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Sustainable Construction

Building Performance Simulation and Asset and Maintenance Management

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Editor

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Editor
João M.P.Q. Delgado
Faculty of Engineering
University of Porto
Porto
Portugal

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Preface

The construction industry is responsible for creating, modifying and improving the living environment of humanity. On the other hand, construction and buildings have considerable environmental impacts, consuming over 40 % of total primary energy, the built environment is in the centre of worldwide strategies and measures towards a more sustainable future. To provide resilient solutions, a simple optimisation of individual technologies will not be sufficient. In contrast, the whole-system thinking reveals and exploits connections between parts. Each system interacts with others on different scales, i.e. materials, components, buildings, cities; and domains such as, ecology, economy and social. Therefore, the sustainability of the built environment, the construction industry and the related activities are pressing issues faced by all stakeholders in order to promote a sustainable development. The forthcoming years are a challenge for practitioners and researchers that have in mind the sustainability of the built environment and the construction industry.

The main purpose of this book, *Sustainable Construction: Building Performance Simulation and Asset and Maintenance Management*, is to provide a collection of recent research works to provide the best practice solutions, case studies and practical advice on implementation of sustainable construction techniques prepared by industry. It includes a set of new developments in the field of building performance simulation, building sustainability assessment, sustainable management, asset and maintenance management and service-life prediction.

The book is divided into several chapters that intend to be a resume of the current state of knowledge for the benefit of professional colleagues, scientists, students, practitioners, lecturers and other interested parties to the network. At the same time, these topics will be going to the encounter of a variety of scientific and engineering disciplines such as civil, materials and mechanical engineering.

João M.P.Q. Delgado

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Fibre Reinforced Polymers in the Rehabilitation of Damaged Masonry

J.S. Nogueira Chagas and G. Farias Moita

Abstract The structural masonry system is a traditional and well-established technology for building affordable housing, largely utilized around the world. However, a series of structural pathologies and collapses have been reported for this construction system. The current work deals with the use of fibre reinforcement to retrofit this kind of structures. In this context, the use of carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) for the rehabilitation of damaged small masonry walls (here called wallettes) was investigated experimentally. This study sought to measure the maximum loading carrying capacity of the wallettes and to assess the possible structural rehabilitation in the damaged masonry structures after their reinforcement with the composite polymers. The experimental results presented, in general, the recovery (or even rise) of the original compressive loading bearing capacity of the structures due to the external fibres bonding. These results are a good indication of effectiveness of the use FRP in these situations.

Keywords Masonry · Damage · Rehabilitation · CFRP · GFRP

1 Introduction

The structural masonry is a well-established traditional technology for the construction of affordable buildings. It is widely used throughout the world. Nowadays, simplicity and rationalisation of the construction process, aesthetic correctness, durability, low costs, good thermal and acoustic performance and fire resistance, among others, are characteristics that turn the masonry structures construction

J.S. Nogueira Chagas (✉) · G. Farias Moita
Centro Federal de Educação Tecnológica de Minas Gerais (CEFET-MG), av. Amazonas 7675, Minas Gerais 30510-000, MG, Brazil
e-mail: juniasnc@civil.cefetmg.br

G. Farias Moita
e-mail: gray@dppg.cefetmg.br

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system into one of the most economical technology readily available (Hendry 2002). In Brazil, structural masonry has been extensively used in the construction of the inexpensive buildings since the early 1960s and, up to now, represents one of the promising solutions for the housing deficit in the country. However, in Brazil and in several other countries, most of these buildings have been constructed without the adoption of additional reinforcement techniques that complement the loading bearing capacity in relation to the out-of-plane efforts. In these cases, the structural system is called unreinforced masonry (URM) (Facconi et al. 2015).

Nonetheless, problems with structural pathologies, failures and collapses have been reported as the result of the lack of more rigorous quality control for the materials and inadequate production processes, as well as, in some cases, due to the application of inaccurate empirical dimensioning methods, without the wide use of computational tools, which would yield a more accurate structural analysis results. In addition to these factors, others contribute to aggravate these problems, such as: the application of unpredicted loads, due to different uses and architectural modifications of the structure; foundation settlement; wrong structural conception; natural deterioration of the materials and components; and, impacts, collisions or explosions. In such situations, the reinforcement or rehabilitation of the damaged existing structures have been, often, more attractive or desirable than replacing it with a new construction due to heritage, economic and environmental reasons (Asteris 2012).

The adoption of low invasive and high efficient strengthening techniques is one key aspect for the success and viability of the rehabilitation interventions. In this aspect, the usage of fibre reinforced polymers (FRP) to enhance the structural performance of masonry structures is a promising technique because of its high specific strength, high stiffness and small thickness compared to the conventional materials (Hollaway 2001).

When the polymer composite materials are used to “repair” or for “rehabilitation”, they act to repair functional or structural deficiency in the structure, that can be observed as cracks or more severe degradations. In these cases, the composite materials can bring the structure to its original strength and effectiveness. On the other hand, the strengthening process is a specific application in cases in which the use of composite it is only desired to strengthen the designed performance level. Hence, here rehabilitation is understood as the act or process to bring the structure back to its former, original or normal condition of endurance and performance. In the current context, both reinforcement and strengthening mean the process whereby the action of rehabilitation can occur.

In the literature, numerous studies on the strengthening of reinforced concrete structures with externally bonded FRP sheets have been published for many years. In the last decades, several experimental and numerical studies have been conducted about the usage of the FRP for the structural rehabilitation and strengthening of masonry walls. Very good results have been reported, what contribute to the success on this approach (Masia 2003; Prakash 2008; Fedele 2010; Faella et al. 2012; Carrara and Ferreti 2013).

This work brings the experimental results obtained from the application of the carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) for the structural strengthening of small masonry walls (here called wallettes). This study measured the maximum loading bearing capacity of the wallettes and assessed the possible structural rehabilitation in the damaged masonry structures after their reinforcement with the FRP.

2 Masonry Strengthening Techniques and Rehabilitation

The strengthening techniques applied to vulnerable structures and for repair and rehabilitation of damaged constructions has emerged as a challenging and timely issue for the technological development of civil engineering worldwide. There is an urgent need for the development of effective, durable and cost-efficient repair/strengthening/retrofit materials and methodologies. In these circumstances, unreinforced masonry (URM) buildings represent a large proportion of the historic buildings throughout the world, with great heritage importance. However it is characterized by very low tensile and flexural resistances, on top of its brittle behaviour and the need for strengthening interventions and repair.

The structural masonry is mainly characterized by its high capacity of resistance to compressive loads. However, its main weakness is related to the poor bonding strength between mortar and blocks or bricks. Because of these inherent characteristics of URM, during the structural design its tensile strength is often neglected. However, it is observed that, in practice and frequently, there are situations where the axial compressive loads are applied with some eccentricity, i.e., outside the centroid axis of the resistant cross section of masonry. The eccentric loading produces nonlinear effects onto masonry walls by the interactions between changes in their geometry and their low tensile response. Thereat, the eccentric loading has a destabilising effect on masonry elements. Consequently, even small eccentricities in axial loadings for masonry can mean serious problems, and may even lead to total collapse of the structure. As the eccentricity increases, the mechanical performance shows a progressive loss of strength due to the effects of flexural deformation and crack distribution on the masonry structure (Cevallos et al. 2015).

Also, masonry structures designed as unreinforced masonry (URM) do not possess strengthening to withstand out-of-plane and dynamic actions. Therefore, the majority of these buildings are vulnerable to collapse in moderate to large magnitude earthquakes and thus poses a safety risk to their occupants, besides the destruction of the structure itself. During earthquakes, walls of a building are subjected to in-plane as well as out-of-plane actions. In an out-of-plane loading situation, the masonry walls are supported by cross-walls and by floors above and below resulting in load transfer by two-way action (Bernat-Maso et al. 2015; Kadam et al. 2015).

On the other hand, many masonry constructions have already exhausted its design service life, according to suggestion of major standards (more than 50 years old).

In addition, their very existence exposes the building to all kinds of incidents, so as to cause damage to the walls, which often leads to significant faults of structural nature, with regards to both static and seismic actions (Facconi et al. 2015).

Due to the security risks inherently associated to structural masonry buildings, especially URM ones located in seismic regions, and those already damaged must be either strengthened or retrofitted. In most cases, demolition is not suitable due to the heritage importance. The sustainable restoration of historical buildings is an important topic nowadays worldwide. For this reason, the development of strengthening and repairing innovative techniques has been the subject of several experimental studies performed in the last few years by many researchers.

2.1 Conventional Strengthening Techniques

Shear failure mechanism is a common collapse mode of masonry structures which is determined by the low tensile strength of the material. Many studies have been made with the aim to improve the tensile response of the unreinforced masonry structures, in order to prevent their main fragility (Bernat-Maso et al. 2015).

In general, conventional reinforcement methods usually include the addition of other structural elements such as columns and beams of steel or concrete. The treatment of the masonry surfaces by applying resistant coatings, using reinforced mortar, concrete and steel plates may also be effective. Another technique for increasing the resistance of masonry is the grout injection with or without addition of steel bars. The application of these elements and materials aims to increase the strength and/or ductility of the walls. These strategies have been applied successfully in many cases (ElGawady et al. 2004).

A steel plates or tubes can be used as external reinforcement for existing URM buildings. Steel system can be attached directly to the existing walls. This external steel system provides an effective energy dissipation mechanism (ElGawady et al. 2004).

Surface treatment is a common method, which has been largely developed based on previous experiences. Surface treatment incorporates different techniques of resistant coatings such as ferrocement and shotcrete. These procedures cover the masonry exterior and can affect the architectural or historical appearance of the structure besides to increase mass on the walls. The resistant coating can be applied onto masonry surfaces. In this way, the loading bearing capacity is improved, both axial and transversal. These coatings can be executed by steel reinforced micro-concrete layers sprayed on both lateral faces of the walls, with or without transversal steel ties through the thickness of the specimens (Pinho et al. 2012).

Currently, walls can also be strengthened or repaired by means of a thin coating made of a calcium aluminate steel fibre reinforced mortar (SFRM) containing nano-silica. This strengthening method represents a novelty with respect to both the nano-reinforced SFRM and the practical application procedure adopted. The experimental results show the enhanced performances provided by the proposed technique in terms of strength and stiffness increment (Facconi et al. 2015).

In several countries, ferrocement is a technique aiming to enhancing flexural capacity of URM walls against out-of-plane action. Ferrocement technique involves the application of a steel or welded galvanized wire mesh onto the masonry surface using a strong cement–sand mortar or micro-concrete. The technique uses horizontal and vertical strips and splints of ferrocement (known as bandages or “bands”) applied on both sides of walls. The bands are applied on the masonry in different levels such as lintel, sill, plinth and roof (Kadam et al. 2015).

Other widely used strengthening and repair technique is the grouting injection. Grout may be injected to masonry with the purpose to fill cracks, voids and pores. It is a thin mortar containing a considerable amount of water so that it has the consistency of a viscous liquid. The success of a retrofit by injection depends on the injectability of the mix used, and on the injection technique adopted. For injection, epoxy resin is used for relatively small cracks (less than 2 mm wide); while, cement-based grout is considered more appropriate for filling of larger cracks, voids. An adequate grout can fill the visible and invisible cracks, the voids of the filling material, as well as the void between walls and filling material. As a consequence, masonry becomes homogeneous and its mechanical properties are recovered. Grout injection is a popular strengthening technique, as it does not alter the aesthetic and architectural characteristics of the existing buildings (Tomazevic and Api 1993; Perret et al. 2002; Vintzileou and Miltiadou-Fezans 2008).

There are many other efficient strategies that are variations of the aforementioned ones. However, all these conventional strengthening techniques are usually time-consuming and costly.

2.2 Polymeric Composite Materials

The use of composite materials has emerged as a technologically advanced, adequate and effective option, as well as efficient, in engineering applications. Typically, composite materials consist of a combination of two distinct phases which are a continuous matrix involving a fibre that reinforces the structure.

The matrix plays several important roles in the overall composite characteristics. It bonds the fibres in the right positions and allows the stress to be transferred correctly. In addition, the matrix protects the reinforcement against damage and deterioration. The fibre has a high strength and stiffness and is used at relatively high volume fractions within the matrix. The fibres are typically glass, carbon or aramid in the form of continuous filaments or fabrics. The constituent properties and structural configurations are responsible for the overall mechanical performance of the composite (Hollaway 2001).

Composites Materials offer low maintenance in comparison with steel and concrete. For this reason, in the last decades, many researchers have studied several strengthening techniques based on the use of polymeric composite materials, such as fibre reinforced polymer (FRP) for repair, strengthening and rehabilitation of civil structures. The main advantages for the use of FRP are:

- low weight;
- low maintenance;
- low coefficient of thermal expansion;
- high strength to weight ratio;
- high corrosion resistance;
- high fire resistance;
- fast application rate;
- thin cross-section;
- easy handling;
- good surface finish.

Depending on the type of composite—carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP) or others—and on the form in which it is presented (fabrics, strips, bars or meshes), as well as the type and the characteristics of the substrate wherein it will be used, the reinforcements can be placed in the mortar joint, glued directly to the masonry through either epoxy resin or a thin mortar plaster or embedded in a mortar coating.

Several studies considering experimental, numerical and computational simulation analyses have been conducted by many researchers to assess the response of masonry reinforced with FRP. Studies have been done both in small specimens and, to a lesser extent, in full scale models. The analyses take into account mainly the performance of the walls subjected to out-of-plane loadings and also to in-plane actions with second-order effects on the structures analyzed.

The experimental setup and loading arrangements try to analyze the performance of walls reinforced with FRP in various configurations in order to simulate the real situations experienced by URM. FRP systems have been applied onto the substrates with the fibres configuration in the polymer matrix in horizontal, vertical or diagonal direction relative to the main axis of the wall and also in a wallpaper-like fashion. The main types of FRP fibres used for masonry reinforcement are carbon, CFRP (Anil et al. 2012; Ismail and Ingham 2014; Mansourikia and Hoback 2014; Dizhur et al. 2014; Babaeidarabad et al. 2014), and glass, GFRP (Valluzzi et al. 2002; Al-Salloum and Almusallan 2005; Marcari et al. 2007; Proença et al. 2012).

For the test configurations, the walls have been exposed to axial and lateral loads, and to dynamic loading cycles. In most studies, the performance of URM reinforced with FRP has been satisfactory and promising. Nonetheless, more experiments are still needed, especially to understand the performance in full-scale of enhanced URM structure.

The response of the compressive loading bearing capacity of the walls has not been typically analyzed in relation to these strengthening systems. Moreover, these vertical loads are usually applied with some eccentricity, which contributes to sudden failure mechanisms which are due to the second order bending effects associated with the slenderness of the walls and the eccentricity of the load. There are few experimental studies about the influence of strengthening systems on the compressive loading bearing capacity response. Even though, these studies proved that superficial strengthening techniques might be effective for the increase of the bearing capacity of masonry walls subjected to eccentric axial loads (Jai et al. 2000; Bernat-Maso et al. 2013; Bernat-Maso et al. 2015).

In the last two decades, especially after catastrophic events such as major earthquakes, there have been an increasing number of studies on the use of FRP strengthening systems to promote the rehabilitation of structural masonry. The results obtained indicate that this technique can be a promising strategy in such situations. However, most of the studies take into account only the loading settings that analyzes the response of these structures URM in relation to tensile and flexural resistance (Albert et al. 2001; Augenti et al. 2011; Capozucca 2011; Santa-Maria and Alcaino 2011). For this reason, the literature survey has not provided enough evidences about the performance of damaged walls after strengthening with FRP systems and submitted again only to a in plane compressive loading configuration. Thus, this analysis is a topic that needs to be addressed to better understand and to assess the mechanical behaviour of these structures after the rehabilitation with FRP systems.

With regard to the effectiveness of the reinforcement and the failure behaviour of fibre reinforced structures, they are strongly influenced by the properties and characteristics of the substrate where the reinforcement is applied (CNR-DT200.2004 2004). The main properties and characteristics are: bond length, geometry of the specimen, tests set-up, and type of the fibre reinforcing system. In addition, it also can be observed that the wide variety of the masonry substrates, formed by clay or concrete bricks (or blocks), affects the overall performance of the reinforcement system (Benrahou et al. 2006; Mendola et al. 2009; Willis et al. 2009). Experimentally, it was noted that the stress concentrations occurring at the FRP/substrate interface could lead to the detachment of the reinforcement from the support and to the premature failure of the structure due to debonding (Grande et al. 2011; Chagas and Moita 2015).

3 Experimental Program for Rehabilitation of Damaged Masonry

The experimental program for rehabilitation of reinforced masonry with FRP was conducted to characterize the mechanical properties of the structural and reinforcement systems and to evaluate the mechanical strength to axial compression of the reinforced specimens, as shown below.

3.1 Characteristics and Mechanical Properties of the Specimens

The masonry wallettes used in the research were built using concrete blocks and 1:2:6 (cement:hydrated lime:sand) mortar and had the following dimensions:

height = 100 cm; length = 80 cm; thickness = 14 cm, as schematic illustrated in Fig. 1. Two different concrete blocks were utilized to build of the wallettes: (a) single-hole blocks (dimensions: 14 cm × 19 cm × 19 cm), and (b) two-hole blocks (dimensions: 14 cm × 19 cm × 39 cm) as shown in Fig. 2.

Their average compressive strengths were, respectively, 6.30 and 5.64 MPa. The mean compressive strength for the mortar specimens was 6.49 MPa. The experiments for the characterization of the mechanical properties of these materials were conducted according to the Brazilian standards NBR 7184/82 (ABNT 1982) and NBR 13279/2005 (ABNT 2005), respectively.

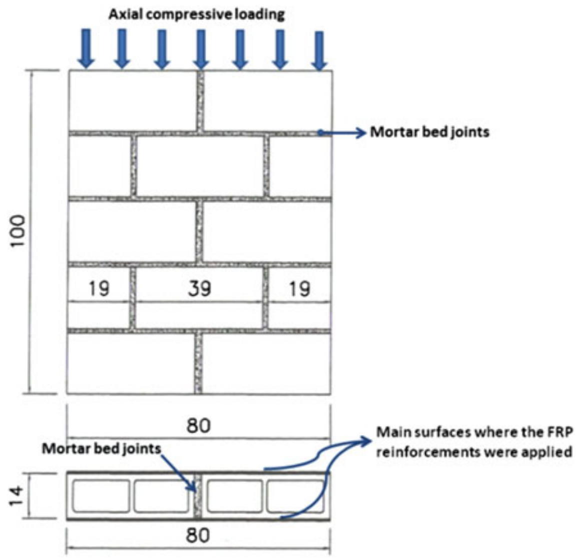

Fig. 1 Geometric configuration of the wallettes with the applied compressive loading. **a** frontal view and **b** top view with indication of the FRP reinforcement. Dimensions in centimetres. *Source* Chagas and Moita (2015)

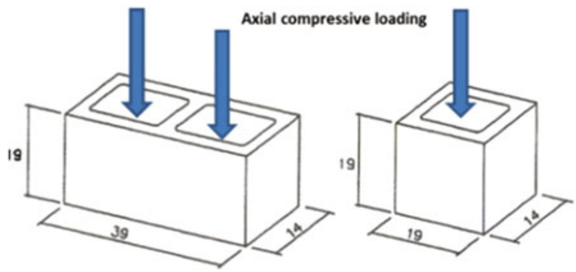

Fig. 2 Concrete blocks used with the axial compressive loading applied during testing. Dimensions in centimetres. *Source* Chagas and Moita (2015)

3.2 Characteristics and Mechanical Properties of the Strengthening System

The reinforcement system was made of polymeric fibre (FRP) and resins. The main mechanical properties of the FRP used in this work, given by the producer (BASF 2014), were: for the CFRP (one-directional fabric mesh), Young's modulus E = 227 GPa and tensile strength ft = 3800 MPa; and, for the GFRP (two-directional fabric mesh), E = 68.9 GPa, and ft = 1517 MPa. Epoxy resins provided the bonding for the reinforcement system. The resins used were a primer, a saturant and a leveling compound called putty. They are two-component materials consisting of resin and hardener. For the primer epoxy resin, E was 717 MPa. For the putty and the saturant glue epoxy resins, the characteristics were E = 1800 MPa and E = 3034 MPa, respectively.

3.3 Mechanical Properties of the Reference Wallettes

Three specimens, namely RW1, RW2 and RW3, were subjected to axial compressive loading up to failure, which meant a mean load of 427 kN. The load was applied perpendicularly to the bed joints, in increments of the 2 kN, in an universal testing machine under vertical displacement control. During the loading, the strains along the loading axis were calculated. The test setup was established in accordance with the Brazilian standard NBR8215/83 (ABNT 1983). These samples were considered the reference wallettes.

In order to cause damage to the wallettes, the seven remaining specimens were submitted to axial compressive loading of 75 % of the average collapse loading of the reference wallettes, which resulted in a load of 320 kN. The loading was applied in the same direction as above. The applied loading was big enough to damage the specimens, as desired, in order to simulate pathology. From the visual inspection, micro-cracks and cracks could be observed in the blocks and the mortar joints of the structure, i.e., the wallettes were in fact damaged.

3.4 Preparation of the Substrate and Application of the Reinforcement Over the Damaged Wallettes

Before the application of the fibre reinforcement, the wallettes were prepared using high pressure water blasting in order remove the powder and any other particles from the substrate. They were dried in room temperature for 7 days. Subsequently, the damaged specimens were then prepared and strengthened by the application of FRP. The wallettes that received one-directional fabric CFRP were denominated CW1, CW2, and CW3. The specimens GW1, GW2, GW3 and GW4 received two-directional fabric of GFRP. The FRP layers covered both the two main surfaces of all damaged specimens, according to Fig. 1.

An adequate chemical and physical bonding between the FRP and the substrate of the masonry was utilized. Firstly, the substrate of the wallettes was prepared with the application one layer of the primer. This primer is a two-component solvent-less epoxy system which when mixed yields a penetrating medium viscosity compound. This primer is used to penetrate the pore structure of the cementitious substrates and to provide a bridge adhesion between the substrate and adjoining resins. Figure 3 illustrates the primer application. Since the damaged wallettes did not present crushed parts, only cracks or micro-cracks, there was no need to fill the collapsed regions with mortar.

Subsequently, a two-part epoxy resins, composed by epoxy putty and the saturant resin as the glue, formed the bonding system. A thin layer of the epoxy resin, the so-called putty, was applied for regularization of any small surface imperfections and to provide a smooth surface to which the reinforcement system would be applied. Figure 4 depicts the substrate regularisation when the putty was used. The wallettes GW1, GW2, CW2 and CW3 were treated with the putty regularisation. The remaining walls, CW1, GW3 and GW4, did not receive the putty treatment.

The system was glued with a resin denominated saturant applied in two coatings. One layer is applied over the primer, or the putty, already dried. At around one hour, before the saturant became tacky, the FRP fabric was applied. Later, a second layer of saturant was applied on top of the FRP (Fig. 5). Finally, the whole cure process took 7 days in room temperature, ranging between 25 and 35 °C.

The main direction of the fibre was positioned horizontally in the walls, that is, in the direction perpendicular to the axial loading application. This configuration was chosen so that a more effecting enveloping (or confining effect) in the damaged structures could be obtained. The enveloping mentioned above can be understood as the wrapping effect on the wallettes, once the hypothesis is that the thickness of the walls is much smaller than the FRP covered surfaces. The Fig. 6 illustrates this configuration. As a result of such a configuration, an increase in the compressive strength and the shear capacity of the structures was expected.

Fig. 3 Application of the primer on the damaged wallettes. *Source* Chagas (2005)

Fig. 4 Putty application. *Source* Chagas (2005)

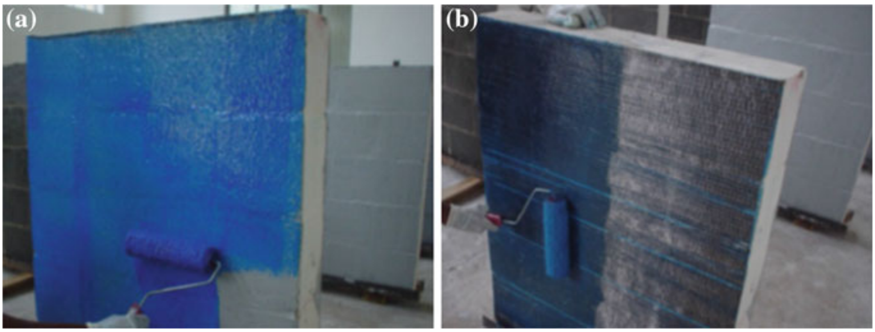

Fig. 5 Application of the saturant resin: **a** first layer and **b** second layer on top of the FRP. *Source* Chagas (2005)

Fig. 6 Horizontal direction of the fibres in the wallettes. *Source* Chagas (2005)

3.5 Experiments with the Damaged/Reinforced Wallettes

After the application of the reinforcement system onto the damaged wallettes, they were again subjected to a vertical compressive loading, up to their collapse. In this second loading, the relative vertical displacement was measured until the total load reached approximately 250 kN, which was around 60 % of the reference collapse load. This procedure prevented damage in the measurement equipment if a sudden structural fail should occur. The experiments were performed in accordance with the Brazilian standard NBR8215/83 (ABNT 1983). For comparison with the reference wallettes experimental results, the Young's modulus was also determined for these reinforced wallettes.

4 Analyses and Considerations About the Experimental Results

Next, the analyses and considerations about the experimental results are presented.

4.1 Mechanical Strength to Axial Compression

The results of the experiments of the specimens RW1, RW2 and RW3 under compression are shown in Table 1.

Tables 2 and 3 present the efficiency obtained in the compressive strength for each of the applied reinforcement systems when compared to the reference wallettes. It can be noted, in general, all the tested specimens were able to recover the original strength (and even achieving higher values).

It can be seen from the tables that the specimens reinforced with CFRP that received the putty (CW2 and CW3) presented a much better performance in relation to mechanical resistance as compared to the wallette that was not prepared with the putty (CW1). The overall compressive strength gain was up to 39 % for CW2 and CW3, whereas CW1 achieved roughly the reference strength, with a small 4 % increase. On the other hand, the wallettes reinforced with GFRP presented non-uniform results, which does not allow for a definitive conclusion over their mechanical behaviour: the wallettes treated with putty presented a compressive strength increasing of 5 and 21 %, while those that did not received the putty presented a strength improvement of 17 and 49 %, as shown in Table 3.

According to the manufacturers, the use of a proper adhesive system does not confer any extra mechanical strength to the FRP composite, but the adhesive is capable of creating a link between the substrate and FRP system and is able to

Table 1 Compressive strength of the reference wallettes

Wallettes	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation	Variation coefficient (%)
RW1	3.93	3.82	0.10	2.64
RW2	3.75			
RW3	3.79			

Table 2 Obtained efficiency of the wallettes reinforced with one-directional fabric of CFRP

Wallettes	Set up	Achieved maximum strength (MPa)	Reference strength (MPa)	Efficiency	Standard deviation	Variation coefficient (%)
CW1	Without putty	3.96	3.82	1.04	0.77	15.84
CW2	With putty	5.27		1.38		
CW3		5.31		1.39		

Table 3 Obtained efficiency of the wallettes reinforced with two-directional fabric of GFRP

Wallettes	Set up	Achieved maximum strength (MPa)	Reference strength (MPa)	Efficiency	Standard deviation	Variation coefficient (%)
GW1	With putty	4.02	3.82	1.05	0.72	15.28
GW2		4.62		1.21		
GW3	Without putty	4.46		1.17		
GW4		5.71		1.49		

distribute the applied loads. The above results confirm that the bonding between the FRP external reinforcement and the substrate is one of the key issues for the recovery of load capacity for reinforced structures (CNR-DT200.2004 2004; Carrara and Ferreti 2013).

4.2 Young's Modulus

The Young's modulus was also determined for the reinforced wallettes and a comparison with the reference ones was made. The results indicated that the reference (before reinforcement) and the FRP reinforced (after reinforcement) wallettes presented very similar behaviour under the compressive loading, as shown in Tables 4 and 5. These results suggest that the stiffness of the wallettes was also recovered after the application of the FRP reinforcement.

With regard to the stress–strain behaviour, the performance of the wallettes reinforced with CFRP was very similar when compared with their GFRP counterpart. Besides, both reinforcement systems presented stress–strain curves comparable to the curve for the undamaged specimens (before receiving the reinforcement), as depicted in Figs. 7 and 8, indicating the rehabilitation of the strengthened structures.

Table 4 Initial tangential young's modulus for the wallettes reinforced with CFRP

		Before of the reinforcement			After the reinforcement		
Wallettes	Set up	E (MPa)	Average value (MPa)	Variation coefficient (%)	E (MPa)	Average value (MPa)	Variation coefficient (%)
CW1	Without putty	5869	6100	8.50	5625	6170	8.38
CW2	With putty	6110			6653		
CW3		6320			6233		

Table 5 Initial tangential young's modulus for the wallettes reinforced with GFRP

		Before of the reinforcement			After the reinforcement		
Wallettes	Set up	E (MPa)	Average value (MPa)	Variation coefficient (%)	E (MPa)	Average value (MPa)	Variation coefficient (%)
GW1	With putty	5890	7050	12.09	6117	6837	9.81
GW2		7078			6821		
GW3	Without putty	7927			6676		
GW4		7306			7734		

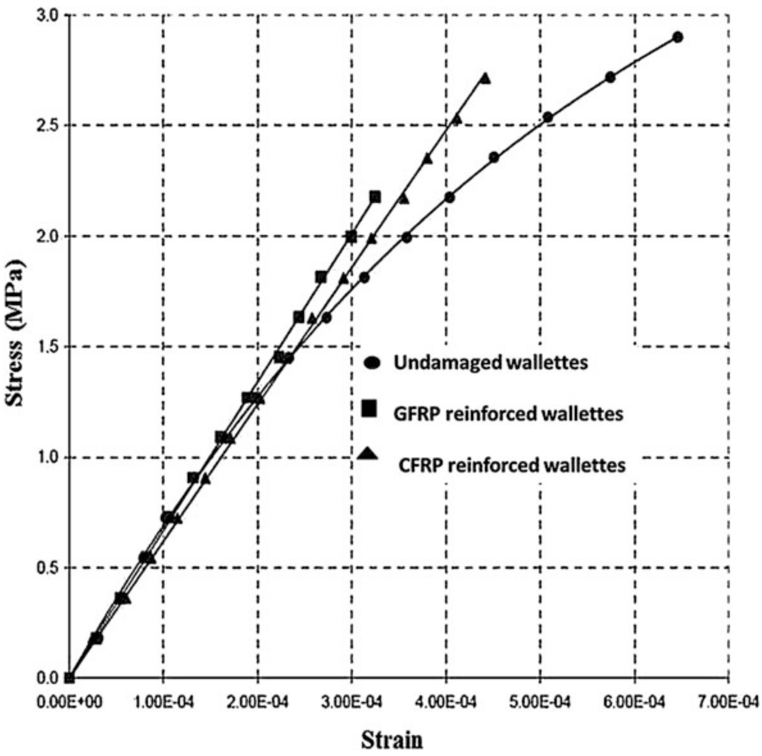

Fig. 7 Mean values for stress–strain curves of the wallettes behaviour before and after the FRP reinforcement

4.3 Failure Mode

From the experiments, it could be observed that a fragile, localized and sudden collapse occurred in the reference wallettes. In the majority of the cases, the cracks started when the loading approached its failure limit, i.e., approximately 75 % of the estimated maximum load. This confirms the low ductility of the walls and the well-known expected fragile behaviour of the masonry structures.

From the experiments in this study, it could be observed that the FRP reinforcement applied did not exhibit, during the entire loading process, faults that could be visible to naked eye. Figures 9 and 10 show that the CFRP reinforced wallettes that received the putty treatment (CW2 and CW3) presented failure of the reinforcement system only after the total collapse of the structures, without presenting fibre debonding. The failure mode of the specimen CW2 (Fig. 9) suggests that the fibre reinforcement allowed for the structural masonry wallette to reach its maximum working loading capability, even after suffering the imposed damaging. This fact, combined with the maximum loading bearing capacity shown by the CW2 and CW3 specimens (as in Table 2), implies that the application of the putty

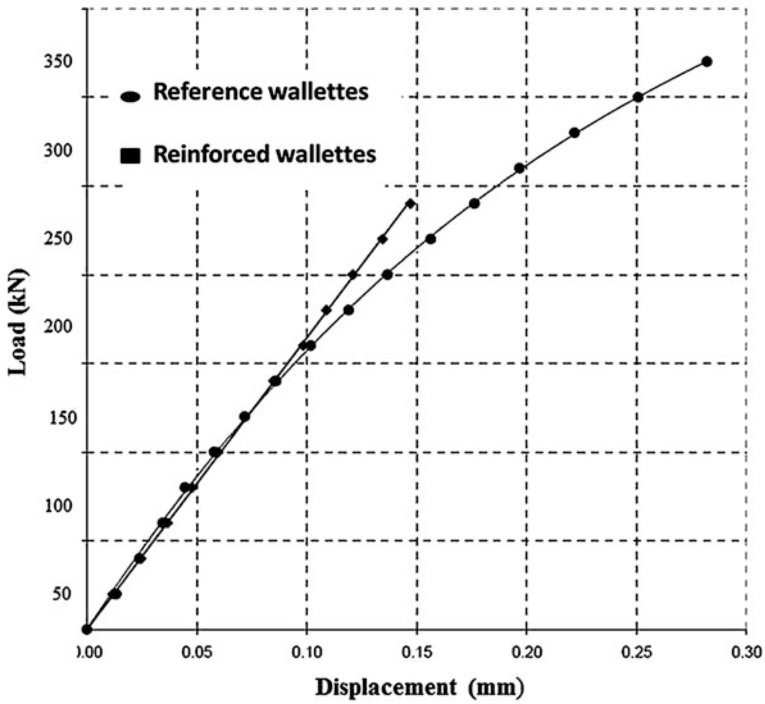

Fig. 8 Mean values for the load-displacement curves of the wallettes behaviour before and after the FRP reinforcement

contributes to the rehabilitation, as well as to the increase of the loading bearing capacity, as the result of a better bonding of the reinforcement system to the substrate.

However, the specimen that did not receive the putty treatment, CW1 (Fig. 11), offered a premature failure when compared with the specimens CW2 and CW3, as shown in Table 2. From Fig. 11, it is possible to observe the debonding of the reinforcement fibres, when the wallette reached its original failure loading, i.e., the lack of bonding of the FRP limited its performance and it only displayed a small loading capacity improvement.

The experimental results confirmed, in general, the recovery of the original compressive loading bearing capacity of the structures. Moreover, it could be seen an increasing of up to 39 % and up to 49 % of the compressive strength for the damaged masonry wallettes reinforced with CFRP and GFRP systems, respectively, as shown in Tables 2 and 3.

The ultimate load attainable by FRP reinforcement depends essentially upon the compressive and tensile strengths of the substrate. Debonding between the FRP composite and the substrate has been recognized as the principal failure mechanism of the reinforcement system. Debonding occurs when the system shear capacity is reached and the FRP reinforcement is detached from the element. Since the

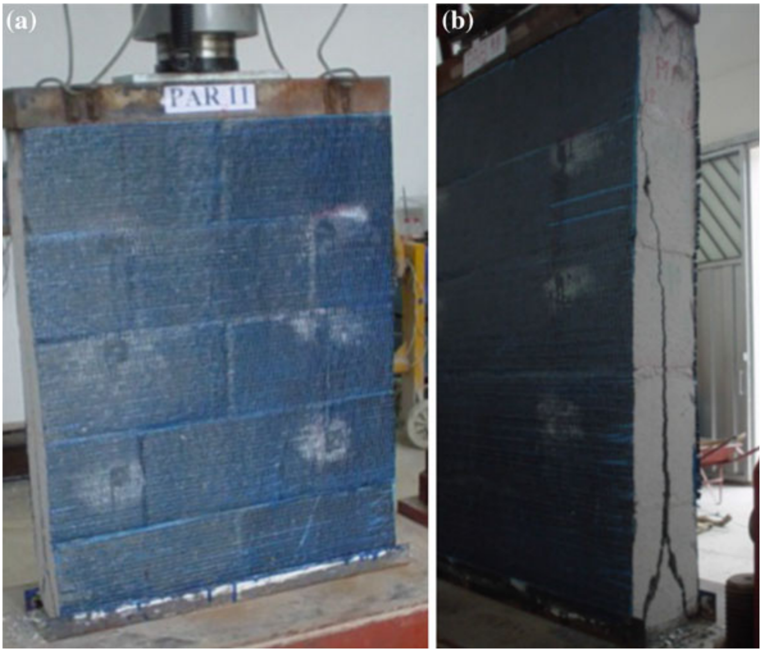

Fig. 9 Failure of the CW2 wallete reinforced with CFRP (with putty). **a** Frontal view and **b** lateral view. *Source* Chagas (2005)

Fig. 10 Failure of the CW3 wallette reinforced with CFRP (with putty). *Source* Chagas (2005)

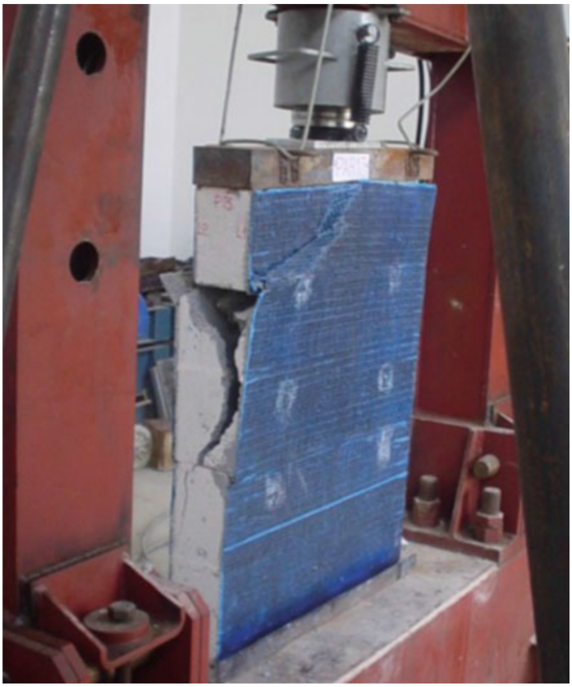

Fig. 11 Failure of the CW1 wallette reinforced with CFRP (without putty). *Source* Chagas (2005)

substrate is usually weaker than the glue and the reinforcement, failure is normally associated with the removal of a material layer during debonding. In the current investigation, this fact can be observed and confirmed.

In addition, it is believed that an "enveloping effect" was obtained with the FRP reinforcement. Also, the small confining action on the wallettes and, especially, the maintenance of the original geometry of the specimens were observed. These factors were considered responsible for the rehabilitation of the bearing capacity of the structures under the applied vertical compressive loads. The reinforcement application, and its potential of avoiding new cracks opening and the growth of the existing cracks, was also important to the final rehabilitation of masonry walls.

5 Final Considerations

The main objective of this work was to present the rehabilitation potential offered by the CFRP and GFRP applied over previously damaged masonry wallettes. The wallettes were tested under axial compressive loading, before and after the application of the FRP reinforcement.

It could be noted that the damaged, and later rehabilitated, wallettes could stand the maximum reference loading, with gains of 4–49 % on the compressive strength in comparison with the measured failure loading of the undamaged reference wallettes. Both CFRP and GFRP reinforced wallettes showed load-displacement and stress–strain curves similar to those obtained from the reference wallettes.

Debonding between the FRP composite and the substrate could be attributed as premature failure of the reinforcement system and, consequently, of the reinforced wallettes, as observed here. Moreover, the small confining action and the maintenance of the geometry contributed for rehabilitation of the damaged wallettes. However, the performance of masonry elements externally strengthened with fibre reinforced polymers can be strongly affected by the bond behaviour between the composite material and the masonry substrate.

The increase in the compressive loading bearing capacity of the unreinforced masonry due to the external fibres bonding is a good indication of their effectiveness in the studied situations. The obtained results point out the potential and applicability of the FRP reinforcement system technique in full-scale problems for URM.

Acknowledgments The authors would like to acknowledge CEFET-MG for the support during the course of this work.

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Energy Cost-Efficient Rehabilitation Measures for the Portuguese Residential Buildings Constructed in the 1960–1990 Period

A. Brandão de Vasconcelos, M. Duarte Pinheiro, A. Cabaço and A. Costa Manso

Abstract The Directive on the revised Energy Performance of Buildings (EPBD) 2010/31/EU required the Commission to establish, by means of a delegated act, a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. This chapter aims to contribute to the phasing proposed in the Directive mentioned. The results obtained from the thermal rehabilitation of the building envelope of a Portuguese residential reference building constructed in the 1960–1990 period make it possible to identify the best cost-efficient thermal rehabilitation measures. Conclusions on cost-efficient thermal rehabilitation are as follows: (i) the thermal rehabilitation of the roof produces the greatest variation in the primary energy building consumption (and the floor measures the smallest), (ii) the combination of thermal envelope rehabilitation measures creates synergy effects that lead to better results than single measures (regarding global costs and primary energy consumption), and (iii) it is more advantageous to proceed with a thermal rehabilitation package of measures rather than doing nothing.

Keywords Energy performance · Energy efficient measures · Reference building · EPBD directive

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A. Brandão de Vasconcelos (✉) · A. Cabaço · A. Costa Manso
Buildings Department, National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal
e-mail: avasconcelos@lnec.pt

A. Cabaço
e-mail: acabaco@lnec.pt

A. Costa Manso
e-mail: armando.costa.manso@gmail.com

M. Duarte Pinheiro
Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
e-mail: manuel.pinheiro@tecnico.ulisboa.pt

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1 Introduction

The building sector is responsible for about 40 % of Europe's total energy consumption and for one third of the global greenhouse gas (GHG) emissions (Directive 2010; Graham 2010). As urbanization is increasing in the world's most populous countries, building sustainability is seen as a key factor in achieving sustainable development. Therefore, a major effort is being done nowadays, all over the world, to find methods for optimising the energy performance of buildings.

Refurbishment, as part of the construction industry, has a strong global impact, not only from the viewpoint of economies but also from social and energy-efficiency perspectives. A thermal refurbishment process, in particular, relies on the making of numerous decisions and choices. Therefore, life-cycle perspectives are being increasingly considered in the decision-making process and involving participants with different interests (Hernandez and Kenny 2011; Sartori and Hestnes 2007).

At European level, as a result of these energy efficiency challenges, the European Energy Performance of Building Directive (EPBD) (Directive 2010) recast, which aims to ensure energy savings and CO_2 emission reduction, required the Member States to establish, by means of a delegated act, a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. This Directive was further supplemented by the Commission's Delegated Regulation (EU) No. 244/2012, of 16 January 2012 (Regulation No. 244 2012), and by the guidelines accompanying this Regulation (Guidelines Regulation No. 2012), which are not legally binding.

Following these EU Directives' recommendations, the authors propose a criterion based on technical and economic points of view, with a view to identify the cost-optimal package of energy efficient solutions from among a set of possible refurbishment construction solutions (Brandão de Vasconcelos et al. 2014, 2015a, b, c), within the life cycle of buildings. By 'cost-optimal level' we mean the energy performance level which leads to the lowest cost during the estimated economic life-cycle.

In this chapter it is proposed the steps and objectives involved in the calculations of the cost-optimal levels referred to in the EPBD recast, within the Portuguese context. It is particularly focused on cost categories and cost calculations applicable to a Portuguese reference building, with a view to develop a national optimal methodology within the Portuguese market conditions. The results obtained for the Portuguese reference building make it possible to determine which thermal rehabilitation measures of a building envelope are the most cost-efficient.

In the introduction (Sect. 1), this paper sets out the main objectives of the research work. Section 2 proceeds with the definition of the steps that make up the cost-optimal methodology and it is then applied to a Portuguese residential building constructed in the 1960–1990 period. The results obtained are discussed in Sect. 3. Finally, in Sect. 4, the conclusions of all the research work are presented.

2 Cost-Optimal Methodology: Application to a Portuguese Reference Building

The cost-optimal methodology phasing proposed in this chapter is based on the requirements established by the Commission's Delegated Regulation (EU) No. 244/2012, of 16 January 2012 (Regulation No. 244 2012), and by the guidelines accompanying this Regulation (Guidelines Regulation No. 2012). Through the phasing proposed, it is possible to determine the energy performance of buildings and building components and its economic issues, in order to establish an optimal balance between the investments made and the energy savings achieved throughout the life cycle of the building. The five proposed phases are characterised in the following sections.

2.1 Phase 1: Definition of the Reference Building

The first phase of the cost-optimal methodology involves the definition of the reference buildings. This is an important step as these buildings must be as representative as possible, in order to determine, as well, a representative economic optimum point for each building or for a market segment.

In Portugal, the first earthquake-resistance code in the '60s [RSCCS (Decree-Law No. 41658 1958) and RSEP (Decree-Law No. 44041 1961)] as well as the first code on thermal behaviour characteristics of buildings in the '90s [RCCTE (Decree-Law No. 40/90 1990)] constituted historical boundaries in the evolution of the housing stock. From 1960 to 1990, 50 % of the total housing stock was built (INE [Statistics Portugal] 2012). More than 85 % of buildings constructed before 1990 are classified as a C or less energy label (ADENE 2011) and many of its constructive elements have reached today the end of their useful lifespan (Silva 2011). These aspects make buildings constructed between 1960 and 1990 representative of the Portuguese building stock, having rehabilitation needs and presenting a large potential for an energetic performance improvement (Brandão de Vasconcelos et al. 2012).

Therefore, the reference building selected takes into consideration the most representative characteristics and construction solutions of buildings completed over this period in Lisbon. The reference building consists of a 7-storey residential building with two dwellings per floor, each having a 78 m^2 net internal floor area. This reference building has been fully described in Brandão de Vasconcelos et al. (2015) and its main characteristics are presented in Table 1. The climatic conditions considered correspond to Lisbon's ones [source: LNEG (Aguiar 2005)].

For this reference building Fig. 1 depicts the common floor plan of the reference building and Fig. 2 its principal façade.

Table 1 Main characteristics of the reference building

Main characteristics		Unit	Reference building solution
Net internal floor area		m^2	78
Clear height		m	2.7
Type of structure		–	Reinforced concrete
Location		–	Latitude: 38.73°; Longitude: −9.15°; Elevation: 71 m
Orientation		–	North-South
Building configuration	Number of rooms	–	2
	Number of floors	–	7
	Number of floors of the dwelling	–	1
	Number of dwellings/floor	–	2
	Number of façades	–	2
Roof	Total gross area	m^2	215.3
Vertical envelope	Façade width	m	16.3
	Façade total area	m^2	684.6
	Area of the opaque external envelop	m^2	458.56
	Share of window area of total building envelope	%	15 %
External walls (Wall 00)	Construction solution	–	Single walls of hollow ceramic brick, with 30 × 20 × 22 mm and without thermal insulation, plastered and painted
Roof (Roof 00)	Construction solution	–	Sloped roof without thermal insulation with a horizontal solid reinforced concrete slab, 0.23 m thick, with ceramic roof tiles
Ground floor (Floor 00)	Construction solution	–	Ground floor without thermal insulation with a solid reinforced structure slab, 0.23 thick, and application of wooden blocks coating directly on the screed
External windows (Wind 00)	Construction solution	–	Aluminium window frames (no thermal break) with single clear glass, 6 mm thick.
Internal walls	Solar shading	–	Outdoor clear plastic blinds
	Internal walls for room separation	–	Single walls of hollow ceramic brick, with30 × 20 × 11 mm and without thermal insulation, plastered and painted
	Internal walls for dwelling separation	–	Single walls of hollow ceramic brick, with 30 × 20 × 15 mm and without thermal insulation, plastered and painted
	Internal walls for circulation area separation	–	Reinforced concrete wall, 0.30 thick

(continued)

Table 1 (continued)

Main characteristics		Unit	Reference building solution
Internal floors	Construction solution	–	Internal floor without thermal insulation with a solid reinforced structure slab, 0.23 m thick, and application of wooden blocks coating directly on the screed
Ventilation	Natural/mechanical	–	Natural
Solar thermal collectors		–	Not installed
Heating system			Split (COP: 3.4)
Cooling system			Split (EER: 3.0)
Heating energy source		–	Electricity
Cooling energy source		–	Electricity

Fig. 1 Reference building common floor plan

Fig. 2 Reference building principal façade

2.2 *Phase 2: Identification of Energy Efficiency Rehabilitation Measures for the Reference Building*

In accordance with Directive 2010/31/EU (2010) and the Regulation (EU) No. 244/2012 (2012), the Member States must define the energy efficiency measures to be applied to the established reference building. By energy efficiency measure we mean a change to a building leading to a reduction in the building's primary energy needs (Regulation No. 244 2012).

Several sources list a number of possible energy efficiency measures that can be considered as a starting point for defining packages of measures to be applied to the reference building. Annex III of Directive 2006/32/EC (2006) shows an indicative list of examples of eligible energy efficiency improvement measures in the residential sector, divided into 7 groups: (a) heating and cooling; (b) insulation and ventilation; (c) hot water; (d) lighting; (e) cooking and refrigeration; (f) other equipment and appliances; (g) domestic generation of renewable energy sources, whereby the amount of purchased energy is reduced.

Annex III of Commission Delegated Regulation (EU) No. 244/2012 (2012) presents an illustrative table containing a list of characteristics of the measures selected for the cost-optimal calculation. Examples of measures, such as roof insulation, wall insulation, windows, heating system, ventilation system, building-related measures, DHW, among others, are presented.

Paragraph 4.1 of the guidelines accompanying the Commission's Delegated Regulation (EU) No. 244/2012 (2012) lists both the possible energy efficiency measures and the renewable energy source-based measures, which can be taken into account as a starting point for establishing the measures for the calculation process. These can be applied both at building structure level (additional insulation system of existing walls, roofs and existing slabs, increased thermal inertia, better framing of doors, windows and sun shading, better air tightness, building orientation and solar exposure for new buildings, change of share transparent/opaque surfaces, etc.)

and at system level (installation or improvement of heating systems, hot water supply system or ventilation, insulation of pipes, etc.).

Several authors (IEA 2013; Sadineni et al. 2011) point out a number of other energy efficiency measures to be applied to buildings. However, building energy refurbishment requires a variety of solutions to work with different types of support. These solutions should be easy to implement and quick to carry out, hence avoiding the need for demolition, with satisfactory results, and should contribute to reduce energy consumption.

Thus, to improve the energy efficiency of an existing building, some of the following specific measures can be adopted (Paiva 2000; Paiva et al. 2006):

(a) Thermal rehabilitation of the building envelope—by reducing the building's energy consumption, through reinforcement of the protection of opaque elements (external walls, roofs and floors over unheated spaces) and windows and through the use of passive solar technologies;
(b) Use of active solar technologies—by implementing renewable energy, particularly solar thermal, for DHW production;
(c) Rehabilitation of energy systems and facilities—through the deployment of more efficient and less consumption equipment;
(d) Energy sources available—change in the energy source by diversification of sources and guidance to less polluting energy resources.

The building envelope has been reported by several authors (Florides et al. 2002; IEA 2013; Ramesh et al. 2010; Sadineni et al. 2011) as a key element in determining levels of comfort, natural lighting and ventilation, as well as in determining the amount of energy required for heating and cooling a building.

The building envelope, also known as the building shell, fabric or enclosure (IEA 2013), is the boundary between the conditioned interior of a building and the outdoors. The energy performance of building envelope components, including external walls, floors, roofs, ceilings, windows and doors, is critical in determining how much energy is required for heating and cooling. Energy loss through the building envelope is highly variable and depends on numerous factors, such as the building's age and type, the climate, the construction techniques, the orientation, the geographical location and the user's behaviour.

Results from several studies (Balaras et al. 2005; Lechtenböhmer and Schüring 2010; Petersdorff et al. 2006) indicate that major energy savings lie in improving the building envelope of the existing building stock. Other authors (Altan and Mohelnikova 2009) stress the importance of insulation of the building envelope, together with the application of new windows, to reduce total energy consumption. Morelli et al. (Morelli et al. 2012) shows in a study that the theoretical energy use can be reduced by 68 % as compared to the energy use prior to retrofitting by the installation of insulation, new windows and a ventilation system with heat recovery (Arumägi and Kalamees 2014).

The energy efficiency measures selected for the reference building are considered in the context of energy rehabilitation. These measures are applied to the building envelope, in line with the research studies mentioned.

Table 2 illustrates the energy efficiency rehabilitation measures selected for the reference building described in this chapter. For the determination of the cost-optimal level, these measures were combined with each other creating 35.000 combinations of packages of measures.

