CLADDING OF BUILDINGS

Alan J. Brookes and Maarten Meijs

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This new edition has been considerably revised and updated to take into account new developments over the last decade. It includes new chapters on terracotta rain screens and timber cladding.

As new materials and processes are gradually introduced into the building industry, manufacturers respond to the demand for new technology to relate to changes in performance requirements. Under these conditions architects need to assess the different products available and to distinguish between those products appropriate to their clients' needs. Nowhere is this more critical than in the cladding of buildings.

This book enables the specifier to compare the eight main types of materials available for lightweight or non-traditional cladding and to understand how the materials behave by appreciating the processes of their manufacture, transportation and assembly which are fundamental to their proper design. The performance of the cladding assembly depends upon its water-tightness and method of jointing which are described in detail for each cladding type.

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Fourth Edition

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Preface

In the past architects were trained to be aware of the types and uses of traditional materials and their means of assembly. It was not unusual for an architect to select the type of brick to be used knowing the source of its clay and the appropriate type of mortar, its thickness and how the bricks would be laid. The actual construction of the wall would be dependent on the craftsmanship of the bricklayer but there would be a common understanding between the workman, and the specifier of the standard of construction and the appropriate means of detailing. Each would be effectively checking the other. As building construction has become more complicated and the choice of materials increased, this sense of understanding between the builder and the architect can no longer be relied upon. In many cases the architect is not totally aware of the sources of the subcomponent parts which make up an assembly; for example, only relatively few architects would know the difference between polyurethane and polystyrene insulation in a composite metal panel, but this is fundamental to the fire performance of that panel. Partly this is because of education, partly lack of interest and partly because of the complexity of designing and organizing a modern building project. In this situation the architect is more dependent on specialists for advice on the parts of a building such as cladding.

The role of an architect has also changed. On smaller projects they may still be responsible for materials used, but on larger, more complex projects they may be replaced by the design and build contractor, who may influence the specification based on economic concerns. The contractor will often subcontract the major packages and may not always be aware of the issues of quality control and storage on site of the material for these packages that he would have known about in the past.

The trend away from nomination and named specification to performance specification is a mixed blessing in that it further distances the designer from the maker.

All parties to the building contract thus need to be more aware of the parameters of the manufacturing process and its related quality control procedures. These are defined in the following chapters, which are intended to inform the reader of these manufacturing processes and their influence on component design.

In our teaching roles at Delft Technical University we have been aware of the constant need for background knowledge on cladding by our students of architecture and building technology. We have thus decided to expand the previous six chapters of earlier editions with two new chapters, on timber and terracotta/brick slip cladding – both of which are increasing in popularity after some years out of vogue in modern architectural design.

The new chapter on wood cladding describes the types of timber typically used and shows how joints and fixings need to be designed to allow for particular characteristics. We also point towards issues of sustainability which are increasingly important

to control the environmental impact of felling trees for wood products.

The new chapter on terracotta and brick slips describes the process of manufacture and currently available systems. Other chapters have been updated to show how the design and specification of components must reflect their limits of production in the factory, during transportation, and handling on site.

With the increased complexity of building technology the whole building team is more and more reliant on mutual dialogue between contractors, manufacturers, fabricators, suppliers of base materials and subcontractors responsible for fixing the cladding assembly. The architect also needs information on systems, techniques and materials for the manifestation of their conceptual design. In order to have this conversation with a prospective subcontractor they must have some knowledge of the materials and systems available. The purpose of this book is to allow the reader to have general knowledge of the manufacture of the main cladding types and their limits of assembly.

Naturally only the architects can co-ordinate the exact performance requirements of a building to their client's needs and how these are translated to the overall design. The more that all the members of the building team understand the availability of appropriate materials and assembly methods, the easier the translation from concept to materials will become.

Since the last edition of this book, in 1998, there has been considerable interest by architects in the use of new and lightweight building materials. Adrian Beukers's seminal book *Lightness* raised the expectations of students of architecture, who now avidly read books about the use of new materials – well illustrated by the book *Materials World* – to gain knowledge about translucent concrete, synthetic spider silk, microfibres, and translucent silicone gels, without always realising that these materials are still very costly to produce.

Another significant development has been in rapid prototyping, enabling three-dimensional objects to be formed one layer at a time, using materials from polymers to metals. Another technique allowing quick prediction of form related to strength is the introduction of finite element analysis software to create a virtual prototype of the object. All these techniques have offered the opportunity for architects to explore new forms, and yet the constructional back-up and availability of components has not always been available. The use of computers and the availability of finite element analysis has led to architects experimenting with these new forms with the support of engineers able to carry out necessary predictions of structural strength and environmental performance. As Whitfield writes (*Financial Times* 21 November, 2003): 'Computers have become a ubiquitous feature of the design process making it easier for architects to play about with irregular shapes and test whether they would withstand the pressure of construction.'

It has not been our role to describe these new materials and techniques in detail as many of these are still in a time of experiment and development. We only wish to point to their availability and the possibility of expanding the vocabulary of building materials in the future.

Since 1998 there has also been a resurgence of interest in the use of glass-reinforced plastics using pre-pregnated fibres. Companies such as SP Systems in England and Holland Composites Industrials in the Netherlands have developed from custom boat engineering into manufacturers of composite structures for industrial and building purposes. They are now able to manufacture sophisticated shapes using CNC (computer numeric controlled) milling machines

and finite element analysis for determining the optimized material combination and construction. Their recent experience in manufacturing the roof for the Yitzhak Rabin Centre (architect Moshe Safdie) in Tel Aviv is described in Chapter 3.

Glass technology has also continued to advance with developments in laminate glass beams and, despite some problems with nickel sulphide in toughened glass, architects continue to be interested in the ultimate transparency of glass facades. To some extent this has been offset by the awareness of the disadvantage of transparency in terms of environmental control, and the next generation of architects should be more aware of the need to introduce shading devices and the means of reducing solar gain.

It is natural that in each generation architects should continue to seek new techniques and manufacturers should produce new products to respond to this demand. In other industries the first example of a new use of a material would be seen to be a prototype. In the building industry, the building is in effect the prototype; defects and long-term durability are determined after a period of time in use. Some clients may be reluctant to undertake these new techniques until evidence exists to support their success. Additionally architects are often required to work to tight schedules and these may simply not allow for examination of an innovative method, forcing them to make do with established materials or methods of construction.

Even so we should continue to seek improvements in our methods of building. Eric De Mare when writing about new ways of building immediately after the Second World War wrote, 'We have great tools in the box, we have yet to make humane cultural use of them' (1998). A similar sentiment is expressed by Mike Davies of Richard Rogers Partnership (Brookes and Poole, 2004)

> Most innovation and much of the best design stems from being more questioning, more honest, more economical with materials, more direct in response and as a result creating a more challenging, uplifting and magical solution. Invention and innovation are key parts of our lives and it is through this that we can contribute to architecture, urbanism and society at large.

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Acknowledgements

Introduction

> I find it incredible that there will not be a sweeping revolution in the methods of building during the next century. The erection of a house wall, come to think of it, is an astonishingly tedious and complex business: the final result is exceedingly unsatisfactory.
>
> H. G. Wells (1902)

Non-loadbearing claddings in building, often in panel form, are most commonly used in conjunction with a structural framework Before considering the eight main types of cladding system in detail we should first briefly examine two concepts that have most closely influenced the development of these types of construction.

First, there was the development of frame construction, and second, the introduction of systems of prefabrication, whereby component parts of a building could be fabricated in a builder's yard or workshop prior to their assembly on an actual building site.

The frame

The first building with a skeleton of wrought iron was the Menier chocolate factory near Paris (Fig. 1), built 1871–72, in which the external skin acts purely as a non-loadbearing panel infill. However, it was in Chicago in the latter part of the nineteenth century that the steel-frame building acquired a dominant position in the growth of ideas about panel and frame construction.

The use of the frame offered two main advantages: first, the potential for more square footage per floor area than for masonry construction. As much as one floor in a 10-storey block could be saved by the use of a frame. Second, the whole weight of the building could be carried on the frame, and by reducing the self-weight of the skin the load on the foundations could be reduced.

This combination of advantages led to the intensive development of the Chicago skyscraper, with such examples as the first Leiter building in 1879 and Louis Sullivan's Carson, Pirie, Scott department store of 1899–1904, with its facade of an exposed grid of steel with large glazed infill panels. Subsequent developments led to a position where, as Colin Rowe (1956) commented,

> The frame has been the catalyst of an architecture, but one might notice that it has also become architecture, that contemporary architecture is almost inconceivable in its absence.

Examples of industrialization and prefabrication had occurred all through the nineteenth century, culminating in the spectacular Crystal Palace building for the London Great Exhibition of 1851. Russell (1981) has shown how, following the Battle of Trafalgar in 1805, the mechanized blockmaking plant at the Royal Naval Dockyard at Portsmouth heralded the introduction of machine tools for prefabrication. Herbert (1978), in his excellent study of pioneers of prefabrication, gives an early example in the John Manning portable colonial cottage in 1833, using a timber frame with interchangeable timber panels, all designed for ease of erection. Pressure of prefabrication implied the use of some sort of panel system. Beginning in the twentieth century, prefabrication

exploited new techniques and materials. In addition to timber corrugated metal and cast iron, precast concrete emerged as a new system of building with an enormous potential for prefabrication.

Knowledge of new materials

As early as 1905, J. A. Brodie, city engineer of Liverpool, built a three-storey block of flats using the principle of the 'dovetailed box' with panels cast off site including apertures for doors and windows. Russell (1981) also reports on what must be the first example of sandwich panels in precast concrete at Watergraafseer Garden City, Amsterdam, designed by D. Greiner and built during 1922–24 as part of an experiment to encourage innovative methods in the face of rapidly increasing brick prices. The cladding consisted of an outer layer of concrete, a layer of insulation and an inner layer of lightweight concrete. It may seem surprising, therefore, that the first real guidance on the design of precast concrete was not published until 40 years later (see for example Morris, 1966), when, following the rush to promote and develop housing systems in the 1950s and early 1960s, guidance from the Cement and Concrete Association became widely available. But this is a familiar story in the building industry, where general acceptance of new techniques occurs slowly, and where established texts on building technology tend to be mainly concerned with traditional forms of construction.

Experience has shown that with the use of relatively untried components and techniques, the architect can no longer rely on the traditional means of communication between design and production. In these circumstances architects may have leaned too heavily on manufacturers' expertise in building construction, not realizing that the quality control procedures on site are often insufficient for the site

1 Menier chocolate factory.

research and development techniques and accelerated testing, and hence predict their performance in use more accurately. Even so, it takes time for the results of this research to filter through into common use. Also, in the building industry it is often difficult to carry out sufficient tests to predict the possibility of failure accurately.

In some cases architects may be wary of using a material because of past experience with similar products. For example, most architects respect the corrosion of metals, and until better means of protection became available there was a general reluctance to use metal panels in building. Thus although techniques for forming or shaping metals were sufficiently well known in 1932 for the development of lightweight metal cladding panels, as used by Jean Prouvé at the Roland Garros Aviation Club building, it was not until much later (Wachsmann, 1961; Sebestyen, 1977) that the principles of design were discussed in detail, and then with little reference to Prouvé.

In general, architects feel a responsibility towards their clients and are reluctant to use a material until it is well tried and tested. This may explain why it was not until the mid-1950s, with the Monsanto 'House of the Future' at Disneyland, that serious investigation of moulded plastics as building panels began, although a survey, published by the *Architects' Journal* (1942), of possible future applications of plastics for the industry reported on building units of comparatively large size being made by a number of moulding methods 10 years earlier. Even so, it was not until conferences such as the one organized by the University of Surrey in 1974 that advice on the design and specification of glass-reinforced polyester (GRP) cladding became more widely available, but 20 years later there are still concerns with the effect of ultraviolet light on certain pigments. Similarly, despite extensive guidance from Pilkington on the use of glass-reinforced cement, there

agent to check that the components have been correctly installed.

Changes in the scale of use of materials can create problems of their own. For example, the characteristics of manufacture and behaviour in use of terracotta tiles were well known in Europe at the turn of the century. Even so, failures occurred because of inadequate provision for thermal expansion and contraction processes when such tiles were applied to tall framed buildings in the USA. At such buildings as Atlanta City Hall and the Woolworth building, New York, the original terracotta has been replaced with another innovative material, precast concrete reinforced with Fibreglass, which itself has also to take account of thermal movement. When specifying new materials we are today able to take advantage of

is widespread concern over the performance in use of some of the early formulations.

Changes in use for different building types and markets can also influence architects' attitudes towards a material. Technical guidance on aluminium and steel profiles cladding was hardly thought necessary when its use was restricted to industrial needs. Architects relied entirely on the technical literature produced by the various manufacturers, which although generally very comprehensive did not always show the material in relation to others. It was not until the 1970s that comprehensive guidance to designers on profiled cladding was available from the Central Electricity Generating Board and the Property Services Agency, thanks to the extensive building programme using these materials. Ten years later, British Steel produced their design manual on profiled steel, but interestingly, this did not include manufacturers of composite steel panels with laminated or foamed cores, which were then being widely used. Over the last 10 years there has been rapid development in the design of curtain walling and suspended glazing. The principles of weather resistance using pressure-equalized systems are still not widely understood, and for that reason it has been dealt with in some detail in this book.

Architects and engineers had continued to explore the possibilities of suspended glazing assemblies to take account of the combined action of the glazing and its structural framework. This in turn has led manufacturers to seek ways in which the fittings and fixtures could be designed to take account of the movement within the assembly under wind load.

Principles of jointing

In any study of cladding it is important that the principles of weather protection are fully understood, as the joints are normally the most critical parts of the assembly.

Forty years ago the Norwegians initiated a scientific investigation into the mechanism of water leakage. Initially they were concerned only with the performance of casement windows, but their investigations subsequently led to a more thorough understanding of the behaviour of the wall itself. Birkeland (1962) published a treatise in which the principles of what was then referred to as the 'rain barrier' and its implications were discussed.

Following the Norwegian studies, scientists at the Canadian National Research Council's Division of Building research institute began similar investigations, and a year after the Norwegian publication a small pamphlet entitled *Rain Penetration and its Control* by Garden (1963) appeared. This publication, in which the terms 'rain screen' and 'rain screen principle' were clearly defined, is still considered to be a prime reference source.

A publication by the Architectural Aluminium Manufacturers Association in the USA (AAMA, 1971) summarizes the principles applied to curtain walling, and makes the point that the terms 'rain screen principle' and 'pressure-equalized design', though closely related, are not strictly synonymous. The rain screen is the outer skin or surface of a wall or wall elements backed by an airspace, and so designed that it shields the wall joints from wetting. These principles are described in Anderson and Gill (1988), *Rainscreen Cladding – A Guide to Design Principles and Practice*. The rain screen principle is a principle of design that describes how the penetration of this screen by rainwater may be prevented. The use of pressure-equalized design is an essential part of this principle. Before discussing the application of this principle in detail, it is important to describe how rainwater acts on the surface of a wall.

2 East Croydon Station. (Architects: Brookes Stacey Randall)

Forces moving water through an opening

None of the rainwater striking a metal and glass curtain wall is absorbed, as it would be with masonry construction, and a substantial film of water will flow down the surface. If wind is present, the water may also flow laterally or even upwards on parts of the building: the taller the building, the greater will be the accumulated flow over the lower parts of its walls. Lateral flow under wind pressure is greatest near the windward corners of the building, and upward flow is greatest near or at the top of the facade facing the wind. Lateral flow will also be concentrated at vertical irregularities in the wall surface, either projections or depressions, and these may often be joints. In general, the flow of water at vertical joints is much greater than the average flow of water over the wall.

A number of forces then act to move the surface water through any available opening. All of these forces are illustrated schematically in Fig. 3. Probably the most familiar of these is the force of **gravity**, and appropriate methods of counteracting this force are well known. Another force is **kinetic energy**: raindrops may approach the wall's surface with considerable velocity, and their momentum may carry them through any opening of sufficient size. Cover battens, splines or internal baffles can be used to prevent rain entry due to this type of force. A third factor that contributes to leakage is **surface tension**, which gives the water the ability to cling to and flow along soffit areas. The preventive to this action is in the form of a drip at the outer edge of the overhang. Fourth, **capillary action** is likely to occur whenever the space separating two wettable surfaces is small. The way to control water flow by capillarity is to introduce a discontinuity or air gap in the joint that is wider than the capillary path.

It is the next two forces caused by wind action that are the most critical, and the most difficult to combat. **Air currents** may result from differences in wind pressure over the wall surface, or from convection within wall cavities. These may carry water into the wall. Also, if water is present on one side of an opening and the air pressure on that side is greater than that on the other side, the water will be moved through the opening, no matter how small, in the direction of the pressure drop. This **pressure difference** may be caused by even the gentlest of winds and cause most of the leakage at wall joints.
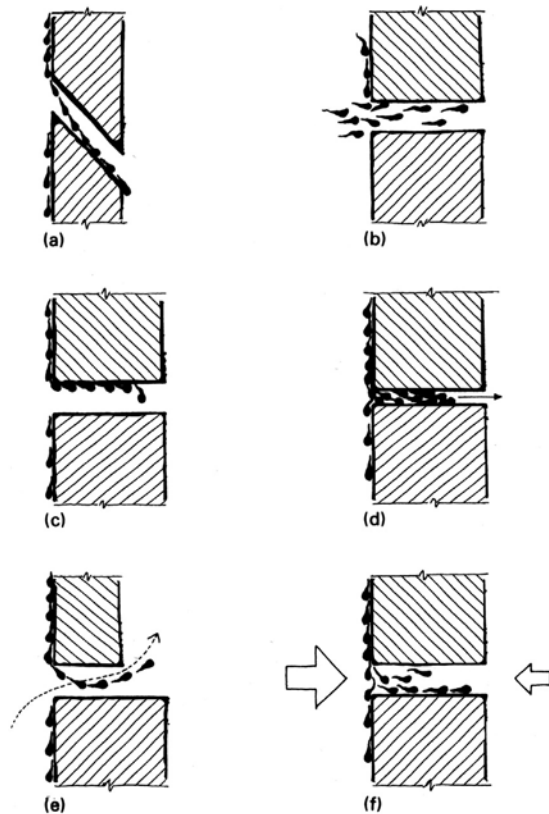
3 Forces acting to move water through an opening: (a) gravity; (b) kinetic energy; (c) surface tension; (d) capillary action; (e) air currents; (f) pressure difference (based on AAMA, 1971).

The conventional approach to combating the last two forces was to attempt to eliminate all openings by using a tight seal, but the more effective and reliable approach is to eliminate the pressure differential across the opening. It is this approach that is known as the **rain screen principle**. The essential features of the rain screen and pressure-equalized wall construction are shown in Fig. 4. Sketch (a) indicates how, with the larger pressure on the outside, water is normally drawn in through the joint. Sketch (b) shows the condition where the pressures on two sides of the outer surface are made equal, thus preventing leakage by gravity, kinetic energy, surface tension or capillary action. Sketch (c) shows how, in order to withstand the effects of air currents and wind pressure, a continuous air space must be provided between the inner and outer skins of the construction.

The pressure-equalized wall consists essentially then of an outer skin (the rain screen) and an inner tight wall with an air space between the two. The pressure equalization is maintained by not tightly sealing the air space with the outside. The seals on the outer skin are known as the **airseals** (Figs 5, 6).

Segmentation of the air space

This is the basic theory. The difficulty in practice is that positive pressures on a facade near the ground are much less than those near the top, and those near the centre of the facade are usually greater than those near the corners. Projecting elements, such as column covers, mullions and transoms, have their effect on the micro-pressures. A horizontal rail may be subjected to pressure at one end and suction at the other. Air flowing through this member trying to equalize the pressure could have a negative pressure at one end, and thus the water would be drawn into its joint. An important requirement therefore in the design of the air chamber is that it should not be a space with a number of widely spaced openings to the outside. Instead it has to be of limited size, subdivided into relatively small areas with ideally one opening in each compartment to the exterior. If mullion or column covers are used as air chambers, they should be blocked off horizontally at height intervals of not more than two storeys to minimize chimney action. Reference should be made to Garden and Dalgleish
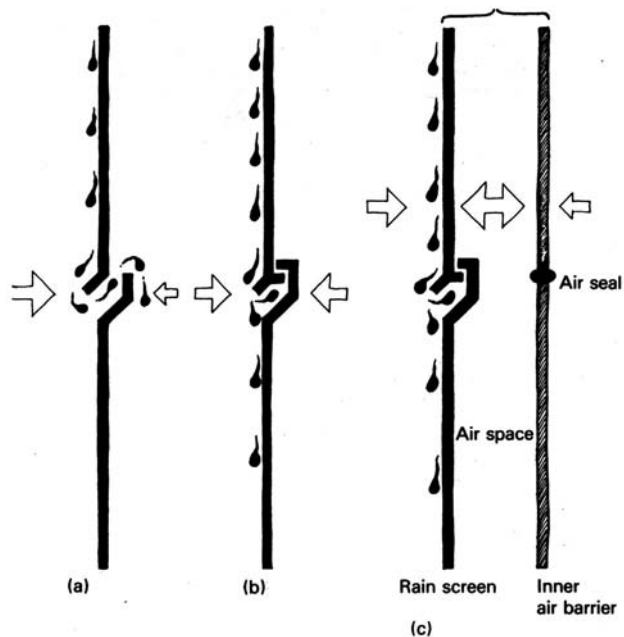
4 Essential features of the rain screen and pressure-equalized wall construction (based on AAMA, 1971).

(1968), who recommend that vertical closures should be provided at each outside corner of the building and at 1.2 m intervals for about 6 m from the corners. Horizontal closures should be used near the top of the wall. Both horizontal and vertical closures should be positioned up to 10 m on centres over the total area of the wall.

Airseal on inner face

The importance of maintaining the air seal on the inner face cannot be overstressed. Any leakage of air would result in the pressure dropping in the air moved through the gaps to try and equalize the pressure between the air chamber and the inner environment. Another oversight in this respect could be the pro-

vision of weepholes in the window sill to allow condensation to pass through. Any such weepholes must be carefully designed to avoid any reduction of air pressure within the chamber. Where openings are provided to the air chamber, they should be large enough to be bridged by water in a heavy rainstorm causing a pressure differential or capillary action.

Development of 'high tech'

'High tech' is a misnomer. It is not a style of architecture as such, but more of an attitude towards design, taking account of and being involved in the process of construction. Technology-led architecture can be seen as a natural development for the Modern Movement in architecture, allowing the use of appropriate technology to inform the designer's intentions. Some authors have identified a thread through Paxton, Prouvé, Gropius, Waschmann, Ehrencrantz, Foster and so on.

The concepts of flexibility and interchangeability, as illustrated by such buildings as Farrell and Grimshaw's Herman Miller factory near Bath (GRP panels), and Foster's Sainsbury's Centre (aluminium panels), have now become an acceptable part of an architect's vocabulary. The serviced-shed approach is increasingly familiar, illustrated by the Reliance Controls factory (Team 10), advanced factory units at Kiln Farm (Milton Keynes architects) and, more recently by the Stratford Market Maintenance Depot, London, 1988, by Chris Wilkinson Architects. Many of these big serviced sheds rely on bright colours, profiled panels and exposed structural grids, all posing new methods of jointing and fixing, not covered by established texts on building construction. Architects' demands for brighter colours with contrasting colours for gaskets, window surrounds and flashings have resulted in a need to reconsider the standards of colour matching and finishes of cladding materials.

As new materials and processes are gradually accepted by the architectural profession, manufacturers respond to an increased demand for these new products and materials by introducing their own proprietary solutions onto the market. Under these conditions, architects need to make an initial assessment of these systems in order to select the component most suitable for their clients' needs. In order to do this they require a comparative study of the various products to allow them to understand the limitations of the manufacturers' proposals, their performance criteria, finishes and assembly techniques. They need to be able to distinguish between the various jointing solutions available and analyse the weathering characteristics of each cladding material. This book is intended to meet their requirement.
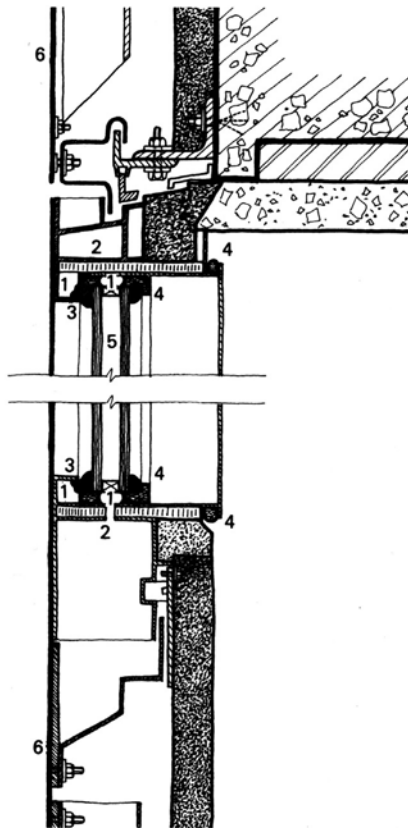
5 Pressure-equalized standard wall system (vertical section): (1) pressure-equalized wall chamber; (2) slotted openings; (3) deterrent seal; (4) air seal; (5) hermetically sealed double glazing; (6) spandrel face (based on AAMA, 1971).
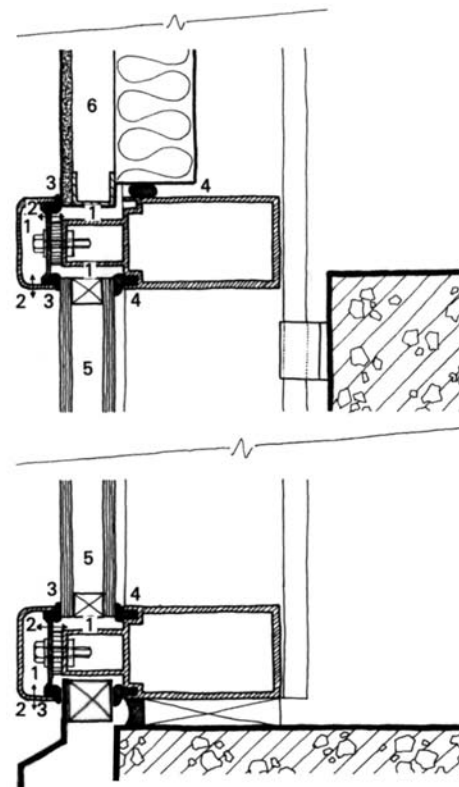
6 Sketch detail, pressure-equalized wall: (1) pressure-equalized air chamber; (2) slotted opening; (3) deterrent seal; (4) air seal; (5) hermetically sealed double glazing; (6) spandrel face (based on AAMA, 1971).

The main theme underlying the following chapters is the method of production of each of the eight cladding types discussed. To understand how a material behaves in use it is first necessary to appreciate the processes of its manufacture. Issues such as quality control, cost of production and transportation are fundamental to the proper design of an assembly, and affect decisions on size, shape and finish. The performance of a cladding assembly and particularly its watertightness depends upon its method of jointing; where possible, details are included for each of the applications described. Similarly, the variation in joint size will depend upon the tolerances of construction and the method of fixing used. These are therefore described in detail.

Each chapter contains a description of methods of manufacture, standardization, performance criteria, finishes, durability, jointing, fixing and methods of transportation, storage and erection. There is no particular reason for the order of the chapters other than the fact that precast concrete is arguably the best-known technology, whereas sheet metal and their carrier systems (curtain walling) are the least understood. Glass-reinforced polyester and glass-fibre-reinforced cement tend to be associated with each other; because of the method of their reinforcement, but in fact they are quite different materials, as Chapters 3 and 4 will explain.

Finally, although this book may appear to be about construction, it is also a book about design, for the two are interrelated. It is only through the understanding of technology that the designer can develop design images with confidence. The following chapters summarize the state of the art of cladding technology, and are therefore intended as a contribution towards better design in that field.

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1

Precast concrete cladding

Introduction

The main benefits of precast concrete over other cladding materials are its good strength-to-weight ratio, its mobility and, because it is a non-combustible material, its fire performance.

Precast concrete came into its own for use in cladding during the 1950s and early 1960s with the development of high-rise housing. British architects quickly followed the examples of Le Corbusier's Marseilles Unité block, built between 1947 and 1952, although manufacturers such as Trent Concrete and Empire Stone had been manufacturing high-quality cladding elements in the 1920s and 1930s. Morris (1966) has described the history of the development of precast concrete in Great Britain, France and the USA up to 1964. One of the most famous examples is the LCC flats at Roehampton Lane (facing slab manufacturer Modular Concrete), which marks the beginning of the continuous use of concrete cladding in the UK.

Precast concrete has been used for both non-loadbearing and loadbearing cladding units. Both Morris (1966) and the Pre-Stressed Concrete Institute (1973) describe the Police Administration building in Philadelphia, built in 1962, as a major step forward in the structural use of precast concrete wall panels.

The three main advantages of using precast as against *in situ* concrete are:

– speed of erection;
– freedom from shuttering support on site;

— better quality and variety of surface finish, because panels are manufactured in controlled factory situations.

The economics of precast concrete panel production are a function of standardization of mould shape. Similarly, rationalization of panel size and the means of fixing is important for reducing the cost of transportation and assembly. However, obsession with standardization of mould size and lack of research into applied finishes have hindered development of the variety of size and finish now demanded by the architectural profession.

