deposited in stone specimens was calculated by the weight increase after drying.

The hygric properties of both treated and untreated stone samples were assessed by water capillary absorption tests according to UNI EN 15801:2010 (2009a) and water vapor permeability tests according to UNI EN 15803:2010 (2009b). The stone-product stability and product penetration depth was determined by FTIR.

To estimate color changes of treated samples the total color difference (ΔE*) were obtained by reflectance using a spectrophotometer (CM-2600d, Konica Minolta). The changes in the porosity and pore size distribution were evaluated by mercury intrusion porosimetry (MIP) before and after consolidation. Porosity measurements were recorded on specimens with a volume of around 1 cm^3 using a Quantachrome Autoscan 60 porosimeter, in the 2–4,000 nm range. Mechanical properties of the treated stone samples were evaluated by: (a) dynamic elastic modulus (E_d) determination, using PUNDIT ultrasonic non-destructive digital tester and (b) tensile strength measurements, according to the Brazilian test.

3 Results

3.1 Characterization of the Nano-Calcium Oxalate

The CaOx−p was analyzed by FTIR, in order to: (a) characterize the products from the reaction of CH and Oxac and (b) to determine the required time for the completion of the reaction. The spectra of the synthesized CaOx illustrated in Fig. 2a in a reaction time of 8 h (spectrum a), 24 h (spectrum b) and 36 h (spectrum c), showed a characteristic absorption of CH at 3643 cm^{-1} indicating the residual CH (Blesa et al. 2003). It can be clearly seen that the intensity of the band is significantly decreased after a curing of 36 h. Consequently, the greatest yield in COM was achieved 36 h after the initiation of the reaction. The identification of COM was based on the symmetric O–C–O stretching vibration at 1,317 cm^{-1} (Petrov and Soptrajanov 1975; Schmelz et al. 1957). Moreover, the anti symmetric carbonyl stretching band, indicative of the COM, was located at 1,621 cm^{-1}, along with two

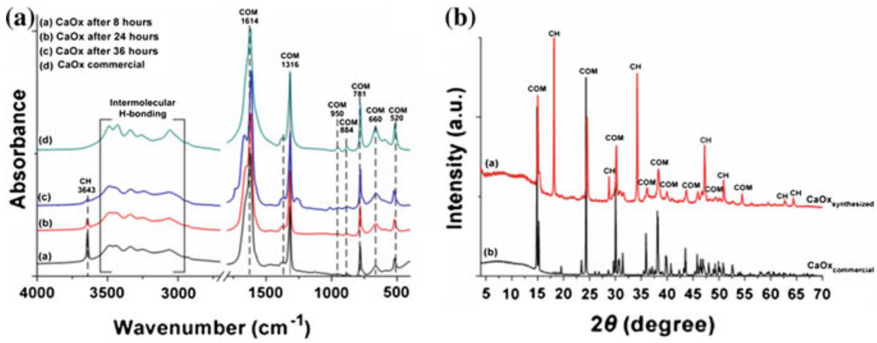

Fig. 2 **a** FTIR spectra of the synthesized CaOx-p after a curing of 8 h (aa), 24 h (ab) and 36 h (ac) and commercial (ad) CaOx; **b** XRD pattern of the synthesized (ba) and commercial (bb) COM

weak bands around 782 and 517 cm^{-1} attributed to C–O stretching. A wide band appearing between 3,500 and 3,000 cm^{-1} was attributed to intermolecular hydrogen bonded OH stretch, from the water molecule present in the COM crystal. The synthesized CaOx compared well with the spectrum of the commercial CaOx (Fig. 2a, spectrum d).

The results of FTIR analysis are corroborated by the XRD analysis. Figure 2b shows the XRD patterns of the synthesized CaOx−p (Fig. 2b, spectrum a) and the commercial calcium COM (Fig. 2b, spectrum b). As it can be clearly seen, the diffraction peaks as observed at around 16°, 30°, 48–50° are attributed to whewellite (COM), while the peaks in the areas of 18° and 34.1°, were assigned to portlandite (CH). Quantitative evaluation by the Rietveld method indicated that the CaOx−p comprised 75 % of COM, as well as 25 % of CH, whose presence does not create any problems in the overall reaction process, since it can be transformed to calcite over time. Using the XRD data and Scherrer formula, the crystallite size of the compounds of the synthesized CaOx−p were calculated; according to these results, the crystallite size of COM and CH were approximately 42 and 1,300 Å, respectively.

Figure 3 shows representative SEM images of the synthesized CaOx−p. All images revealed that aggregates were formed from the reaction of CH with Oxac (Fig. 3a). These aggregates are composed of rod-shaped crystals, where the majority of crystals exhibit a width of about 40–55 nm and a length of 80–130 nm (Fig. 3b, c).

The physical-microstructural characterization of the final product revealed a mesoporous material with an intact crack-free mass. The designed hybrid sol was characterized as a Newtonian liquid, with viscosity value 1.56 mPa s, close to that of the commercial products. This low viscosity value attributes to the SiOx sol a great potential for sufficient and uniform penetration into the network of pores of inorganic materials.

The effect of the CaOx addition to the TEOS-octylamine system was revealed by a comparative FTIR investigation (Fig. 4). The characteristic peak of the hydrolysis of TEOS at 1,169 cm^{-1} which is related to the rocking of the C–H bond in $–CH_3$ of TEOS, is not present in the spectra derived from an initial sol mixture containing

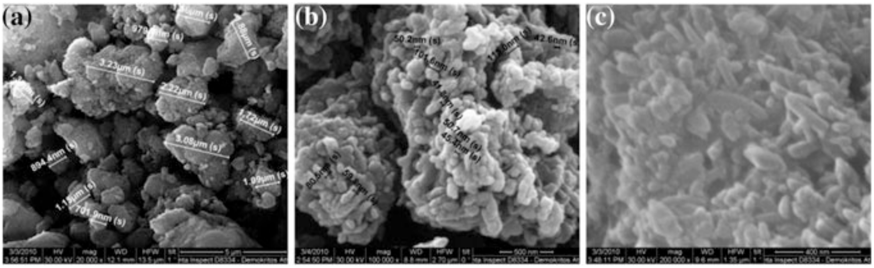

Fig. 3 SEM micrographs of the synthesized calcium oxalate in isopropanol: view of the aggregates (**a**), details of the crystals with a width of about 40–55 nm and a length of 80–130 nm (**b**) and (**c**)

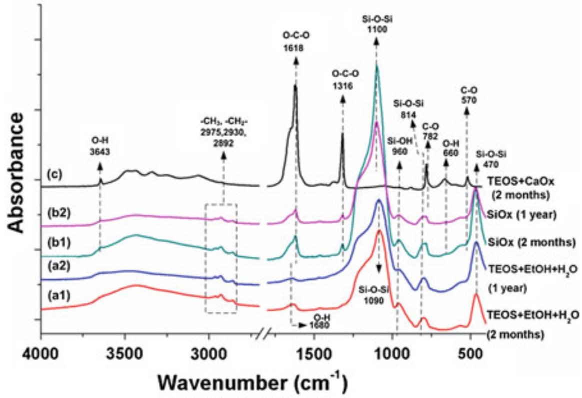

Fig. 4 FTIR spectra of a xerogel containing TEOS, n-octylamine and isopropanol after a curing of 2 months (a1) and 1 year (a2), along with the xerogels SiOx after a curing of 2 months (b1), 1 year (b2) and a xerogel containing TEOS and CaOx-p in the same molar ratios with SiOx after a curing of 2 months

TEOS, EtOH and H_2O after a curing of 2 months (spectrum a1) and 1 year (spectrum a2), as well as the xerogel SiOx derived after a curing of 2 months (spectrum b1), and 1 year (spectrum b2), suggesting that the hydrolysis was successfully completed (Rubio et al. 1998). The basic Si–O–Si bonds formed upon hydrolysis and condensation of TEOS with the influence of n-octylamine showed characteristic absorptions at 1,082, 798 and 460 cm^{-1} (Rubio et al. 1998). In Fig. 4c the sol mixture containing TEOS and powder of CaOx−p in the same ratio with SiOx xerogels showed the absence of TEOS, which evaporated, due to the inhibition of its hydrolysis in the absence of water and alcohol. It is worth mentioning that, in the SiOx−x, the main symmetric Si–O–Si stretching at 1,082 cm^{-1} has been shifted to a higher wavenumber (1,100 cm^{-1}). This is an indication of the chemical differentiation induced by the nano-COM addition, resulting in the shifting of Si–O–Si symmetric stretching to higher wavenumbers (e.g. 1,082 shifts to 1,100, 798 shifts to 814 cm^{-1}). Both the

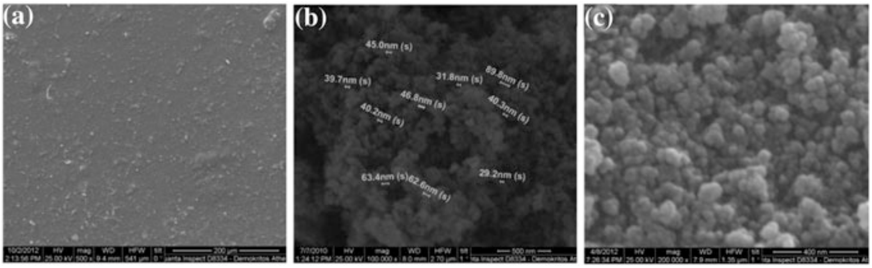

Fig. 5 SEM micrographs of the xerogel derived from SiOx after a curing of 1 year; crack free layer of the SiOx (**a**); details of SiOx reveal that the nanoparticles range from 30 to 90 nm (**b**); compact assembly of uniform sphere-like particles of the SiOx (**c**)

shift to higher wavenumber and the sharpening of the bands indicate shortening of Si–O bond distance and a reduction in mean Si–O–Si bond angle and angular distribution (Rubio et al. 1998). The absorption at 3,643 cm^{-1} indicative of the non-hydrogen bonded OH from $Ca(OH)_2$ denotes that the remained quantity of the non-reacted CH has not carbonated, while the absorptions of $–CH_3$ and $–CH_2$- groups in the range of at 2,900 cm^{-1} correspond to ISP which is already included in the sol, as well as to the ethyl group derived from the hydrolyzed TEOS. All the above findings from the FTIR analysis confirm that both the hydrolysis of TEOS and the copolymerization of CaOx within the silica network were completed, giving rise to the formation of a homogeneous hybrid xerogel.

In order to investigate the textural properties of the SiOx nanocomposite, nitrogen adsorption-desorption isotherms were obtained. The SiOx−x showed lower specific surface area, a higher pore volume and meso- and macropores compared to the pure TEOS/EtOH/H_2O (1/4/16) xerogel, which exhibited mostly micropores (Gregg and Sing 1982). The average pore value of SiOx−x (15.15 nm) is higher than the TEOS–H_2O xerogel (1.57 nm). This large pore radius of SiOx−x can be attributed to the incorporation of nano-COM into its matrix, augmenting the pore size of the network.

The micro-morphological characterization of the xerogel conducted through SEM provided supporting evidence to BET results. Typical electron micrographs for the SiOx−x are illustrated in Fig. 5, showing a compact assembly of uniform sphere-like particles. The interstices formed between the particles of SiOx−x (of about 40–70 nm average diameter are around 30 nm in size and are in accordance with the nitrogen absorption results (Fig. 5b). As shown in Fig. 5c, the SiOx−x produces a network composed of "distorted" spheres.