2.3 Phase 3: Calculation of the Primary Energy Demand Resulting from the Application of Measures to the Reference Building

The comparative methodology framework defined in Directive 2010/31/EU (2010) requires Member States to assess the final and primary energy needs of the reference building, both with and without the application of energy efficiency measures. In the present case study, these energy efficiency measures are the ones listed in Table 2.

According to Directive 2010/31/EU (2010) "the energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs".

The energy efficiency measures selected in Sect. 2.2 are included in a group of previously described solutions: "(a) Thermal rehabilitation of the building envelope". This group of measures affects directly the energy consumption for heating and cooling, without contributing to greater efficiency of the energy requirements for the preparation of hot water for domestic use. Since the measures for increasing efficiency in energy consumption for hot water preparation are within group "(b) Rehabilitation of energy systems and installations" (not addressed in this work), the energy needs for this type of consumption were not calculated.

Thus, this study refers only to the calculation of the energy performance of the energy needs for heating and cooling, with and without the application of the measures defined in Table 2. This calculation provides the energy needs for heating and cooling per net internal floor area of dwellings. The primary energy needs are calculated according to the conversion factors of primary energy established in the Portuguese Legislation (Decree order (extract) No. 1579).

The measures presented in Sect. 2.2 are grouped into a set of energy efficiency measures forming packages of measures. The latter are applied to the reference building and the energy needs for heating and cooling, associated to the 35.000 packages of measures, were calculated (Coelho et al. 2015), following the EPBD procedure and using the EnergyPlus software. The parameters considered in the calculation were based on the Portuguese EPBD thermal regulations for Residential Buildings—REH, 2013 (Decree-Law No. 118/2013 2013). The reference building primary energy demand was calculated for the climatic conditions of Lisbon, Portugal.

Table 2 Energy efficiency rehabilitation measures applied to the reference building envelope

Measure ID	Measure location	Solution
Existing solution		
Wind 00	Window	Aluminium window frames (no thermal break) with single clear glass, 6 mm thick
Roof 00	Roof	Sloped roof without thermal insulation, with a horizontal solid reinforced concrete slab, 0.23 m thick, with ceramic roof tiles
Floor 00	Ground floor	Ground floor without thermal insulation with a solid reinforced structure slab, 0.23 thick, and application wooden blocks coating directly applied on the screed
Wall 00	External wall	Single walls of hollow ceramic brick of 30 × 20 × 22 mm without thermal insulation, plastered and painted
Proposed solution		
Wind 01–Wind 03	Window	Replacement of the existing window by an aluminium window frame (no thermal break): with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 01), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 02) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 03)
Wind 04–Wind 06	Window	Replacement of the existing window by a PVC window frame: with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 04), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 05) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 06)
Wind 07–Wind 09	Window	Replacement of the existing window by an aluminium window frame (thermal break): with double clear glass (4 + 6 mm thick) and 6 mm air space (Wind 07), with double clear glass (4 + 6 mm thick) and 16 mm air space (Wind 08) and with double low emissivity clear glass (4 + 6 mm low-e thick) and 16 mm air space (Wind 09)
Roof 01–Roof 06	Roof	Application of EPS, with the thicknesses as follows: 20 mm (Roof 01), 30 mm (Roof 02), 40 mm (Roof 03), 60 mm (Roof 04), 80 mm (Roof 05), 100 mm (Roof 06), over the concrete slab
Floor 01–Floor 07	Ground floor	Application of vinyl floor coating without thermal insulation (Floor 01), over EPS with the thicknesses as follows: 20 mm (Floor 02), 30 mm (Floor 03), 40 mm (Floor 04), 60 mm (Floor 05), 80 mm (Floor 06), and 100 mm (Floor 07)
Floor 08–Floor 13	Ground floor	Application of marble natural stone over EPS with the thicknesses as follows: 20 mm (Floor 08), 30 mm (Floor 09), 40 mm (Floor 10), 60 mm (Floor 11), 80 mm (Floor 12), and 100 mm (Floor 13)
Floor 14–Floor 19	Ground floor	Application of pine wood parquet (on wooden intermediate support structure) over EPS with the thickness as follows: 20 mm (Floor 14), 30 mm (Floor 15), 40 mm (Floor 16), 60 mm (Floor 17), 80 mm (Floor 18), and 100 mm (Floor 19)
Wall 01–Wall 06	External wall	Application of ETICS with 20 mm of EPS (Wall 01), 30 mm of EPS (Wall 02), 40 mm of EPS (Wall 03), 60 mm of EPS

(continued)

Table 2 (continued)

Measure ID	Measure location	Solution
		(Wall 04), 80 mm of EPS (Wall 05), and with 100 mm of EPS (Wall 06), from the outside of the existing external wall
Wall 07–Wall 12	External wall	Ventilated façade of metal plates over EPS with the thicknesses as follows: 20 mm (Wall 07), 30 mm (Wall 08), 40 mm (Wall 09), 60 mm (Wall 10), 80 mm (Wall 11), and 100 mm (Wall 12)
Wall 13–Wall 18	External wall	Construction of a drywall (with metallic intermediate support structure) from the inside of the existing external wall over EPS with the thicknesses as follows: 20 mm (Wall 13), 30 mm (Wall 14), 40 mm (Wall 15), 60 mm (Wall 16), 80 mm (Wall 17), and 100 mm (Wall 18)
Wall 19–Wall 24	Exterior wall	Construction of a 7 cm brick wall from the inside of the existing external wall over EPS with the thicknesses as follows: 20 mm (Wall 19), 30 mm (Wall 20), 40 mm (Wall 21), 60 mm (Wall 22), 80 mm (Wall 23), and 100 mm (Wall 24)

2.4 Phase 4: Calculation of the Global Costs for the Reference Building

The definition of an economic calculation method is necessary for calculating the costs of the energy efficiency measures defined in Phase 2, during the expected economic life cycle applied to the reference building. This economic calculation method should take into account: the initial investment, the sum of the annual costs for every year and the final value, as well as the disposal costs.

In order to calculate the global cost of the energy efficiency measures it is also necessary to define the type of individual perspective and expectations as regards the investment to be made: the financial perspective or the macro economical one (Aggerholm et al. 2011; Guidelines Regulation No. 244 2012).

2.4.1 Financial Perspective

In the financial perspective, only the immediate costs and benefits from the investment decision are taken into account. Thus, the global cost of each package of solutions corresponds to the price paid by the end consumer, including taxes, such as VAT, and all applicable subsidies and incentives. The global cost for the financial perspective is (1):

$$C_g(\tau) = C_t + \Sigma[\Sigma\left(C_{m,i}(j) \times R_d(i) + C_{s,i}(j) \times R_d(i) + C_{e,i}(j) \times R_d(i) - V_{f,\tau}(j)\right] \tag{1}$$

where τ is the calculation period, $C_g(\tau)$ the global cost referring to the starting year (τ_0) over the calculation period, C_t the initial investment costs per measure or set of measures *j*, $C_{m,i}(j)$, $C_{s,i}(j)$ and $C_{e,i}(j)$ maintenance, replacement and energy costs, respectively, during year *i* per measure or set of measures *j*, $V_{f,\tau}(j)$ the residual value per measure or set of measures *j* at the end of the calculation period (discounting the starting year) and $R_d(i)$ the discount factor for year *i*. The discount factor is calculated using formula (2), where *p* means the number of years since the starting period and *r* means the real discount rate:

$$R_d(p) = (1/(1 + r/100))^p \tag{2}$$

The different types of costs considered (initial investment costs, maintenance costs, operational costs, energy costs, GHG emission costs, and disposal costs) (EN 15459 2007; Guidelines Regulation No. 244 2012) are calculated in reference to the starting year by applying the selected discount rate. The discount rate adopted in this perspective is 6 %. This value was established in accordance with the discount rates considered in the Portuguese energy private investment studies (Ferreira et al. 2014) and in other cost-optimal reports published by EU countries (Department for Communities and Local Government 2013; European Commission 2015).

2.4.2 Macroeconomic Perspective

The macroeconomic perspective is used when the justification for introducing energy performance regulations is to make organisations or individuals to take actions that do not reflect their own direct interests (and are therefore unattractive as investments) but that can prove to be beneficial to society as a whole (Aggerholm et al. 2011). This macro perspective includes benefits and costs of "externalities", such as damages from climate changes associated with carbon dioxide emissions. Thus, the global cost of each package of solutions corresponds to the price paid by the end consumer, excluding all applicable taxes, subsidies and incentives, and including the cost of GHG emissions—$C_{c,i}(j)$—, as indicated in formula (3):

$$C_g(\tau) = C_t + \sum\left[\sum(C_{m,i}(j) \times R_d(i) + C_{s,i}(j) \times R_d(i) + C_{e,i}(j) \times R_d(i) + C_{c,i}(j) \times R_d(i) - V_{f,\tau}(j)\right] \tag{3}$$

The discount rate adopted in the macroeconomic perspective should give emphasis to political priorities rather than to the financial context and to the mortgage credit conditions in the country. The value adopted is 3 % and corresponds to one of the two values (3 and 4 %) most cited in studies (Department for Communities and Local Government 2013; European Commission 2015; Ferreira et al. 2014; Regulation No. 244 2012).

2.4.3 Cost Calculation

For both perspectives, the investment costs, the maintenance costs and the replacement costs are obtained from the ProNIC (Protocol for Technical Information Standardization in Construction) database (Monteiro et al. 2014) and are complemented by prices taken from standard offers of construction companies and from LNEC's database on construction prices (Manso et al. 2004). The residual value of each measure is calculated on the basis of the remaining lifetime of the last replacement of the measure until the end of the calculation period, assuming a straight-line depreciation over its lifetime. For the macro perspective, the GHG emission costs are calculated according to the Portuguese information on GHG emission allowances (DGEG 2014).

The definition of the maintenance activities, periodicity and lifespan of each construction element and solutions, are obtained from the information included in preventive maintenance plans and scientific publications (Abate et al. 2009; Albano 2005; Housing Association Property Mutual—HAPM 2003; Institut de Tecnologia de la Construcció de Catalunya 1991; Silva 2011; Viegas 2006). The energy costs are directly calculated from the energy needs for heating and cooling the building (obtained in Phase 3), multiplied by the Portuguese annual energy costs (DGEG 2014), which are defined on the basis of EU's forecasts for energy cost trends (European Commission 2014). The different types of costs considered (initial investment costs, maintenance costs, operational costs, energy costs, greenhouse gas emission costs, and disposal costs) (EN 15459 2007; Guidelines Regulation No. 244 2012) are calculated in reference to the starting year by applying the selected discount rate. The calculation period adopted is 30 years, as proposed in the EPBD.

2.5 Phase 5—Determination of the Cost-Optimal Level of Energy Performance

The cost-optimal level is obtained after calculating the global cost (phase 4) of the packages of measures (defined in phase 2) applied to the reference building (characterised in phase 1) and by considering the reference building energy performance (phase 3).

Figure 3 shows the cost-optimal curve that is found when assessing all the combinations of measures of the reference building from a macroeconomic perspective. The primary energy consumption (x-axis) represents the total energy consumed by all the 14 dwellings belonging to the reference building and the global cost (y-axis) refers to each package of measures applied to the reference building. The lowest point of the curve (red point) corresponds to the package of measures with the lowest global cost. The cost-optimal level of minimum energy performance requirements is given by the x-axis position of the lowest cost. The cost-optimal level of packages with the same or similar costs corresponds to the one with the lower primary energy use (circle dots with different colors). The part of the curve to the right of the cost-optimal level represents solutions that underperform in both aspects (environmental and financial). The left part of the curve, starting at the cost-optimal level, represents the cost-optimal energy-performance levels for both low and nearly zero energy buildings (BPIE 2010).

The cost-optimal level package of reference building measures corresponds to Wind 01, Wall 24, Roof 04 and Floor 02. This package consists of the procedures as follows: replacement of the existing window by an aluminium window frame (no thermal break) with double clear glass (4 + 6 mm thick) and 6 mm air space, construction of a 7 cm brick wall from the inside of the existing external wall over a 100 mm thick EPS, application of a 60 mm thick EPS over the roof concrete slab and application of vinyl floor coating over a 20 mm thick EPS.

The shadowed zone illustrated in Fig. 3 includes the thermal refurbishment packages of solutions having less primary energy consumption and less global costs than the ones assigned to the reference building base package of solutions. Therefore, from the cost-optimal point of view, it is more advantageous to proceed with any thermal refurbishment package of measures located inside the shadowed zone rather than doing nothing on the reference building considered.

The cost-optimal package of solutions found in the financial perspective is exactly the same as the one obtained for the macro perspective. The graphics for both perspectives have the same shape, differing only as refers to the position of the dots cloud. The dots cloud, in the financial perspective, is located above (on y-axis)

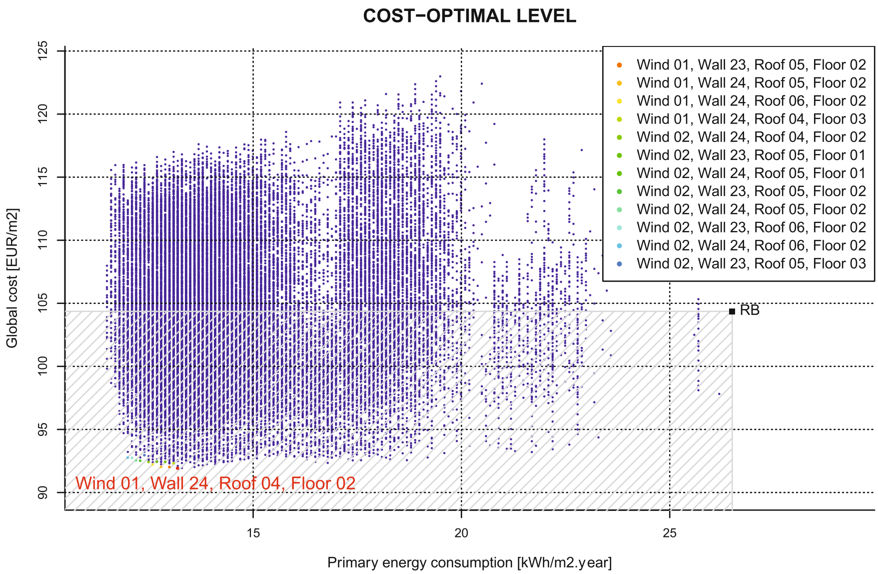

Fig. 3 Cost-optimal level from the macroeconomic perspective

the macroeconomical one, which means that the global costs assigned to the first are higher than the latter.

3 Discussion of Results

In Sect. 2 a phasing methodology to obtain the cost-optimal package of measures for residential buildings was proposed. Following that methodology, the approaches, tools and parameters chosen have led to the analysis of a particular Portuguese residential building case. Similar analyses can be also done for different residential buildings in other countries, by following the same described phasing methodology. Taking into consideration the results obtained in phase 5 for a Portuguese reference building, as refers to the application of the different thermal rehabilitation measures to the building envelope, some concluding remarks are presented.

Figure 4 illustrates the cost-efficiency of the different thermal rehabilitation packages of measures applied to the reference building envelope, in terms of primary energy consumption versus global cost. The sets of “W_”, “F_”, “R” and “WW_” lines summarise, respectively, the results obtained from the applications of the package of measures to the walls, floor, roof and windows. Each line specifically refers to a certain type of measure (e.g.: “Fv”—application of vinyl coating on the floor surface with different types of thermal insulation thickness), being drawn by points that represent, in the case of walls, floor and roof measures, the primary

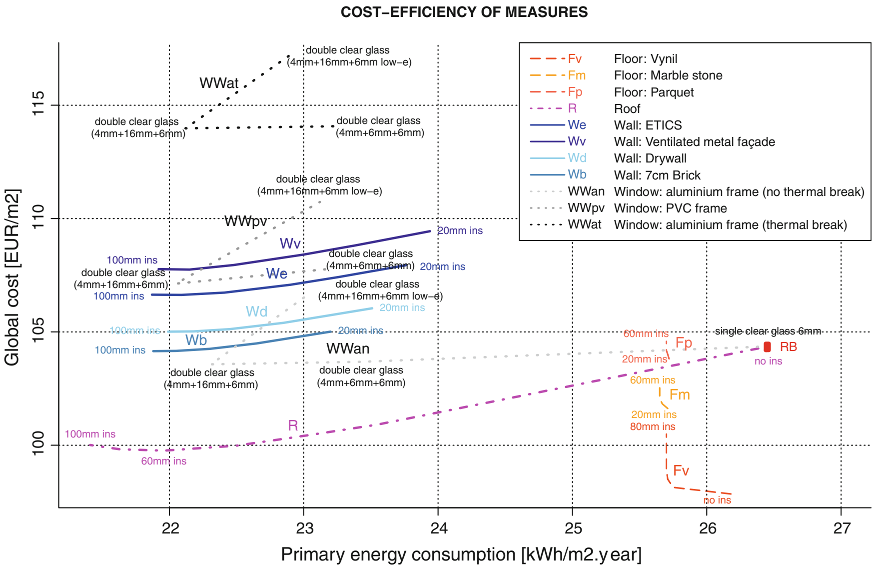

Fig. 4 Overview of the cost-efficiency of the thermal rehabilitation measures applied to the reference building envelope

energy consumption and the global cost resulting from each thermal insulation thickness, and, in the case of windows measures, the results from each type of glass considered.

The base solutions adopted correspond to the construction solutions that characterised the reference building (Floor 00, Roof 00, Wall 00 and Wind 00). For each set of lines ("W_", "F_", "R" and "WW_"), each specific rehabilitation type of measure is made to vary by keeping the other base solutions fixed. The "W_" set of lines (solid line ———) is drawn by taking into consideration a variation in the wall measures. The "F_" set of lines (longdash line - - - - - -) considers variations in the floor measures. The "R" line (dotdash line -·-·-·-) corresponds to variations in the roof thermal insulation. The "WW_" set of lines (dotted line ·········) considers variations in the type of window.

The imposition of the different measures to the reference building base solutions leads to the curves shown and allows identifying which are the best rehabilitation solutions from a cost-efficiency point of view. The influence of the efficiency of each thermal insulation thickness or of each type of glass is illustrated in Fig. 4, considering the eleven types of measures. If other than the reference building construction solutions were considered as the basis, the results and lines shown would not change significantly in the geometry and in the range of values of each line; and only the translational movements in x-axis and y-axis would occur.

Figure 4 also shows the reference building base solution with its associated cost-efficiency ("RB" dot). As expected, when compared with the reference building solution, all the rehabilitation measures considered have led to lower primary energy consumption, but not all of them have led to a lower global cost.

The results obtained for the wall set of lines ("W_") show that, considering the wall type rehabilitation measures, the construction of a 7 cm brick wall from the inside of the existing external wall (22 cm brick wall) of the reference building is the best cost-efficient type of wall solution. This solution achieved better results than the application of drywall from the inside or the application of ETICS and ventilated façade of metal plates from the outside. For the reference building considered, interior solutions achieved better results than solutions from the outside of the external wall as these have shown to lead to lower global costs.

As for the floor set of lines ("F_"), referring to floor type rehabilitation measures, the results obtained have shown that the application of vinyl floor coating is the best cost-efficient floor solution from among the solutions studied. As floor rehabilitation measures do not significantly influence the energy consumption of the reference building, the best cost-efficient solutions correspond to the ones having the lower global cost. Although vinyl coatings are not commonly adopted as floor solutions in Portuguese residential buildings, their study aimed to assess how a low investment and maintenance cost floor solution can be included in a cost-optimal package of measures.

The roof line ("R") indicates that the thermal insulation measures on the roof have the biggest range of the total energy consumption on the reference building, much depending on the thickness of the thermal insulation. The cost-effectiveness of these insulation measures is also highly dependent on the thermal insulation thickness, with good or poor performances just within a small interval variation in that thickness.

Finally, the types of window frames ("WW_"), indicate that aluminium window frame (no thermal break) is the best cost-efficient window frame solution, when compared to PVC and aluminium (thermal break) window frames. The type of glass strongly influences the energy consumption of the building, whereas the double clear glass (4 + 6 mm thick) and 16 mm air space has proven to be the best cost-efficient type of glass solution. However, the low emissivity glass solution does not seem to be the most adequate for a North-South reference building orientation under Lisbon's climate.

By comparing the results shown in Figs. 3 and 4, it can be noticed that the cost-optimal package solution (Wind 01, Wall 24, Roof 04, Floor 02—red dot in Fig. 3) does not correspond to all the best cost-efficient solutions identified in Fig. 4. The wall (construction of a 7 cm brick wall from the inside of the existing external wall over EPS, 100 mm thick) and roof (application of EPS 60 mm thick over the concrete slab) measures correspond to the cost-optimal package solution. Nonetheless, the floor (application of vinyl floor without thermal insulation) and window (aluminium window frame—no thermal break, with double clear glass and 16 mm air space) measures do not correspond to the cost-optimal package solution as they consider a 20 mm thermal insulation thickness for the floor and a 6 mm air space for windows. This means that the energy performance of one solution affects the energy performance of the other solution and that the combinations of measures create synergy effects that lead to better results (regarding global costs and primary energy consumption) than single measures (as can be seen by the primary energy consumption of each measure in Fig. 4, when compared to the primary energy consumption of the package of measures in Fig. 3). For instance, the cost-optimal package solution includes a floor measure (20 mm of thermal insulation) that is not cost-effective (as shown in Fig. 4); however, its results, in terms of primary energy consumption and CO_2 savings associated to the building unit, reveal that the overall package provides more benefits than costs over the lifetime of the building.

Combining these results with those obtained from phases 3 and 4, we can point out the existence of some packages of measures with lower life cycle costs, comparatively with other packages with lower investment costs (e.g.: marble natural stone floor vs. pine wood parquet floor).

Globally, and for the reference building characterised in this chapter, measures applied to the roof are the best cost-efficient ones and lead to the lowest energy consumption. This is due to the fact that the energy consumption of the last floor (7th floor of the reference building) has a strong impact on the overall energy consumption of the building; so, from a global energy building perspective, acting on the thermal insulation of the roof is more effective than insulating the external walls and replacing all the windows in all the floors. Together with the best global building energy performance, the roof thermal insulation also leads to the best cost-efficient solution. This is due to the low investment costs associated with the easy application of a thermal insulation on a horizontal solid reinforced concrete roof slab, which requires no extra mechanical protective layer (contrary to external walls and floors).

Similarly but conversely, the construction solution that leads to the smallest variation in the total energy building consumption corresponds to the measures applied to the floor.

4 Conclusions

This chapter clarifies the phasing methodology referred to in the EPBD Directive for determining the cost-optimal packages of measures. The analysis done for a Portuguese residential reference building can be similarly done for other countries' residential buildings under similar conditions.

The methodology phasing proposed in this chapter works as a decision model tool that is helpful to assist construction stakeholders (private or public decision makers) in deciding on which building components should they focus and where, so as to establish an optimal balance between the investments made and the savings in energy costs attained throughout the life cycle of the building. Ultimately, the main goal to pursue is to achieve more sustainable buildings, as a whole, from the energy efficiency viewpoint.

Results obtained from the application of the methodology to a thermal rehabilitation of the building envelope of a Portuguese residential reference building constructed in the 1960–1990 period are limited to the reference building characteristics and to Lisbon's climatic conditions. However, these results have led to the following main conclusions:

- the thermal rehabilitation measures with the best cost-efficient results correspond to measures applied to the roof, from a total energy building consumption perspective. The variation in the thermal insulation thickness implies a great variation in the total primary energy building consumption (even in a 7-storey building);
- the thermal rehabilitation measures that lead to the smallest variation in the primary energy building consumption correspond to measures applied to the floor;
- internal wall thermal rehabilitation measures achieved better results than measures from the outside of the external wall, as they have shown to have lower global costs;
- combinations of thermal envelope rehabilitation measures create synergy effects that lead to better results than single measures (regarding global costs and primary energy consumption).

Following these findings, the private and public decision makers in Portugal are encouraged to strongly focus their thermal rehabilitation investments on measures applied to roofs of residential buildings. This study has also demonstrated that it is more advantageous, from the cost-optimal point of view, to proceed with any thermal rehabilitation package of measures located inside the shadowed zone illustrated in Fig. 3 rather than doing nothing on the reference building considered (representative of the Portuguese residential buildings).

The work presented has been developed as part of a LNEC/IST PhD thesis, of which the main purpose is to define a cost-optimal comparative methodology for the energy performance of buildings. In this work, sensitive analyses of the results achieved in this research are also performed, such as the assessment of variations in the building orientation, in climatic conditions, in discount rates, in energy costs evolution, among others.

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Ventilation System for Drying Out Buildings After a Flood

O. López López and M.I. Morais Torres

Abstract One of the most important pathologies in historical buildings is the presence of moisture. Moreover, for historical reasons, particularly easier access to water supply, some of Portugal's most striking buildings were built near waterways and on floodplains and are therefore much more exposed to the risk of flooding. The occurrence of a flood can suddenly increase the moisture content in various building elements, which causes damage. It is very important that the moisture level of the walls is reduced as quickly as possible after a flood has occurred. This chapter presents the results of a major investigation undertaken under a collaborative project involving the Institute for Research and Technological Development in Construction Sciences (ITeCons) and the Civil Engineering Department of the Faculty of Science and Technology of Coimbra University. The main objective was to perform numerical simulations to validate the efficiency of a wall-base ventilation system as a technique to improve the drying out of walls of historical buildings after a flood.

Keywords Historical buildings · Flood · Ventilation system

1 Introduction

Moisture can be the source of serious problems in new and old buildings, though it is more common in the latter. Of the main causes of moisture in building walls (Fig. 1) rising damp is the most common and important in old buildings because of its consequences. Floods are also included because they are a weather event whose occurrence

O. López López · M.I. Morais Torres
Institute for Research and Technological Development in Construction Sciences, Rua Pedro Hispano, s/n, Pólo II, 3030-289 Coimbra, Portugal
e-mail: oscar.lopez@itecons.uc.pt

M.I. Morais Torres (✉)
Civil Engineering Department, Faculty of Science and Technology, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal
e-mail: itorres@dec.uc.pt

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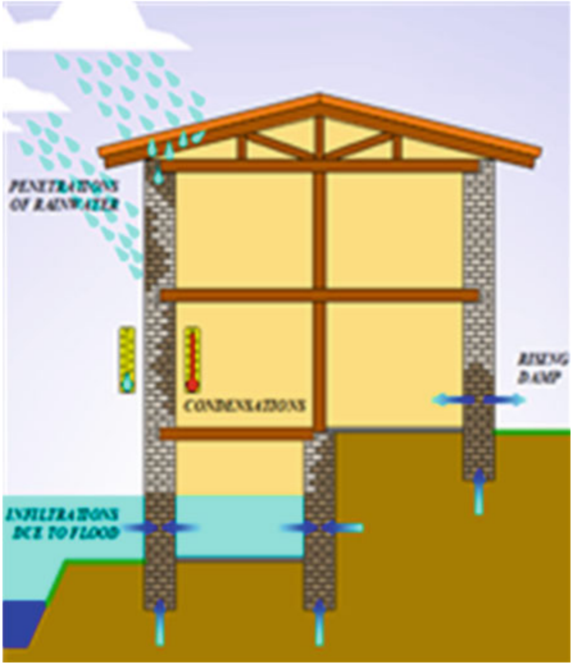


Fig. 1 Main causes of dampness in building walls. Moisture causes loss of strength in load-bearing walls which directly affects the safety of buildings and structures. In old buildings such problems are mainly due to the rise of water by capillarity. This phenomenon, known as rising damp, affects both the external cladding and structural elements and the inside environment. Thus, building pathologies may develop, such as cracks, leaks, water stains, mould, bacteria, odours and rotting wooden elements inside buildings. Higher groundwater levels and poor drainage normally generates this problem

will increase in the coming years as a result of climate change. This chapter focuses on the drying out of the walls of historical buildings, since caused by the presence of moisture techniques for doing this must be improved so as to reduce pathologies.

The presence of moisture is one of the major causes of pathologies in historical buildings (Guimarães et al. 2012c; Torres 2004; Torres and Freitas 2007). It is responsible for the degradation of materials, for unsuitable indoor thermal-hygrometric conditions, for reducing the thermal insulation efficiency and for reducing the mechanical performance of the masonry (Franzoni 2014). In most cases this excess of moisture is due to the presence of rising damp.

In Portuguese historical buildings, humidity and rising damp are aggravated because, for historical reasons, these buildings were built near natural waterways or on floodplains. Additionally, climate change has contributed to a rise in extreme weather events such as heavier rainfalls and floods across the country. Therefore, much of this Portuguese cultural heritage already is or eventually will be at a high risk of flooding (Guimarães et al. 2015). During the course of a flood, which can last hours or even days, building elements, especially foundations, floors and walls come into contact with water and their moisture content can increase until saturation. So, it is very important that the moisture level of the walls is reduced as quickly as possible after flooding to prevent worse consequences.

With this in mind, research has been carried out over recent years at the Department of Civil Engineering of the University of Coimbra, in collaboration with the Department of Civil Engineering of the University of Porto, to develop a method to minimise the effects of rising damp. This method consists of installing ventilated channels at the base of the walls (Guimarães and Freitas 2009). The system was experimentally validated in the laboratory using reduced models, numerically validated with computational programs and validated in situ by applying it to historical buildings, with satisfactory results (Delgado et al. 2013; Torres 2004; Torres and Freitas 2007).

ITeCons is therefore collaborating with the Department of Civil Engineering of Coimbra University to develop a numerical method to validate the efficiency of the wall-base ventilation system as a technique for drying out buildings after a flood (Torres and López 2015a, b, c, d) (Fig. 2).

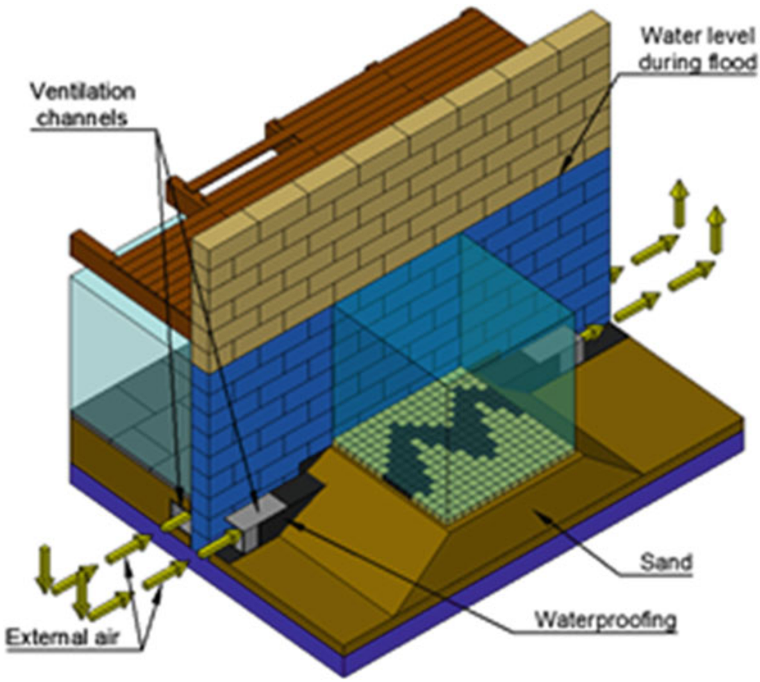


Fig. 2 Ventilation technique for drying out buildings after a flood (Torres and López 2015b). It consists of forcing the circulation of air through peripheral channels in contact with the base of the walls for the purpose of preventing lateral infiltrations and increasing the evaporation of moisture, thereby reducing the water content of the wall. Hydro-regulated mechanical ventilation devices can be installed to increase the circulation of air in these channels and to improve the drying efficiency of the ventilation system

2 Ventilation System for Drying Out Buildings After a Flood

Interventions in older buildings and architectural heritage require extensive objective knowledge.

Traditional methods of dealing with rising damp (physical barriers, electro-osmosis, etc.) have proved to be relatively ineffective, being either inappropriate or too expensive to be used in historical buildings (Freitas et al. 2008; Guimarães et al. 2013). This is the context in which the wall-base ventilation technique was developed. It consists of installing two C-shaped channels in contact with the wall base and these, either naturally or mechanically with the help of a ventilation device, promote the circulation of air inside it, thereby increasing the evaporation of moisture from the wall (I'Anson 1986; Torres 2004). These channels are installed underground, very close to the ground surface or flooring. They are therefore hidden and thus preserve the conservation status and visual appearance of the walls (Fig. 3).

The ventilation system was developed by performing experimental studies in laboratory using reduced physical models to characterise the rising damp phenomenon with different boundary conditions. Numerical studies were carried out with the aid of simultaneous heat and moisture transfer calculation software (Figs. 4 and 5).

The results showed that numerical analysis provide a good approximation of the experimental behaviour. The software used was WUFI-2D, developed in Fraunhofer Institute for Buildings Physics (Guimarães et al. 2012a, b; Torres 2004; Torres and Freitas 2007).

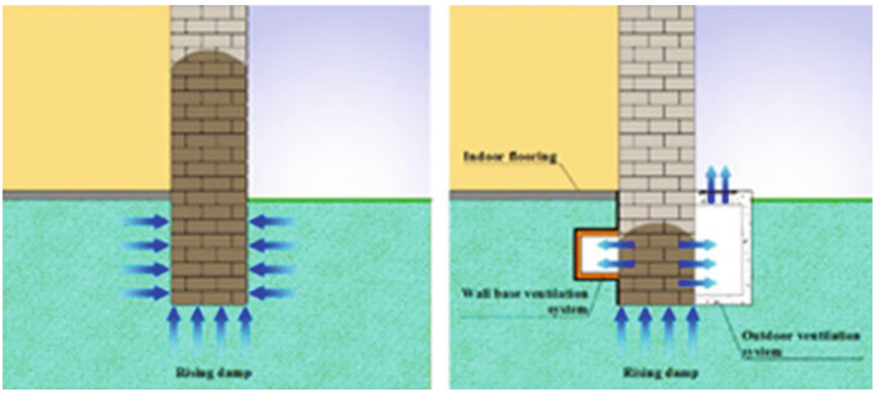
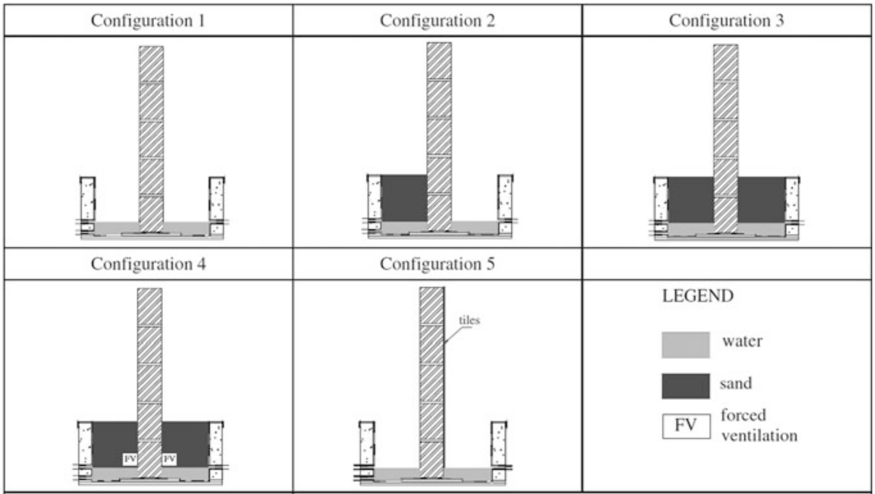


Fig. 3 Operating principle of a wall-base ventilation system



Configuration 1	The wall's base is immersed up to 8 cm
Configuration 2	One of the gaps is filled with sand
Configuration 3	The second gap is filled with sand
Configuration 4	A forced ventilation system is placed at the base of the wall
Configuration 5	Wall with one side covered with tile in all its height, whose base is immersed up to 8 cm

Fig. 4 Different boundary conditions of reduced models for experimental validation. The selected models consisted of prismatic stone walls built into reservoirs to simulate rising damp with different boundary conditions (Torres 2004; Torres and Freitas 2007)

Fig. 5 Configuration 1 and 4 for experimental validation. In all configurations the wall base was immersed to a height of 8 cm to simulate rising damp. Additionally, the moisture front was monitored by probes at various points in the wall. Configurations without and with a ventilation system are presented (Torres 2004)

When results from experimental models with and without a wall-base ventilation system were compared it was found that the moisture front advanced much less in the first configuration. The efficiency of the ventilation system was further validated through numerical simulations to study the influence of other important parameters on rising damp, such as the wall thickness, channel sizes and different building materials (Torres 2014; Torres and Freitas 2010).

Subsequent studies have focused on finding a methodology for designing the ventilation system to optimise and automate the performance and prevent condensation problems that occurred inside the channels in some cases where the system was implemented (Delgado et al. 2012, 2013; Freitas et al. 2011; Guimarães 2011; Guimarães et al. 2010, 2012a, b; c, 2013; Hall and Hoff 2002).

This wall-base ventilation system is also applied to a sixteenth-century church, classified as a national monument, located in the north of Portugal. It had pathologies of rising damp, infiltration and condensation. The circulation of air is governed by a hydro-regulated device which can vary the rate at which air flows into the channels. (Delgado et al. 2013; Freitas et al. 2002).

Drying out a wall after a flood and removing moisture from a wall with rising damp are two operations governed by the same processes: simultaneous transfer of heat and moisture. The only difference is that while rising damp is a continuous source of moisture, infiltrations due to floods are temporary sources and disappear when the water source that causes this extreme event returns to its normal level.

Actual cases have shown us that walls that become damp due to water infiltrations during a flood take a long time to dry naturally. When rising damp is also present, it is almost impossible to dry out the lower part of the wall by natural processes (Fig. 6).

However, when a wall-base ventilation system is installed, the lower part of the wall dries faster because of the “extra” evaporation of moisture into the ventilation channels (Fig. 7).

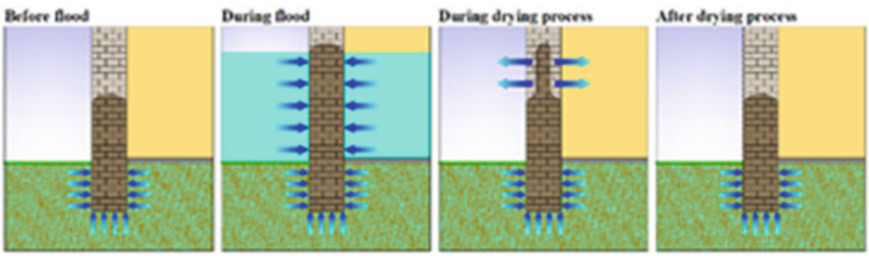


Fig. 6 Drying out a wall without a ventilation system

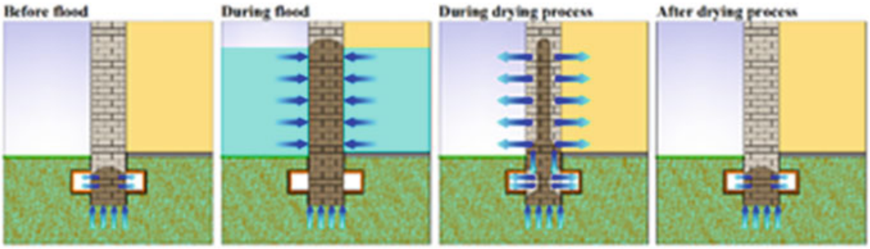


Fig. 7 Drying out a wall with a ventilation system

3 Numerical Simulation

3.1 Calculation Software Used

The numerical simulation of heat and moisture transfer in construction materials has been the subject of important research. A number of models have been produced since 1950, based on fluid mechanics using the mass diffusion laws (liquid phase, Darcy, and vapour phase, Fick) and heat diffusion laws (Fourier).

We used the WUFI-2D calculation program developed at the Fraunhofer Institute for Buildings Physics to simulate the drying process of a wall after a flood because it had been successfully validated to simulate the rising damp phenomenon. We used Version 3.3 for the experimental and numerical validation of the wall-base ventilation system, not Version 2.1, which was used in the studies mentioned above. Both versions analyse changes in water content, relative humidity, temperature and vapour pressure over time in elements subjected to certain initial conditions and climates, on the basis of the following heat and moisture transfer Eqs. (1, 2) (Holm and Künzel 2003; Krus 1996; Künzel 1994).

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \nabla(\lambda\nabla T) + h_v\nabla(\delta_p\nabla(\Phi p_{sat})) \tag{1}$$

$$\frac{dw}{d\Phi}\frac{\partial \Phi}{\partial t} = \nabla(D_\Phi\nabla\Phi + \delta_p\nabla(\Phi p_{sat})) \tag{2}$$

where dH/dT [J/m^3] is the heat storage capacity of the moist building material, $\partial w/d\Phi$ [kg/m^3] the moisture storage capacity of the building material, λ [W/m K] the thermal conductivity of the moist building material, D_Φ [kg/m s] the liquid conduction coefficient of the building material, δ_p [kg/m s Pa] the water vapour permeability of the building material, h_v [J/kg] the evaporation enthalpy of the water, p_{sat} [Pa] the water vapour saturation pressure, T [°C] the temperature and Φ [–] is the relative humidity.

One of the important updates of version 3.3 of WUFI-2D is that it allows, unlike the previous version, the introduction of “air change sources”. This lets us simulate the renewal of the air in the ventilation channels. The program uses the value of the air changes per hour to automatically determine the heat and moisture source strengths of the air change source.

The air change heat source is determined according to Eq. (3).

$$Q_t = \rho_{out} \cdot \frac{ACH}{3600} \cdot d_{cavity} \cdot C_{p,air} \cdot (T_{out} - T_{cavity}) \tag{3}$$

where Q_t [W/m^2] is the heat source strength, ρ_{out} [kg/m^3] is the density of the outdoor air, ACH [h^{-1}] is the air change rate of the ventilation cavity, d_{cavity} [m] is the thickness of the ventilated cavity, $C_{p,air}$ [J/kg K] is the specific heat capacity of dry air at constant pressure (effect of moisture content neglected), T_{out} [K] is the outdoor temperature and T_{cavity} [K] is the temperature of the ventilated cavity (mean value of all involved grid elements).

The air change moisture source is determined according to Eq. (4).

$$Q_m = \frac{ACH}{3600} \cdot d_{cavity} \cdot (C_{out} - C_{cavity}) \tag{4}$$

where Q_m [kg/m^2 s] is the moisture source strength, C_{out} [kg/m^3] is the water vapour concentration of the outdoor air and C_{cavity} [kg/m^3] is the water vapour concentration of the cavity air (mean value of all involved grid elements).

ACH [h^{-1}] is one of the most important parameters in the drying process because the evaporation depends on air velocity and air characteristics. Depending on the geometry of the ventilation channels, it can be calculated from Eq. (5).

$$ACH = \frac{Q}{V} = \frac{A \cdot u}{A \cdot L} = \frac{u}{L} \tag{5}$$

where Q [m^3/h] is the air flow rate, V [m^3] is the volume of the channel, A [m^2] is the cross-sectional area of the channels, u [m/h] is the air velocity into channel and L [m] is the length of the channel (Torres and López 2015b).

3.2 Analysed Parameters

The influence of four parameters was analysed to assess the efficacy of our wall-base ventilation system to dry out buildings after a flood:

- the air change rate (ACH) into channels;
- the wall thickness;
- the building material;
- the depth of phreatic level;

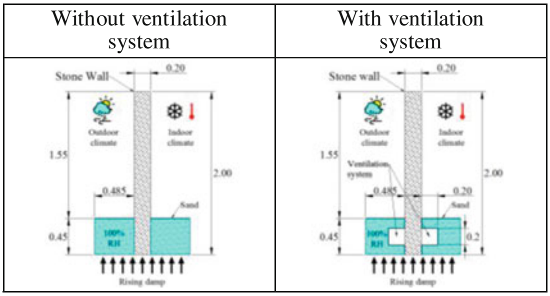


Fig. 8 Simulation models. In each study we used two numerical models: one without a wall-base ventilation system and one with it. The ventilation system consisted of two channels measuring 0.2 × 0.2 m placed on either side of the base of the wall. There was assumed to exist a waterproofing barrier between the sandy ground and the ventilation system to prevent lateral infiltration into the channels

Simulation models were the same for all studies and consisted of a wall 2.0 m high and 0.2 m thick (Fig. 8), except for the thickness study when it ranged between 0.2 and 1.0 m.

In all studies, the material of the wall was a calcareous stone, except for the study on the influence of the building material when two other natural stones with different hygrothermal properties were used: Ançã stone and dolomite. Table 1 presents the hygrothermal properties of calcareous stone and underground sand (Fig. 9).

Table 1 Hygrothermal properties of calcareous stone and underground sand

Hygrothermal property	Calcareous stone	Underground sand
Bulk density [kg/m^3]	2155	2000
Open porosity [%]	18.8	10.0
Thermal conductivity [W/m K]	1.33	2.00
Water vapour diffusion resistance factor [–]	29.4	50.0
Water absorption coefficient [kg/m^2 $\sqrt{s}$]	0.024	0.090
Free water saturation [kg/m^3]	188.0	100.0

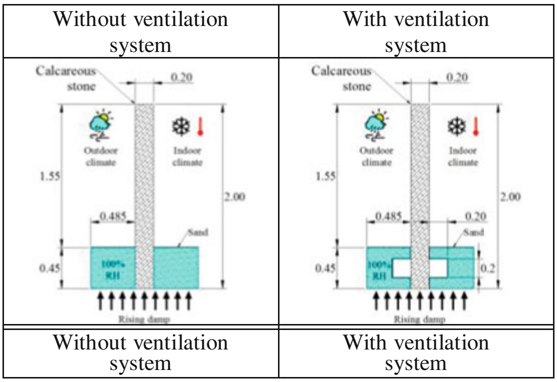


Fig. 9 Configurations to analyse the influence of the air change rate on the drying process. In this study, we considered a total of seven sub-configurations (one without and six with ventilation systems, with *ACH* values of 1, 20, 40, 60, 80 and 100 h^{-1}, respectively)

To simulate the drying process, all simulations started assuming that the entire wall had a relative humidity of 100 %. As climatic conditions, on one side of the wall we applied a test reference year from Lisbon, with measurements of wind, rain, barometric pressure, temperature, relative humidity and solar radiation, and on the other side we considered a normal indoor climate usually found in historic buildings. Because the drying process begins after a flood, all simulations started in the winter, i.e. the rainy season, and lasted for one year.

4 Results

4.1 *Influence of the Air Change (ACH) Rate in the Channels*

It is always advisable for the channels to be short to improve the evaporation power of the circulating air, and for the air velocity into the channels to be low (<3 m/s) to prevent noise and vibration (Guimarães 2011). However, air velocity depends on the length of the ventilation system and the *ACH*, in accordance with Eq. (5) (Torres and López 2015b). In Table 2 we present the dependency relationship between these parameters.

Table 2 Airflow rates and air velocities into ventilation channels depending on the length of the ventilation system and on the value of *ACH*

ACH $[h^{-1}]$	Length of the ventilation system									
	5 m		10 m		50 m		100 m		200 m	
	Q [a]	u [b]	Q [a]	u [b]	Q [a]	u [b]	Q [a]	u [b]	Q [a]	u [b]
1	0.2	0.001	0.4	0.003	2	0.014	4	0.028	8	0.06
20	4	0.03	8	0.06	40	0.28	80	0.56	160	1.11
40	8	0.06	16	0.11	80	0.56	160	1.11	320	2.22
50	10	0.07	20	0.14	100	0.69	200	1.39	400	2.78
60	12	0.08	24	0.17	120	0.83	240	1.67	480	3.33
80	16	0.11	32	0.22	160	1.11	320	2.22	640	4.44
100	20	0.14	40	0.28	200	1.39	400	2.78	800	5.56
200	40	0.28	80	0.56	400	2.78	800	5.56	1600	11.11
500	100	0.69	200	1.39	1000	6.94	2000	13.89	4000	27.78
1000	200	1.39	400	2.78	2000	13.89	4000	27.78	8000	55.56
2000	400	2.78	800	5.56	4000	27.78	8000	55.56	16000	111.11
5000	1000	6.94	2000	13.89	10000	69.44	20000	138.89	40000	277.78

[a]Airflow rate, in m^3/h

[b]Air velocity, in m/s

A historical building such as a monastery or a church with perhaps one main chapel and two side chapels can have walls over 150 or 200 m long, and this requires one, two or even more independent ventilation systems with their respective devices to force the airflow. Short channels less than 10 m long are clearly not economically viable because many ventilation devices would be required. Furthermore, it is not desirable for the system to be overly dependent on being split into short lengths to ensure efficient evaporation. Therefore, considering a maximum admissible air velocity into channels of 3 m/s, the most useful length of each system section should be in the range 50–100 m, preferably nearer to 100 m. Thus, *ACH* may take reasonable values from 0 to 100 h^{-1}.

Figure 10 shows the change in the water content of a calcareous stone wall over one year of simulation, obtained with WUFI-2D, for each air change rate.

Table 3 shows the total water content, the total water content reduction, the water reduction for each configuration with the ventilation system compared with that for the wall without a ventilation system, and the efficiency of the ventilation system (compared with the configuration with *ACH* of 100 h^{-1}) for each configuration. We considered that maximum efficiency is achieved for an *ACH* value of 100 h^{-1} because it will be difficult to achieve higher efficiency for minimum system lengths close to 100 m under these boundary conditions.

Figure 11 presents the water content of the middle section of the wall after one year of drying out and Fig. 12 shows the percentage of moisture removed from that middle section after one year of drying out.

Figure 13 shows the water content removed from the wall for all the configurations with ventilation system, after one year of drying out.

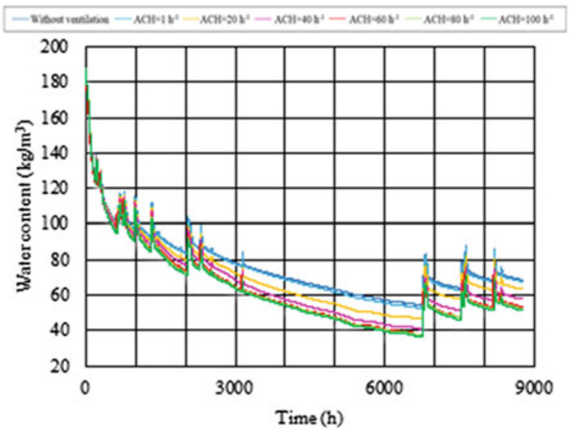


Fig. 10 Change in water content of the wall over one year of drying, for each air change rate. The peaks in the graphs are increments of moisture content of the wall, due to rainwater. We can see that the higher the air change rate, the more moisture is removed from the wall

Table 3 Total water content, total water content reduction, water content reduction and efficiency of ventilation system after one year of drying out

Ratio	Without ventilation system	Air change rate					
		1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
Total water content [kg/m^3]	68.7	67.8	63.4	57.9	54.1	52.7	51.5
Total water content reduction [kg/m^3]	119.3	120.2	124.6	130.1	133.9	135.3	136.5
Water content reduction [%]	–	1.3	7.8	15.7	21.2	23.4	25.0
Efficiency [%]	–	5	31	63	85	93	100

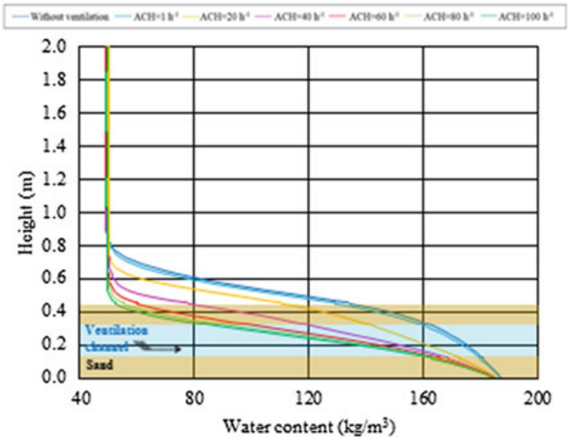


Fig. 11 Water content of the central section after one year of drying out. The higher the air change rate, the more moisture removed from the wall

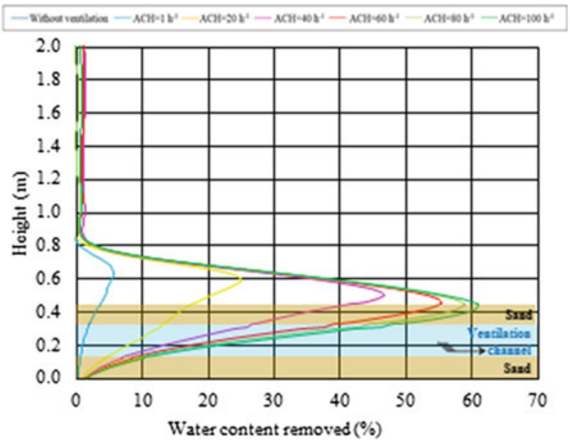


Fig. 12 Percentage of water content removed from the central section of the wall by the ventilation system after one year of drying out. The ventilation system is able to remove up to 61.0 % of water content for higher values of *ACH*, but only up to a specific height, in this case approximately 0.8 m

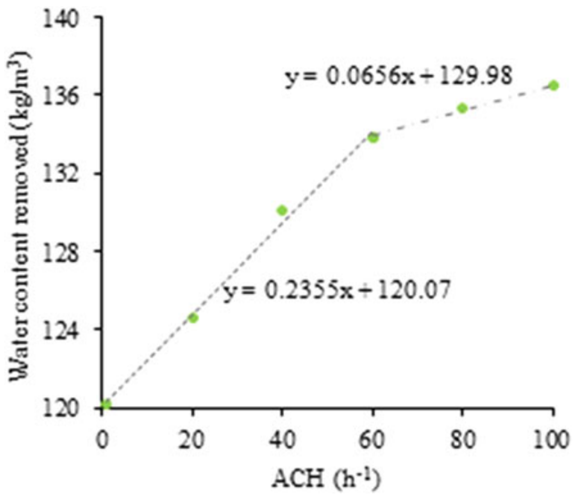


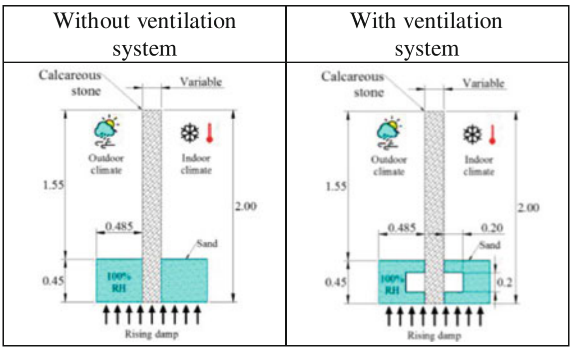
Fig. 13 Water content removed from the wall after one year of drying out. According to Fig. 12, the higher the value of *ACH*, the higher the moisture content that will be removed by the ventilation system. The figure shows that the relationship between these two variables is not linear but for these values we can approximate two linear trend lines: one for *ACH* values up to 60 h^{-1} and other for *ACH* values over 60 h^{-1}. We can conclude that the optimum *ACH* value is 60 h^{-1} because higher values do not significantly increase the water content removed from the wall

4.2 *Influence of the Thickness of the Wall*

The influence of the wall thickness on the drying process was also studied for values of 0.2, 0.4, 0.6, 0.8 and 1.0 m (Fig. 14). In addition, for each wall thickness the air change rate was changed in the same way as in the previous study, keeping all the other initial and boundary conditions.