1.1 Construction of precast and *in situ* concrete at the Les Espaces d'Abraxas, a monumental housing scheme near Paris (architect: Ricardo Bofill).


The industry has relied for too long on the range of finishes possible with aggregates. Much of the precast concrete cladding in the UK is in natural stone, granite or brick. However, times are changing. Examples of more sophisticated finishes from Europe, such as epoxy coating in Holland and Germany, and the work of Ricardo Bofill in Paris and Spain (Fig. 1.1), have shown the exciting possibilities of the material.

Some projects are now being built in the UK that exploit the use of decorative precast concrete units. A recent example is John Outram's work at Sir William Halcrow's pumping station for the London Docklands Development Corporation and the Thames Water Authority, using painted precast concrete fins. These units, manufactured by Diespeker Marble and Terrazzo, are finished in bright colours, using Icosit paint with a clear lacquer top finish (Fig. 1.2). In this case, intricate curves were formed in the timber mould using two 3 mm layers of laminated plywood.

One of the reasons for the previous lack of research by the industry to provide finishes of this type has been the lack of research into the methods of bonding of the finishes to the concrete surface. Developments in penetrating sealer and primers now allow a smooth non-porous surface to the concrete, thus providing a good base onto which the paint coating can be applied.

Design guides

During the 1970s a number of guides were produced to assist the designer to determine the panel size, shape and composition and to select the surface finish in relationship to the appropriate method of casting the panel, many of which are still relevant today. Guides were produced by the Cement and Concrete Association (now the British Cement Association) and the British Precast Concrete Federation.
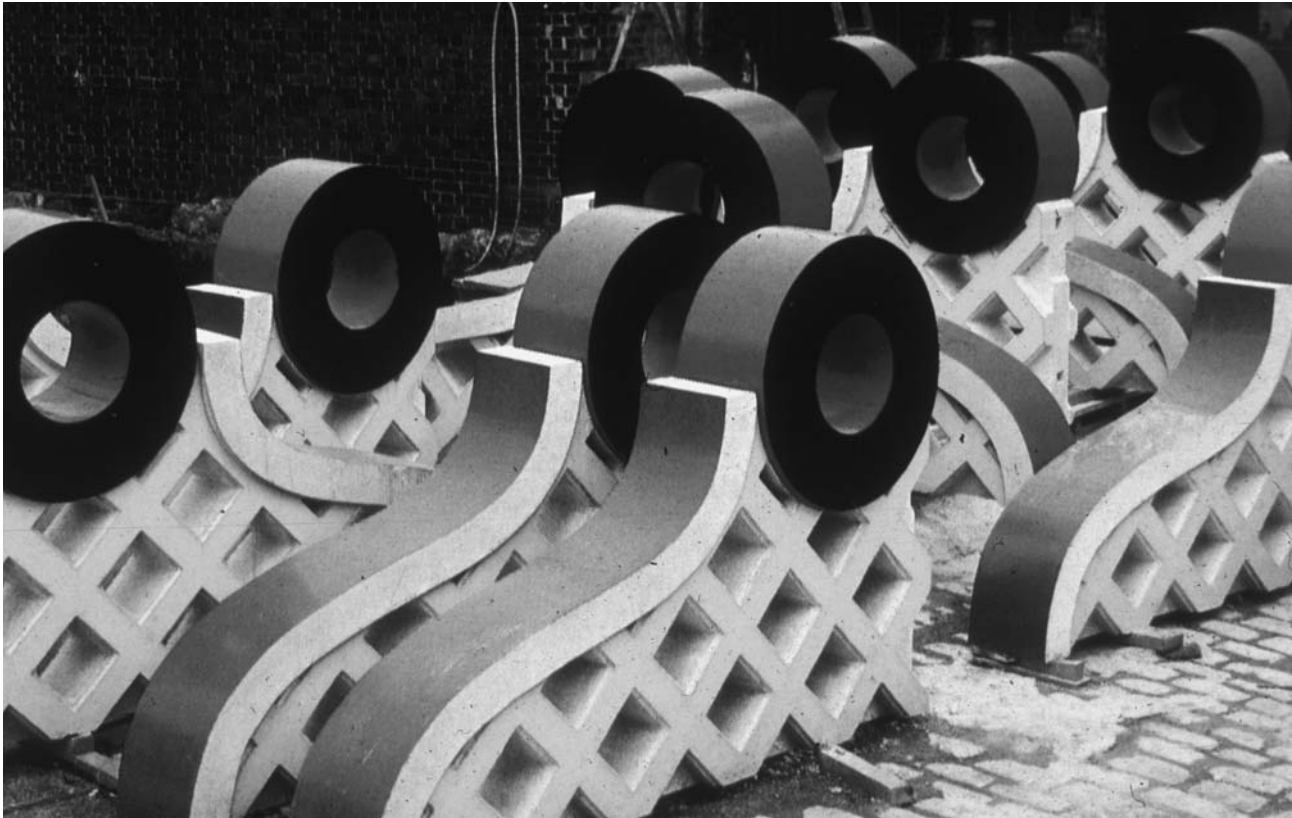
1.2 Precast fin units in the manufacturer's yard, painted and awaiting transportation to the LDDC Pumping Station on the Isle of Dogs (architect: John Outram).

Useful advice based on American experience was given in the Pre-Stressed Concrete Institute (1973) guide *Architectural Precast Concrete*. Types of finishes related to the method of casting (face up or face down) were covered in articles in the *Architects' Journal* by Michael Gage (23 March 1969), later developed as a book by the Architectural Press (Gage, 1974). Gilchrist Wilson's (1963) *Concrete Facing Slabs* gives examples of surface finishes, using colour illustrations. R. A. Hartland's (1975) book *Design of Precast Concrete* covered all aspects of precast concrete design, including cladding. Detailing of non-loadbearing precast concrete cladding panels for concrete-framed buildings was also described by Brookes and Yeomans (1981) as part of the *Architects' Journal's* Art of Construction series.

A most useful source of guidance on panel design was produced by the PSA Method of Building

Branch (1978) as the result of a comprehensive survey of industry methods by the National Building Agency. This gave guidance on such points as:

- panel types and size limitations;
- panel web thickness;
- design of vertical strengthening ribs;
- removal of moisture from behind panels;
- open drained joints;
- baffle strips, air seals and flashings;
- fixings for panels (cleats and dowels).

Another publication by the Architectural Cladding Association (Dawson, 1995) updated this information and showed recent case studies of the use of precast concrete. It also included a good account of the history of architectural concrete.

Standardization and adjustable moulds

Economic use of precast concrete can be achieved only if there is a high degree of standardization in the design of the units. Costs are inevitably higher when greater numbers of panel types are used. There is not only the additional cost of extra moulds, but if moulds have to be continually altered to cast 'specials', the daily casting cycle is disrupted. Moreover, special units require separate stacking and delivery at a particular time. On site, special lifting and erection procedures may be required for non-standard units. The Cement and Concrete Association's (1977) Technical Report No 14 gives the main advantages of standardization as follows:

- lower production and erection costs;
- less time for detailing, mould making and production periods;
- reduced risk of detailing and production errors;
- reduced risk of delays due to units being damaged;
- speedier erection.

Architects should therefore make every effort in the early design stages to reduce the number of panel types. Usually it is easier to standardize panel widths than panel heights, because of the frequent requirement to have different storey heights and parapet levels. In this case it is sometimes possible to adjust the design of the supporting *in situ* concrete frame to avoid the use of non-standard panels (Fig. 1.3). Any additional costs in terms of the shuttering of the main structure can be offset against the savings in greater standardization of precast units. Part of the skill of designing with precast units is this choice between standardizing precast and *in situ* construction. A good example is the student residence for Christ's College, Cambridge (architects: Denys Lasdun & Partners), where the architects have used a basically precast aesthetic *in situ* construction using a limited range of panel forms (Fig. 1.4).

Adjustable moulds

It may also be possible to provide some variety of panel size by adjusting the mould during manufacture. For example, Fig. 1.5 shows an adjustable mould for face-up casting, in which the stop end can be repositioned in the mould. This is more easily done with a panel of uniform thickness than with a coffered panel, where the coffer former will also need to be repositioned. Early consultation with the manufacturer will establish whether or not an adjustable mould is possible for any particular project.

Size of panels

The size of the precast concrete unit is influenced by three factors:
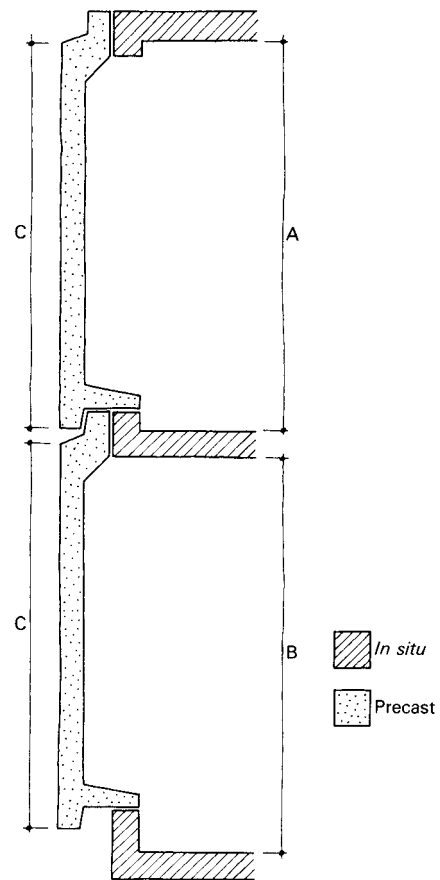
1.3 Different storey heights A and B allow standard panel height C.
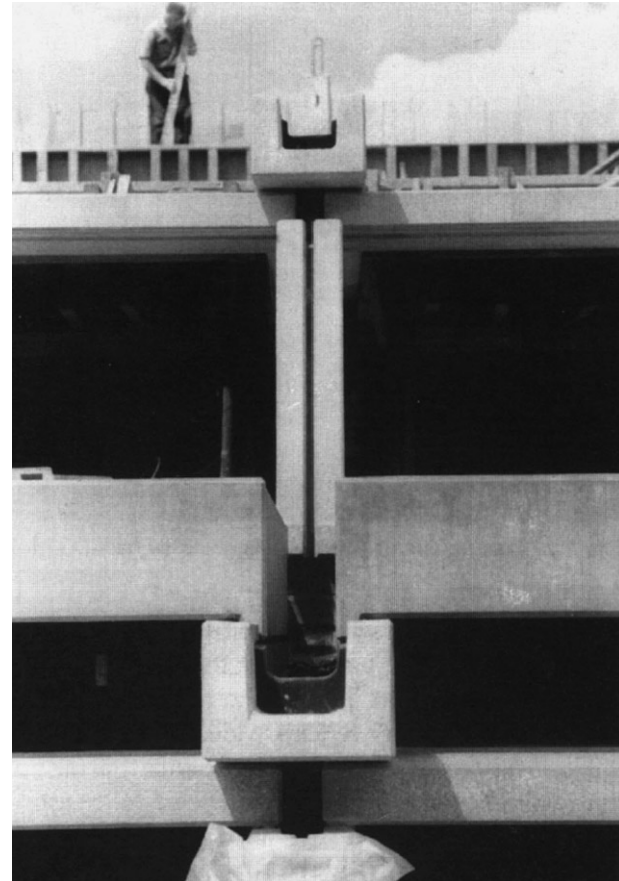
1.4 Student residence for Christ's College, Cambridge (architects: Denys Lasdun & Partners).
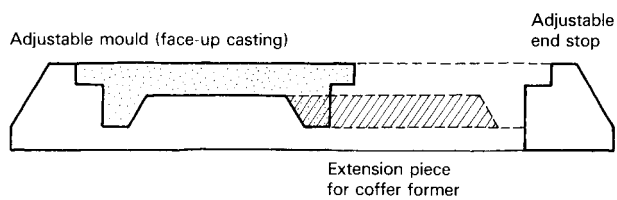
1.5 Adjustable mould for a variety of panel sizes.

–   ease of manufacture;
–   method of transportation;
–   weight of lifting.

The width of the unit is related to the method of manufacture, depending upon the type of finish required. For a polished smooth finish the width is

1.6 Cladding unit in course of finishing by hand.

restricted to about 1.2 m to allow a man to lean over the unit to polish. Figure 1.6 shows a typical width of unit being polished by hand. If large aggregate is placed by hand, then units should not exceed 2 m in width, unless a moving gantry is used.

Transportation will also limit the size of units. If units are placed flat on a trailer the width is related to payload restriction. There is no restriction on trailers up to 2.895 m (9 ft 6 in) wide. Trailer widths of 2.895–3.500 m (11 ft 6 in) need police permission, and loads exceeding 3.500 m wide need police escort. Thus 1.2–3 m seems to be an economical size for the width of units.

Wider units can be transported on A-frames supported on their long edge. Figure 1.7 shows two methods of transporting units on their edge, where the maximum height when loaded should not exceed 4.880 m. Allowing for the height of the trailer and bearers, panels of up to 4.130 m width are possible.
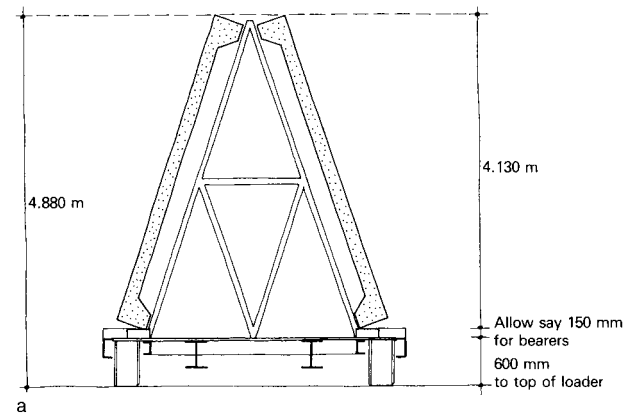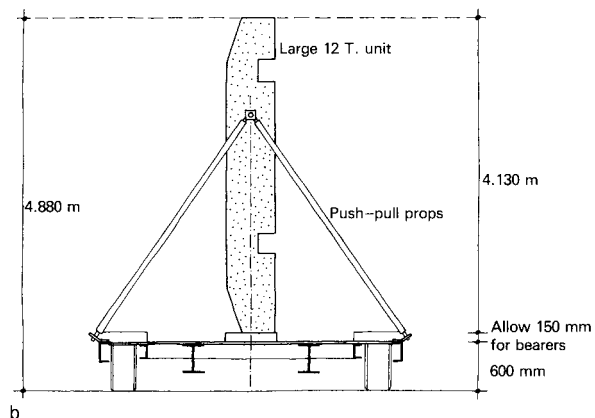
1.7 Width of panel related to safe height during transportation: (a) unit transported on A-frames supported on edge; (b) large unit held vertically.

Figure 1.8 shows wall panels being loaded on an A-frame trailer.

Lengths of units are normally 3 × width, and will also be affected by the maximum lengths of the trailers, normally no longer than 12 m. The thickness

1.8 Wall panels being loaded onto A-frame trailer.

of the panels is related to the required cover for the reinforcement in the panel web (Fig. 1.18). As a rough guide to deciding the typical thickness of panel related to the longest side of the units, Table 1.1 can be used. Once the panel width, length and thickness have been determined, the cubic volume × the density of concrete will determine the overall weight of the unit.

In most cases wall panels should not exceed 7 t to allow easy handling during manufacture and on site. However, some manufacturers have facilities for handling units up to 20 t in weight.

Table 1.1 Rule of thumb for panel thickness related to its length

Panel length (m)	Approximate thickness (mm)
2.0	75 (using stainless steel reinforcement)
3.0	90
4.0	100
5.5	125

Types of mould

The choice of material for the moulds is usually determined by the number of uses, and is essentially a matter of economics. Thus, although moulds may be made of timber, steel or GRP there is a considerable cost difference between these materials. Another factor influencing the choice of mould material may be the time taken to make the mould and the rate of output required to meet the erection programme. The shape and size of the units to be cast may also be a consideration.

Timber moulds

Timber moulds are normally used because of their versatility in manufacture. They are certainly the cheapest method for simple panel shapes, with an average of 20–30 castings possible for a complicated panel and 50–60 castings from each mould for a more simple shape. However, they suffer more from wear than steel moulds do, and they do not have the same degree of accuracy. Panels are normally manufactured with a variability of ±3 mm. Inaccuracies in bow can be a problem with long units using timber moulds, but these can be reduced by the use of push-pull props (Fig. 1.9). A high standard of finish can be obtained on the moulding by spraying the mould surface with a thin film of GRP.

Steel moulds

Steel moulds offer a better degree of accuracy of manufacture. Also more panels, at least 150 per casting, can be made from the same mould. However, they cost more than timber moulds, and they take longer to make. Steel moulds are usually used only for long runs of absolutely standard units, as they are less easily adjusted than timber moulds.

GRP moulds

Glass-reinforced-polyester moulds, although offering a better standard of accuracy, are more easily damaged and may need frequent repair. Thus the life of the mould is longer than that of timber, but shorter than that of steel. When deeply coffered panels are required, GRP may be cheaper than timber, and also copies of the mould can be made more easily. It will of course be necessary to make the master mould in timber or fibrous plaster to cast the GRP moulds. They are normally used for any unusually shaped or deeply coffered panels. A thin skin of GRP can be used in a timber mould for a better standard of finish (see above).

Casting method

The choice of casting method is normally related to the type of finish required and to the mould table available to the supplier. Four alternative casting methods are normally available for factory production (Fig. 1.10):

– face-up casting;
– face-down casting;
– double-layered facade elements;
– tilting moulds.

Face-up casting

Face-up casting, although seldom used today, allows various surface finishes to be applied to the top surface while the unit is still in the mould. It is not suitable for tiled finishes or where a smooth surface is required. A disadvantage is that the 'fat' tends to rise to the surface of the concrete, resulting in a weaker face. However, the reinforcement may be easily supported on spacer blocks without detracting from the external appearance.
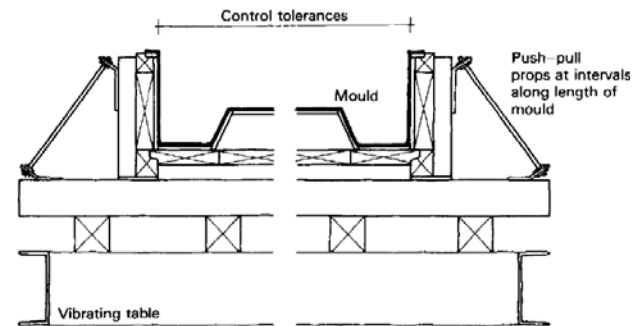
1.9 Push-pull props to reduce bowing of timber moulds.
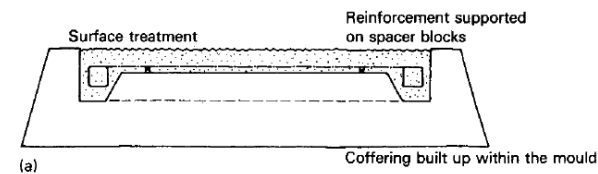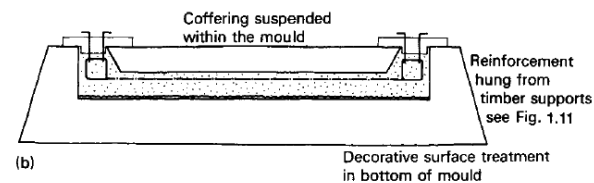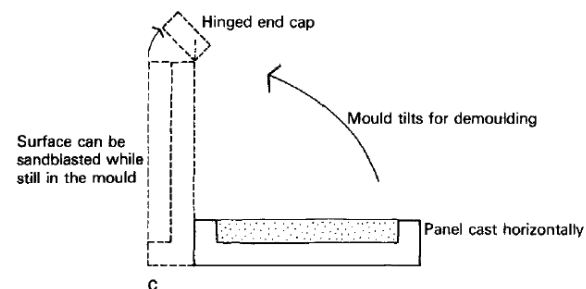
1.10 Three alternative methods of casting: (a) face up; (b) face down; (c) tilting moulds.

Face-down casting

Face-down casting is most suitable for stone veneers, brick, tiles and profiled surfaces. However, if profiled surfaces require a surface treatment, this is done remote from the casting area after the panel has been demoulded. Support of the reinforcement needs attention to ensure adequate cover. Figure 1.11 shows a typical device to control the cover to the reinforcement. Lifting sockets or loops in the back of the panel are easily inserted for demoulding. If these are used, care should be taken to ensure either that they do not interfere with the erection of the panel, or that they are cut off before delivery to site.

Double-layered facade elements

Double layered concrete facade panels can be made with or without a cavity and with a load bearing or non load bearing inner leaf.

The cheapest method is without a cavity. During manufacturing the cast outer layer can stay in its mould, face down, but this mould is already adapted for the double construction. Stainless steel anchors

1.11 Device for controlling cover to reinforcement in face-down casting.

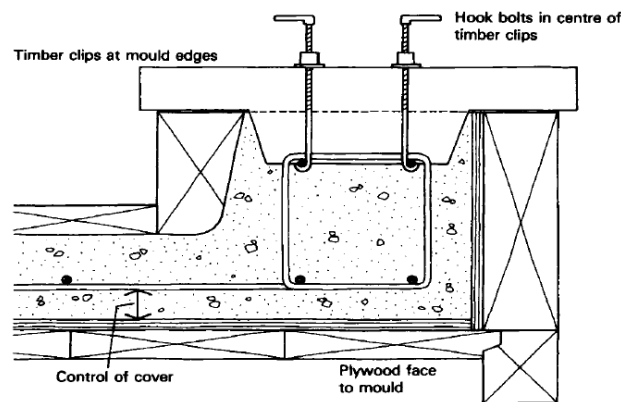project from the outer layer. Thermal insulation material is put on the back of the outer layer. This now acts as the bottom of the mould for the inner leaf. Reinforcement and anchors can be put in as in single layer construction. The inner leaf is then cast on top of the thermal insulation. The inner side of the element will stay somewhat rough.

If a cavity is needed the process is more complex. First the inner leaf is made and demoulded. Stainless steel anchors are cast in and project outwards. Thermal insulation is attached to the inner side of this inner layer. Then the outer layer is cast in another mould. After that, the inner leaf, with the projecting anchors, is pushed into the not yet hardened concrete. Spacers between the inner leaf and the mould of the outer blade maintain the desired distance between the outer layer and the thermal insulation. Although the latter solution is more expensive it has some advantages, for instance both faces of the facade element have a mould side with a high degree of finish. The outer side needs no treatment at all; the inner side is often painted. The other advantage is the cavity, especially when a damp-proof outside finish is used, like (glazed) tiles. The risk of damage to the tiles by frozen condensate accumulating behind the tiles is reduced by the ventilation in the cavity. In most cases, a cavity is not needed.

The risk of fire propagation in the cavity can be reduced by using mineral wool. Foams like polystyrene and polyurethane are however virtually waterproof and the concrete can be cast on to them directly. If a fire-retardant type of foam is used in a construction with a cavity, it reduces the risk of the fire spreading quickly through the cavity, as the supply of oxygen will be reduced. As the outer leaf hangs on steel anchors, the material, design and position of these anchors must be chosen taking a possible fire into account. The problems of different thermal movement between the outer and the inner leaf can be solved by using a fixing

somewhere in the centre of the panel, and pendulum anchors in the form of steel plates on the four corners. These plates allow the panel to expand and shrink, but prevent rotation (Fig. 1.12).

Joints

The water sealing in the outer leaf can be made as described in single layer construction. Attention must be paid to the air seal. As both blades are placed at once it is not possible to make an air seal on the cavity-side of the inner leaf. Attaching a broad tape containing tar over the joint is the best and cheapest solution. The joint must be made by sealants or rubber profiles that maintain their flexibility over the years.

If the inner leaf is load bearing a conflict might arise between the accuracy in position of the element one can reach in the rough construction to position the element and the accuracy needed to reduce the width of the joints in the outer leaf to an acceptable level.
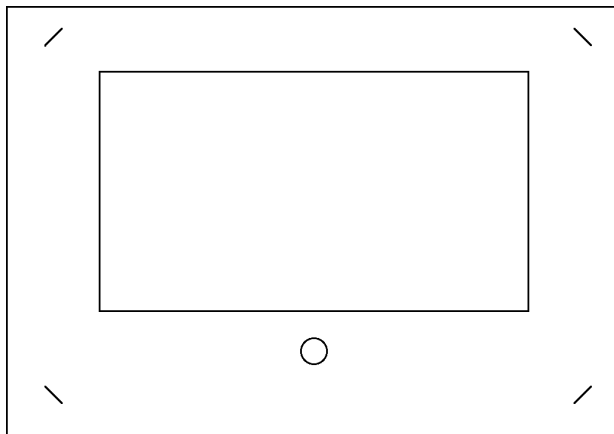
1.12 Placement and type of anchors in double layered facade element. In the middle is a fixed anchor. In the four corners are steel plates that can deform slightly perpendicular to their plane but prevent rotation

Tilting moulds

Tilting moulds are ideally suited to casting panels of uniform profile. Not all coffered panels can be satisfactorily demoulded. Because handling stresses are less after the panel has been tilted to a vertical position, certain lifting provisions can be omitted and the required quantity of reinforcement for handling can be reduced: in which case the units must be handled vertically during transportation and erection. Thus panels made in tilting moulds are generally thinner than those produced using other casting methods. Care must be taken to ensure that there is adequate reinforcement to resist wind loading when fixed in place.

Tolerances

Three kinds of inaccuracy arise in building: those of manufacture, those of setting out the *in situ* construction, and those of erection of the precast components. Manufacturers prefer to work with deviations ± from the work size, and common practice allows for deviations of ±1.5 mm and ±6 mm depending on panel sizes up to 6 m in length and height. When used in conjunction with *in situ* concrete frame construction with typical deviations of ±15 mm or more, then joints of 5–25 mm between panels can be expected.

In addition to these **induced** deviations, **inherent** movement deviations can also be expected, caused by shrinkage, elastic deformation, creep or changes in thermal and moisture content A variety of factors influence the extent of these movements, and although not susceptible to precise calculation, generally they are in the order of 1 mm per 3 m depending upon the range of temperature expected. These movements are of course reversible, and should be allowed for in the design of fixings.

Handling of units during transportation and on site

Panels require to be lifted from the mould and handled through storage, transportation and finally erection on site. Lifting provision is required in the panels at each stage. One of the main points to consider in the design of precast concrete panels is their weight for handling. Most manufacturers would recommend panels not exceeding 7 t for lifting and 'shuffling' into place on site. This can often place a restriction on the size of the panel, depending upon the density of the concrete used, and the architect must therefore be aware of any weight restriction when determining panel size.

Lifting provision for transportation and erection should if possible be above the centre of gravity, so that when the panel is suspended it will hang in a vertical plane. Tilting of the panels during lifting on site can cause difficulties in placing and fixing. Often it is not possible to suspend a cranked unit, such as a spandrel panel, from its outer face because of difficulties of patching over the fixing sockets. Special lifting devices are then used (Fig. 1.13) to support the panel and keep the centre of gravity below the crane hook (Fig. 1.14).

Panels are often transported horizontally, and require additional reinforcement and lifting provision for handling when lifted into their vertical position. One method of reducing the stress on the panel during such handling is to use a tilting platform (Fig. 1.15). Tight access for crane jibs in relation to the building form should be checked in advance, and
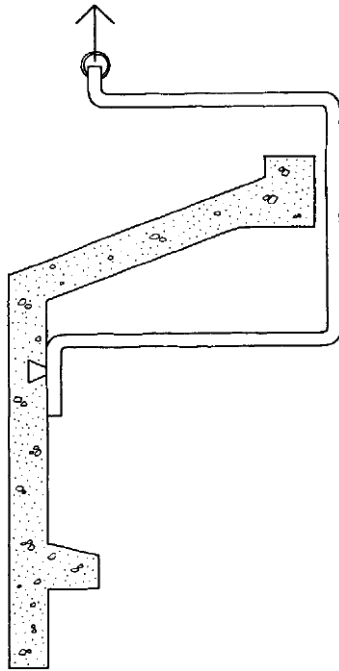
1.13 Special lifting device for cranked units.

1.14 Special lifting tackle for cranked units.

1.16 Clearance required for crane jib.

1.15 Tilting platform as used at Liverpool Royal Insurance building.

allowance should be made for clearance for the jib of the crane above panel fixings (Fig. 1.16).

Fixings for handling are usually loops of reinforcement or cast-in sockets for use with patent lifting devices, which take the form of shackles, stranded steel loops, collared eyes or clip-on bolts. Common proprietary lifting devices are shown in Fig. 1.17. Screw-in lifting devices should not be used singly because of the danger of their becoming unscrewed during lifting. Generally speaking, the shackle device has been found to be the most reliable, but it is expensive. Loops are the most common method. These can be left intact, or burnt off when not required. Collared eyes and

shackles are useful for side-hung lifting provision. Clip-on fixings are useful, but the width of hold makes them unsuitable for thin slabs.

Levelling devices

Levelling devices can be used to facilitate panel assembly. They take the form of a cast-in threaded plate and a bolt, which engages in the plate and bears on the floor slab.