3.2 Treatment Assessment

The performance of the SiOx as a consolidant and protective agent was assessed on both Alfas and PRC, widely used as monumental stone in Crete. The treatment

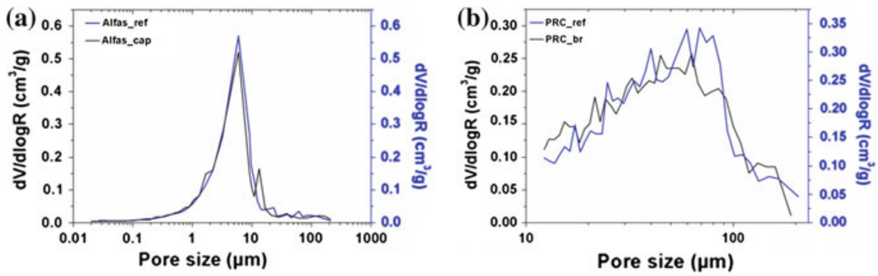

Fig. 6 Representative graphs of pore size distribution for both Alfas (**a**) and PRC (**b**) stone specimens before and after treatment with SiOx by mercury intrusion porosimetry

assessment included the study of hygric behavior of the treated stone samples, their microstructure and bonding, as well as their mechanical properties. The low viscosity value of SiOx−s enabled it to penetrate into the treated limestone and sandstone up to a depth of 2 cm and 5 cm from the surface, respectively, as it was revealed by FTIR and SEM analyses (Verganelaki et al. 2014).

The treatment with SiOx–s, as it was verified by the MIP measurements, induced an insignificant modification of the microstructure especially for Alfas samples (Fig. 6a), which show that the basic pore size distribution was maintained after the product application; more specifically, only the pores showing a diameter between 10–100 μm have been modified. This modification of pore-space can be explained by a quasi targeted deposition of the SiOx particles on the internal side of pore-walls, maintaining the pore space within the capillary range. The avoidance of pore occlusion is another important criterion to be fulfilled. Silicate consolidants usually significantly alter the stone porosity, inducing irreversible modifications of the hygric properties of the treated stone. Figure 6b illustrates that treated PRC presented an insignificant decrease in the whole pore size distribution.

The application of SiOx to the Alfas resulted in a slight yellowish surface, which corresponds to a total color variation of ΔE* = 2.01 with parameters ΔL* = −0.52 (± 0.87), Δa* = 0.13 (± 0.06) and Δb* = 1.76 (± 0.27) which cannot be detected by the naked eye. On the contrary, the SiOx application attributed a whiter surface to the sandstone samples.

WVP coefficient was additionally reduced by approximately 43 % in the treated Alfas samples (Table 1). These reductions lie within acceptable limits. In the case of PRC, the modification of WVP coefficient was insignificant (only 11 %). After treatment, the WCA coefficient of Alfas stone was decreased by 32 %, while the TWAC was decreased by 51 %. PRC specimens gave similar results respect to Alfas. After consolidation WCA coefficient was decreased approximately 30 % and TWAC was modified by 13 %. The decrease of WCA coefficient indicates that the nano-oxalate-silica composite can be effectively used as a protective agent against stone deterioration.

The effectiveness of SiOx as a strengthening agent was investigated by measuring the E_d and indirect tensile strength according to the Brazilian test (Table 2).

Table 1 Coefficients of the water capillary absorption (WCA), total water absorbed by capillarity (TWAC) and water vapour permeability (WVP) of Alfas (untreated and treated) and PRC (untreated and treated) stone specimens

Sample	Dry matter (g cm^{-2})	WCA (g cm^{-2} $s^{-1/2}$)	TWAC (%)	WVP (g cm^{-2} h^{-1})
Alfas_ref		0.0137 (±0.0008)	13.66 (±0.24)	0.0007 (±0.0001)
Alfas_cap	0.0408 (±0.0120)	0.0093 (±0.0030)	7.02 (±0.05)	0.0004 (±0.0001)
PRC_ref	–	0.060 (±0.010)	28.02 (±2.88)	0.0037 (±0.0007)
PRC_br	0.4392 (±0.1091)	0.042	24.45	0.0033 (±0.0003)

Table 2 Color parameters (a*, b* and ΔE*), dynamic modulus of elasticity (E_d) and tensile strength measurements of Alfas (untreated and treated) and PRC (untreated and treated) stone samples

Sample	Color parameters			E_d (GPa)	Tensile strength (MPa)
	a*	b*	ΔE*		
Alfas_unt	2.10 (±0.00)	12.42 (±0.01)	–	10.34 (±0.09)	2.81 (±0.12)
Alfas_tr	2.23 (±0.06)	14.18 (±0.26)	2.01 (±0.22)	13.15 (±1.69)	3.46 (±0.49)
PRC_unt	8.7 (± 0.00)	25.43 (±0.01)	–	2.74 (± 1.14)	0.59 (±0.18)
PRC_tr	8.56 (±0.73)	23.69 (±1.01)	9.45 (±3.64)	4.23 (±1.05)	0.78 (±0.08)

For both treated types of stone, a noticeable increase was observed in E_d. More specifically, E_d was increased by 27 % in the treated Alfas samples and was almost doubled in the PRC consolidated samples. The indirect tensile strength increased up to 23 % in the case of Alfas specimens, while for PRC specimens, the tensile strength increased by approximately 32 %, providing a considerable consolidation effect for both types of stone (Table 2). Overstrengthening is not desired since it has usually been related to the presence of the applied material into the outermost zone, therefore, subsequent scaling of the material cannot be excluded.

4 Conclusions

The hybrid SiOx product performs effectively as a consolidant by improving the performance characteristics of two types of calcareous stone with different porosities, without significant alteration of the microstructure and, consequently, of its ability of liquid and vapor circulation in its bulk. In fact, SiOx has the property, because of the incorporation of CaOx into TEOS, contrary to other commercial products, to not modify noticeably the pore size distribution while it slightly reduces the water absorption of treated stone. These beneficial properties are mainly due to the presence of calcium oxalate, which is the main compound identified in well preserved surface patina layer on stone monuments. Moreover, given that tensile strength and dynamic modulus of elasticity increased after consolidation up to a desirable level, it is considered that the designed SiOx can be used as stone strengthening and protective agent against the environmental loading.

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Ammonium Oxalate Treatment Application in the Presence of Soluble Salts: Laboratory Results on Soft Limestone

Tabitha Dreyfuss and JoAnn Cassar

Abstract Ammonium oxalate treatment of calcareous stone has, in recent years, emerged as a conservation treatment with both consolidating and protective properties through the surface conversion from calcium carbonate to calcium oxalate. This treatment on Maltese Globigerina Limestone has also produced positive results, increasing the acid resistance while retaining the water transport properties of the stone. Furthermore, treatment in the presence of sodium chloride did not impede the conversion. This paper focuses on ammonium oxalate treatment application in the presence of sodium chloride as well as sodium sulphate and sodium nitrate, in a comparative study where the treatment was applied to quarry samples of this soft Limestone under laboratory conditions. The resistance to salt crystallisation and the water absorption properties were subsequently studied. This stage in the understanding of ammonium oxalate treatment of calcareous stone under different soluble salt content conditions is an important step towards carrying this treatment forwards to real site conditions where soluble salts are naturally present in the stone and where desalination may prove to be difficult or impossible. Results obtained were positive in all respects and show that ammonium oxalate treatment may be relevant in the treatment of this stone type.

1 Aims of Study

The aims of this research were multiple: to investigate the different possible outcomes when ammonium oxalate treatment is applied to Globigerina Limestone that contains different types of soluble salts; to understand the role played by the stone's pathology vis-à-vis the treatment; and to assess the effect of treatment contact time

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so as to consider the impact that this may have on the resulting formation of calcium oxalate. This paper focuses on that part of the research concerning the resistance to salt crystallization of weathered limestone samples treated with ammonium oxalate.

1.1 Introduction

The Maltese Islands, which are located in the centre of the Mediterranean Sea, consist of a small archipelago measuring 316 sq. km. The Islands have numerous historic limestone buildings and monuments that span the millennia. These are mostly built in Maltese Globigerina Limestone—a highly porous (total porosity up to 40 %) calcareous stone which deteriorates, often catastrophically, in an environment that is exposed to both high moisture levels and elevated amounts of soluble salts. Globigerina Limestone exists as one of two types—the more durable franka and the less durable soll (Cassar 2002). Many of the historic stone edifices in Malta and Gozo were built before the insertion of a damp proof course became mandatory, thus allowing water entry in the form of rising damp together with any soluble salts present.[1] Additionally, traditional wall construction generally utilised soil infill, usually salt laden, between two masonry wall leaves. The Island environment further enhances salt contamination through wind driven and aerosol borne salts. The context is therefore a porous limestone which has a continual supply of moisture and soluble salts. Treatment of exposed Globigerina Limestone which has lost cohesion, manifested as powdering/granular disintegration must therefore take this context into account.

1.2 Ammonium Oxalate Treatment

Ammonium oxalate treatment of calcareous stone has, over the past 30 years, emerged as a conservation treatment with both consolidating and protective properties (Matteini and Moles 1986; Matteini et al. 1994; Cezar 1998; Miliani et al. 2007; Matteini 2007; Bracci et al. 2008; Charola et al. 2010; Conti et al. 2011; Booth et al. 2012). The surface conversion of calcium carbonate to calcium oxalate is ideal for calcareous stone. Results from studies on Globigerina Limestone have confirmed that the resulting calcium oxalate is harder and more resistant to acid attack, with a lower solubility than calcium carbonate, and with an improvement in surface cohesion occurring after treatment (Mifsud 2006; Mifsud and Cassar 2006; Dreyfuss and Cassar 2012). Although the treated stone undergoes some reduction in surface porosity (detailed studies in this respect are ongoing), its wetting and

[1] The insertion of a damp proof course in buildings was first introduced to Malta in the mid 19th Century as part of the new Police Laws providing new sanitary regulations (Mallia-Milanes 1988).

hydrophilic properties are retained (Croveri 2003; Croveri et al. 2004). Furthermore, treatment in the presence of high levels of sodium chloride does not impede the conversion to calcium oxalate (Mifsud and Cassar 2006; Pinna et al. 2011). This is an important factor, especially in a marine environment like the Maltese Islands where marine aerosols are ever present. Other salts that are commonly present in historical masonry include both sulphates and nitrates. This study has centred on Globigerina Limestone of the franka type and includes both these salt types—as sodium sulphate and sodium nitrate—as well as sodium chloride, in a comparative study where ammonium oxalate treatment was applied to samples of this soft limestone under laboratory conditions.

2 Sample Selection and Preparation

In an attempt to recreate site conditions in a controlled laboratory environment, the range of franka samples tested included artificially weathered types as desalinated samples as well as salt contaminated samples. In addition, stone that was treated with different contact times was also included. The selection of samples included in this part of the research programme is summarised in Table 1. The sample types outlined in this table were prepared as 50 mm × 50 mm × 50 mm cubes as described in Sects. 2.1–2.4.