Figure 15 presents the change in the water content of a calcareous stone wall over one year of simulation for thicknesses of 0.2, 0.4, 0.6, 0.8 and 1.0 m, with the air change rate varying from 1 to 100 h^{-1}.

Fig. 14 Configurations studies to analyse the influence of the wall thickness



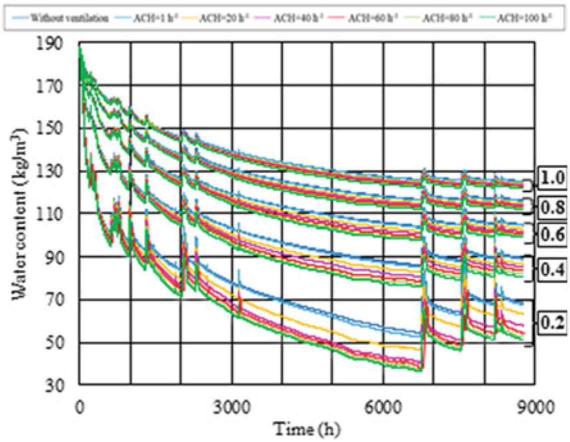


Fig. 15 Change in the water content over one year of drying out, for each wall thickness and air change rate of the ventilation channels. [0.2] wall thickness of 0.2 m, [0.4] wall thickness of 0.4 m, [0.6] wall thickness of 0.6 m, [0.8] wall thickness of 0.8 m and [1.0] wall thickness of 1.0 m

Tables 4, 5 and 6 show, respectively, the total water content reduction, the water reduction for each configuration with ventilation system compared with that for the wall without a ventilation system, and the efficiency of the ventilation system (compared with the configuration with a wall thickness of 0.20 m and an *ACH* value of 100 h^{-1}), for each wall thickness and air change rate in the channels.

Table 4 Total water content reduction after one year of drying out depending on the wall thickness and the air change rate in the channels

Wall thickness [m]	Total water content reduction [kg/m^3]						
	Without ventilation system	Air change rate					
		1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
0.2	119.3	120.2	124.6	130.1	133.9	135.3	136.5
0.4	98.4	99.1	101.3	102.8	104.4	106.0	107.4
0.6	83.0	83.5	85.1	86.2	87.1	88.1	88.9
0.8	71.6	72.0	73.3	74.0	74.7	75.4	76.0
1.0	62.8	63.1	64.1	64.7	65.2	65.8	66.2

Table 5 Water content reduction after one year of drying out depending on the wall thickness and the air change rate in the channels

Wall thickness [m]	Water content reduction [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
0.2	1.3	7.8	15.7	21.2	23.4	25.0
0.4	0.8	3.3	4.9	6.8	8.5	10.1
0.6	0.5	2.0	3.0	3.9	4.8	5.6
0.8	0.4	1.4	2.1	2.7	3.3	3.8
1.0	0.2	1.0	1.5	2.0	2.4	2.7

Table 6 Efficiency of ventilation system after one year of drying out depending on the wall thickness and the air change rate in the channels

Wall thickness [m]	Efficiency [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
0.2	5	31	63	85	93	100
0.4	3	13	20	27	34	40
0.6	2	8	12	16	19	23
0.8	1	6	8	11	13	15
1.0	1	4	6	8	9	11

Figure 16 shows the water content of the central section of the wall after one year of drying out, for each wall thickness and air change rate in the channels.

Table 7 shows, for each wall thickness, the maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the wall without one.

As expected, when the thickness of the wall increases the efficacy of the ventilation system decreases and its influence on the drying of the inner part of the wall decreases, too. Therefore, thicker walls need longer drying times.

Figure 17 presents the water content removed from the wall by the ventilation system, for each wall thickness and each value of *ACH* after one year of drying out.

One option to further increase the evaporation in thicker walls is to increase the value of *ACH* by shortening the ventilation system. Another option is to increase

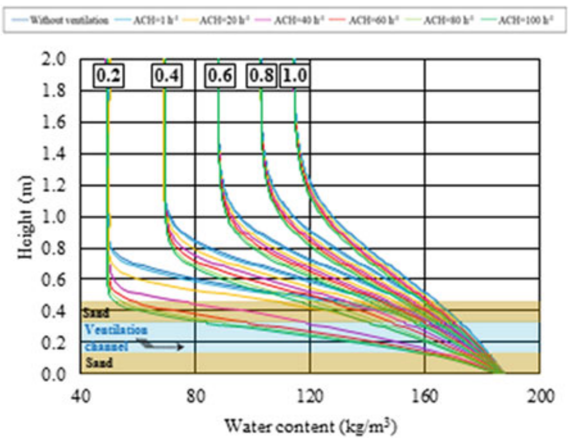


Fig. 16 Water content of the central section after one year of drying out. [0.2] wall thickness of 0.2 m, [0.4] wall thickness of 0.4 m, [0.6] wall thickness of 0.6 m, [0.8] wall thickness of 0.8 m and [1.0] wall thickness of 1.0 m. The greater the wall thickness, the higher the influence height of the ventilation system due to the lower moisture front of the damp

Table 7 Maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the simulation without one

Wall thickness [m]	Maximum percentage of water content removed from the wall at a vertical central profile [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
0.2	5.6	25.0	46.6	55.4	58.8	61.0
0.4	2.3	8.4	13.5	18.6	22.5	25.1
0.6	1.1	4.1	6.2	8.2	10.1	11.7
0.8	0.6	2.3	3.5	4.5	5.6	6.4
1.0	0.4	1.4	2.2	2.8	3.4	3.9

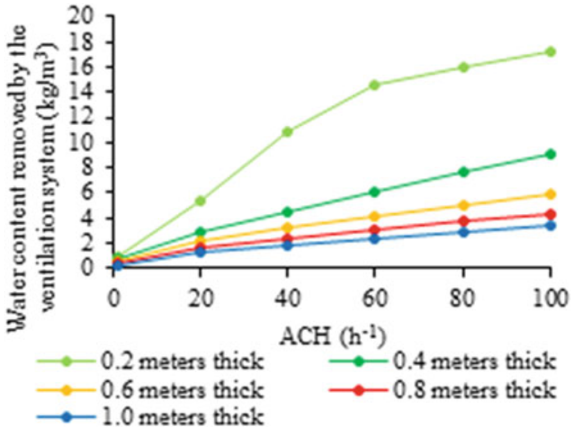


Fig. 17 Water content removed from the wall by the ventilation system after one year of drying out. When the wall thickness is greater than 0.2 m, an optimum *ACH* cannot be seen, and the higher the *ACH* value the greater the moisture content removed from the wall. This is because increased thickness makes the capillarity action of rising damp more important than infiltrations due to a flood in the lower part of the wall, because the moisture front reaches a higher level

the size of the channels to reduce the level reached by the moisture front of the rising damp, but this is often impossible because the space available for executing them is often restricted.

4.3 Influence of the Building Material

The main characteristics which can determine the moisture content of building materials and so influence the drying process of a wall after a flood are the water absorption coefficient, the vapour diffusion resistance factor and the hygroscopic

Fig. 18 Configurations studies to analyse the influence of the building material on the drying process

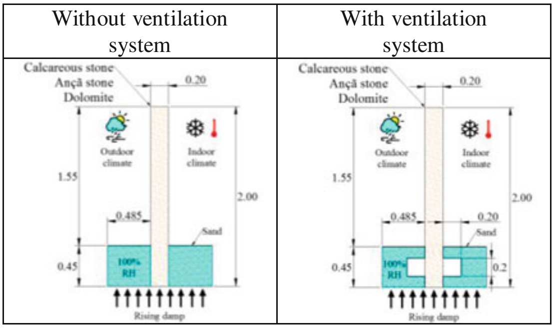


Table 8 Hygrothermal properties of Ançã stone and dolomite

Hygrothermal property	Ançã stone	Dolomite
Bulk density [kg/m^3]	2256	2278
Open porosity [%]	16.3	30.1
Thermal conductivity [W/m K]	1.01	1.50
Water vapour diffusion resistance factor [–]	13.21	23.0
Water absorption coefficient [kg/m^2 $\sqrt{s}$]	0.145	0.067
Free water saturation [kg/m^3]	162.5	300.7

curves. This section therefore describes the influence of the building material on the efficiency of the ventilation system, with the inclusion of two more building materials for a wall thickness of 0.2 m and air change rates from 1 to 100 h^{-1}: Ançã stone and dolomite (Fig. 18).

The characteristics of Ançã stone and dolomite are presented in Table 8. All properties were determined experimentally.

Fig. 19 Change in the water content of the walls over one year of drying out, for each building material and each air change rate of the ventilation channels. *[Cal]* Calcareous stone, *[Anç]* Ançã stone and *[Dol]* dolomite

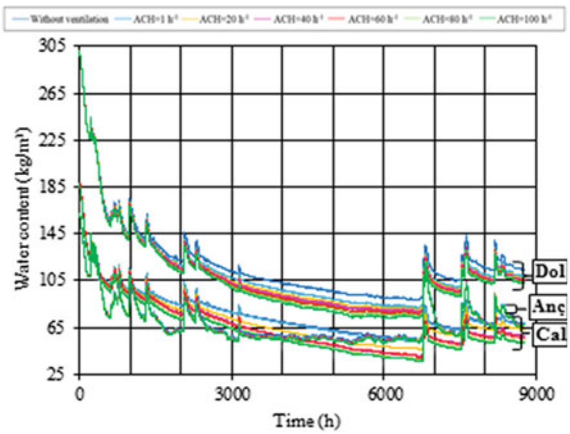


Table 9 Total water content reduction after one year of drying out depending on the building material and the air change rate in the channels

Building material	Total water content reduction [kg/m^3]						
	Without ventilation system	Air change rate					
		1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
Calareous stone	119.3	120.2	124.6	130.1	133.9	135.3	136.5
Ançã stone	93.6	94.2	94.7	94.9	95.1	95.3	95.5
Dolomite	185.9	191.7	193.8	194.9	195.9	196.8	197.7

Table 10 Water content reduction after one year of drying out depending on the building material and the air change rate in the channels

Building material	Water content reduction [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
Calareous stone	1.3	7.8	15.7	21.2	23.4	25.0
Ançã stone	0.8	1.6	2.0	2.3	2.5	2.7
Dolomite	5.0	6.8	7.8	8.7	9.4	10.3

Figure 19 presents the change in the water content of calcareous stone wall, an Ançã stone wall and a dolomite stone wall over one year of simulation, using WUFI-2D, and varying the air change rate from 1 to 100 h^{-1}.

Tables 9, 10 and 11 present, respectively, the total water content reduction, the water reduction for each configuration with a ventilation system compared with that for the wall without a ventilation system, and the efficiency of the ventilation system (compared with the configuration calcareous stone and an *ACH* value of 100 h^{-1}), for each building material and each air change rate in the channels.

Figure 20 shows the water content of the central section of the wall after one year of drying out, for each building material and air change rate in the channels.

Table 12 shows, for each building material, the maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the simulation without one.

Table 11 Efficiency of ventilation system after one year of drying out depending on the building material and the air change rate in the channels

Building material	Efficiency [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
Calareous stone	5	31	63	85	93	100
Ançã stone	3	6	8	9	10	11
Dolomite	20	27	31	35	38	41

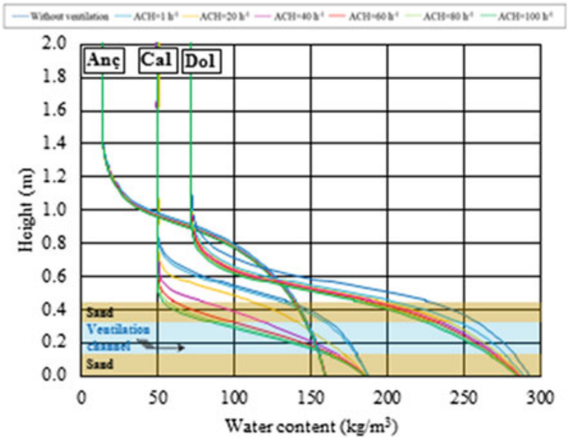


Fig. 20 Water content of the central section after one year of drying out. *[Cal]* Calcareous stone, *[Anç]* Ançã stone and *[Dol]* Dolomite

Table 12 Maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the simulation without one

Building material	Maximum percentage of water content removed from the wall at a vertical central profile [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
Calareous stone	5.6	25.0	46.6	55.4	58.8	61.0
Ançã stone	4.5	8.3	10.4	12.0	13.3	14.6
Dolomite	15.4	19.1	21.1	22.9	24.5	26.0

The ventilation system is less efficient for building materials with a high water absorption coefficient because these materials are more prone to quickly replace the evaporation moisture with water from rising damp or infiltration due to rainwater.

However, the water absorption coefficient is not the only hygrothermal property that influences the drying process. Whether or not there is a ventilation system in the wall base, it is concluded that Ançã stone is the material that dries out fastest. The main reason is its low water vapour diffusion resistance factor compared with the calcareous stone and dolomite. Another important variable in the drying process is the hygroscopic curve of materials. This determines the water content of a material through a function of relative humidity of the environment. In this case, the water content over time is highest for dolomite, followed by Ançã stone and calcareous stone, for the same environmental conditions. Although Ançã stone has a higher water content than calcareous stone under certain environmental conditions, its lower water vapour diffusion resistance than the other two means that this material is more favourable to water evaporation during a drying process.

Figure 21 presents the water content removed from the wall by the ventilation system, for each building material and each value of *ACH* after one year of drying out.

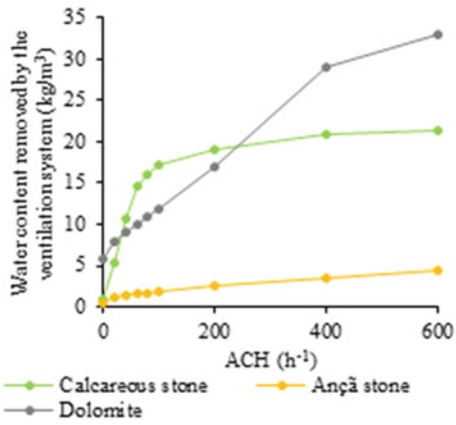


Fig. 21 Water content removed from the wall by the ventilation system after one year of drying out. For Ançã stone and dolomite there is no optimum value for *ACH* values between 1 and 100 h^{-1}. To increase the efficiency of the ventilation system it is necessary to increase the air change rates in the channels by reducing the system's length. So, it is expected that the optimum air change rate for dolomite is a value near to 400 h^{-1}, equivalent to a maximum ventilation system length of 27 m. The optimum value has still not been found for Ançã stone for values of *ACH* up to 600 h^{-1}

4.4 Influence of the Depth of the Phreatic Level

From the results presented above it was possible to see that the efficiency of the ventilation system is strongly influenced by rising damp, because this is a continuous source of moisture which is very close to the ventilation system and therefore prevents the lower part of the wall from drying out. In this section the influence of other depths of the water table are analysed.

The drying process for two underground levels was studied by comparing the behaviour of a calcareous stone wall with a thickness of 0.2 m where the base is in direct contact with the water table (Configuration 1) with that of another configuration where the phreatic level is lower (Configuration 2), 20 cm below the wall base (Fig. 22).

Figure 23 shows the change in the water content of a calcareous stone wall over one year of simulation, using WUFI-2D, varying the air change rate from 1 to 100 h^{-1} and with a phreatic level at 20 cm below the wall base.

If we compare the change in the water contents of the wall over one year of drying in configuration 1, when the phreatic level is in direct contact with the wall base (Fig. 10, Sect. 4.1), with those in configuration 2, when the phreatic level is lower (Fig. 23), we can see that the second configuration achieves a lower water content. Additionally, in configuration 1, the water content curves are close together for *ACH* values over 60 h^{-1} while in configuration 2 this already happens for values over 20 h^{-1}.

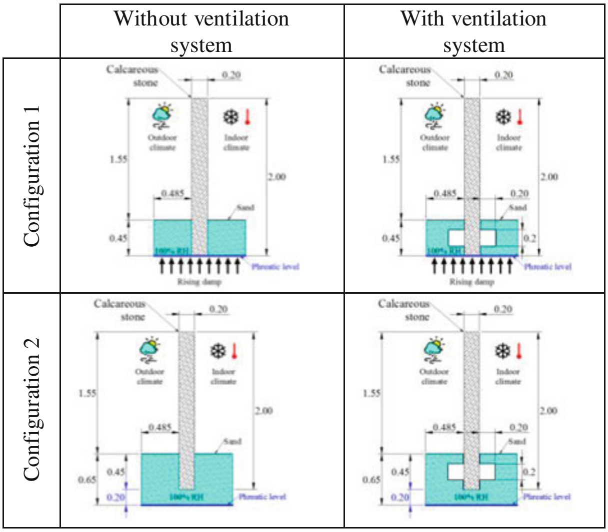


Fig. 22 Configurations studied to analyse the influence of the depth of phreatic level on the drying process

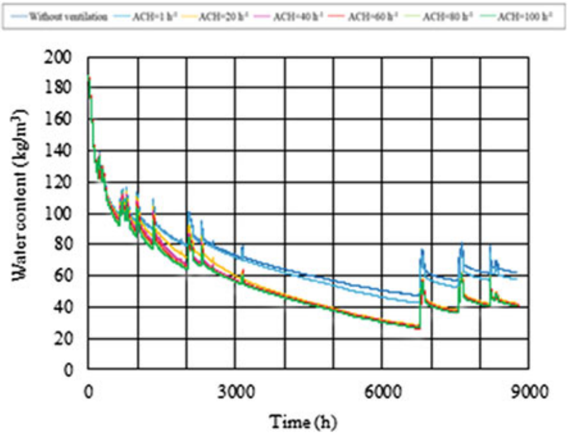


Fig. 23 Variation of water content in the wall over one year of drying out, with the air change rate varying from 1 to 100 h^{-1} and a phreatic level at 20 cm below the wall base

Tables 13, 14 and 15 present, respectively, the total water content reduction, the water reduction for each configuration compared with that for the wall without a ventilation system, and the efficiency of the ventilation system (compared with the configuration using calcareous stone and with an *ACH* value of 100 h^{-1}), for each building material and each air change rate in the channels.

In this case, efficiency of configuration 2 for values of *ACH* up to 20 h^{-1} is higher than 100 % because the boundary conditions of the simulation model change

Table 13 Total water content reduction after one year of drying out depending on the depth of the phreatic level and the air change rate in the channels

Config. (Depth)	Total water content reduction [kg/m^3]						
	Without ventilation system	Air change rate					
		1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
1 (0 cm)	119.3	120.2	124.6	130.1	133.9	135.3	136.5
2 (20 cm)	126.1	130.3	145.8	146.9	147.1	147.3	147.3

Table 14 Water content reduction after one year of drying out depending on the depth of the phreatic level and the air change rate in the channels

Config. (Depth)	Water content reduction [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
1 (0 cm)	1.3	7.8	15.7	21.2	23.4	25.0
2 (20 cm)	6.7	31.8	33.6	33.9	34.3	34.3

Table 15 Efficiency of ventilation system after one year of drying out depending on the depth of the phreatic level and the air change rate in the channels

Config. (Depth)	Efficiency [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
1 (0 cm)	5	31	63	85	93	100
2 (20 cm)	27	127	134	135	137	137

completely when the depth of the phreatic level is modified. The moisture content is thus lower because less water is absorbed by the wall base, too.

Figure 24 shows the water content of the central section of the wall after one year of drying out, when the phreatic level is 20 cm below the wall base, for each air change rate in the channels. Again, if we compare the water contents in configuration 1 (Fig. 11, Sect. 4.1) with those in configuration 2 (Fig. 24), we can observe that, in the second configuration, the drying of the zone of influence of the ventilation system is achieved with lower values of *ACH*. In fact, for a value of 20 h^{-1} or higher, the lower part of the wall dries more quickly than the upper part of the wall, where the drying is governed only by natural processes. Thus, the wall base ventilation system dries the lower part of the wall excessively, wasting energy, reducing the efficiency and running the risk of generating other important pathologies (salts attack).

Table 16 shows, for each configuration, the maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the wall without one.

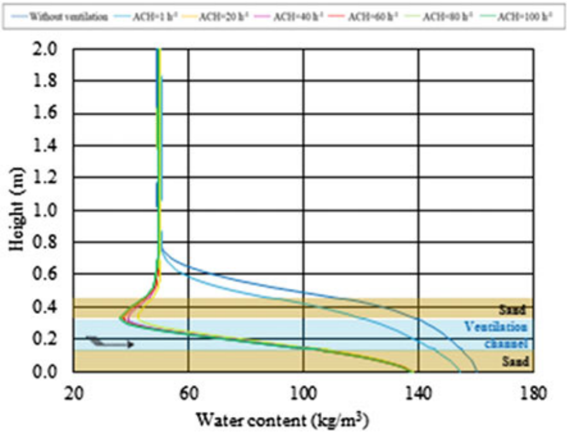


Fig. 24 Water content at the central section after one year of drying out when the phreatic level is 20 cm below the wall base (to make the comparison when the phreatic level is in direct contact with wall base, see Fig. 11 in Sect. 4.1)

Table 16 Maximum percentage of water content removed from the wall at a vertical central profile that the ventilation system is able to evaporate, compared with the simulation without one

Config. (Depth)	Maximum percentage of water content removed from the wall at a vertical central profile [%]					
	Air change rate					
	1 h^{-1}	20 h^{-1}	40 h^{-1}	60 h^{-1}	80 h^{-1}	100 h^{-1}
1 (0 cm)	5.6	25.0	46.6	55.4	58.8	61.0
2 (20 cm)	21.2	69.3	72.1	73.0	73.6	74.0

Figure 25 presents, for each configuration, the water content removed from the wall by the ventilation system, for each value of *ACH* after one year of drying out.

When the phreatic level is in contact with the wall base the phenomenon of rising damp is more pronounced and hinders the drying process. This is because the

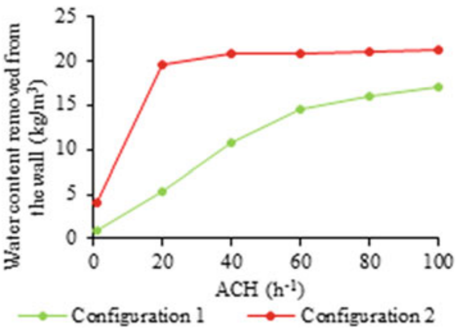


Fig. 25 Water content, in kg/m^3, removed from the wall by the ventilation system, for each value of *ACH* after one year of drying out. It can be concluded that the optimum *ACH* value is approximately 20 h^{-1} after one year of drying out when the phreatic level is only 20 cm below the wall base, whereas when it is in direct contact with the wall base this optimum value was 60 h^{-1}

wall has available water to absorb by capillarity, whereas when the phreatic level is 20 cm below the wall base the amount of water that it can absorb is only caused by the transfer of moisture between the bottom surface of the wall and underground sand. This is the reason that the wall dries out with lower air change rates.

5 Conclusions

The main conclusions of our study to validate the efficiency of a wall-base ventilation system as a technique for drying out historical buildings after a flood, influenced by several parameters, are:

General conclusions

- A wall-base ventilation system is a simple technique for controlling rising damp and for improving the drying out of historical buildings after a flood that has great potential for protecting architectural heritage.
- The system speeds up the drying process of the lower part of the wall (up to a certain height) and facilitates the natural drying out of the upper part.
- The efficiency and efficacy of the ventilation system depends on a large number of parameters, including length and cross section of the ventilation channels, air velocity in the channels, characteristics of ventilation air, wall thickness, building material (mainly because of the water absorption coefficient, water vapour diffusion resistance factor, hygroscopic curves and open porosity, the most significant material properties), ground moisture, existence of external sources of dampness, etc.

Parameter 1: Air change rates (ACH) in the channels

- Varying the air change rate has a great influence on the drying out of the wall base and on reducing the level reached by the moisture front of the rising damp. For a calcareous stone of 0.2 m thick, the ventilation system is able to remove up to 25.0 % of the moisture content for an *ACH* value of 100 h^{-1}.
- The maximum reduction in the water content at a vertical central profile of the wall when a ventilation system is installed is 61.0 %.
- There is an optimum value of *ACH* in the channels for each case studied (building material, size of the channels, environmental conditions, etc.).

Parameter 2: Wall thickness

- Varying the ventilation air change rate has a high influence on the efficiency of the wall base ventilation system when the walls have small thickness, but has less influence on high thickness walls. We can see that for a calcareous wall 0.2 m thick the water content reduction when we introduce the ventilation system with an *ACH* value of 100 h^{-1} is 25.0 %, for the wall 0.4 m thick it is 10.1 %, for the wall 0.6 m thick it is 5.6 %, for the wall 0.8 m thick it is 3.8 % and for the wall 1.0 m thick it is 2.7 %.

- The drying efficacy of the ventilation system at a vertical central profile of the wall decreases with increasing wall thickness. We can see that for the 0.2 m-thick wall the maximum decrease of the water content when we introduce the ventilation system is 61.0 %, for the wall of 0.4 m the decreased is 25.1 %, for the wall of 0.6 m the decreased is 11.7 %, for the wall of 0.8 m is 6.4 % and for the wall of 1.0 m is 3.9 % after one year of simulation and for an *ACH* value of 100 h^{-1}.

Parameter 3: Building material

- The variation of air change rate has considerable influence on the efficiency of the ventilation system in walls built with materials with low absorption coefficients. It was observed that for a calcareous stone, with a water absorption coefficient of 0.024 kg/m^2 $\sqrt{s}$, the maximum decrease in the water content when a ventilation system is installed with an air change rate of 100 h^{-1} is 25.0 %, for Ançã stone, with a water absorption coefficient of 0.145 kg/m^2 $\sqrt{s}$, the decrease is 2.7 % and for dolomite, with a water absorption coefficient of 0.067 kg/m^2 $\sqrt{s}$, the decrease is 10.3 %.
- The drying efficacy of the ventilation system at a vertical central profile of the wall decreases with the increase of the absorption coefficient because the material is more prone to replace the evaporation moisture by water for rising damp. We can see that for a calcareous stone the maximum decrease in the water content when a ventilation system is installed is 61.0 %, whereas for Ançã stone it is 14.6 % and for dolomite it is 26.0 %, after one year of simulation and for an *ACH* value of 100 h^{-1}.

Parameter 4: Depth of the phreatic level

- The position of the phreatic level influences the efficiency of the ventilation system. We can see that the water content reduction is 25.0 % when the phreatic level is in direct contact with the wall base, whereas it is 34.4 % when the phreatic level is at a lower level, in both cases for an *ACH* value of 100 h^{-1}.
- The drying efficacy of the ventilation system at a vertical central profile of the wall increases as the influence of external moisture sources decreases, because the material is less able to replace the evaporated water with underground water. It was observed that for a calcareous stone wall with a thickness of 0.2 m the maximum decrease in water content is 61.0 % when the phreatic level is in contact with the wall base and 74.0 % when it is at lower level.

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Risk Assessment of Urban Fire—Method for the Analysis and Management of Existing Buildings

Miguel Chichorro Gonçalves and André Correia

Abstract Fire Protection and Safety in Buildings is a delicate matter with recognized importance and ample opportunity for development, particularly regarding the analysis and/or interventions in existing buildings. Fire Protection and Safety in Buildings (FS) is of added importance in older buildings whose building typology followed a lower legislative requirement vis-à-vis the legislative requirements in effect today, thus giving these buildings greater vulnerability. Interventions in such buildings should be based on an assessment of Fire Risk in order to better gauge the degree of safety and identify key shortcomings, so the most appropriate measures can be adopted in order to reduce risk to acceptable levels. Considering the recurrence of casualties resulting from urban fires, the study of Fire Risk of buildings is urgent, especially in older urban centers. The aim is to produce a map detailing risk as well as intervention plans that allow for a better response and mitigation of the effects of urban fires. The CHICHORRO method—a new approach to urban fire risk assessment—is introduced in this paper. Its application to buildings in the historic district of Porto is also described.

Keywords Risk · Fire · Building · Map · Method

1 Introduction

It is widely acknowledged that building rehabilitation remains a complex task involving the contribution of a multitude of experts. Their main goal—as well as that of any FS initiative: protecting human life.

Whereas the current FS regulations must be implemented for any new construction, rehabilitation projects may fall under any of the following situations:

M.C. Gonçalves (✉) · A. Correia
Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, s/n 4200-465, Porto, Portugal
e-mail: miguelcg@fe.up.pt

A. Correia
e-mail: up200706629@fe.up.pt

J.M.P.Q. Delgado (ed.), *Sustainable Construction*,
Building Pathology and Rehabilitation 8, DOI 10.1007/978-981-10-0651-7_4

- The general rule: current regulations are mandatory when refurbishing a building;
- Special case for protected buildings where regulations are neither applicable nor practical: contingency protection measures are implemented;
- Ad hoc FS measure implementation for any building with an atypical risk profile, meaning standard regulations are wholly inadequate. These situations must be detailed in full by those responsible to enable a thorough risk-based analysis of proposed measures.

The proposed method: Chichorro, (Portuguese acronym for Holistic Calculation of Fire Risk of Construction and Enabled Optimization of its Reduction with Construction Works) differs from other methods of risk assessment of urban fire, by proposing specific criteria considered relevant for the maintenance of desirable environmental conditions to evacuate the buildings. This method also distinguishes itself from the others, through the quantification of the influence of the fire safety devices, reducing the time of evacuation of buildings. In Chichorro method, the time required to achieve specific conditions, which are considered harmful to the evacuation, is compared with the time required for total evacuation of the fraction in question. The respective partial factor is the value resulting from this comparison.

2 CHICHORRO Method

2.1 Introduction

The proposed CHICHORRO method for the evaluation of the risk of fire for a given building, serves two purposes: risk analysis for the current situation, and post-rehabilitation risk analysis (thus allowing optimal health and safety implementation).

CHICHORRO is a generic method and is applied regardless of the current usage of a building. Highly complex situations requiring specific analysis fall outside the scope of MARIEE (Correia 2013; Louçano 2014). Full or partial rehabilitation of a building may be at stake, with diverse variations in scope.

This method introduces scenario-based analysis in order to determine the most effective way to handle a fire situation. Where several scenarios exist, the method is applied to the one with the highest risk. The resulting safety recommendations should then be tested against the remaining scenarios.

Two aspects set CHICHORRO method apart from similar Fire Risk analysis methods: the creation of criteria for building maintenance and the analysis of fire safety devices—both from the perspective of effective building evacuation, particularly the incremental gains that each provide.

With CHICHORRO method, we take the time required for building evacuation (partial or in full), and compare it to the time required in a fire situation for specific circumstances impairing the evacuation effectiveness to be reached. It is this delta that merits our attention.

2.2 Principles of Development of the CHICHORRO Method

Any risk analysis includes a method of dynamic analysis. In a first phase a building's Fire Risk assessment is carried out. In a second phase, Fire Safety Engineering (FSE) methodologies are iteratively applied until Fire Risk is considered acceptable. Thus, the development of this method involved a careful numerical evaluation of the initial Fire Risk, i.e.:

(a) the current state of the building itself or any part of it;
(b) how fire risk is affected by the FSE implementations.

This method is the result of the evolution of other risk fire methods, having evaluated how they are impacted by numerous factors. By including those factors but occasionally with a new calibration, as well as new ones, we have developed a new method. This involved extensive study of concepts and thorough verification of any assumptions early in the calculation, as well as the final impact in the results, when some technical issues of FSE are implemented to achieve an acceptable Fire Risk. A lot of effort went into static and dynamic validation of all aspects with influence on the results. We carried out a sensitivity study for about 12 types of buildings (standard uses) covered by the law and their four risk categories. For each we applied 29 suggestions of improvement of construction/improvement of FSE. We did this in specific sets for standard use in different degrees of degradation of the construction and positioning in the urban area. In these sets we identified three intervention levels (level G1, G2 or G3) to be smaller or larger depending on the intervention in terms of construction work and costs, respectively. A lot of care was taken from the degree of intervention that was intended for the interventions package, combining active and passive measures, and increasing the difficulty of implementation with the degree of intervention.

2.3 How CHICHORRO Method Works

CHICHORRO method relies on 4 global Fire Risk dimensions:

- POI—The probability of occurrence of fire;
- CTI—The full consequences of a fire;
- DPI—How a fire propagates;
- ESCI—The effectiveness of firefighting and assistance measures.

Note that the second dimension above includes two important concepts in risk analysis: how dangerous a fire is and one's exposure to it. The threat level depends on the chemical reactions during a fire, and the resulting fumes, gases, and heat. Exposure is measured by the time required to evacuate the premises.

Combining the 4 dimensions above enables a full view of Fire Risk analysis, and resulting implications for both individuals and property. The expressions for the calculation of Fire Risk (FR) in CHICHORRO method are presented next. These include descriptors for the building conditions presented during the analysis:

$$FR = P \times G \tag{1}$$

where

FR Fire Risk;
P The probability of a fire event = POI;
G The seriousness of the consequences of a fire

$$G = CTI \times (DPI + ESCI)/2 \tag{2}$$

where

$$CTI = \frac{2 \cdot CPI_{CI} + (CPI_{VHE} + CPI_{VVE})/2}{3} \tag{3}$$

where

CPI_{CI} Partial Consequences of a Fire, associated with a fire event in a Compartment Scenario (CI);
CPI_{VHE} Partial Consequences of a Fire, pertaining to Horizontal Escape Routes (VHE);
CPI_{VVE} Partial Consequences of a Fire, pertaining to Vertical Escape Routes (VVE)

The consequences resulting from a fire depend on the danger level of the fire and the exposure, as shown in Eq. (4), (Correia 2013):

$$CPI = \frac{P}{E} \tag{4}$$

where

CPI Partial Consequences of a Fire;
P Potential Danger;
E Level of Exposure

To sum up, Fire Risk in CHICHORRO method is derived from Eq. (5):

$$FR = POI \times CTI \times (DPI + ESCI)/2 \tag{5}$$

In addition other variables in this Fire Risk method have the follow significance:

$$\begin{aligned} POI = (&P_{CC} + P_{IEE} + P_{IA} + P_{ICONFA} + P_{ICONSA} + P_{IVCA} + P_{ILGC} + P_{EF} \\ &+ P_{EA} + P_{FA} + P_{PPP} + P_{ATIV})/12 \end{aligned} \tag{6}$$

where each partial factor represents a contribution in the probability of occurrence of fire:

P_{CC} Construction characterization
P_{EE} Electric power facilities
P_{IA} Heating systems
P_{ICONFA} The cooking facilities
P_{ICONSA} Food storage facilities
P_{IVCA} Ventilation installation, air conditioning
P_{ILGC} Liquids facilities and combustible gases
P_{EF} Frontiers buildings
P_{EA} Adjacent buildings
P_{FA} Adjacent fractions (same building)
P_{PPP} Procedures or prevention plans
P_{ATIV} Activity

$$CPI_{CI} = (3 \times \mathrm{CPI}_{\mathrm{CIP}} + 2 \times \mathrm{CPI}_{\mathrm{CIF}} + 1 \times \mathrm{CPI}_{\mathrm{CIMR}})/6 \tag{7}$$

where each partial factor characterizes his contribution in the Partial Consequences of a Fire, associated with a fire event in a Compartment Scenario:

$\mathrm{CPI}_{\mathrm{CIP}}$ Fire Scenario—Power
$\mathrm{CPI}_{\mathrm{CIF}}$ Fire Scenario—Smoke
$\mathrm{CPI}_{\mathrm{CIMR}}$ Fire Scenario—Coating Materials

$$\mathrm{CPI}_{\mathrm{VHE}} = (2 \times \mathrm{CPI}_{\mathrm{VHEF}} + \mathrm{CPI}_{\mathrm{VHEMR}})/3 \tag{8}$$

$$\mathrm{CPI}_{\mathrm{VVE}} = (2 \times \mathrm{CPI}_{\mathrm{VVEF}} + \mathrm{CPI}_{\mathrm{VVEMR}})/3 \tag{9}$$

where each partial factor characterizes his contribution in the Partial Consequences of a Fire, pertaining to Horizontal and Vertical Escape Routes:

$\mathrm{CPI}_{\mathrm{VHEF}}$ Horizontal Evacuation Route—Smoke
$\mathrm{CPI}_{\mathrm{VHEMR}}$ Horizontal Evacuation Route—Coating Materials
$\mathrm{CPI}_{\mathrm{VVEF}}$ Vertical Evacuation Route—Smoke
$\mathrm{CPI}_{\mathrm{VVEMR}}$ Vertical Evacuation Route—Coating Materials

$$DPI = (\mathrm{DPI}_{\mathrm{REIC}} + \mathrm{DPI}_{\mathrm{EI}} + \mathrm{DPI}_{\mathrm{AV}} + \mathrm{DPI}_{\mathrm{PE}} + \mathrm{DPI}_{\mathrm{OGS}})/5 \tag{10}$$

where each partial factor characterizes his contribution in how a fire propagates:

$\mathrm{DPI}_{\mathrm{REIC}}$ Fire Resistance REI of CI and VVE
$\mathrm{DPI}_{\mathrm{EI}}$ Fire Resistance EI of walls and doors of CI
$\mathrm{DPI}_{\mathrm{AV}}$ Spacing between outer spans the same vertical lines
$\mathrm{DPI}_{\mathrm{PE}}$ Fire Resistance of exterior walls and firewall
$\mathrm{DPI}_{\mathrm{OGS}}$ Organization and Safety Management—Emergency Plans

$$ESCI = (\mathrm{ESCI}_{\mathrm{GP}} + \mathrm{ESCI}_{\mathrm{SID}} + \mathrm{ESCI}_{\mathrm{AE}} + \mathrm{ESCI}_{\mathrm{HE}} + \mathrm{ESCI}_{\mathrm{EXT}} + \mathrm{ESCI}_{\mathrm{RIA}} + \mathrm{ESCI}_{\mathrm{CPB}})/7 \tag{11}$$

where each partial factor characterizes his contribution in the effectiveness of firefighting and assistance measures:

$\mathrm{ESCI}_{\mathrm{GP}}$ Degree of Readiness
$\mathrm{ESCI}_{\mathrm{SID}}$ Lighting Signaling and Detection
$\mathrm{ESCI}_{\mathrm{AE}}$ Accessibility to the Building
$\mathrm{ESCI}_{\mathrm{HE}}$ Outdoor Hydrants
$\mathrm{ESCI}_{\mathrm{EXT}}$ Extinguishers
$\mathrm{ESCI}_{\mathrm{RIA}}$ Armed Fire Networks
$\mathrm{ESCI}_{\mathrm{CPB}}$ Private Fire Department

A full explanation of this method is outside the scope of this chapter. By and large, whenever a partial factor is not applied, then it will not enter in the arithmetic mean (we consider the appropriate denominator in the respective equation).

We need to explain the possible values each partial factor can take. As an example, we consider the global risk factor associated with the likelihood of fire—the beginning of the fire (POI) and more specifically to $\mathrm{POI}_{\mathrm{CC}}$, the partial factor reflecting the condition and use of the building in the beginning of the fire. One may want to translate the contribution of the state of the construction to short circuits, and also the occupation of the building. Thus were considered as key factors to the infiltration of water and type slab fuel or not and furthermore the surface painting in common areas (which affects leakage reduction). Depending on the combinations of those factors the discrete values of $\mathrm{POI}_{\mathrm{CC}}$ can be: 1.00, 1.10, 1.20, 1.30, 1.40, 1.60 or 1.70.

The same goes for all other partial factors, i.e. they are characterized by taking values (whose range is distinct from factor to factor) depending on the respective characteristic elements considered influential in this amount.

3 Proposal Building Classification According to Fire Risk

CHICHORRO method can be used in different contexts, be it older or newer property, as well as any building undergoing rehabilitation. It allows for a systematic analysis of Fire Risk in urban spaces, thus enabling local authorities to create Fire Risk urban maps, identify high-risk areas and act accordingly. Is shown the proposed classification of buildings according to the Fire Risk in Fig. 1. This classification is detailed in 12 categories of risk (A++, A+, A, B+, B, B−, C+, C, C−, D, E and F), respectively, the first one corresponding to a Fire Risk equal or smaller than 0.9, the last one to a Fire Risk higher than 1.7, and the remaining ones at value ranges corresponding to intermediate Fire Risk.

A++	• VERY LOW Fire Risk:	$FR \le 0.90$
A+	• LOW Fire Risk:	$0.90 < FR \le 0.95$
A	• ACCEPTABLE LOW Fire Risk:	$0.95 < FR \le 1.00$
B+	• MODERATE+ Fire Risk+:	$1.00 < FR \le 1.05$
B	• MODERATE Fire Risk:	$1.05 < FR \le 1.10$
B-	• MODERATE- Fire Risk:	$1.10 < FR \le 1.15$
C+	• MEDIUM+ Fire Risk+:	$1.15 < FR \le 1.20$
C	• MEDIUMFire Risk:	$1.20 < FR \le 1.25$
C-	• MEDIUM- Fire Risk:	$1.25 < FR \le 1.30$
D	• HIGH Fire Risk:	$1.30 < FR \le 1.50$
E	• VERY HIGH Fire Risk:	$1.50 < FR \le 1.70$
F	• IMMINENT Fire Risk:	$FR > 1.70$

Fig. 1 Proposal building classification according to Fire Risk: FR

Building construction year	Maximum Fire Risk acceptable value
After 2008	**1.00**
Between 1991 and 2008	**1.05**
Between 1975 and 1990	**1.10**
Between 1968 and 1974	**1.15**
Between 1951 and 1967	**1.20**
Before 1951	**1.25**

Fig. 2 Maximum acceptable FR value in line to building construction year

One can take the maximum acceptable Fire Risk level according to the year of construction (Fig. 2). Technological and regulatory advances in building construction throughout the years are the main influence on these limits for Fire Risk. Both these limits and the dates were thoroughly evaluated.

4 Interventions in the Process of Rehabilitation

Tables 1 and 2 present possible interventions to adopt in the process of rehabilitation of a building or any part (respectively active and passive measures in Fire Safety Engineering) which have a bearing on the results of the application of CHICHORRO method.

Table 1 Possible interventions of active measures of FSE in CHICHORRO method

Measures	Interventions	
Actives	1	Extinguishers
	2	Signalling (common area)
	3	Lighting (presence and emergency) (common area)
	4a	Detection within fractions with average reliability (100 seg)
	4b	Detection within fractions with high reliability (50 seg)
	5	Detection in public areas
	6	Plan prevention + TRAINING
	7	Smoke control: skylights—passive air intake (common areas)
	8	1st intervention—systems and equipment's
	9	Outdoor hydrants < 30 m
	10	Smoke control—(not at housing uses)
	11	Signalling and illumination—CI (not at housing uses)
	12	Sprinklers (not at housing uses)
	13	Plan Emergency + Drill
	14	Reduction of conditioning parking by City hall to enable accessibility of firefighters

Table 2 Possible Interventions of passive measures of FSE in CHICHORRO method

Measures	Interventions	
Passives	15	Reducing infiltration (enveloping facade-roof)
	16	Paints and finishes in VHE and VVE (ceilings and walls) (when there are no VHE and VVE consider CI)
	17	Revision of electrical installation
	18	Review of the gas installation
	19	Installation of AVAC review
	20a	Small heating installation review (autonomous units)
	20b	Big heating installation review
	21	Confection installation review and conservation foods
	22	Compartmentation—fire Resistance of doors in CI—and repair of walls in Fire Resistance if necessary
	23	Protection of openings for frontiersmen buildings (POI => improvement of the fire reaction) (DPI => improvement Fire Resistance E30)
	24	Protection roof (firewall) and gable to neighbouring buildings/improved of fire reaction of facade
	25	Sealing the ducts floor (only affects when stairway enclosure)
	26	Compartmentation—stairway enclosure
	27	Compartmentation—fire resistance of slabs
	28	Access to the basement separate from access of the rest of the building or Fire Resistance door or chamber fireproof
	29	Installation or repair of rescue stairs (corresponding not consider the VVE in the model)

5 CHICHORRO Method—Sensitivity Analysis

5.1 Implementation

The application of this model involves the assessment of the impact of decision-making at three levels.

First, the importance of choosing the parameters that will influence the value of Fire Risk, and furthermore their quantification and mathematical articulation in response to the physical concepts explained in Sect. 2.

Second, the need for a static analysis i.e. the assessment of the Fire Risk of a particular building as is. We must evaluate the results according to the assumptions of the first level, when applied to a universe of buildings of up to 12 types. In other words, it was necessary to calibrate the model to give an assertive response for the Fire Risk value for any of the 12 building types considered in the Portuguese Law (Portugal and Decreto-Lei nº 220/2008; Portugal and Portaria nº 1532/2008). That takes into account the many different uses of buildings which has influence on architectural order such as dimensions, typological organization, materials used, compartmentalization, number of people using the building, and the status of fire safety equipment and systems.

Third (dynamic analysis), it is necessary to calibrate the model to include the potential building interventions (rehabilitation/improvements) promoted in order to measure the impact of these interventions in reducing the Fire Risk value, considering the year of construction of the building. Here we intend that each intervention has adequately modeled the response within the holistic assessment of building in terms of Fire Safety Engineering.

Taking into account these three levels of implementation, it was necessary to establish the variables to consider and their proper articulation (referred to in Sect. 2), and also characterize a set of building types that have a real representation of existing buildings. We then made a static application of the model as well as dynamic gauging and adjustment to obtain the state of the art presented in this work. The following subsections summarize the 306 cases studied, as well as combinations of logical operations (a G1 intervention level perspective, G2 or G3) and correspondent's results.

Extensive effort was made to statically and dynamically validate all aspects which influence the results. This involved a thorough verification of the implications early in the calculation, as well as the final impact in the results, whenever technical aspects of FSE are implemented to achieve an acceptable Fire Risk.

5.2 Buildings Standards

This method can distinguish various types of buildings according to the rate of development of a fire, $t\alpha$. There is furthermore a subdivision along the typical

Table 3 Growth rate of fire for different types of occupations

Use-type	Growth rate of fire	tα(s)
Housing	Average	300
Hospital	Average	300
Hotel	Average	300
Library	Fast	150
Office	Average	300
School	Average	300
Shopping	Fast	150
Theater	Fast	150
Transport	Slow	600

characteristics of each built. We analyzed 306 typical cases in order to finetune the performance of our method.

According to NP EN 1991-1-2 (1991) the evolution of heat output released during a fire is given by a parabolic growth curve. Further in accordance with NP EN 1991-1-2 (1991) we present in Table 3 the characteristic curves of growth rate of fire, tα, and the correspondence with the respective Use-Type (UT) of buildings.

To do the sensitivity analysis of this method we considered three groups of building types, taking into account, the growth rate of fire according to the NP EN 1991-1-2, (NP 1991):

Type "A" with $t_\alpha = 300$ s
Type "B" with $t_\alpha = 150$ s
Type "C" with $t_\alpha = 75$ s

In Type "A" we consider two main groups of buildings:

A1 (Housing, Administrative and Hoteliers);
A2 (Schools/Nurseries, Elderly homes/Hospitals/Wards).

The Type "B" can be divided into:

B1 (Restaurants, Coffee, Shopping);
B2 (Shows, Museums, Libraries, Industry).

Figure 3 shows the various existing building types and the number of cases that have been studied for each of these buildings to calibrate the model. These were based on common usage differentiating features for each type in order to make a parametric analysis of results.

In Type "C" we only considered Warehouses with a 75 s fire growth rate, according to that document. Transport hubs (growth rates of 600 s) were not considered as this is a special case that merits specific analysis, and leading to constraints in the development of this generic model applicable to different types of buildings.

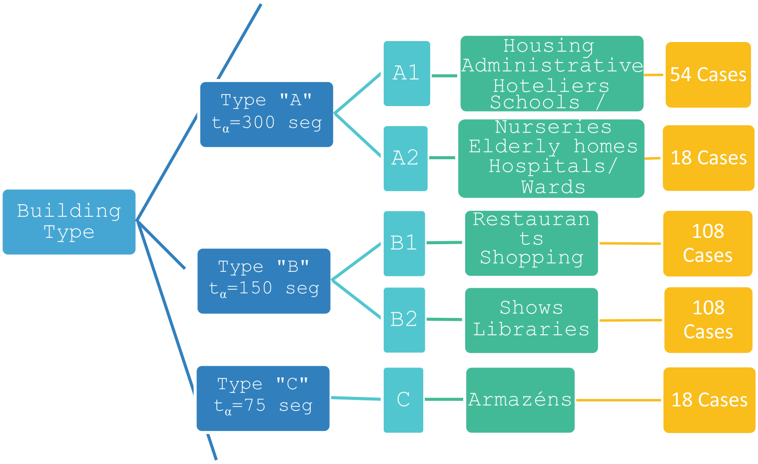

Fig. 3 Building type and number of studied cases

5.3 Sensitivity Analysis in Standard Uses of Buildings

Table 4 shows combinations of active and passive interventions of building works that can be adopted in a process of rehabilitation of a building: housing fraction, accounting for combination ***i***, the case without any intervention.