Shape of precast concrete cladding panels

The principal types of non-loadbearing panel are storey height and spandrel units (Fig. 1.18). These are either of uniform thickness or coffered at their edge to provide a jointing profile. Most panels employ strengthening 'ribs' as beams to transfer dead and vertically applied loads to the structure; the panel 'web' then acts as a slab spanning between these beams.
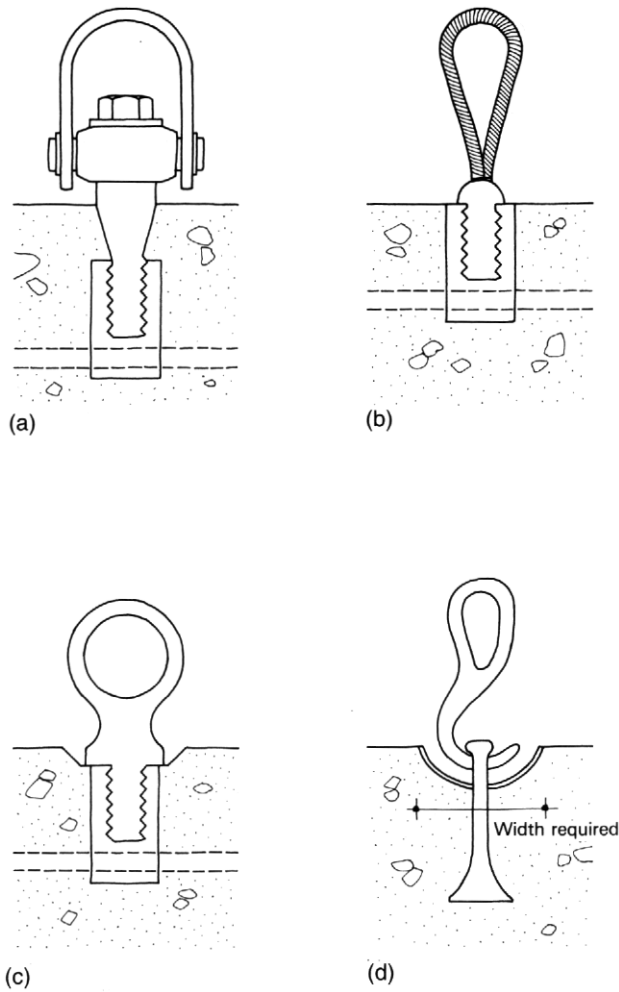
1.17 Principal lifting devices: (a) shackle; (b) loop; (c) collared eye; (d) clip-on.
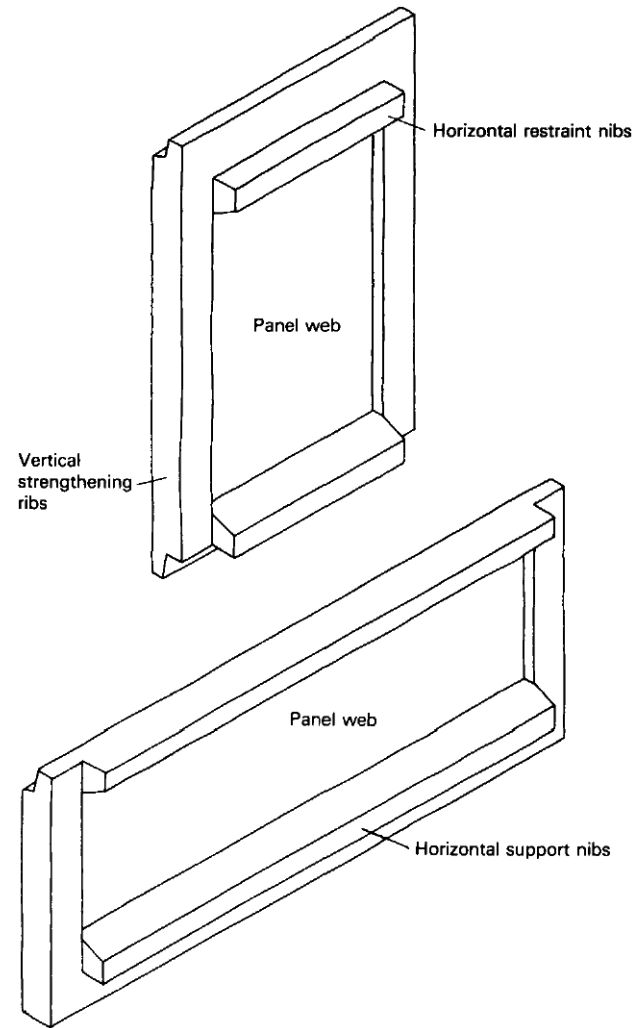
1.18 Strengthening ribs and support nibs on storey height and spandrel units.
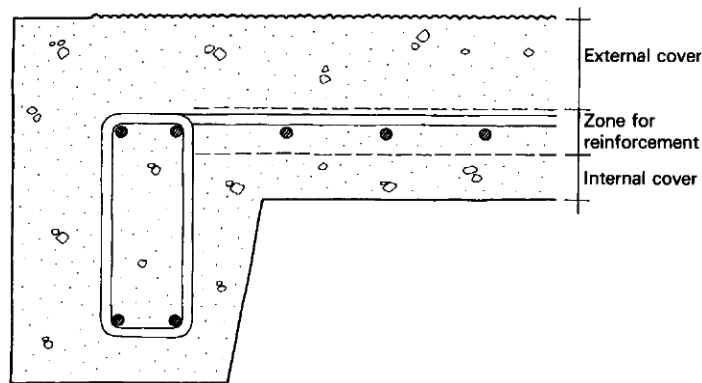
	Concrete grade	
	25 N/m²	30 N/m²
External cover	50	40
Reinforcement zone	25	25
Internal cover	25	20
Total depth	100	85

1.19 Panel web thickness (mm) related to zone for reinforcement and cover for two types of concrete mix.

The shape of the precast concrete cladding units is therefore related to:

– panel web thickness;
– horizontal support/restraint nibs;
– vertical strengthening ribs.

Panel web thickness

In practice the web thickness is governed by the requirements of cover to the reinforcement. This is dependent on the degree of exposure to weather, the grade of concrete used (25 N, 30 N/mm²), and whether a facing mix is required to obtain a special finish. Figure 1.19 shows the depths to be allowed for panel web thickness for two types of concrete mix. The thickness of the panel web is determined from the following factors:

– the external cover to reinforcement;
– the zone reinforcement;
– the internal cover to reinforcement

The depth of external and internal cover should be determined according to the grade of concrete to be used and the conditions of exposure. Normally, external cover is either 40 or 50 mm and internal cover 20 or 25 mm. A zone of 25 mm should be allowed for the reinforcement, stiffening bars and variability of placing the steel in the mould. For most conditions, a nominal thickness of 100 mm can be used for web thickness in design. Using a span:depth ratio of 1:27, the web would then span 2.7 m.

Horizontal support and restraint nibs

The depth of the horizontal support nib is determined from the loadbearing and fixing requirements. The most important consideration is that there should be a minimum bearing of 100 mm on the structural slab plus an allowance of 25 mm for any inaccuracies in the edge of the slab and any danger of spalling. Figure 1.20 shows the minimum dimensions of the horizontal support nib and its bearing upon the type of fixings to be used. Allow for 175 mm with dowel fixings and 125 mm using cleat fixings.

In addition to providing space for reinforcement, the height of the nib is usually affected by the type of fixing used and whether or not it is necessary to provide cast-in fixing sockets. Where an angle cleat fixing is used, the suggested height of nibs is 150 mm. For a dowel fixing, this can be reduced to 125 mm. Concrete corbels and stainless steel bearing angles
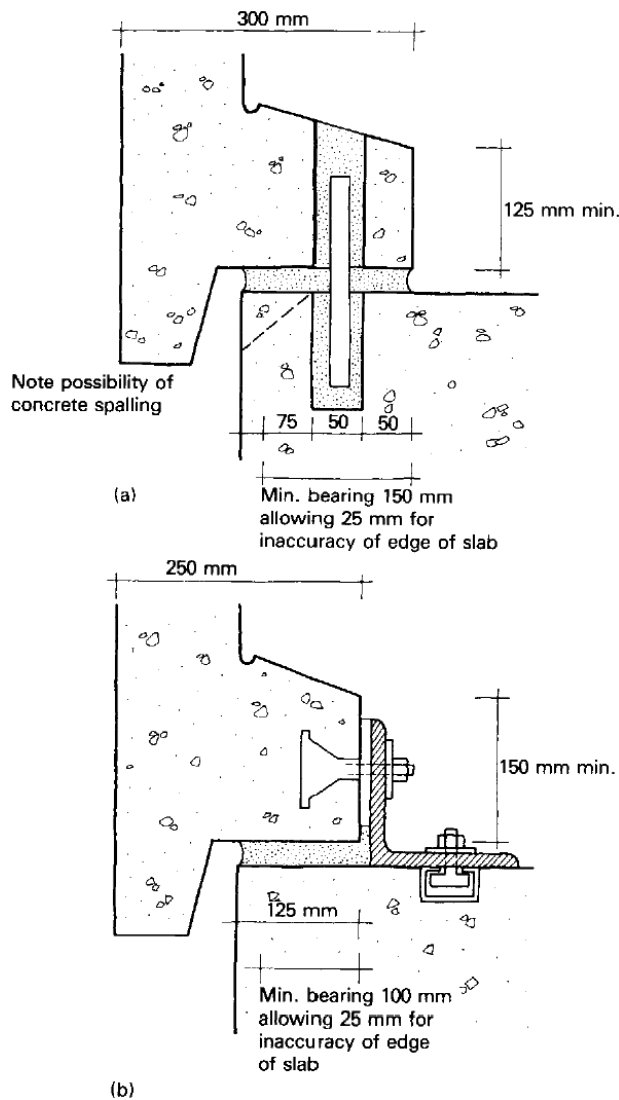
1.20 Minimum dimensions of horizontal support nibs: (a) dowel fixing; (b) cleat fixing.

are extensively used to restrict the height of the gravity support device to fit under raised floors.

Vertical strengthening ribs

The depth of the vertical strengthening ribs is related to the span between the supports. For coffered panels the web is designed using a span:depth ratio of 1:27, whereas the ribs can be designed as beams with a span:depth ratio of 1:17. Sufficient depth is often necessary to accommodate the elements of an open-drained joint (see Figs 1.21 and 1.27), especially where the profile incorporates a drainage groove or where an upstand is provided at the head of the panel. Figure 1.21 shows vertical strengthening ribs of 250 mm to coincide with the depth of a panel needed to incorporate an upstand joint.

The breadth of the rib is governed by such factors as:

- cover to vertical reinforcement;
- the dimensions of columns at panel junctions;
- the accommodation of push–pull sockets for alignment and fixing.

Additional cover will be required if open-drained joint grooves are incorporated in the edge of the panel.

Figure 1.22 shows that for panels abutting columns a breadth of 100–125 mm is normally sufficient, but when the panels occur in front of the structural columns, this may have to be increased to allow for the dimension of the column, so that panel fixing can be within the rib dimension.
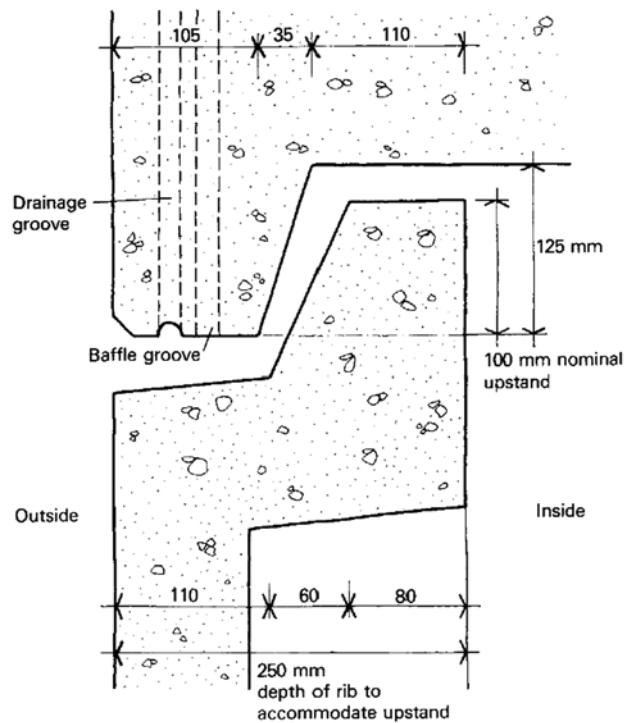
1.21 Depth of rib to accommodate upstand at head of panel.

Jointing

Sealants

Sealant joints are designed to provide a complete watertight barrier in the form of a single-stage joint positioned towards the panel face. The main types of sealant joint for use with concrete cladding are polysulphide (one- and two-part) acrylic and low-modulus silicone. Sealant joints are often used for highly profiled units such as spandrel or parapet panels.

Two-part polysulphide sealants are most commonly used because they have good movement capability and thus can offer greater joint size ranges. However, on large jobs with several mixes the colour of sealant can vary, and some manufacturers prefer to use one-part polysulphide, with which the colour is more constant.

Low-modulus silicone (typically Adshead Ratcliffe 1090 or 1099) is used for its good movement capability and longer life expectancy.

Rectangular- or circular-section sealant backing of closed-cell polyethylene foam is used to ensure the correct depth of sealant and to separate it from incompatible materials, which could cause its breakdown (Fig. 1.23).

It must be accepted that the sealant joints will need to be repointed during the life of the building, as the proven life of the best sealants is as yet only 20 years. However, sealants in locations protected from the effects of ultraviolet light and extremes of weather may have a greater life expectancy than those in more exposed positions.

Although most cladding manufacturers continue to use sealant joints, possibly because of their ease of detailing, gasket joints can offer a more stable jointing product, particularly when used as a two-stage joint in conjunction with an air seal.
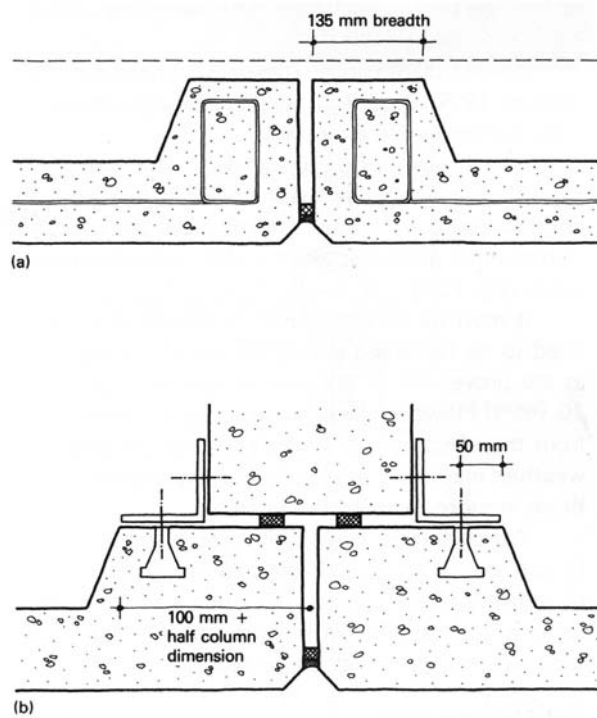
1.22 Breadth of vertical strengthening rib related to dimension of column: (a) junction without column; (b) junction with column.

Open-drained joints

The most popular gasket joint is the open-drained baffle joint, first introduced from Scandinavia in the 1950s. With proper detailing, correct specification and control of installation on site, it has proved to be fairly successful. Correct detailing, however, is essential. Open-drained joints are explained in BRE Digest No 85 *Joints between concrete wall panels: open drained joints* (BRE, 1967). This covers the principles of and recommendations for details, especially flashings at crossover joints (Fig. 1.24).

The principle of the open-drained joint is to use the geometry of the joint to trap most of the rain in
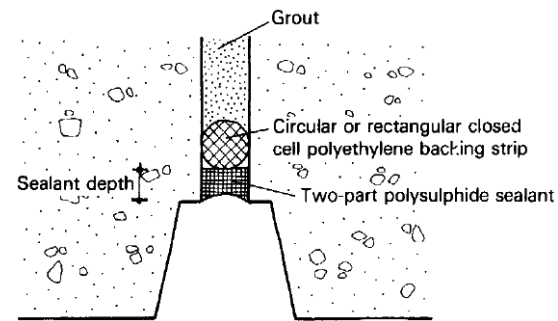
1.23 Polyethylene backing strip to ensure correct depth of sealant.

an outer zone and to provide a barrier (air seal) at the back of the joint to prevent air and water (that gets past the baffle) from penetrating into the building. Although the baffle strip acts as a primary barrier to wind-driven rain, the real effectiveness of the joint depends upon maintaining the performance of the air seal. The theory is that, because the seal is positioned at the back of the joint, it is sheltered by the baffle from the ultraviolet light and direct rain, and is subject to less thermal and moisture movement than if it were positioned nearer the face of the panel.

The main elements of the open-drained joint are therefore:

–   the baffle strip;
–   the baffle groove;
–   the air seal;
–   an effective upstand at the base of the panel;
–   the horizontal flashing at crossover joints.

Baffle strips

Neoprene is the most common material for baffle strips, and is normally used in 50, 63 and 75 mm widths. There are various ways of supporting the baffle

strip, including fixing it into plugs in the top surface of the panels. There can be some difficulty in preventing spalling of the concrete using these plugs, and another method devised to facilitate renewal of the baffle is to turn it over a stainless steel pin restrained by bolting through the return ends (Fig. 1.25). The baffle should not be fixed over the pin using staples alone (Fig. 1.26). The steel pin is located in grooves on either side of the panel joint, which should be wide enough to contain the diameter of the pin (not less than 6 mm) plus two thicknesses of baffle. This will probably be wider than the baffle groove in the side of the panel.

1.25 Baffle fixed over stainless steel pin for easy renewal.
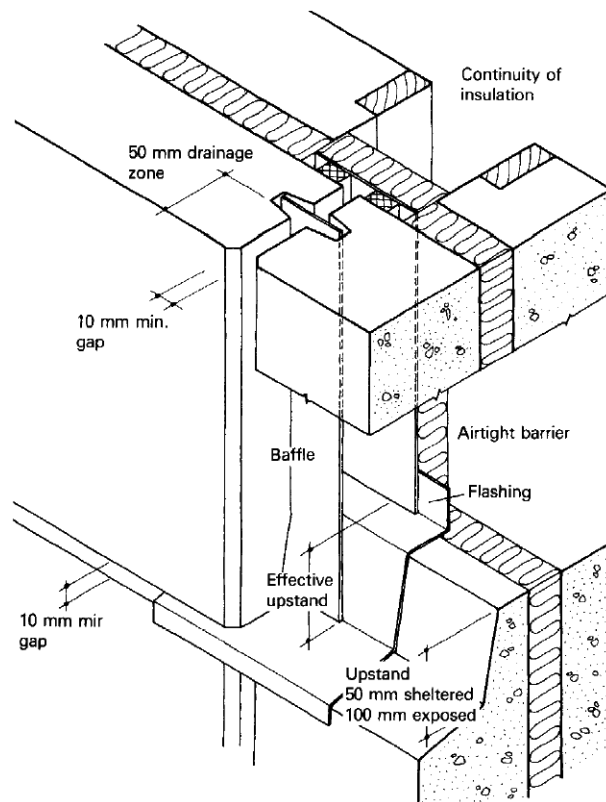
1.24 Crossover open-drained joint.

When using baffle strips these should not be stretched before cutting at the base of the panel, otherwise they spring back up the joints, and are then short.

Baffle grooves

Grooves are normally formed by fixing a timber insert to the edge of the mould, and a width of 15–25 mm is normally sufficient to allow a screw fixing and demoulding from the mould. The depth of the groove will vary according to the joint range expected, but 35 mm is normally adequate to accommodate a 75 mm baffle.

The recommended distance of the baffle groove from the front panel is 50 mm, which should be increased to 75 mm if an additional drainage groove is provided (Fig. 1.27).

Air seals

Air seals can be in the form of flexible membranes, gaskets, compressible foam strips and sealants. In practice, this seal has proved difficult to apply. The

main difficulty is that of providing a satisfactory air seal at the back of the joint, especially in positions where panels pass in front of floor slabs or where panel joints occur on the centre line of concrete columns. In this case it is not normally possible to apply the seal directly to the back face of the joint.

Upstands

The matching upstand and downstand profile at the horizontal joint is one of the primary features of the open-drained system. The heights of the upstand and downstand are related to the site exposure conditions. The effective lap should be 50 mm, and for severe conditions this should be increased to 100 mm (Fig. 1.28).

Flashings

A horizontal flashing must be provided at the junction of horizontal and vertical joints. The principal materials used for flashings are bitumen/polythene or butyl rubber. The width of the flashing should be 300 mm in order to span the vertical joint.
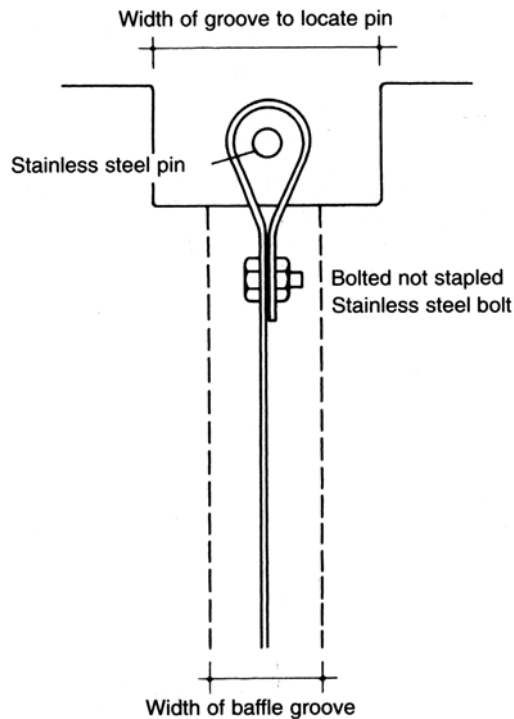
1.26 Method of restraining the baffle using a stainless steel pin.
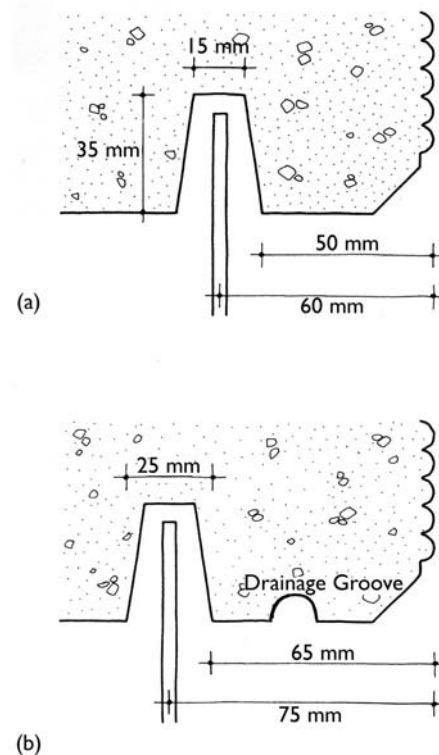
1.27 Depth of baffle groove from the face of the panel: (a) without drainage groove; (b) with drainage groove.

Gasket joints

Although a number of gasket joints have been used, including cellular, tubular, cruciform and fircone gaskets, they all require to be constantly under compression with continuous contact with the panel edge. This is not easy to achieve, because of the variation of joint widths normally attainable on site (typically 10–30 mm). The possibility of blowholes and other unevenness on the concrete panel joint profile also makes it difficult to attain continuous contact with the panel edge. Cruciform gaskets are produced in rolls, and are difficult to straighten out.

The cost of the jointing system depends on the quality of the materials used. For sealant joints, the cost is generally related to the volume of sealant, and is influenced by the expected range of joint sizes. For gaskets, the labour in cutting and welding the section and the correct selection of gasket size are of particular significance.

Removal of moisture from behind panels

No matter which type of joint is used, there is a general consensus of opinion by BRE and panel manufacturers that from time to time moisture will occur on the inner surface of panels as a result of condensation and/or rain penetration, and panels should be designed to include facilities for its removal by weepholes left in the moulding. Condensation is collected in a groove on top of the bottom horizontal ribs. Different weephole designs and condensation grooves are shown in Fig. 1.29. Weepholes should not be less than 13 mm internal diameter to prevent blocking, and they should project from the face of the building to prevent, as far as possible, any staining of the panel surface. In order to prevent such staining, it is sometimes possible for the weephole to be cast into the panel so that it drains moisture into the horizontal joint.

Site exposure	A	B
Sheltered	50	75
Moderate	75	100
Severe	100	125
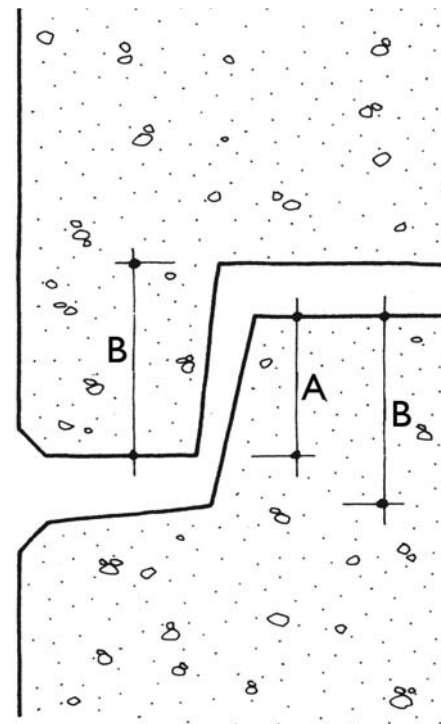
1.28 Heights of upstands and downstands (mm). A = effective lap and B = actual lap or downstand.

Panel fixings

Panels can be either top hung from the structure or supported from their base. Nibs projecting from the back of the panel transmit the load to the structure by means of a mortar bed. Panels can then be restrained

either by dowel bars or by angle cleats, both of which must be fixed so as to permit vertical movements arising from the deformation of the structure or movement of the panels. Various combinations of dowel and cleat fixings are shown in Fig. 1.30. Contractors often prefer cleat fixings at the top with dowel or cleat fixings at the bottom (types a and b) because this facilitates quick erection; however, building inspectors sometimes prefer panels to overhang the slab, as in theory should the fixing fail the panel would fall inwards under its own weight and wind loading.

Although the dimensional inaccuracies in manufacture of medium-sized precast concrete panels are not likely to be in excess of ±3 mm, the inaccuracies imposed during assembly because of deviations in the frame and erection deviations on these panels are likely to be much more than this, possibly ±25 mm. Thus tolerance must be allowed in the method of fixing and in the allowable clearance between the panels and the structure to take account of such inaccuracies of construction. Allowance must be made in the design of the fixings for thermal movement of the panel (Fig. 1.31). Avoid three fixings at different

1.29 Alternative positions of weepholes.
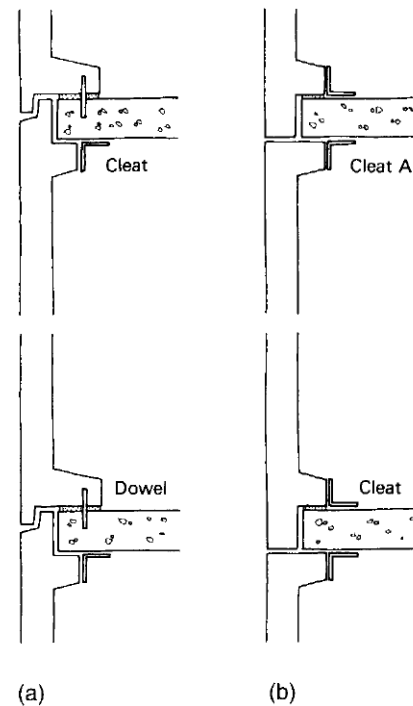
1.30 Various combinations of dowel and cleat fixings: (a) cleat to dowel bottom; (b) cleats top and bottom.

levels (Fig. 1.32). Two types of fixing are in common use in addition to the fixings for handling listed earlier. These are:

— angle cleats
— dowel fixings
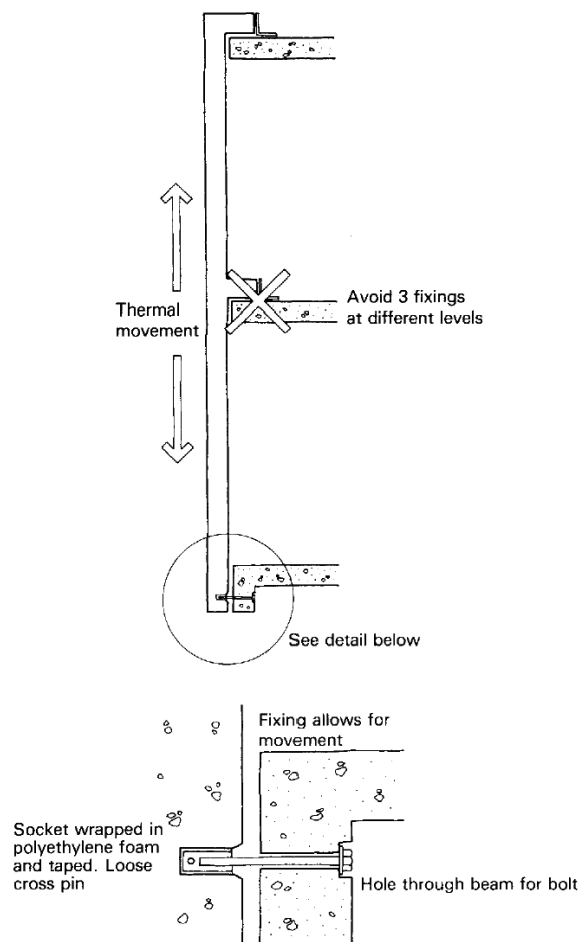
1.31 Allowance in the design of fixings for thermal movement and inaccuracy.