2.1 *Sample Preparation*

Quarry franka samples in the form of stone blocks (approximately 410 mm W × 230 mm D × 267 mm H) were obtained from the main quarry area of Qrendi from the area known as Ta' l-Iklin (quarry coordinates: 51,500, 66,500) at a depth of

Table 1 Range of samples included in the study

Weathered franka	Untreated
Desalinated samples	5 h treatment
	24 h treatment
Weathered franka	Untreated
Samples contaminated with a saturated solution of sodium chloride	5 h treatment
	24 h treatment
Weathered franka	Untreated
Samples contaminated with a saturated solution of sodium sulphate	5 h treatment
	24 h treatment
Weathered franka	Untreated
Samples contaminated with a saturated solution of sodium nitrate	5 h treatment
	24 h treatment

12 m below ground level. Cubes measuring 50 mm × 50 mm × 50 mm were dry cut from the stone blocks. The samples were then dusted/brushed with a dry nylon brush to remove superficial surface dust resulting from the cutting procedure. The weathered pathology of the franka samples was then induced through artificial weathering through 2 cycles of salt weathering as per EN12370:2000 using anhydrous sodium sulphate. This resulted in a powdering surface texture with an increased surface area, visible to the naked eye.

2.2 Desalination

The desalinating procedure was first carried out on all the samples. These were immersed in distilled water, repeatedly changing the water until its conductivity revealed that soluble salts were no longer present. The conductivity of the distilled water used (≤3μS) was measured by means of a conductivity meter (HI98308 PWT—Hanna instruments). The conductivity of the distilled water containing the immersed samples was measured after each immersion until its conductivity was ≤3μS. All of the samples—including those that were to be salt contaminated—were thus desalinated and then oven dried for 24 h at a temperature of 105 °C, then cooled in the laboratory to constant mass at 20 °C room temperature. One fourth of the samples were then retained as is, to represent the desalinated type samples, while the remaining samples were selectively salinated as described in Sect. 2.3.

2.3 Selective Salt Contamination (Chlorides, Sulphates, Nitrates)

Following the desalination procedure, those samples that were designated for salt contamination as per Table 1 were selectively contaminated. The chloride group were immersed in a saturated solution of sodium chloride, the sulphate group in a saturated solution of sodium sulphate and the nitrate group in a saturated solution of sodium nitrate—all for a duration of 2 h. Following immersion, the samples were air dried to constant weight.

2.4 Ammonium Oxalate Treatment

A saturated (at 5 %) ammonium oxalate (monohydrate) treatment was applied in a cellulose pulp poultice for 2 different contact times—5 and 24 h. Calcium oxalate had already been found to form on franka limestone after a 5 h contact time of an ammonium oxalate paper pulp poultice (Mifsud 2006). The 24 h contact time is however considered to be more practical in the field since this allows treatment to be applied up until the end of the working day rather than limiting treatment to take place 5 h before the end of the working day. For this reason samples with a 24 contact time of treatment were included in this study. Following treatment, the poultice was manually removed and the samples left to air dry at room temperature. The excess pulp was brushed off with a soft and dry nylon brush. Only the top surface of the cube samples was treated. For every treated sample type, an untreated control sample was included.

3 Testing

The determination of resistance to salt crystallisation was carried out in accordance with EN 12370:2000 on the treated and untreated samples, to determine whether or not the ammonium oxalate treatment improved the stones' ability to resist this type of deterioration. The number of cycles carried out was 4 and the resistance to salt crystallisation was calculated as the percentage mass of material lost against the initial dry mass. The results obtained are given in Fig. 1.

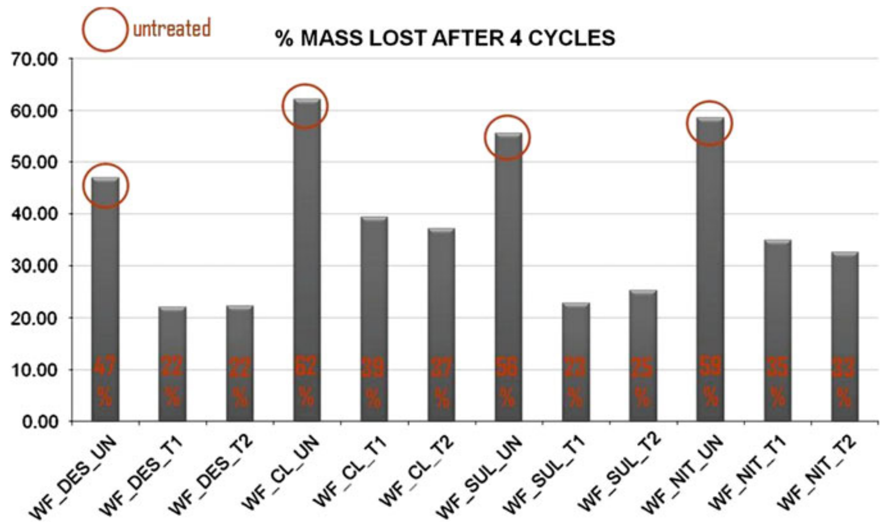

Fig. 1 % mass lost after 4 cycles of the sodium sulphate weathering test. (*WF* weathered franka; *DES* desalinated; *CL* contaminated with sodium chloride; *SUL* contaminated with sodium sulphate; *NIT* contaminated with sodium nitrate; *UN* untreated; *T1* treated for 5 h; *T2* treated for 24 h.)

4 Results and Discussion

For all sample types—desalinated, contaminated with sodium chloride, contaminated with sodium sulphate and contaminated with sodium nitrate—all of the untreated samples were found to have lost a greater percentage of their initial mass when compared to treated samples of the same type. Although the ammonium oxalate treatment was only applied to the top face of the cube samples, the difference between treated and untreated samples was significant for all cases. Untreated samples in the desalinated group, chloride group, sulphate group and nitrate group lost 47, 62, 56 and 59 % respectively while treated (5 h) samples lost 22, 39, 23 and 35 % respectively and treated (24 h) samples lost 22, 37, 25 and 33 % respectively. This suggests that ammonium oxalate treatment does in fact provide protection from salt crystallization even when this is formed in the presence of sodium chloride, sodium sulphate or sodium nitrate. This is also evidenced visually—Fig. 2—where the top untreated row is significantly more deteriorated, less sound and with less pronounced corners and edges than the bottom two rows (which were treated). The differences in resistance to salt crystallization between those samples treated for a 5 h contact time and those treated for a 24 h contact time were less significant, indicating that the increased contact time is probably neither crucial for nor detrimental to salt crystallization protection.

Given the increased salt crystallization resistance in the weathered franka samples following ammonium oxalate treatment, the treated and untreated sample types were studied through water absorption tests, to verify whether the treatment had affected the water transport properties. Samples shown in Table 1 were prepared as per Sects. 2.1–2.4 above and then tested. The samples were evaluated by means of the water absorption test through capillarity in accordance with EN15801:2009.

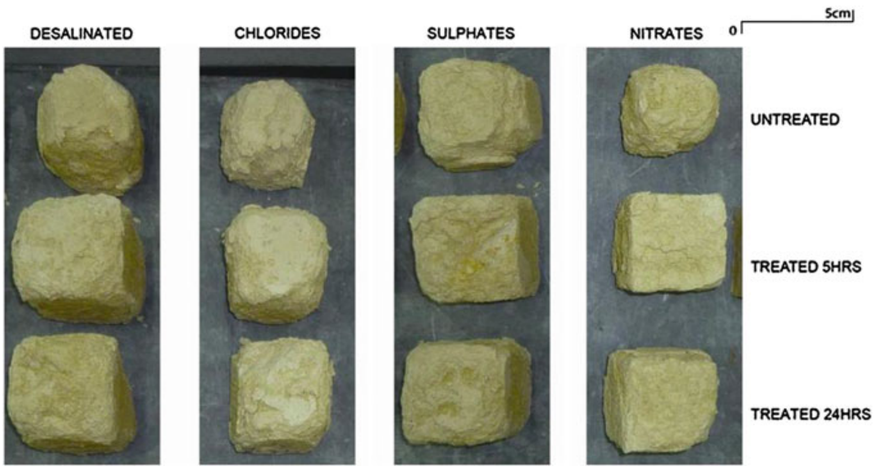

Fig. 2 Photographs of the samples after the 4th cycle of the salt crystallization test

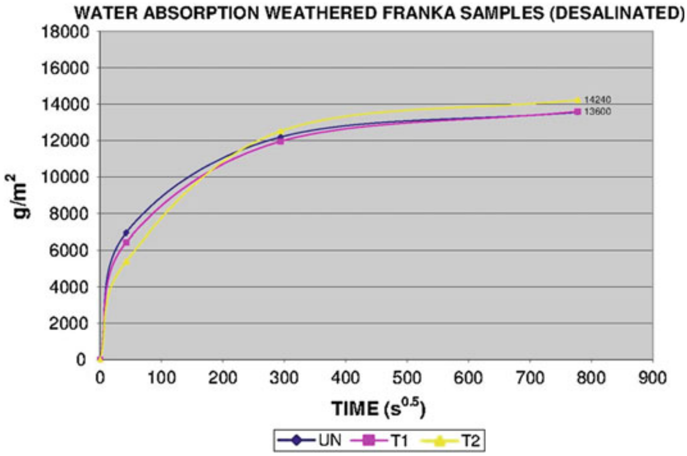

Fig. 3 Water absorption graphs for desalinated weathered franka samples

The samples were placed over a 10 cm bed of paper pulp, the bottom 8 cm of which was saturated with distilled water. The treated samples were placed face down with the treated face in contact with the paper pulp. The reason for using paper pulp as opposed to filter paper as specified in the EN15801:2009 was due to the uneven surface of the naturally weathered stone samples which were seen not to have had full contact when placed on a wad of filter paper. The quantity of water absorbed per unit surface area during a given amount of time was measured. The results are expressed graphically in Figs. 3, 4, 5 and 6, where the mass of water absorbed per unit surface area (y-axis) is plotted against the square root of time taken (x-axis).

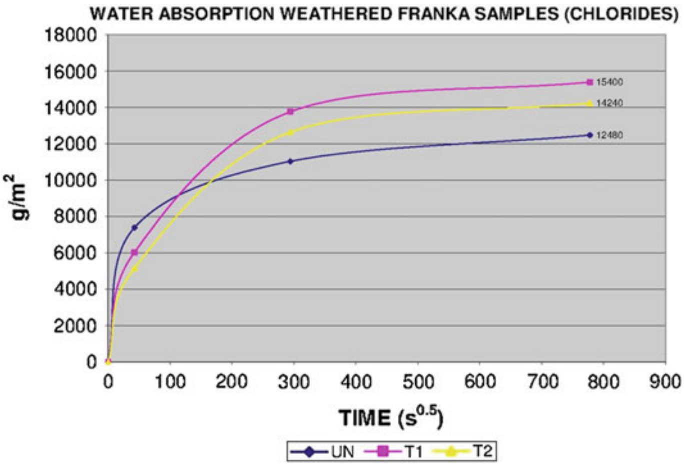

Fig. 4 Water absorption graphs for sodium chloride contaminated weathered franka samples

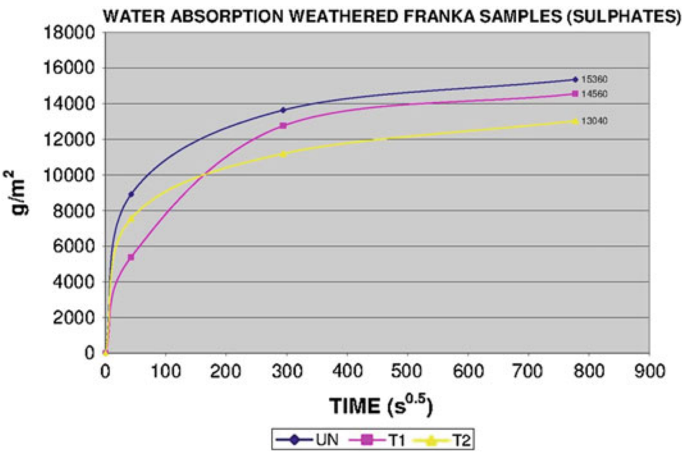

Fig. 5 Water absorption graphs for sodium sulphate contaminated weathered franka samples