The interventions to be made in buildings are classified in three different levels, G1, G2 and G3. These classifications are briefly detailed below:

G1 Slight level intervention—Intervention type: painting (no need for demolition); Detection, lighting, fire extinguishers, fire signalization;

G2 Medium level intervention—Need for demolition or wall refurbishment, electrical installation; Placing Firewall doors, general compartmentation and fire hydrants;

G3 High level intervention—Change of Architecture; enclosure of stairwell

Table 4 Combination of interventions adopted in the housing buildings

			Combinations of Interventions	
			Actives	**Passives**
Housing	***ii***	G1	1+2+3+6	15+17
	iii		ii+4a	ii+21
	iv	G2	iii+4b+5+7	iii+16+18+19+20a
	v		iv+9	iv+22+23
	vi	G3	v+8	v++24+29
	vii		vi+10+13+14	vi+20b+25+26+27

Table 5 Fire Risk rating of 18 housing type cases (*i*) and interventions adopted (*ii–vii*) according to the CHICHORRO method

Housing (H=18m)			Fire Risk (FR)						
			Combination of Interventions						
Condition	**Access**	**Hydrants**	**i**	**ii**	**iii**	**iv**	**v**	**vi**	**vii**
Good	Possible	< 30m	1.50	1.31	1.12	0.93	0.87	0.85	0.54
		> 30m	1.55	1.34	1.15	0.96	0.90	0.88	0.56
		NO	1.60	1.38	1.18	0.98	0.93	0.90	0.58
	Light vehicles of firefighters	< 30m	1.56	1.35	1.15	0.96	0.91	0.88	0.56
		> 30m	1.61	1.38	1.19	0.99	0.93	0.90	0.58
		NO	1.66	1.42	1.22	1.02	0.96	0.93	0.60
Medium	Possible	< 30m	1.74	1.39	1.19	1.00	0.92	0.88	0.55
		> 30m	1.79	1.43	1.23	1.03	0.95	0.90	0.57
		NO	1.85	1.47	1.26	1.06	0.97	0.92	0.59
	Light vehicles of firefighters	< 30m	1.79	1.43	1.23	1.03	0.95	0.91	0.57
		> 30m	1.85	1.47	1.26	1.06	0.98	0.93	0.59
		NO	1.91	1.51	1.30	1.09	1.01	0.95	0.61
Bad	Possible	< 30m	2.06	1.59	1.37	1.09	1.00	0.94	0.57
		> 30m	2.12	1.63	1.41	1.13	1.03	0.97	0.59
		NO	2.19	1.67	1.44	1.16	1.06	0.99	0.61
	Light vehicles of firefighters	< 30m	2.14	1.65	1.42	1.13	1.04	0.97	0.59
		> 30m	2.20	1.69	1.45	1.16	1.07	1.00	0.61
		NO	2.27	1.73	1.49	1.20	1.10	1.02	0.63

Table 4 describes the combination of active and passive interventions adopted in the Housing buildings interventions.

The 306 cases were studied in total. We present 18 cases of Housing buildings (of a total of 54—these are buildings with a height of 18 m, and no access for fire trucks).

Table 5 shows the initial value of Fire Risk for these 18 Housing types, and the impact of the six combinations of interventions adopted in the value of Fire Risk according to CHICHORRO method. The impact of Fire Risk modification for all 54 housing buildings and the corresponding rating change is shown on Table 6.

6 Case Study—Risk Assessment in Porto Urban Area

6.1 Historical Background of Old Porto Center

We applied the CHICHORRO method to a small urban area of Porto. A brief historical background of this area follows. We also define the boundaries of the historic district of Porto.

In the last decade we have been witnessing a growing dynamism of the Porto historic center policy. This is mainly due to the exponential increase in tourism,

Table 6 Impact assessment of Fire Risk to the adopted interventions *(i–vii)* and the change of classification of buildings according to CHICHORRO method

Package of interventions		i	ii	iii	iv	v	vi	vii
Average impact of Fire Risk (ΔFR)		0	0.37	0.59	0.81	0.89	0.93	1.27
Housing (54 cases)	A++				0	4	14	54
	A+				4	16	21	
	A				11	13	15	
	B+				11	12	4	
	B			1	11	7		
	B−			4	8	2		
	C+			13	8			
	C			8	1			
	C−		1	8				
	D	1	31	19				
	E	16	18	1				
	F	37	4					

which brought another elan to the metropolitan area, and resulted in increased investment in the real estate sector as well as the creation of new hotels and hostels and small businesses. Furthermore the development of nightlife leisure activities has made the Porto historic center one of the most dynamic and attractive in Europe.

The historical center has a unique architectural and cultural heritage and a community of about 10,000 inhabitants (Vivo-SRU 2011), endowed with a strong identity. Its rehabilitation process started 40 years ago, and it was internationally recognized in 1996 as a UNESCO World Heritage cultural asset. Its specificity and authenticity are deemed fundamental for the development of creative activities.

The Porto historic center is part of the former parishes of Victoria, São Nicolau, Miragaia and Sé—these are now part of the Parish Union of Cedofeita, Santo Idelfonso, Sé, Miragaia, São Nicolau and Victoria. It is an area of about 50 ha, comprising 91 blocks and roughly 1800 buildings.

The World Heritage Historic Center comprises the medieval urban area inside the Fernandina wall (XIV century), including the Tower and Church of the Clérigos of São João Theatre, the Old Building of the Civil Government, the block bounded by the 31 de Janeiro street, Batalha and Madeira streets, the block formed by the streets Barbosa de Castro, Passeio das Virtudes, Dr. António Sousa Macedo and also the D. Luis I Bridge, Church and Monastery of Serra do Pilar in Vila Nova de Gaia, (blue line in Fig. 4).

The area belonging to the historic district of Ribeira/Barredo extends between the banks of the Douro River and Rua Infante D. Henrique, representing a territory where with 27 blocks and 266 buildings (green zone in Fig. 4).

Fig. 4 Aerial image of part of Porto city with delimitation of the Porto historic center (*blue line*), and the Ribeira/Barredo, (*green zone*), adapted from Google Earth

6.2 Buildings Analysis of Ribeira/Barredo Block

6.2.1 Uses Type of Buildings

The CHICHORRO method assesses fire risk for a building through analysis of whichever part of the building that presents the highest risk category. It is of course possible to make a risk assessment of any part of the building, but the fraction that most affects this building in terms of Fire Risk will be the most relevant for our classification map. With this in mind, we need to examine all buildings regarding their occupation and use, and find out which is the determinant use (Fig. 5).

Fig. 5 Map of uses type of buldings at Ribeira/Barredo

The data collected namely during site visits allowed the characterization of the buildings analyzed, i.e. their utilization according to Portuguese legislation, (I-Housing, III-Administrative, IV-School, V-Hospital, VI-Show, VII-Hotel, Restaurant, VIII-Shopping and X-Museums)—see Fig. 5. Each building is defined by a number and block name. Thus the identification of buildings is unambiguous.

6.2.2 Risk Category of Buildings

Figure 6 shows the classification map of the categories of Fire Risk of each building of Ribeira/Barredo block according to the criteria of the Portuguese legislation.

6.2.3 State of Preservation of Buildings

The condition of the buildings at Porto historic center was evaluated—the criteria followed the framework of CHICHORRO method and FSE specifications as follows:

Good: Building in good conditions. May need maintenance work (conservation of the facades or minor repairs of building elements). In this case, it is impossible to ensure compliance with the current legislation of FSE and rehabilitation is kept to a minimum, so it does not intervene at the level of solutions and major building systems;
Medium: Building with some visible wear and tear and shortcomings in the infrastructure. The works involved in interventions of this type generally include replacement of electrical and plumbing systems, improvement of functional and environmental conditions. These mostly concern kitchens and bathrooms, and repairing coatings of facades and gables and interior walls;
Bad: Building in poor conditions of use. Requires major work, concerning both infrastructure and building systems and distribution and typological organization.

Fig. 6 Categories of fire risk of the buildings at Ribeira/Barredo

The type of intervention for these buildings requires a project, given that they involve demolitions and reconstructions of vertical and horizontal structures. They also require the temporary evacuation of buildings;
Unoccupied/Ruins/Construction works (URC): These are similar to buildings in poor condition, in terms of conditions of use, though they are unoccupied dwellings (leading to further degradation). In general, these have a higher priority intervention, since they do not have any conditions of use and pose a risk to local residents. Buildings with ongoing construction works were also considered in this category.

Figure 7 shows a map of Ribeira/Barredo, and indicates overall building conservation status according to the criteria presented above.

6.2.4 Accessibility Map of the Firefighters

Given the urban morphology of these sites, which is characterized mainly by roads of reduced width, the access for firefighting vehicles is extreme difficult, (PA—Possible Access, ALFV—Access to Light Firefighting Vehicles, NO—NO access possible), Fig. 8.

6.2.5 Map of the Hydrants

Therefore, the maintenance of hydrants in good condition turns out to be central to the FS in historical centers, as fire-fighting is very dependent on this type of external equipment.

The location of the fire hydrants and single fire hose in the study area is represented in Fig. 9.

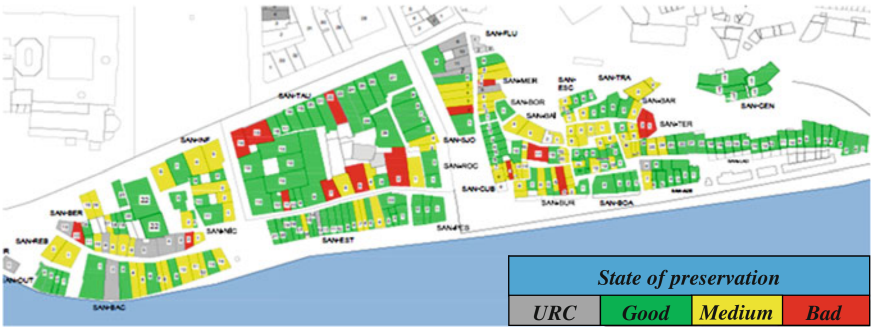

Fig. 7 Conservation status of buildings at Ribeira/Barredo

Fig. 8 Accessibility map of firefighters at Ribeira/Barredo

Fig. 9 Hydrants map at Ribeira/Barredo

6.3 Application of CHICHORRO Method to a Region of Urban Area: Ribeira/Barredo—Static Analysis

Figure 10 the results of the application of the model to the historical centre of the city of Porto, particularly the block Ribeira/Barredo (Gonçalves and Correia 2015a, b, c, d; Gonçalves and Ramalho 2015; Gonçalves and Correia 2014a, b). It is based on the classification presented in Sect. 3, and the information previously presented for the application of CHICHORRO method.

6.4 Application of CHICHORRO Method to a Single Block —Dynamic Analysis

One of the advantages of the CHICHORRO method is that it can calculate the Fire Risk of each plot of a building, and also shows the combination of measures that

Fig. 10 Fire risk map of Ribeira/Barredo

can be introduced to reduce the fire hazard of a particular building. This chapter presents a case study.

The block Berlengas in Porto lies in the west of Ribeira area, located between the Reboleira Street, the São Nicolau Street and D. Infante Henrique Street, Fig. 11.

Table 7 shows the final results of choosing the combination of interventions that can achieve an acceptable Fire Risk with minimal cost and intervention level.

Through intervention combinations already described in Chap. 3, the authors will propose measures that promote the reduction of Fire Risk for all buildings to an acceptable Fire Risk according to the year of construction of each building (New FR—Fig. 2).

Fig. 11 Location of the Berlengas block

Table 7 Chosen interventions and new fire risk

Building number	FR	Classification	Interventions combination	Intervention level	New FR	New Classification
1	1.74	F	*iv*	G2	0.91	A+
2	2.14	F	*iv*	G2	1.13	B-
6	1.79	F	*iv*	G2	1.03	B+
7	1.82	F	*iv*	G2	1.04	B+
8	1.74	F	*iii*	G1	1.20	C+
10	1.74	F	*iii*	G1	1.20	C+
11	1.51	E	*iii*	G1	1.12	B-
12	1.99	F	*iv*	G2	1.07	B
14	1.46	D	*iv*	G2	0.91	A+
15	1.88	F	*xi*	G1	1.07	A++
16	1.68	E	*iv*	G2	0.98	A
17	1.68	E	*iv*	G2	0.98	A
18	1.46	D	*iv*	G2	0.91	A+
19	1.46	D	*iv*	G2	0.91	A+
20	1.46	D	*iv*	G2	0.91	A+
21	1.46	D	*iv*	G2	0.91	A+
22	1.85	F	*x*	G2	0.95	A+

Before choosing the intervention measures of construction, the authors gathered information about the year of construction of the last rehabilitation of the building to be renovated, using information of Vivo-SRU (2011). The authors also used their evaluation of the analyzed buildings. The result of this analysis is shown in Table 7. This afforded the static analysis of Fire Risk, i.e. the Fire Risk to the building as we found it.

After this analysis, we proceeded to study of the impacts of every combination of interventions (active and passive measures) until you arrive at an acceptable Fire Risk. Is evident in Table 7 what combination of interventions provide an acceptable Fire Risk, with minimal cost and possible intervention level.

Looking at Table 7, it can be concluded that most buildings have a medium level of intervention. Figure 12 shows the single block in the historical center of the city of Porto under study, with the buildings and respective values of the Fire Risk obtained before and after the implementation of intervention measures with the application of CHICHORRO method.

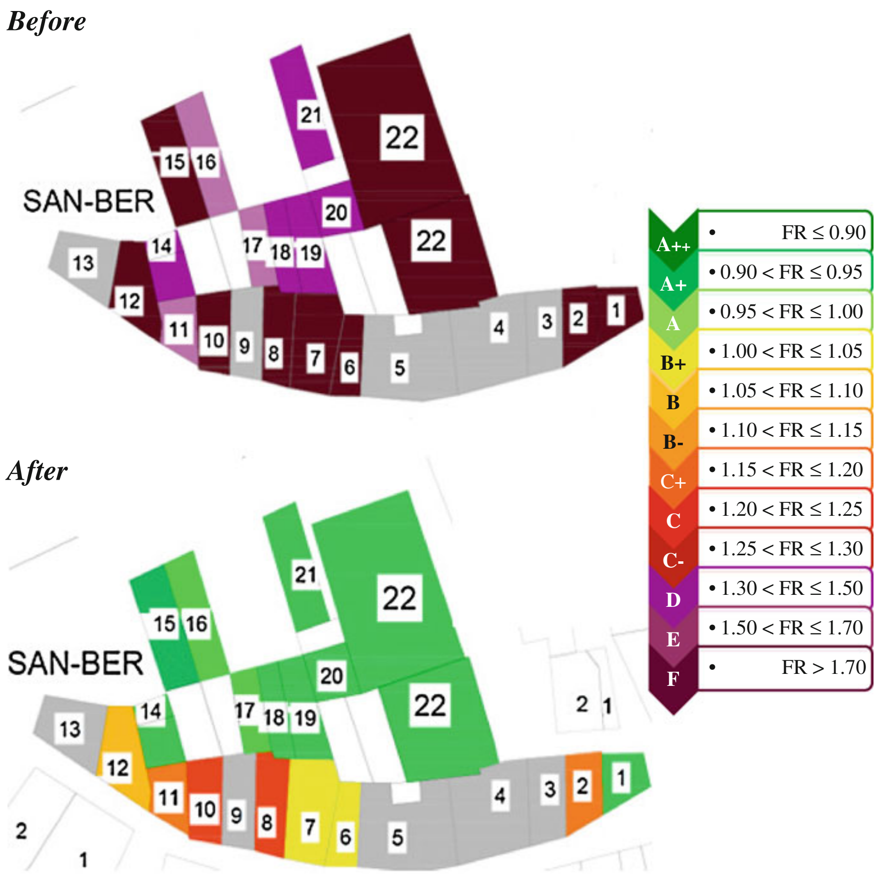

Fig. 12 **a** Application of CHICHORRO method to the historical centre of Porto city, Berlengas block—fire risk before and after proposed rehabilitation of each building

7 Conclusions

The proposed method allows us to assess and acknowledge the Fire Risk in urban areas so that in cases where it proves to be unacceptable, possible interventions are devised with the aim of improving the Fire Protection and Safety in Buildings. Considering the recurrence of casualties resulting from urban fires, it is urgently required to study in an adequate manner the Fire Risk in buildings, especially in older urban areas so as to draw a mapping of this risk and contingency plans for intervention that allow for a better response and enhance mitigation of effects of urban fires.

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Economic Relevance of Building Elements—Studies, New Framework, Evolutions and Support for Refurbishment Operations

Pedro Mêda, Hipólito Sousa and Frederico Ferreira

Abstract A supported decision-making based on aspects as the construction costs is considered essential in different stages of the construction process. The awareness of the relevance of each part of a building in its global cost is also helpful to the several actors involved and to a more efficient project management. Naturally, the economic relevance of each part of a building can be considerately different as it is influenced by many factors, namely the technical solutions applied, the construction products, the dimension of the construction, the type of use and the age of the design. The present work is focused on this topic. Through a review of the several studies performed in Portugal until present time concerning cost breakdown structures (CBS) of residential buildings and developing new studies to fill the information gaps it is intended to provide a perspective of the evolutions occurred. Besides the analysis of the main changes, the work also proposes a different approach and update for the work breakdown structure (WBS) in which the CBS's are organized. From the data collected it is possible to state that significant changes have happened in the CBS's of the Portuguese residential buildings since the 1980s.

Keywords Cost · Value · Refurbishment · Decision-making

P. Mêda (✉)
Construction Institute, Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal
e-mail: pmeda@fe.up.pt

H. Sousa · F. Ferreira
Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal
e-mail: hipolito@fe.up.pt

F. Ferreira
e-mail: fferreira@fe.up.pt

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1 Introduction

Over the past decades Portuguese residential building stock suffered several changes in what regards to the structure, spatial organization, systems and components. The construction technologies, the building performance requirements, the awakening to new concerns such as security and the increasing regulatory requirements for thermal and acoustical comfort, among others, led to significant differences between the buildings constructed during the last decade and the older ones, namely those from the 1980s. The development and application of new construction processes, materials, components and systems, naturally resulted in changes in the cost of each work and on the relevance of the parts. Indeed, given the broad differences between the buildings of the 1980s and the current ones, a more or less significant change on the cost relevance of some construction elements of the buildings of each of the decades is fully expected. The work developed aimed the review and discussion of previous studies developed in Portugal related with this theme. From the analysis, different needs were identified, setting the roadmap for developments. Therefore, is was identified the need of developing a new structure, that would be capable of integrate and maintain secure the previous results and at the same time perform an update following the trends and requirements. The samples that were collected presented some flaws. During the work, a new study was developed following the main assumptions of the older ones and framed with the new requirements. The objective of filling the inexistence of Building Cost Structures that would allow having a complete evolutionary history of the residential buildings from the 1980s until 2010 was achieved. Notwithstanding, some of the collected samples did not have the robustness that was intended. With all the data, conclusions are drawn from the results. Besides presenting the evolution of the economical relevance of building elements during 30 years, for what is considered a representative type of building stock in Portugal, the study performs a literature review updating and proposing a new work breakdown structure that assumes new terminology and most recent concepts, to be used by other authors in further studies.

2 State of the Art

Comprehensive studies regarding the technological evolution of the building stock, by function, as well as other construction types can be very useful as a tool to predict with more accuracy budget estimates on early design stages, as well as other information more related with statistical issues. Notwithstanding, there are few studies focused on this topic. This part introduces and explores each of these studies, lining their contribution for the work developed. From the Portuguese authors that have produced relevant work concerning economic relevance of building construction elements and building cost structures (BCS), the study performed by Bezelga (1983) in the early 1980s, can be pointed as the one that set the main principles for the following. It is, therefore, considered a reference. Until Bezelga have focused this issue through a comprehensive and extensive approach in 1983, just few experienced professionals involved in a great number of projects and playing roles related with management or budgeting of construction works could have a reasonable perception of the relative importance, in terms of costs, of the several elements or parts that compose a building. The recognized relevance of the work developed on this study led other authors to the development of others studies, totally grounded on the previous work. The main objectives of the following studies was to propose evolutions regarding the construction elements work breakdown structure that supports the building cost structure. In fact, during the 2000s the works developed by Pinto (2007) and Mendes (2011) were published. These aimed to fill the gaps they have identified in the study of Bezelga due to its obsolescence in terms of construction technologies and regulatory framework. The next points are addressed to the three mentioned studies. They are briefly described, in way of summarizing the most relevant work developed in Portugal concerning cost structures of residential buildings.

2.1 Residential Buildings—Techno-economic Characterization and Estimation (Bezelga 1983)

2.1.1 Construction Elements Work Breakdown Structure (WBS-CE)

According with Bezelga, the main principles considered for the definition of the work breakdown structure need to attend three key criteria related with the needs of the potential users of the information:

- The breakdown level—level of detail/disaggregation in a way that could allow a friendly use of the results;
- Technical, economical or financial control of construction works—elements organization according with the construction work process;
- Technical and economic analysis of designs—elements organized in accordance with the process of preparing the project, namely the production of the bill of quantities.

From the assumptions resulted a WBS constituted by 23 first line elements. Some of these elements are further decomposed on second line elements.

The mutual compliance of the three mentioned criteria can be difficult to satisfy in some situations. Therefore the achieved structure results from commitments that will be further highlighted.

Table 1 presents the original WBS defined during Bezelga's study. It was this structure that served as base for the development of the more recent WBS's of Pinto (2007) and Mendes (2011). It was also an important source of information for the development of the new proposed WBS that will be presented further.

Table 1 Bezelga's work breakdown structure for residential buildings

	Chapters and construction elements
1	Earth works
2	Foundations
	2.1 Foundation elements
	2.2 Ground slab
	2.3 Walls below the ground floor
3	Superstructure
	3.1 Columns
	3.2 Beams
	3.3 Walls
	3.4 Slabs and other elements
4	Masonry
	4.1 Internal masonry
	4.2 External masonry
5	Roof
	5.1 Roof structure
	5.2 Coverings and other elements
6	External wall openings
	6.1 Trims and sills
	6.2 Frames and doors (including door frames)
	6.3 Glazing
	6.4 Shutters or other protections
7	Internal wall openings
	7.1 Frames
	7.3 Doors
8	Water system
	8.1 Pipes
	8.2 Taps/faucets
9	Sewage system and ventilations
	9.1 Septic tank
	9.2 Sewage and ventilation pipes
	9.3 Other elements
10	Electrical systems
	10.1 Pipes and boxes
	10.2 Cables
	10.3 Other elements
11	Lifts
	11.1 Doors and rails
	11.2 Cabin and machinery
12	Coatings/finishes of stairs and galleries
	12.1 Coatings/finishes of steps, common galleries and pavements
	12.2 Coatings of walls and ceilings
	12.3 Finishes of walls and ceilings

(continued)

Table 1 (continued)

	Chapters and construction elements
13	Coatings (first layer) of walls and ceilings
	13.1 Internal plasters
	13.2 External plasters
14	Internal wall finishes
	14.1 Stylobate on wet zones
	14.2 Remainder interior wall finishes
15	Internal ceilings finishes
16	External finishes (walls and ceilings)
17	Coatings (first layer) of pavements
18	Finishes of pavements of dry zones
19	Finishes of pavements of wet zones
20	Kitchen and washing equipment
21	Sanitary equipment
22	Miscellaneous
	22.1 Other carpentry/woodwork
	22.2 Other locksmith/metalwork
	22.3 Other stonework
	22.4 Wardrobes
	22.5 Garbage evacuation systems
	22.6 Gas systems
	22.7 Other elements
23	Landscaping/external works

As mentioned before, the full satisfaction in the same WBS of the 3 criteria referred was rather difficult. Therefore the structure presented in Table 1 results from an iterative process developed based on reflections. In the next paragraphs, a short resume of the conventions defined by Bezelga on the most critical aspects concerning the allocation of construction elements to the WBS is presented:

Element 2.3 The reinforced concrete (RC) load bearing walls are not considered in this element. The remaining walls from the foundations to the superior part of the ground floor and respective waterproofing systems are herein considered.

Element 4 This element includes the masonry and pre-casted panels with infill or partition functions in a building, except the following masonry located above the roof slab: parapets, small support walls and other masonry with functions related with the roof (Element 5). Machine rooms, chimneys and other partitions on the rooftop are herein considered.

Element 5.2 Pavements of terraces are allocated to this element.

Elements 8, 9 and 10 These elements include the costs of opening and closing the grooves for embedding of pipes, cables and other systems components.

Element 12.1 In this second line element of the WBS, the first layer of the coating and the finish are grouped. There is no distinction.

Elements 14.1 e 19 The garages are considered wet zones so the costs of their coatings must be included in the elements 14.1 and 19. Situations where the walls of wet zones have their surfaces completely covered with coatings that are usually applied only in the stylobate, all the coating may be included on the element 14.1.

Element 22.7 The costs of TV aerials and interior illumination accessories must be included in this element.

Element 23 This element includes all the works that are specifically related with the building but outside its gross area.

Besides the listed situations, the allocation of the several construction elements/works to the elements of the structure presented on Table 1 is clear and can be performed without ambiguities or big difficulties.

2.1.2 Sample of Analyzed Designs

The number of designs analyzed during this study is considered very relevant once it allows a good statistical robustness of the achieved data. The sample was constituted by 150 designs, almost all dated from 1980 to 1983.

Such a large sample could not have the ambition of having just one type of building. Therefore the analysis and presentation of results were made according to an organization in groups and classes of buildings. The first big division, is in groups, and made according with the type of structure:

- Group 1—buildings with a reticulated reinforced concrete frame (114 designs analyzed)
- Group 2—buildings with laminar reinforced concrete frame (25 designs analyzed)

The second division performed sets 11 classes inside the groups referred above. This division is made according with the type of foundations (direct or indirect), number of floors, use of each floor (residential or commercial), single-family or multi-family buildings and the existence or not of elevators/passenger lifts.

It's important to highlight that in this study the majority of the designs produced by public and private entities in Portugal on the 3–5 years that preceded the conclusion of the work, in 1983, were analyzed. Thus, it is possible to evidence the preponderance of reticulated RC frame in the Portuguese residential buildings of the 1980s.

2.1.3 Main Results/Conclusions

As mentioned, the study analyzed a sample of designs that integrates considerately different buildings. These were classified according with groups and classes. Within the scope of the present work it has interest a part of the sample, namely the building classes 1.4, 1.5 and 1.6.

Bezelga (1983) presents the cost structures that have resulted from his study, exclusively in the WBS presented in Table 1. However, that division may be excessively specific when the goal is to present that information in a simple and eventually graphical way. Thus, during the present work it was decided to use a fundamental WBS with just 7 elements, in order to have an overview of the information:

1. Foundations and Structure—includes 1, 2, 3 e 5.1
2. Masonry (without coatings and finishes)—includes 4
3. Openings—includes 6 e 7
4. Coatings and Finishes—includes 5.2, 12, 13, 14, 15, 16, 17, 18 e 19
5. Systems—includes 8, 9, 10, 22.5 e 22.6
6. Transportation Equipment and Furnishings—includes 11, 20, 21 e 22.4
7. Miscellaneous—includes 22.1, 22.2, 22.3, 22.7 e 23.

The next pages present the cost structures for the classes mentioned in Table 2, as well as figures to promote an improved understanding. Table 3 summarizes the cost structures obtained from the sample buildings of classes 1.4, 1.5, and 1.6.

In order to promote an improved understanding and to allow further comparison of the results obtained with those of the new developed study, the following figures are presented. Figure 1 presents the cost structure for the buildings of class 1.4 organized according the fundamental WBS.

In the Fig. 2 is possible to observe the relevance of the "Foundations and Structure" in the global cost of the building. In fact, this part of the building has a cost that represents about 30 % of the total cost. One other parcel that assumes a close relevance when compared with the previous one is the "Coatings/Finishes" that's of about 28 % of the total.

Table 2 Classes defined for multi-family buildings with reticulated RC frame (Bezelga 1983)

Cl. 1.4.	Multi-family buildings with 2 and 3 floors
Cl. 1.5.	Multi-family buildings with number of floors ≥4 and without lift
Cl. 1.6.	Multi-family buildings with number of floors ≥5 and elevator

Table 3 Overview of the building cost structures for the classes 1.4, 1.5 e 1.6

	Cl. 1.4.	Cl. 1.5.	Cl. 1.6.
Foundations and structure	30.1	34.3	33.5
Masonry (without coatings and finishes)	10.5	9	8.5
Openings	10.7	13.3	10.5
Coatings and finishes	28.2	23.4	22.3
Systems	13.1	14.5	13.55
Transportation equipment and furnishings	3.5	3.2	9.25
Miscellaneous	3.9	2.3	2.4
	100.0 %	100.0 %	100.0 %

Fig. 1 Fundamental cost structure for the class 1.4

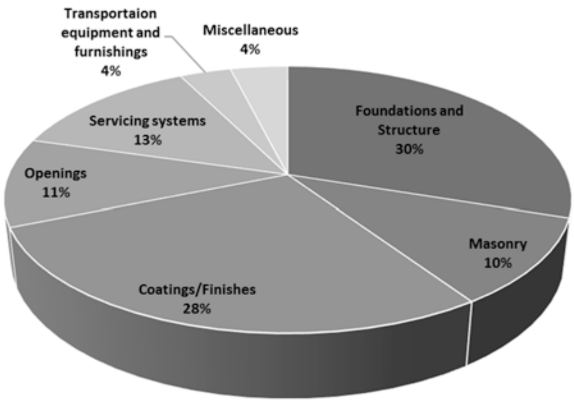
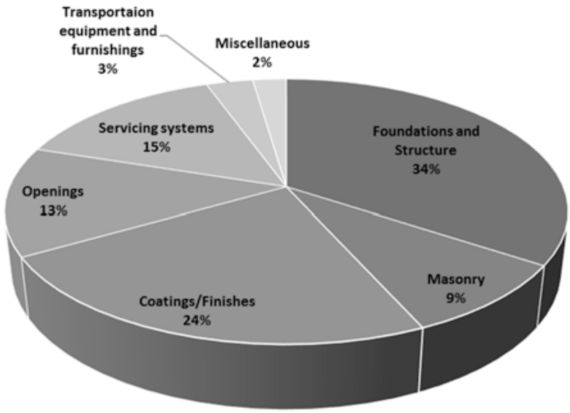


Fig. 2 Evidences the cost structure for the class 1.5 buildings



It is also found important to note the low weight of the "Transportation equipment and Furnishings" in this kind of buildings, around 4 % of the total cost. This is clearly because, as seen before, the buildings of this class do not have elevators. Therefore 4 % represents entirely the relevance of the furnishings. Figure 2 evidences the cost structure for the class 1.5 buildings.

When compared, the cost structures of the class 1.4 and class 1.5 buildings are considerably similar. In fact, the order of relevance of the several elements remains the same. Notwithstanding, it is important to highlight variations of 4 % on two WBS elements. The 1.5 class buildings present a higher relevance of the "Foundations and Structure" (34 %). On opposite way, the "Coatings/Finishes" (24 %) lose weight. The furnishings present a very low variation, maintaining a low relevance around 3–4 % of the global cost.

The class 1.6 buildings introduce a new construction element; the lift. Its introduction brings however no significant changes to the cost structure. In fact, in these buildings, despite the introduction of the elevators that have a significant monetary value, the cost structure remains relatively stable when compared with the

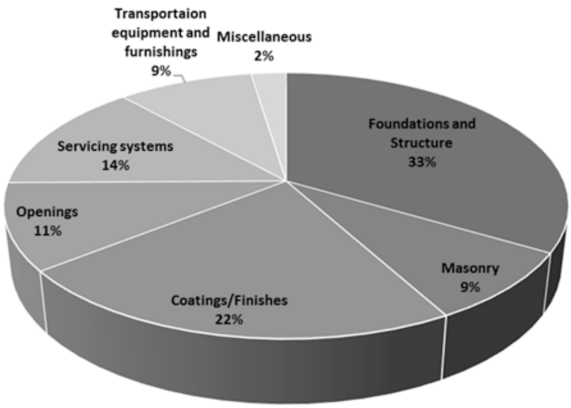


Fig. 3 Fundamental cost structure for the class 1.6

other classes previously presented. In brief, all the fundamental elements tend to suffer a slight decrease of relevance, being compensated by an increase of 5–6 % on the "Transportation equipment and Furnishings" caused by the introduction of the lifts. Figure 3 presents the cost structure for the class 1.6 buildings.

From the stated, it is possible to conclude essentially the following about the cost structures of multi-family residential buildings with reticulated RC frame from the 1980s:

- The "Foundations and Structure" is the most relevant division in terms of cost on the global value of the building;
- The "Coatings/Finishes" comes consistently in second with a close relevance. The major weight difference can be observed on the class 1.6 buildings, being 11 %;
- The "Masonry" is the most stable division of the cost structures maintaining a range of relevance from 9 to 10 % in all classes;
- One of the major variations observed on the cost structures of the 3 considered classes is on the "Transportation equipment and Furnishings". This occurs on the 1.6 class in contrast with classes 1.4 and 1.5. It results from the introduction of lifts on the class 1.6;
- The hierarchy of relevance of the divisions does not suffer any changes according with the different class of the buildings.

2.2 *Construction Observatory of TMAD—Cost Structure of Residential Buildings (Pinto 2007)*

2.2.1 Work Breakdown Structure

Many years after the previous work development, Pinto (2007) performed a new study, clearly based on the older one, in which analyses a sample of building designs from the 2000s. The work included an update of the existent construction elements work breakdown structure generating a new building cost structure. The main objective of these changes was to fit the specificities of more recent buildings.

In what regards the sample, it became clear that the ambition and statistical robustness of the obtained data would be lower. In fact, the number of building designs analysed is quite inferior (only 5 designs, dated from 2003 to 2007). On the work presentation (Pinto 2007) the author states that its study does not have the same ambition as the one previously presented.

Despite the identified limitations, there are some advantages that worth to be highlighted, namely the fact that all the building designs analysed have RC structure with infilling masonry walls and 6 floors. This means that the sample of building designs is homogeneous and representative of a type of residential buildings also studied by Bezelga. This way the BCS of the two studies can be compared.

In brief, this is found to be a good study to be settled as a starting point for a more extensive update of the older one developed in the 1980s. Concerning this aspect, it becomes important to carefully analyse the pertinence of the several changes introduced on the breakdown structure.

The Table 4 presents the WBS for residential buildings developed by Pinto.

From the analysis, some differences can be easily identified. To start, the older structure presents 23 first line elements, this presents less elements, seventeen (17).

In what regards the organization of the foundations and structures, there are significant differences. Pinto (2007) created a new element of the WBS called "Non-structural foundations" that is meant to include buried elements with no structural functions as water tanks (when buried) or retention cavity for rainwater, for example. Generally, the term foundation is inextricable from the structural concept, once it is associated to construction elements that serve as a structural basis for others. The association of construction elements with functions exclusively related with the water supply or the water drainage for example, with the term "foundations" can be rather debatable.

Pinto (2007) intended to introduce simplifications on his WBS. One was by presenting a lower breakdown level, not only in what concerns the RC structure (aggregating all the second line elements of the older WBS, i.e. columns, RC structural walls, slabs), but also on the roof and all building systems. The adoption of a lower breakdown level contributes for a streamlined analysis of the designs for the purpose of the definition of cost structures for buildings. However and by opposition, less levels imply the loss of detail. A more aggregated structure may or may not be problematic depending on the intended use of the information related with costs.

The organization of the several types of coatings and finishes is probably one of the most sensible aspects of the entire approach. In this point, the options assumed by Pinto clearly diverged from the assumptions set by Bezelga. The main division criteria adopted by Pinto was the location (internal or external coatings/finishes). No distinction is made between layers (base coatings and finishes) neither between the finishes of the wet or dry zones. As mentioned previously, this options leads to a decreased detail level of the WBS. The detail levels of each WBS regarding this

Table 4 Pinto's work breakdown structure for residential buildings (Pinto 2007)

Chapters and construction elements	
1	Earthworks
2	Non structural foundations
	2.1 Earth slab
	2.2 Basement partition walls
	2.3 Rainwater retention tank
	2.4 Water deposit
3	Concrete structure
	3.1 Foundations, walls, columns and slabs
4	Masonry
	4.1 Interior masonry
	4.2 Exterior masonry
5	Roof
6	Coatings
	6.1 Interior coatings 6.1.1 Walls 6.1.2 Ceiling 6.1.3 Flooring 6.1.4 Openings 6.1.5 Accesses, atriums and staircases
	6.2 Exterior coatings 6.2.1 Walls 6.2.2 Ceilings of balconies and consoles 6.2.3 Flooring 6.2.4 Openings
7	Paintings
	7.1 Paints and varnishes
8	Insulation
	8.1 Walls, floors and roof
9	Plumbing
10	Drainage and ventilation systems
11	Power system
12	Lifts
13	Gas system
14	Central heating
15	Kitchen equipment
16	Others
	16.1 Carpentry others
	16.2 Metalwork others
	16.3 Fire equipment
	16.4 Electropressure groups
17	Exterior finishes

subject are questionable depending on the assumptions. This issue is found to be essential on the new proposal, as it will be presented further.

One other option taken by Pinto that can be questionable is the definition of the openings as a second line element of the WBS, namely as a sub-element of the coatings/finishes. In fact, traditionally openings and coatings are considered on the same level. They both might be set as sub-elements when the upper level is the Envelope, as an example. One other aspect that can contribute to this is the significant cost relevance of the openings in the global cost of the buildings (11–13 % in the buildings from the 1980s). Therefore, the option taken offers some discussion.

To end, it worth's to remark the importance given to elements for insulations and fire safety equipment.

In resume, it can be referred that the WBS presented in Table 4 is clearly based on the older. Yet, it is evidenced the concern of achieving to a lower breakdown level by performing different organization of the construction elements and by introducing new elements as a result of technological advances.

2.2.2 Sample of Designs Analyzed

Pinto analysed designs of multi-family buildings with reticulated RC frame. All cases have 6 floors (1 of these floors is the basement) and 2 lifts. The number of analysed projects was 5, with execution dates varying from 2003 up to 2007.

2.2.3 Main Results/Conclusions

From the analysis and statistical treatment of the sample, Pinto obtained a cost structure for multi-family residential buildings with reticulated RC structure, 6 floors and lift. In order to promote the comparison of that cost structure with the one set by Bezelga, Pinto's cost structure was also converted to be presented in the fundamental WBS previously presented (7 elements) (Table 5).

Table 5 Overview of the cost structure of Pinto (2007)

Foundations and structure	26.4 %
Masonry (without coatings and finishes)	4.8 %
Openings	11.8 %
Coatings and finishes	36.1 %
Systems	11.3 %
Transportation equipment and furnishings	7.0 %
Miscellaneous	2.5 %
	100 %

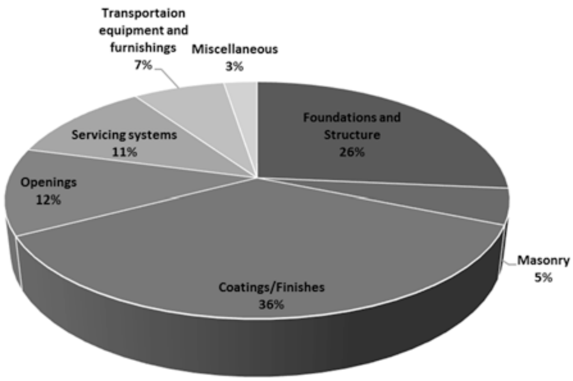


Fig. 4 Fundamental cost structure based on the study of Pinto (2007) for buildings from the 2000s

Thus, the original elements of Pinto's WBS were distributed by the 7 fundamental elements as it follows:

1. Foundations and Structure—includes 1, 2.1, 2.2, 3
2. Masonry (without coatings and finishes)—includes 4
3. Openings—includes 6.1.4 and 6.2.4
4. Coatings and Finishes—includes 5, 6.1.1, 6.1.2, 6.1.3, 6.1.5, 6.2.1, 6.2.2, 6.2.3, 7 and 8
5. Systems—includes 2.3, 2.4, 9, 10, 11, 13 and 14
6. Transportation Equipment and Furnishings—includes 12, 15, 16.3 and 16.4
7. Miscellaneous—includes 16.1, 16.2 and 17.

Figure 4 presents the fundamental cost structure based on Pinto's sample.

Looking at Fig. 4 and comparing it with Fig. 3 the following observations can be drawn:

- The relevance of the "Foundations and Structure" drops from 33 % on the 1980s to 26 % on the 2000s. Given this decrease, this element loses its place as the most relevant changing to second;
- The relevance of the "Coatings/Finishes" suffers a major increment, achieving to 36 % of the global building cost. Through this change it becomes the most relevant element in terms of cost;
- The "Transportation Equipment and Furnishings" loses importance on the global cost of the buildings from the 1980s to the 2000s passing from 9 to 7 %.

In brief, it can be stated that almost all the fundamental elements loses relevance on the cost structure for the "Coatings/Finishes". This element assumes a major relevance on this study, representing more than one third of the total building cost.

2.3 Cost Structure of Residential Buildings (Mendes 2011)

The third and last study analyzed is the most recent, dated from 2011. As the previous, it performs a cost study based on the analysis of residential building designs and proposes an original WBS.

2.3.1 Work Breakdown Structure

Following what was previously mentioned, the WBS developed by Mendes (2011) for residential buildings from the 2000s is based on the one defined by Bezelga. The reasons pointed for the changes are similar to those pointed by Pinto, and are namely to meet the technological update of modern buildings construction.

In fact, this WBS considers, as an example, elements as the fire-safety systems, insulations products and the central vacuum system that did not have specific place on the previous WBS. Notwithstanding, the way the proposed WBS integrates these elements offers some reflection. The following paragraphs introduce some topics for further discussion.

The WBS developed by Mendes (2011) presents singularities relatively to those previously presented, namely the separation of the elements located on garages in a single element (Element 3) that includes coatings/finishes of walls, floors and ceilings, the signaling and all the others construction elements within that space. The idea of separating the construction elements of garages from the construction elements on other locations is understandable and can be justified by the constant presence of this space and with this function in the buildings from the 2000s occupying considerable areas, contrarily to what was frequent on the buildings from the 1980s. Notwithstanding, when confronted with the methodology used for the definition of the costs (based on analysis of the bill of quantities), although the separation could be interesting, it becomes clear that the advantages of this option are clearly surpassed by the disadvantages (often bill of quantities do not separate the solutions by spaces, to get this information detailed measurement sheets need to be analyzed. The process can be rather slow). Additionally, the allocation of the coatings/finishes of the garages to a single element of a WBS together with completely different construction elements existing on the same space is very discussable. The WBS loses the ability of providing feasible information related with the relevance of several construction elements in the global cost of the buildings, which is probably the most demanded cost information.

The existence of an element on the WBS exclusively dedicated to the thermal issues evidences the intention of performing an update. Yet, the way it is presented raises some questions. The separation on the bill of quantities of the insulation elements from the construction elements being insulated was not traditionally performed. Nowadays, it happens frequently given the changes in terms of design practice, but it can raise some difficulties. On the other hand, the definition of a second line element called "Equipment" within a first line element "Thermic" in which according Mendes (2011) the cost of all the equipment with thermal functions must be allocated can cause some problems on the correct definition allocation of parts of the servicing systems. As an example, there is also an element of the WBS exclusively for the HVAC systems (that has thermal functions). The inclusion of photovoltaic panels (that does not have any thermal function) in this second line element dedicated to thermal equipment is also questionable.

In what concerns the already identified critical point of the breakdown structures, the "Coatings/finishes" and excluding the option taken relatively to the garages mentioned above, Mendes performed what can be considered a pertinent reorganization of these elements, making the use of its WBS potentially more intuitive.

Table 6 presents the WBS developed by Mendes. It sets 20 first line elements against 23 and 17 of the previously presented.

2.3.2 Sample of Designs Analyzed

From all the studies presented, this can be considered the one that has the smallest sample of building designs. Mendes has just analyzed 4 designs. All present distinct characteristics concerning the number of floors and the type of structure. It is found important to highlight that one the analyzed designs is addressed to a refurbishment process, in which the original facades were maintained and the interior was rebuilt. Thus, considering the size and the heterogeneity of the cases, the robustness and representativeness of the data collected can be considered short. The structure of costs obtained based on this sample of designs has therefore a questionable relevance and its use as a comparative pole with the older studies might be therefore difficult. Additionally, the dates of the designs is not known.

2.3.3 Main Results/Conclusions

Concerning the conclusions that can be drawn about this study it is important to remark the limitations of the sample. Nevertheless, maintaining the same approach practiced on the two previous studies, the conversion to the fundamental elements and the presentation in a figure was performed. Thus, the elements of the original WBS defined by Mendes (2011) were allocated to the 7 fundamental elements previously referred as following presented:

1. Foundations and Structure—includes 1, 2, 4 and 15.1[1]
2. Masonry (without coatings and finishes)—includes 5 and 15.1 (see Footnote 1)
3. Openings—includes 7 and 8

[1]The second line of the WBS (15.1) created for the thermal insulations is included in the fundamental elements "Foundations and Structure", "Masonry" and "Coatings/Finishes" in equal parts once, as mentioned before, the bill of quantities traditionally did not separate items for the insulation and the support construction elements being insulated.

Table 6 Mendes's work breakdown structure for residential buildings (Mendes 2011)

Chapters and construction elements	
1	Earthworks
2	Foundations and retaining walls
2.1	Foundation elements
2.2	Retaining systems
2.3	Ground slab
3	Basement
4	Superstructure
4.1	Columns
4.2	Beams
4.3	Slabs
4.4	Walls
5	Masonry
5.1	Interior masonry
5.2	Exterior masonry
6	Roof
6.1	Roof structure
6.2	Roof coverings and other singular elements
7	Exterior openings
7.1	Furnishing
7.2	Windows and doors
7.3	Glass
7.4	Protections
8	Interior openings
8.1	Frames
8.2	Furnishing
8.3	Doors
9	Plumbing
10	Sewage system
11	Rainwater system
12	Power system
12.1	Installations
12.2	Apparatus
13	Fire system
13.1	Basements
13.2	Common areas
14	Gas system
15	Thermal conditions
15.1	Insulation
15.2	Installations
15.3	Equipment
16	Lifts

(continued)

Table 6 (continued)

Chapters and construction elements	
17	Coverings
17.1	Coverings of staircases and galleries
17.1.1	Steps, skates and decks
17.1.2	Initial coverings on walls and ceilings
17.1.3	Final coverings on walls and ceilings
17.2	Initial covering on walls and ceilings
17.2.1	Interior initial coverings
17.2.2	Exterior initial coverings
17.3	Initial covering on floors
17.4	Final coverings
17.4.1	Stylobate on interior wet zones
17.4.2	Other interior wall coverings
17.4.3	Exterior
17.4.4	Interior ceilings
17.4.5	Dry zones floor coverings
17.4.6	Wet zones floor coverings
18	Equipment
18.1	Kitchen
18.2	Bathroom
19	Other
19.1	Carpentry details
19.2	Metalwork details
19.3	Stonework details
19.4	HVAC system
19.5	Central vacuum system
20	Exterior finishes

4. Coatings and Finishes—includes 17 and 15.1 (see Footnote 1)
5. Systems—includes 15.2, 15.3
6. Transportation Equipment and Furnishings—includes 16, 18
7. Miscellaneous—includes 19 and 20 (Fig. 5; Table 7).

2.4 *Conclusions of the State of Art*

The analysis of these 3 studies provides an overview of the work developed in Portugal related with economic relevance of building parts or cost structures of residential buildings. This review had the aim of providing an improved perception of the methodology used on all the works, as well as the need for a new WBS fitted for recent buildings.

Fig. 5 Fundamental cost structure based on the study of Mendes (2011)

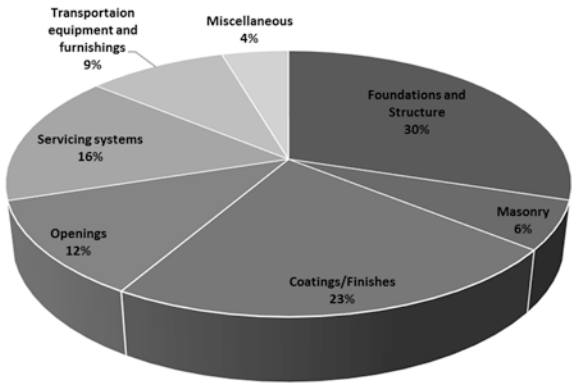


Table 7 Overview of the cost structure of Mendes (2011)

Foundations and structure	29.9 %
Masonry	5.9 %
Openings	11.7 %
Coatings and finishes	22.7 %
Systems	15.9 %
Transportation equipment and furnishings	9.5 %
Miscellaneous	4.5 %
	100 %

As stated, there are several elements of the WBS whose organization and breakdown levels are consensual. However, for some parts it is very difficult to define the best organization in order to satisfy multiple criteria, namely, easiness of use, detail of the information, type of information provided (organized according construction elements, according the construction chronology, etc.). Thus, considering the discussion performed during the presentation of each study, the Table 8 that summarizes the discussion points that must be considered during the development of a new WBS.

3 A New Framework for Building Costs

3.1 *Main Principles*

Though the studies review and questions raised, it was possible to identify points of discussion for the definition of a new WBS. The purposes for this development go further than the update of the previous WBS. The WBS presented was made with the objective of adding the following gains relatively to the existing WBS's:

Table 8 Overview of the most difficult decisions to take when developing a new WBS for buildings

Construction elements in cause	For discussion
Coatings/finishes	Distinguish or not the finishes and other layers of the coatings Distinguish or not finishes of dry and wet zones Coatings of garages in a 1st level element of the WBS
Waterproofing elements	Allocate or not the cost of the waterproofing to the element of the WBS that include the cost of the element being waterproofed
Thermal and acoustic insulations	Allocate or not the cost of the insulation to the element of the WBS that include the cost of the element being insulated
Systems	Breakdown level of the several systems of the buildings in the WBS
Miscellaneous	Costs being allocated to the element of the WBS named "miscellaneous"
Electrical systems	1st level element called "ITED" (communication system) 1st level element called "video systems"
Heat and ventilation systems	1st level element called "HVAC"
Fire safety systems and equipment	Firefighting systems and fire detection systems in a single 1st level element

- Fit the current technological and regulatory reality;
- Fit to a most large spectrum in what respects building types (not only residential, but also services and commercial buildings);
- Multi-purpose development giving the possibility of delivering different information and adapted to the purposes and needs of different professionals;
- Possibility of preserving/use several different breakdown levels depending on the objective of the information to explore;
- Presentation of a fundamental breakdown level with the ability of being used as converter/basis for comparison between different WBS's. Additionally, it aims a streamlined reading of the cost information, designedly through figures.

3.2 Laws, Standards and Academic Sources Considered in the Development of the New WBS

3.2.1 Portaria No. 701-H/2008 (Diário da República 2008)

The most significant contribute of this legal diploma for the development of the new WBS is related with construction terminology. In fact, it is considered a national referential that "updates and completes the concepts and definitions" (Diário da República 2008). This document, that establishes instructions for the elaboration of public works design process, served also as a basis for the integration on the development of the new WBS, of the concerns/work logic of the designers that are potentially one of the professional groups that can take more advantage of the existence of this work.

3.2.2 Portaria No. 19/2004 (Diário da República 2004)

This document establishes the legal framework for the ingress and permanence in the construction activity defining categories and subcategories of permits. The main objective of considering this legal diploma in the development of the new WBS was the incorporation of an organizational logic by construction arts (disciplines) in line with the contractor's needs/vision/organization. The contractors, are identified as other professional group that can benefit from a new WBS. Presently, this diploma was withdrawn and a new document was published, Lei no. 41/2015 (Diário da República 2015). This introduces some changes but that do not conflict with the scope of this work.

3.2.3 Information of Costs—LNEC (Manso 2013)

The cost information developed by LNEC (National Laboratory of Civil Engineering) during the last decades also constitutes an important reference for the development. Besides organizing the information by construction works and their inherent costs it sets a model as the several construction elements that compose a building can be divided and organized. Summarily, this document contributed more with the organizational logic followed than with the content itself.

3.2.4 ISO 12006-2:2015 (International Organization for Standardization 2001)

This international standard establishes the framework for the classification and organization of the information related with the construction sector. It recommends a set of tables for the classification of different construction facets, from the construction process through involved agents, including construction tasks, construction products and materials or construction elements. The analysis of this standard allows the consubstantiation of some decisions necessary to the development of the WBS. Another fundamental aspect of this document is the definitions chapter. This part of the document allowed completing and updating the terminology adopted at the different levels.

3.2.5 ProNIC—Protocol for Construction Information Normalization (Mêda et al. 2014; Sousa et al. 2011, 2012)

ProNIC is, among other aspects, a technical referential for the construction in Portugal that contains an information classification system for construction works. It materializes what is assumed as one of the ISO 12006-2 (International Organization for Standardization 2001) tables. It was developed to be used by all the agents involved on a construction process and has been applied in large projects of construction/refurbishment of public secondary schools. Summarily, ProNIC contributed with its own work breakdown structure for buildings that is used for the production of bills of quantities (i.e. the WBS of ProNIC has a very high breakdown level). The higher breakdown level of the new WBS integrates elements that are on different breakdown levels of ProNIC WBS.