Angle cleats

Although usually used for top restraint panels, angle cleats may also be employed at the base support position. There should be at least two cleats per panel, irrespective of panel size, and their size should be calculated by a structural engineer according to the loading for each job. They should be designed to give three-dimensional adjustments by the use of slotted holes and/or by packing pieces. Figure 1.32 shows a typical angle cleat system with packing allowance adjustment at right angles to the face of the building. Vertical adjustment is provided by the use of a slotted hole and low-friction washer, and horizontal adjustment is provided by means of a 150 mm length of proprietary channel cast into the floor slab. Care is needed in the accurate location of such channels during the casting of the slab, and reliable placing is more easily achieved when this channel is cast into the soffit of the slab (where it can be fastened to the shuttering), rather than in the top surface.

Bolts fixing the angle cleats are normally fixed to cast-in sockets or expanding sleeves. Cast-in sockets are used with precast concrete, as they can be accurately cast in place in the factory. However, with *in situ* concrete, their precise location cannot be guaranteed, and channels are used to allow adjustment Where channels are not suitable, the structure is drilled to receive bolts with expanding sleeves, taking care to avoid reinforcement.

In all fixings relying on bolts or set screws, the designer must ensure that there is adequate space for tightening the bolt, or other device, in the completed assembly.

Dowel fixings

Dowel bar fixings are a common and simple method of locating and restraining the panel at its bottom support nibs. The main reason for their use is that

they are considerably cheaper than non-ferrous angle cleats and can more easily accommodate dimensional inaccuracies in the structure. Usually, they are set in a 50 mm × 50 mm pocket in the *in situ* floor slab, a 50 mm diameter hole being provided in the panel to receive the dowel bar. The space around the dowel is grouted with either neat cement or an epoxy resin grout.

Where dowels are used in conjunction with panels supported at their head, some provision for vertical movement may be required. In this case, the bars can be bound with Sellotape to avoid adhesion of the grout. A resilient pad between the panel nibs allows movement and prevents grout loss.

Finishes

The range of finishes that can be produced on precast cladding can be summarized according to their method of production as:

–   surfaces cast direct from the mould, e.g. smooth centre, board-marked concrete, grooved or serrated, including reconstructed stone finishes;

–   finishes in which the cement surface is removed to expose the aggregate in the concrete;
–   applied finishes, such as tiles, stone facings and bricks;
–   surfaces textured by tamping or shaping.

The various methods to produce these finishes are dealt with by Gage (1974) in his guide to exposed concrete finishes. In addition, examples of various exposed aggregate finishes can be seen in Oram (1978). Most precast concrete cladding panels use such exposed aggregate finishes, and their colour and texture are largely affected by the type of aggregate used. The use of applied finishes affects the type of casting used (Fig. 1.10).

Many buildings incorporate natural stone-faced cladding fixed with dowels or retention angles, and it is clear from examples of failures seen recently that there is a need to detail the fixings of stone panels to avoid spalling of the stone facing. Manufacturers normally advise the minimum thickness of limestone as 60 mm and of granite as 50 mm. Fixing dowels must not penetrate the stone to more than two-thirds of its thickness.

The incorporation of stone into curtain walling has promoted an interest in lightweight stone cladding consisting of a thin layer of natural stone (granite, marble or limestone) bonded to a unidirectional glass filament and phenolic resin skin bonded either side of an aluminium honeycomb core. Panels can be typically produced to a maximum size of 2400 mm × 1200 mm, 25 mm thick. Typical weight is 25 kg/m^2 compared with 50 mm thick granite, which weighs 135 kg/m^2, and 60 mm thick limestone, 144 kg/m^2.
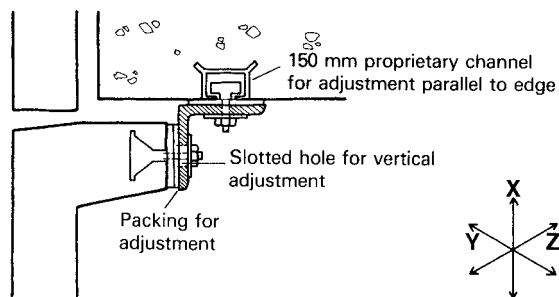
1.32 Method of adjustment with cleat fixing offering movement in x, y and z axes.

Weathering

The quantity of rainwater, the velocity and the angle at which it hits a building change for different positions in the building, and therefore one must expect unequal weathering of the parts. This is particularly true for precast concrete, for which water absorption can cause blotches or streaking on finished surfaces. Concrete finishes vary considerably in their ability to take up and release dirt under weathering conditions. They should, therefore, be chosen for so-called self-cleansing properties.

Some buildings have been designed to take advantage of the unequal weathering in the profile of the panel: for example, faceted panels (now removed) were used at the mathematics building at Liverpool University (architects: Westwood, Piet, Poll and Smart). Vertical ribs or striations also help the appearance of panels. Panels for Portsmouth Dockyard (architects: Arup Associates) were produced by Minsterstone, using concrete moulds and ribbed to control weathering marks (Fig. 1.33).

The imaginative use of precast concrete panels by Peter Rice was shown in the precast concrete arches at Seville Expo (Fig. 1.34).

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1.33 Ribbed concrete panels.

1.34 Precast concrete arches at Seville Expo 1992 by Peter Rice.

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2

Terracotta and brick slips

Production of terracotta

Whilst, like bricks, terracotta is made of clay, the process of manufacture is much more demanding. The type of clay used, and the source of the clay, relates to shrinkage during production and the colour of its surface.

A typical production cycle includes:

– storage;
– grinding;
– mixing;
– extrusion;
– drying;
– squaring and brushing;
– baking;
– removal of residual calcium carbonate.

Storage

The clay is extracted from local quarries. The colour and quality of the final product is often dependent on the location of these quarries, e.g. Bardeau (France), Argeton (Germany) and Cotto Sannini (Italy). It is sorted, any large stones removed, and then stored in sheds where it is mixed several times to release natural gases, which may be harmful during the production process.

Grinding

Clay and lithic granules are ground finely and stored in silos.

Mixing

It is then mixed into a plastic compound which is fed by conveyor belt into the molding machine.

Extrusion

Here the clay is pushed through an extrusion mould. Any air present in the compound is removed, the clay is formed into the desired shape and is cut to length. The size of the piece is about 7% larger than its final size because the raw piece undergoes shrinkage when dried and baked in the kiln.

Drying

These raw pieces are then placed in the drying chambers, which are heated to approximately 100°C by hot air recovered from the kilns. The moisture is gradually removed using fans which continuously recirculate the air. It is important to remove this moisture slowly to avoid cracking in the final terracotta product.

Squaring and brushing

When the piece is completely dry it proceeds to the squaring and brushing line where the edges are ground to shape to remove any remaining irregularities before being brushed to give it a smooth appearance. A rustic appearance can also be introduced at this time by using a set of steel brushes.

Baking

The pieces are then loaded automatically into pre-heating kilns, before being loaded into the baking kiln, where the temperature is increased gradually to 970–980°C. After baking, the pieces are cooled. It is important to avoid a sudden drop in temperature at this stage and the time required from preheating to cooling depends upon the type of clay, but can be over 70 hours. Shrinkage is an inherent part of this process. European regulations allow for tolerance on the final product to be 1.3% of the finished piece.

Removal of residual calcium carbonate

Some sources of clay include calcium carbonate which, despite fine grinding and baking, remains active and can swell if exposed to moisture in the atmosphere. It is therefore good practice, in order to avoid deterioration of the surface of the tiles, for these to be immersed in water for several hours to remove the calcium carbonate.

History of terracotta tiles

Terracotta was a popular material in the UK during the Victorian period chiefly because it enabled the use of decorative sculptured forms, but also because its dense and often glazed surface meant it was unaffected by atmospheric pollution.

Terracotta was not only used for public buildings such as the Natural History Museum by Waterhouse but also as a decorative relief for brickwork in many domestic buildings. As styles changed, and in the Modern Movement architecture became more restrained in its surface treatment, terracotta fell out of favour (Yeomans, 1997).

More recently an increasing requirement by Planning Authorities for buildings to fit into the local character, and perhaps a stylistic rejection of smooth metal facades, has led to an increasing demand for brick facades and terracotta.

Since the early use of terracotta tiles by Renzo Piano at the IRCAM building, next to the Pompidou Centre in Paris (Ellis, 1992) and the pioneering work of Thomas Herzog (see below) there are now several companies offering terracotta tile systems, which are mainly used as rainscreens, throughout Europe.

Brick manufacturers have also realized a potential market for lightweight brick slips mounted on a secondary support system which can be fixed either to a concrete/masonry back-up wall or mounted within a metal framework. These can either be used as a rainscreen with open joints or more typically sealed to represent conventional brickwork.

Prefabricated brick panels have developed since the 1940s, being mainly linked with industrialized building systems but their weight, the possibility of damage to their edges, and difficulty of linking panels together has never led to their widespread use.

Examples of the use of terracotta

There are several examples of the recent use of terracotta which have influenced architects to use this material.

IRCAM building

One of the early uses of terracotta as a cladding material in the palette of modern architecture was by Renzo Piano in 1988 at the extension of the IRCAM studio and the housing project at Rue de Meaux in Paris. At IRCAM, he wanted a cladding system which fitted into the traditional Parisian fabric, and thus invented a new system where the 300 mm × 210 mm terracotta tiles are threaded on to metal bars, like kebabs, and fixed to a prefabricated frame, to be used as a rainscreen.

The frames are 12 tiles wide. These hollow tiles are mounted on aluminium circular bars spanning across the frame. The whole assembly has a hierarchy of open joint sizes. The vertical joints are 20 mm. At the junction with floors the joints are 80 cm. Close up you are aware of this hierarchy, from a distance you see a massive terracotta-covered volume.

2.1 IRCAM building, Paris, by Renzo Piano (photo © Christopher Grech).

Rue de Meaux, Paris

At Rue de Meaux, Renzo Piano used a different type of terracotta, resembling tiles, which was individually mounted on site on prefabricated glass fibre reinforced cement (GRC) elements. The use of these special storey-height prefabricated elements was possible due to the large scale of the project, which consisted of 220 houses and 3 shops.

The tile size is 430 mm × 180 mm × 12 mm thickness. Their appearance is similar to the commonly known rectangular ceramic cladding tiles of today.

Cité Internationale, Lyon

Both IRCAM and Rue de Meaux use a rigid geometry and a relatively small element size. Later, Renzo Piano developed the use of terracotta in his design for the Cité Internationale in Lyon. Here larger and more curved components are used. He developed a system using twenty different models of cladding panels,

2.2 Rue de Meaux, Paris, by Renzo Piano.

2.3 Cité Internationale, Lyon, by Renzo Piano.

including curved corner elements. Their size varies in length from 0.2 m to 1.4 m and they are mounted on aluminium rails. This system formed the basis of the 'Bardeau' system now marketed in the UK, USA and Europe by Terreal.

Terracotta systems

There are essentially four types of terracotta system.

'Bardeau' system

The Bardeau system using French clay was originally imported into the UK by Smithbrook Building Products but is now marketed by Terreal using a French tile manufacturer, Guirard Freres. It was originally used at Cité Internationale de Lyon by Renzo Piano. The maximum size of the tiles is 1400 mm × 300 mm × 70 mm; they are fixed to a metal framework using proprietary stainless steel clips at each end of the tile. It can be used in conjunction with the Bardeau tubular

'mulots' or sunscreens to ensure continuity in the facade's architectural expression around openings.

Argeton system

Another family of cladding using terracotta originated from Germany, where it was developed by the architect Thomas Herzog and known as the Argeton system.

In the early 1980s, Professor Herzog became interested in the concept of a curtained ceramic facade and developed it into a system. In order to bring this system to market maturity, Argeton, a consortium of German roof tile production plants, was founded. From 1981 until market introduction in 1986, Professor Herzog was the sole development partner of the Möding GmbH & Co KG roof tile production plant. As a result of close collaboration, in 1984 the Möding roof tile plant produced its first facade tile, which was used on a building in Munich Lohhof.

During the 1990s the system was developed with special clip holders and introduced as the Möding Argeton tile facade. The appearance of the product somewhat resembles the Rue de Meaux project by Piano. Herzog's design is simpler and was not developed specifically for one project but for more general use. The system was first imported into the UK by SJW (now ceased trading) and marketed by James & Taylor, who later went on to sell the system as Möding Alphaton. The name 'Argeton' was retained in UK by the Telling, Architectural Group. An early use of the system was at the De Montfort University's library extension in Leicester (architect Eva Jiricna) using standard format tiles, size 400 mm × 200 mm × 30 mm.

The Argeton System was also used by Brookes Stacey Randall Architects at Churchill Centre in Rotterdam.

2.4 Argeton terracotta at Churchill Centre Rotterdam (architects: Brookes Stacey Randall). Photo: Christian Richters and Nik Randall.

2.5 Churchill Centre Rotterdam (architects: Brookes Stacey Randall). Photo: Christian Richters and Nik Randall.

Lockclad system

The Lockclad system, supplied in the UK by Red Bank, uses terracotta tiles made from English clay fixed to an aluminium lock rail. Each tile is securely and independently retained on the supporting rail by fixing clips, allowing individual tiles to be removed and replaced. Rainwater penetrating the rainscreen is collected by the tray that forms the top of the sigma rail. It is then efficiently drained to the front face of the facade at every horizontal joint. Openings should be suitably baffled to minimize the ingress of water and be protected with mesh against birds and vermin. They can be expensive to detail.

The sizes available from Red Bank are: heights (including 10 mm joint) 185 mm, 200 mm, 210 mm, 225 mm, 235 mm, 250 mm and widths 210 mm–400 mm.
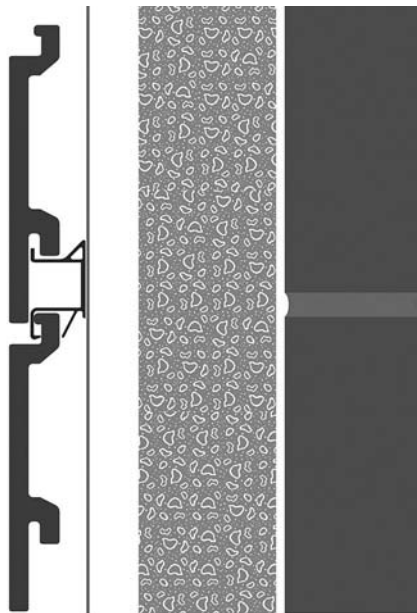
**2.6** Typical detail of terracotta panel used as a rainscreen.

GIMA Longoton

Möding has now been purchased by a larger company, GIMA, which has developed its Longoton System. This is marketed in the UK by NBS Group and in the USA and Canada by Shildan USA.

The first UK project completed using GIMA tiles was The Shambles, Deansgate, Manchester in 2001. The architect was BDP London, the structural engineer was ARUP and the fixing subcontractor for the terracotta was Tellings Ltd.

This project used a very simple and cost-effective form of substructure for the terracotta. This involved T-section aluminium vertical rails fixed back at approximately 870 mm centres. The tiles were secured to the rails using an aluminium lip at all four corners.

The second UK project was the Liverpool Biosciences Building for Liverpool University, completed in 2002. The architect was David Morley and the subcontractor for the terracotta was Dane Architectural.
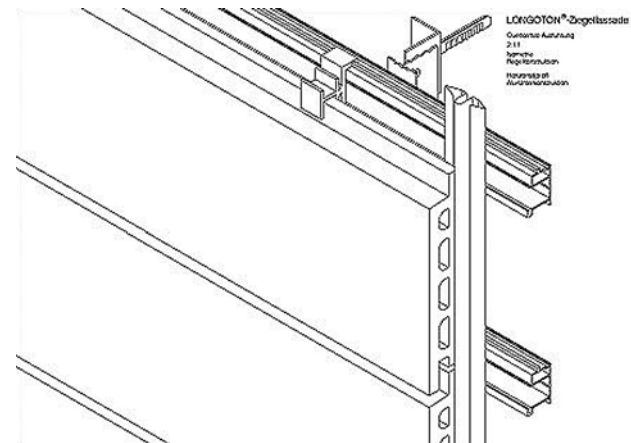
2.7 Longoton cladding systems.

Development of tile size and finish

In general it can be seen that over the last twenty years there has been a gradual development and greater interest in the use of terracotta tiles, particularly used as a rainscreen.

The challenge has been to offer systems with larger tiles that can be quickly fixed to, or dismantled from, a metal supporting structure, in a wider range of sizes as prefabricated elements within the restraints of the budget. Generally these terracotta systems are more expensive than the brick slip systems.

Sizes of tiles have gradually increased, as shown in Table 2.1.

The range of colours has also increased. Möding Alphaton has 12 colours with 5 types of finish, Red Bank's Lockclad is supplied in 4 colours. GIMA Longoton has 6 colours.

Brick slip systems

Brick slip systems have the advantage that they are light and easy to handle on site and it is possible to replace individual slips if they are damaged.

There are essentially two types of system:

1) Where the brick slips are adhered to a polyurethane foam board and the whole system fixed to a back-up wall.
2) Where the brick slips are locked into a supporting framework of steel or aluminium channels which can in turn be fixed to a metal supporting framework.

In 2005 the following brick slip systems were available in the UK.

Gebrick (marketed by Taylor Maxwell & Co – Bristol)

Brick slips are bonded to polyurethane foam mounted as panels (typically 1375 mm long, 688 mm wide and 60 mm thick) with bridging slips bonded on site. The system has an Agreement Certificate No. 02/3946 which states the system is suitable for walls up to and including 30 m in height. The approximate weight of the panel is 30 kg/m^2.

Table 2.1 Development of panel size

	Length	Height	Thickness
IRCAM building	300 mm	210 mm	50 mm (with hole)
Rue de Meaux	430 mm	180 mm	12 mm
Cité Internationale	200–1400 mm	–	–
Bardeau (Terreal)	500–1400 mm	300 mm	70 mm
Möding Alphaton (James & Taylor)	150–500 mm	150–250 mm	30 mm
Lockclad (Red Bank)	210–400 mm	185–250 mm	30 mm
GIMA Longoton (Telling NBS)	600–1400 mm	400 mm	30 mm
Argeton	1200 mm	400 mm	30 mm

ISO – NET (marketed by the NBS Group)

These are brick tiles bonded on to a reinforced mesh cloth in 215 mm × 65 mm UK brick size, in either 9 mm or 15 mm thicknesses. This is then bonded to an aluminium honeycomb panel to a length of 1260 mm and a height of 675 mm, typically with a 30 mm air gap behind it. In 2005, the system was undergoing testing in the UK for BBA certification.

CORIUM (developed by Terrapin International Ltd)

These are brick tiles by Baggeridge Brick plc, mounted on 0.55 mm thick steel profiles by CORUS and finished in plastisol coating. Vertical support is required every 600 mm.

The system has the BRE/Wimlas Certificate of Assessment No. 082/01 Sept 2001. Limitations of use are given as maximum design wind loading of ± 2 KN/m^2.

For all these systems the architect or engineer must satisfy themselves that the bond strength of the fixings is adequate to withstand maximum wind loads, particularly suction loads on the building.

The essential difference between the brick slip systems and the terracotta systems is that the former has face-sealed joints with bridging slips to match conventional brickwork, whereas the latter is mounted with open joints as a rainscreen system, with a back-up wall behind it.

In Holland, the use of ceramic cladding tile dates from 1992, when Onno van den Berg and Liesbeth van der Pol designed a prototype house for the Bouwrai. This later resulted in a project in Almere, where sixteen of these houses were built. Another well known Dutch architect showing innovation in terracotta is Rudy Uytenhaak, with his wave-shaped bricks.

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3

Glass-reinforced polyester

Introduction

Many different materials have been used to form composites within the field of reinforced plastics. The concept is to combine a strong tensile fibrous material, to give tensile strength, with a resinous binder to hold the material together and provide compressive strength. Thus GRP is a composite of durable resin with glass-fibre reinforcement. Its principal characteristics are as follows:

- It has a high strength and low density, leading to lightweight products. Despite its high tensile strength, however, it has a low modulus of elasticity, and therefore high loads can be sustained only at the expense of large deflections.
- Glass-reinforced polyester has good corrosion and weather resistance, making it suitable for long-term use in external conditions.
- Its most useful characteristic is that, being a thermosetting material, it can be moulded without the use of pressure or high temperature. This characteristic makes the moulding of relatively short runs of large awkward shapes possible. It also gives GRP its versatility of appearance as, in theory, almost any colour or texture can be produced.

Glass-reinforced polyester is more expensive on a volume basis than most other building materials, and it is therefore essential to use it in thin sections to achieve cost comparability.

To understand how GRP behaves in use, it is first necessary to understand the process of manufacture. The **gel coat**, a layer of resin that forms the outer surface of the GRP, provides protection for a mixture of glass-fibre reinforcement and a polyester **lay-up** resin. Coloured pigments can be added either to the resin or to the gel coat, and, in addition, chemicals and fillers can be added to improve the fire retardancy of the composite.

The liquid resin is **polymerized** or cured into a hard solid by the addition of chemical catalysts, which are mixed into the resin shortly before the material is laid up – in the mould – with the glass fibre. Any of these factors can change for a particular application. Unlike profiled steel, aluminium, or even precast concrete, for which – within limits – the constituents remain constant, with GRP there are a number of variables that could affect the long-term durability of the material, unless it is designed with care. In most cases the laminate is laid up using hand rollers or spray techniques in contact moulds. Mechanical processes such as vacuum bags or press mouldings are only really applicable for long production runs.

GRP production

Thus the factors of GRP production to be discussed further are:

– the polyester resin;
– the glass-fibre reinforcement;
– fabrication – the mould;
– quality control and faults in curing.

Polyester resin

The resin is supplied as a viscous syrup, which, when chemically activated, sets to a hard solid, binding the glass fibre together. Pigments can be added to the resin

to provide the required colour. Finely ground filler may also be added to increase the resin's viscosity or improve its fire performance. Ultraviolet stabilizers may be added to reduce discoloration of GRP when exposed to sunlight. These pigments, fillers and stabilizers, however, in turn may affect the properties of the resin. The liquid polyester resin is polymerized into its hard solid state by the addition of chemical catalysts, preferably under controlled heat conditions. (Polyester materials are thermosetting, which signifies that they cannot be turned back into liquid form, unlike thermoplastic materials, such as polyethylene.) The mixing of resin and catalyst takes place shortly before the material is required for fabrication. The hardening process is sometimes called **curing**, and the rate of cure is temperature dependent.

A vital part played in the manufacturing process is that of ensuring that the final product is fully cured, for it is only in this state that structural and dimensional stability are ensured. Excessive catalyst will cause the mixture to overheat, because the chemical reaction produced is exothermic, resulting in cracking and crazing, while inadequate catalyst will produce an inadequate state of curing. (Such typical faults are contained in Chapter 6 of Scott Bader Co. Ltd (1980); see Fig. 3.1.) Usually, after demoulding, the panels are placed in a curing box under controlled temperature and humidity conditions. The manufacturer can make special curing boxes for large panels, although space in the factory may not necessarily be available, and the optimum size of the available kilns should be checked in advance of the design.

Glass-fibre reinforcement

Molten glass can be drawn out into a filament of glass fibre, and in this form has an ultimate tensile strength per area 10 times that of steel. The existence of the material has been known since the Egyptian XVIIIth

Dynasty, about 1500 BC (Fibreglass Ltd, 1977a). However, glass fibres of sufficient fineness and consistency for reinforced plastics were not commercially available until the 1930s.

Although several types of glass can be drawn into fibres, the standard fibre used for all resin systems is E glass, which is a high-quality electrical-grade glass fibre. This is bundled together to form strands, which in turn can be processed into various products.

Chopped strand mat

This is the most common form of general-purpose reinforcement, which is used mainly for the hand-laminating process.

Continuous strand mat

In continuous strand mat the strands are not chopped, but just allowed to swirl randomly. The product is used for press moulding and resin injection moulding.

Continuous rovings

These consist of long bundles of fibres, which are fed into a machine that chops and sprays them onto the moulding in conjunction with the resin. This **spray-up** technique is used very widely to reduce the labour content of normal hand lay-up moulding.

A continuous thread of glass

This can be wound round the component being impregnated with the resin as it proceeds. This filament winding process produces high-performance components such as pressure piping, but is limited in form, and is expensive to set up.

Other reinforcement materials have been developed that give improved properties, albeit at increased cost. These are **carbon fibre**, a crystalline fibre developed by the Royal Aircraft Establishment in 1963, with a strength and modulus superior to that of glass fibre, and **aramid fibre**, a lightweight, low-modulus fibre developed by Du Pont Industrial Fibres, under the trademark of Kevlar.

Fabrication – the mould

The process of fabrication involves laying up successive layers of resin, into which glass-fibre reinforcement is embedded to follow a mould profile (Fig. 3.2). Reid and O'Brien (1973) have described the basic laying-up
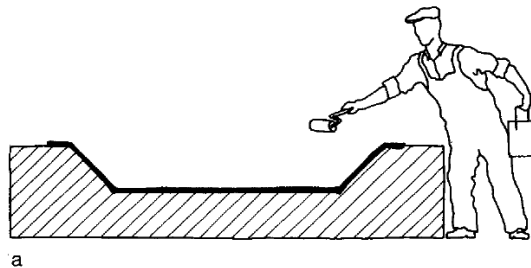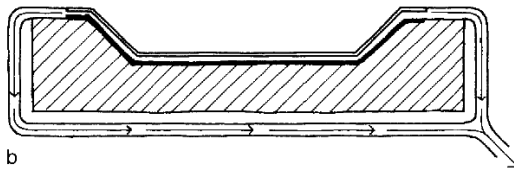
(a)
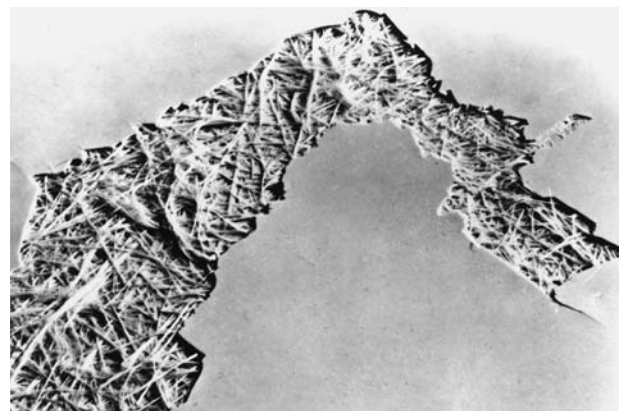
(b)

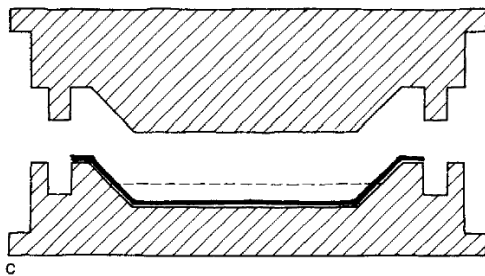**3.1** Faults: (a) crazing of GRP surface; (b) internal dry patch.

techniques. The open mould **contact process** uses either hand lay-up or spray-up application. There are, in addition, some other mechanized processes, such as **press moulding** (hot or cold), using matching moulds to press out panels so that both sides of the panel

3.2 Methods of GRP preparation: (a) contact moulding; (b) vacuum moulding: (c) press moulding.

have moulded surfaces. The moulds for this process are expensive and are more difficult to adapt to accommodate variations in panel shape. Other processes use **resin-injected techniques**, in which the glass fibre reinforcement is placed in a mould of the required shape and resin is forced under pressure, or a combination of pressure and vacuum, into the mould space.

Hand lay-up or contact process

The simplest and most common method of building up the reinforcement and resin is by the hand lay-up technique. First, the mould is waxed and polished using a non-silicone-based wax (Fig. 3.3). It is usually sufficient to do this once every three to five usages of the mould. A release agent, the most common type being polyvinyl alcohol (PVAL), is then applied over the entire surface of the mould and allowed to dry thoroughly. When the mould has been 'run in', it is possible to do away with this operation, except at the edges, relying only on the waxed surface for separation.

The durability of a moulding is mainly dependent on its surface. Moisture will attack the glass-fibre reinforcement so it is protected by a layer of resin known as the **gel coat**. This gel coat is applied to the mould by brush or roller at 450–600 g/m^2. Gel coat resins differ from lay-up resins in that they are thixotropic to avoid draining from a vertical surface, and they also gel with a tacky surface where exposed to air to facilitate a good bond to the rest of the laminate. The utmost care and skill are needed in this operation if an even coating is to be achieved without the entrainment of air bubbles or trapping of dirt. The thickness should be carefully controlled, for where the coating is in excess of 600 μm thick, crazing and cracking, coupled with reduced impact resistance in use, are likely to occur. Faults in the surface of the gel

3.3 Mould waxing prior to moulding.

3.4 Rolling out the lay-up to remove air bubbles.

coat will result in water penetration and a subsequent breakdown of the glass-fibre reinforcement, leading to swelling and rupture of the laminate.