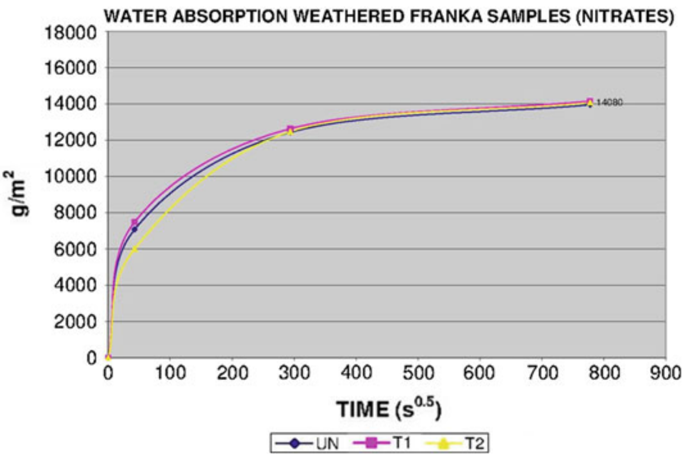

Fig. 6 Water absorption graphs for sodium nitrate contaminated weathered franka samples

(WF = weathered franka; DES = desalinated; CL = contaminated with sodium chloride; SU = contaminated with sodium sulphate; NIT = contaminated with sodium nitrate; UN = untreated; T1 = treated for 5 h; T2 = treated for 24 h.) The graphs obtained show that, for all cases, they are similar in shape. This confirms that although ammonium oxalate treatment improves the salt crystallization resistance of weathered *franka*, it does not inhibit the mode or amount of water uptake through capillarity through the treated face.

5 Conclusion

This stage in the understanding of ammonium oxalate treatment of Globigerina Limestone under different soluble salt content conditions is an important step towards carrying this treatment forwards to real site conditions, where soluble salts are naturally present in the stone and where desalination may prove to be difficult or impossible. The results obtained have shown that even in the presence of sodium chloride, sodium sulphate or sodium nitrate, a degree of protection from salt crystallization is achieved with ammonium oxalate treatment. This protection is achieved both for treatment applied for a 5 h contact time as well as for treatment applied for a 24 h contact time. Additionally, the pathology of powdering weathered franka is conducive to the successful consolidation of the stone as seen through the increased resistance to salt crystallization of weathered types. Moreover, this increased salt crystallization resistance does not alter the water transport properties of the stone. This is an important aspect to retain when considering historical limestone buildings and monuments that are exposed to moisture and soluble salts. The progression from laboratory to site is an important step to be considered in the development of this treatment for the conservation of Globigerina Limestone and it is hoped that through this research programme, a reliable conservation procedure may emerge that will assist within the overall conservation of Globigerina Limestone in real restoration projects.

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Calcium and Magnesium Alkoxides for Conservation Treatment of Stone and Wood in Built Heritage

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Abstract In the frame of the EU-project NANOMATCH new consolidants based on metal alkoxides were developed and tested. New compounds were prepared with different synthetic pathways to overcome the oligomerization issue, which can strongly influence solubility and therefore application of alkoxides as conservation materials for built heritage. Calcium alkoxides react in presence of humidity and carbon dioxide to give $CaCO_3$ and alcohols. This peculiar behavior -in atmospheric conditions- makes this class of chemicals suitable for consolidation of carbonate stones, plasters and wall paintings and also for pH buffer to avoid acidification of cellulose based materials such as wood and paper. Within the frame of the project, it has been demonstrated that the developed calcium compounds are more soluble than the corresponding commercial Ca-bearing consolidants and, after reaction with air, they evolve into different calcium carbonate structures, i.e. amorphous carbonate or crystalline calcite and vaterite. The ratio among these forms can be

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oriented by environmental conditions and treatment with water, in order to force a carbonate phase in place of other ones. Commercially available magnesium alkoxides solutions were also tested as consolidants precursors. Carbonation of magnesium compounds brought to precipitation of low crystalline Mg hydroxide and carbonate coatings. Moreover, hydrated Mg carbonate phases were identified. Many of them are salts sensitive to water and prone to ion-exchange, possibly evolving to soluble magnesium salts deleterious for stone. These experimental evidences led to the decision to discard magnesium alkoxides for conservation purposes.

1 Introduction

In the last century, historic building materials have been strongly affected by atmospheric pollutants in industrialized countries leading to heavy deterioration of many outdoor and indoor precious artifacts. Although reduction of pollutants, thanks to a more sustainable industrialization, and conservation treatments which have certainly reduced the deterioration of built heritage, recently new threats, such as the climate change and ageing of conservation treatments, are jeopardizing the present and future conservation of these historical materials.

On the basis of these premises, the development of innovative surface consolidants specifically designed to meet the requirements of historic building substrates has been addressed in the frame of the EU-project NANOMATCH. In particular, alkaline earth metal alkoxides were synthesized for conservation of stone and wood materials, while aluminum alkoxides synthesized in the EU-project CONST-GLASS- were prototyped for the treatment of deteriorated glasses.

Calcium alkoxides react in presence of humidity and carbon dioxide to give $CaCO_3$ and alcohols. This behavior in atmospheric conditions makes this class of chemicals suitable for consolidation of carbonate stones, plasters and wall paintings (Favaro et al. 2008; Ossola et al. 2012) and also potentially for pH buffer to avoid acidification of cellulose based materials such as wood and papers (Giorgi et al. 2002).

To produce effective consolidants precursor materials, different calcium alkoxides have been synthesized, allowing a modulation of the physico-chemical properties of the final compounds, in order to ensure a good penetration and a homogeneous distribution inside the pore network of the stone/wood materials. Particular attention was focused on synthetic routes to reduce the high tendency of calcium alkoxides to olygomerize (by inter-molecular bonding between O and Ca atoms), because the oligomerization strongly affects the solubility properties of alkoxides, thus limiting their solubility and consequently their use as consolidants (Bradley et al. 2001; Turova et al. 2002).

Carbonation is a very complex process, influenced by many factors related to reagents (concentration, solvents) and reaction conditions (T, RH). Precipitation of Ca^{2+} and $(CO_3)^{2-}$ ions from saturated solution usually brings first to amorphous calcium carbonate (ACC), that can evolve to one or more of the polymorph crystalline forms (vaterite, aragonite, calcite) (Brecevic 1989). Vaterite is kinetically the most favourite phase that transform—via dissolution-reprecipitation mechanism—to the thermodynamically stable calcite (Beck and Andreassen 2010) Regarding magnesium alkoxides, their synthesis and their use as precursors for the preparation of complex oxides or solid oxide solutions is extensively described in literature (Diao et al. 2002; Turova et al. 2002), while studies on subsequent carbonation of Mg compounds can hardly be found.Concerning carbonation of simple alkoxides, preliminary studies demonstrate that it can take place by two reaction pathways: one through the insertion of CO_2 and subsequent elimination of ROH and the second one by firstly an hydrolysis and then the carbonation of the $Ca(OH)_2$ formed (Favaro et al. 2008).

In the present work, the study on the carbonation process of newly synthesized calcium alkoxides and commercial magnesium alkoxides in different conditions is reported, to assess if they have the minimum requirements to evolve to carbonate structure suitable for stone consolidation.

2 Experimental Section

2.1 Calcium and Magnesium Alkoxides

With the aim to increase solubility, starting alcohols sterically hindered and/or with additional coordinating atoms were chosen for the synthesis of calcium alkoxides, in order to reduce or avoid oligomerization processes. Different synthetic pathways to produce calcium alkoxides were tested and several products obtained.

Concerning magnesium alkoxides, although several synthetic methodologies can be used (Turova et al. 2002), they were finally not synthesized as preliminary carbonation tests, performed with available commercial products, demonstrated that they are unsuitable for conservation of built heritage (see Sect. 3.4).

2.1.1 Synthesis of Calcium Alkoxides

Synthesis and manipulation of calcium alkoxides were carried out in nitrogen filled glove-boxes with exclusion of moisture and oxygen. Five different procedures were tested to obtain calcium alkoxides. A short description of them is given below (Bradley et al. 2001; Turova et al. 2002).

Direct reaction between alcohol and metallic calcium. Under a nitrogen atmosphere, pieces of metallic calcium are vigorously stirred -with or without reflux- in an excess of anhydrous alcohol, with or without the presence of another solvent. Calcium alkoxides are finally recovered by crystallization, precipitation or removal of the solvent by evaporation.

Alcoholysis reaction. Refluxing a solution of $Ca(OEt)_2$ in the appropriate alcohol, with or without the presence of a co-solvent (toluene), allows the formation of the new $Ca(OR)_2$ alkoxide and represents a simple methodology to have new compounds. Ethanol formed can be removed by (azeotropic) distillation.

Rieke calcium. Rieke metals are usually prepared by a reduction of a THF suspension of an anhydrous metal chloride with an alkali metal, with or without a catalytic amount of an organic electron carrier (such as biphenyl or naphthalene). The resulting highly reactive form of activated metallic calcium, with high surface area and lacking of surface oxides (which retard reaction) is reacted in situ with the appropriate alcohol.

Ammonia method. According to literature, liquid ammonia can dissolve and activate the metals. Under inert atmosphere, metallic calcium in freshly anhydrous distilled solvent was cooled between −45 and −60 °C and gaseous ammonia was bubbled inside. Once the metal had dissolved, a solution of the desired alcohol in the appropriate solvent was added, and the temperature carefully raised to room temperature.

Synthesis from $Ca(OH)_2$. calcium hydroxide represent the cheapest source of calcium; when it is possible to force the reaction by removing the water with a Dean Stark apparatus, a synthesis starting from $Ca(OH)_2$ can be considered an useful tool to have alkoxides derivatives by high b.p. alcohols.

The obtained alkoxides were characterized by Elemental Analysis, FT-NMR and ESI-MS.

2.2 Preparation and Analysis of Carbonate Coatings

To assess the kinetic and the final products of the carbonation process, the calcium alkoxides produced by different synthetic pathways and commercially available magnesium compounds were dissolved in alcohol, deposited and the corresponding coatings were analyzed by different techniques.

Saturated solutions of calcium alkoxides (concentration of Ca higher than 40 g/L), commercial available $Mg(OCH_3)_2$ in MeOH (ca. 10 %; Sigma Aldrich) and magnesium methylcarbonate in DMF 2 M (Sigma Aldrich) were prepared under dry atmosphere and spread on a flat golden surface to be studied by micro-FTIR measurements to assess the carbonation time. A Nicolet microscope connected to a Nicolet 560 FTIR instrument, equipped with a Mercury Cadmium Telluride (MCT) detector, was used. Investigated microareas were about $50 \times 50\ \mu m^2$ of size. IR spectra were recorded in reflectance mode in the 4,000–650 cm^{-1} range (resolution of 4 cm^{-1}).

The coatings obtained from carbonation of Ca alkoxides were prepared as follows. The saturated solutions were spread on pre-cleaned glass slides and left to carbonate for 14 days in lab environment (≈25 °C, 40 % RH) and in closed vessels to simulate two different environment (≈25 °C, 50 % and 90 % RH) in order to establish the effect of different RH on the alkoxide decomposition. The CO_2 inside the vessel was slowly balanced with CO_2 of the atmosphere. Coatings developed from magnesium compounds were analyzed after 20 days of air exposure in lab environment (≈25 °C, 50 % RH).