3.3 Proposal

The new proposed WBS has 3 different breakdown levels for the construction elements/construction tasks. The reason for adopting this structure is to allow users to get the information in a way that serves better its objectives. It is possible to have the levels isolated or combined. It is important to highlight that each WBS element of a determined breakdown level is included in an element of the previous breakdown level, meaning that all the elements of the breakdown level n are sub-elements of the level n − 1. With exception to the higher breakdown level (Level 3), the others can be used isolated. The use of the WBS with the 3rd level implies the consideration of the 2nd level as well, once there are some elements of the 3rd level that just make sense as sub-elements of the 2nd level (like the landscaping, for example).

3.3.1 Work Breakdown Structure Levels

Level 1

The first level is constituted by seven elements (Foundations and Structures; Openings; Coatings/Finishes; Systems; Transportation Equipment and Furnishings; Miscellaneous) and reduces to a minimum the tasks/construction elements/parts of a building. Despite a high breakdown level may generally mean a higher detail and more precise information, sometimes it can be very difficult to the major part of the potential users to take advantage of it, because of the visualization difficulty and workability for performing comparisons. The cost structures of the previous referred studies were originally organized according different WBS's. During this study they were reorganized according with the 1st level of the new WBS in order to promote comparisons and a streamlined visualization of tendencies/evolutions.

Level 2

The second breakdown level of the proposed WBS was developed according with the same organizational logic as the previous level but with a higher disaggregation. It constitutes the intermedium breakdown level provided by the new proposed WBS and is principally fitted for statistical purposes or as a tool for construction works management.

Level 3

The third level is a pure more disaggregated version of the previous level. The main uses for which it is fitted are several and related with the substantial needs of detailed information. The management of construction works, the organization of cost information for specialized contractors and manufacturers of construction products and materials, constitute examples of possible uses.

3.3.2 Discussion and Decisions for the WBS Organization

Insulation and Waterproofing Construction Elements

Concerning the waterproofing and the insulation elements there was a doubt identified on Table 8 related with the ideal way of structuring them in the new WBS. The possible options were to separate each of these types of construction elements on 1st level elements or to allocate their cost to the element to be insulated/waterproofed. The second possibility was the followed. The option taken was related with the process used for the allocation of the construction works to the WBS. The bills of quantities may or may not provide separate costs for the insulations and waterproofing. When this does not happen it becomes very difficult the identification of the relevance of these elements, becoming also more difficult the methodology completion. Through this option it becomes easy to set the cost structure on this topic whether there is or not the distinction of the works on the bill of quantities.

Roof

On the new WBS it was taken the option of not considering any element exclusively dedicated to the roof. This because it is found that coverings/waterproofing must be allocated to the WBS element "External coatings/Finishes" and the roof structure must be allocated to the element "Structure".

Coatings/Finishes

The breakdown level practiced for the organization of the coatings/finishes on the new WBS is less extensive. This option follows a trend that was already practiced on two of the analysed studies. Although it could be useful to provide such a level of detail, the present bill of quantities are not organized to give immediate answer to that kind of organization. Many times they lead to interpretations and assumptions that could lead to ambiguity. Therefore, the new structure intends to balance the level of detail of the information related with costs with the capacity of the traditional bill of quantities on providing the information.

3.3.3 New Construction Elements Work Breakdown Structure to Support Building Cost Structures

Table 9 presents the proposal.

4 Evolution of Building Construction Costs

As presented, the developed studies provide data for buildings from the 1980s and 2000s. Given the dimension of the 1980s sample, it can be considered that the others do not have the same level of robustness. The objective of this work was to update the WBS that supports the cost structures as described previously, but also obtain data that would allow explore the evolution of buildings from the 1980s until 2000s. Therefore a sample of Portuguese residential buildings from the 1990s was produced. To improve the robustness of the 2000s sample, another sample was constituted. The analysis of these two samples performs a new study that will be presented in detail. Thus, it became possible to fill the observed gap, gaining a perspective of the evolutions occurred concerning the building elements cost.

4.1 New Study

4.1.1 Cost Structure of Portuguese Residential Buildings from the 1990s

Sample of Designs Analysed

The analysis of buildings designs from the 1990s is more difficult than the analysis of designs from the 2000s once the information is generally available just in paper format. Beyond the effort of analysing the designs, it was also observed the difficulty on finding well organized designs, in some cases more than 20 years after its

Table 9 Proposal of a new WBS for buildings

Level 1	Level 2	Level 3
Foundations and structure	Preparatory works and demolitions	Preparatory works
		Demolitions
	Earthmoving works	Earthmoving works
	Foundations	Direct, indirect and special foundations
		Retaining works
	Structure	Columns
		Beams
		Walls
		Slabs
		Ground floor
		Other elements
Masonry	Masonry	Envelope walls and other external masonry
		Partitions and other internal masonry
Openings	Openings	External openings
		Internal openings
Coatings/finishes	Coatings and finishes	External coatings and finishes
		Internal coatings and finishes
Servicing systems	Water and drainage servicing systems	Water servicing system
		Sewage servicing system
		Rainwater drainage servicing system
		Fire suppression systems
	Electrical servicing systems	Energy supply servicing systems
		Earth termination system
		Communications servicing systems
	Gas servicing system	Gas servicing system
	HVAC servicing system	HVAC servicing system
	Other mechanical servicing systems	Other mechanical servicing systems
Transport equipment and furnishings	Transport servicing systems	Passenger lifts
		Freight lifts
		Escalators and moving walks
	Equipping construction elements	Equipping construction elements
Miscellaneous	Miscellaneous	Other elements—carpentries[a]
		Other elements—metalwork[b]
		Other elements—stonework[c]

(continued)

Table 9 (continued)

Level 1	Level 2	Level 3
		Other plastic elements
		Fire safety signage and movable extinction equip.
		Other elements
	Landscaping	Pavements
		Fences
		Plants and vegetation
		Facilities
		Others

[a]Other elements: Carpentries excepting those from the doors and windows, claddings, floorings and furnishings
[b]Other elements—metalwork: Handrails and guards of balconies, floor access stairs, grids
[c]Other elements—stonework: Capstone

production. The storage conditions founded were very different. Although the ideal objective was to have a high amount of designs, in order to achieve a good statistical robustness of the sample, this study focused the most on the quality (homogeneity and comparability of the sample with the one defined by Bezelga) rather than the quantity of building designs analysed. Three building designs of residential complexes were analysed each one containing at least three similar isolated buildings. General characteristics of the buildings:

- Floors: 4 floors (each building)
- Dwellings: from 24 up to 44
- Construction dates: from 1995 to 1997
- Total Costs: from €630.00000 to €1.900.00000.

Results

The results that are presented constitute the average values of the sample. They are set in accordance with the fundamental WBS to allow a fast understanding of the costs distribution and comparisons between the several cost structures. Figure 6 presents the results for 1990s buildings.

Table 10 presents the cost structure expressed graphically on the Fig. 6. Beside the cost structure itself, some statistical data (standard deviation and variation) are also presented.

From the analysis of the Fig. 6 and Table 10 the following conclusions can be drawn:

- The “Foundations and Structure” are the most relevant construction elements of residential buildings from the 1990s (31 %);

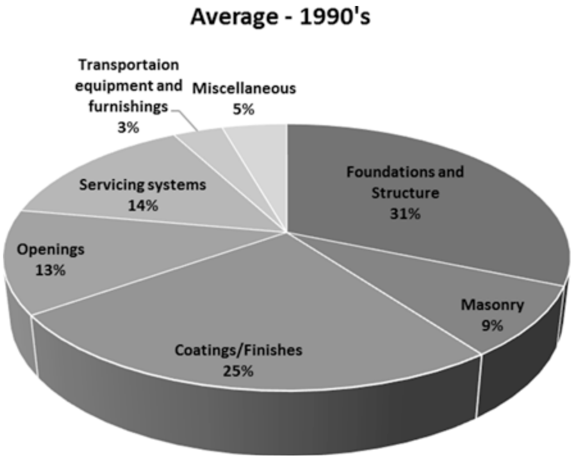


Fig. 6 Fundamental cost structure of residential buildings from the 1990s (average)

Table 10 Cost structure and statistical data for the designs sample of buildings from the 1990s

Construction elements	Average (%)	Std. dev (σ)	Variance
Foundations and structure	31.34	7.23	52.31
Masonry	8.54	1.17	1.36
Coatings and finishes	25.35	3.23	10.45
Openings	12.58	0.59	0.35
Servicing systems	14.38	3.27	10.66
Transportation equipment and furnishings	3.40	0.21	0.04
Miscellaneous	4.41	2.41	5.83

- The “Coatings/Finishes” are the 2nd most important fundamental construction elements (25 %);
- The elements of the cost structure that reveal a greater dispersion are precisely those that have a greater importance in the global cost, namely the “Foundations and structure”, the “Coatings/Finishes” and the “Servicing systems”.
- The elements of the cost structure with lower dispersion are the “Transportation Equipment and Furnishings” and the “Openings” with values of standard deviation of just 0.21 and 0.59 respectively.

4.1.2 Cost Structure of Portuguese Residential Buildings from the 1990s

Contrarily to what was presented regarding the Portuguese residential buildings from the 1990s for which there was no recognized study concerning cost structures, there are already as viewed other studies concerning cost structures of residential buildings from the 2000s. Once the design samples considered in the existing studies could be improved, the opportunity to perform that was introduced in this study in order to have a more robust cost structure for buildings from the 2000s. The sample is detailed on the following paragraphs.

Sample of Designs Analysed

Although it would be useful to have a big sample, the number designs collected was not as extensive as expected. There was the possibility of analysing 5 designs of residential complexes. Notwithstanding, it was observed that all these designs are comparable. They have similar characteristics, also close to the sample of previous studies, and therefore considered homogeneous. The main characteristics of the building sample are following presented:

- Floors: from 5 to 8 floors
- Dwellings: from 74 up to 212
- Construction dates: from 2002 to 2007
- Total Costs: from nearly €6.000.00000 to €14.300.00000.

Besides all the information already referred it's also important to mention that all the buildings have a basement and are served by passenger lifts.

Results

Following the same principles adopted on the previous point, the results are presented in accordance with the new fundamental WBS.

Figure 7 presented above evidences the average cost structure obtained for the Portuguese residential buildings from the 2000s. It is important to remark the importance of the "Foundations and structure" (27 %) as the most relevant element of the WBS, closely followed by the "Coatings/Finishes" (22 %). The "Masonry"

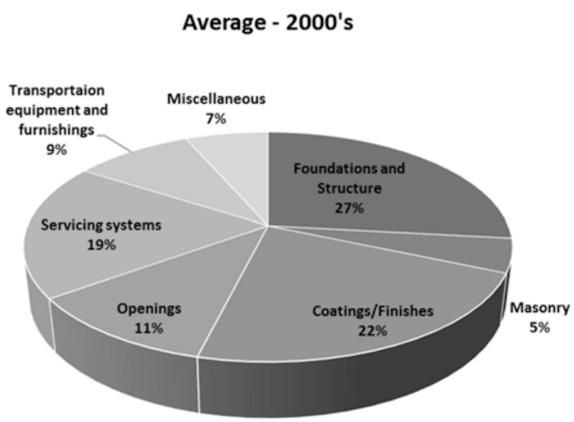


Fig. 7 Fundamental cost structure of residential buildings from the 2000s (Average)

Table 11 Cost structure and statistical data for the designs sample of buildings from the 2000s

Construction elements	Average (%)	Std. dev (σ)	Variance
Foundations and structure	26.75	2.92	8.50
Masonry	4.74	1.21	1.47
Coatings and finishes	22.38	2.97	8.85
Openings	11.13	2.03	4.11
Servicing systems	19.10	1.45	2.11
Transportation equipment and furnishings	9.36	2.07	4.27
Miscellaneous	6.54	2.60	6.77

(5 %) appears as the less important element of the cost structure. Table 11 expresses the cost structure and the respective statistical dispersion of the data.

In what regards the dispersion of the building designs sample in each fundamental element of the WBS, the conclusion previously drawn for the 1990s can be applied equally on this sample. This means that the most relevant elements of the cost structure are those that also present greater dispersion values, namely the “Foundations and structure” and the “Coatings/Finishes”. Comparatively to the sample from the 1990s it can be stated that the dispersion of the present sample is more uniform.

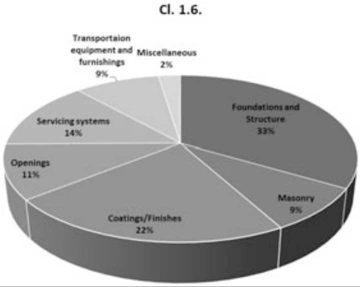
5 Results

5.1 Overview

As previously described, cost structures of residential buildings from the 1980s, the 1990s and the 2000s were explored and presented. However no comparisons were yet made in order to observe the occurred evolutions. This part has the main aim of presenting does results, following an approach similar to the already followed for the presentation of the studies several results.

As exposed, the first study presented is recognized as the more expressive in terms of main principle definitions and size of the sample. The cost structures that characterize the reality of the residential buildings from the 1990s and the 2000s are those graphically expressed on Figs. 6 and 7 respectively, obtained from the analysis of building designs performed within the scope of the present work. As it was also mentioned, the passenger lifts is an aspect that affects the relevance of the several elements. Therefore, this element is considered fundamental for the distinction of the different classes of buildings. Table 12 structures the collected information for each decade. As it can be seen, there are two gaps on the information. These are related with the previous mentioned aspect, the passenger lifts. It is found that one of the gaps is more relevant for the comparisons than the other. In fact, most of the buildings from 2000s forward have passenger lifts, meaning that

Table 12 Main available cost structures of Portuguese residential buildings from the 1980s, the 1990s and the 2000s

<table>
<tr><th></th><th>With passenger lift</th><th>Without passenger lift</th></tr>
<tr><td>1980s</td><td>
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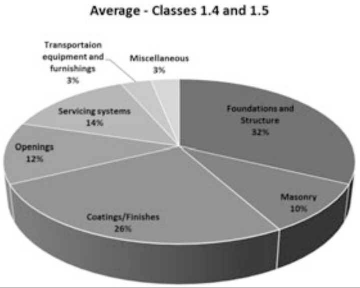
<tr><td></td><td>
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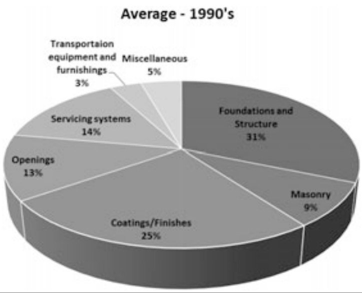
<tr><td>1990s</td><td>–</td><td></td></tr>
<tr><td></td><td>
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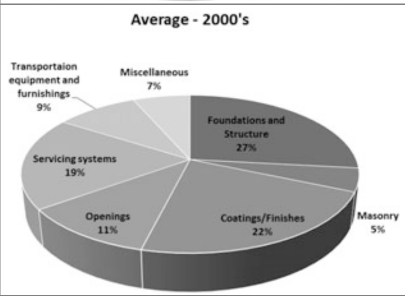
<tr><td>2000s</td><td>
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</table>

this situation could be considered as default for further studies. It constitutes an imperfection to this work the fact of not being possible to find a sample of building designs from the 1990s with passenger lifts. Continuous effort will be perform in order to achieve to this data.

With the information available 3 different findings can be established for further analysis:

- Evolution of the cost structure of the buildings with passenger lifts from the 1980s to the 2000s (without data from the 1990s);
- Evolution of the cost structure of the buildings without passenger lifts from the 1980s to the 1990s;
- Evolution of the cost structure of the Portuguese residential buildings (with or without lifts) from the 1980s to the 2000s, considering the impact of the passenger lifts in the global cost of a building (variation from 6 % in the buildings from the 1980s to 2–3 % in the buildings from the 2000s).

These different analysis can be performed by the observation of the graphics presented on Table 12. Notwithstanding, the last option referred, was chosen to be explored in higher detail, as it provides the most global vision of the processed evolutions.

5.2 1980s to 1990s

Figure 8 presents the cost structures to be used for the comparison of the decades of 1980 and 1990.

Figure 9 evidences the variations of the cost structure from the 1990s relatively to the one from the 1980s.

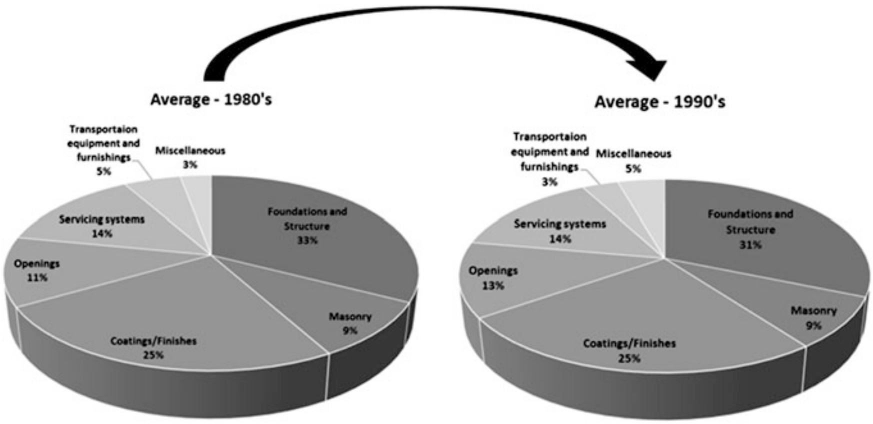

Fig. 8 Average cost structures from the 1980s and the 1990s

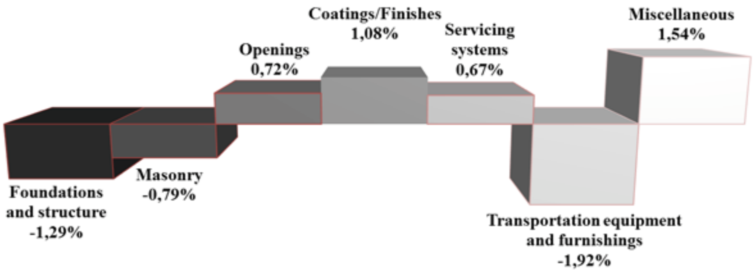

Fig. 9 Evolution of the typical cost structure of the Portuguese residential building from the 1980s to the 1990s

From the analysis of Figs. 8 and 9, the following conclusions can be drawn:

- The variations observed between the two cost structures are very low (<2 % for all the fundamental elements of the WBS). This is found to be a very good indicator on the proximity of the sample with the reality;
- The major difference between the two cost structures occurs on the relevance of the "Transportation equipment and furnishings" that suffers a decrease of almost 2 % from one decade to the following. However, it is important to remember that all the buildings considered from the 1990s do not have passenger lifts (that have an importance of 6 % of the global cost of the buildings from the 1980s and 2–3 % of the buildings from the 2000s);
- One of the elements of the fundamental WBS that suffers the major increase of relevance is the "Coatings/Finishes".

5.3 1990s to 2000s

Figure 10 presents the cost structures to be used for the comparison of the decades of 1990 and 2000.

Figure 11 evidences the variations of the cost structure from the 2000s relatively to the one from the 1990s.

From Figs. 10 and 11, the following conclusions can be drawn:

- The variations are clearly higher than those verified between the cost structures from the 1980s and the 1990s;
- The relevance of the "Foundations and structure" and the "Masonry" decrease, following the tendency of the early period;
- The relevance of the "Servicing systems" increases, following also the trend of the period 1980s–1990s;
- The "Foundations and structures" was the fundamental element of the WBS in which the decrease of relevance was most significant (−4.59 %);

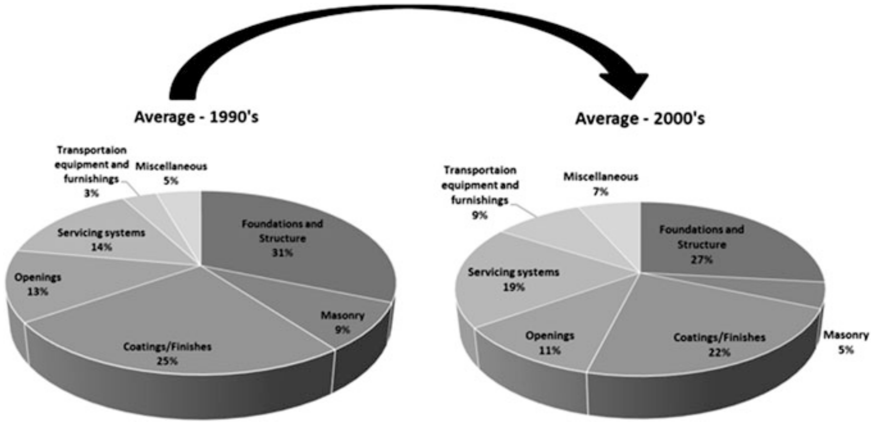

Fig. 10 Average cost structures from the 1990s and the 2000s

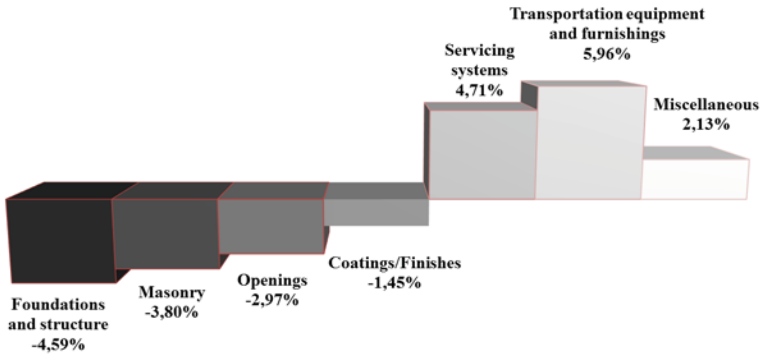

Fig. 11 Evolution of the typical cost structure of the Portuguese residential building from the 1990 to the 2000

- The "Transportation equipment and furnishings" was the fundamental element of the WBS in which the increase of relevance was most significant (+5.96 %). Notwithstanding, it is important to highlight that the sample from 1990s do not have passenger lifts.

5.4 1980s to 2000s

Figure 12 presents the cost structures to be used for the comparison of the decades of 1980 and 2000.

Figure 13 shows the variations of the cost structure from the 2000s relatively to the one from the 1980s.

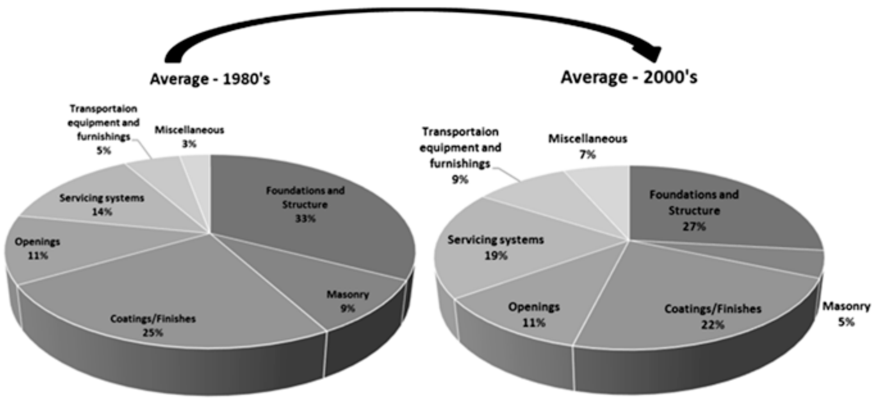

Fig. 12 Average cost structures from the 1980s and the 2000s

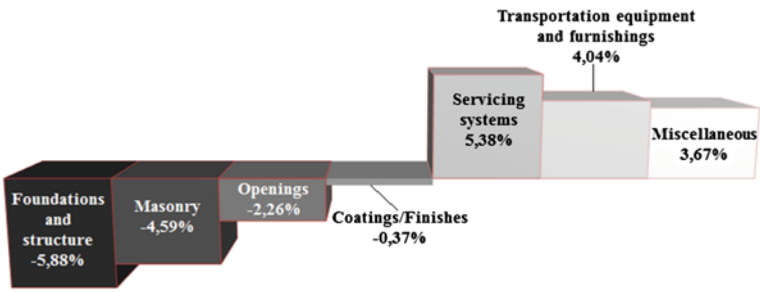

Fig. 13 Evolution of the typical cost structure of the Portuguese residential building from the 1980s to the 2000s

From the analysis of Figs. 12 and 13, the following conclusions can be drawn:

- All the elements of the fundamental WBS that lost relevance from the 1990s to the 2000s also lost relevance from the 1980s to the 2000s. Similarly, all the elements of the fundamental WBS that gained importance from the 1990s to the 2000s also gained importance from the 1980s to the 2000s. This is a very interesting indicator regarding the realism of the data obtained on this study;
- The most substantial difference between the cost structures is observed on the relevance of the “Foundations and Structures”;
- The relevance of the “Servicing Systems” suffered a very significant increase (5.38 %) being thus the fundamental element of the WBS that gained most importance on the cost structure;
- The “Masonry” suffered a significant loss of importance on the cost structure (−4.59 %);

- The "Transportation equipment and furnishings" suffered a significant gain of importance (4.04 %). It is easily explained by the common adoption of passenger lifts in the 2000s, contrarily to what was tradition during the 1980s.

6 Conclusions

- The availability of structured cost information for buildings and for other constructions is relevant for several stakeholders, designedly contractors, owners, real estate professionals and public organizations related with the construction and real estate markets;
- Although there are interesting studies developed in the past that provide important cost information of residential buildings, their organization in different work breakdown structures hampered the comparisons between them. The development and proposal of a new work breakdown structure in this study has the intention of providing a wider organization with the ability to fit other types of buildings and yet preserving the available information given by previous studies;
- The typical cost structure of the Portuguese residential buildings has suffered significant changes over the last decades;
- There is a clear trend for the decrease of the cost relevance of the reinforced concrete structure in the global buildings cost;
- The cost of the servicing systems have consistently gained relevance over the last decades, as a result of the technological developments, the implementation of more systems and the increasing requirements set by the regulations and legal framework.

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Maintenance as a Tool to Avoid Building Pathology—The Oporto Building Example

P. Fernandes Rocha and R. Calejo Rodrigues

Abstract Many problems related to building's service behaviour are due to unintentional options during the design process. The building maintenance issue is a relevant aspect to be considered, because it contributes to the memory preservation as it allows continuing using solutions with heritage values. The importance of preserving our historical legacy in the cities, as a mark of our identity, and the need to preserve and protect those venues from increased aging and its subsequent degradation, leads to a discussion of the preservation and maintenance of the built heritage. When constructive solutions do not correspond to the necessary requirements to ensure their performance, the quality and nature of the intervention may be affected, and so, it is important to understand how to maintain this performance during the service life. In fact, the buildings service behaviour is deeply conditioned by the decisions made during the architectural design process which the issue of maintenance has been absent. The present work focused on research aiming to point out the importance of the inclusion of maintenance since the preliminary stages of the project, giving as an example a case study validated in the context of bourgeois house of Oporto, not only because of the importance of the issue, but also, by the evident characteristics of the generality of buildings belonging to the late 19th century which today represent an excellence legacy heritage. The results allowed us to clarify the importance of the role played by maintenance in preliminary design stages and its later consequences and also, on the other hand, to create a decision support system—DSS to be used by project author(s) still in the architectural design stage. This system represents an auxiliary instrument for the entire process, allowing defining, as a guidance tool, relevant aspects based on maintenance procedures that can contribute to avoid building pathology.

Keywords Building maintenance · Architectural design · Functional performance requirement · Decision support system

P. Fernandes Rocha (✉) · R. Calejo Rodrigues
Faculty of Engineering, University of Porto (FEUP), Porto, Portugal
e-mail: patfrocha@fe.up.pt

R. Calejo Rodrigues
e-mail: calejo@fe.up.pt

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1 Introduction

The need for maintenance operations throughout the building's service life becomes clear by thinking that buildings are designed with an expectative life of several decades. While it is true that "buildings do not last forever", strategies and policies for maintenance must be implemented along the building's service life, in order to ensure the performance of functions for which they were originally designed. When this fails to happen, the buildings are subject to more accelerated processes of degradation.

The state of degradation of many of the existing buildings on the one hand confirms the total absence or deficiency of maintenance and on the other hand, corroborates the importance that certain decisions still might have during the design process, as a way of ensuring the buildings' service behaviour (Fig. 1).

In fact, the solutions identified during the design process, when not corresponding to the necessary requirements to ensure its correct functional performance can decrease the intervention's quality and character and, as such, should reflect on how to maintain its functional performance over the service life.

To support a given assumption, in this case on how the decisions in the project phases can influence the future of the service behaviour, it may help to look at examples of buildings that have already exceeded more than 50 years and in counterpoint analyse the constructive solutions adopted.

When studying the work of Alvar Aalto architect (Fig. 2) it is possible to note the importance that the conceptual options may have on the buildings' service behaviour. His whole work reflects the importance given to the integration of the building in the surrounding landscape, the study of the detail and the care in the study, selection and use of materials and application of new technologies.

The proper confirmation of effectiveness and predisposition of the solutions adopted in response to the user's needs and the fulfilment of the demands and requirements, are effectively able to obtain with the permanence of the work in

Fig. 1 State of degradation that implies the adoption of late corrective measures

Fig. 2 Aalto House. Helsinki, 1936

time. But to materialize and achieve all these assumptions, it must be possible to ensure this demand along the design process.

Taking as example the work of the architect Alvar Aalto, it can be said that it is effectively at the level of the design process that the main decisions are taken, and these may have a determinant role in the definition of the building, with aspects that interfere in their future behaviour and their maintenance.

Whereas all these assumptions, there was the need to identify a decision support model, by stating the fact that there is a poor or absent definition of maintenance operations and procedures during the design process, given that the constructive solutions are not indifferent to the actions of maintenance.

For which the project's author could ensure service behaviour, he needs to bear in mind the existence of a set of functional performance requirements, to which the several elements that constitute the building in question must respond, and simultaneously, planning its service life considering a set of maintenance operations that should be implemented.

The developed model was based on the assumptions that by establishing how the maintenance operations contribute to maintain the performance of different requirements over time, it contributes to understanding how the building can behave in normal occurrence situations, hopefully contributing to increase its service life.

2 Building Maintenance Operations

The ISO 15686-1 (ISO 2011) defines maintenance as "*combination of all technical and associated administrative actions during the service life to retain a building, or its parts, in a state in which it can perform its required functions*". In practice if maintenance is not implemented the degradation process of a building is much more accelerated. An adequate maintenance of the various system elements, can avoid numerous constructive anomalies. It can be considered that there is a cause-effect relationship (Calejo Rodrigues 1989).

The main maintenance operations considered by Calejo Rodrigues (2004) are: Inspection, Pro-action, Cleaning, Correction and Replacement. For each of these operations there is a set of procedures and, for each of these, a set of actions.

The assessment methodology includes two variables: the maintenance operations and the functional performance requirements.

Some considerations should be taken regarding the variables as a way of framing the guidance methodology that was the basis of the development of the research work.

Regarding the **Inspection** operation, it aims to "*collect indicators of the behaviour of a building, maximising performance before manifestation.*" (Calejo Rodrigues 2004), in other words, it aims to identify the phenomena of pre-pathology, although an unplanned strategy will usually also require a prior inspection.

The implementation of this operation depends on some procedures, such as visual inspection, measurements and laboratory tests, and each has a set of necessary actions in function of the state of the building.

Regarding the **Pro-action** operation, this has as the objective to obtain indicators of functioning of the various elements and ensure its correct performance. It can also include actions of inspection and cleaning in the process.

The implementation of this operation depends on some procedures such as the guarantee of performance during service life, functional adjustment and pro use. This operation can be particularly important, given the phenomena of pre-pathology, because it can contribute to prevent the emergence of anomalies, or the development of other more serious, which demand an early replacement of the element or component.

Regarding the **Cleaning** operation, the objective is to obtain an improvement of technical performance similar to initially planned and ensure its cleanliness. This operation is in general, considered to be of less importance, however their role in the prevention of anomalies arising mainly from general dirt and waste collection is relevant.

The implementation of this operation depends on some procedures, such as current cleaning and technical cleaning. The hygienization intends to implement a set of actions to keep the element wholesome and clean. This procedure can be performed by the user.

The technical cleaning intends to implement a set of actions to improve the technical performance of the element. This procedure must be performed by a trained technician. This maintenance operation is not properly analysed and estimated, and the majority of the regulations around maintenance, do not refer Cleaning, or consider it as a procedure of hygienization. It would be important to research in more detail the cleaning actions necessary to implement for the various elements and components of a building.

The **Correction** operation has as its main objective, through a set of required actions, to correct pathological manifestations or malfunctions. The repair of an element and its components is to restore its initial performance, without which their replacement and preventing spreads to the whole component. The implementation of this operation depends on some procedures, such as the correction of deficiencies and the diagnosis (specific intervention/global). The various procedures should only be performed after identifying the causes and sources of anomalies, since only in this way it is possible to solve the problem, avoiding again the appearance of phenomena of pre-pathology.

Regarding the **Replacement** operation, the main objective is to obtain indicators in order to return the initial performance of elements through his replacement. The implementation of this operation depends on some procedures, as in the case of functional rupture and at the end of service life. In regard to the replacement operation, this has as objective to obtain indicators in order to return the initial performance of elements upon its replacement. The implementation of this operation depends on some procedures, as in the case of functional rupture and end of service life.

The functional rupture leads to the partial replacement of the element and components. The end of life leads to total replacement of the element and components, corresponding to its end of cycle. The total or partial replacement means replacing by another similar and with identical characteristics. Otherwise, it is a rehabilitation intervention.

3 Functional Performance Requirement

The ISO 15686-10 (ISO 2010) defines requirement of functional performance as "*type and level of functionality that is required by stakeholders of a facility, building or other constructed asset, or of an assembly, component or product thereof, or of a movable asset, for a specific function*".

This performance unfolds under specific conditions of use. The requirements referred, in other words. The general criteria, can also be subdivided into more specific criteria. The basic requirements of a building, in terms of human needs require that it is convenient and comfortable, secure and durable. This translates into requirements of comfort, safety and durability.

In the specific context of building maintenance and being aware of their importance in anticipation and forecast of possible anomalies, it is also important to establish a set of requirements as support. It is consensual that during the process of architectural design several main issues should arise regarding the importance of foreseen requirements which will have an affect on the functional performance of certain elements of the building.

It is at this stage, that the main issues that will be crucial to ensure the functional performance of a constructive solution effectively arise. Should thus be guaranteed:

- **Safety** requirements: all the safety conditions to support the requested function should be assured at the level of project elaboration, according to the needs of users and that guarantee the implementation of the main procedures and maintenance actions.
- **Comfort** requirements: should be assured at the level of project elaboration all primary conditions, welfare and hygiene of users to support the requested function, according to the needs of users and that guarantee the implementation of the main procedures and maintenance actions.
- **Adequacy** requirements: should be assured at the level of project elaboration, all conditions of flexibility and adjustment of system components of the construction and the respective spaces to support the requested function, according to the needs of users and that guarantee the implementation of the main procedures and maintenance actions.
- **Durability** requirements: should be assured at the level of project elaboration, all conditions of performance of materials and equipment to support the requested function, according to the needs of users and that guarantee the implementation of the main procedures and maintenance actions.
- **Economy** requirements: should be assured at the level of project elaboration all conditions of viability of costs to the users, to support the requested function, according to the needs of users and to guarantee the implementation of the main procedures and maintenance actions.

4 Decision Support Model

Based on the indication of a set of rules that identify the need to include maintenance issues since the preliminary design stages a decision support model was developed as an auxiliary tool in the definition of constructive solutions for the various elements.

The objective of the model is to define a methodology to support the project's author, where it is possible to identify solutions that manifest aptitude to ensure the implementation of the maintenance operations and procedures, whose end result is expressed in an Maintainability Index (MI) obtained by the combination of two indicators: Importance (Iid) and Facility (Fid).

The variables of the model (Table 1) are established assuming that the whole building has to respond to a set of requirements. These requirements must be guaranteed in the design process and also, during its behaviour in service. To be able to maintain the functional performance, it is necessary to implement a set of maintenance operations over the service life that guarantee behaviour.

Table 1 Variables and decision criteria of calculation model

For each **i** (maintenance operation) take **j** functional performance, so that j = 1, …, n, n = 5		For **i** maintenance operation, so that **i** = 1, …, n, n = 8	
$\mathbf{j}_1$ →	Safety	$\mathbf{i}_1$ →	Inspection
$\mathbf{j}_2$ →	Comfort	$\mathbf{i}_2$ →	Pro-Action
$\mathbf{j}_3$ →	Adequacy	$\mathbf{i}_3$ →	Cleaning
$\mathbf{j}_4$ →	Durability	$\mathbf{i}_4$ →	Sustainability
$\mathbf{j}_5$ →	Economy	$\mathbf{i}_5$ →	Correction
		$\mathbf{i}_6$ →	Replacement
		$\mathbf{i}_7$ →	Legal Compliance
		$\mathbf{i}_8$ →	Conditions of use

4.1 Importance Indicator

It is intended, by the Importance Indicator (Iid) to establish a close relationship of dependence, in order that the guarantee of compliance requirements also depends on how the maintenance is implemented. It is assumed that the maintenance is inherent to the use of a building, allows to ensure the initial conditions, and simultaneously to maintaining its performance over time.

The values for this indicator were obtained through the realization of a questionnaire with a set of project's authors, so that the value is pre-defined. There was a request to assign a value to the importance of each operation in order to ensure each requirement of functional performance. The indicators represent:

– **Importance Indicator (Iid)**—the evaluation of the importance of a maintenance process to ensure a certain operational performance requirement and its conditions;

The evaluation of this indicator was established as given in Table 2.

4.2 Facility Indicator

It is intended, by the Facility Indicator (Fid), to assess the effort that each solution requires to the implementation of a certain procedure/action of maintenance, in other words "*of their suitability to be maintained, so that it can fulfil a function required, when maintenance is performed under conditions set*." (IPQ 2007).

Obtaining the values for this indicator was achieved through a set of parameters for assessment, which will be assigned by the project's author before a given

Table 2 Evaluation of the importance indicator

Importance indicator (Iid)		
Weighting (%)	Appraisal	Description
[0;20]	No importance	The maintenance operation has very little influence on ensuring the operational performance requirement
[20;40]	Limited importance	The maintenance operation has little influence on ensuring the operational performance requirement
[40;60]	Moderate importance	The maintenance operation has a moderate influence on ensuring the operational performance requirement
[60;80]	High importance	The maintenance operation has a high influence on ensuring the operational performance requirement
[80;100]	Very high importance	The maintenance operation has a very high influence on ensuring the operational performance requirement

Table 3 Evaluation of the facility indicator

Facility indicator (Fid)		
Weighting (%)	Appraisal	Description
[0;20]	No facility of maintenance	The maintenance procedures/actions require considerable additional effort
[20;40]	Little facility of maintenance	The maintenance procedures/actions require some additional effort
[40;60]	Moderate facility of maintenance	The maintenance procedures/actions require little additional effort
[60;80]	High facility of maintenance	The maintenance procedures/actions require very little additional effort
[80;100]	Very high facility of maintenance	The maintenance procedures/actions require no additional effort

constructive solution of a Maintenance Source Elements—MSE. The indicators represent:

- **Facility Indicator (Fid)**—the evaluation of how easy maintenance procedures/actions are for each process, for any given constructive solution for a Maintenance Source Elements—MSE.

The evaluation of this indicator was established as given in Table 3

The values are assigned by defining a weight comprising a percentage of the value established on the basis of a guideline, which is itself defined by several assessment parameters of the solution, relating the various maintenance processes and procedures/actions to their feasibility as against that same solution.

With the assignment of this indicator, it can be said that the costs and the difficulty to maintain the building tend to increase in accordance with a degree of increased effort to perform the various procedures/actions. In fact, the building will

Table 4 Evaluation of the maintainability index

Maintainability index (MI)		
Weighting (%)	Appraisal	Description
0	Insufficient	No readiness to perform maintenance operations
1	Very poor	Very little readiness to perform maintenance operations
2	Poor	Little readiness to perform maintenance operations
3	Sufficient	Reasonable readiness to perform maintenance operations
4	Good	Good readiness to perform maintenance operations
5	Very good	Very good readiness to perform maintenance operations

have greater difficulties in fulfilling its life cycle, presenting a degree of more accelerated degradation, the greater the difficulty in performing the maintenance procedures/actions or, within the limit, by the lack of them.

4.3 *Maintainability Index*

This index, to be assigned for each constructive solution and for each Maintenance Source Element—MSE, determines the readiness of a solution to perform maintenance operations. It is, therefore, the combined weighting of the two indicators.

It is obtained by the use of a mathematical model supported by a spreadsheet. This allows a double reading, in other words, to obtain information about the importance of each maintenance operation to ensure each functional performance requirement and, on the other, allows determining the "facility" of implementation of a particular maintenance operation.

The evaluation of this index was established as given in Table 4.

Shows an example of the spreadsheet (Table 5):

In this sequence, for each variable **i** is assigned a value that corresponds to the Intermediate Note, in accordance with Table 6:

Subsequently, the project's author enters the value corresponding to the Facility Indicator (Fid), (Table 3) according to the solution under analysis and whose value belongs to the range [0;100], in other words, corresponds to a percentage.

At the end, you get then five values (corresponding to the number of functional performance) to multiply by this assessment, which will provide us with a final grade for each functional performance, as can be seen in Table 7 defined by the expression (3):

It is also applied a conversion to NFj distinct for each Functional Performance, because the Importance Indicators greatly minimize the values corresponding to the Final Notes, these being allocated after a detailed study of the behaviour of each particular Functional Performance having been conducted.

Table 5 Example of the spreadsheet the maintenance operation—inspection; requirement—safety in use and the respective requirements

Maintenance operations	Functional performance—safety		
	General criteria	Specific criteria	Importance indicator
Inspection	Safety in use	Manoeuvres and circulations	Value (pre-defined)
		Mechanisms of protection against the risk of falling	Value (pre-defined)
		Limit state for the use	Value (pre-defined)
Intermediate note (1)	Σ Importance indicators/Nº specific criteria		Value (pre-defined)
	Structure and stability/against fire and intrusion		Value (pre-defined)
Total intermediate note (2)	Σ Intermediate notes/Nº general criteria		Value (pre-defined)
Facility indicator (Fid)	*Assigned by the project's author in accordance with the guidelines*		
Final note (3)			Value
Conversion (4) (5)			[0;5]
Σ Conversions/Nº of functional performances = (6)			[0;5]

Table 6 Mathematical model for the expressions (1) and (2)

For each i is assigned a value (intermediate note):
$NIk = \Sigma\, Idi/n$ (1)
Such as: **NIk** → Intermediate note for each general criteria, [0;100] **Idi** → Importance indicator assigned for each specific criteria, [0;100] (%) **n** → Number of specific criteria
In the end, the weight corresponds to the Total Intermediate Note for each Functional Performance:
$NIT_j = {}_{\Sigma}NI_{k/}n$ (2)
Such as: $\mathbf{NIT_j}$ → Total intermediate note or weight for each functional performance requirement, [0;100] $\mathbf{NI_k}$ → Intermediate note for each general criteria, [0;100] **n** → Number of general criteria

Table 7 Mathematical model for the final note for each functional performance (3)

$NFj = (NITj * Fid)/2000$ (3)
Such as: $\mathbf{NF_j}$ → Final note for each functional performance, [0;5] $\mathbf{NIT_j}$ → Total intermediate note for each functional performance, [0;100] **Fid** → Facility indicator assigned for each maintenance operation, [0;100]

In this sense, it applies the j1, j2 and j5 a Higher Non-Linear Conversion, defined in accordance with the expression (4):

$$\mathbf{Fcs}\,(0.0503 \times \mathrm{NF}_j^4 + 0.5721 \times \mathrm{NF}_j^3 - 2.2527 \times \mathrm{NF}_j^2 + 4.0975 \times \mathrm{NF}_j + 0.7467) \tag{4}$$

Such as:

Fcs Function of Higher Non-linear Conversion, [0;5];
NFj Final Note for each Functional Performance, [0;5]

To j3 and j4 was applied a Polynomial Conversion, defined in accordance with the expression (5):

$$\mathbf{Fcl}\left(-0.006 \times \mathrm{NF}_j^6 + \mathrm{NF}_j^5 - 0.5957 \times \mathrm{NF}_j^4 + 1.8489 \times \mathrm{NF}_j^3 - 3.1169 \times \mathrm{NF}_j^2 + 3.6726 \times \mathrm{NF}_j + 0.7467\right) \tag{5}$$

Such as:

Fcl Polynomial Conversion Function, [0;5];
NFj Final Note for each Functional Performance, [0;5]

Finally, the Final Note average, or Maintainability Index, is also determined for each **i**, as defined by the expression (6):

$$\mathbf{MNF} = \Sigma\,\mathrm{Fc}/\mathrm{n} \tag{6}$$

Such as:

MNF Final Note Average for each Maintenance Operation [0;5];
Fc Conversion Function [0;5];
n Number of Functional Performance

Table 8 summarizes the main aspects of the developed model:

The final values are then translated into graphs of easy apprehension that summarize the information of the results obtained in the map of calculation. Two charts are submitted, namely the Polygon chart and the Density chart. The Polygonal chart allows you to establish a relationship among the variables: demands for functional performance and maintenance operations. The spirals reflect the scale of assessment of [0;5] corresponding to the evaluation of requirements, being that, in each radius, the note measured through the final conversion functions (Fc) is placed. It is from these two synthesis charts of the results of the final values of the decision support model, which a set of recommendations for maintenance are established, which must then integrate the Maintenance Plan.

Table 8 Decision support model—maintainability index

Scope	Residential buildings
Aim	To define a support tool for the designer as an aid in the design process to choose a solution encompassing the relevant implications for maintenance
Breakdown	Functional performance: **5** requirements and **41** topics
	Maintenance operations: **8** operations
Evaluation method	Audit with interview and questionnaire; applicable regulation inquiry and available technical data; definition of importance and facility indicators
Evaluation criteria	Importance indicator [0;100]
	Facility indicator [0;100]
Weightings	Importance indicator—evaluating the importance of each maintenance operation and procedure to ensure operational performance (requirements and conditions)
	Facility indicator—evaluating how easy maintenance procedures and actions are for each process and for each constructive solution
Calculation methods	Total intermediate grades with polynomial, higher non-linear conversion and final weighted average
Final result	Maintainability index [0;5] Polygon and density chart; maintainability sheet (document with data for the initial maintenance plan)

These recommendations aim to establish an alert to possible future limitations of the solution during its service life to guarantee the maintenance and, as such, with consequences for the behaviour in service of the various elements of the building in question. It is also intended to realize some considerations to be present in the maintenance and use of the building in service.

5 Case Study

It was considered by the relevance of the theme, that the scope would be the buildings with patrimonial value of Porto, by the evident characteristics of the generality of buildings owned by the end of the nineteenth century.

In the context of rehabilitation should not only be concerned to maintain only the buildings, their techniques and their systems, the mode of use, because the need to occupy and keep the old centres alone cannot be a justification to ignore the evolution of building technology and its materials, and its respective contribution in improving the performance of the building.

The building of the case study is located in the historic centre of Porto, whose intervention was performed in 2003/2004. The building was in a state of considerable generalized degradation. The serious state of degradation presupposes a lack of maintenance measures, associated with the inappropriate use.

Fig. 3 Current state of the building in 2013 (main and rear facade, respectively)

The architectural intervention by the project's author was based on an almost full rehabilitation of the existing elements (Fig. 3) Some of them, given the highly bad condition, did not allow its recovery, so they were replaced by identical ones. The new elements of constructive system shall be considered in the exterior environment, openings and roofing, which were replaced by identical components that exists before the rehabilitation.

In the beginning of 2013 a visit was carried out to the building accompanied by the project's author and the responsible for the promotion and use of the building. The visit's main objectives were to analyse the options according to the project's author and perceive how these options have influence in the space appropriation and which needs and difficulties were encountered in the implementation of procedures/maintenance actions.

Approximately 10 years after the intervention, the building has a good state of maintenance, emphasizing some aspects referenced by the responsible on the feedback of users:

- Some problems related to noise;
- Some problems of humidity;
- Need for heating the housing (even in the period of summer);
- Some problems of condensation inside the toilet room on floor 2;
- Some problems of fungi in the roof of the dwelling on floor 2.

Table 9 Map values calculation corresponding to the facility indicator and to maintainability index

Maintenance operations	Facility indicator	Maintainability index
Inspection	30	3
Pro-action	50	3
Cleaning	50	3
Sustainability	50	3
Correction	50	3
Replacement	50	3
Legal compliance	10	2
Conditions of use	40	3

5.1 The Inclusion of the Component of Maintenance

With the visit and analysis to the building *on site* it was possible to conclude that the inclusion of the component of maintenance in the preliminary project stages would have allowed to correct and alert for some constructive options.

Table 9 presented a summary of the model application values for the Element Source of Maintenance—exterior walls—the rear façade:

According to the results presented in Table 9 it was possible to make the following considerations:

In the case of the Maintenance Source Element- exterior wall—the rear facade, the adopted solution—galvanised sheet steel—presents weaknesses in several aspects, and to highlight the parameters of accessibility and safety, ease of fast implementation of the maintenance operations, and in particular, accessibility to the facade in case of fire.

For example in the case of inspection measures to the rear façade, some limitations were detected, since it involves the use of support equipment as well as it presents limitations in the use of floor 0 and during inspection, by the reduced and cramped dimensions of the "backyard" and by the impossibility of accessing it, from the shop (see Fig. 4).

The final representation of results obtained was translate in graphs of Density and Polygonal, respectively (Fig. 5).

The values obtained with the Maintainability Index allow to conclude that the constructive solution of the Maintenance Source Element—exterior wall- of the rear façade, presents limitations, and in general, a reasonable predisposition to the performance of maintenance operations.

Table 10 presents summary values of application of the model for the Element Source of Maintenance—openings—main façade:

According to the results presented in Table 10 was possible to make the following considerations:

Fig. 4 Rear façade: coating made from galvanised sheet steel painted

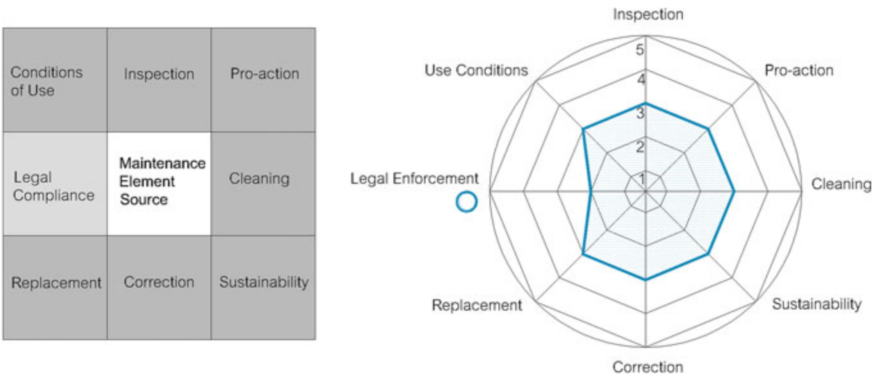

Fig. 5 Graphical representation of results: density and polygonal chart

Table 10 Map values calculation corresponding to the Facility Indicator and the Maintainability Index

Maintenance operations	Facility indicator	Maintainability index
Inspection	30	3
Pro-action	70	4
Cleaning	50	3
Sustainability	70	4
Correction	70	3
Replacement	50	3
Legal compliance	50	3
Conditions of use	100	4

Fig. 6 Introduction of sealants in the window of the main façade

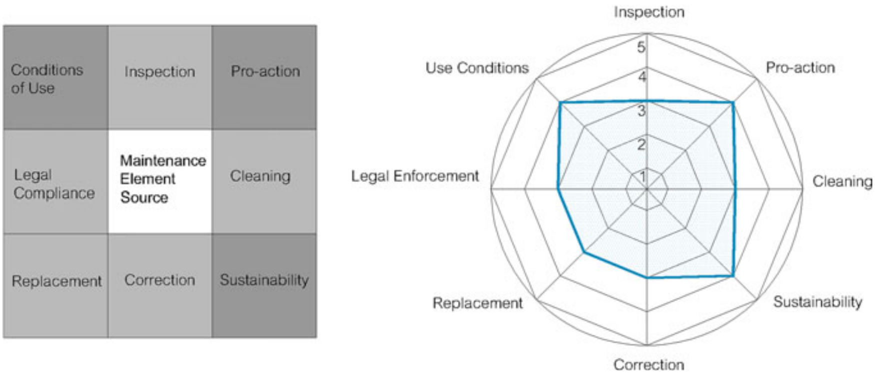

Fig. 7 Graphical representation of results: density and polygonal chart

In the case of Maintenance Source Element—openings—of the main façade, it was later verified, already in the service phase, the need to improve the performance of the openings of the main facade, which meant as a measure to improve the interior acoustic behaviour. The adopted solution was the introduction of seals (that minimized the problem).