For a small moulding, mixing is done by the laminator using a volume-measuring device to measure in the catalyst. In the simplest case it is done by hand. Where larger volumes are required, measuring and mixing would be done by a machine in a separate area under the charge of a responsible person.

The lay-up of the glass-fibre reinforcement and resin can start as soon as the gel coat has hardened sufficiently not to come away on the finger when

touched. The resin is mixed as before and a liberal coat is applied over the gel coat. The optimum quantity of lay-up resin can be calculated from the weight of glass reinforcement. For chopped strand mat the resin:glass ratio should be between 2.5:1 and 2:1 by weight. The first layer of reinforcement is pressed into the mould and consolidated with a brush or roller. The lay-up is consolidated with a roller, and subsequent layers of resin and glass mat are applied until the required thickness is built up. Figure 3.4 shows rolling out the lay-up to remove air bubbles.

Spray lay-up

An alternative method of building up the resin and reinforcement in the contact moulding procedure is by the simultaneous deposition of resin and chopped glass fibre by spray-moulding equipment. **Spray lay-up** considerably reduces the labour content of the process, although rolling out is still required to

consolidate the laminate and ensure that the resin is mixed.

Machine moulding

There are several methods of producing GRP mouldings by more mechanized methods than the contact moulding technique described so far. These mechanized processes, such as **resin injection, vacuum forming** and **pultrusion** (only applicable to long continuous runs) are not normally relevant to cladding units. This is partly because of the limits of size possible with these processes, and partly because of the capital investment in the necessary machinery. Cladding panels are not often produced in long continuous runs, and because architects are normally designing a one-off panel system requiring only a few hundred panels, the capital outlay for relatively sophisticated machinery becomes inapplicable. One of the few exceptions to this would be the roof panels for Covent Garden Market, London, which were produced by Armshire Reinforced Plastics using resin injection and pressing techniques (Holloway, 1975, p. 69).

It is interesting to make a comparison with the boat-building industry, where this 'tooling up' process is done once and is paid for by the production of a large number of products. In cladding this would require a complete development programme every time a new contract was initiated. Glass-reinforced polyester being a complex design material leads to development time for this process to take place, whereas building components, such as cladding, are often subcontracted, there being a short time between the design and requirement of the product, putting the manufacturer under considerable pressure to met specific deadlines in relation to other design work construction processes. Hand lay-ups and spray techniques are slow; the production of one panel per day per mould is the norm, causing the manufacturer to use a number of moulds to meet the requirement. This in turn increases costs, coupled with the fact that a mould may only last 50–100 panels, after which it would have to be discarded.

The mould

Before an item can go into production, a considerable amount of work has to be done to prepare the mould required for its manufacture. The quality of the mould will ultimately dictate the quality of the finished product. For most projects where a number of panels are required, the moulds are formed of GRP. Master patterns can be made in materials such as timber, steel or plaster, from which this GRP mould is taken. A GRP laminate during curing may shrink by 0.1–0.4% (linearly), and as there are two moulding processes between the pattern and the finished product, the net shrinkage may be as much as 0.8% (one manufacturer gave as an example a 9 m long panel being oversized by 1.2 mm to allow for shrinkage). The manufacturer gradually knows from experience how much to allow for shrinkage, depending upon the shape of the unit, the resin and the temperature change expected. Tooling is one of the highest costs in GRP manufacture. Moulders and finishers are considered to be skilled labour, and most of the larger manufacturers have introduced training schemes for apprentices to this trade.

Because of the bespoke nature of the industry and the number of panels involved for each job, the manufacturers cannot afford too many prototypes before a satisfactory target dimension is achieved. A large number of panels will have to be produced for a number of moulds, not all necessarily to the same master pattern. This is a factor affecting manufacturing deviations of panel size (tolerances).

Another difficulty of manufacture is that some of the stresses set up in the matrix are inherent, pro-

duced by the differential shrinkage between fibre and resin when the GRP composite is cooled to room temperature during fabrication, as a result of differing coefficients of thermal expansion ($70–100 \times 10^{-6}$°C for resin versus 5.0×10^{-6}°C for glass). Resin additives can alleviate these effects by reducing shrinkage.

Although it is clearly desirable to design for simple moulds, it is possible to develop **split moulds** with movable sections to achieve return angles. A flash line is then seen on the face of the panel at the junction of the two sections of the mould. It is possible to buff this out in finishing operations, or render it less obvious by designing the 'split' to coincide with a change of profile. It is vital that reasonable access be given to the fabricator in order to lay up evenly all sections of the mould and to facilitate consolidation of the material by means of a hand roller to expel any air bubbles that may be entrained in the laminate. Too large a mould, or one of a complicated shape, means that the fabri-

3.5 Tilting moulds being used for production.

cator cannot get to all the areas in order to lay up an even coating of glass fibre and resin, while at the same time ensuring good compaction and ease of rolling out. The ideal panel width is one for which the operator can reach all parts of the mould easily, say 2 m wide. The domed panels at Castle Park, Nottingham (architects: Nicholas Grimshaw Partnership) were manufactured as one-piece units using a tilting mould allowing access to all areas for the fabricator. These tilting moulds are similar to those used in boat production (Fig. 3.5).

Quality control and faults in curing

Because the GRP panel industry has a high labour content, the designer/purchaser is totally dependent upon the quality of the labour force employed and the conditions under which they work in the factory. Environmental control on the shopfloor is very important in terms of evenness in temperature and constant relative humidity if the final product is going to be lasting and of good quality. For an illustration of a typical production process, see Fig. 3.6.

Although in its simplest form the laying up of glass fibre in layers looks easy, the process leading to the successful application in large wall elements is much more complicated. There is the initial difficulty of choosing a resin to make a laminate by reference to the resin properties alone. The properties and performance required of the whole matrix must be considered for different resins, and their additives will perform different functions with regard to weathering, flame retardance and colour stability. Depending upon choice, these various constituents may be used in different proportions to each other, and the right control of temperature and humidity limits is essential. The temperature in the workshop should be controlled between 18°C and 25°C, and ideally should be maintained overnight. The workshop should not be
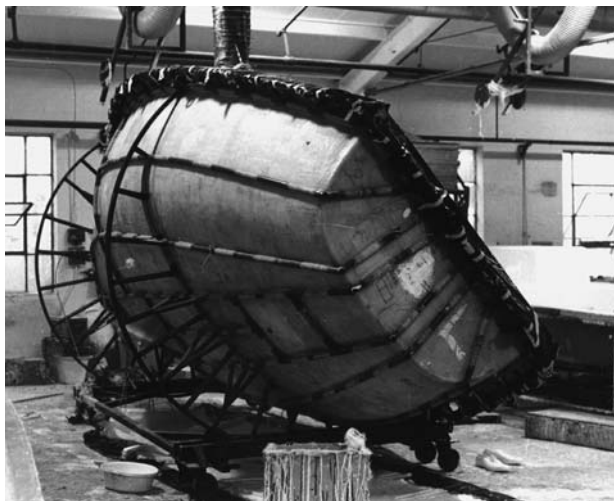
damp, as this causes the glass reinforcement to soak up water, and could lead to delamination of the finished article and a breaking up of the resin/glass-fibre matrix. Cleanliness is of importance, as any contamination in the lay-up will degrade appearance and strength, while good ventilation is also a necessity in order to control styrene content in the atmosphere.

Cutting catalyst levels and reducing workshop temperatures will produce inferior laminates, which perform badly. Blemishes can include gel-coat wrinkling, surface pinholing, poor adhesion of the gel coat and resin, spotting of the gel-coat surface, striation in pigment flotation, pattern of fibres visible through a gel coat, patches of pale colour or 'fish eyes', blisters, crazing of surface of resin, and star mat and leaching after leaving glass fibre exposed to moisture.

As the performance and durability of the GRP product depend mainly on the cure of the polyester

3.6 Typical GRP production with large curing box at the rear of the factory.

resin, it is essential that there should be some means of establishing whether or not the laminate is suspect. Such a method is recommended in Appendix A of BS 4549, Part 1: 1970 *Guide to quality control requirements for reinforced plastic mouldings*, the 'Barcol test', which is a form of the impact test.

The weight of the laminate measured against that of the requirements laid down in the specification will give a check as to whether a layer of reinforcement has been omitted, while the Barcol test for hardness, although not giving an absolute measurement of the cure, will differentiate between a really bad laminate and a reasonable one with a little more accuracy than is possible by casual observation. The laminate should have a hardness of around 35 within a few days. Post-curing for 16 hours at 40°C can improve this to around 40 with decreased water absorption and little effect on the other mechanical properties. Test laminates can be used to check the strength of a specified lay-up, although these may not necessarily be representative of the overall quality achieved in the product.

The heat distortion point for GRP is particularly important for cladding applications where high external temperatures are expected: for example, the use of dark-coloured panels in south-facing elevations. For such applications, resins with higher heat distortion points must be used, while it is vital that test and post-curing are carried out at or above temperatures that the panel may sustain in use. Any creep in the material that can be anticipated can be taken into account in the design by adding stiffeners to the panel.

To achieve a quality product, therefore, it is necessary for the panel to be manufactured in the right conditions, by experienced workers, in the correct proportion, using the right techniques. Ignorance of

these controls may lead to what appears to be a satisfactory product on the shopfloor, but one that is unlikely to perform satisfactorily throughout its expected design life. All this leads to a situation where great care has to be taken in quality control during production. It is not outside the designer's field to be able to set out these conditions in the specification, and it is essential to request record sheets from the manufacturer for each unit provided. Manufacturers should therefore be asked whether they:

– keep a record sheet for each unit manufactured, containing a unique reference number, date of casting, mix details, tests carried out, etc.;
– check weighing of each unit after curing;
– have an established procedure for dealing with minor blemishes and defects discovered in the units at various stages.

Some specifiers have found it necessary to have direct quality control over all the units during manufacture. The specification for the works and materials at Mondial House, London (demolished 2006), for example, includes a clause that 'each panel will be inspected dimensionally, and for gel surface defects and signs of poor laminating, by the consultants and marked if approved'. The GRP panels for the Herman Miller factory at Bath were also inspected individually by the architects, Farrell and Grimshaw, in the factory. Although this may still be necessary for prestigious jobs, most reputable manufacturers will now have the correct quality control procedures. Indeed, it could be said that architects' standards for cladding are higher than can be reasonably expected, and it is interesting to reflect that GRP-coffered slab formers are often acceptable with lower standards of workmanship.

GRP cladding in use

The first applications of GRP in the building industry were in the mid 1950s, when there was intense design activity in the material. In 1956 the Monsanto 'House of the Future' was exhibited at Disneyland, making revolutionary use of structural GRP. By 1961 the technology had been advanced to the point where GRP foam sandwich buildings had been erected as relay rooms for British Railways, and the system extended to produce a research laboratory in the Antarctic. In 1966 pressed GRP panels with a concrete backing were produced by the Indulex Engineering Company, used at a multi-storey block of flats in Paddington, London, and known as the SFI System (Building Research Association of New Zealand, 1981). With this rapid advance in the application of the material, it is not surprising that many people expected a breakthrough in the advance of GRP structures leading to the widespread use of the material in building. This breakthrough has never really come about. Glass-reinforced polyester has, however, established itself in some less wide-ranging areas of building construction, the premier one being the manufacture of cladding panels.

The simplicity of the manufacturing process allowed many small fabricators to set up without the need for large capital expenditure. There are, however, only a handful who specialize in cladding and have had experience of large contracts. A designer wishing to use GRP as a cladding material, even now, 40 years after it was first used, is liable to face some difficulties. R. D. Gay (1965) at the Conference on Plastics in Building Structures stated:

> The data on properties of these materials do not exist in the form required – the plastics industry has not yet learned to present them in that way;

some data are not yet available because the professions have not made known what they require and how. There are no codes of practice, and no textbooks are available for the design of building structures.

Thus the designer was dependent on information from the manufacturer, such as Fibreglass Ltd (1977b, 1977c).

Standardization of components

Because of its mouldability, GRP is often marketed offering a variety of shapes and sizes, and many manufacturers' catalogues stress its versatility of shape. Even so, economy of production can only be really achieved with standardized identical units.

Manufacturers' moulds are high-cost items, and repetitive identical units are desirable for maximum economy, although this similarity need not extend to uniformity of colour.

Specials or non-standard units increase costs and involve the structural engineer in numerous adjustments in the design of the fixings. Curved or shaped panels need special moulds.

If special units are to be incorporated it is an advantage if they are smaller than the standard-sized panel used in the majority of the scheme, for it is much easier to adapt the original mould than to make a new one for four or five specials. Gillingham Marina is a good example of the use of adaptable moulds using the same basic shape with filler pieces for door and window panels (Brookes and Ward, 1981, p. 1137).

Strangely, although we tend to associate the boat-building industry with one-off large boat designs, the reason why GRP is widely used for boats is that the production of large numbers of identical products pays for the initial tooling up and capital expenditure in such items as rotating moulds.

Fire resistance

In the UK a Class 0 resistant laminate to BS 476 is required for claddings on buildings above 15 m high, or Class 2 or 3, within 1 m of the boundary. In order to provide this degree of fire resistance, it has been usual to improve the fire retardancy of polyester resins by:

– the addition of fillers;
– the use of additives, such as antimony oxide plus chlorinated paraffin, which can be mixed up with the resin;
– building in certain groups in the chemical structure of the resin, for example dibromone-opentyl glycol, hexachloro-endomethylene, tetra-chlorophthalic acid, chlorostyrene.

It has been found, however, that the weathering qualities of the laminate produced in these ways are reduced in positions exposed to ultraviolet rays, and even white will yellow with age.

An additional way is to coat the internal surface of the GRP structure with an intumescent coating. Intumescent polyesters are now available, which contain compounds designed to give a carbonaceous foam on application of a flame. However, all methods used so far in trying to improve the fire retardancy of polyester resins have considerably lowered the GRP's resistance to breakdown (loss of gloss, colour change) when exposed to the outdoor environment. Tests have shown that on one common type of fire-retardant GRP sheet, using tetrachlorophthalic acid polyester as an inhibitor, the surface deterioration was 2.5–3.0 times faster than that of sheets based on general-purpose/conventional polyester resins.

Another solution to the problem of providing the required fire rating has been to apply a two-pack polyurethane surface coating in order to protect the

3.7 Mondial House, London, demolished 2006 (architects: Hubbard Ford & Partners).

laminate from the effects of ultraviolet light: for example, An-o-clad by Anmac Ltd. This uses a modified gel-coat system, which in itself adds to the fire characteristics of the panel and is then coated with the two-pack polyurethane to give good weatherability. This system, when tested to BS 476 Part 7 for a Class 1 test, had 'nil' spread of flame on the test samples. Good resistance to the breakdown of the gel coat is also achieved by coating GRP panels with a lacquer based on an ultraviolet-stabilized acrylic resin.

A more usual solution is either to position the building away from the boundary or to ask for a relaxation to the Class 0 fire requirement. In this case a general-purpose isophthalic gel coat can be used, which itself has no fire-retardant characteristics, but which protects the laminating resin containing the fire-retardant additive from ultraviolet light. But, of course, it does not get a Class 0 fire rating. When applying for such a waiver it may be necessary for tests to be carried out that stimulate in-service conditions on full panels, including the appropriate jointing technique used. The configuration and design of the joints must significantly affect the performance of the panels during a fire. The panels for Mondial House (Fig. 3.7), designed

by Peter Hodge Associates, and manufactured by Anmac Ltd and Brensal Plastics Ltd, were tested by Yarsley Laboratories. Two sets of fire tests were performed, the first on tested coupons in accordance with BS 476, the second on two complete panels with a joint, set up in the attitude to be used in service. A large gas flame with heat output of 190 W/min was set up beneath the bottom of the panels. The results of the test showed that there was no uncontrolled spread of flame over the surface, and even after an hour's exposure the panel still retained its form.

This project was probably the largest structure erected using GRP cladding in the UK, and the inclusion of mini-rib finish to these panels resulted in them still maintaining their appearance 25 years after installation.

Thus the two main problems associated with GRP, that of weathering (especially as a result of ultraviolet degradation) and fire resistance, tend to work against each other. The addition of fillers and pigments to reach some sort of fire resistance acceptability through tests laid down in the Building Regulations tends to weaken the material's capacity to resist weathering, and a darkening of the surface pigments may take place.

Weathering

The selection of colour can significantly affect the overall weatherability of the panels. In general, the stronger colours, such as oranges and reds, have a tendency to fade under the effect of ultraviolet light; the ultraviolet light will cause the surface of the material to chalk. Architects often specify these colours in ignorance of the problems associated with some pigments, and all too often the manufacturers will supply the colours as requested. The current fashion

for oranges, browns and reds has exaggerated this difficulty, which is not confined to GRP claddings.

In general, colouring of the GRP panels is best done by pigment in the resin or gel coat, and not as an applied finish. However, Blaga (1978) claims that good resistance to the effects of moisture- and/or temperature-induced stress fatigue is achieved by coating the GRP sheets with a lacquer based on ultraviolet-stabilized acrylic resin:

> The acrylic acting protects the glass-resin interface against the effects of stress fatigue and the underlying matrix against the action of UV light. This type of coating may be particularly useful for fire-resistant GRP sheets, which are especially susceptible to breakdown in outdoor exposure. Similarly, GRP sheets protected with a UV-stabilized (in-plant laminated) PVF surfacing film (0.025 mm thick) have remarkable resistance to the effect of weathering.

The difficulty may be to achieve a permanent bond between the laminate and this polyvinyl fluoride film (Tedlar).

No completely satisfactory method of assessing the weathering resistance of plastics materials in service by laboratory simulation has yet been found. Weatherometer testing and xenon arc testing are popular methods, but these can, at most, give only an identification of performance in use. After 1000 hours' exposure to the xenon test, any change of colour should be moderate and uniform.

Blue GRP panels with red fascias were used at the Water Research Centre, Swindon. They have suffered from some colour fading (Fig. 3.8).

Colour fastness tends to be uniform within any one batch of panels, but can vary from batch to batch. One method of anticipating differences in colour
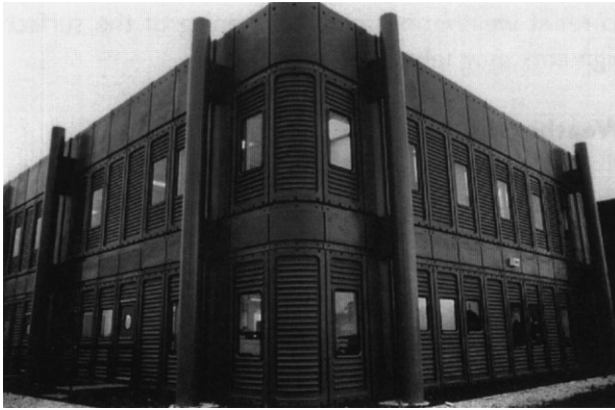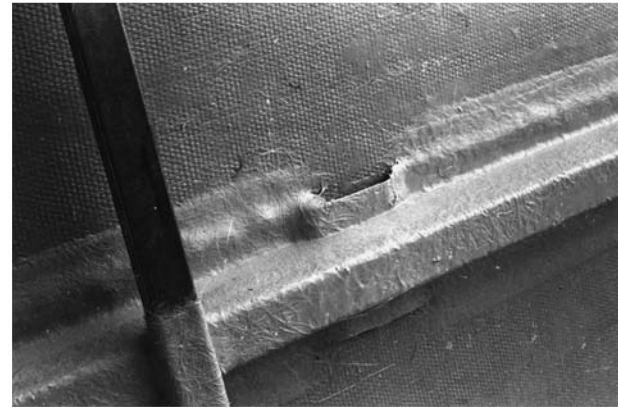
3.8 Blue GRP panels with red fascias used at the Water Research Centre, Swindon.

3.9 Ventilated top-hat stiffener to prevent distortion during manufacture.

fastness between panels is to use a striped effect, as at the Olivetti factory, Haslemere (architect: James Stirling) (Fig. 3.10). The colour of the outer skin can also increase any possibility of delamination of sandwich panels due to temperature build-up on the surface. The darker the colour and the higher the temperature, the greater the risk of delamination. Interior use of GRP is usually successful.

In theory, minor blemishes in GRP can be made good on site, provided there are correct weather conditions, and a highly skilled labour force is available. In practice, such conditions hardly ever exist, and, as yet, methods of curing on site are not available. Thus normally the panels are returned to the factory for repair. To prevent accidental damage on site, it is important to protect the panels during assembly. Panels for the Herman Miller factory, for example, were protected with a plastic coating while being installed (Fig. 3.11).

Surface scratching, which can be caused by something as simple as a window cleaner's ladder that has no padded protection, produces unsightly defects.

The client should be warned that if weather is allowed to get to the back of a panel, the uncoated side will deteriorate. Where panels such as balustrades are exposed to the weather on both sides it is necessary to gel coat both inner and outer surfaces. Condensation on the back face of a panel that has no gel-coat protection on its inner skin can also lead to premature breakdown of the laminate if the glass fibres are exposed at the surface.

Surface finish

Large shiny surfaces in GRP will show warping when used extensively over large, flat elevations. Panels up to 1 m wide with a high gloss can be accommodated, but over that width, surface ripple may become apparent. This is not only a problem of GRP – even plate glass and aluminium sheeting suffer in this respect. For this reason, some surface treatment may be appropriate, such as a matt-textured finish. Within reason, the coarser the texture the more surface deflection it will accommodate. However, if the texture becomes too

coarse, it can slow down the rate of lamination, increasing the cost of production. Probably the optimum finish is a riven slate texture created in the master pattern mould, which has all the advantage of accommodating surface deflection, while being economical to laminate. However, riven slate has the disadvantage that it is limited in size and therefore has to be panelled, though this does not necessarily create difficulties if designed with care.

Vinyl cloth is very good for producing a light striated panel. For example, panels for a store in Nottingham, shown under construction in Fig. 3.12, were produced with a matt surface after laying vinyl wallpaper onto the mould from which the production mould was manufactured. However, against this, vinyl cloth is available only in set widths, with resulting difficulties in hiding the joints. Random spray-on textures have advantages when compound curves are a feature of the design.

It is not uncommon, because of the ease of moulding GRP panels, for them to be used in conjunction with other materials for solving special corner or flashing details. For example, at the factory at Winwick Quay, Warrington (architects: Nicholas Grimshaw Partnership) (Fig. 3.13), GRP corner panels are painted to match the silver-grey Alucobond aluminium sandwich panels. This mixing of materials can lead to problems of colour matching and difference in rates of colour change.

3.10 Olivetti Training Centre at Haslemere (architect: James Stirling).

3.11 Panels at Herman Miller factory, Bath (architects: Farrell and Grimshaw).

Panel stiffening

Glass-reinforced polyester has a high tensile strength but low modulus of elasticity. Although it can accept quite high loads, this is done only at the expense of great deformation or deflection. High deflections are undesirable as they can result in gel-coat cracking. Because of the cost of the material, thickening of the laminate overall would be too expensive. Four basic ways of stiffening panels in common use are shown in Fig. 3.14. These are:

- shaped profiles;
- ribbed construction;
- sandwich construction with foamed core;
- sandwich construction with sheet core.

Shaped profiles

Panels can be designed for stiffness in a geometric form. Even for a nominally flat panel, a shallow profile, pyramid, dome or dish can make a considerable improvement to its stiffness. In some cases it may be possible to design the panels so that the form for stiffening also acts structurally. For example, the spandrel panels at the American Express European Headquarters building at Brighton (architects: Gollins Melvin Ward Partnership), which are 7.2 m × 1.4 m × 0.8 m Class II GRP channel sections, not only form the cladding but also act as structural elements supporting the glazing above (Fig. 3.15)

3.12 Nottingham Co-op under construction.

3.13 Corner panels at Winwick Quay (architects: Nicholas Grimshaw Partnership).

Ribbed construction

Single-skin construction can be stiffened by a system of ribs on the back of the panel, such as those at Mondial House, London (Fig. 3.16). Ribs are normally made from GRP, laminated over a rib former in a mould, but they can also be formed by incorporating another material of appropriate shape and stiffness into the panel. Polyurethane foam or cardboard tubes can be used as rib formers. Where timber or metal sections are laminated into, or over-laminated onto, the back of the GRP skins, these materials have different coefficients of thermal expansion from that of the GRP, and it may be necessary to ensure a mechanical key grip rather
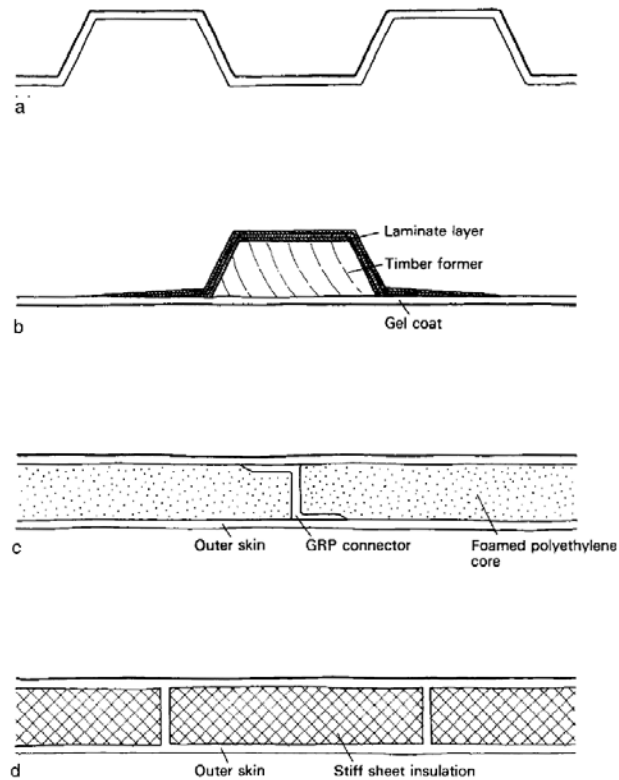
3.14 Methods of stiffening GRP panels: (a) shaped profile; (b) ribbed construction; (c) sandwich construction using GRP connector and foamed insulation core; (d) sandwich construction – stiff insulation sheet laid into lamination.

3.15 Section through GRP panels at American Express building, Brighton (architects: Gollins Melvin Ward Partnership).

than rely upon adhesion. Aluminium sections are particularly useful, because they have similar properties to GRP with regard to thermal expansion.

Rib patterning/shadowing on the face of the panel has also been known to occur, and some manufacturers have found that to overcome this the top-hat section or rib should be vented by cutting during the fabrication process (Fig. 3.9). This results in an even balance of temperature over the total face

area of the panel when heat build-up occurs, either during curing or on site due to direct sunlight.

Sandwich construction

As an alternative to using shaped profiles or ribbed construction, it is possible to stiffen the panel using sandwich construction techniques. The advantages here are that the insulation is integral within the panel, cutting down on the number of site processes involved,

thereby saving time, and the whole skin is manufactured to the same tolerances and quality control within the factory.

In sandwich construction two skins of GRP are separated by an insulating core. The edge of the panels is usually formed by bringing the two laminates together. In order to ensure maximum structural connection between skins, it is customary to use GRP connectors at intervals when using foamed polyurethane. Problems can occur because of the differential expansion and contraction rates of the skin and the core. With poor bonding of core to face, surface blistering may occur.

Panels at the Herman Miller factory (Fig. 3.18) were produced by two separate sandwich skins, the function of the core being to keep the two skins a constant distance apart during deflection and to keep them rigidly connected so that they act as a composite element.

Jointing

Most problems of jointing GRP cladding panels occur at the external panel-to-panel joint, particularly at the crossover situation. These external joints and their jointing materials must be able to accommodate the thermal movements and deflection movements of the mouldings under maximum dead and live load conditions, as well as allowing for manufacturing tolerances and errors in erection.

Three types of joints are commonly used:

– mastic sealant joints;
– gasket joints;
– open-drained joints.

Mastic sealant joints

The performance of this type of joint depends on the skill of the site applicator. There have been a number of examples of sealant failures with GRP panels. For example, the *Architects' Journal* (Reid and O'Brien, 1973) reported on two projects, *HMS Sealand* and British Gas Corporation, Solihull, where joints between panels showed unsightly mastic failure. This type of failure is often due to insufficient account being taken of the expected thermal and moisture movement at the design stage, and in some cases is caused by failure to remove all traces of releasing agent at the panel edge before sealant is applied. Recent developments in silicone rubbers have improved the performance of sealants because of their much greater movement accommodation and lower stress at the bond face.

Gasket joints

This type of joint normally incorporates a neoprene-extruded section; because they are factory produced, they are not so dependent on the site operative for their successful application. As an alternative to neoprene, ethylene propylene diamine monomer (EPDM) has better inherent resistance to oxidation attack and subsequent ageing. However, its drawback is poor resistance to attack from lubricating oils and various solvents. EPDM's ability to recover from compression is also less than that of neoprene. Although it is possible, according to their formulation, to obtain rubbers with good or bad tear resistance in both neoprene and EPDM, generally speaking EPDM has less resistance to tearing than neoprene, and thus is less easy to handle on site.

Site bonding of neoprene sections is now quite common for crossover joints. For example, the neoprene gasket joint used at the Herman Miller factory (Figs 3.19 and 3.20) is a simple glazing technique for both vertical and horizontal joints. A top-hat section is screwed into an aluminium carrier system, which in turn is supported by the main framing.