The white coatings produced on the surface of the glass substrates as a result of the $M(OR)_2$ (M = Ca, Mg) reaction with air were structurally investigated by XRD, and their morphologies observed by high resolution scanning electron microscopy. X-Ray Diffraction (XRD) measurements were carried out by using a Philips PW 3020 powder diffractometer with a Bragg-Brentano θ-2θ geometry. The radiation used was the Cu Kα (λ = 1.05456 Å) operating at 40 kV and 30 mA. All the patterns were collected in the 10°–70°/5°–75° *2θ* range and the phase identification was performed with the support of the standard patterns reported in 2002 ICDD databases. Observations of the inorganic coatings deposited on glassy substrates have been performed by using a Fei Quanta 200 FEG-ESEM instrument, using an accelerating voltage of 20 keV, to evaluate their morphology. The samples were analyzed in low vacuum mode (pressure 60 Pa) without any conductive coating.

3 Results

3.1 Synthesis of Calcium Alkoxides

According to the literature, the use of different synthetic methodologies modifies not only the rate of the reaction but also the nature of the products. The chemicals obtained with the different methodologies have been isolated, purified and analyzed. The synthesis based on the assisted ammonia reaction has been chosen for the final production of alkoxides, as the obtained products have an high solubility (Ca content >40 g/L), therefore, the use of their solutions should ensure a greater penetration depth in comparison to consolidants available as suspended nanoparticles. The other synthetic pathways did not assure a good yield or a good solubility of the product. Actually the synthesis of soluble alkoxides revealed to be a challenging task because the compounds can be obtained in different oligomeric forms. Particular attention has been devoted to the characterization of the species present in solution because this is a crucial point to identify chemical parameters affecting the solubility of the alkoxides. NMR spectrum, although in most cases the peaks can be clearly attributed to the proposed structure doesn't allow a complete characterization of the compound because it cannot differentiate among the diverse species. ESI-MS of the calcium 2-methoxyethoxide, e.g. evidenced the presence of the monomeric and of the dimeric forms. Higher oligomerization numbers can be found for this product which crystallizes as $Ca_9(OCH_2CH_2OMe)_{18}(HOCH_2CH_2OMe)_2$ (Goel et al. 1991). ESI-MS was very useful because it demonstrated that the detection of monomeric or oligomeric forms is not necessary bound to the solubility of the species: the crucial point in fact seems to be the reactivity/stability of the species in the experimental conditions. Additional donor atoms reduce the appearance of polymeric forms in the spectra. The results indicate that it is possible to limit the formation of oligomers choosing appropriate ligand but it is impossible to avoid this phenomenon, being in principle due to the calcium coordination chemistry. It is interesting to note that for the first time a methodological study of these chemicals is in progress and first encouraging results of a method to clearly identify them is under investigation (Peruzzo et al. 2013). Chemical ligands of synthesized alkoxides will be published as soon as the submitted patent will be accepted.

3.2 Assessment of Carbonation Process Via FTIR Measurements

Exposure of calcium and magnesium alkoxides solutions to the atmosphere gave rise to spontaneous reactions with air and deposition of white coatings on the surfaces of the vessels. Reflectance IR measurements have been performed on a gold surface after deposition of a drop of alcoholic solution of the alkoxides. As already reported by Favaro and co-authors for short chain and ethoxylated Ca alkoxides, the main route also for those newly developed compounds is through insertion of CO_2 in the Ca–O bond of the calcium alkoxides, producing the corresponding calcium alkyl carbonates. Alkylcarbonates absorptions decrease until disappearance in about 3–6 h depending on the steric hindrance of the alkoxide group, while new signals in the regions 1,390–1,450 and 880–864 cm^{-1}, characteristic of $CaCO_3$, appear and rise. IR spectra collected after no evidence of pattern changes (5–10 days) clearly show the absorptions of vaterite (1080, 864 cm^{-1}) and hydrated magnesium carbonate ($MgCO_3 \cdot 5H_2O$: 3648, 3512, 3435, 1119, 884, 853, 793, 721 cm^{-1}) on coatings developed in lab environment for calcium alkoxides and magnesium methoxyde/methylcarbonate, respectively. The characteristic bands of calcite (1410, 875, 712 cm^{-1}) were instead detected after wetting the ACC coating developed from calcium 2-methoxyethoxide (Fig. 1), indicating that presence of water could induce recrystallization.

3.3 Carbonate Coatings from Calcium Alkoxides

The coatings developed from different calcium alkoxides after 2 weeks of air exposure are composed of vaterite with hexagonal structure (*ICDD: 01-072-0506*), with the exception of that developed by calcium 2-methoxyethoxide, that turned out to be completely amorphous. Even coatings produced at controlled RH and T were mainly constituted by vaterite (*ICDD: 01-072-0506*) as the main carbonatic phase, in some cases also calcite with rhombohedral structure (*ICDD: 01-086-2341*) can be detected.

To investigate if amorphous calcium carbonate obtained at room environment may evolve to a more crystalline structure, coatings were wetted with water and left in air at room temperature for 2 weeks. Collected XRD pattern on that coating showed that all ACC evolved to polycrystalline calcite as the only phase (Fig. 2)

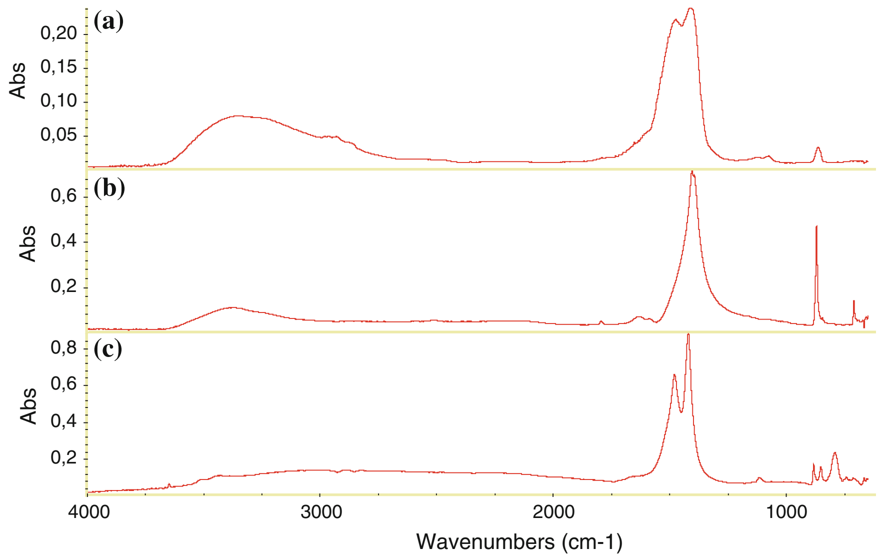

Fig. 1 IR spectra collected on the coating after carbonation of $Ca(OR)_2$ in i-PrOH in lab environment (**a**), on the same coating after its wetting with liquid water (**b**) and on the one obtained from decomposition of Mg $(OCH_3)_2$ in MeOH (**c**)

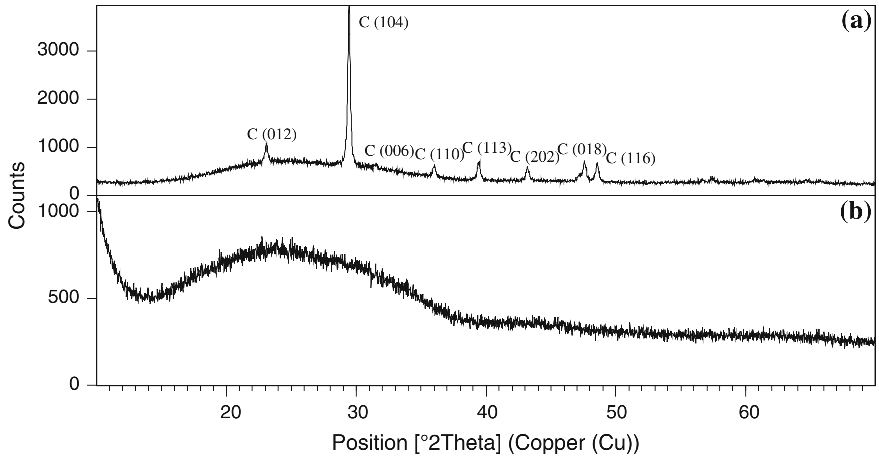

Fig. 2 XRD patterns of (**a**) samples wetted with water and left at the atmosphere at RT for 2 weeks (with C = calcite) and (**b**) samples exposed to air for 2 weeks

with crystallites' dimensions of about 40 nm, calculated for the more intense reflections by using the Debye-Scherrer equation. No preferential orientations were detected. The broad band shown in Fig. 2 is mainly due to the amorphous glass used to prepare the samples, even if an overlapping of an amorphous component deriving from calcium compounds cannot be excluded.

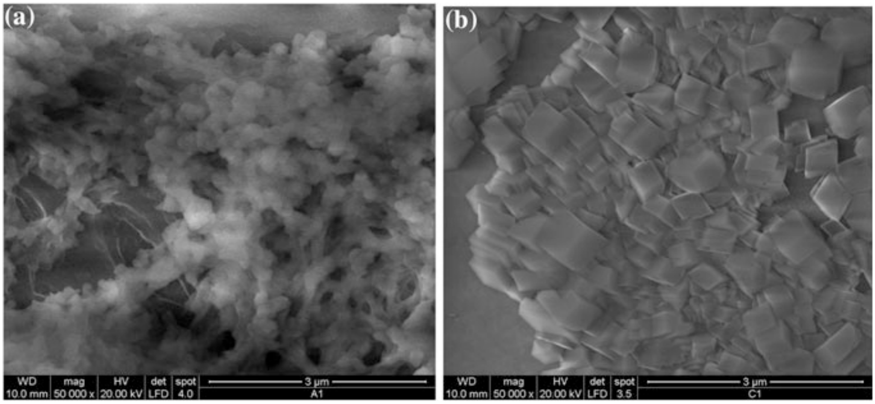

Fig. 3 SEM Back scattered images collected at 50.000x from amorphous calcium carbonate coating of Ca methylethoxyde before (**a**) and after (**b**) wetting with liquid water. It is evident from the morphology of the coating the conversion of roundish particles of amorphous calcium carbonate to rhombohedral particles of calcite

SEM images collected at high magnification clearly show the conversion of roundish particles of ACC to rhombohedral ones of calcite (Fig. 3).

IR spectra of the coatings obtained at different RH conditions confirm the results of XRD measurements, showing no differences between the samples and proving that the conversion process from the alkoxides to calcium carbonate follows preferentially the insertion of CO_2 as first step. RH higher than 50 % induced the formation of calcite in association to vaterite, that is the preferential phase when carbonation takes place at RH < 50 %. An interesting result for application of alkoxides is that liquid water plays a crucial role to convert the amorphous calcium carbonate into the desired thermodynamically stable calcite phase.

3.4 Carbonate Coatings from Magnesium Alkoxides and Alkylcarbonate

XRD patterns collected on the coating developed by $Mg(OCH_3)_2$ and magnesium methylcarbonate show a very low crystallinity in both cases. The one belonging to the alkoxides shows that the most probable phase formed seems to be brucite (hexagonal $Mg(OH)_2$, *ICDD: 00-044-1482*), while in the coating developed from the alkylcarbonate the presence of hydrated magnesium carbonate (unknown crystal system $5MgO \cdot 4CO_2 \cdot 5H_2O$, *ICDD: 00-001-0168*) and monoclinic hydromagnesite [$Mg_3(CO_3)_4(OH)_2 \cdot 4H_2O$, *ICDD: 00-005-0211*] phases can be assumed. The presence of Mg oxide in periclase phase (MgO) and magnesite ($MgCO_3$) can be excluded in both cases. IR measurements performed on the same coatings confirmed the presence of hydrated magnesium carbonate and low-ordered carbonate structure (broadening of the bands around 1,420 cm^{-1}) (Fig. 1c), that might explain the amorphous phases identified in the XRD patterns.