This situation justifies that there should have been a better weighting between the replacement of existing frames by another (wood) with author's drawing and between its replacement by another (wood) but duly approved and certified in the market. Even if indirectly (the issue of noise), has implications at the level of the implementation of procedures for maintenance (Fig. 6).

The final representation of results obtained was translate in graphs of Density and Polygonal, respectively (Fig. 7):

Another aspect that could have been considered relates to the type of openings in the toilet compartments.

It should have been foreseen that the interior compartments could have an excessive presence of humidity, by ensuring a regular ventilation of the same. It

Fig. 8 Superficial Condensation in the roof of the toilet room on floor 2

was verified the existence of superficial condensation in the roof of the toilet room on floor 2. Once on floor 1, this situation is not found, it is concluded that this fact is due to inadequate ventilation of this compartment.

The solution at the level of the architecture should have been reconsidered, in other words, instead of the external openings being with open frames, it should have been with turn frame. The latter type of framing allows for a more adequate ventilation and in the case of toilets, given the likelihood of occurrence of surface condensation it would probably resolved or limited the existing problem (see Fig. 8).

The latter option would have facilitated the implementation of some maintenance procedures of Inspection, Cleaning and Pro-action.

With the practical case, it was possible to demonstrate that there is an in-depth knowledge about the importance of ensuring that there is a set of functional performance requirements, and understanding that maintenance can safeguard and minimize the advent of some pathologies, it may contribute to the buildings effective compliance for which they were designed and simultaneously to ensure their service performance.

6 Conclusions

The application of the evaluation methodology to this case study, led to the conclusion of the importance that the maintenance issues show in general, how they can affect the performance and predisposition of the solutions adopted and also, contribute to ensure the behaviour in service of the building during its lifetime, in other words, to warn about and prevent some pathological manifestations that are likely to arise on adopted constructive solutions in the future.

The application of the evaluation methodology to the present case study proved the importance of maintenance in general, as well as its capacity to influence the performance and predisposition of the constructive solutions. It also proved maintenance is useful for guaranteeing the building's service behaviour throughout its service life, i.e. for warning and preventing pathologies that may arise on constructive solutions in the future.

The presented examples corroborate the importance of how issues related to maintenance can have an active role on the prevention and limitation of future incapacities on building performance, among other aspects such as increased costs derived from the emergence of certain pathologies.

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An Interoperable ICT Tool for Asset and Maintenance Management

Bruno Daniotti and Sonia Lupica Spagnolo

Abstract Managing information related with actual maintenance works and inspection activity (condition assessment) allows handling Building Information Systems and this is fundamental in order to fit the reliability and service life evaluations for maintenance planning. For this reason, an ongoing research activity at Politecnico di Milano is developing some methods and tools for Service Life Planning and Management, which can be easily integrated by maintenance data to be used during planning, design, facility and maintenance activities. The aim is to develop an interoperable Life Cycle Management System (LCMS) platform where this kind of data are available and where different stakeholders can store and share information about building and constructed assets. This LCMS platform can be then used on actual maintenance works management and this has benefits as for economic (Life Cycle Costs) and environmental achievements (Life Cycle Assessment).

Keywords Maintenance · Facility management · Database · ICT · Interoperability

1 Introduction

Asset and maintenance management needs to store and use much information about the behavior over time of different building materials, products and components. Service life planning and data capitalization from facility management are only the first steps for an efficient asset management because it is necessary to develop specific ICT tools for life cycle data use and sharing. In fact, the use of ICT tools

B. Daniotti (✉) · S.L. Spagnolo
Politecnico Di Milano, Piazza Leonardo Da Vinci 32, Milan, Italy
e-mail: bruno.daniotti@polimi.it

S.L. Spagnolo
e-mail: sonia.lupica@polimi.it

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can allow a proper data integration, which can reduce inefficiencies during the exchange among different stakeholders.

This operation has to be compliant to the international standard for service life planning of building and constructed asset procedures ISO 15686, in particular in conformity with the fifth part on Life-cycle Costing (ISO 15686-5:2008), which allows a cost analysis of the entire building life cycle (maintenance included).

At present, existing methods for SL prediction are usually not applied because too complex or too unreliable whereas existing databases are full of blanks and most of the times data source is not clear. The lack of effectively usable and reliable methods, together with the necessity of creating an open data collecting and sharing tool, bring to the impossibility of obtaining trustworthy LCC and LCA evaluations.

Moreover, the recent Italian standard UNI 11337:2009 introduced a new and standardized approach for codifying each construction object, from the simple product to the entire work (independently from its complexity). Thanks to the use of ID code, it is possible to store correctly the set of data referring to that object, using also the potentialities of Building Information Modelling.

Consequently, it is fundamental not only to improve existing methods for SL planning but also to create innovative tools for data sharing, where data are linked to a unique code and, using IFC 2 × 4 standards (Building Smart International 2013), represented as BIM objects.

With this aim, in the last few years Politecnico di Milano has been working on the development of an open and interoperable database for asset and maintenance management, designed to store objects with different level of complexity (from simple products to entire construction works) which can be reciprocally linked and completed with an articulated data set. This research project was born from the expertise in developing the international Reference Service Life database in collaboration with CSTB (Hans et al. 2008; Daniotti et al. 2008a, 2010) and, after a three years research project called INNOVance, from the Italian database for construction (Pavan et al. 2014a, b).

Hereafter a description of a new tool for a wider data sharing and collection is presented: this database is also capable to allow Service Life prediction thanks to an enhanced Factor method application (Daniotti et al. 2008b) and this is particularly useful for an effective maintenance planning.

2 The Development of a Database for Asset and Maintenance Management

The creation of an international database for asset and maintenance management in the construction field needs firstly to be applicable to every object, system and process belonging to the entire sector. That is why, after fathoming existing databases (national and international ones) which collect environmental impact factors, Service Life data and Life Cycle costs estimation, it was necessary to find a proper classification and coding system that could allow the unambiguous individualization of each product, layer, component, activity, work and environment. It was, in fact, important to find every significant parameter to be stored at different level of object complexity (also according to reference standards) and to define dataset structure and properties, considering that the database has to be comply with UNI 11337:2009 in order to be immediately operative—at least—at Italian level.

According to this, it was then essential to choose the most suitable ICT tools, evaluating if it was better to structure a relational database or not, completed by different modulus (SW/web services) to design or manage works and developed to fulfil needs of stakeholders such as Designers, Maintenance Planners, Real Estate and Facility Managers.

Such tools focus on one side on Service Life and maintenance issues, developing the knowledge on Service Life Prediction Methods to plan maintenance and inspection of works. On the other side, they allow economic planning considering Life Cycle Costs and sustainability evaluation for Life Cycle Assessment (LCA) (Daniotti and Lupica Spagnolo 2007). The database, in fact, contains environmental parameters, both those indicated in EN 15804:2012 and those used by sustainability certification such as LEED, BREEAM, ITACA, Casaclima Nature, HQE and Minergie-ECO. Thanks to this data intersection within the same sharing tool, the aim is to provide efficiently the possibility to evaluate LCA and to calculate reliable LCC, according to the specific design maintenance strategy.

2.1 The Proposed Methods for Service Life Planning and Management

The first two parts of ISO 15686-1:2011 and ISO 15686-2:2012 give all the necessary indications in order to face Service life planning and to solve it through an integrated methodological and experimental approach. According to ISO 15686 "Buildings and constructed assets. Service life planning", which provides at international level the general framework about service life's appraisal and management, UNI 11156-3:2006 defines precisely the duration or service life of a component and describes a procedure for its evaluation, considering a minimal maintenance level (the ordinary maintenance operations).

The appraisal of Service Life finds in the "Reference Service Life" value an in-put datum: this duration is obtained experimentally through ageing tests under the action of stressing agents. The term "reference" is used to indicate the boundary conditions that are assumed.

In order to give scientific strength to collected data, it is therefore necessary to finalize the standard approach to gather SL data from laboratory evaluations. The developed research project, in fact, also evaluated the general applicability and efficacy of a pioneering procedure to define accelerated ageing cycles for RSL evaluation. In few words, this innovative method is based on a statistical treatment of climatic data and on the individualization of the frequency of critical weather conditions for the tested building component or material. The frequency allows defining the most proper accelerated ageing cycle to be set in climatic chambers for lab durability tests (Daniotti et al. 2008c). To do that, it was therefore important to develop new lab tests which could validate the applicability of the proposed accelerated ageing cycle to different climatic conditions, even extreme ones (Lupica Spagnolo 2009).

These laboratory-based methods include short-term accelerated testing procedures, property measuring and long-term experimental set-ups. As a result, test procedures and data can be correlated with in-service conditions of components and materials, providing a guiding way to use the platform for Service Life prediction and management, which can be taken as reference for the update of ISO 15686-6:2004.

The outcomes of reference service life appraisals, according to the proposed procedure, can then be elaborated in order to estimate Service Life in design condition, using one of the methodologies described in ISO 15686-2:2012, which mainly differentiates for complexity (and therefore for the quantity of information and resources necessary for their application).

In analyzing the most suitable methodology to adopt, it is necessary to under-line that the official appearance on ISO 15686 series of Factor method created some unrest. In reality, over recent years a debate at international level opened on the possibility of an effective use of methods based on factors in Service Life evaluation: such methods, in fact, had already been adopted in building field in Germany and in Japan. In particular, in the short version of the Principal Guides published in English, a method to pass from the Standard Service Life—equivalent to the RSL defined in the ISO—to the ESL through factors very similar to those introduced in Europe was developed.

As an example, in a study about service life planning of a multifamily building built in Gavle, Sweden, in 1999, the ISO 15686-1 procedure was applied. Service Life planning was integrated in the building's design and it was followed from the design phase to the construction one. Only few tests were undertaken to simulate all the different effects on building component in real conditions. The accuracy of the estimated service life suffers from this fact. If the aim is to find a precise value, it is obvious that this is not fulfilled, while Factor method can be a tool aimed to better manage service life planning. However, this study shows that such method does not improve it very much. This opinion is justified by the following uncertainties:

- about RSL and factors values: the factorial formula presents the reference value (RSL) and corrective factors from A to G, so if the reference value cannot be carefully determined, it's not appropriated to correct such value with a series of uncertain factors;
- about the effect of the combination of the factors: the concatenation of the various effects turns out to be of difficult appraisal and needs a study extremely deepened of all the possible degradation phenomena of those technologies taken into consideration.

At international level, the term "Lifetime Engineering" is intended as the harmonized group of the procedures thought in order to solve the asynchrony between designed performances and real ones, over time, in a building product. "Lifetime Engineering" includes:

- lifetime investment planning and decision-making;
- integrated lifetime design;
- integrated lifetime construction;
- integrated lifetime management;
- modernization, reuse, recycling and disposal;
- integrated lifetime environmental impact assessment and minimization.

In particular the "Integrated Lifetime management" foresees, besides maintenance planning, the continuous appraisal of performances' levels (condition assessment), the predictive performances modeling and the management of maintenance alternatives based on the analysis of technical elements' reliability and durability (decision making reliability and durability based).

From these considerations it is clear therefore that if we want to continue to speak about Service Life Prediction finalized to the optimization of maintenance interventions and to the cost reduction of buildings' life-cycle (LCC), it is necessary to implement the today available estimating methods and tools because their application is operatively too difficult and, economically, still not favorable.

This research has the aim to contribute operatively but also methodologically for an effective application of such existing methods, through:

- the creation of a database which collects all currently available Reference Service Life;
- the definition of evaluation grids in order to drive the designer in the application of Factor method, limiting the subjectivity of the method itself (over-coming, therefore, the critics that such methodology moves, but maintaining its simplicity of use);
- the experimental activity in laboratory for the determination of Reference Service Life, input data for estimation methods;
- the experimentation of the actual applicability of Factor method for Service Life assessment and the method for reliability's appraisal through documents as the performance specifications and the maintenance plan, with also a critical analysis of real designers' difficulties (Fig. 1).

Through these implementations, therefore, it is possible to predict Service Life and exploit such information for a better design and an optimized maintenance planning. Each of these activities is closely connected to the others, using as in-put data the output data from the previous ring of the chain and supplying itself the input for the successive one. For this reason, it is indispensable to move on each of these fronts, highlighting troubles and proposing further methodologies to resolve them.

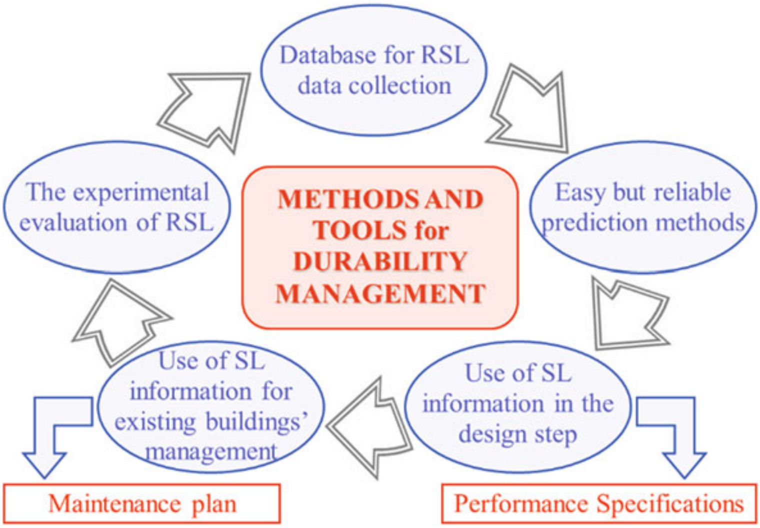

Fig. 1 "Chain" for the management of durability (Lupica Spagnolo 2009)

The development of each single ring of the chain for Service Life prediction wants therefore to make usable the methodology proposed from ISO 15686 for a real durability assessment.

Manufacturers of building and construction products are usually in possession of considerable knowledge concerning Service Life and durability of their products. However, such information is seldom publicly shared, typically in product declarations, other documents, company websites and/or databases. The use of this International Standard is expected to motivate manufacturers to compile their knowledge and provide Service Life data following what guidelines and requirements state (ISO 15686-8:2007). That is why it is necessary to create a hub for Service Life management systems, where needed information is properly stored and shared.

2.2 *The Proposed Tools for Service Life Planning and Maintenance Management*

Tools for service life prediction gather input data from a series of different in-formation sources, as foreseen in ISO 15686. Specific tools manage information related to current maintenance and inspection activities, so to obtain a feedback on management systems for building information, useful for the appraisal of building components service life and reliability.

In Europe, the only currently available database (with information about materials' standard duration) comes from England: called Construction Durability Database, it contains a wide number of elements and technical sub-elements. An insurance society (the Housing Association Property Mutual) commissioned such a database, whereas BRE (the Building Research Establishment) realized it thanks to the studies carried out by that worked on 15 years of collection data and testing from the Building Group Performance and from other similar organizations.

Besides the standard duration, this database provides some corrections to apply in order to consider other elements that can increase or decrease reference service life.

Through the analysis of the necessary information to allow designers evaluating duration and planning maintenance, CSTB (the French Scientific and Technical Centre for the Building Industry) and Politecnico di Milano started structuring an international RSL database (Hans et al. 2008; Daniotti et al. 2008a, 2010); such a database contains some input data necessary to ICT tools for service life management.

Reference Service Life data is, in fact, the information that include the Reference Service Life itself and any qualitative or quantitative data describing the validity of that Reference Service Life. As reported in the standard proposal ISO 15686-8, which provides guidance on the provision, selection and formatting of Reference Service Life data and on the application of this data for the purposes of calculating Estimated Service Life, a RSL and the reference in-use conditions, together with additional required or useful information concerning the RSL, form a set of RSL data. A set of RSL data should be formatted into a RSL data record.

Thanks to the experimental tests Politecnico contributed not only to RSL definition, but also to create some grids for the application of Factor method, considering moreover the elaborations on statistical basis lead on the climatic agents, necessary for accelerated ageing cycle definition. As a consequence, the database for RSL collection became necessary not only for the convergence of all the information coming from the experimental researches, but also in order to constitute an indispensable tool for the application of existing methods for SLP (ISO 15686-2 and UNI 11156-3:2006) and in particular of Factor method.

Spontaneous duration and performance decay ways constitute the basic acquaintances to organize design and maintenance interventions planning for construction works and their parts.

The reliability and duration values influence maintenance choices. The knowledge of failure rate at the beginning and at the end of service life permits, in particular, to plan preventive threshold interventions, for example, at the average value of service life. This involves costs and use of resources according to a cost-performances equilibrium: the cost is the total one (considering design, construction, management and demolition steps) and the quality consequently assumes the connotations of whole quality along the entire building process stages. If the concept of resources' use (economic and material ones) is associated to the cost concept, building quality cannot ignore the problem of the constructions' sustainability. In particular, it is clear that durability of building objects, at different levels of complexity, constitutes one of the factors to manage the sustainable consumption of resources. That is to say that the fundamental scope of the maintenance planning is to realize necessary interventions with the maximum economy and that the executed work meets the productivity and efficiency criteria. The maintenance program, in fact, contains all the necessary technical type information for scheduling over time every periodic check (maintenance under condition) and substitution (preventive or after failure maintenance).

Therefore, thanks to maintenance planning, interventions are scheduled over time, necessary resources are characterized and allocated; in such a way, the performance levels of building assets are maintained over time, in actuation of the estate strategies predetermined by the property. Together with a complementary executive plan, maintenance scheduling aims at preserving over time functionality, quality, efficiency and economic value of constructed asset.

Moreover, it is important to remember that:

- a breakdown strategy tends to decrease the total cost of maintenance and management of constructed assets;
- a preventive strategy tends to guarantee the efficiency;
- a strategy according to condition (predictive) tends to take part in the moment of effective necessity;
- the opportunity strategy, tends to take advantage of the concomitance of another necessary intervention, optimizing the costs.

The information about building component service life turns out therefore to be an indispensable input data for maintenance design. Considering this, data collected inside the database on Service Life and the failure modes not only contain explicitly the information about maintenance frequency, but they are immediately usable during planning, thanks also to the interoperability of the database itself.

2.3 A Database for the Entire Construction Field

A construction work, before becoming a physical object, is identified through a bulk of structured information, which represent it with a certain degree of detail. When a project has been realized and it becomes a real building, the amount of data that are tied to it is extremely big and it increases more and more during its whole life cycle.

Therefore, the building process, as many other construction processes, is generating not only products but, mainly, information. At any level of development along the life cycle of a product (the construction work is the outcome product), the building itself and its parts (environments, systems, elements and components), on one hand are made of physical elements and on the other hand are represented by one, or many, information entities that are not material. Managing the construction process and its final product, then, has a physical aspect (building, maintaining, supplying, etc.) and, more important, a non-material/informational side (knowledge based).

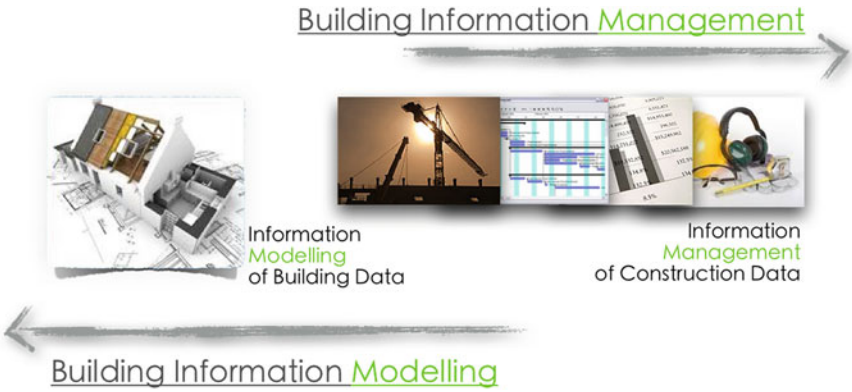

Fig. 2 Building information modelling versus building information management (Pavan et al. 2014)

Handling information is the typical critical issue of a complex process such as the building process is, since it is involving a number of different actors and it is involving almost the 90 % of the manufacturing sector and nearly the whole services industry. The key word of beginning of this century, for the building sector, is Information Management, starting from the very well known acronym of BIM (Building Information Modelling), ending up with Construction Information Management (CIM) (Pavan et al. 2014) (Fig 2).

A strategic step towards the optimization of both the building process and the whole construction sector is represented by the rationalization of the information flows connecting construction process stages (planning, design, construction, use, management, maintenance, disposal or reuse) and the various involved stakeholders (customers, users, designers, contractors, components manufacturers, etc.).

With this aim, INNOVance research project, funded by the Italian Ministry of Economic Development, wanted to push a radical innovation into the Italian Construction sector by creating a national construction database, containing information about products, works, environments, etc., along the whole constructions service life. This research wanted to improve the efficiency in using and maintaining objects information, exploiting the potentialities of Building Information Modeling, throughout the entire life cycle. The achieved work consists of three main steps:

(a) to give an unambiguous name to everything in the construction process, from single products to entire components, from activities to buildings, etc.;
(b) to define structure and content of the information related to each named entity;
(c) to pair each entity in the database with a BIM object.

The multitude of rules, definitions and practices that characterizes Italian construction sector causes difficulties in data sharing among different stakeholders, so the first priority of INNOVance was to create a coding system based on a standardized and unequivocal name.

Fig. 3 Main functions available on INNOVance web portal

To manage and use information through the construction process technical datasheets have been defined and standardized among homogeneous objects categories (construction products, spaces, construction operations, etc.) to allow users in easily and quickly comparing and retrieving information (Fig. 3).

Data is then freely accessible throughout a web-based portal that relies on the INNOVance database. This web portal aims at allowing users to manage their projects, by these functions:

(a) objects creation: thanks to the INNOVance objects structure, navigation in the database becomes easier and users have the possibility of creating BIM objects, entering codes, technical datasheets and additional life-cycle information;
(b) object search: as previously stated, users (also inexperienced ones) can search, download and manage information related to INNOVance objects, also with pre-formatted "views" targeted to different users' categories (clients, designers, contractors, constructors, producers, etc.);
(c) project management (BIM server): consultants and professionals have a specific section of the web portal dedicated to project management, from the early phases (design brief, site acquisition, etc.) to construction, use, maintenance and disposal or handover;
(d) standardized BIM objects exchange (BIM library), where users can download or upload every BIM object that can then be used in their own models (Fig. 4).

Through this website:

- manufacturers can create and modify the technical specifications of their construction products and they can enclose BIM objects too;
- designers can describe the designed technical solutions;
- users can consult datasheets.

Fig. 4 Homepage of INNOVance web portal

Depending on the authentication of different users, the portal will contain a section of private or public data. Indeed, sensitive data are accessible only by the owner.

In addition to this web portal, specific plug-ins can allow creating, updating and linking objects directly from BIM software (Fig. 5).

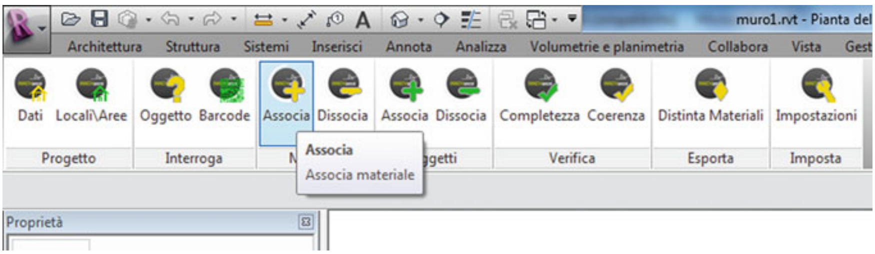

Fig. 5 INNOVance Autodesk Revit add-in

2.4 The Creation of a Life Cycle Management System Platform

Starting from the expertise in developing the Reference Service Life database, Politecnico di Milano has been structuring a new and wider platform for data col-lection and exchange, where Service Life data and "Factor methods referring grids" about opaque vertical and horizontal enclosures taking into consideration different climatic contexts are already stored. This platform contains also a tool for durability evaluation, which allows exploiting the developed Factor methods grids to evaluate Service Life also for technical solutions with design conditions different from reference ones: the user will be able to obtain ESL just selecting the real factors configuration.

The information of Estimated Service life, elaborated by means of the application of an enhanced Factor method, which guides the user in the choice of the corrected multiplicative factors and in the obtaining of a sufficiently reliable value of ESL, is eventually associated to a BIM object in order to make information us-able also by interoperable software.

The proposed methods and tools, therefore, bring out advances in finalizing the developed knowledge on Service Life Planning and Management, to make it available to users involved in maintenance: only integrating them inside the database, it can become a Life Cycle Management System platform (Daniotti and Lupica Spagnolo 2015).

To induce relevant advances in Building Components Service Life data collection and appraisal methods to support users in Service Life Planning, it is in fact necessary the implementation of Service Life prediction methods needs to undertake a set of experimental accelerated tests in order to finalize and standardize data col-lection procedure. In this way, it is possible to:

- build up a Reference Service Life information platform with an agreed European structure and guidance rules for the use at regional level;
- define Reference Service Life evaluation methods based on laboratory-accelerated ageing;
- capitalize Reference Service Life Data from all sources thanks to the platform.

The database contains Reference Service Life data, with a transparent indication of each data source, but also the necessary parameters and procedures to estimate SL in different contest conditions. To do that, a proper section of the database is dedicated to keep data of the specific context, such as dimensions, volumes, surfaces, costs, fulfilled maintenance interventions, etc.

The development of this interoperable LMS prototype has been then applied on actual maintenance works management in order to verify results and to demonstrate the benefit as for economic (life Cycle Costs) and environmental achievements (Life Cycle Assessment). This operation was done according to the international standard for service life planning of building and constructed asset procedures ISO 15686, in particular in conformity with the fifth part on Life-cycle Costing, which allows a cost analysis of the entire building life cycle, including maintenance.

The use of eXtensible Mark-up Language (XML), with a standardized format-ting (ifcXML) allows defining other mark-up languages, which can be immediately read by different software and tools. Even the web platform will use xml, because it offers a higher flexibility than HTML in the definition of tags and it gives the possibility to be extended according to future requirements. One of the propulsive ideas, in fact, is that, without any specific ICT tool to allow an access ubiquity to information about life cycle, service life management and planning cannot be actually undertaken.

Eventually, this ICT-tool is being developed using the standard IFC (Industrial Foundation Classes) of IAI (International Alliance for Interoperability) to define Building Information Models (BIM).

In particular, interoperability is guaranteed by sharing file .ifcxml and therefore using eXtensible Mark-up Language (XML).

Service life data, maintenance information, costs and each parameter for sustainability have in fact to match with Building Information Models attributes, upgrading BIM objects themselves in case of lack of some attributes.

This database can be accessible online from a web platform, which is thought to become an interactive footbridge among different stakeholders. As the quantity of collected information will be huge, there are different views of the database ac-cording to the stakeholder profile: the aim is to facilitate its use, filtering only useful data for the considered stakeholder, but leaving the possibility to search, visualize and, possibly, modify any other information of the database.

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BIM Tools Used in Maintenance of Buildings and on Conflict Detection

Alcinia Zita Sampaio, Diogo G. Simões and Edgar Preto Berdeja

Abstract The development of a building design requires the participation of several parties involved in different disciplines, and a efficient conflict analysis between disciplines is essential to guarantee a well-developed design. The building information modeling (BIM) methodology and tools associated with it present themselves as an excellent asset to support the process of conflict analysis, as they make it possible to merge all disciplines in an integrated virtual environment. In addition, a good maintenance depends on the analysis of the anomalies detected during the inspection of the site and the BIM model is a good tool on the support of maintenance activities, due to their ability to store enough information in one digital model. The aim of the research work was to implement the benefits provided by BIM on a software tool used as support to maintenance of buildings and to evaluate the practical capabilities of the BIM concept in the conflict analysis between building services, namely, the water supply and drainage systems design, and the architectural and structural design. This work contributes to demonstrate the advantages of BIM in the conciliation and coordination between different specialties, as well as the benefits of its application in maintenance activity.

Keywords Maintenance · Inspection · Building information modelling (BIM) · Standard IFC

A.Z. Sampaio (✉) · D.G. Simões · E.P. Berdeja
Department of Civil Engineering and Architecture, Higher Technical Institute, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
e-mail: zita@civil.ist.utl.pt

D.G. Simões
e-mail: simoes_diogo@hotmail.com

E.P. Berdeja
e-mail: edgar.berdeja@tecnico.ulisboa.pt

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1 Introduction

Jung and Joo (2011) claims building information modelling (BIM) as the process of generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way. In addition, Kymmell (2008) defines Building Information Model (BIM) as a virtual representation of a building, containing all the necessary information for its construction, supported by the use of the appropriate hardware and software. BIM is the digital representation of all the physical and functional characteristics of a facility, being used as an information repertoire, which can be shared and updated throughout the facility's life-cycle (NBIM 2014). Similarly, Ju and Seo (2012) describes BIM as a technology supported in BIM based tools that allows the user to go beyond the geometrical representation, placing him in a simulated construction process, that is, the development of a prototype of the final product. These three main concepts together complement each other: process, model and tools. Remarking this notion Barlish and Sullivan (2012) refer that for some stakeholders, BIM is a software application; for others it is a process for designing and documenting building information; for others it is a whole new approach to practice and advancing the profession which requires the implementation of new policies, contracts and relationships amongst project stakeholders. Following this last aspect Gu and London (2010) increments these topics with the need of changing the mentality of people involved, to position BIM adoption in terms of current status and expectations across disciplines. Both technical and non-technical issues that need consideration on the implementation of BIM and they also suggest that there are varying levels of adoption and therefore the need for a specific tool to facilitate BIM adoption.

The parametric creation process of the BIM model provides a chance of performing an automatic detection of conflicts, of promoting a link between the model and the schedule planning stage (the creation of the 4D model), of interconnecting the model with budgeting data (5D model definition) (Hartmann et al. 2008) and of relating the modelling with different processes regarding the facility management and maintenance throughout its life span (referred as the 6D model) (Eastman et al. 2011). The aggregation of several types of information on a single platform provides a positive value to the model, functioning as a resource that can be accessed directly by countless people, avoiding the expense of time and money in work duplications and allowing the constant update of information.

There is currently a growing concern about the maintenance and upkeep of buildings, not only due to regulatory standards set out in the project, but also the requirement of the users in terms of safety, health and building comfort. BIM models have revealed themselves to be an excellent tool not only during the stage of planning and construction, but also in the maintenance phase, mainly because of its large capacity for storing information associated with the three dimensional (3D) representation (Goedert and Meadati 2008). The fact that it is possible to access all the information of the building, through a single platform, combined with the automatic update of the model whenever changes are made, makes the BIM model very advantageous and promising during the exploration stage of a building, for this way, more reliable and accurate maintenance operations can be achieved (Martins and Cachadinha 2012).

Although BIM implementation requires profound process changes of the involved parties, the benefits in new construction projects both of private and institutional owners are manifold and often confirmed by involved stakeholders (Zhanga and Hub 2011). This integration is not so apparent in current building projects, where designers start employing advanced visualization and modelling technologies only at the very late design stages and consequently the design knowledge is mainly not captured (and lost) during early conceptual phase, where the most vital decisions are made (Abrishami et al. 2014). Major benefits consist in design consistency and improved stakeholder collaboration. In addition, professional and educational institutions have started to adopt BIM software tools and adapt their existing delivery systems to satisfy evolving market requirements (Succar et al. 2013). In a school context the development of research works as described here, contribute to improve student skills and better prepare them to their future challenges as civil engineers. Teaching BIM issue in technical schools is then a very important way of disseminate BIM in the AEC industry.

The aim of this manuscript concerns the use of BIM software capacities on the maintenance objectives and the analyses of clash detection. As such, in this work it was developed also an innovative BIM-based software tool, a 4D model, aimed to support the inspection operations of buildings, making them more efficient, due to its rigorous database, allowing the user to identify anomalies in the construction components directly on the BIM model, and associate them with the probable cause, recommended solution, repair method and a photograph (Simões 2013). The manuscript presents also a section concerning BIM/MEP issue. It is followed by the generation of the architectural and structural components of the BIM model. The MEP component is then created over the architectural part. For the analyses of conflicts between elements three distinct software of collision analyses capacity were applied. Finally some conclusions and recommendations are then carried out.

2 Maintenance 4D Model

The implemented strategy for inspection incorporates BIM modelling techniques, programming skills and devices to perform visual exploration tasks. To support the system a data base was created which included a bibliographic research support made in regard to the closure materials used in the roof, and interior and exterior walls of a building, anomalies concerning different kinds of covering material, and corrective maintenance. Repair activities were also studied. The programming skills of those involved in the project had to be enhanced so that they could achieve the integration of the different kinds of data bases needed in the creation of the system.

If on one hand, getting an accurate and omission free update of the models using the industry foundation classes (IFC) standard, is one of the main difficulties encountered when using BIM models during the exploration stage of a building, then on the other, maintenance of buildings has proved to be a rather complex task to accomplish, because the identification and analysis of all kinds of failure in construction requires a considerable effort of the agents responsible for maintaining the facility (Goedert and Meadati 2008). As such, in this work it was developed an innovative BIM-based software tool, aimed to support the inspection operations of buildings, making them more efficient, due to its rigorous database, allowing the user to identify anomalies in the construction components directly on the BIM model, and associate them with the maintenance data. Additionally, it was case study the interoperability between BIM modelling and visualizing software, regarding the preservation of information, especially in the IFC standard.

The interactive application supports on-site inspections and the on-going analysis of the evolution of the degree of deterioration of the coating materials. The following computational systems were used in there development and the scheme of links between software is presented in Fig. 1:

- Revit architecture, in the creation of the 3D model of the building (based on AutoCAD drawings) and saved in the IFC format;
- BIM visualizer Navisworks for the interaction capacity with the elements and to realize the integration to the inspection program;

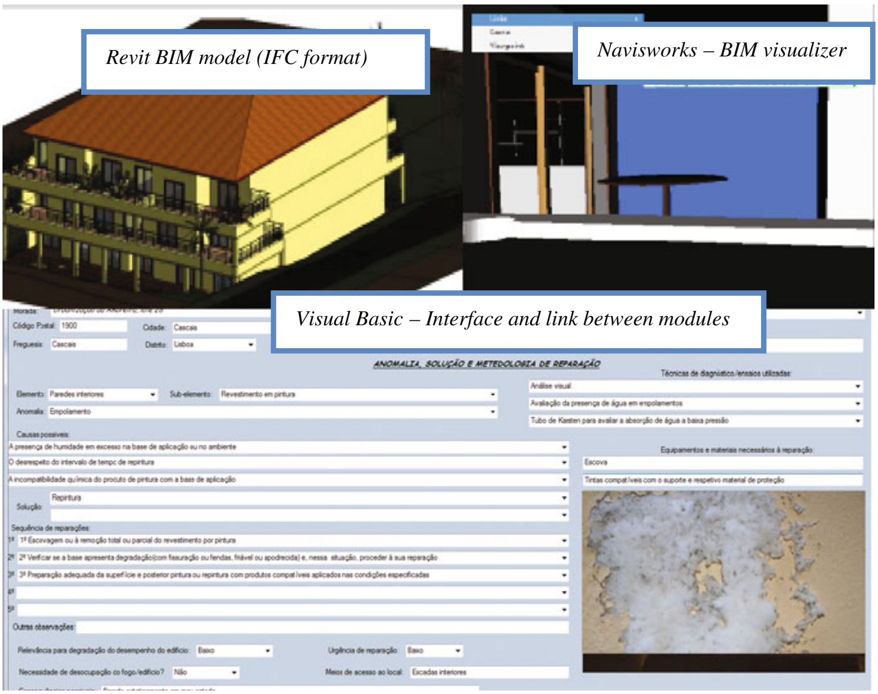

Fig. 1 Sequence of links between software

- Visual Basic in the creation of all the windows of the inspection application and in the establishment of links between the program and the inspection data base;

Microsoft Access on the definition of a relational database.

2.1 BIM Architectural Model

The architectural BIM model was created, using the Revit Architecture software. In order to illustrate how to carry out the modelling of a building using a BIM based software, a small fraction of real estate development in Cascais, near Lisbon, Portugal, was chosen as case study. The building consists of three floors; the ground floor consists of two dwellings and the remaining floors, four duplex dwellings. Each dwelling consists of bedrooms, toilets, kitchen, living room, hall and balcony.

In the model, all elements represented as walls, floors, ceilings, roof, doors, windows, and handrails, were created by adapting existing 3D parametric objects in the Revit library. The components of decorative character and equipment, such as sofas, chairs, toilets, tables were used directly, merely taking into account the scale factor during their inclusion in the model. Some drawings and projections can be obtained from the established model (Fig. 2).

2.2 Inspection Program

The interactive inspection operations sheet, created using the Visual Basic software, has as main objective to support the implementation of an inspection. In its development the database that was used consisted in the compilation of information from previous research developed for maintenance purposes concerning three building components: roofs (Afonso 2013), facades (Rosario 2011) and interior walls (Gomes 2010). The information provided in the present work relates to anomalies, causes, solutions and repair methodology concerning those constructive components. Therefore, during an inspection, the maintenance technician, when

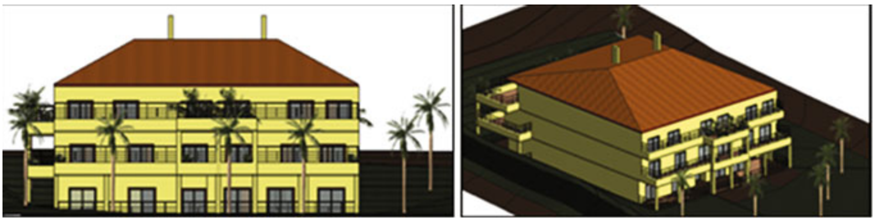

Fig. 2 Projections from the architectural 3D model

observing an anomaly, can consult the database support to fill out the inspection sheets and select the identified anomaly on the site.

Subsequently, the completed inspection sheet is then converted to the pdf format and inserted into the BIM model. This model should be constantly updated, in order to accurately support the facility with repair and maintenance plans. An inspection sheet must include some initial information such as identification of the technician, the date of the inspection and the identity and characteristics of the building (address, city, number of floors, year of construction, etc.). The application allows the user to select a type of element, roof, interior or exterior wall, and the interface of the 4D application provides different lists depending on chosen type of elements. The visualized list of anomalies differs according to the option selected in advance. In the developed software tool, this feature is observed between the elements and sub-elements, among the verified sub-elements and anomalies and between anomalies and possible causes, solutions and repair sequences (Fig. 3).

Fig. 3 Causes, solution and repair sequence automatically filled after choosing the element, sub-element and anomaly

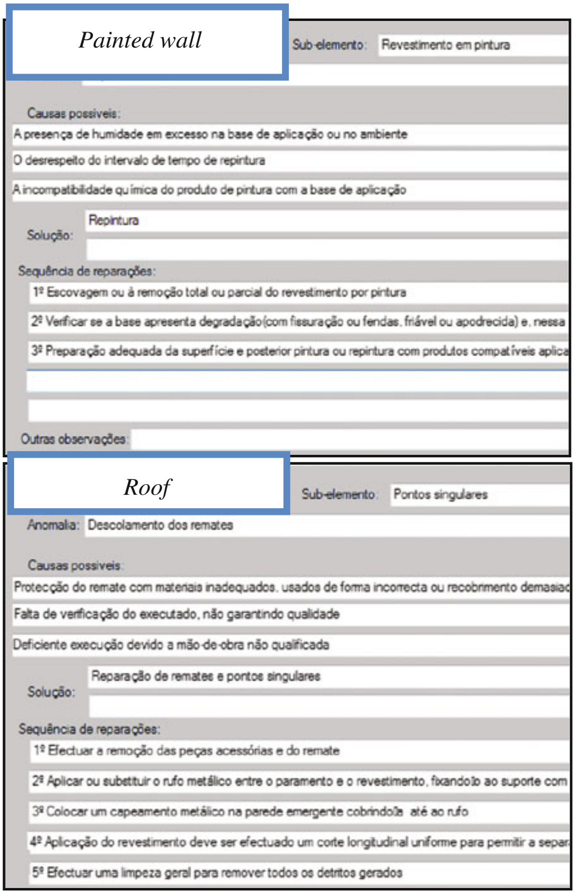

Fig. 4 Interface of the filled out inspection form

The application also allows you to include a photograph of the anomaly taken at the site and convert the information presented in the sheet of inspection to a document in pdf format. Such possibilities are essential for an inspection sheet, because the addition of a photograph allows the user to recognize the anomaly, its severity and location, and conversion to *pdf* format enables the user to save the inspection form in a universal format. The result of filling the form is illustrated in Fig. 4.

2.3 *BIM Model Linked to Inspection Program*

A BIM visualizer is an application that enables access to all information created in the BIM model. Unlike the modeling software, navigation and interaction with the model is performed quickly and lighter, and can also be accessed from mobile devices such as smartphones or tablets. This type of application also allows integrating the diverse information from architectural designs, structures, building installations and budgeting, and also allows the analysis of conflict detection.

The BIM visualizer combines the BIM model of the building and the information from the inspection form. This study requires the analysis of interoperability between the BIM modeler and the BIM visualizer (*Navisworks*), regarding in particular data and information transfer in the IFC format. Furthermore, an inspection form is filled in and, afterwards, saved and included in the model, so that it can be used as a basis for consultation when planning maintenance operations. The data transfer between the BIM modeler and visualizer, in IFC standard, resulted in complete preservation of information and error free. The only limitations observed were the clutter of information and a lack of storage capacity of the

Fig. 5 Navisworks interface showing the color deprivation in the IFC format

previously predefined colors, which led to the total deprivation of color of the model, as illustrated in Fig. 5.

In an inspection activity the maintenance technician, using the developed application, selects the element where an anomaly was observed, in this case an interior wall (shown in blue in Fig. 6). Through the BIM model, the service technician can identify the constituent materials of the interior wall (Fig. 6) and has the possibility to run the inspection program, by selecting the link "Program", fill out the inspection form and store it in the BIM model, through the creation of a new link.

Let us assume for example, that the inspection sheet was recorded under the name "Inspection 29 Oct. 2013—Anomaly—paint blistering". Whilst planning for maintenance operations, or any other inspection activity, the choice of the element in which lies the anomaly (the wall inside the room depicted in blue in Fig. 6) identifies two associated attachments: the inspection program and a sheet of the inspection carried out on the December 2013, concerning an anomaly called paint

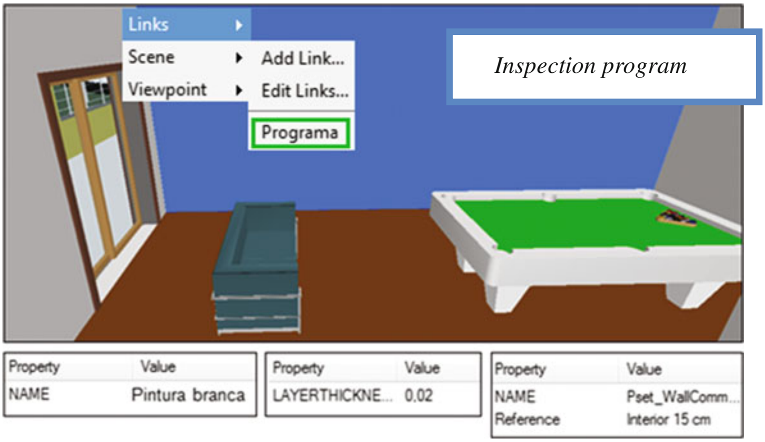

Fig. 6 Selection of an exterior wall and its associated features, and of the link "Program"

Fig. 7 Selection of the inspection file of the anomaly associated with the inner wall

blistering (Fig. 7). By choosing the link "Inspection Dec. 2013—Anomaly—paint blistering", the user is automatically opening the pdf document related to the associated inspection form, i.e. the sheet shown in Fig. 7.

This consultation allows us to better understand what the probable causes that originated the new anomaly are. If the problem shows a degree of severity or has been subjected to some kind of repair, the materials used and the exact location of the anomalies that have already been registered (through photography).

2.4 Implementation Problems

The creation of the inspection sheet had some problems, particularly concerning the creation of a routine that allows the insertion of any picture on the form, and in obtaining the pdf-sharp library that would allow its conversion to pdf format.

However, the creation of an inspection sheet to support the maintenance of buildings, based on a BIM model would be unsuccessful if the digital modeling of a building wasn't performed. Therefore, parallel to the creation of the inspection form, an architectural BIM model was developed from scratch, being described every step of its development, illustrating the procedures of its establishment and insertion of distinct data type, with the objective of providing the building relevant information, which could be reused. Then, the modeling was exported using the IFC format to a BIM visualizer so that it could be displayed in a fast and efficient manner. The implementation of the model was done not only as a necessity, but also in order to study one of the major obstacles to the implementation of BIM, its interoperability under the IFC format. In fact, this work confirms that the IFC format is not yet fully developed in order to properly implement the information models, as, despite not losing any information, it features it in a disorganized manner, not retaining the color added to the model.

A BIM visualizer allows the representation of BIM models in a simple and fast way, allowing the user to add different models and different documents, programs or notes. As such, a program that supports the inspection of buildings was added to the BIM visualizer software. This combination's main objective is to aid in the maintenance activity of a building, because it allows the maintenance technician to perform inspections with the developed software by automatically running it after selecting the building element in the model. You can also save the inspection form in pdf format by entering it again in the model. So any maintenance technician can consult all the information concerning a given building element, not only its materials, dimensions and physical characteristics, but also its historical anomalies, any intervention that it has been subjected to and their exact location on the element, providing an important aid in keeping the building and therefore the comfort of their users.

Adding the program to the BIM visualizer of is done in a fairly simple way, however, it was observed that some visualizers do not support certain applications, which indicates difficult defect to overcome, when the main purpose of these is the aggregation of information in any form. It was also noted that it still wasn't possible to automatically save the inspection sheet onto the building element selected in the BIM visualizer. Overcoming this obstacle would result in even greater productivity, when filling out the forms and then associating them to the model, this being just one more aspect that would support the association between the inspection program and the BIM visualizer.

3 BIM/MEP Design

The second study concerns conflict detection analyses between architecture, structure and MEP services. As conducted in the field of construction, the utilization of BIM is becoming a hot issue for many public work projects (Ju and Seo 2012). Resource scarcity, sustainability challenges and stricter decrees for recycling and resource efficiency in buildings motivate the architecture, engineering and construction industry (AEC), and also Facility Management (FM) to manage resources efficiently. Development of 3D modeling started in the 1970s, based on the early computer-aided design (CAD) efforts in several industries (Jung and Joo 2011). BIM modeling was introduced in pilot projects in the early 2000s to support building design of architects and engineers. The focus of contemporary AEC design projects is increasingly moving from an architecture with aesthetical emphasis towards performance (structure, environment, construction, socioeconomically and cultural, etc.) based architecture. This shift in design attitude is inviting architecture to adopt new technologies that can support this transition. The AEC designers started adopting technology from industrial design, mechanical engineering and product developments, where performance tends to play a crucial role, as well as adopting new computational design methods such as parametric approach and topological space are also being engaged (Abrishami et al. 2014).

BIM requires the development and use of a computer generated model to simulate the planning, design, construction and operational phases of a project. BIM user finds many benefits and resource savings during design, planning, and construction of new buildings (Eadie et al. 2014). However, Ju and Seo (2012) examined the BIM technology regarding its application and find that BIM data in each construction stage, lack of cooperative system, insufficient standard library and guideline. Actually BIM developments suggest that not only is it useful for geometric modelling of a building's performance but also that it can assist in the management of the integration of several components in a building design placed in a unique virtual building model. Following this many industries developed integrated analysis tools and object-based parametric modeling, being the basic concept of BIM. Consequently, major research trends focused on the improvement of preplanning and design, clash detection, visualization, quantification, costing and data management (Porwal and Hewage 2013).

Coordination of mechanical, electrical and plumbing (MEP) systems is a huge challenge for many technical projects. The use of BIM tools and processes promises to address the challenges of the MEP coordination process. Khanzode et al. (2008) present a case study supported on the use of BIM tools and discuss the challenges project team members faced in implementing the BIM tools, processes for MEP coordination, and the specific quantitative and qualitative benefits from the use of BIM tools. The MEP design is critical for decision making, accurate documentation, budgeting, performance forecasting, construction planning and management and, eventually, facility maintenance. However, the design of MEP systems has proven to be a huge challenge in many projects, namely in the technically more complex ones, such as those focused on the high technology, healthcare and biotech industries. In such cases, the MEP systems could comprise as much as 50 % of the total project value. Therefore, the coordination and routing of these kinds of systems is of great importance. Following Olofsson et al. (2008) these systems need to be routed on limited spaces under the design, construction and maintenance criteria established for them.

In this area, the success of BIM technology in construction projects shown by the rapid adoption of its associated tools, have redefined the expectation of clients by MEP consultants. Just as for the structural conception and construction projects, BIM applied to MEP is a project methodology characterized by the creation and use of consistent, coordinated and computable information for the MEP design of a building. Although it's still in a growing stage, BIM technology has revealed itself as a key factor to keep market competitiveness. These are some of the main advantages provided by BIM for the users of the MEP domain (RevitMEP 2014):

- By enabling a holistic approach in the modeling of building service systems, BIM technology can be used to unify all the MEP disciplines within an integrated digital environment for the purpose of design, analysis and documentation;
- The accuracy and, consequently, the reliability factor with MEP engineering designs is higher, due to the fact that BIM offers a higher visibility level which translates to better coordination among engineers and architects, and therefore leading to a significant decrease in errors;
- BIM technology provides automatic clash detection during the development of the building design;
- It bestows the MEP engineers the ability to foresee the end results of their work with a higher precision before the project completion, allowing therefore the development of sophisticated and sustainable buildings within a shorter period of time and comparatively economically.

3.1 Architectural and Structural BIM/3D Models

The case study used for the development of this work, refers to a single family house located in the northern part of Portugal. The available documentation of the real project that was consulted to define the main disciplines BIM components was a set of drawings. The house consists of two floors, with the ground floor comprising the garage and entrance hall and, the first floor containing the living room, kitchen, three bedrooms, two bathrooms, one utility room and hallways.

In the generation process of the BIM model's architectural and structural components, all represented elements, such as walls, windows, doors, floors, columns, roofs and footings, were created by adapting the 3D parametric objects existing in the Revit library, in order to resemble closely the real case. The sequence of steps taken in the modeling of the structural and architectural components of the BIM model is: Initial settings (setting the project units and the levels, project browser organization and adding grids); Architectural component (creating and adding walls, doors and windows, floor coverings, roofs, stairs and adding equipment); Structural component (creating and adding structural columns, footing, beams, concrete slabs). For modeling purposes, Revit 2014 software was used (Fig. 8). these two models were overlapped using Revit capacities (Fig. 9).

3.2 MEP/BIM Model

This section describes the modeling in Revit 2014 of the MEP component of the BIM model, namely, the domestic hot and cold water supply system, the domestic wastewater system and the rain water drainage system. The Revit MEP is steel a

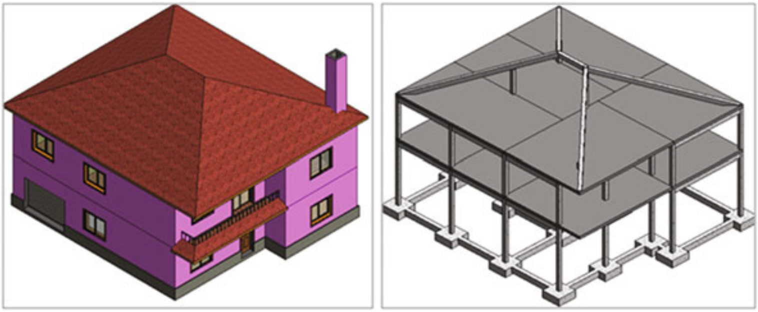

Fig. 8 Architectural component (*left*) and structural component (*right*)

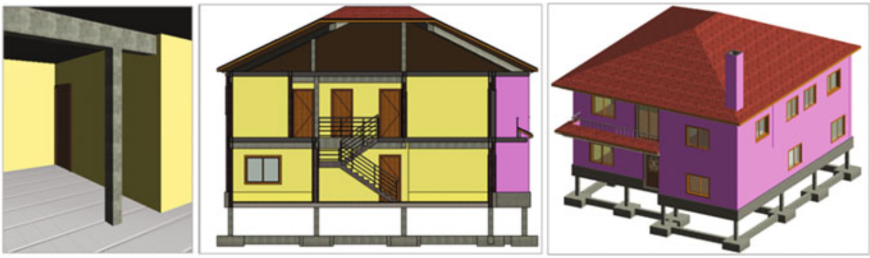

Fig. 9 Overlapping disciplines: 3D interior view (*left*), vertical section (*center*) and general perspective (*right*)

component of Revit in development in order enhance better performance. Actually Revit 2014 version has an intuitive modeling, sufficient and well-conceived design features, direct integration with architectural and structural Revit software tools, and a good drawing sheet management.