A continuous gasket is then pushed into this top-hat section. At parapet level the neoprene vertical joint changes to a narrow mastic sealant, because of difficulties in carrying the top-hat section over the curved jointing profile.

Top-hat rib sections

3200mm

100°

1200mm

Section

1900mm
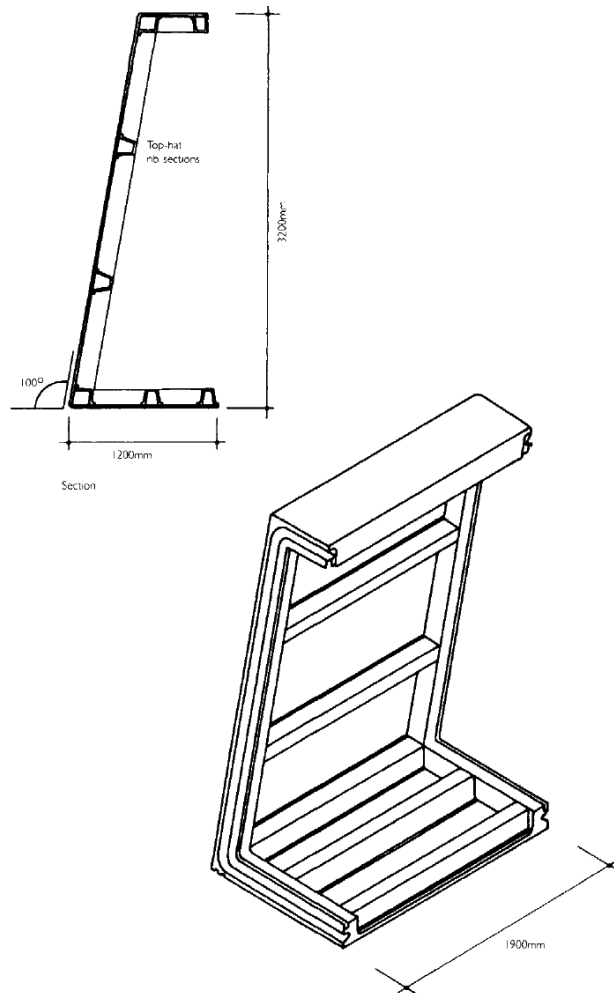
3.16 Stiffening of GRP panels at Mondial House using GRP top hat and box sections (architects: Hubbard Ford & Partners).

Neoprene gaskets work best when they are compressed within the joint, normally on the back side of the panel edge profile. A simple compressible gasket using timber edging pieces with GRP panels was developed for Teesside Polytechnic (architects: Basil Spence & Partners) (Fig. 3.21), for use with panels 1 m × 1 m. A more complicated gasket joint was developed for Mondial House (Hodge, 1968) (Fig. 3.22), which uses a combination of a neoprene baffle, a PVC back channel and a strip sealant under compression from a back plate. The joint was tested successfully by Yarsley Laboratories to BS 4315, simulating 18.75 cm of rain per hour at a wind speed of 56–64 km/h. This very sophisticated joint combines the principles of an open-drained joint with that of a labyrinth joint. As a result of this experience at Mondial House, Anmac Ltd developed its own 'patented' two-stage mechanical joint called LSB. This had the advantage that the jointing product is under compression and hidden from ultraviolet light.

Open-drained joints

This type of joint (see Fig. 1.24 for an example in concrete cladding) is not in widespread use with GRP panels. This may be because of the difficulties that can be experienced in casting the necessary depth of baffle groove. Other problems have been experienced in fixing the baffles at the top of the panel to prevent them from sliding down the groove. Open-drained joints at HMS Raleigh, Plymouth (Fig. 3.24), incorporated a bridging plate at the top of the joint in an attempt to stop the baffle from slipping.

Thermal expansion

Glass-reinforced polyester has a lower coefficient of thermal expansion than those of other plastics, but higher than those of steel, glass or concrete, and similar

to that of aluminium and wood. The coefficient of expansion is linked to the amount of glass-fibre content in the laminate: the higher the glass-fibre content, the lower is the coefficient of expansion. The expansion rate for a chopped strand mat laminate is higher than that of a combination of chopped strand mat and woven rovings.
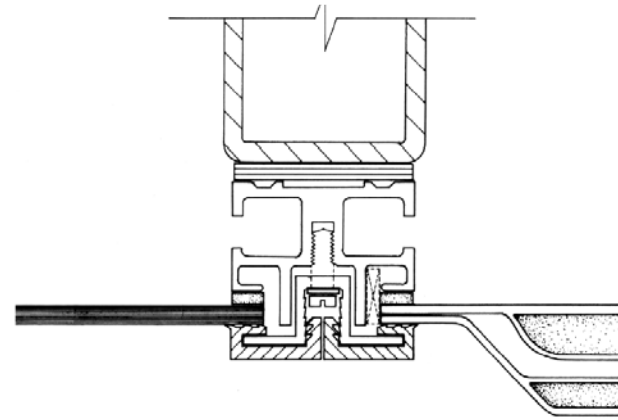
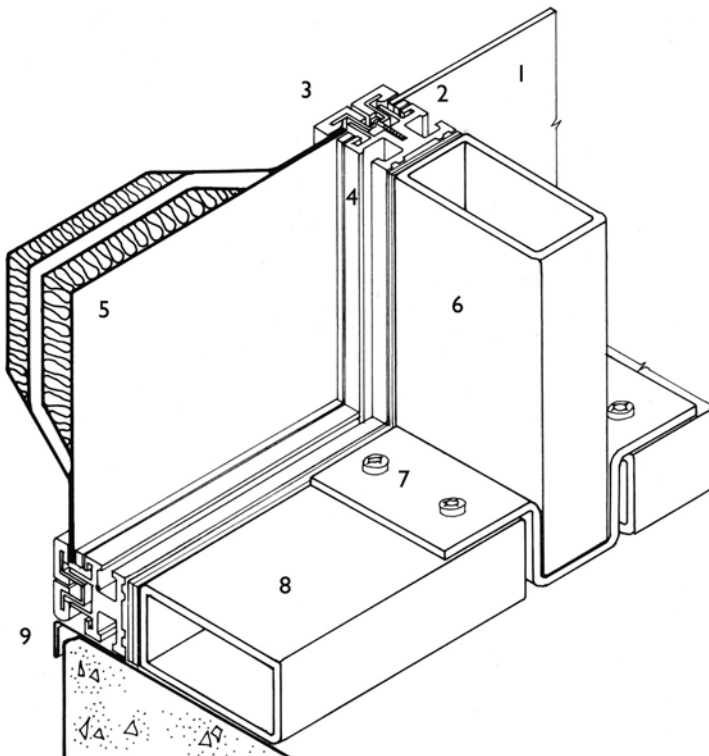In calculating thermal movements the designer needs to assume a realistic figure for the temperature gradient set up within the cross-section of the panel.
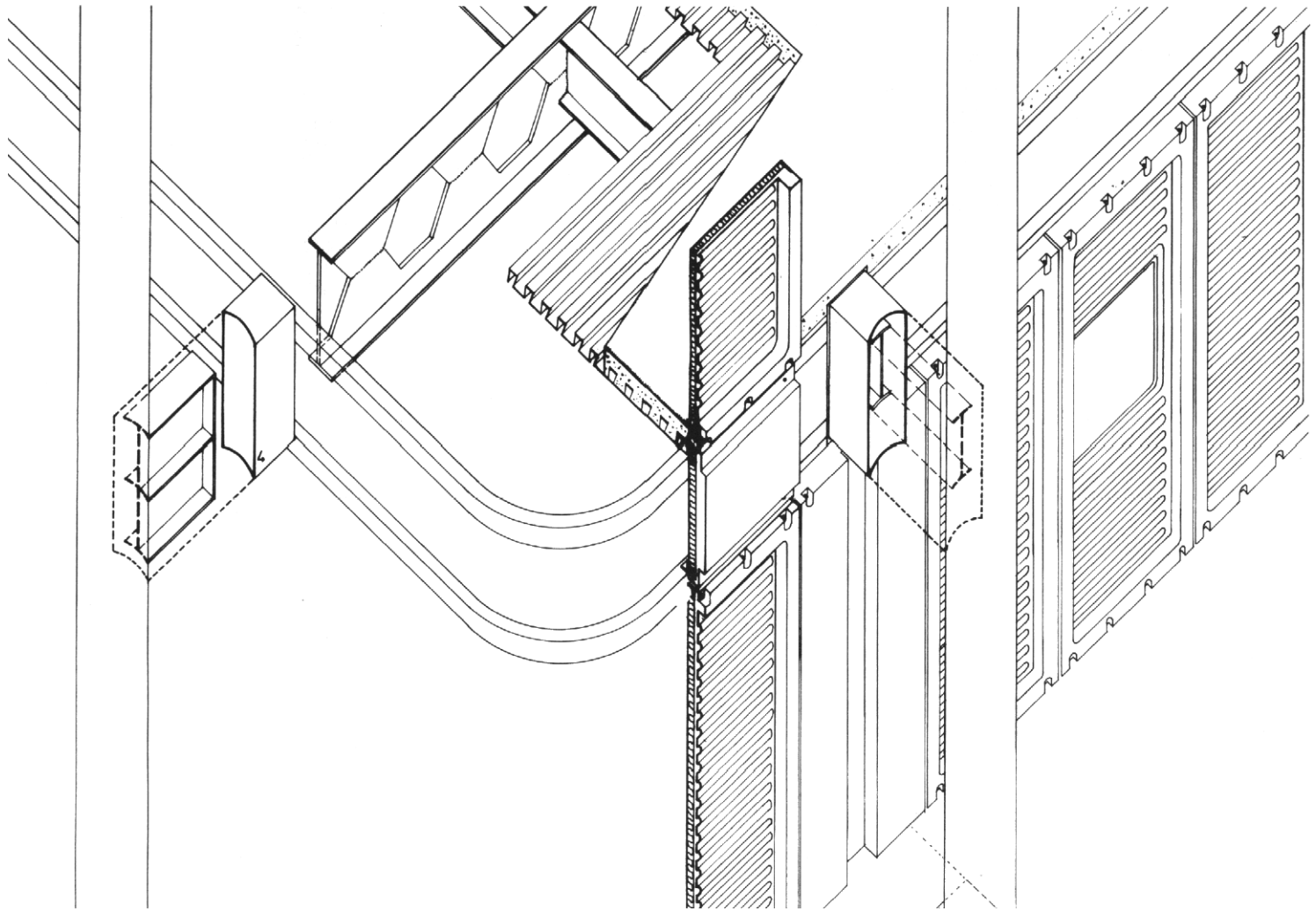
3.17 Detail of GRP panels used at the Water Research Centre.
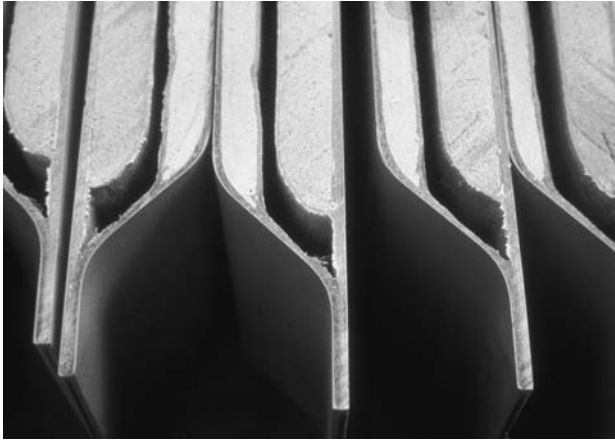
3.18 Sandwich panels as used at the Herman Miller factory.

3.19 Plan of glazing mullion at Herman Miller factory.

3.20 Neoprene jointing gaskets used at the Herman Miller factory, Bath: (1) 6 mm surface-modified solar control glass; (2) resilient packing strip; (3) continuous neoprene gasket fitted to U-shaped aluminium beading screwed back to carrier; (4) extruded aluminium carrier screwed back to steel hollow section; (5) GRP sandwich panel, overall thickness 75 mm, outer insulation 19 mm polyurethane foam, inner insulation 25 mm polyurethane foam; (6) 127 mm × 63.5 mm hollow section steel sub-frame mullion; (7) 6 mm mild steel assembly shoe bolted to concrete slab; (8) 127 mm × 63.5 mm hollow section steel horizontal rail; (9) pressed aluminium sill fixed back behind carrier.

This will depend upon factors such as orientation, colour of cladding, any insulation that may be behind it (sandwich panel), and its fixing and jointing aspects.

It is important to take account of thermal expansion in the design of fixings at the interface of GRP panels and some other finish material or component within the structure.

Fixings

It is obviously not possible to fit the panels on site to an absolutely true and level structure. Tolerances on the base structure must be notified to the designer of the GRP panel system, and reference should be made to BS 5606, which indicates the accuracy of assembly that may be expected on site for given components and construction.

One of the difficulties of fixing any single-skin panel back to the supporting structure is the problem of restraining the fixing device within the thickness of the panel. Several methods have been tried, including fixing plates moulded into the backs of the panels incorporating bolt fixings. Most uses, however, depend upon a system of clamping the panel back to the structure, usually at the joint interface. The American Express building in Brighton uses this method (Anon, 1977). Panels fixed at Mondial House incorporated a non-ferrous threaded fixing plate device hooked back onto the perimeter I-beam. The length of fixing involved resulted in this being an expensive way of achieving the necessary adjustments (Fig. 3.25).

Generally speaking, panels should be fixed rigidly at one point, with all other fixings being designed to accommodate the movement likely to occur. The rigid fixing must in itself be able to be adjusted to accommodate the manufacturing and building tolerances (BRE Digest 223 *Wall Cladding: designing to minimize effects due to inaccuracies and movement*). Often designers
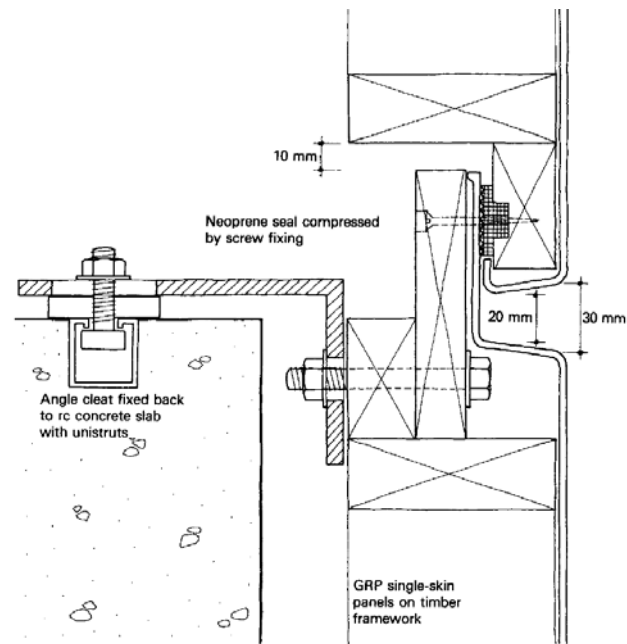
3.21 Joints between panels at Teesside Polytechnic (architects: Basil Spence & Partners).
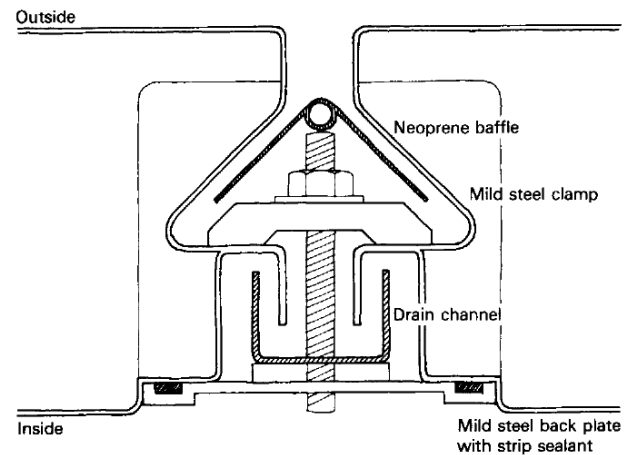
3.22 Vertical joint at Mondial House.

Sketch showing
inner side of panel

Outside

Inside

Galvanised tie straps push GRP
cover strip against sealant joint
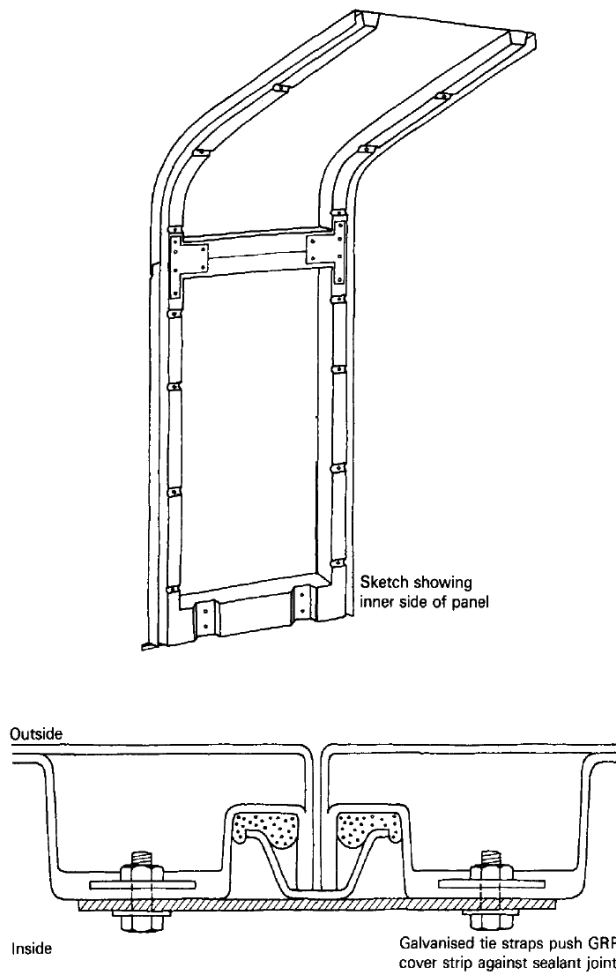
3.23 Typical back sealed joints between GRP units.

de

Inside

Bridging plate at top of baffle

GRP skin

Section

Baffle groove

Airseal

Plan

3.24 Open-drained joint at HMS Raleigh (architects: PSA).

allow for mild steel stiffeners within the flanges of GRP. If these are subsequently site drilled for bolt fixings and not treated or sealed, moisture penetration will lead to rusting and delamination of the flanges.

The designer may need to consider fixings for handling; large panels are often difficult to handle on site because of high wind speeds coupled with their own light weight, and the size and number of fixings for a large panel need careful consideration. Although GRP as a material is relatively tough, surface protection during transport and erection on site to avoid surface scratching may be recommended (Fig. 3.26).
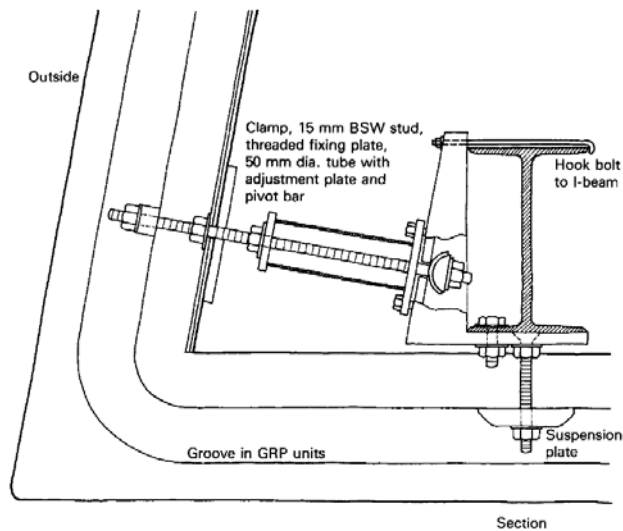
3.25 Fixing to I-beam at Mondial House (architects: Hubbard Ford & Partners).

Composite materials

Since 1998, there has been a resurgence in the use of composite materials. These include thermoplastics and thermosets, either with or without fibre reinforcement. Vinylest and epoxy resins or different fibre materials like carbon and aramid fibres can also be used depending on the purpose and requirements of a product.

VARTM moulding

The latest techniques for moulding include Vacuum Assisted Resin Transfer Moulding (VARTM). This is a process where the resin is pulled through a prepared layer of dry fibre – which can also be pre-coloured – using vacuum.

Together with Octatube, who were responsible for the steel structures and glazing, this technique was used by Holland Composites Industrials to manufacture the roof panels for the Yitzhak Rabin Centre in Tel Aviv (architect: Moshe Safte) where seventy different-shaped panels were made on cost-effective disposable polystyrene moulds using a large CNC milling machine.

The architect's computer model served as input for the CNC milling process, and thus determined the shapes of the roofs. The different segments were made with VARTM and later bonded together on site to obtain the wing-shaped roof. Finally, a finishing topcoat was applied before installation of the roofs onto the building.

3.26 On site assembly and bonding of roof segments by Holland Composites Industrials.

3.27 Installation of lower wing by Holland Composites Industrials and Octatube at Yitzhak Rabin Centre.

3.28 Overall view of Yitzhak Rabin Centre in Tel Aviv by Holland Composites Industrials.

3.29 Assembly of sandwich panels into a monocoque Spacebox structure at Holland Composites Industrials.

3.30 Placement of Spaceboxes as student accommodation in Amersfoort by Holland Composites Industrials.

3.31 Protection of panels using plastic coating during installation.

Pre-impregnated fibres

As well as glass fibre, carbon and aramid fibres can now be supplied to the fabricators as pre-impregnated mats. The advantage of the pre-preparation is that the panels can be cured at 80°C in good stable moulds ensuring a high quality of surface finish. This process was used by Holland Composites Industrials for their Spacebox student and starter housing using GRP sandwich panels with PIR foam and coloured resin.

Conclusion

It can be seen from the foregoing sections that the manufacture of successful GRP moulding is far from the simple process that it may appear at first sight. Although, in its simplest form, laying up layers of glass fibre is relatively easy, the process required to design and fabricate a product to satisfy its function for many years in a hostile environment is much more complicated. There are many types of resin and reinforcement, which can be modified by additives and fillers. The products have to be fabricated in the correct proportions by the right techniques and under the correct conditions to obtain a quality product.

Great care has to be taken in designing the correct stiffening of the panel using ribbed or sandwich construction, although more problems can be associated with the latter. Jointing and fixings must be carefully considered to take account of any thermal movement and inaccuracies (spacing, plumb and alignment) of the structural supports, and detailed specifications of the required standards of manufacture, assembly and repair are essential.

Finally, specification of detailing, fixing and jointing is just as important as requirements for resins, pigment additives and types of glass fibre to be used. Many problems have in the past been attributed to the

properties of GRP, when in essence the problem may lie elsewhere. As with all panel systems, the component will only perform as well as its jointing and fixing allow it to.

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4

Glass-fibre reinforced cement

The material and its advantages

Glass-fibre reinforced cement is a composite material consisting of ordinary Portland cement, silica sand and water, mixed with alkali-resistant glass fibres. It has been described by Young (1980) as an 'ideal marriage between brittle materials, cement, sand and glass, to produce a tough composite'. At that time, the most common percentage constitution of the material by weight was as follows:

Portland cement	40%
Water	20%
Sand	40%
Glass fibre	5% (for spray techniques)
	3–4% (for premix)

Later formulations included 0–5 % acrylic polymer.

The ultimate strength of glass-fibre-reinforced cement (GRC) is essentially determined by the presence of the fibres, and is therefore dependent upon the glass content, the orientation of the fibres, the degree of cure, and the bonding of the fibres to the cement/sand matrix.

The glass fibre is introduced into the cement mix to carry the tensile forces, thus overcoming the main disadvantage of cement, which is unreliable and has a relatively low tensile strength. The glass content controls the maximum loading that the material can withstand, the impact performance and the durability of the composite. The incorporation of sand into the

GRC mix helps to reduce shrinkage during drying out and reduces in-service moisture movement.

When GRC was first developed in the late 1960s, after pioneering studies by Dr A. J. Mujumdar at the Building Research Establishment, it was claimed that it would become a widely used form of building cladding. Metallic claddings were not yet fully developed, and GRC promised to combine the best features of precast with less bulk, lighter weight and tighter tolerances.

These benefits led to early uses on prestigious projects such as UOP Fragrances (architects: Richard Rogers and Renzo Piano) at Tadworth in Surrey (Fig. 4.1). As the use of GRC began to increase, some projects experienced problems with microcracking, surface shadowing and panel tolerances. The industry did not respond positively to these problems, and GRC fell out of favour with British architects, as they became more interested in the development of metal-faced composite cladding.

Thus in the years since the *Architects' Journal*'s detailed coverage of the performance of GRC (Brookes, 1986), UK architects have not used GRC cladding to the extent that was originally predicted. However, GRC continued to be extensively used in continental Europe and in the Middle East, where manufacturers were actively developing their basic formulations, manufacturing methods and cladding systems. European manufacturers include: Dyckerhoff and Widmann in Germany; Besinor, CMEG Creabat, Fiberton in France; Dragados y Construcciones in Spain; and Hibex in The Netherlands. UK manufacturers with an active GRC programme include BCM Contracts, Mouldform, Techcrete (Eire) and Graham Precast.
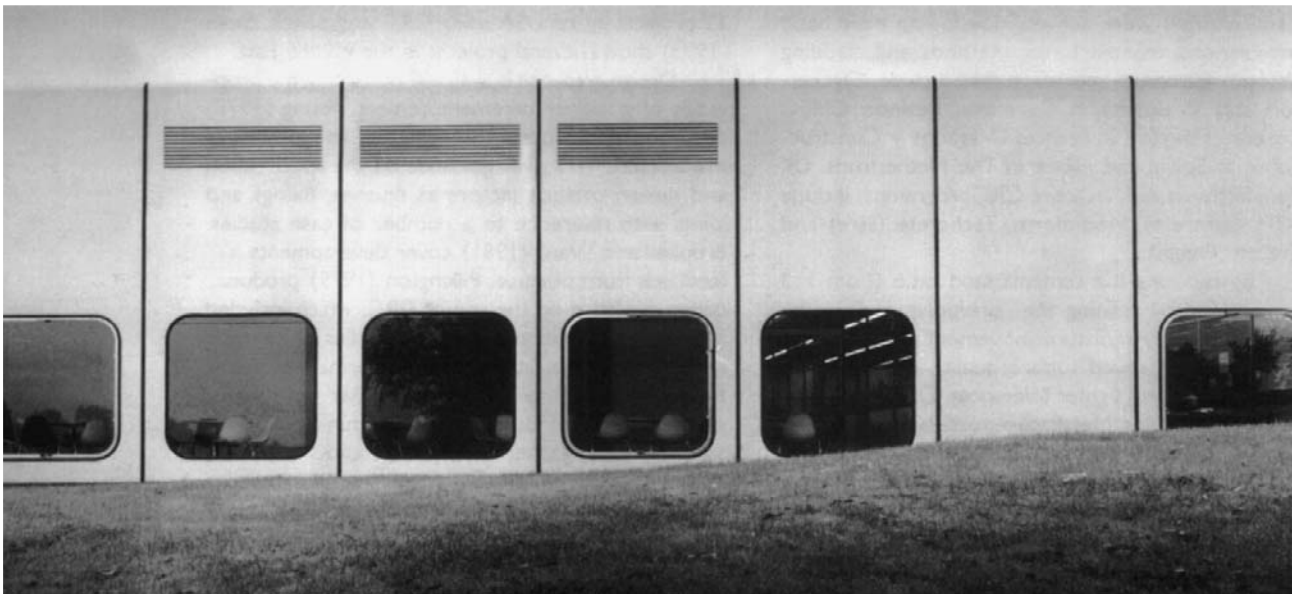
4.1 UOP Fragrances, Tadworth, Surrey (architects: Richard Rogers and Renzo Piano).

By reducing the cement: sand ratio (from 1:3 to 1:1) and by refining the fibre/polymer mix, the amount of daily moisture movement was reduced, resulting in improved surface quality, elimination of microcracking and tighter tolerances. One of the new formulations using Metakaolin pozzolanic aggregate, CemFil 'Star' was marketed by CemFil International Ltd, who claimed that it did not go brittle with age and that it kept its early strength and ductility. Early use of this new formulation includes the Espace Forbin building at Aix en Provence.

As for many new materials, the use of GRC was at first inhibited by lack of experience in use and general rules governing design and adequate codes of practice. At the international congress on glass-fibre-reinforced cement in London, October 1979 (GRCA, 1980), although some speakers complained of the lack of adequate standards, at the same conference M. W. Fordyce and D. Ward described moves towards standard specifications.

A number of major projects have been built using GRC. In the UK, the Credit Lyonnais building in London is still seen as a classic use of GRC moulding, as is the use of composite GRC panels by Richard Rogers at UOP Fragrances Ltd at Tadworth in Surrey. More recent examples include the Grosvenor Hotel and Classic Cinema in Glasgow. A large number of projects have also been built in the Middle East, Spain and Japan, and J. B. Ford (GRCA, 1980) has described 12 projects in the USA using GRC wall panels. Stein (1995) shows several projects in the Middle East.