For both magnesium compounds, i.e. Mg methoxide and Mg methylcarbonate, the XRD and IR results evidenced that they gave rise to coatings with a very low degree of cristallinity. Furthermore, the identified phases revealed that the formation of magnesium carbonate into the required phase magnesite did not occur, while these magnesium compounds preferably convert to different hydrated structure of magnesium carbonate and also magnesium hydroxide. Hydrated magnesium carbonates are reactive towards water and, if applied on stone substrates, could be a possible source of efflorescence of soluble magnesium salts rather than evolve to stable magnesium carbonate. On the other hand magnesium hydroxide, i.e. brucite, is rather insoluble and, once formed, it hardly converts to magnesite.

For this reason, magnesium compounds were abandoned as precursors for carbonate formation.

4 Conclusion

Synthesis of soluble alkoxides resulted to be a challenging task and many different procedures were tested. The solubility of the obtained products was modulated through the choice of the synthetic pathway, the optimization of the experimental conditions and through the correct choice of the ligands, and the obtained calcium alkoxides turned out to be soluble in common organic solvent with a content of calcium higher than 40 g/L, thus ideally ensuring a good penetration depth.

Regarding compounds obtained with the ammonia assisted synthesis, it has been demonstrated that they are more soluble than the corresponding commercial Ca-bearing consolidants and, after reaction with air, they evolve into calcium carbonate structures. The conversion of alkoxides to $CaCO_3$ structures goes through the formation of amorphous calcium carbonate that at T of 25 °C and RH > 50 % evolves to the kinetically favorable vaterite (main phase identified) and, to a minor extent, to the thermodynamically favorable phase calcite. It was also tested that the amorphous calcium carbonate formed by a fast carbonation in air can be easily transformed by a simple treatment with liquid water, thus enabling easy and safe treatments on real site.

On the other hand, despite the behavior of magnesium alkoxides and alkyl carbonate could be assumed to be similar to the one of calcium compounds, it was demonstrated that, in place of the required magnesium carbonate (magnesite), they evolve to products (magnesium hydrated carbonate and hydroxide) that might be deleterious for the further conservation of the stone and wood.

Consolidation tests are currently in progress in order to assess the efficacy of those products in comparison to commercial suspensions of $Ca(OH)_2$ nanoparticles.

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Transparent Hybrid Films for Stone Conservation and Protection

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Abstract In this study a silane polymer and an inorganic nanoparticles (TiO_2)/polymer composite coating have been tested as protective agents on three different substrates, Carrara/Botticino marbles and Angera stone to improve their hydrophobicity features. The coatings obtained turned out to be hydrophobic as concerns the sylane polymer and superhydrophobic in the case of the hybrid coating. Aging tests have demonstrated the stability of the surface colours.

1 Introduction

Conservation of historical buildings is an important issue. The environmental conditions seriously affect the stones; their protection by surface treatment with polymers is a common practice due to their ability to form a protective layer on the surface as well as to control the transport of different fluids from the surface to monument interior (Price 1996; Khallaf et al. 2011). Different classes of synthetic organic coatings have been used for this purpose and in particular acrylic and silane polymers, perfluoroethers, and fluorinated polyolefins (Alessandrini et al. 2000; Castelvetro et al. 2002).

In nature, many plant surfaces exhibit enhanced water repellency, which is attributed to their textured surfaces with hierarchical micrometer- and nanometer-sized structures in connection to hydrophobic surface components (Wu et al. 2005). In the case of water repellent leaves, airborne dust particles can be removed by water droplets that roll off the (self-cleaning) surfaces: this effect is called "Lotus-Effect" (Chen et al. 2013). This remarkable ability of nature has inspired numerous

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researchers to fabricate surfaces which could imitate these superhydrophobic features, by using numerous techniques such as the deposition of nanoparticles-polymer composites on smooth surfaces (Zielecka and Bujnowska 2006; Ono et al. 2008). Because of the two-length-scale hierarchical structure and the hydrophobic character of the surface, enhanced water repellency (superhydrophobicity) is achieved. It is worth noting that inorganic nano-oxides, such as silica and titania, improve the performance of materials used in conservation field (Licciulli et al. 2011). In particular, recently the application of photocatalytic coatings on stone has been investigated for providing surface protection and self-cleaning properties (Hsieh et al. 2005). Titanium dioxide (TiO_2), thanks to its photo-induced hydrophilicity, can be used to realize transparent self-cleaning coatings on stone surfaces also limiting cleaning and maintenance (Quagliarini et al. 2013; Quagliarini et al. 2012).

In the present study a commercially available silane polymer, used as protective agent, has been tested on three different substrates, Carrara/Botticino marbles and Angera stone, to improve their hydrophobicity features. Then the conservation effectiveness of inorganic nanoparticles (TiO_2)/polymer composite coatings was evaluated when applied on the differently porous stone substrates.

2 Experimental

From each stone (Angera (A), Botticino (B) and Carrara (C)), small blocks were obtained and polished with commercial grade diamond abrasive disks (Fig. 1).

The stones were treated with commercial water-repellent protective agent: among the several commercially available resins, ALPHA®SI30 was adopted in the present work since it is soluble in aqueous medium and representing an eco-friendly solution (low toxicity for human health and environment) (Fermo et al. 2013).

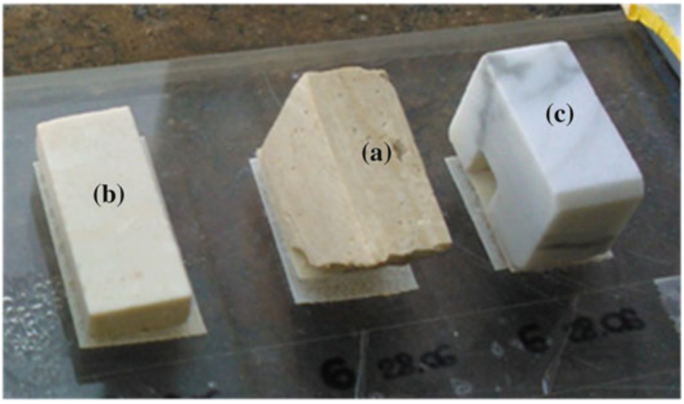

Fig. 1 The three different adopted stones

Moreover, the performance of superhydrophobic hybrid layers (titania nanoparticles + ALPHA® SI30) deposited onto the stone surfaces was evaluated in order to have a comparison with what obtained by using only water-repellent protective agent. Different syntheses have been tested to improve the stability and the transparency of the titania sol. A solution of $Ti(OC_3H_7)_4$ in ethanol was stirred for 15 min at room temperature; then a fixed amount of HCl 37 % and a non-ionic surfactant (Lutensol ON70) dissolved in ethanol were added to the alkoxide solution. The mixture was maintained under stirring for 10 min. Further, the titania sol was mixed with the siloxane polymeric agent ALPHA®SI30 (10 mL: 7(α)-3(TiO_2)). The as-prepared polymer-particle mixtures were sprayed onto three different samples through a nozzle of 700 μm using an airbrush system (Asturo airbrush). The quantity of the spraying mixture was kept steady by controlling the spray pressure (2.5 bars) and the spray time (3 s). The treated specimens were subsequently kept at room temperature for 5 days. After evaporation of the solvent, investigation of the surface properties and evaluation of stone protection efficiency were carried out.

The bare and coated samples were characterized by several techniques, such as SEM-EDS, CIE-Lab colorimetric analyses and contact angle measurements. Diffuse Reflectance Spectra were acquired using a JASCO/UV/vis/NIR spectrophotometer model V-570. Static contact angle (θ) measurements of water on bare and coated stones were performed on a Krüss Easy (see more details in Fermo et al. 2013). SEM-EDS (electron microscopy coupled to an energy dispersive system spectrometer) analyses were performed by a Hitachi TM1000 instrument equipped with an energy dispersive X-ray Spectrometer (Oxford Instruments SwiftED).

3 Results and Discussion

Figure 2 shows, as an example, SEM images of the bare Angera sample, the same stone clad with ALPHA®SI30 and treated with the hybrid coating. It is worth noting that after the coatings application the surfaces were, from a microscopic point of view, homogeneous and without cracks or fractures.

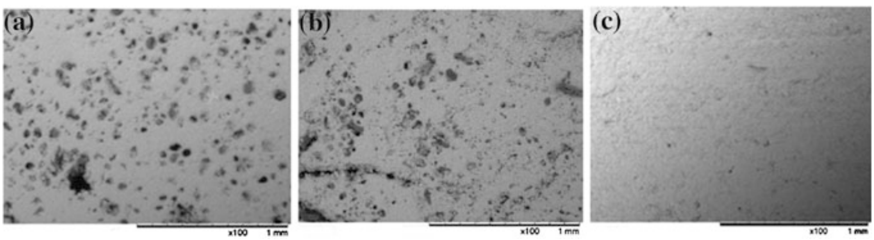

Fig. 2 SEM-EDS spectra acquired on bare stone (**a**), the same stone coated with ALPHA SI30 resin (**b**) and the hybrid transparent layer (**c**)

Static contact angle (θ) measurements on the stone surfaces were performed in order to know their wetting properties. Figure 3 shows the water contact values measured on bare and treated samples. All the obtained values are averaged over ten different measurements and the relative standard deviation is ≤3° for each set of analysis. The low values for the bare stones (<70°) defines a strong attraction between liquid and solid surface; the drop of water is often slowly absorbed from the stone, especially in the case of Angera, the stone characterized by the highest porosity. The application of ALPHA®SI30 coating leads to hydrophobic materials (90° < θ < 100°).

In order to improve the water repellency of the coatings, nanoparticles deposition technique was used to induce superhydrophobicity. This method leads to the formation of a rough two length-scale hierarchical structure that exhibits completely water repellent properties. Static contact angle measurements show that hybrid samples exhibited superhydrophobic behaviour with average contact angles higher than 140° (Fig. 3). Thus, self cleaning materials were obtained: the water drops, deposited on the layers, bounced and rolled off the stones.

In order to investigate the stability of the coatings, accelerated aging tests by UV irradiation (500 W, 250–315 nm, 10 h) were carried out. Colorimetric measurements (CIELab) were performed to verify the colour modification (yellowing) of the protective film due to solar exposition.

Color and static contact angle measurements were carried out for hydrophobic (stone + ALPHA®SI30) and superhydrophobic (stone + ALPHA®SI30 + titania sol) systems before and after 10 h of UV exposure (Table 1). The treated samples did not show neither visible colour nor contact angle variations even after UV irradiation (always ΔE ≤ 4, **Δ**θ ≤ 3).