The modeling was initially performed solely based on the architectural component of the house, with no visual guidance from the structural component. The architectural model was then supplemented with the plumbing fixtures. For the routing of these systems, the fundamentals of "Handbook for the building distribution systems and drainage" (Pedroso 2008) were taken into consideration. The piping diameters used in this work are approximate values of those present in the real design, for it was decided that the predefined nominal diameters from Revit were to be used. The setting of the mechanical properties of the model elements was not taken into consideration, as this aspect is not relevant to the conflict analysis carried out in this work. The sequence of steps taken for the modeling of the MEP component is: hot and cold water supply system (adding plumbing fixtures, creating and adding water supply pipes, adding pipe accessories and insulation); domestic wastewater drainage system (adding floor siphons, creating and adding plumbing fixture drainage pipes and discharge stacks, adding access chambers); rain water drainage system (adding rain gutters, downspouts, and access chambers). Figure 10 illustrates some of the end results.

3.3 Clash Detection

Conflict analysis is an integral and very important part in the development process of a three-dimensional BIM model. The BIM tool in use allows the overlapping of multiple disciplines that coexist in an integrated manner, forming a complete model of the design. Each discipline (structural engineering, MEP engineering, environmental engineering, etc.) creates an independent model using objects, specific to each component, using the architectural BIM model as basis for the development. After each discipline has made its contribution for the BIM model the collision detection can be performed. This process consists in searching objects belonging to different disciplines that conflict with each other, that is, elements that are using the same physical space or that have incompatible parameters or even, in the case of 4D modeling, calendar conflicts. The analysis of these inconsistencies is a critical task, especially regarding MEP and fire protection (FP) designs (Kymmell 2008), since they could eventually severely impact the construction process, causing delays, design changes and increased expenses in materials and surpluses in the budget.

The conflict analysis should be an iterative process in which every notable design incompatibility must be addressed and reassessed, changing and updating

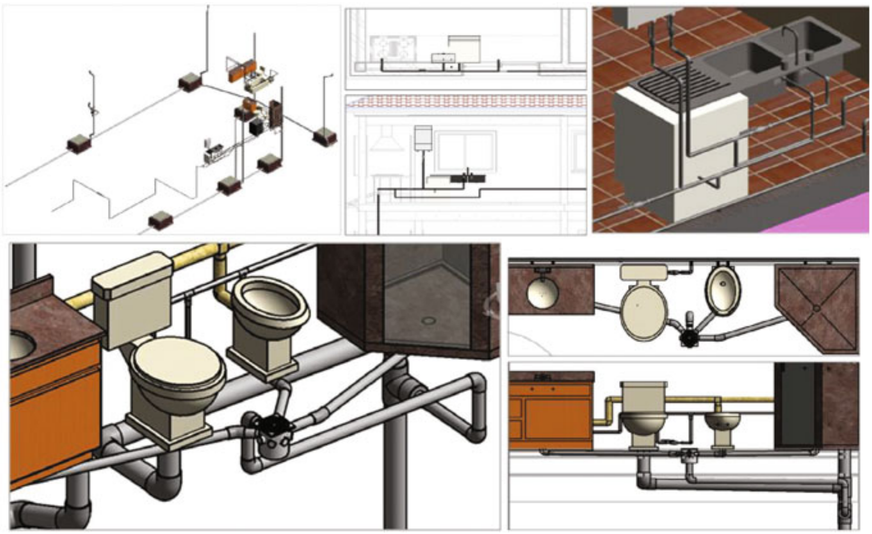

Fig. 10 General perspective of the MEP component and orthogonal views (*top*), 3D views of the water supply system in the kitchen (*bottom left*) and the wastewater drainage system in one of the bathrooms (*bottom right*)

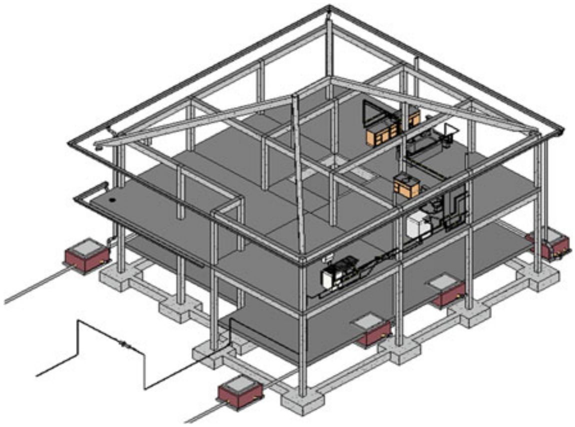

Fig. 11 Structural and MEP disciplines as seen in a Revit 3D coordination view

solutions to achieve the desired level of coordination (Kymmell 2008). If conflicts revealed in 2D, 3D and 4D formats are not thoroughly studied during the discipline coordination, it could lead to an endless cycle of corrections because some times when fixing something in a place may result in another conflict in another. The modeling of the structural and MEP components were carried out using only the architectural component as guidance, that is, the structural component was not visible during the MEP modeling and vice versa. However, Revit, allows simultaneous viewing of all modeled components. This can be done by using the coordination view, one of Revit's features that aids in the coordination of the various building disciplines (Fig. 11).

According to Fies et al. (2010), there are three types of clash: hard clash, soft clash and near misses clash, the latter of which also referred to in some sources as being a clearance clash. The hard clash consists in two objects occupying the same space. The soft clash refers to objects that occupy a space that can affect the movement of another object or person. The near misses clash is a conflict that occurs when a regulation or building code, such as the minimum distance between gas and water pipes, is not met. Various sources group together the definitions of soft and near misses clashes, designating them solely as soft clashes. That being said, for the purposes of clash detection, this work will take that grouping into consideration. Through the handling of the view plan of Revit, there were find 9 hard clashes column versus pipe (Fig. 12), 5 hard clashes beam versus pipe (Fig. 13) and 2 soft clashes concerning usable space versus pipe (Fig. 14). The suggested resolutions were worked out using Revit capacities.

Tekla BIMsight is a project review software that enables the coordination of the different disciplines of a building, making the clash detection possible and therefore aiding in finding a solution. It's a program that has become especially useful in coordinating disciplines modeled by different software using the industry foundation classes (IFC) format to allow their integration.

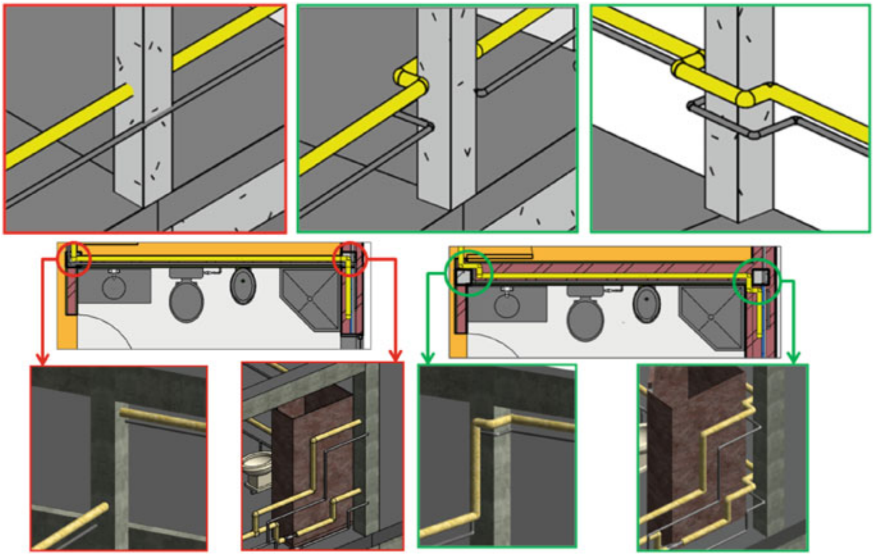

Fig. 12 Hard clash between column and water supply pipes and suggested correction

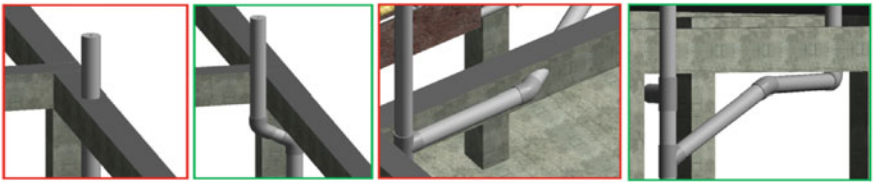

Fig. 13 Hard clash between beam and ventilation pipe and suggested correction

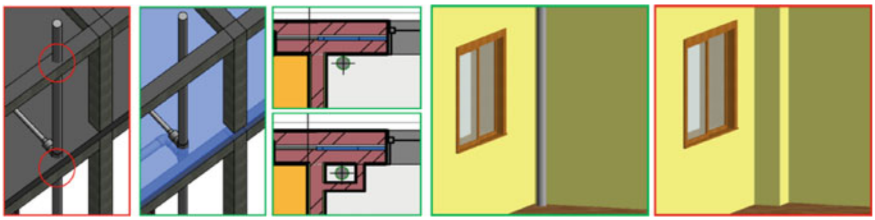

Fig. 14 Soft clash consisting of a visible ventilation pipe in a bedroom and suggested correction

In this work, the various disciplines were modeled always using the same Revit document. Nevertheless, in order to demonstrate Tekla BIMsight's clash detection capabilities, the MEP and structural components where saved in separate documents. After integrating the two disciplines, clash detection can be conducted by using the Conflict Checking function.

But first, it's necessary to establish a rule that makes clash detection possible between the two disciplines. This new rule was designated "MEP versus Structure" and the files to clash are selected. An overlap tolerance value between objects can be defined as well as minimum distance value and also to check for clashes between rebars (Fig. 15). After running the new rule the detected clashes are listed and pinpointed on the model (Fig. 16).

Navisworks is also coordination software from Autodesk and the most used project review software amongst BIM users. The existing Clash Detective function is of great help in conflict analysis and project coordination, especially if the used BIM modeler is Revit. Contrary to Tekla BIMsight, Navisworks allows the clashing of different disciplines within the same model and, therefore, there is no need to save them as separate files. In addition, the viewing of the case study model doesn't require exporting it to the IFC format, because Revit produces files in a readable format by Navisworks, as they are both Autodesk products (Fig. 17).

Fig. 15 Creating a rule to check for clashes between the MEP and structural models

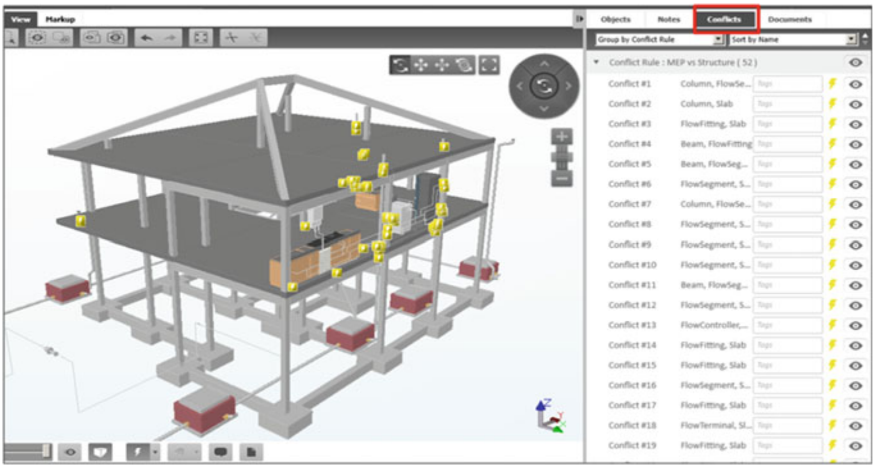

Fig. 16 Detected clashes are listed and pinpointed in the model

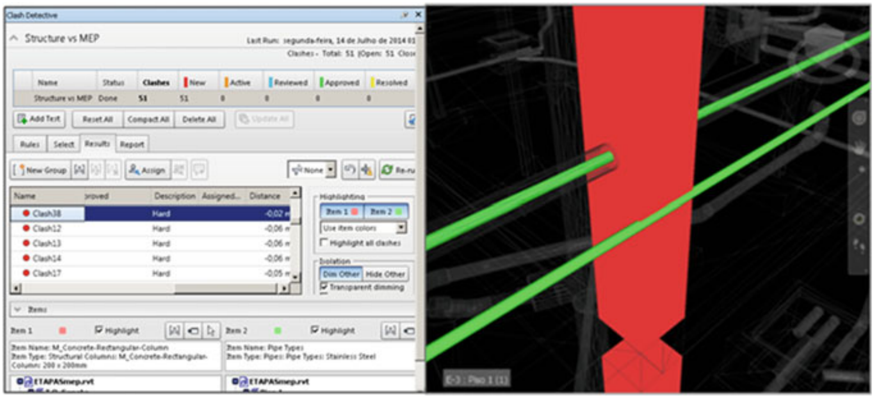

Fig. 17 Clash detective tool

Be it Navisworks or Tekla BIMsight, the conflict resolution must be conducted in the modeler, Revit. However, Navisworks features the Switchback function that, when enabled, opens the Revit model immediately focusing the conflicted elements, thus allowing to quickly fixing the problem. Afterwards, the updated Revit file is saved, taking into account that the previous file must be overwritten. This way, it's only necessary to refresh the model in Navisworks for it to update the changes. This ability to add and update information between Revit and Navisworks with the Switchback function is one of the greatest advantages when using these BIM tools together, for it provides an iterative and efficient workflow that comes a few steps closer to resembling what the BIM methodology really is about.

4 Conclusions

Two perspectives of BIM use was analyzed and tested in study cases: maintenance of buildings and conflict analyses between disciplines in design. It can be concluded that with this work, a useful program was established to support building inspections and future maintenance operations, which associated with an architectural BIM model, and taking into consideration that the benefits would be greater if the BIM model integrated various specialties, it was demonstrated that the great potential inherent in BIM, as a methodology, can be revealed in the actions of maintenance of a building. And the use of BIM tools as a means of conflict analysis presents an irrefutable advantage over traditional methods. The use of modelers, such as Revit, for this purpose enables a virtual visualization of conflicts with a very high level of detail. Solving the problem is immediate because the analysis is being made in the modeling software.

Effective facility maintenance is based on a thorough inspection for anomalies. Therefore, an inspection sheet was developed, with the purpose of enhancing the technical inspection, of a tool that lists anomalies, for the constructive element selected, automatically providing, the repair procedure, its main causes and respective solution. Thus inspections are carried out in greater detail, and hence greater chronological and productivity gains can be achieved. The ability to write in pdf format reveals itself most important for subsequent addition to a BIM model.

An efficient conflict analysis depends mainly on the level of detail of the projects involved, which can currently be attained through the use of BIM modeling software. In this work, the BIM tool Revit 2014 was used to model the architectural, structural and MEP disciplines. It was noted that when compared with more traditional AutoCAD usage, the representation of elements is more complete (non-geometrical information associated) and its 3D viewing is immediate. In addition, the ability to simultaneously conciliate the architectural component with the structural component through the coordination view aids with obvious advantages the process of establishing a structural solution. On the other hand, the complete composition of elements, such as walls, still reveals itself as quite a limiting aspect, as it requires knowing beforehand the main features of the wall's composition. Naturally, afterwards, it's possible to update its composition, while preserving the bonding relations to the neighboring elements that were already established during the modeling, thus reflecting a great advantage when compared to traditional AutoCad modeling. However, the use of project review software must be emphasized, for they have functions targeted specifically to conflict analysis, like Conflict checking, from Tekla BIMsight, and Clash Detective, from Navisworks Manage. To emphasize the latter, which due to the Switchback feature, enables a workflow that tends to resemble the BIM ideology.

The advantages of BIM in the construction domain are more than evident, especially when related to conflict analysis. This will never be a 100 % automated process, because the coordination of different disciplines requires more than just the push of a button and waiting for the problems to get solved. Conflict analysis is an iterative process that requires a joint approach by everybody involved in order to reach and make a final decision. The conflict detection software are only a tool to help in the decision making process.

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Mechanical Pathologies of Reinforced and Damaged Concrete Corbels by Gluing Composite Carbon Fabrics Under Static and Dynamic Tests

Ivelina Ivanova, Jules Assih and Dimitar Dontchev

Abstract Reinforced-concrete (RC) structures are the most used in the world. The concrete is an economical and durable material resistant, insulating and easy to implement. The main causes of deterioration of structures are: mechanical damage, chemical attack (carbonatation), physical deterioration, corrosion, evil design, overloading and improper repairs. All these damage can give rise to rebuild or to repair structures by various methods. This paper presents the repair of reinforced-concrete corbel by bonded carbon fibre fabrics. Seven RC corbels were tested. Two of them are reference RC corbels, one without strengthening and the other one strengthened RC corbel. They were tested under static loading. The other three specimens were damaged at different levels 40, 60 and 80 % of the ultimate load of reference corbel, afterward they are strengthened by wrapping. Finally, the last two RC corbels were tested under dynamic loading, one without reinforcement and last one after strengthening. The ultimate loads are usefully compared and the mechanical behaviour using strain gauges are investigated. The results show that strengthening improves significantly the ultimate capacity load up to 82 %, as well as the increased structure stiffness to third. The different failures modes are described.

Keywords Damaged · Structure · Strengthened · Concrete · Composite

I. Ivanova (✉) · J. Assih
University of Reims Champagne-Ardenne (URCA), Reims, France
e-mail: ivelina.ivanova@univ-reims.fr

J. Assih
e-mail: jules.assih@univ-reims.fr

D. Dontchev
University of Chemical Technology and Metallurgy, Sofia, Bulgaria
e-mail: dontchev@utcm.edu

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1 Introduction

Many concrete structures no longer meet the current safety standards or have excessive cracks. Steel corrosion, concrete carbonation, may also cause the occurrence of high deflection or instability of the structure itself. It is generally manifested by poor performance under service loading in the form of excessive deflections or cracking sometimes, even by inadequate ultimate strength.

According to the European standard (BS EN 1504-9), the main causes of deterioration of reinforced-concrete (RC) and reinforcement of structures are: mechanical damage, chemical attack, physical deterioration, corrosion, evil design, overloading and improper repairs. In fact concrete is then subjected mechanical-type attacks.

The introduction of composite carbon fibre in 1980s in the field of Civil Engineering helps strengthen or repair RC structures with adhesive. Carbon fibre materials have many advantages: their weight, flexibility, implementation easier and also their physicochemical properties (anticorrosion) interesting (Burgoyne and Balafas 2007).

Maintenance of Civil Engineering is to protect them by ensuring better sealing or limiting corrosion. To repair them means to compensate the loss of stiffness and limiting the cracking. The strengthening technic by bonding carbon fibre fabrics can improve performance and durability of these structures. This technics carry out a program of strengthening RC corbels (Ivanova 2013; Assih et al. 2014; Ivanova et al. 2015a) was much more attractive.

Furthermore, corbel is one important element of steel or concrete structure to support the pre-cast structural system such as pre-cast beam and pre-stressed beam. The corbel is cast monolithic with the column or wall elements. It is interesting to study damage and mechanical behaviour of this very short element of structure reinforced by bonding carbon fibre fabrics (Corry and Dolan 2001; Campione et al. 2005; Elgwady et al. 2005; Ahmad et al. 2010; Syroka et al. 2011; Mohamad-Ali and Attiya 2012; Ivanova et al. 2015b). The costs of these materials become available (Bourget et al. 2001; Fernandes and El Debs 2005) and their applications become more interesting. Research conducted on corbels by Fattuhi (1987) and Fattuhi and Hughes (1989) contributed to ACI recommendations and the tests results are showed that reinforced-concrere strength and ductility are enhaned when used fibre-reinforced in the place of classic mix concrete. And so, the damage model introduced by Mazars (1984) improved considerably the studies scientific knowledge damage of reinforced-concrete structures. Today, they are more often used (Assih 1998; ACI Committee 440 2000; AFGC 2011; Giry 2011; Quiertant and Benzarti 2012).

This investigation shows the effect of static and dynamic loading applied to RC corbels without and with strengthen. The damage effect is also taken account in this paper. Local behaviour is examined by using the strain gauges to measure deformation in the steel, concrete and carbon fibre fabrics. The ultimate load, cracking, collapse mechanisms and modes of failure are also studied.

2 Design and Pathology

2.1 History of Reinforced Concrete Corbels

There are few studies on the short reinforced concrete corbels. In France, the first study is done by Chambaud and Lebelle (1953) in 1953 who proposed an approach based on the transmission of loads to the mounting section by inclined rods at 45°. He proposes to divide the horizontal bars over the entire height and to consider the mechanical schematic as overlapping corbel. While Robinson in 1969 used a semi-empirical method based on a simplified equilibrium diagram of the mounting section; which forms the basis of French Regulation (BAEL 83). The method of photoelasticity is used by Franz and Niedenhoff (1963) in Germany in 1961 to confirm the triangulated system a short reinforced concrete corbel after the first cracking; as indeed (Menhmel and Freitag 1967) six years later. However, in the USA, the modelling of local behaviour firing underrun after begin of cracking proposed by Kriz in 1965 was used to determine the ultimate tensile strength of concrete in a short corbel study; even if the method is made entirely empirical. But, Mattock (1974) and Mattock (1976) applied the method of shearing friction to calculate the shear bearing capacity of short reinforced concrete corbels.

These models are only valid at the ultimate state of failure and are failed to describe any corbel behaviour when the first crack appears in fixing section of the structure. In the current state of research, the main interest of these simple models is to design with a large safety for the structures, without forgetting to reduce if necessary the quantities of materials used to minimize the costs.

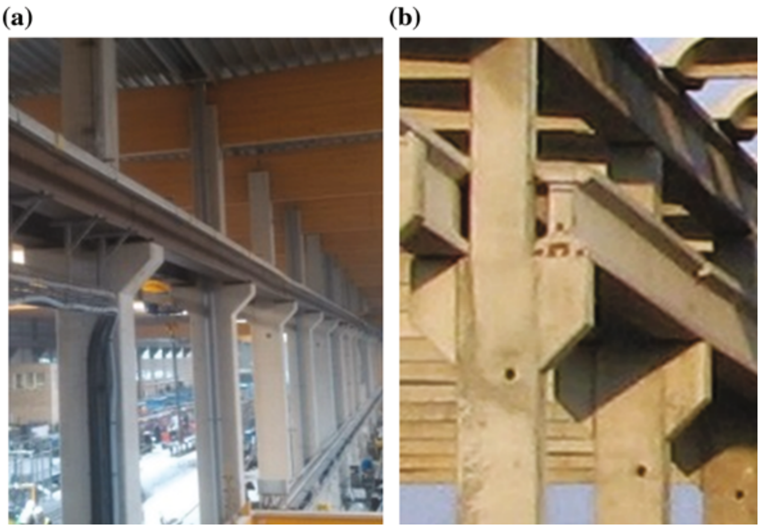


Fig. 1 Examples of corbels in industrial construction (**a**) and structure (**b**)

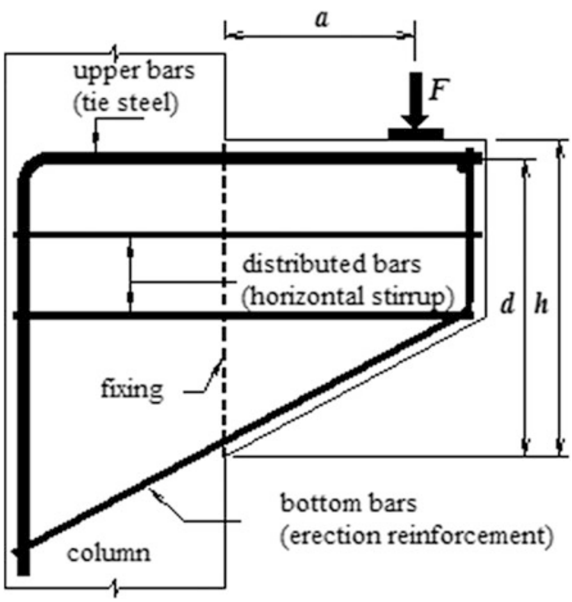


Fig. 2 Design of reinforced-concrete (RC) corbel

2.2 Reinforced-Concrete (RC) Corbel Design

The short RC corbel is a prismatic element of structures frequently used in Civil Engineering, buildings and public works (bridges, constructions, parkings…). For examples, in Fig. 1a, b, the corbels give support to a rolling of an overhead crane or an often prefabricated girder.

A short RC corbel includes upper reinforcement also called steel tie and reinforcements distributed in the form of horizontal steel stirrup. The upper bars are designed to withstand tensile stresses developed by bending. The horizontal steel stirrup are used to shrink the compressed concrete inclined rod to minimize cracking and prevent sudden failure. The corbel is called short when the height of the restrained (fixing) section (h) is at least equal in range (a) is the distance between the mounting section and the applied load, Fig. 2.

In general, a corbel has a mid-plane and a rectangular cross section. The upper part of corbel is always horizontal, but the lower part is often tilted. The conventional beam theory inflected is no longer justified in short reinforced-concrete corbel because of its relative range ($\lambda = a/h$) below 1.

2.3 Pathologies

The durability of structures depends on their behaviour in response to climate and environmental conditions where they are built. So, the mechanical behaviour of concrete and steel deteriorations should depending on environmental conditions defined by the local geographic of structure Fig. 3.

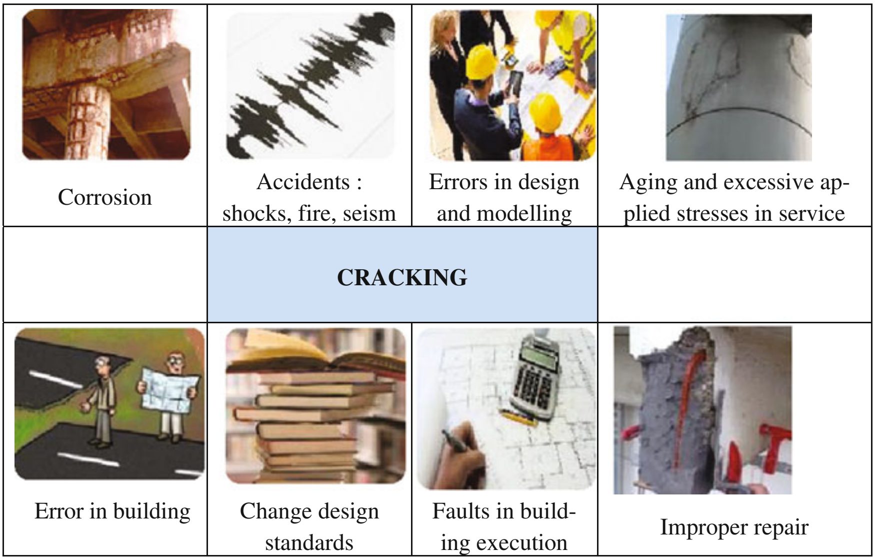


Fig. 3 Main causes of reinforced-concrete degradation

Fig. 4 Natural and mechanical deteriorations of reinforced-concrete structures

According to the European standard (EN 1504-9 NBN), the main causes of summer-deterioration of concrete and steel reinforcement are: mechanical damage, chemical attack, degradation of steel reinforcements as corrosion Fig. 4, inappropriate repairs. In consequence of shock, vibration, subsidence and geotechnical, cracks or chips can be appeared that need to repair and identify conventionally as mechanical damages. The major causes of reinforced-concrete structure deteriorations can be also tied to aggressive agents, improper repair, excessive stresses applied in service.

2.4 Reinforcement of RC Corbels by Bonding Carbon Fibre Fabrics

The main function of RC corbel is the transfer of vertical and horizontal forces principal members as beams and columns. The presence of high values of shear forces

Fig. 5 Distribution of stresses in the corbel under load F

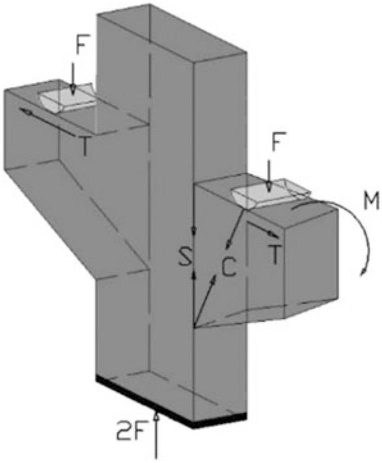
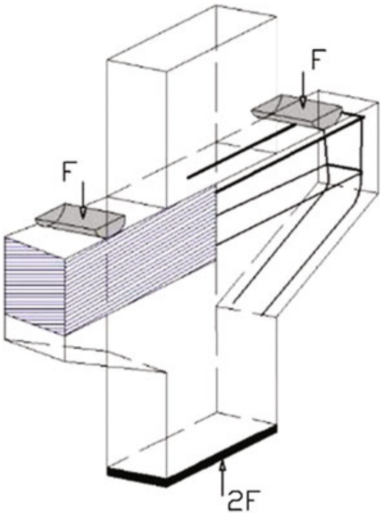


Fig. 6 Strengthening by bonding carbon fabric in tensile stresses areas



reduces their flexural capacity. Upon load F application, mainly three stresses are shown like in Fig. 5: tensile stresses $(\vec{T})$ where tensile in steel bars are overriding; shear stresses $(\vec{S})$ at interface column/corbel and inclined rod $(\vec{C})$ to compression. The latter appears area due to the geometry of the corbel would promote more.

The solution is to provide reinforcement adding the composite fabrics in the tensile part of the RC corbel to increase the bearing structure capacity load. The reinforcement method in this case was carbon fibre fabrics bonded by wrapping. In consequence, this method can compensate failing of tensional member. One example is showing in Fig. 6. However, the strengthening can be achieved directly by bonding the carbon fibre fabrics to face and rear surfaces of concrete.

2.5 Objective

The main objective of this experimental research is based to study the contribution of bonding technique in civil engineering structures such through their bearing capacity:

- To exanimate the mechanical pathologies of different level of damage loads.
- To study the effect of repairing of damaged reinforced concrete corbel.
- To compare of strengthened and repaired reinforced concrete corbels by bonding composite carbon fabric.
- To study the effect of fatigue.
- To investigate and analyzes the different type of failures.

This experimental study is long and tedious process. It would allow to predict and avoid accidents due to sudden failure of this element of the structure. Furthermore, the data thus obtained allow a more accurate modelling of the structure.

3 Experimental Program

3.1 Experimental Model

Details and dimensions of corbels are showing in Fig. 7. In fact, the column supporting two short trapezoidal corbels cantilevering on either side was 150 by 300 mm in restrained section and 1000 mm long, Fig. 7a. Corbels had cantilever projection length of 200 mm, with thicknesses of 150 mm at both faces of column and the free end. All reinforced concrete corbel specimens have the same dimensions and are reinforced in the same way. The specimens Fig. 7b were tested using a single patch load with a shear span to depth ratio, a/d = 0.45.

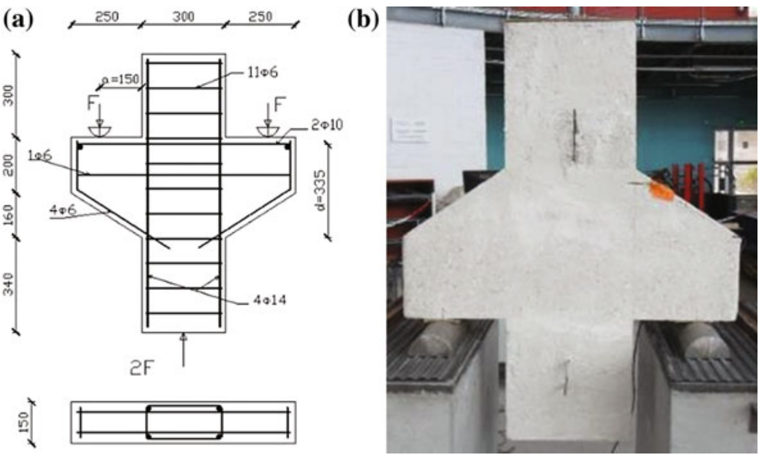


Fig. 7 Detail of short RC corbel, **a**—steel reinforcement, **b**—test specimen

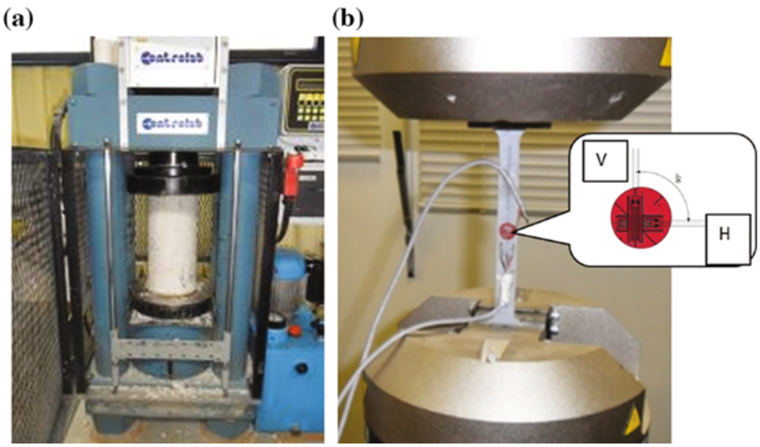


Fig. 8 Compression (**a**) and Tensile (**b**) tests for concrete and adhesive

3.1.1 Materials

Normal strength concrete materials are rolled gravel dried sand and ordinary Portland cement. The cement:sand:gravel proportions in the concrete mix were 1:1.73:2.93 by weight and the water/cement ratio was 0.50. Portland cement type CEM II was used and the maximum size of the aggregate was 16 mm. Five cylindrical concrete specimens 160 mm × 320 mm also are cast and tested when each short corbel is tested to determine the compressive strength of the concrete at 28 days of age. The Young's modulus of concrete is determined by the device below in Fig. 8a. So, in this paper, three captor sensors are fixed on cylindrical concrete specimen forming between them an angle of 120°. The results are given in

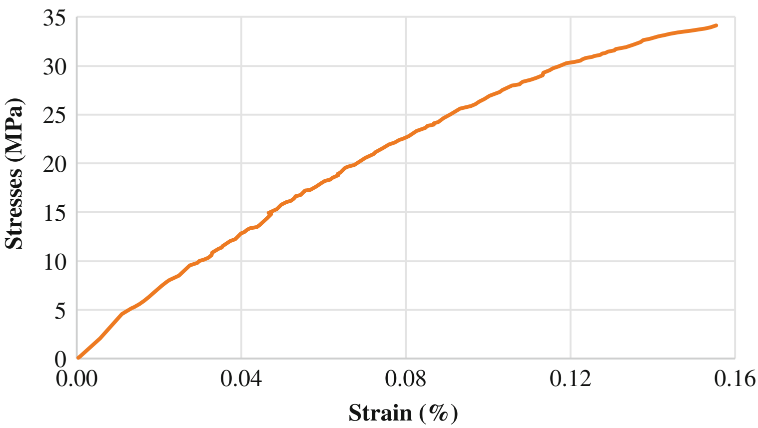


Fig. 9 Mechanical behaviour of concrete under compression loading

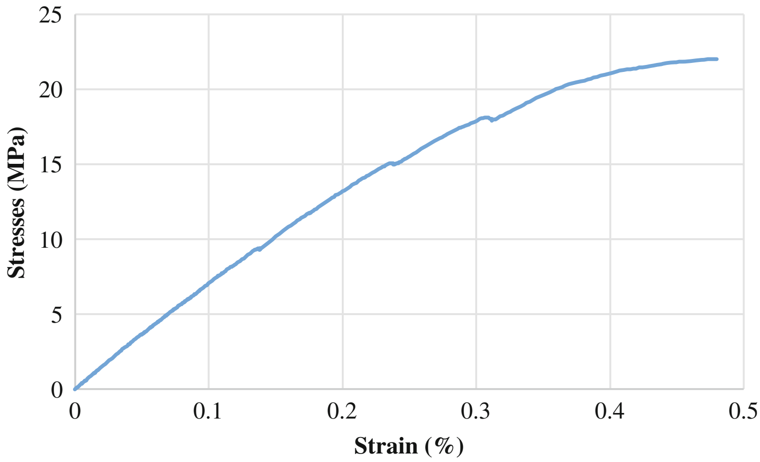


Fig. 10 Mechanical behaviour of adhesive under tensile loading

30 % of the concrete failure strength in compression loading. Figure 9 shows the concrete mechanical behaviour.

The glue used for the carbon fibre fabric by bonding technique was generally in two part systems: a resin and a hardener.

They were mixed just before their application on carbon fibre fabric. The glue had measured by tensile device testing (Fig. 8b). Results show an elastic modulus of 8.7 ± 1.6 GPa and yield stress of 19 ± 1 MPa. Their mechanical behaviour is showing in Fig. 10.

Steel bars, S500, of different diameters of 6, 10, 14 mm are used. The steel specimens are characterized by simple tensile test. The stresses f_c, f_u and the modulus of elasticity E_s values are presented in Table 1. The high strain of steel at the failure reached to 0.5 %. The experimental results obtained for carbon unidirectional fibre fabric and steel ∅10 are shown in Fig. 11. The results show that carbon composite plates have a linear elastic behaviour up to failure whereas steel bar has rather elastic nearly perfectly plastic behaviour. All results are given in Table 1.

The high elongation at failure achieved to 0.8 % for the carbon unidirectional fibre plate. The other characteristic properties of composite materials are presented in Table 1.

Table 1 Properties of materials

Material	Young's modulus (GPa)	Strength (MPa)	Poisson ratio
Concrete	30	33 [f_c]	0.25
Steel bar	200	610 [f_u]	0.30
Adhesive	4	36 [f_u]	0.41
CUF plate[a]	86	1035 [f_u]	0.45

[a]CUF plate: Carbon Unidirectional Fibre Fabric

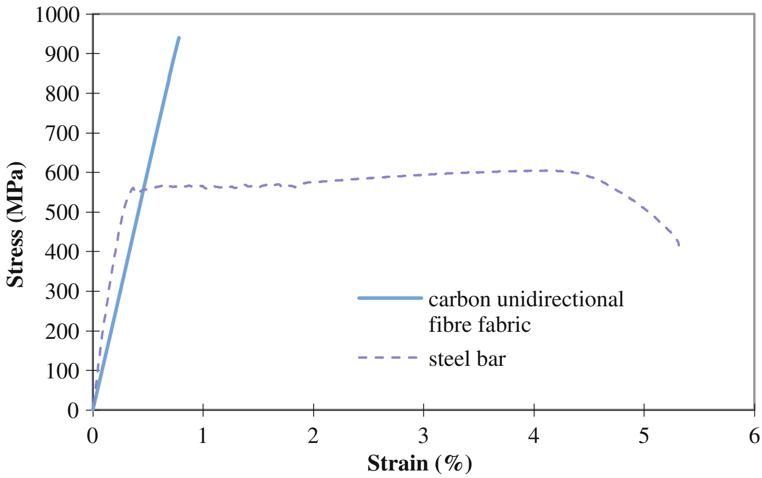


Fig. 11 Mechanical behaviour of Steel and Carbon fibre fabrics used

3.1.2 Preparation of Bonding Surface of Concrete

The surface preparation is of primary importance and calls for care Fig. 12a. It must be carried out to remove any loose or weak material, oil, grease etc. In this case grit blasting was being the good method. The four corners of the corbel are rounded to reduce the decrease in strength and to prevent tearing of the composite material. Preparation of surface should be carried out just prior to the bonding operation to prevent any contamination. After, the contamination can be avoided by applying the adhesive to the concrete and the carbon fibre fabric is applied with the brush, Fig. 12b.

The carrying out of this technique requires much care for a good reinforcement by carbon fibre fabrics. An effective way of eliminating the corrosion problem was

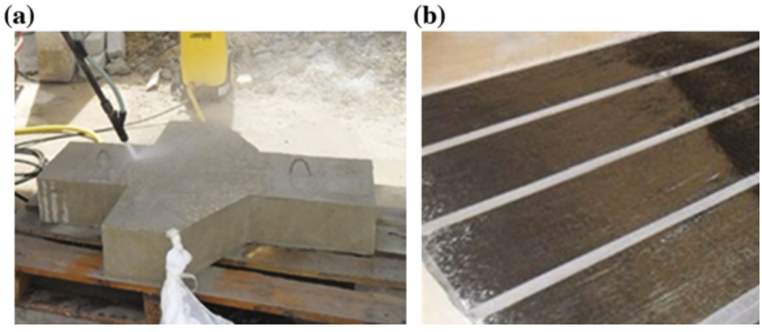


Fig. 12 Sandblasting of short RC corbel (**a**) and carbon fabric (**b**)

to replace steel plates with corrosion resistance materials such as composite materials. Many advantages are: low density, corrosion, mechanical properties, good resistance to fatigue and ease of handling.

3.1.3 Extensometer Technique Based on Strain Gauges

Deformation versus applied load is used to describe the local mechanical behaviour of structure. Load is applied in equal increments and at each increase, readings are taken of strains on concrete surface, composite fabrics and internal steel bars. All readings being at restrained section of corbel. Deformation is measured by strain gauges of 120 Ω with gauge factor of 2.09 %.

The strain gauges (G1, G2 and G3) have a length of 5 mm and used to measure strain on main reinforcement as well as horizontal strengthening, steel tie rod placed along tensile and compression strut. The strain gauges on corbel surfaces are placed in shear span between corbel and column. In fact, two gauges (GC1) and (GC2), length of 10 mm are placed on composite fibre fabrics surface and one gauge (GB1) length of 30 mm on concrete as shown in Fig. 13a, b.

The curves F = f(ε) describing local mechanical behaviour of composite plate, steel and concrete material. F is the applied load and the strain ε indicated by the gauge located at x. The change of slope dF/dε corresponds to the appearance of micro-cracks or a change of state. In the same way the change of sign of dF/dε corresponds to initiation of rapid crack propagation around of ultimate failure load of the structure.

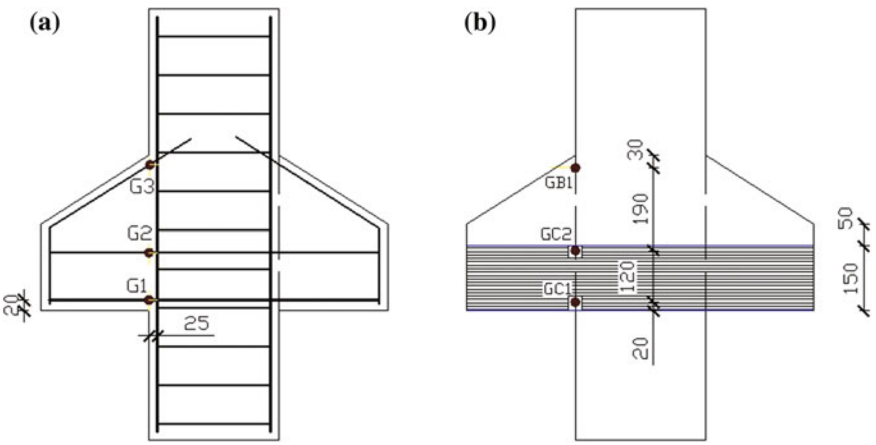


Fig. 13 Position of electric strain gauges, (**a**) on steel in the cross section, (**b**) on composite fabrics and on concrete surface in the same section

Fig. 14 Bending test machine with device of maximum to 1000 kN

3.1.4 Test Procedure

All corbels were tested in bending test span, Fig. 14. The slope of bottom face is selected such as the height of section, in which the application of resultant load point is greater or equal to half of high fixing section for all corbels shear tested. The tie steel of one corbel is continued to cross out the vertical column to form tie steel for the second corbel. In fact, this model ensures a right anchor sufficient given the length of post section, and secondly a better symmetry tensile forwarded to corbels. Indeed, it facilitates the testing device.

The principle of damage involve by mechanically loading taking account to different percentages rate of ultimate load of RC corbel. This different percentages corresponded to damage load. When once reached the value of damaged load, the specimen is unloaded. Afterwards, the same corbel is strengthened and loaded again until collapse. The ultimate loads and strain of materials such as concrete, steel tie and composite plates are compared and analysed.

In the first time were tested the control specimen without strengthened C0 and strengthened corbel CB3u. The second step of this experimental study was damage testing and repeating by wrapping with composite fibre fabrics. The last step was the dynamic test of fatigue with 1,000,000 cycles.

The reference specimen without strengthening is denoted “C0”. The letter “C” means the Corbel and 0 (zero) marks without strengthening. The damaged specimens are denoted C0_40, C0_60 and C0_80 %. The names of the strengthened test specimens is CB3u, made up as follows: The first letter “C” is as previously Corbel. So, the second letter represents the type of strengthening (e.g. B for Bandage). Then digit indicates the number of layers (e.g.: 3). The small letter point to finally the

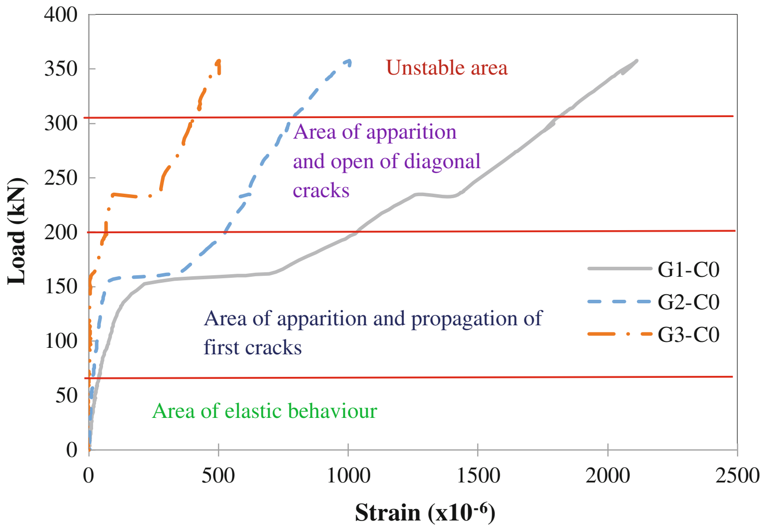


Fig. 15 Strain of steel bars in fixing section of RC corbel C0

type of composite material (e.g. u for unidirectional). The strengthened specimens after damage are indicated by CB3u_40, CB3u_60 and CB3u_80 %.

3.2 Results and Discussions

3.2.1 Reinforced Concrete Corbel

The reference specimen was without strengthening and was submitted to a vertical load to collapse. The ultimate load of RC corbel was 357 kN. The results show that cracking was started when the concrete strength reached at 4.5 MPa. The plasticizing of tie steel bars lead to a high strain beyond 2400×10^{-6}. Three specific areas can be identified from obtained curves, Fig. 15 in the restrained section: elastic area, apparition and propagation of first cracks area, apparition and open of diagonal cracks area. When diagonal cracks appeared, corbel enter in the unstable behaviour and requires special attention.

Indeed, the first part is characterized by the loss of elasticity of the concrete which would correspond to the appearance of the first bending micro cracks as such the curve G1-C0 in Fig. 15. At 150 kN, there would be a resumption of strengths by steel bars. This point is characterized by a bearing with increasing load. The second bearing on the curve correspond to the appearance of the diagonal crack.

Then, the results show that the strains are maximum in the above recessed section in the upper part. Progressively as one descends in the mounting section, the deformations decreases, Fig. 15.

In Fig. 15, the first major crack appeared at 130 kN and it was a vertical crack appearing approximately at the corbel face close to column side. The other crack was a diagonal crack almost at an angle of 45°; at a load level of 65 % of ultimate failure load. Diagonal shear cracks formed at a load level of 240 kN. As the load increased, this crack started to widen and propagated leading to failure. The maximum applied load was 357 kN.

3.2.2 Strengthening Reinforced Concrete Corbels

When the RC corbel is strengthened, the results show 82 % increase of carrying capacity. It was significantly increased by gluing carbon fibre fabrics on tensile face. Strengthened corbels are considerably stiffer than the basic section. Deflection of strengthened RC corbel is decreased to third. Yielding of the main reinforcement is hardly occurred at failure for all specimens. The load-strain curves of steel tie and concrete in compression area are shown in Figs. 16 and 17.

Figure 16 shown the local deformation in steel bar of strengthened corbel obtained by strain gauge G1-CB3u and compared to result of control specimen G1-C0. The results shown that strengthening improve the ultimate load. The deformation in composite fibre fabric is presented by strain gauge GC1-CB3u. So below 200 kN composite fabrics and steel bars deformed identically. In constant load 300 kN composite fabrics deform more than steel bar. In fact the composite resume deformations and highlight the effect of strengthening.

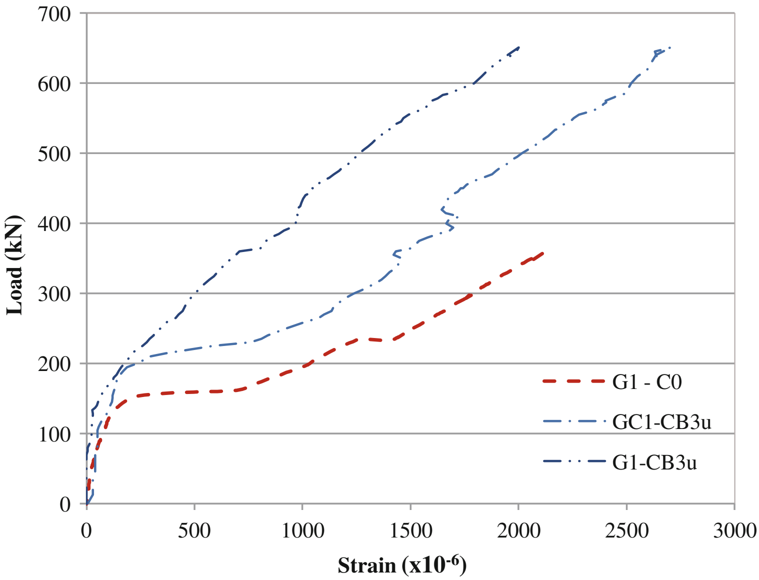


Fig. 16 Strains of steel and composite plate for C0 and CB3u corbels

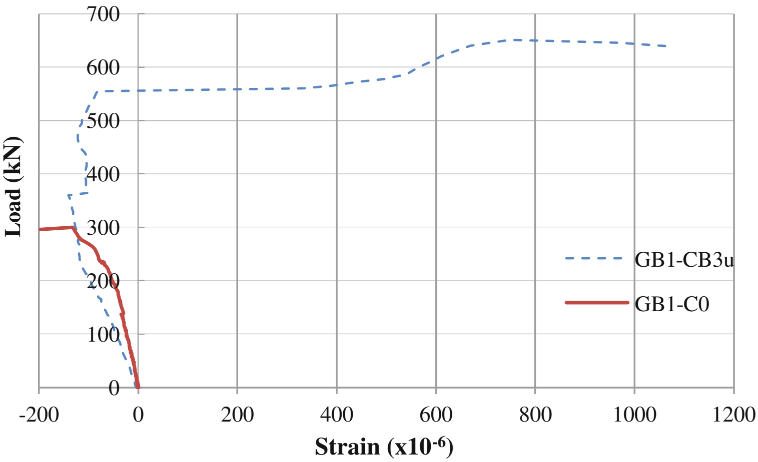


Fig. 17 Strains of concrete for C0 and CB3u corbels

As in RC concrete case, the results show three main fields were found as elastic field, cracking and recovery loading by the steel bar field, and the last field of rapid crack propagation until the sudden collapse of corbel specimen. The results are compared to those of reference RC corbels.

The curves of Fig. 17 describe the concrete mechanic behaviour in compression area. They are evolved negatively to normal compression sign. The concrete confinement effect by strengthening increases very remarkably the resistance of concrete in compression.

3.2.3 Design of Strengthened Reinforced Concrete Corbel

Analytical approach considers the bonded composite fabric as a tie rod and two load cases. A point load in Fig. 18 and a distributed load in Fig. 19 on the metal plate causing the existence of a concrete strut, Eurocode2 (2009).