Design guidance is available describing the properties of glass reinforcement cement. Young (1978) describes the properties of GRC and its methods of manufacture, and gives guidance on the specification and design of such factors as finishes, fixings and joints with reference to a number of case studies. Brookes and Ward (1981) cover developments and feedback from practice. Pilkington (1979) produced design guidance on the use of GRC, which included a detailed description of such properties as its creep and stress rupture, fatigue, density, thermal expansion, thermal conductivity and air and water permeance, with methods of design for determining working stresses, loading, thermal, acoustic and fire performance of a particular design. Information was also given on component testing, quality control and typical specifications.

Designers intending to use the material in complicated shapes or in conjunction with composite insulation core materials should seek further advice from the manufacturers involved. They also may wish to review the recent guidance notes on GRC published by Fachvereingung Faserbeton (FVF), the German GRC trade association. A similar guide is published in the UK by the GRCA entitled GRC Architectural Components, and a *Guide to Fixings for Glass Reinforced Cement Claddings* is also available from GRCA.

Production methods

Process methods that have so far been developed for the fabrication of GRC components are **spray** and **premix**. Premix processes are those where the constituents are mixed together into a paste and subsequently formed by casting, press moulding or slip forming. Spray processes, in which wet mortar paste and chopped glass fibre are simultaneously deposited from a dual spray-head into a suitable mould, currently account for a large percentage of GRC production.

The properties of GRC premix are inherently different from, and usually inferior to, those of sprayed-up GRC, because more air is introduced into the mixture, and there is less control over the fibre orientation. Thus for cladding panels spray processes

4.2 Typical hand lay-up operation.

are normally used. Three ways of spraying GRC are available:

– manual spray;
– mechanized spray;
– spray-dewater process.

Manual spray

Manual spraying is labour intensive, but offers the designer more flexibility in shape and profile than other methods of fabrication. Using the manual spray the operator moves the spray backwards and forwards across the mould surface until the required thickness of GRC, typically 10–12 mm, as opposed to an average 3–6 mm for GRP, is built up. Greater thickness tends to increase GRC production costs. As with GRP, the material can be built up locally around fixings and inserts, while roller compaction ensures total contact with the mould and removal of entrapped air. Roller compaction should be used after the first 3 mm layer

has been sprayed to ensure a good surface finish. For an operator to spray effectively from either side of the mould a dimension of not more than 2 m width is recommended. For greater widths it is possible to erect some sort of working platform above the mould, but this makes spraying difficult, and could affect the quality and cost of production. Figure 4.2 shows manual spraying of GRC wall panels. Robotic spray techniques have also been developed for three-dimensional products.

Mechanized spray

The hand spray can be easily mechanized for the production of simple flat components; the moulds are moved along a conveyor and pass below a boom on which the dual spray-head is mounted, moving to and fro to give uniform thickness and correct fibre distribution through the composite. The mechanical spray thus ensures greater consistency and more uniform thickness than hand spraying. The restriction on width of the mould, as mentioned above, also does not apply. It has been shown possible to automate the manual spray method completely using computer-controlled robot units. However, the cost of mechanized spraying of complicated shapes and window openings becomes prohibitive unless continuous mass production runs are used, and so far these production methods have not been used for one-off cladding designs in the UK. Post-forming of flat sheets can also be used to produce two-dimensional products.

Spray-dewater process

A variant of the mechanized spray process is the **spray-dewater process**, in which the mould surface consists of a filter membrane through which excess water can be drawn off by vacuum immediately after spraying. The mechanical properties of the laminate are

improved by the dewatering process, which produces a denser composite.

A typical automatic spray-dewater plant for the continuous production of flat sheets consists of a mixer and pump conveying the GRC slurry to a slurry spray and glass chopper mounted on a traversing head. A conveyor belt passes the sprayed sheet through a finisher and vacuum box to draw off the excess water. After cutting and trimming, the 'green' sheet so produced can be removed, using a vacuum lift, in its limp state for post-forming into simple shapes. Although such production processes are used in the UK, manufacturers tend to use dewatering processes only for the production of small flat units, such as wall or ceiling tiles, and find the manual spray methods more suitable for complex shapes. However, the increasing use of superplasticizers has reduced the benefits of this process, which has limited application.

Insulated panels

The inclusion of insulation between two skins of GRC is carried out in two main ways, as follows.

–   Panels of polystyrene may be placed in position and then covered with a slurry, or preformed webs of GRC used between the sheets of insulation to stiffen the panel.
–   Suitable foam may be injected between the two preformed skins of GRC. Foams include polyisocyanurate, polyurethane and phenolic. In the last case internal webs of GRC are also used, because the shear performance of the foam is inadequate.

Moulds

Although GRC, being a moulded material, offers the architect great flexibility in shapes and contours to be

designed, in practice the types of mould and methods of spraying may restrict the size and shape of the unit. This is particularly true for sandwich panels. As with GRP, the effect of the mould costs on the finished panel is dependent upon complexity, the numbers taken off the mould, and the number of specials required. It is therefore necessary to keep the number of specials to a minimum. Where possible, the basic mould should be adaptable to produce panel variants. For example, at the UOP Fragrances factory, Tadworth, Surrey (architects: Piano and Rogers), various adaptor pieces were inserted in the timber and marine ply moulds to provide the seven panel variants, and detachable pieces were needed to allow moulding of the complex edge shapes.

Most GRC production using the spray method requires anything up to 24 hours before demoulding. Thus the speed of production will be determined by the number of moulds available. Requirements for higher mould utilization have led to developments in rapid-setting types of Portland cement and accelerated dewatering processes.

The number of units to be cast will determine the material from which the mould is made. In general, timber moulds are used for 'short' runs, where a small number of units are required (approximately 30 castings can be obtained from a single mould). For most purposes, moulds in GRP are the most appropriate material, because they are more durable than timber and offer a better standard of surface finish. Steel moulds can be used for long continuous runs.

Using spray production, it is possible to obtain a smooth finish only on the mould side. The non-moulded face will have the textured surface of the compaction roller or a trowelled finish.

Cast or moulded GRC allows for the formation of very intricate surface detailing in cladding panels, as demonstrated on the renovation of existing buildings

such as St George's Hospital at Hyde Park Corner and the Grosvenor Hotel in Glasgow. The Woolworth building in New York also makes extensive use of GRC. While it does not offer the aesthetic flexibility of reconstituted stone, it does have an advantage in terms of lower weight and thinner sections.

Typical dimensions of GRC panels are shown in Fig. 4.3.

Finishes

Normally, GRC components would cure to the greyish colour of ordinary Portland cement. White Portland cement has often been used for cladding panels to improve their appearance, but complete uniformity of colour from one panel to another may not be achievable because of variations during manufacture. Panels produced in smooth-surfaced moulds will have a glossy finish on one side only, which tends to

accentuate small surface defects and show up the inherent post-curing patchiness of the material. The cement-rich layer at the surface may also show a slight surface crazing. For example, according to Young (1978), panels at the Melrose Centre, Milton Keynes (architects: Colquhoun and Miller) showed that a combination of white cement, a smooth glassy mould surface and the inherent post-curing patchiness of the material and slight surface crazing produce an effect not unlike marble.

There are four basic ways in which the colour and texture of GRC can be modified:

- surface treatments and textured moulds;
- pigmented colouring;
- applied paint coatings;
- PVC film.

Surface treatments and textured moulds

As with concrete, some surface treatments can be applied either during moulding using textured moulds or after casting using acid-etching, grit blasting or smooth grinding techniques. These techniques can be particularly valuable in removing any excess cement/ sand laitance, and hence can reduce the tendency to crazing. Considerable skill is needed in retaining minimum component thickness after the treatment has been applied. Any textured layers must be considered as surface treatment only, and must not be taken into account in determining the structural performance of the cladding.

Large-aggregate finishes, as used with precast concrete, are not normally recommended, because they have to be embedded in 10–15 mm of cement, making the panels heavier and less manoeuvrable. Normally only aggregate less than 12 mm is used because of the excessive amount of GRC required behind larger aggregate.
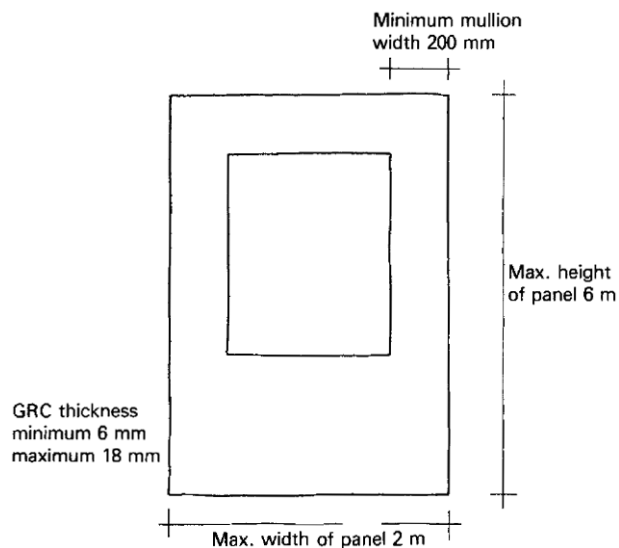
4.3 Typical panel dimensions.

Surface finishes of GRC can also be modified using applied acrylics, formed textures, or exposed aggregates. Typically, very fine aggregates may be used, opening up a wide range of aesthetic possibilities, including reclaimed ground glass as the aggregate. High-gloss finishes are possible but expensive; also, these have the disadvantage that any surface irregularity will be emphasized in bright light.

Pigmented colouring

Like precast concrete, coloured panels have been manufactured using pigments and coloured sands, or by adding coloured Metakaolin pozzolanic aggregates. Naturally, the colours tend to be muted and limited in range to softer colours.

Applied paint coatings

As with all cement-based systems, GRC is also subject to moisture movement in that it expands during water uptake and contracts when drying. Great care should therefore be taken in the consideration of any applied coating. Impermeable coatings for external use should generally be avoided, as they can lead to an increased risk of interstitial condensation, particularly with sandwich panels. If the panels are not allowed to 'breathe', then moisture migrating to the surface will cause any impermeable paint to blister or flake.

Proprietary textured permeable finishes, such as those used for coating external masonry, e.g. Muro-plast, Sandtex and Glamrock, are often used. Such finishes were used at Heathrow Eurolounge and at Newton Heath Library.

Clear surface coatings of the silicon type, which are particularly useful in protecting the surface of white GRC panels against dirt and fingermarks, can be used without fear of blistering, as they allow the GRC to breathe.
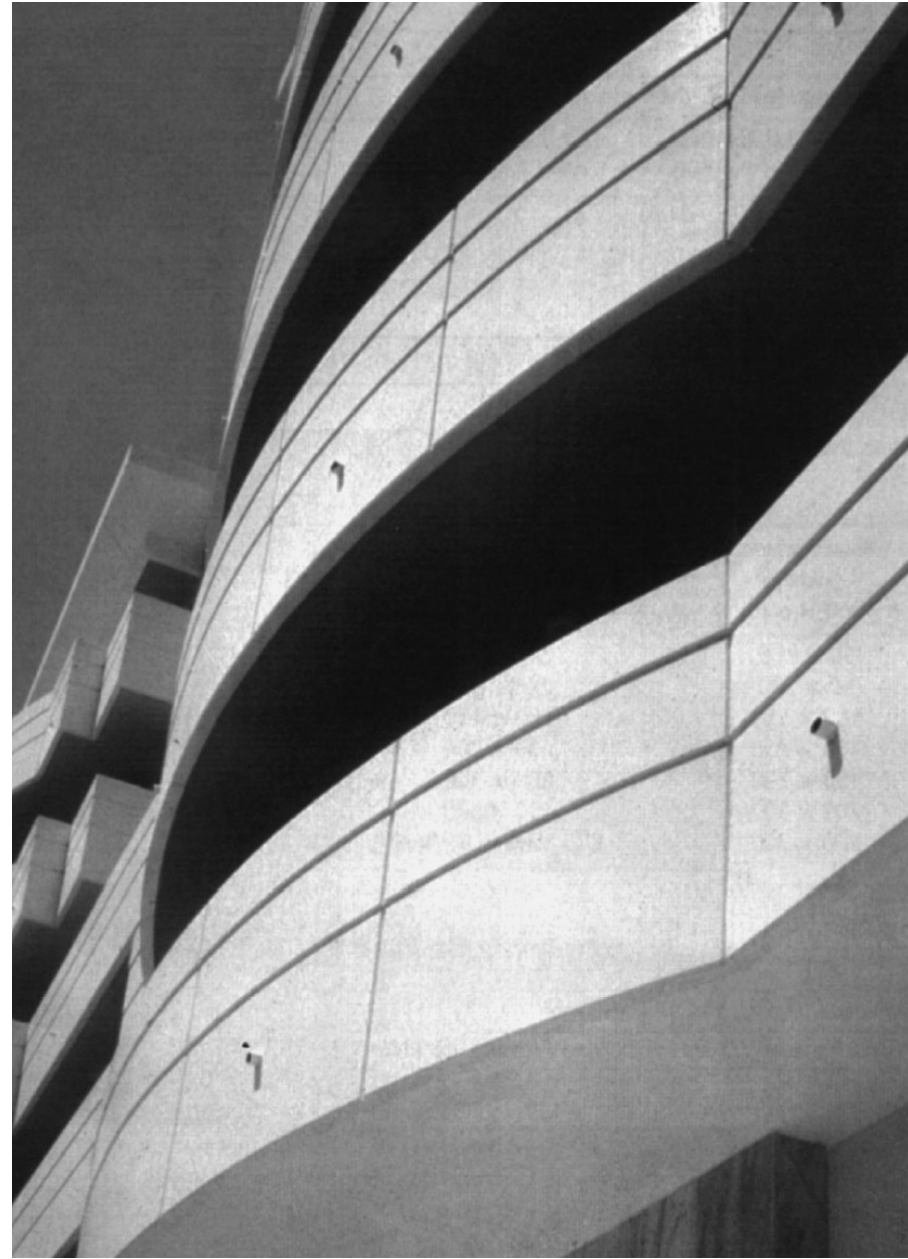
4.4 Curved GRC panels.

Care must be taken when applying paint coatings, whether in the factory or on site, to ensure that the surface is free from grease or any trace of mould release agent, so that an adequate bond is maintained between the GRC and the paint system base coat.

Some GRC panels have been produced to emulate the aesthetic features of flat metal systems by incorporating a PVC finish. The PVC sheets are either cast in line integrally with the PVC facing or adhesive bonded to the GRC subsequent to moulding. Such panels were used at the Oxford Ice Rink (architects: Nicholas Grimshaw & Partners) (Fig. 4.14) and at the Sheffield Arena (architect: HOK).

Thus coloured panels can be obtained by the use of pigments and coloured sands or by adding coloured Metakaolin. However, these colours are muted and limited in their colour range, and architects may prefer to specify acrylic-based emulsion applied on site or in the factory. High-gloss finishes are possible but expensive. Also, these high-gloss surfaces have the disadvantage that any surface irregularities will be emphasized in bright light.

Performance characteristics

Wind loading

Simplified tables are now available for determining the spanning characteristics of varying thicknesses of GRC in relation to wind loading (Table 4.1). For example, 10–12 mm flat sheets will span 1.0 m under a wind pressure of 1.0 N/m^2, but sheet of the same thickness can be profiled or ribbed to span up to 4.0 m under the same wind pressure. For greater spans or wind pressure, it may be necessary to design using sandwich construction, ribs or, more commonly today, a stud frame construction.

Thermal characteristics

A 20 mm single-skin GRC construction of approximate density 1800–2100 kg/m^3 gives a negligible insulation value, in the region of 5.0 $W/m^2°C$. For improved thermal insulation (up to a U value of 0.7 $W/m^2°C$), it is necessary to incorporate an insulation core into the construction or to incorporate some form of insulation behind a single-skin facade, a method that is finding increasing use in continental Europe. Table 4.2 shows the thermal performance of varying thicknesses of GRC sandwich panels.

Fire performance

In terms of fire performance, GRC is non-combustible when tested to BS 476. Even with an organic paint finish, GRC performs to Class 0 standard when tested in accordance with Part 6. This is generally comparable to metal and precast performance. However, it is important to check the use of polymer additives, because they affect the fire performance of the panel. In terms of fire rating, 1.5 hours fire resistance is claimed by some sandwich panel manufacturers, such as Veldhoen.

Acoustic performance

A 10 mm single skin of GRC at 20 kg/m^2 density gives sound reduction indices from 22 dB at 350 Hz to 39 dB at 4000 Hz, or an average of 30 dB over the normal range of frequencies. Even if the single skin is increased to 20 mm, which is beyond the thickness normally recommended, the average reduction indices will increase to only 35 dB. For greater acoustic performance it is possible to specify sandwich construction; however, if it is necessary to connect the outer and inner skins for structural reasons, this will reduce the sound insulation for the whole panel.

Table 4.1 Panel thickness and span

The following tables give a guide to the recommended panel thickness for different panel types.

Single skin flat sheet

Panel span metres	Minimum recommended overall panel thickness, mm		
	Wind Pressure 0.5 kN/m^2	Wind Pressure 1.0 kN/m^2	Wind Pressure 1.5 kN/m^2
0.5	4	6	7
1.0	8	11	14
1.5	12	17	*
2.0	16	*	*

Use profiling, stiffening ribs or sandwich panel

Profiled single skin (10 mm thick)
For a profiled single skin panel the table below should be used to select the panel design type based on the required span and wind pressure.
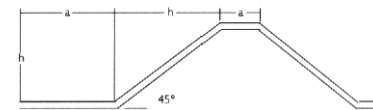
Panel span metres	Wind Pressure 0.5 kN/m^2 h (mm) × a (mm)	Wind Pressure 1.0 kN/m^2 h (mm) × a (mm)	Wind Pressure 1.5 kN/m^2 h (mm) × a (mm)
1.0	50 × 100	50 × 100	50 × 100
1.5	50 × 100	50 × 100	50 × 100
2.0	50 × 100	100 × 150	100 × 150
2.5	100 × 150	100 × 150	100 × 200
3.0	100 × 150	150 × 200	200 × 300
3.5	150 × 200	200 × 300	200 × 300
4.0	200 × 300	200 × 300	Use sandwich panel

Sandwich construction
In selecting parameters for sandwich construction panels, it should be noted that the panel thickness includes two 10 mm thick GRC skins.

Panel span metres	Minimum recommended overall panel thickness, mm		
	Wind Pressure 0.5 kN/m^2	Wind Pressure 1.0 kN/m^2	Wind Pressure 1.5 kN/m^2
*2.0	50	50	50
*2.5	65	65	65
*3.0	70	70	75
*3.5	80	80	95
*4.0	95	95	120
4.5	105	105	145
5.0	115	125	175
5.5	140	145	210
6.0	150	170	245

Can also use profiled or ribbed single skin GRC

Table 4.2 Thermal performance of varying thicknesses of GRC sandwich panels. Material from BS 5427:1976 is reproduced by permission of the British Standards Institution, 2 Park Street, London WIA 2BS

Composition of GRC sandwich panel		*U-value (W/m²°C)*
	GRC 20 mm	5.0
70 mm	GRC 10 mm PBAC 50 mm GRC 10 mm	2.0
110 mm	GRC 10 mm PBAC 100 mm GRC 10 mm	1.3
100 mm	GRC 10 mm PBAC 30 mm Polystyrene 20 mm PBAC 30 mm GRC 10 mm	0.9
150 mm	GRC 10 mm PBAC 50 mm Polystyrene 30 mm PBAC 50 mm GRC 10 mm	0.7

Note: PBAC-polystyrene bead aggregate concrete.

Density

A piece of flat GRC 10 mm thick weighs approximately 20 kg/m².

Shrinkage and moisture movement

Like other cement-based materials, GRC exhibits non-reversible shrinkage during the curing process, and long-term moisture movement caused by changes in humidity. The incorporation of 40% silica sand into the matrix reduces both types of shrinkage but, even so, actual movements in use could in theory be 1.5 mm/m. In practice, movement of 1.0 mm/m may be experienced, which is approximately double that of ordinary reinforced concrete. Care has to be taken in the design of fixings to allow for this movement.

Impact loading

GRC is also good at withstanding impact loading. CemFil International quote an impact strength of 10–25 kJ/m² for hand or machine spray products and 10–15 kJ/m² for vibrated cast products.

Types of cladding

Several systems of GRC cladding and roofing have been developed over the past decade, including:

–   single-skin cladding or roofing;
–   profiled sheeting;
–   composite panels with foamed polyurethane;
–   cast or moulded products.

In single-skin form, GRC can be mounted onto a metal stud framing (Fig. 4.5). This framing provides support and stiffness against out-of-plane forces, and permits expansion and contraction of the GRC skins. This approach has been extensively used in Germany and the USA and increasingly in the UK and continental Europe.

The choice of the type of construction (single skin, profiled or sandwich) will be governed by a combination of requirements that need to be satisfied: fire, thermal, acoustic, weight etc. Table 4.3 shows the relationship between various types of wall construction and the performance requirements for spans, fire resistance and weight, which are usually the most critical.
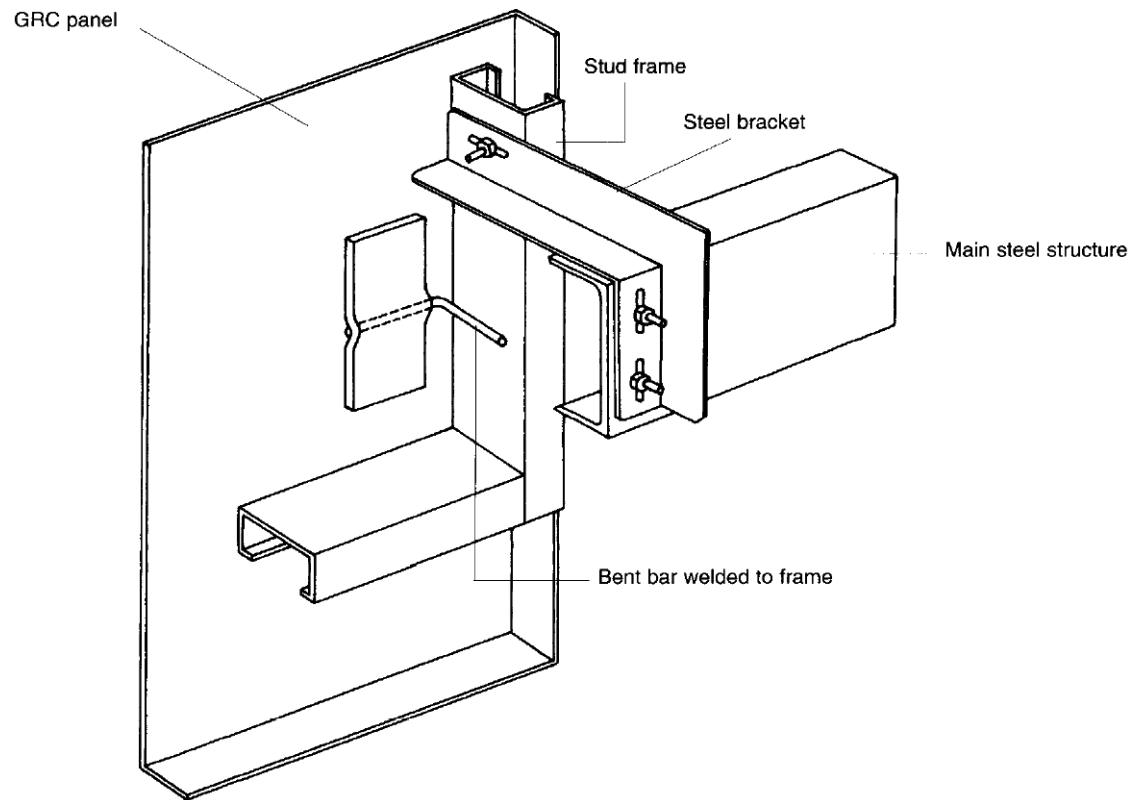
4.5 Fixing method for a stud frame system.

The total effective depth of large panels can usually be reduced using sandwich construction, as large single-skin panels would require deep stiffening ribs to prevent deflection under load.
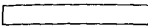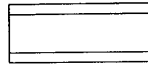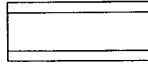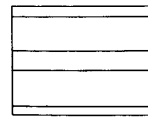
In sandwich construction a larger overall thickness than indicated by strength calculations would usually be used to satisfy fire and thermal characteristics and also minimize bowing. This may also be minimized by limiting panel length or width, because the effect is proportional to the square of either dimension; increased panel thickness has a directly beneficial effect in minimizing bowing. Bowing has

not been a problem in single-skin construction with separate insulation applied on site.

If the panel is required to act as a true sandwich, and for the core to have sufficient shear strength, it is important to form a good bond between the GRC and the insulating core in order to prevent delamination of the core from the skin, which may be caused, in turn, through the bowing of the panel.

Sandwich panels have tended to predominate in the UK. For example, the RACS Superstore, Thanet, Kent (architects: Royal Arsenal Co-operative Society Ltd) is clad with what were claimed at the time of

Table 4.3 Relationship between wall construction and performance requirements

Wall construction		Maximum recommended span (1.0 kN/m² wind pressure)	Fire resistance BS 476 Part 8	Weight (approximate)
Single skin		Metres	Hours	kg/m²
	Flat GRC 8 mm thick	0.8	None claimed	16
	Flat GRC 12 mm thick	1.1	None claimed	24
	Profiled or ribbed GRC + 50 mm glass-fibre insulation + plasterboard	Up to 4	0.5	40
	Profiled or ribbed GRC + 50 mm glass-fibre insulation + 100 mm concrete block	Up to 4	4	100

Increased depth of profile and stiffening ribs increases the spanning capability of the panel

Sandwich construction				
	10 mm GRC 50 mm polystyrene 10 mm GRC	3.0	2	60
Overall panel thickness 70 mm				
	10 mm GRC 60 mm polystyrene 10 mm GRC	3.0	None claimed	46
Overall panel thickness 70 mm				
	10 mm GRC 50 mm PBAC 30 mm polystyrene 50 mm PBAC 10 mm GRC	5.5	4	150
Overall panel thckness 150 mm				

Note: PBAC – polystyrene bead aggregate concrete.

construction to be the largest GRC panels manufactured in Europe. These panels weigh just over 4 t and have thermal insulation of 0.9 W/m^2°C. In overseas contracts, however, this requirement for thermal insulation and other performance requirements were achieved using single-skin construction, ribbed where necessary, with separate insulation applied on site. For example, the Sports and Leisure Centre in Saudi Arabia (architects/consulting engineers: Slater Hodder/ Cooper McDonald) uses GRC on the fascia panels to the roof and barrel vaults. This move away from sandwich panels is due partly to the greater thermal stresses and hence bowing problems in hot countries and partly to manufacturing difficulties.

Bridging webs used to give stiffness to larger panels can cause ghosting of the surface finish, as in the case reported by Young (1978) at the UOP Fragrances factory, where, although a special case using a site-applied urethane paint finish, the egg crate construction could be seen on the panel face. Young suggests the most probable explanation is that paint on the insulated skins (130 mm polystyrene) cured at a different rate from that in those areas where webs linked skins and at the edges of window surrounds. However, he also reports (1980) feedback from the Melrose Centre, Milton Keynes, where 77 mm polystyrene core was used with two skins of 6 mm GRC, and no ghosting of stiffening webs occurred. He suggests that this may be because the panels were left as white Portland cement on all surfaces, and because the method of production meant that the insulation was not added until about 2 hours after spraying. The decision to use the non-moulded finish on the outside of the panels may account for the same lack of apparent ghosting on the panels at the Scion Computer Centre, where 50 mm polystyrene core was used.

In order to improve the thermal performance of the panel and, at the same time, improve its fire resistance and stiffness characteristics, multiple sandwich panels of GRC and rigid polystyrene foam have been used (Table 4.2).

Jointing

The techniques used to seal joints in GRC components or panels are similar to those used for precast concrete or GRP. There are essentially four main ways of dealing with joints:

– gaskets;
– baffles in an open-drained joint;
– face sealants;
– cover strips.

Gasket joints

Gaskets are effective only where positive pressure is available to deform or compress them. A typical joint incorporates a top-hat section with captive nut to pull back a metal cover strip against a neoprene gasket. Advantage can be taken of the quality of the edge profile, which is normally possible in GRC, to use push-in fir-cone gaskets, as used, for example, at the UOP Fragrances factory (architects: Piano and Rogers) (Fig. 4.6). These gaskets incorporate barbed legs, which can be pushed into position in the joint. One problem in using such gaskets is that the moulded GRC nibs to receive the gasket have only one mould face, and however well the back face is compacted, minor variations in thickness will occur, which can cause points of weakness for an effective weatherproof seal. These nibs can be wrapped in tape to take up any tolerances in surface defects resulting from manufacture, in order to gain a tight fit before applying the compression gasket. The UOP Fragrances factory also used a push-in gasket on the inside face; some difficulty may be experienced in sealing past the adjustable clamps in such a detail.