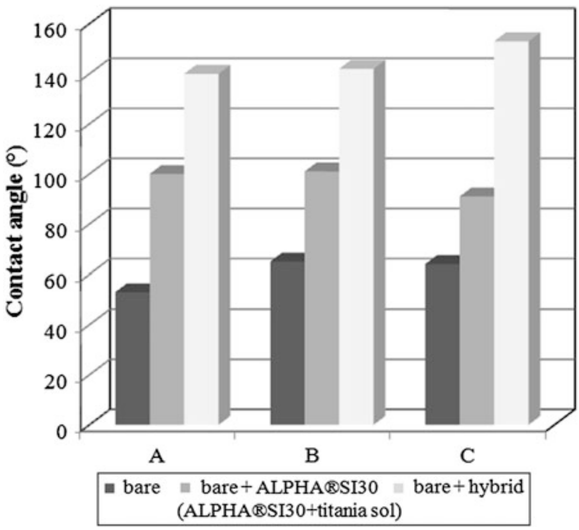

Fig. 3 Contact angles values for the bare and treated stones

Table 1 Variation of CIELAb parameters (ΔE) and contact angles (Δθ) before and after UV ageing for hydrophobic (stone + ALPHA®SI30) and superhydrophobic (stone + ALPHA®SI30 + titania sol) systems

Stone/treatment	ΔE	Δθ
A + ALPHA®SI30	4.0	–
A + ALPHA®SI30 + titania	2.0	−2
B + ALPHA®SI30	1.9	–
B + ALPHA®SI30 + titania	0.9	+3
C + ALPHA®SI30	3.1	–
C + ALPHA®SI30 + titania	3.0	−3

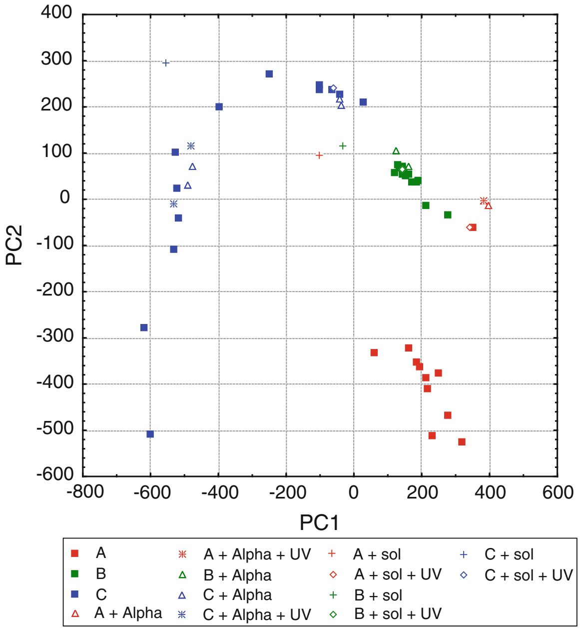

Fig. 4 PCA score plot reporting the bare stones (*A* Angera; *B* Botticino; *C* Carrara), the stones coated with Alpha resin, the stones coated with TiO_2 hybrid coating (defined sol in the graph) and the samples aged by UV radiation for 10 h

Finally, chemometric analysis was performed on reflectance spectra acquired for each stone before and after each treatment. This analysis allowed to bring out similarities and differences in the behavior of the material respect to the different treatments (Fig. 4).

As concerns Angera stone, two main groups are present in the score plot: one formed by the bare samples and the other one composed by the stones covered either with the Alpha resin or by the resin Alpha with TiO_2 sol, both untreated (i.e. without UV) and exposed to UV radiation (10 h). As already deduced from the values obtained from CIELab analysis, the samples change their color only slightly ($\Delta E < 5$) thus confirming the complete transparency of the protective treatments applied. In the case of Botticino marble the points are all grouped in a single area denoting a strong persistence of the material color characteristics even after the treatments. Respect to Angera stone and Botticino marble, Carrara marble does not show a clear splitting of points in the graph probably due to the intrinsic properties of this material. Actually a great distribution of the points can also be observed for the bare samples due to the inhomogeneity of the marble colour, sometimes characterized by grey veins.

This kind of approach could be very useful to monitor colour variation of the materials during time, especially if the aim is to control the degradation and alteration of the materials once the protective coating has been applied.

4 Conclusions

A commercial siloxane resin, ALPHA®SI30, and an inorganic nanoparticles (TiO_2)/polymer hybrid coating have been applied to stones normally used in architecture (i.e. Angera, Botticino and Carrara). A characterization of the surfaces has been carried out by a multi-analytical approach. The coatings obtained turned out to be hydrophobic or superhydrophobic as demonstrated by contact angle measurements. SEM observations have shown that the surfaces were homogeneous from a microscopic point of view and without cracks or fractures. Finally, colorimetric measurements have confirmed the transparency of the films.

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Survey of Repaired and Artificial Stones of the Archaeological Site of Pella Five Years After Application

Ioanna Papayianni, Maria Stefanidou and Vasiliki Pachta

Abstract An extensive restoration project was realized in the Archaeological site of Pella, in order to consolidate ancient stone remnants by filling them with mortar and manufacture artificial units of stone for anastylosis purposes. Samples of ancient stones were analyzed, regarding their morphological, physico-mechanical and chemical properties. Based on the evaluation of the analysis results, repair mortars were designed and tested for their compatibility with old stones. An in situ monitoring of the repair works took place, while samples for testing were taken from the site 2 and 5 years after the interventions. In this paper the results of the analysis of an adequate number of repaired and artificial stones are presented. The survey showed some cracks on few large stone units (100 × 50 × 30 cm) precast or cast in place. The analysis followed comprised color determination, measurement of compressive strength, modulus of elasticity and porosity properties. Microstructure examination was made, assisted by stereoscope and SEM-EDS, while soluble salt content and residual resistance to wetting-drying cycles were also carried out. The results were compared with the previous ones at earlier age, as well as with those of the authentic stone of Pella. Based on them, it seems that properly designed mortars are effective for consolidating or for completing missing parts of old stones without problems related with the existing microstructure and the resisting environmental cycling of the area. The characteristics of the designed repair mortars seem to be compatible with those of the old stones. The cracks appeared in some artificial stone units could be attributed to thermal load effects, as well as to lack of adequate curing.

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1 Introduction

The imitation of natural stone is a multi-phase problem as parameters of color, geometry, structure and texture should combine with the physical and mechanical properties of the stones (Fatiguso et al. 2013; Pecchioni et al. 2005). Meanwhile, issues of compatibility and durability of the produced system also arise. The design of repair materials should be based on the properties (physico-mechanical and chemical) of the existing structures, as well as on the environmental conditions to which they will be exposed (Van Balen et al. 2005; Rilem TC 2009).

Methodologies for recording the artificial stones have been developed emphasizing the structure and the appearance and the pathology of the new ones (Fatiguso et al. 2013; Pecchioni et al. 2005).

The present study refers to the archaeological site of Pella near Thessaloniki, at a distance of 39 km to the north which comprises the largest Agora (70,000 m^2) of Antiquity. Pella was the capital of the kingdom of Macedonia since the 5th century AD and a great commercial and administrative center (Akamatis and Sagiach 1998).

The conservation and upgrading of the Ancient Agora has been a long-term project, starting from 2002 and is still continued (Lilibaki-Akamati and Akamatis 2009). The responsible Committee decided to focus on the protection of stone remnants with repair mortars and to reconstruct the low walls with natural or artificial stones cast in place, in order to highlight the ground plan of the Ancient Agora (Lilibaki-Akamati and Akamatis 2008).

The Laboratory of Building Materials of the Aristotle University of Thessaloniki was asked to study the design of a repair mortar and a mixture for casting on site artificial stones of low specific gravity (≤2.0), resistant to climatic conditions of the area and in harmony with the old stone remnants. The proposed materials have been applied from 2004–2008 and 2008 up to nowadays.

Five years after the first phase of the intervention, a survey was made, aiming at checking the performance of the materials after their exposition to the environmental conditions of the site.

2 Methodology Followed

The methodology followed was developed during the 1990s for the needs of a large programme (NATO Science for Stability) regarding materials for Restoration (Papayianni 2004; Papayianni and Stefanidou 2003).

At first, a systematic analysis of the old stones was made, by taking an adequate number of samples from sound and problematic stones. A series of laboratory tests were realized in order to determine their physico-mechanical properties. Microstructure observation was performed with stereoscope (Leica Wild M10) assisted by image analysis (ProgRes). Porosity and apparent specific gravity were performed according to RILEM CPC 11.3, Dynamic Modulus of Elasticity according to ASTM C597-71, while flexural and compressive strength according to ASTM C191-81. An archive with their morphology, color, physico-chemical and mechanical characteristics, as well as with photos and other analysis was created (Papayianni et al. 2008).

Then, mortar mixtures for superficial repair and artificial stones were designed, based on the characteristics of the existing old stones and taking into account the environmental aspects of the area. Therefore, a set of criteria concerning colour, apparent specific gravity, compressive strength, porosity properties and resistance to wet-dry cycling were adopted.

The available raw materials were selected and tested. A series of trial mixes were prepared and tested in laboratory. After evaluation of the results, two mortar compositions were proposed, followed by a technical description of the materials and manufacturing process, as well as guidance about application.

A survey made 5 years after the intervention of the 2004–2008 period, showed that some artificial stone units presented cracks through the section, while very few microcracks appeared on the superficial repair mortars. The cracking pattern and depth were recorded and a number of samples were taken for testing mechanical strength and porosity.

3 Experimental Part

3.1 Characterization and Properties of the Natural Stones of the Ancient Agora of Pella

The stone used for the construction of the ancient Agora in Pella was a local marl limestone, taken from the nearby old deposits. As shown in Figs. 1 and 2, pores, nests and venules of well crystallized limestone were observed. In the existing remnants of the archaeological site, the stones presented a different grade of deterioration. There were hard compact pieces, as well as gravel-like pieces (Figs. 3 and 4). Additionally,

Fig. 1 Natural stone with calcite venules (stereoscopy x10)

Fig. 2 Natural stone with pores (stereoscopy x10)

Fig. 3 Compact limestone

biological alteration, localized mainly on the surface or up to some millimeters in depth, was observed. Flakes of 1 mm depth were often detached from the surface, leading to the loss of the material.

From the point of view of the mechanical and physical properties recorded in structural samples, Table 1 shows the variations in compressive strength, porosity, specific gravity and water absorption according to the different deteriorating grade.

3.2 The Design of the Superficial Repair Mortar

As shown in the previous chapter, the basic properties of the stones, on the surface of which the repair mortar would be applied, differed greatly according to their degradation state. The strength of unsound pieces ranged from 12 to 30 MPa and

Fig. 4 Deteriorated limestone

Table 1 Mechanical and physical properties of structural limestone

Samples	Compressive strength (MPa)	Porosity (%)	Specific gravity	Absorption (%)
Healthy samples	30.0–45.0	1.5–3.5	2.35–2.60	0.64–1.50
Medium deteriorated	15.0–30.0	4.0–9.0	2.30–2.40	1.50–2.50
Heavily deteriorated	11.5–15.0	9.0–11.0	2.17–2.27	2.50–4.85

Table 2 Composition of the superficial repair mortar applied in old stones

Materials	Parts by weight
Hydrated lime	1
Pozzolan ground (90 % pass sieve 45 μm)	0.8
White cement	0.2
River sand (0–2 mm) of light brown color	4.0
Superplasticizer of polycarboxylic base 1 % by mass of binders	
Water for required workability (flow table extension 15 ± 1 cm)	

the open porosity from 11 to 4 % respectively. The gypsum content of the calcitic matrix of the stone of Pella, as well as the high humidity of the environment, in particular during mornings, should be taken into account.

Since most of the stone pieces which needed superficial interventions suffered from deterioration, it was decided to design a soft repair mortar of higher porosity than that of the authentic stone core.

The composition of the proposed mortar is reported in Table 2.

The porosity measurements ranged from 15–19 % and compressive strength from 4–7 MPa.