Moment's equilibrium in write face of column at points A and B are:

$$M_A = F_v.a + F_h.a_h = C.a.\sin(\theta) \tag{1}$$

$$M_B = F_v.a + F_h(a_h + z_0) = F_s.z_0 + F_f(z_0 - \frac{a_f}{2}) \tag{2}$$

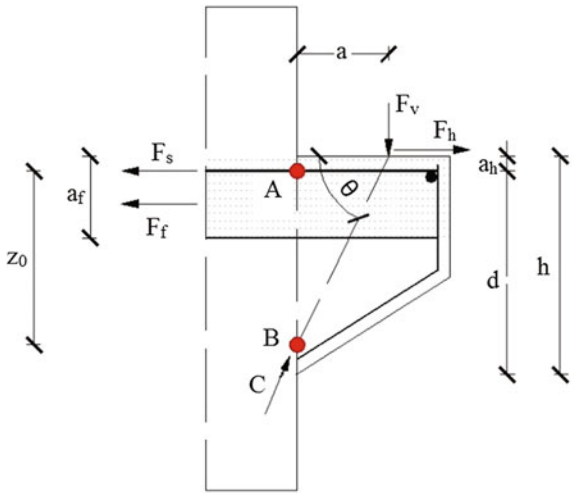


Fig. 18 Design of Strengthened reinforced-concrete corbel under load F_v

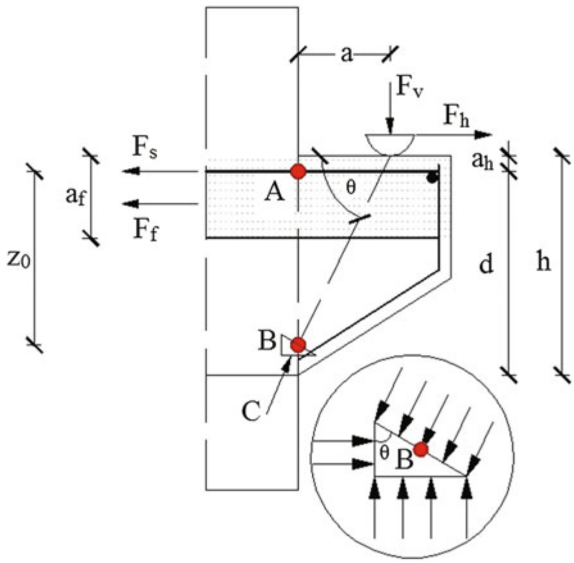


Fig. 19 Design of Strengthened reinforced-concrete corbel under bearing support load F_v

From Eqs. (1) and (2), one deduced:

$$C = \frac{F_v.a + F_h.\frac{a_h}{a}}{\sin(\theta)} \tag{3}$$

$$F_f = \frac{F_v.a + F_h.(a_h + z_0) - F_s z_0}{(z_0 - \frac{a_h}{a})} \tag{4}$$

where F_v = ultimate vertical force, F_h = ultimate horizontal force at corbel, F_s = horizontal force of steel, F_f = horizontal force of composite fabric, a = distance of F_v to face of column, a_f = width of composite fabric, a_h = distance from upper face of support force to steel tie position, h = height of corbel, z_0 = distance of strut bottom to horizontal axis of steel tie, d = effective depth of corbel and b = width of corbel section.

Considering the composite fibre fabrics as linear elastic behaviour until failure, the resultant strength can be expressed by:

$$F_f = A_f.E_f.\varepsilon_u \tag{5}$$

The area section A_f of composite fabric for strengthening is giving by:

$$\mathrm{A_f} = \frac{F_v.a + F_h(a_h + z_0) - F_s z_0}{(z_0 - \frac{a_h}{a})E_f \varepsilon_u} \tag{6}$$

where A_f = area of composite fabric reinforcement, E_f = elastic module of composite fabric and ε_u = ultimate strain of composite fabric.

The corbels can be studied using tie-strut model defined by tie: Nearest reinforcement of the upper face of corbel and composite fabric; and strut: rod compressed concrete element at an angle θ to the horizontal, starting from the axis cross of the vertical force F_v with the horizontal axis of the tensile steel upper and intersecting the plane of the vertical face of column.

The horizontal equilibrium of corbel internal strength is:

$$\Sigma\vec{F} = \vec{0} \tag{7}$$

Equation (7) can be writing as following:

$$C = F_f + F_s \tag{8}$$

Ultimate flexure moment M_u

$$M_u = F_v.a + F_h(h - d) \tag{9}$$

The strength reduction factor is taken 0.85 because the major action in corbel is dominated by shear stress. Then, according ACI code using shear friction theory, the resultant of compressive force of the concrete is:

$$C = 0.85 f_c b_w a_w \cos(\theta) \tag{10}$$

F_h is the ultimate horizontal force must be resisted by tension reinforcement in Eq. (12).

$$F_h = 0.2F_v \tag{11}$$

The equilibrium of forces allows writing

$$0.85 f_c b_w a_w \cos(\theta) = A_s.f_y + A_f.f_{yp} \tag{12}$$

The composite fibre fabric area can be determined as:

$$A_f = \frac{0.85 f_c b_w a_w \cos(\theta) - A_s f_y}{E_f.\varepsilon_{fu}} \tag{13}$$

where C is compressive force resultant of concrete, f_c is concrete cylinder strength, b_w is width of corbel, a_w is depth of concrete compression zone, F_s is tensile force resultant of steel flexure reinforcement, A_s is area of flexure steel reinforcement, f_y is yield strength of the steel bar reinforcement and f_{yp} is yield strength of the composite fabric reinforcement.

3.2.4 Damage Procedure

The main objective of damaged concrete is to investigate the effect of their repair. Knowing the ultimate load who is average value of 357 kN, obtained from three RC corbel test results, allows to choose the different damaged load. In the same way, three new corbels are damaged at F_d, 30, 40, 60 and 80 % of ultimate load F_R of reference corbel, Fig. 20.

When the RC corbel damaged at 30 % no visible cracks, Fig. 20a. Then the test is continued up to 40 % of F_R, where two bending visible cracks are appeared, Fig. 20b. The allowable stress of concrete in tensile is achieved at 4.5 MPa. Cracking evolves at 60 % of F_R, Fig. 20c. The last specimen was damaged at 80 % of F_R where the diagonal cracks emerged, Fig. 20d. Cracking evolves to reveal the diagonal cracks. All RC corbels are strengthened and tested up to failure.

The Fig. 21 shows the mechanical behaviours for damaged RC corbels load versus strain. The results highlights the presence of cracks when the curve slope changes.

Onto damaged RC corbel to 30 % of ultimate load, no visible cracks appeared. The new micro-cracks is indicated by change of slope of curve G1-C0_30 % in beginning. But for damaged corbel at 40 % bending cracks are beginning in the cross section. These cracks develop more in the case of curve G1-C0_60 %, see Fig. 21. However, RC corbel damaged at 80 % of ultimate load shows the bending and diagonal cracks.

3.2.5 Repair Reinforced-Concrete Corbels

Three reinforced concrete corbels (CB3u_40, CB3u_60, CB3u_80 %) were first damaged at various loading of 40, 60, 80 % relatively of the failure reference concrete corbel load. Secondly, damaged corbels were strengthened and tested. The value of corresponding load of 40, 60 and 80 % are respectively 143, 214 and 286 kN.

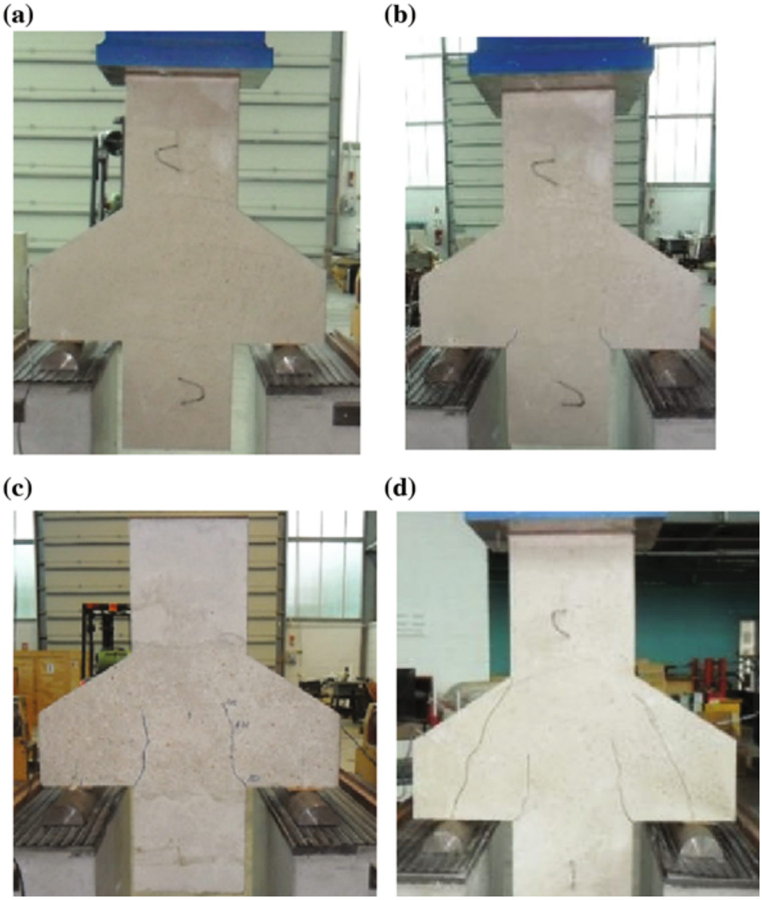


Fig. 20 Cracks of damaged corbels at 30 % (**a**), 40 % (**b**), 60 % (**c**) and 80 % (**d**) of ultimate load F_R before their strengthen

Figure 22 presents the results of damaged RC corbels at 40 and 80 %, because there are extreme cases and interesting points. The corbel damaged by 80 % of failure load was strengthened successfully below 17 % consider reference corbel C0. But the ultimate load of CB3u_80 % is reduced to 35 % consider the ultimate load of strengthened corbel CB3u.

However, mechanical damage of strengthened reinforced concrete corbel have an effect on ultimate load of reference corbel C0. With 80 % of damage, corbel repair was successful up to 17 % the ultimate load. In fact the strengthening can increase and improve the bearing capacity of the structure. The number of cracks was relatively insensitive by bonding carbon fibre fabrics. Yielding of steel bar in tensile zone was achieved before the corbel failure. Type of reinforced concrete corbel failure changed with bonded carbon fibre fabrics on reinforced concrete corbels. So, the choice of adhesive and fabrics is very important.

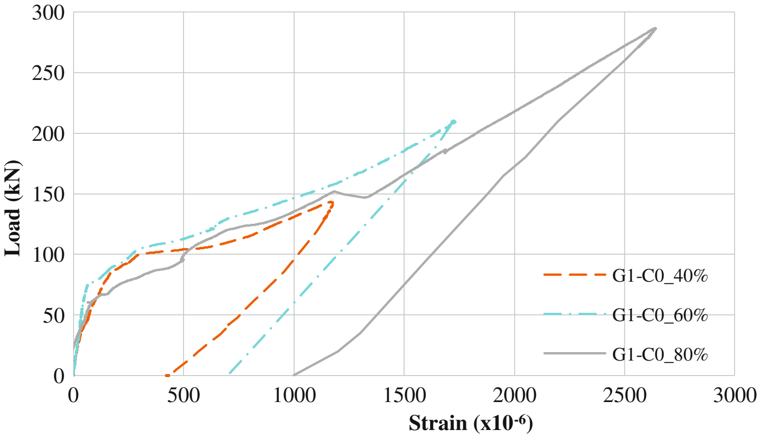


Fig. 21 Deformations of steel tie in the cross section

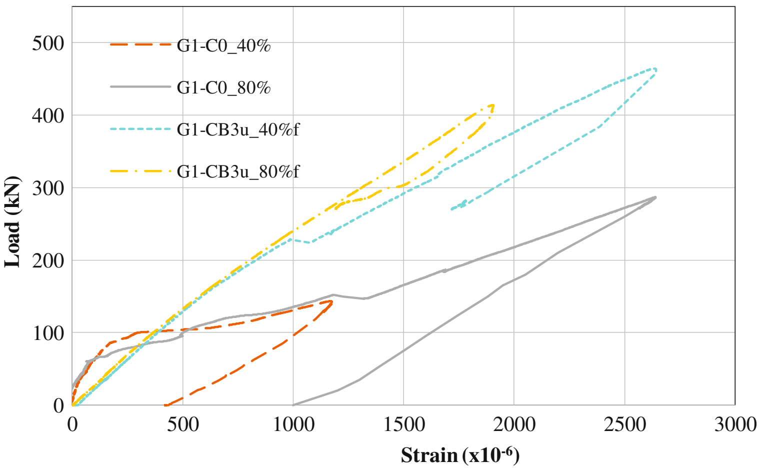


Fig. 22 Damage effect on corbels tested under bending control

Global elastic range disappears in the case of repair of damaged corbels, Fig. 22. The repaired is successful.

3.2.6 Fatigue Damage of Reinforced-Concrete Corbels

Fatigue is a process (series of mechanisms) which under the action of stresses or deformations in varying time changes the local properties of the material and can lead to the beginning cracking and eventually the failure of structure (Norman and Dowlings 1993; Vassilopoulos and Krller 2011; Ivanova and Assih 2015).

In industry and civil engineering, to estimate the degree of damage related to material fatigue, is often used by Wohler curve. For graphic, it is generally carried out simple tests of subjecting each sample to cycles of periodical strength, constant load magnitude, it's fluctuating around an average set value and noted the number of cycles at which the beginning crack is observed, called that number of cycles to failure. Fatigue is characterized by including a stress that may be below of yield strength of the material. The main steps of fatigue crack initiation are (if defects are not already present in the material), the propagation of cracks and the collapse of structure.

Indeed, this part of study focuses on the behaviour of reinforced concrete corbel bonded carbon fibre fabrics under cycle loading up to one million. When the first crack is created, the cycle load is applied for one million to follow the propagation of this crack to failure.

The results of previous tests show for unreinforced corbels, the ultimate loads at 357 and 651 kN for strengthened corbels. In fact, the cycle loads are made from 71 to 130 kN for corbels without strengthen and 143 to 260 kN for strengthened corbels. The frequency is set to 0.5 s. The shape of applied load was a triangular wave. Knowing the load-strain curve, an average value of load is defined. This value is corresponded to average load in between 20 and 40 % of maximum tensile strength. The magnitude and number of fatigue of the repeated loads are fixed to one million cycles.

Table 2 shows values of ultimate load F_u, minimal load F_{min} and maximal load F_{max} in between 20 and 40 % of maximum load F_u. In fact, with a cyclic load in this range, the development of crack can be followed. The previous experimental study identified the occurrence of cracks and their propagations.

The results allowed to know when the first crack appeared. This crack is created before fatigue loading. The changed slope is proof that a crack is created. A repeat test load discharge repeats growing shows the same pace that undamaged corbel with a drop of about 10 % of the ultimate load. This study needs to follow crack propagation. Initially, the reference corbel C0 is charged up to the initiation of the first crack. It is characterized by a change in slope and then a second time, is applied a triangular signal with a mean stress up to one million cycles. Triangular signal is applied with a mean stress. Next, short reinforced concrete corbel is subjected to cyclic loading up to one million cycles. After one million cycles, reinforced concrete corbel was static loading until failure.

Table 2 Conditions of fatigue loads

	F_u (kN)	F_{min} (kN) 20 %	F_{max} (kN) 40 %
Reference corbel: C0	357	71.4	142.8
Strengthened corbel by wrapping: CB3u	651	130.2	260.4

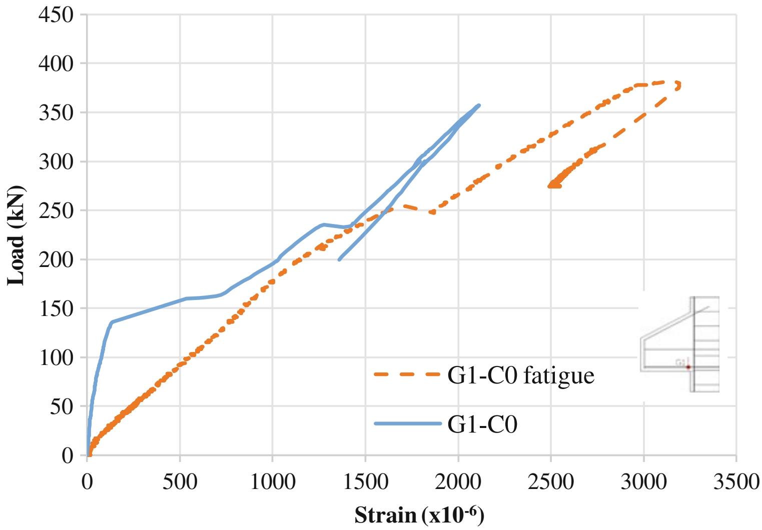


Fig. 23 Strains of steel for C0 and C0 fatigue corbels

Table 3 Comparison of ultimate loads for static, damage and dynamic tests

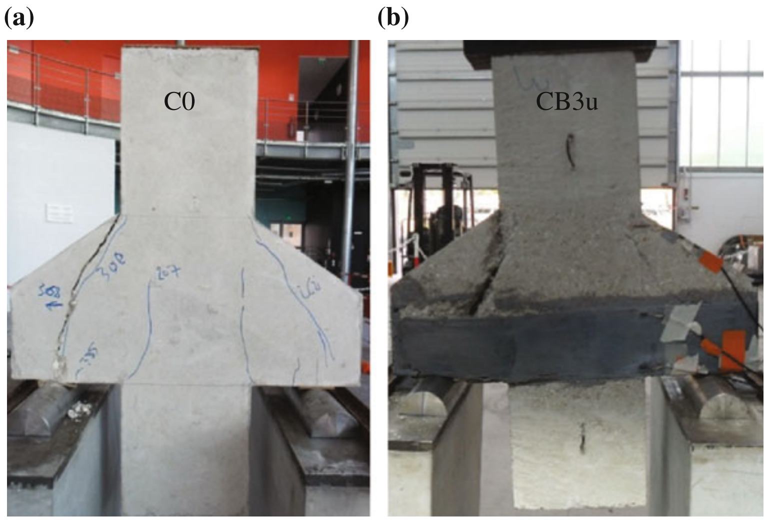
	F_d Damage load (kN)	F_{max} Static test (kN)	F_{max} Dynamic test (kN)
C0	–	357	381
CB3u	–	651	584
CB3u_40 %	143	520	–
CB3u_60 %	214	480	–
CB3u_80 %	286	420	–

Secondly, it was the same proceeding with strengthened reinforced concrete corbel "CB3u". Figure 23 shows the comparison of steel local deformation of RC corbel without strengthening under static and dynamic loading. The effect of fatigue shows de disappearance of the global elasticity of the structure. But the fatigue not reduce the load bearing capacity of the structure.

3.2.7 Modes of Failures

Table 3 presents the ultimate strengths of corbels in statics, dynamics and damage tests. The results show the bonding technic appears as a good alternative in the field of building structures.

Specimen C0, without strengthening—the ultimate load failure the specimen C0 was 357 kN, Table 3. Type of failure is classic shear failure with two major cracks,



C0-Splitting Flexion failure

CB3u-Shearing and splitting failure

Fig. 24 Cracks and failures of corbels C0 (**a**) and CB3u (**b**)

as depicted in Fig. 24. The first micro cracks appeared at 60 kN. They were a vertical cracks approximately at the corbel face close to column side. However the other cracks were diagonal line at an angel of 65°. Where corresponds to 66 % of the ultimate failure load. Diagonal shear cracks appeared at 235 kN. In fact as the load increased, the cracks started to widen and propagated leading to failure (Fig. 24a).

Specimen CB3u with strengthening—To study the effect of strengthening RC corbels, three layers of carbon fibre fabrics were bonded by externally by wrapping. The first micro cracks started at the load of 140 kN. A diagonal shear crack appeared almost at an angel 45° and it started at the bearing step. This diagonal crack caused the collapse of the corbel, at 651 kN as such as Fig. 24b. The mode of failure is shearing and splitting.

The repair specimen modes failures are presented in Fig. 25. The results show three mode of failure: Splitting failure (Fig. 25a), Shearing and splitting failure (Fig. 25b), and Shearing failure (Fig. 25c). After strengthening to 40 % of mechanical damage—CB3u_40 %, the ultimate load is increased by 45 % compared with the reference specimen C0. For CB3u_60 % corbel an increase of the ultimate load by 35 % and less than 20 % of the ultimate load to 80 % of mechanical damage CB3u_80 %.

The cracking modes change slightly with the presence of composite material. For example for the damaged corbel to 80 %, the rupture occurs by shearing failure with two cracks.

(a) CB3u_40%-Splitting failure

(b) CB3u_60%-Shearing and splitting failure

(c) CB3u_80%-Shearing failure

Fig. 25 Cracks and failures of damaged corbels

Fig. 26 Reinforced-concrete corbel after one million cycles of loading test

The results showed that after fatigue testing a new crack is appeared in reinforced concrete corbel. Their propagations are different into static tests (Fig. 24a) which proves the fatigue effect with the appearance of a diagonal crack in the concrete column, see Fig. 26. The difference is depending on the type of loading.

Strengthened corbel after one million cycles has no visible cracks, when the corbel is strengthened by wrapping, Fig. 27. In fact, the results show the same failure cracks as CB3u static test, see Fig. 24b, where the specimen ruptured in shearing and splitting failures.

Fig. 27 Strengthened reinforced-concrete corbel after one million cycles of loading test

4 Conclusions

In the repair or in the rehabilitation of concrete structures, different techniques can be adapt as solutions by addition or injection of fresh concrete or steel with their pros and cons. Repair of concrete structures by bonding technique with composite materials is another solution. Corbel is a reinforced concrete member is a short-haunched cantilever used to support the reinforced concrete beam element. This study contributes with strain gauges techniques measurements local behaviour of corbel. The contribution of strengthening or repair short RC corbels is very significant and interesting.

The result shows an increase of ultimate load capacity of structure to 82 % by bonding carbon fibre fabric. The use of strain gauges allow the more local study of the mechanic behaviour of the specimens, as steel bars, composite fibre fabrics and concrete. This technic is been validated by Chatelain (1969). Three main areas are found: area of elastic behaviour, area of apparition and propagation cracks and area of apparition and open of diagonal cracks.

The damage study was examined through three steps: Minor damage at 40 % of ultimate load with small areas of concrete lost, moderate damage at 60 % of ultimate load with minor cracks and severe damage 80 % of ultimate load with major cracks. After strengthening the results show that the repairing was successfully up to 17 % compared to reference corbel C0. This allows mechanical damage to work together steel and composite material, although it remains well below the capacity of a composite plate.

Repair or strengthen by bonding would be the real solution in the field of civil engineering and building to rehabilitate structures and buildings. Consider the mechanical behavior in the case of repair, the cracks are initiated and caused three mode of failure. Then the elastic field of concrete disappears.

The fatigue test had a definite influence on the cracking of reinforced concrete corbel and modified stresses in the specimen and their cracking. Of course, in the case of reinforced concrete corbel, after fatigue damage, the ultimate load is substantially the same as to undamaged reinforced concrete corbel. The results show also that, the effect of fatigue on strengthened short RC corbel, in a lower tensile strength by 10 % relative to strengthened short RC corbel load under monotone static test.

The experimental results of this study are interesting and must be completed by further tests to highlight the significant damage parameters in the numerical and analytical modelling of strengthened specimens.

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Pathologies in Reinforced Concrete Structures

E. Garrido Vazquez, A. Naked Haddad, E. Linhares Qualharini, L. Amaral Alves and I. Amorim Féo

Abstract There are healthy structures and diseased structures. The diseased ones can be described as those that had problems in one of the stages of its development (in this case, design, implementation, maintenance and repairs). Problems can also be caused by the use of defective or improper materials. The rapid growth of the construction sector in the country, the development of new construction techniques, the lack of specific technical standards and unintended failures of malpractice cases have been observed in reinforced concrete structures generating performances below expectation for initial proposal project. This set of factors generates a phenomenon called "structural deterioration". Among the causes of deterioration are the "natural" aging of the structure, accidents, design errors, failures among the building phase, among others. This paper aims to present a case study that exemplifies some of the most important types of pathologies in concrete structures, making a detailed analysis of its possible causes, its impact on the final performance of the building, and plausible actions to mitigate or even eradicate the pathology in question. The case study was absolutely essential to clarify the information obtained by reading and ratified in practical analysis. The pathologies were identified from the analysis in situ and by analyzing photographic history of the building, divided by categories where the following topics will be highlighted: cause, consequence, and treatment. Thus, it is extremely important to accomplish studies to equalize

E. Garrido Vazquez · A. Naked Haddad · E. Linhares Qualharini · I. Amorim Féo
Escola Politécnica/UFRJ (POLI/UFRJ), Rio de Janeiro, Brazil
e-mail: elaine@poli.ufrj.br

A. Naked Haddad
e-mail: assed@poli.ufrj.br

E. Linhares Qualharini
e-mail: qualharini@poli.ufrj.br

I. Amorim Féo
e-mail: italo.feo@poli.ufrj.br

L. Amaral Alves (✉)
Centro Federal de Educação Tecnológica Celso Suckow da Fonseca (CEFET), Rio de Janeiro, Brazil
e-mail: aalves.lais@gmail.com

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effective ways to predict, analyze, and address the pathologies of structures, and in this particular case, reinforced concrete structures.

Keywords Reinforced concrete structures · Pathology · Performance

1 Introduction

The term pathology is used in civil engineering when a loss or decay in performance of a product or component of structure occurs. Therefore, it can be said that a structure with any deterioration presents a pathological symptom or develops pathology. According to Carmo (2000), pathology in construction can be understood, in analogy to medical science, as the branch of engineering that studies the symptoms, manifestations, origins and causes of diseases or defects that occur in buildings.

According to Souza and Ripper (1998), pathology in buildings involves a multidisciplinary evaluations field for the study of the origin of the problem, with its diverse mechanisms manifestation.

Regarding reinforced concrete structures, for a symptom to be considered pathological it must compromise some of the building requirements. If the mechanical ability is affected, the pathology interferes directly on the resistance, according to calculation and design settings. If the anomaly is considered functional, the ability to adapt or not the use of the structure to its pre-established order is compromised. At last, considering the aesthetic requirement, the pathology must occur in case of predefined curves, or on developments in exposed concrete and large structures (Cánovas 1988).

Thus, there is a relation between the pathology condition and the performance of the building, and the evaluation is dependent on the behavior of the presented structure.

In addition to the mechanical, functional, and aesthetics ability, the analysis of the pathology also considers two essential aspects: time and exposure conditions. This associates the condition with the concepts of durability, lifespan and performance.

The builders and, mainly, the construction clients, expect that structures, especially RC, have long lifespan, reducing costs on maintenance and repairs. Although concrete has excellent durability, inevitably, the structure will lose some characteristics over time by the strong interaction with the environment.

For Sarja and Vesikari (1994), generally, the term durability can be defined as the capacity of a building, component, structure or product to maintain a minimum performance at a particular time, under the influence of aggressive agents.

Specifically for concrete, the concept of durable is given by s the capacity to resist weathering, chemical attack, abrasive wear or any other deterioration process, retaining its original shape, quality and usability, when exposed to the surrounding environment (Helene 1988).

The Brazilian Standard NBR 6118 (ABNT 2003), despite claiming that the concrete structure should maintain its security, stability and capability in service during its lifespan, does not yet specify what that period should be. The difficulty of introducing the “time” factor in addressing the durability of concrete or concrete structures depends on the complexity of the deterioration mechanisms involved (Souza and Ripper 1998).

Thus, to say that concrete is durable, it would be necessary to set the minimum performance required for the material in a certain range of time, to be reached within an environment that always interacts with the reinforced concrete structure.

The loss of performance may not be associated at the structural level, which is the most serious and is directly related to the stability of the building and the safety of users, but may compromise also under the aspect of comfort or from the visual and aesthetic point of view.

Reinforced Concrete is the most used type of structure in Brazil. Structures have a determined lifespan and require maintenance over time. To delay the most of this necessity, it is important to control possible pathologies that may attain these structures. This study aims to present a case study that illustrates some of the most important types of pathologies in concrete structure, making a detailed analysis of possible causes and credible solutions to mitigate, or even eradicate the anomalies in question.

This paper identified the pathological manifestation in three distinct phases, referred to as project and interpretation, execution, and use of materials. In the case study, it is possible to assign causes, consequences and appropriate solutions to certain conditions in reinforced concrete structures, identifying the reason and the impact of the problem. Thus, the proposed solution would address, mitigate the effects of the problem and prevent the emergence of similar pathological symptoms.

2 Main Causes of Appearance of Pathologies on Concrete Structures

This section describes the main causes of pathological manifestation in reinforced concrete structures, in three distinct phases, referred to as project and interpretation, execution, and use of materials.

2.1 Failure in Project and Interpretation Phase of a Concrete Structure Project

The structural conditions of a building can be traced at different stages of their lifespan, starting with their design. Each type of use of a building requires different and particular care. There are different types of calculations, safety factors, and care for a building that hosts a library, a theater or a residential building, for example. If any information is ignored in the embryonic phase of the project, the possibility of having some pathology in the structure increases.

It is extremely important that, at the initial stage, the Technical Standards are followed, and, in case of not applying the requirements of the standards, have the justification. Each calculation step may interfere with the functioning of the structure, and can be decisive for the occurrence of problems such as cracks, fissures, gaps, etc. (Sarja and Vesikari 1994).

However, in many circumstances, a good design can be observed, and the structure is calculated correctly, but the defects, when analyzed, indicate that there were errors on behalf of designers who passed the project for the execution plants, that lead to a misinterpretation of the plants, etc. In fact, between the projects and the execution, there are mistakes that can be avoided when making a careful review to rectify whatever is necessary before the start of the work.

According Ripper (1996), when in doubt or in case of design flaws, the designer should be consulted, because the decision should account the purpose of the construction element in question. In exceptional cases, only an engineer can make the necessary arrangements, knowing how the various components of the reinforced concrete structure works. The field engineer must decide only when confident of the solution.

2.2 *Execution Faults (Form and Shoring, Reinforcing Step, Concrete Step and Concrete Curing Step)*

Forms and shoring are fundamental to ensure that a structure or any concrete piece can fulfill its function as determined on the project, and its execution is the key part to the success of subsequent activities. Pathologies caused by poor execution in this step can cause undesirable effects on the concrete, producing hollow spaces, undulations and deformations. (Sarja and Vesikari 1994). To Canovas (op. cit., pp. 130–131), these unwanted effects can be summarized in Table 1.

There are also pathologies which may be considered as consequence of lack of control in cleaning, such as, employment of dirty forms with mortar or cement paste remnants from previous uses; placing cleaning windows at the bottom of the forms of pillars, etc.

Table 1 Side effects on reinforced concrete structures

1	Cavities groups shaped stones nests, due to segregation, poor compression or paste leaks through the joints of the mold
2	Detachments by concrete adherence to the mold
3	Deformations due to deficiencies in the alignment of the mold
4	Deformation of the mold due to concrete weight

Adapted from Cánovas, op. cit., pp. 130–131

Ripper, E. (op. cit., pp. 18–21) says that there are some necessary precautions to achieve stiffness of forms and obtain concrete as projected, listed in Table 2.

Reinforcement placement errors can occur in the structures and generate pathologies such as inefficiency and poor positioning.

Inefficiency of reinforcement placement may occur due to poor human resources, distraction, or incompetence of the professional appointed to carry out the activity. A conference is essential to reduce the probability of error.

Regarding poor positioning, it should be noted that all reinforcement project must specify the required distance between two bars, or the coatings required for the proper functioning of the structure. The field must also have devices that help workers maintain proper positioning, such as crabs, spacers, pads, etc. It is

Table 2 Precautions at the moulding stage

Structure	Precautions
Pillars	Predict bracing in two directions perpendicular to each other (this is usually done only in one direction)
	The bracings can receive tensile stresses, so must be firmly secured with enough nails in connection with the mold and the support on the ground
	In the case of high pillars, provide bracing in two or more points. In long bracings provide shoring with battens to prevent buckling
	Leave at the base of the pillars a window for cleaning. In the case of tall pillars, attent to intermediate windows for concrete steps
Beams	Check that the molds have the moorings, shoring and bracing (inclined side stanchions) enough to not suffer displacement or deformation during the casting of concrete
	Special care of the supports on the ground to avoid the discharge, and consequently, the bending beams and slabs
	For side molds (especially in the case of high beams) and walls (retaining walls, curtains) also provide good lateral bracing with fixation between the top of the vertical strut and the battens or to the floor or ground
	On beams of large span dislocation should be predicted. When not indicated in the project, can be performed with about 1/300 of the span
Slabs and joints	The joints between boards and offset plates should be sealed with plastic mass (even if poor quality). It is important to place the tablets to the side of the core facing towards the inside of the molds to prevent the joints from opening
	It is recommended that the closing of the joints only slightly before the concrete casting because, when exposed to the sun, the molds begin to suffer deformations
	Cleaning and applying release agent to formwork before concrete casting, not to cause distortions on the structural elements (which leads to the need for larger mortar fillers and consequently overweight of the structure)
	Failure on the tightness of molds makes the concrete porous because the cement paste leaks through joints and cracks
	Not allow premature removal of the formwork and shoring, which would result in undesirable deformations in the structure and, in many cases, severe cracking

Adapted from Ripper, op. cit., pp. 18–21 important to note that the Brazilian Standard provides minimum coatings for different types of structures as well as distribution and mounting brackets to help the designer and hence the performance of the structure.

A chronic problem that can affect the performance of the structure is the movement of people in reinforced slabs. This fact, in addition to harm both the coatings and the spacing between bars, may damage the positioning of the bars, bringing numerous problems to the final product.

According to Helene (1988), a good coating, with high compactness concrete, without nests, with adequate and homogeneous mortar content, ensures, by impermeability, steel protection from the attack of external aggressive agents.

During the concreting step, failures can occur in the concrete density that can generate different pathological symptoms. The most frequent problems are nests of stones and bubbles.

With the use of a motor vibrator, during the execution of concrete, it is important to compact the concrete while being released. This procedure ensures the greater compactness possible for the concrete, which is important for the concrete to reach, in its final state, the required strength. The compacting of the concrete is also known as vibration or compression.

According to Coutinho *apud* Helene (1988), wall effect means that the mortar drains along continuous surfaces limits that restrict the concrete, such as molds and armor. This movement can only be achieved at the expense of the mass impoverishment of the interior of the concrete (op. cit., p. 23).

It should be noted that the vibration should be applied uniformly throughout the mass of concrete. Both extremes are undesirable, parts not enough compacted, and should parts with excessive vibration. The latter can cause breakdown of concrete components, which is also harmful to final performance.

The use of immersion vibrators (those which are put directly in contact with the concrete mass) should be introduced in an upright or slightly inclined position, but never greater than 45° from vertical axis, in order to maintain uniformity the concrete. The duration of vibration depends on the concrete, ensuring a good mixing of aggregates, but avoid a long exposure should be avoided, because it can lead to disaggregation of concrete.

Cánovas (op. cit., p. 129) affirma that a vibration poorly executed can cause problems in the concrete, which appear as different pathological symptoms, though the most common are the nests of stones and bubbles.

Sometimes the vibrator does not compact all layers, as required. In this case, it creates an interface between layers, generally weak, formed by the mortar that was not hit when vibrated at the lower layer and the aggregate at the bottom of the new layer.

Canovas also warns that an undesirable effect which can happen during bad performed vibration is the loss of concrete adherence with armor; another error, is to put water in the concrete, on the premisses that although the characteristics of concrete worsens with water, it can improve with vibration. This generates concrete laminated with excess paste on the surface and lower layers of very poor quality (ibid., pp. 129–130).

2.3 Concrete Joints (Cold Joints)

In all concrete construction, the ideal is that concreting is continuous, but often this is not possible. In addition, some joints are necessary and required by the structural engineer or consultant, to prevent any cracks caused by shrinkage.

The joint is not always given due attention. In many cases it is improvised in the field. This important decision is often left in the hands of workers who know little of distribution efforts in the structures. The concrete joints are so important that it is mandatory that are provided by the project, with the endorsement of an engineer. When not provided in the project, it should be done in the field under supervision and with the approval of the engineer responsible.

Dias (1990) indicates, as shown in Table 3, the following locations for the execution of the concrete joints.

Before performing the union of the joint should, the effects of shrinkage should be prevented and, therefore, wait until ensured that the concreted part has deformed freely.

The surface of the joint should be treated, to guarantee that the constructive discontinuity that the joint creates, does not result in discontinuation of the structure, in order words, ensure that the structure fits the constructive difficulty and does not present efficiency problems.

In concrete healing phase, it is necessary to promote hydration of the cement. According to Neville (1997), healing is the name given to the procedures resorted to promote the hydration of cement and consists on controlling the temperature and moisture flux into to the concrete (op. cit., p. 325). To Dias, healing aims to keep the water inside the concrete mixture, to complete hydration of the cement. (op. cit., p. 270).

In general, the aim of the healing of concrete is to keep the concrete as close to saturated, until the cement hydration products, to a desirable condition, fill the spaces, initially filled with water. Normally, on the construction site, healing is stopped before the maximum hydration possible occurs.

For a good concrete, it is necessary to have a well dosed mixture, casted and compacted, as well as, during healing and hardening, guarantee the appropriate

Table 3 Execution of the joints

Structure	Joint location
Pillars	A few centimeters below the top, before the junction with the beam
Beams	In the mid-span or the middle third of the beam
Reinforced slabs in one direction	Located in the middle and in the normal direction of the span. If located in the direction of the span, must be positioned in the middle third of the slab
Reinforced slabs in two directions	In the middle third of the slab (for both gaps)
Joint between slab and beam	It is necessary to ensure a good connection and if necessary, use additional armor to absorb the shear stresses

Adapted from Dias (1990)

conditions of temperature and humidity so that the hydration reactions take place normally, preventing the appearance of superficial or deep cracks, or decreases on resistance.

As temperature and humidity are important to the hydration reaction, healing has, as main purpose, to avoid water lacking to the concrete and ensure adequate temperature.

2.4 Material Failures

In definition, reinforced concrete is a mixture of cement, aggregates, water, possibly additives and steel. The latter gives the piece the necessary fiber to complete the structural system due to its good tensile strength. When one of these components does not comply with the recommended characteristics, arisings of pathologies (cracks and fissures) may occur, and in extreme cases, can even lead the structural piece to ruin (Sarja and Vesikari 1994).

According Souza and Ripper (1998), some common cases of incorrect use of non-standard materials can be listed as, i.e., concrete with tensile strength lower than specified, by error in the supply of concrete, or error in the execution of the concrete piece on the field. Importantly, the concrete structure is sized to a concrete with a determined resistance. This resistance is verified by samples (specimens) that are removed from moments before concreting. The control should be strict and resistance problems cannot occur.

Another case of incorrect materials is the use of steel with different specified characteristics, for example, diameter, steel type or quality of the material. The diameter specified in the project should be the same used, on the risk of compromising the structure, which would cause a number of complications, such as cracks, fissures, or greater shock. It is important to note that the equipment used has no rust or any sign of wear, either by exposure to inclement weather or poor storage of the bars.

In addition to the problems already listed, the improper use of additives is also common, changing specific characteristics, especially those related to strength and durability. In some cases, it is necessary to use of additives such as accelerators or retarders of hardening to cast the concrete adequately. What is reprehensible is the indiscriminate use of these additives, without dosage monitoring by engineer, or specialist. A dosage error in this case may bring difficulties to achieve the required strength, or cause undesirable cracks on the concrete.

3 Presentation and Analysis of Results

The case study was the project “Cidade da Música”, located in the city of Rio de Janeiro. From the structural point, this building has several characteristics, starting with the double reinforced walls, with 32 mm steel, and a 50 MPa concrete, in a piece full of angles and curves. The building is basically composed of four floors, which are: underground, terrace, floor blocks (+10 m) and roofing (+30 m).

3.1 Structural Conditions in the "Cidade da Música" Building

The *Cidade da Música* was one of the biggest projects carried out in Brazil in recent decades, both in technical, financial, or ideological aspect.

The building is divided into functional assemblies located between the planes of the esplanade and coverage, in the quotas +00 and +30 m, respectively. The main blocks are the chamber music hall, the Administration, the dressing rooms, the Electroacoustic room, the cinemas, the media library, the restaurant and the Great Room, considered the most important of all equipment of the complex.

The terrace and roof are developed in five independent blocks, which house rooms with related concepts. The four floors that define the building are considered the main structure.

Secondary structures are the remaining structural elements (slabs, beams, stairs, walls and pillars) that compose the five blocks between the level of the terrace and coverage.

Translated in numbers, the main structures are supported on walls and 20 pillars, which rest directly on footing foundations or deep foundations (excavated and pile caps). The walls develop with gradual increase in the size, initially with reduced dimensions over the foundation blocks. The pillars, some of them inclined, also begin on the foundations and reach the coverage with a constant section.

The secondary structures rely on the pillars that are on the foundations, or pillars and walls that are born at level +10 m, or yet, hanging on the coverage.

According to observations made on site, and analyzing photographic history of the building, a list of structural pathologies evident in the execution can be observed. These conditions are listed below in the form of study cases, where topics will be highlighted as causes, consequences, and solution.

3.2 Case 1: Constructive Methodology Employed in the Enterprise

This pathology developed in the project DESIGN phase. To give greater agility in the process of implementing the structure, framework towers and iron beams were used to anchor the slab +30 (Fig. 1). Using this material, two problems would be solved. The first, and most important, is the fact that the slab could be performed without the main pillars, which are their main support, and this would cause both the slab as the internal compartments of the work to be performed simultaneously.

Fig. 1 Towers and beam from methodology (Chamber music)

Furthermore, the mesh that would be used to anchor the slab without this methodology would make unfeasible any movement in the outside areas.

The methodology used was quite interesting and definitely helped considerably in obtaining deadlines that are more acceptable. Unfortunately, a serious visual aesthetic pathology was observed when the auxiliary structure was removed. At several points, the marks of the bases of these structures were quite clear in the concrete (Fig. 2).

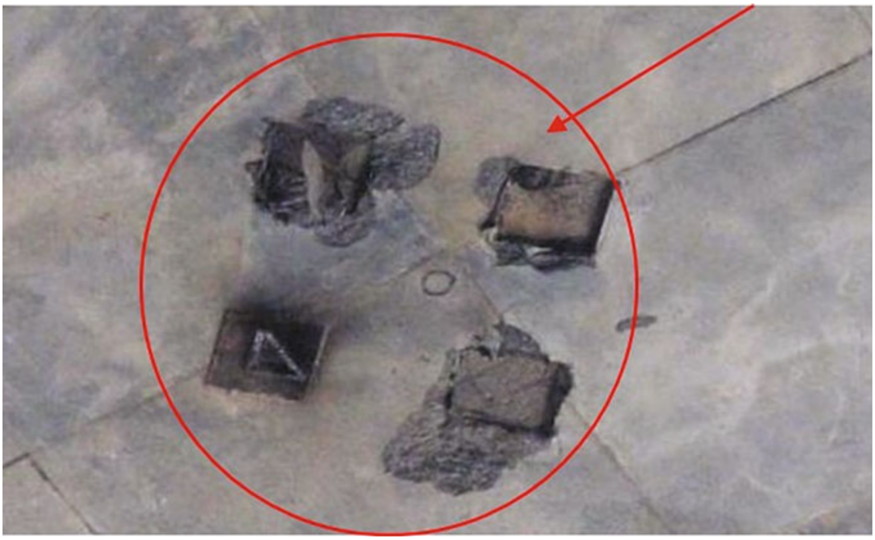

Fig. 2 Marks on the slabs of the methodology towers

Table 4 Pathological manifestation (case 1)

Pathological manifestation	
Cause	Use of constructive methodology incompatible with the proposal of bare concrete. It is a condition generated at the time of project design, which is not suited to the proposed structural element
Consequence	The consequence is purely aesthetic. There is not any kind of change regarding strength. The most serious problem is the difficulty in repairing a slab of this size
Solution	To resolve this pathology, it is necessary to clean the site and remove any remaining material that may still be integrated on the concrete. Then, it is necessary to correct the geometry left by the base of the methodology. Finally, the regularization takes place, with a mortar of the same nature as the original concrete. It is important to note that, unfortunately, there is no way to achieve the original aspect of the piece in any treatment used. This solution is a way of softening the pathology generated, but is not able to eliminate it

In Fig. 2 the bottom of the slab +30 can be observed, in a region that has 20 m in height. Due to the conditions presented, whatever the treatment used to correct this pathology would have a very significant cost.

It is also important to note that this case is not a specific problem, but a chronic one. All metal structure parts caused the same look on the slab, causing a severe visual pathology in the project.

Table 4 shows the description of the pathologic manifestation identifying the causes, consequences and solutions.

3.3 Case 2: Concrete with Apparent Imperfections

This pathology is classified as material failure. In the exposed concrete structures, and in regard to the execution of the structural piece, the first step to ensure concrete in a satisfactory condition is the analysis of the moulds used in the structure. Figure 3 shows pieces of exposed concrete executed with poor quality moulds. According to the recommendations of consultants and the engineering team project, all exposed concrete should be executed with moulds coated with Formica, which would provide the concrete the proper aspect.

Many pieces were concreted with moulds of wood in poor conditions, which were certainly responsible for the aesthetic pathologies detected in the final structure. As a result, parts that should not have any coating had a very bad visual aspect, requiring treatment to recover.

Table 5 shows the description of pathological manifestation identifying the causes, consequences and solutions.

Fig. 3 Poor quality frames for exposed concrete

Table 5 Pathological manifestation (case 2)

Pathological manifestation	
Cause	The main cause of this condition is the material used.
Consequence	This pathology provides no consequence regarding the strength of the piece; its importance is only aesthetic. This condition shows that the efficiency of the final product was not achieved, by not having all of its functions attended. One of the functions of these pieces, is to be self-sufficient for aesthetics, i.e., it should not require any coating to be considered finished
Solution	The product with the best performance for this type of treatment is a thin mortar called Nafuquick (Manufacturer: MC-Bauchemie), whose function is to precisely regulate the contact surface, while maintaining a very similar appearance to concrete. The treatment is done superficially, throughout the piece. It is very efficient, and the aesthetic pathology is, in many cases, cured

3.4 *Case 3: Concrete Reinforcement Exposed*

Figure 4 shows that the concrete reinforcement has not reached the required overlay and after removing the moulds from the slab, much of the reinforcement was exposed. This type of pathology is characterized as a execution problem.

This condition was caused by the incompetence or recklessness of the field team. Figure 4 shows that the pathology was generated at various points of the slab, classifying as a chronic problem.

Human resources responsible for this action has the function to manage and receive the services performed by the team. Part of the reinforcement consists in placing spacers for the armor, which are responsible for ensuring the minimum

Fig. 4 Concrete reinforcement exposed

required coverings. When these spacers are not fitted, or are tied up in the wrong way, they can break off at the time of concreting and cause a displacement of the armor, towards the mould.

Table 6 shows the description of pathological manifestation identifying the causes, consequences and solutions.

3.5 Case 4: Geometric Imperfections

Cidade da Música has the peculiarity of having many curved lines in its structure. Definitely, execute these curves accurate to the millimeter is not a simple task, some precautions can prevent pathologies associated with the structure.

To avoid problems, a specialized topography team is present before each casting of concrete. Concreting should only start after the approval of the topographer.

Table 6 Pathological manifestation (case 3)

Pathological manifestation	
Cause	Analyzing the problems presented, it can be said that this pathology happened in the execution phase of the structure. Forcibly this condition was caused by the inexperience or recklessness of the field team, which are responsible for ensuring the minimum overlay required
Consequence	An aggravating factor is the building's location. Due to the proximity to the beach, it is exposed to the effects of salt spray from the sea, which is even more harmful to the reinforcement. A structure needs all its elements in good working order for it to work satisfactorily. The exposed reinforcement may weaken the structure and compromise its operation, resulting in weaknesses or, in extreme cases, collapse
Solution	The reinforcement should be brushed, to eliminate any trace of remaining rust. The region must be properly isolated, so that the region of the pathology is delimitated. The next step is to use a product that is able to ensure that the exposed steel can be adhered to the concrete again. The most suitable material is a kind of adhesive mortar. This product, in addition to having a natural protection against corrosion and oxidation, helps create a bridge of adhesion between the steel and concrete, ensuring that there will not be any subsequent detachment

Unfortunately, this procedure is not always followed and therefore the concreting was carried out without the supervision of these professionals.

What can be noted is that there are cases where the imperfection can be observed throughout the workpiece surface, and there are others in which only a few stages of concreting was discontinuity in the form. Figure 5 presents one case where the failure occurred just in the last stages of concreting. As observed, the failure could have been avoided if the correct procedure had been applied at all stages of the process.

Table 7 shows the description of pathological manifestation identifying the causes, consequences and solutions.

4 Final Considerations

The structure is the core of an entire enterprise. If the structure is well designed, without many problems or pathological symptoms, chances are that the following construction runs with less risk.

This paper identified the pathological manifestation in three distinct phases, reffered to as project and interpretation, execution, and use of materials. The case study shows that many of the pathological processes presented could be avoided with a greater focus of the engineering team or work leaders. The engineering of a great edification requires that all professionals involved exercise the activity aiming satisfaction at the final product, achieving good performance levels.

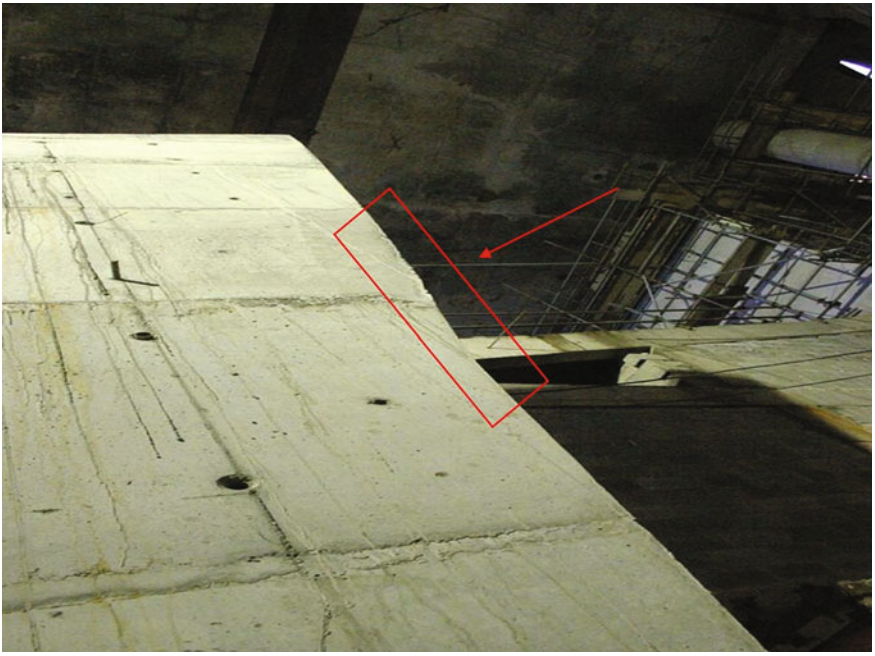

Fig. 5 Geometric imperfections

Table 7 Pathological manifestation (case 4)

Pathological manifestation	
Cause	The problem presented can be classified as an execution phase pathology. If all stages of the procedure had been met and the topography team had supervised all the concreting stages, the condition would be less likely to occur
Consequence	This pathology does not bring consequences for resistance or structural performance of the structure, but has a major burden due to the difficulty of recovering a piece with this kind of problem. A specialized company and special machinery should perform the treatment procedure for such problem, which results in lost time and higher costs
Solution	The best way to treat the geometry problem is to fill the most remote areas of the structure with mortar to homogenize the curves. A sufficient adhesion area should first be created on the area, avoiding adhesion problems by the correcting mortar. The application of the mortar can start after the treatment, with the due attention that the smoothing compound is greater than 5 mm. The use of a docking display is necessary to ensure that there is no peeling or cracks in the union of he mortar with the concrete. This screen is fixed on the concrete, and the procedure used is similar to masonry, and functions as a “frame” to the mortar

In all cases presented there is a way to treat and rectify the condition shown. Also, in all cases, it involves loss on the three major pillars that support the construction, namely: term, cost and quality. The loss in term occurs because, whatever the treatment used, the activity can also be recognized as a rework, and so, it is configured that, to repair the pathology, an activity that was already considered terminated must be redone. Regarding cost, the solutions require a financial contribution, an extra cost to the contractor, not expected, that may even impact on profit. About the lost in quality, when a piece was done and needs to be addressed, it is clear that the required quality of that element was not met, and the treatment cannot always restore 100 % of the original features of the structure.

Thus, it can be concluded that the best way to avoid certain problems in a building is to prevent pathologies from arising, instead of finding efficient solutions for each type of pathology. It is extremely important that the engineering team considers the procedures and processes that make the progress of activities and product quality go hand in hand, and also that everyone involved in the process have the consciousness of the correct procedure and work so that each step is successfully performed, in order to reduce the pathological symptoms of the structures.

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