3.3 The Design of the Mixture of the Artificial Stone Units

Based on a market research, the archaeologists found a similar but limited in quantity limestone deposit from the area of Koufalia, from where they decided to take only some compact pieces of large dimensions, for the need of anastylosis of columns or large stones. However, the limestone had to be checked and compared with the existing natural stones of the Pella site. Therefore, 6 samples of stone from Koufalia were tested and results are given in Table 3.

There was also need for a great number of cast in place stone pieces, to highlight the ground plan of the huge Agora of Pella, or to complete large missing parts of stones by using metallic connections of stainless steel (Fig. 5). Therefore, a specific mortar had to be designed (Table 4).

This design was based on the characteristics of the old stone pieces, as shown in Tables 3 and 4. It is obvious that the compressive strength drops from 30–45 MPa for the sound stones to 11.5–15.0 MPa for unsound pieces. In case of completion of the deteriorated stones, the latter strength level would be preferable to be considered for mortar design. On the opposite, in the case of new stones which will not

Table 3 Physico-mechanical properties of stones from Koufalia and Pella

Characteristics	Stone from Koufalia	Old stone from Pella
Color (Munsel scale)	10YR 8/2 very pale brown 10YR 8/1 white 7.5YR 8/2 pinkish white	10YR 8/2 very pale brown 10YR 8/1 white 7.5 YR 8/2 pinkish white
Petrography	Marl limestone	Marl limestone
Stereoscopic observation	Pores with re-crystallization phases	Pores and “nests” are recorded in the structure as well as venules of well-crystallized limestone
App. specific gravity	2.05–2.55	2.17–2.60
Porosity (%)	1.38–9.4	1.5–11
Compressive strength (MPa)	20–45	11.5–45

Fig. 5 Metallic connections (stainless steel) for completing missing parts of stones

Table 4 Mortar composition for artificial stone

Materials	Parts by weight
White cement CEM II/A-LL42.5 N	2.8
Sieved dry soil	0.7
Sand 0–2 mm	0.65
Sand 2–4 mm	0.15
Crushed recycled old stone (0–2 mm)	1.2
Superplasticizer max 1 % by mass of binders, free of sulfate	
Water for required workability (flow table extension 10 ± 1 cm)	

cooperate with the old ones, the former compressive level of 30–45 MPa could be considered for mortar mixture.

Furthermore, since it was impossible to achieve strength of 45 or 20 MPa by combining lime and pozzolan as binders and keeping the calcitic matrix, it was decided to select white cement as binder, because it has a low alkali content and suits better to the case. The use of sieved soil and inert fine material coming from the recycled old stone was necessary for color harmonization.

After an adequate number of trial mixes, the composition reported in Table 4 was proposed. This mixture in hardened state presented good color harmonization with the original stone of Pella, classified as 7.5YR8/1 very pale brown according to the Munsel scale. The morphology of the surfaces of the prismatic artificial stones was modified by grooving with chisel (Figs. 6a, b)

The target strength was around 40 MPa, so as to have characteristic f_c strength of 30 MPa, with a possibility of 5 % of specimens to be below that level. The porosity had to be greater than that of 5 % of the authentic stone of Pella.

All raw materials were selected after testing their salt content to be insignificant. A polycarboxylic-based superplasticizer free of sulfates was chosen for use.

The 28-d compressive strength and dynamic modulus of elasticity were measured in laboratory (Table 5), as mean value of 6 specimens (15 × 15 × 15 cm). The mean values for porosity and apparent specific gravity measurements are also

Fig. 6 Modification of artificial stones' surface by grooving with chisel

Table 5 Porosity and mechanical characteristics of artificial stone

Samples		Porosity (%) mean values 6	Ap. specific gravity	Compressive strength (MPa)	Dyn. modulus of elasticity (GPa)
Authentic natural stone		5.13	2.3	41.25	–
Artificial stone prepared at Laboratory (28d)		5.78	2.365	45.8	27.4
Artificial stone cast on site	1y	13	1.729	24.85	11.35
	2y	12.35	1.78	34.12	12.42

given in Table 5. In parallel with the proposed composition, cast site specimens were manufactured, which were exposed to local climate, after 14 days of moist curing with net burlaps. At age of 1 and 2 years they were transported to the laboratory and their physico-mechanical properties were determined. The mean values are also shown in Table 5.

The strength level obtained on site was lower than the one of the laboratory but it was acceptable, because porosity values were higher than those of the original stone. Therefore, in the case of completion missing parts, the moisture movements towards the outer surface was not disturbed. The lower strength values could be explained taking into account greater discrepancy on site. For example, water quantities were not precisely estimated. The extra moisture of sand was not evaluated in the water added and it is well known that the Water/Binder ratio is of great importance for strength development.

3.4 Survey of the Performance of Mortar for Superficial Repair of Stones

The repair mortar of Table 2, has been used to cover parts of the surface of old stones (Figs. 7 and 8) which have been deteriorated. In general, the performance was quite good. Color hue was harmonious with that of the old stone. The adhesion with the substrate was very good and long-lasting after the natural wet-dry cycling and thermal changes. Salts on the surface were not detected. However, very few repaired pieces (Fig. 9a, b) have shown visible cracks, due to improper application, such as thin layer of mortar on a bulging part of the stone or insufficient wetting of the substrate before mortar's application.

Fig. 7 Mortar for superficial repair of stones

Fig. 8 Cracks of repaired stones

3.5 Survey of the Artificial Stone Pieces

At first, it was decided by the responsible Committee for restoration, that the large stone units greater than 1 m length had to be supplied by natural stone deposits, while smaller pieces had to be cast on site. Later, as technicians became familiar with the manufacturing process, they tried, as a cost effective alternative, also to cast on site large stone pieces. A number of these large stone units with length equal or greater than 1 m such as 100 × 50 × 60 cm, during the period of 2004–2008, presented cracks through the section and were splitted in smaller compact pieces (Fig. 9a, b).

Then, in 2011 they inserted a galvanized steel cage with 3–4 cm covering and polypropylene fibres inside the mortar mass. However, thin cracks appeared at the surface especially after summer period. It should be said that the temperature rises 35–37 °C during summer and decreases to −5 °C in winter, and according to the location of the stones the sought-west side is exposed for longer period in extreme temperatures. The crack pattern and depth on the side of the artificial stones is pictured in Fig. 10. It is obvious that the cracks were superficial and due to shrinkage deformation.

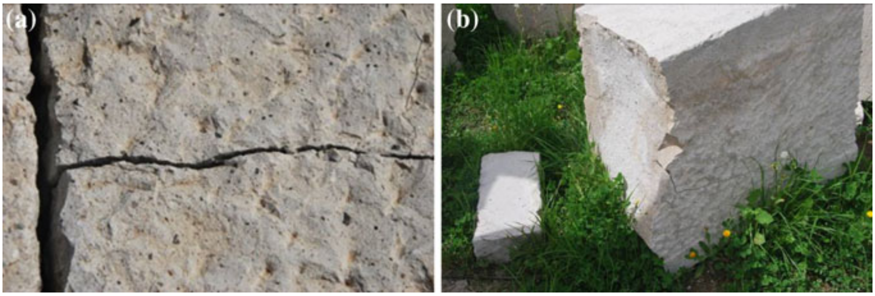

Fig. 9 Cracks and splitting of large artificial stone units

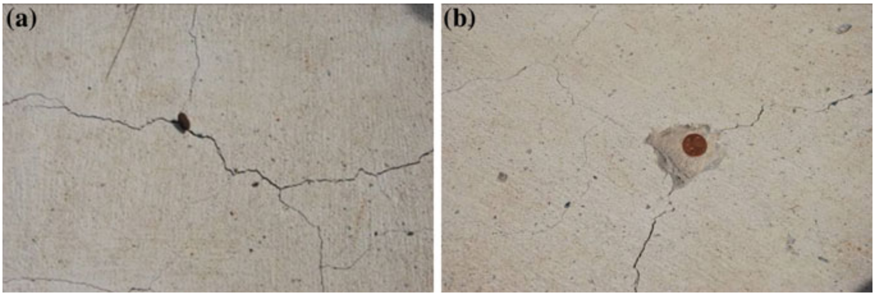

Fig. 10 Crack pattern of artificial stones

To find the cause, 7 samples were taken, of around 15 × 15 × 15 cm, from stones with cracks (numbered 1, 2, 3, 4, 5) manufactured in 2008 and from stones without visible cracks manufactured in November 2012 (the survey was made in April 2013). The results from testing strength and porosity characteristics are indicated in Table 6.

A first remark was that large stones did not present the requested bearing capacity to withstand deformations induced by thermal loads, shrinkage or even

Table 6 Results of testing artificial stones

Year	Sample nr	Dimensions (cm)	Compressive strength (MPa)	Ap. specif. gravity	Porosity %
2008	1	13.5 × 13 × 14	20.1	1.910	10.09
	2 (2008)	13.5 × 14 × 14	17.01	2.010	12.50
	3	13.5 × 14 × 15	19.87	1.855	14.8
	4	15 × 14 × 13.5	17.73	2.230	18.7
2012	5	13.5 × 15 × 12	29.04	1.968	9.9
	6 (with reinforcement)	14 × 15 × 15	30.60	1.856	8.10

Table 7 Proposed changes in the composition of artificial stone

Materials	Parts by weight
White cement CEM II/A-LL42.5N	2.8
Sieved dry soil	0.7
Sand 2–4 mm	0.65
Sand 4–6 mm	0.15
Crushed recycled old stone (0–2 mm)	1.2
Superplasticizer max 1 % by mass of binders, free of sulfate	
Water for required workability (flow table extension 10 ± 1 cm)	
Stainless steel fibres 1 % by volume of the mixture	

creep mechanisms. The parts separated from the stone core with cracks from side to side of the section, were compact without any softening or powdering effect. The salt content in soluble anions determined by ionic chromatography was: chlorides = 0.03 % w/w, nitrate < 0.01 % w/w, and sulfates = 0.84 % w/w.

The cut sound pieces from stones with through section cracks showed compressive strength from 17–20 MPa. Besides, the small pieces of artificial stone cast in the period 2004–2008 were sound for long-time after their manufacture.

The use of steel reinforcement and the polypropylene fibres addition seemed to be beneficial for avoiding through section cracks but shrinkage cracks continued to appear on the stone blocks.

It was suggested that the shrinkage deformations developed with time were considerable and impaired resistance to cracking. After reconsidering the mortar composition (shown in Table 4), it seemed that the fine content was relatively high and favored high shrinkage. A modification of the fine content was proposed as well as the manufacture of smaller stone units. In the case of larger stone units stainless steel fibres could be used instead of the reinforcement used. The proposed changes in the composition without changing the color hue are shown in Table 7.

New specimens of large stone units (100 × 50 × 60 cm) cast with modified mixture and the addition of steel fibres have been constructed for testing flexural strength fracture energy and shrinkage deformation.

4 Concluding Remarks

In restoration projects many particularities are encountered and a step by step process must be followed. Compatibility and durability aspects should be taken into account properly. The first may imply a set of requirements about mechanical strength and elasticity, while for the latter, porosity properties influencing moisture transport phenomena, as well as soluble salt content and tendency to freezing should be checked and modified to increase as much as possible the longevity of artificial stones. Specific guidelines regarding the application of the proposed repair materials in accordance with the particularities confronted should be given.

Continuous monitoring of the behavior of the repaired components of the site is of great importance. A system for checking the quality of the materials and works done is necessary to be established within the project and according to post estimated characteristics some modifications of the composition should be made.

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