Steel lattice
beam

Adjustable clamp

Lightweight precast
GRC strengthening ribs

Insulation
cone

GRC panel

Fir cone gasket

Retained by angle

Steel bottom rail
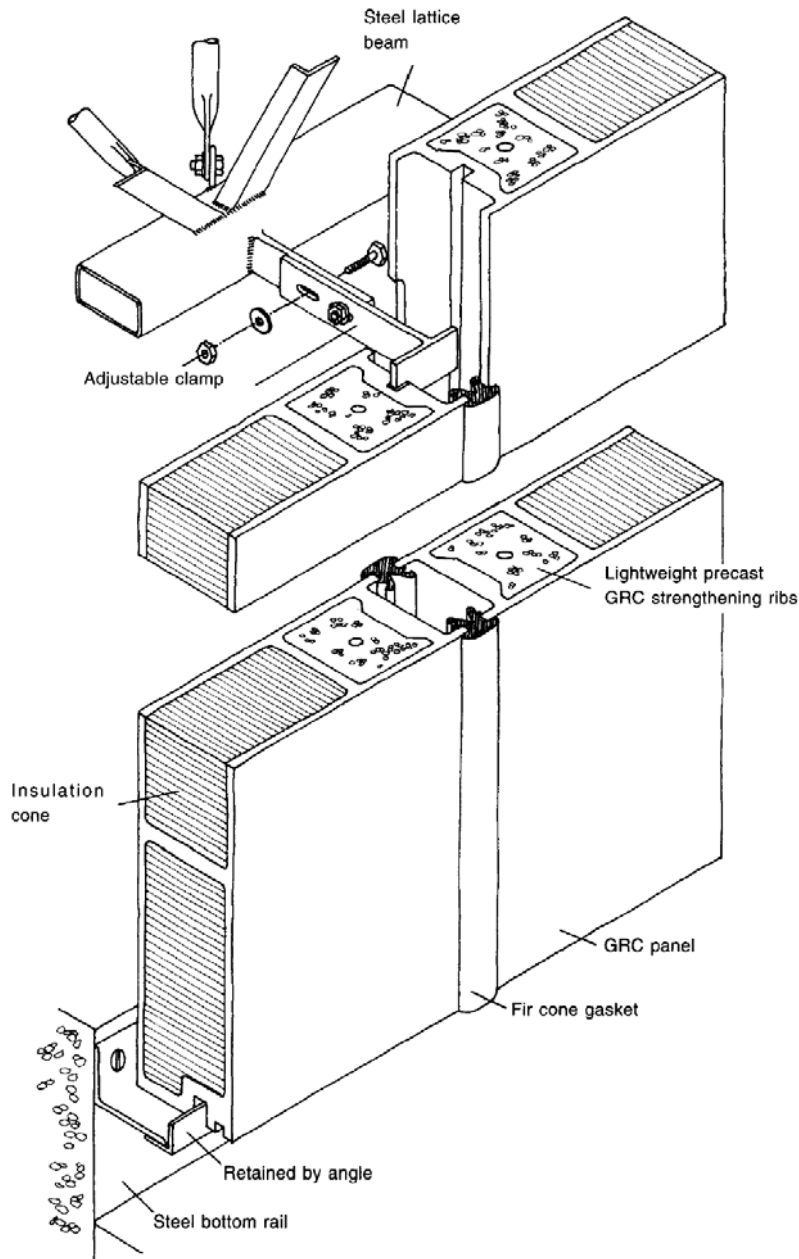
4.6 Gasket joint at UOP Fragrances factory, showing insulation core foamed between skins.

Another problem with gasket joints is that they depend upon extremely tight tolerance in joint size, and may only really work in conjunction with a system of adjustable fixing devices. Typical permissible joint range clearances are 5–10 mm. The use of slotted holes and T-clamps at UOP Fragrances resulted in precise location of panels, allowing the use of this method of gasket jointing even at the corner detail. Direct glazing of windows into GRC is also possible using neoprene gaskets.

Open-drained joints

One of the requirements of an open-drained joint is that the baffle groove is deep enough to accommodate the baffle at the maximum and minimum joint ranges. Typical baffle groove depths are 30 mm. Such deep grooves are difficult to form during GRC manufacture. Furthermore, it is not always easy to fix the baffle strip at the head of the joint. For these reasons this form of joint is not often used for GRC panels.

Mastic sealants

Various mastic sealants, including polysulphides, polyurethane and silicone rubbers, have been used, but their success depends upon good surface preparation and the use of correct primers. The sealant surface may be exposed to ultraviolet light, and its long-term attributes are therefore questionable. Manufacturers' recommendations for sealants must be closely followed at all times. Sealants designed to bond to smooth surfaces should be specified, and care should be taken to ensure that any silicone face sealer to the panel is not carried round the edges of the panel, as this inhibits adhesion of the sealant.

Cover strips

Although in theory it is possible to disguise the joint using a cover strip, these are not often used, partly

because they are not normally visually acceptable, and partly because the design of the intersection between vertical and horizontal cover strips makes it almost impossible to maintain weather tightness.

Top-hat sections are used for fixing back foamed GRC panels onto a structural framework (Fig. 4.7), and proprietary methods can be used for secret fixing (Fig. 4.8).

Fixings

Fixing methods using angle cleats and dowel fixings are similar to those used for precast concrete. Glass-fibre-reinforced cement panels are best supported at the base and restrained at the top; intermediate fixings should be avoided. Typical fixings for fixing panels back to their supporting framework are shown in Fig. 4.9.

It is most important that allowances are made for the thermal, moisture and any structural movements of the GRC, which are approximately double those of precast concrete. For cladding panels these provisions for movement are usually accommodated in the top restraint fixings in the form of slotted or oversize holes (Fig. 4.10). Frictionless washers or bearing pads of neoprene or polytetrafluoroethylene (PTFE) and spacer tubes, or a resilient rubber bush or spring, must be incorporated to allow the component parts to slide and move (Fig. 4.11). If a fixing is tightened on site without such devices, the forces will be transferred into the panel, leading to bolt failure or local failure of the GRC.

Cast-in fixings should be encapsulated in a zone of good-quality GRC with a minimum width of 12 times the bolt diameter and a minimum of six times the bolt diameter between the centre of the bolt fixing and the edge of the panel (Fig. 4.12). Only cast-in fixings should be used for structural connections. Site-drilled holes are adequate for secondary fixings,
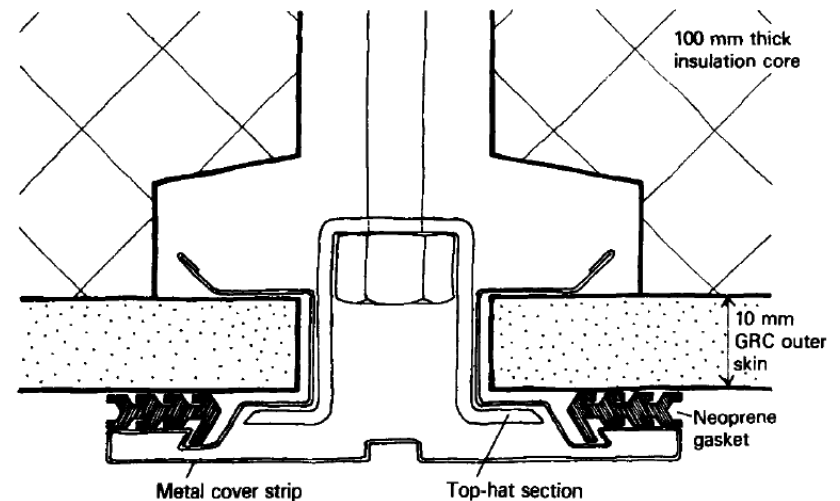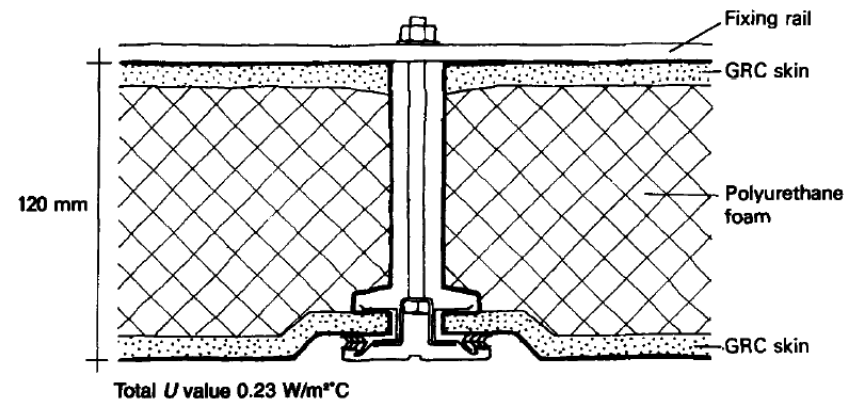
4.7 Top-hat section for fixing foamed GRC panel back onto a structural framework.
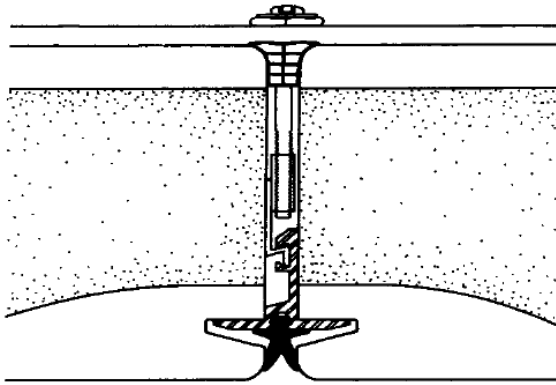
4.8 Proprietary method of secretly fixing GRC back onto a structural framework.

although it is usual even in this case to provide plastic area fixings to allow a degree of dimensional flexibility.

Where single-skin construction in GRC is used, the panels can be fixed back to the secondary framing using cleats mounted on the stiffening ribs. Figure 4.13 shows a typical example, where the panel is fixed to a horizontal rail supported by steel uprights at intervals along the perimeter of the facade.

Panel dimensions and tolerances

Although in theory there is no real restriction on the length of panel, in practice this is normally limited to 4–6 m because of problems of lifting, handling and fixing of units. Maximum widths of panels depend upon the method of production. For manual spraying this is normally limited to 2 m. Where windows are incorporated within a panel, a minimum mullion width of 200 mm is recommended. Glass-fibre-reinforced cement single-skin thickness is minimum 6 mm and maximum 18 mm for sprayed material. For premix material the minimum thickness is normally 10 mm, with no upper limit within reason.

Tolerances in panels are similar to those used for precast concrete, but should not exceed ±3 mm for small panels.

Handling of units on site and storage

Because of the ease with which GRC can be formed in a variety of shapes, it is not uncommon to avoid the potentially troublesome eaves detail by cranking or curving the panels at their junction with the roof (Fig. 4.4). Such panels were used at the fire station at the National Exhibition Centre and at Heathrow Euro-lounge. Special equipment may be necessary for handling such units on site, and care must also be taken in designing the fixing devices for lifting to ensure that these do not show on the outside face. Highly profiled panels are also difficult to store and transport, and cranked panels will twist and distort if stacked unsupported on edge (Fig. 4.15).

Also, large upstands and long unsupported ends tend to settle when in their 'green' state, and care must be taken during manufacture and storage to avoid sagging of unsupported ends. If this is not done, problems can occur in controlling the size of joints between panels because of difficulties in ensuring alignment of panels during erection.

Repair on site

Although it is possible for specialist contractors to repair minor defects on site using manually applied cement/sand slurry where structural damage has taken place in the form of large holes and the fibre/cement bond has been broken down, panels should be removed and returned to the factory for repair under closer quality workmanship control, or pre-ferably replaced by a new panel. Panels with surface texture treatments should be resprayed to avoid any
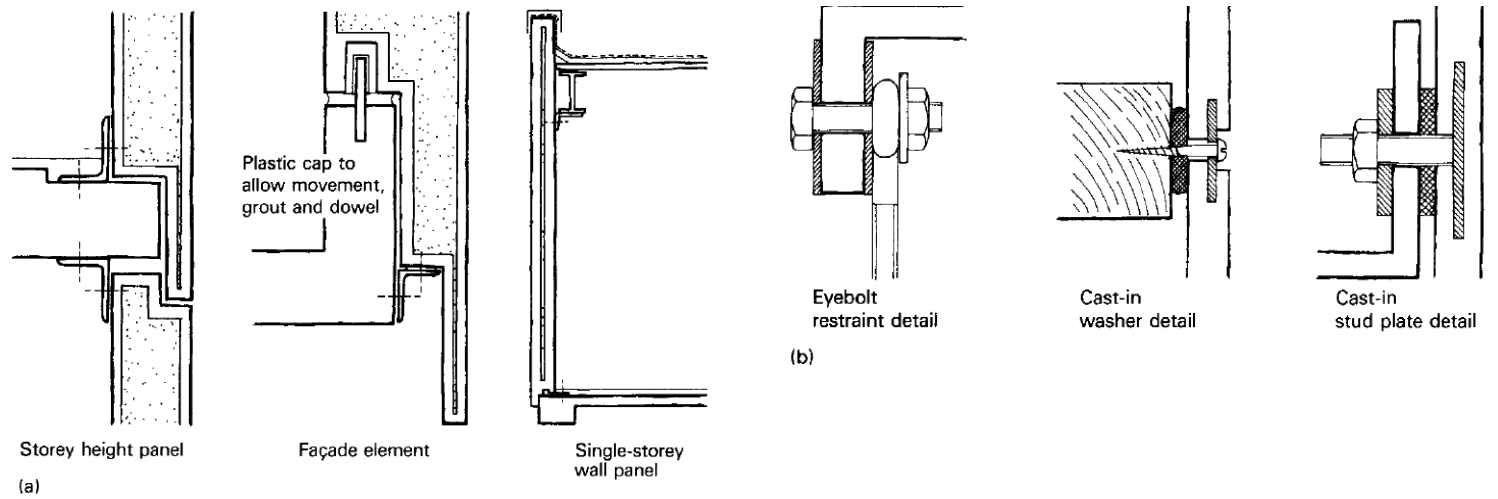
4.9 Typical fixings using GRC: (a) sandwich construction fixings; (b) single skin fixings.
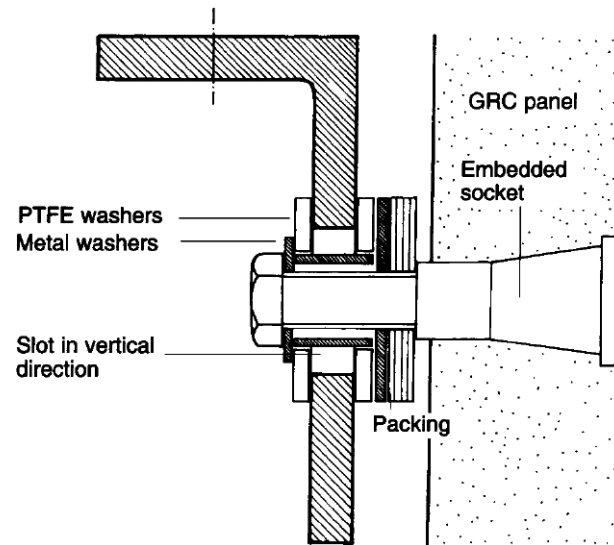
4.10 Slotted fixings to allow movement at top of panel.
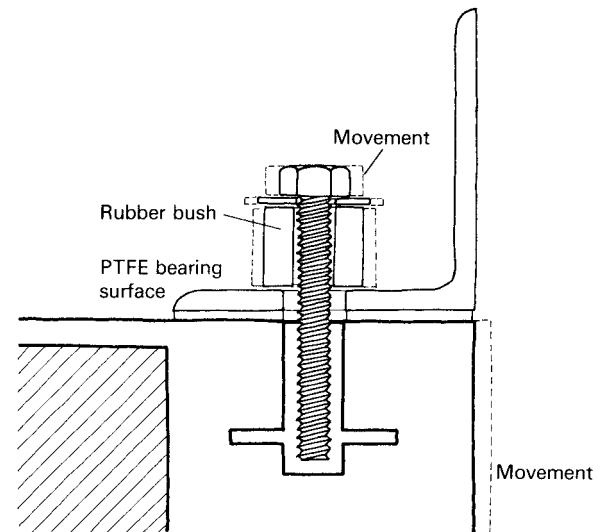
4.11 Resilient rubber bush fixing to allow movement.
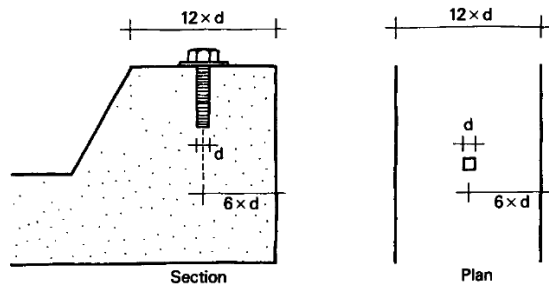
4.12 Minimum cover to cast-in fixings.
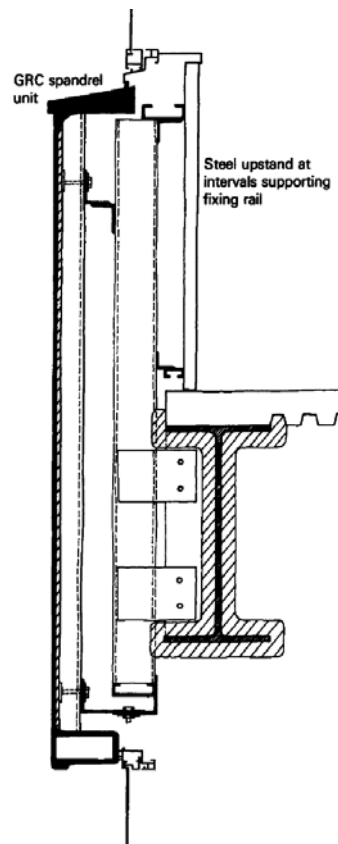
4.13 Example of single-skin GRC spandrel panel detail on metal framework.

patchiness occurring on the panel face where the repair has taken place.

Conclusion

If GRC systems have a persistent fault, it tends to lie in relatively unsophisticated detailing between the panels and in the details relating to the panels to adjacent windows, doors, curtain walling and louvre systems. Clearly GRC systems have not kept pace with metal-based cladding systems (see Chapter 6), with their interchangeable panels and sophisticated crossover joints.

The lack of sophisticated detailing explains why, even in continental Europe, GRC systems are predominantly specified on factories, middle market offices, schools and sports facilities, which have a need for the performance characteristics of the material. Architects working on projects that have higher aesthetic requirements have found the detailing unsuitable.

Manufacturers now, however, seem more interested in taking this problem on board, especially in the light of the downturn in the traditional markets experienced over the past ten years. Advances are being made in cutting and forming the edge of the material to allow more sophisticated arrangements. Other opportunities include the inclusion of EPDM or neoprene gaskets mounted within the panel edge. Some manufacturers are developing horizontal panel arrangements as well as a fully integrated system of panels and windows.

Given improvements in GRC technology, which are backed up by a strong track record of successful projects in Europe, the performance advantages of modern GRC may warrant reconsideration. In terms of costs, the installed costs of GRC sandwich constructions average from £80 to £150/m², which is

roughly equivalent to some flat metal sandwich constructions and about twice the cost of corrugated metal constructions. Costs for moulded GRC constructions are 20–30% more expensive than those for equivalent precast concrete, depending on its complexity and the quantities involved. However, GRC may be more cost-effective than precast when savings on superstructure are considered.

It can be seen that the glass fibres constitute only a small percentage by weight of the material, and although, for example, fibres for GRC (Cem-fil) cost twice as much as fibres for GRP (£2000/t in 1981), the resultant material cost of a total 12 mm composite is only approximately half that of the material needed for an equivalent GRP composite. Having said that, of course, the material costs represent only a small percentage of the total costs, which will include overheads on production for more complicated panel shapes.

Glass-fibre-reinforced cement can be seen as an alternative to ordinary reinforced concrete in respect to its weather resistance, non-combustibility and low thermal movement. Advantage can be taken of its higher strength-to-weight ratio than those of other cementitious materials to produce strong, fire-resistant yet lightweight claddings. (Its strength-to-weight ratio is, however, less than that of GRP or metals.) Inevitably, though, it is compared with GRP in respect to its
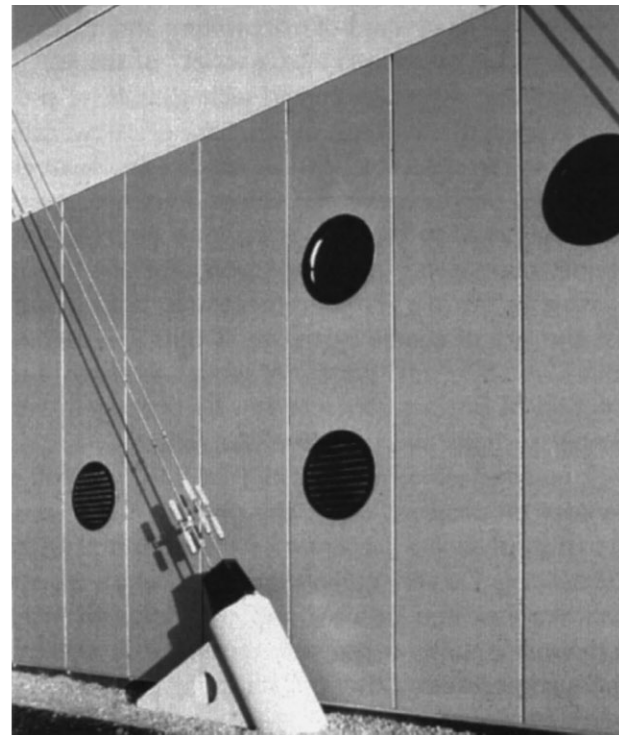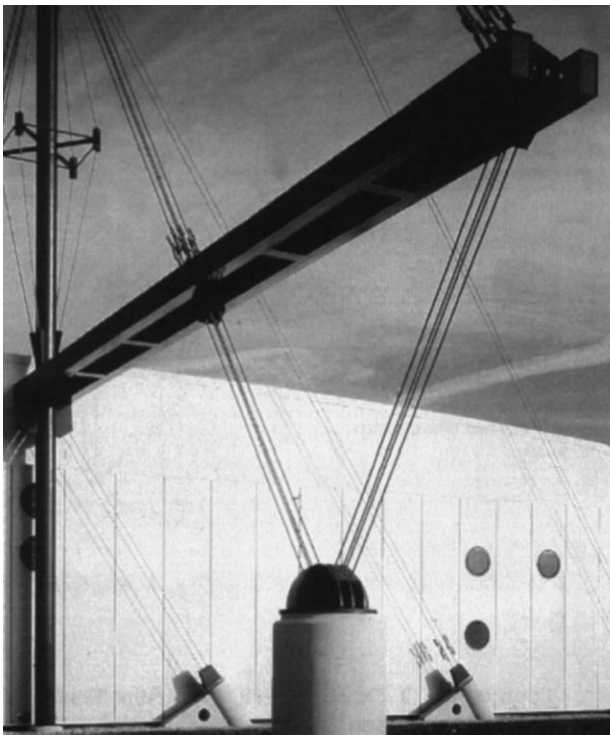
4.14 Oxford Ice Rink (architects: Nicholas Grimshaw & Partners).

method of manufacture and its resultant ability to be formed into a variety of shapes.

Cement, when reinforced with glass fibre, produces precast elements much thinner – typically 10 mm – than would be possible with traditional steel-reinforced precast concrete, where 30 mm or more concrete cover to the steel is essential as protection against corrosion. Thinner sections are also made possible by the low water:cement ratio of the material, the lack of coarse aggregate, and its low permeability. As a result, panels of equal strength and function of precast concrete can be produced with thinner sections and therefore less weight.

In conclusion, it appears that GRC can offer benefits on projects where the physical characteristics of the building can enhance the performance of the building. On very complex projects, which require very
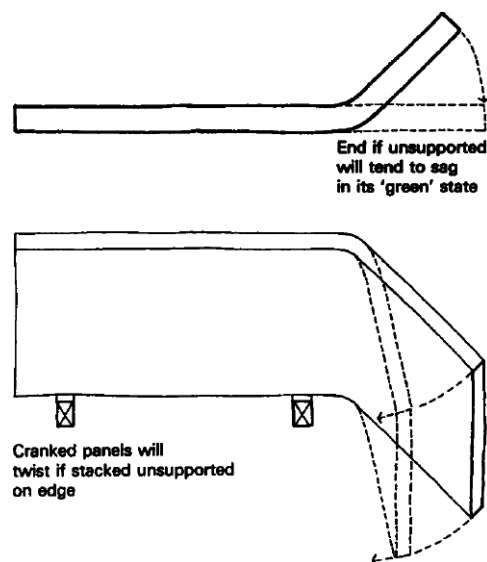
sophisticated detailing and integration of many components, GRC is probably unsuitable at present, although promising advances are being pursued.

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End if unsupported will tend to sag in its 'green' state

Cranked panels will twist if stacked unsupported on edge

4.15 Cranked panels need supporting to avoid distortion during curing.

5

Formed metal including profiled metal

This chapter discusses steel or aluminium sheeting, profiled, pressed or formed to impart stiffness and hence strength to thin and otherwise flexible skins.

Forming of metal

Forming of sheet metal can be carried out in five different ways (Fig. 5.1):

– brake pressing;
– folding;
– rolling;
– stamping;
– deep drawing.

The size and shape of the final product is influenced by the type of production method used.

Brake pressing

Bending of metal sheet in its cold state is a relatively simple process, using a **brake press**, and once a sheet of metal (usually 2–4 mm thick) has been cut at the corners, it can be formed into a tray using a V-shaped bending tool (Fig. 5.2) and the corners welded. In order to do this the sheets must first be cut at their corners prior to brake pressing (Fig. 5.3). Today, brake presses can be computer controlled to produce a wide variety of edge profiles (Fig. 5.4). The size of the panel produced in this way is limited only by the size

of the sheet and the length of the brake press (maximum length 6 m). Finishes, such as anodizing, would be applied to these panels after fabrication.

Folding

With the introduction of more sophisticated computer control mechanisms such as CNC (Cambridge Numerical Controls), it is now possible to fold metal into more complicated shapes using a twin-head folder where the previous limitation of providing space for access by the V-shaped bending tool can be avoided.

Rolling

This is normally carried out on a continuous line, either by rolling direct from coil (see 'Steel profiled cladding' p. 96) or by rolling separate sheets. There is no limit to the length of the final product other than that governed by handling or transport (normally 13 m).
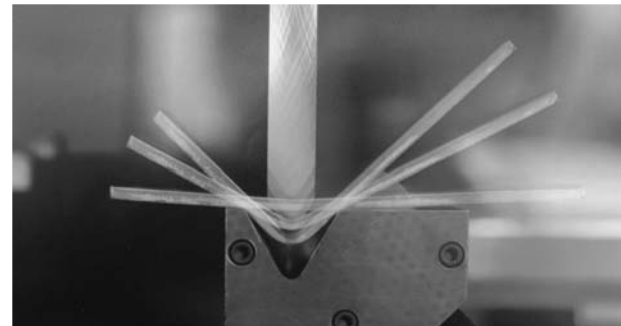
5.2 V-shaped bending tool (photo © PSP metal facade systems).

(a) simple bend

(b) double bend

(c) crimped profile

(d) return end

(e) double return end

(f) complex profile

deep draw }

(g) deep section in tray form

5.1 Methods of forming metal to shape.

5.3 Sheets cut at corners prior to brake pressing.
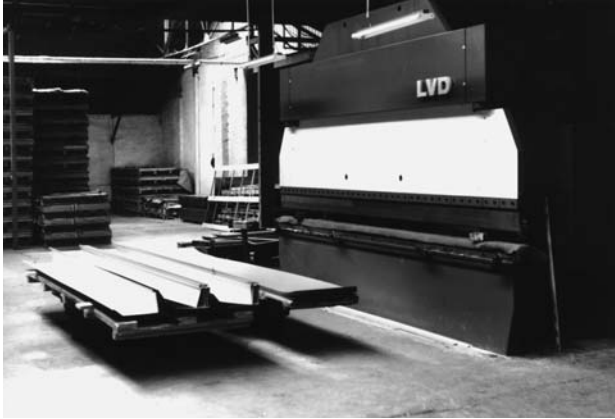
5.4 Brake press.

Simple rolling lines are possible for thinner gauges of metal (up to 1 mm), but more complex profiles for long-span cladding need fixed-stand machines (Fig. 5.5).

Metal stamping

Pressing of sheet metal in one operation is more difficult, and the panels formed in this manner in the UK are normally restricted to 2 m × 1 m. Such panels were produced for the parapet units at the Brunel Centre by Dowty Boulton Paul Ltd, and are typical of panels formed by metal-forming techniques (Fig. 5.6). These techniques are normally associated with the

5.5 Typical rolling line.

5.6 Brunel Centre, Swindon (architects: Douglas Stephen/Building Design Partnership).

automobile industry, where the cost of the stamp can be amortized over a large number of identical units (Fig. 5.7). The steel panels for the Milton Keynes factory Kiln Farm (architects: Milton Keynes Development Corporation) were also stamped out in one operation (Fig. 5.8). Aluminium sheets were stamped out for the Herman Miller extension, Bath (architects: Nicholas Grimshaw Partnership), 2.4 m × 1.2 m, by the Kinain workshop. The panel can be stamped as a 'tray' in one operation, as against brake pressing, which can form only one edge at a time (Fig. 5.9). With large panels, it is normal to stamp profiles and then brake press to form edges. Details of the panel joint are shown in Figure. 5.10.

Deep drawing

Where panels need to be pressed in three dimensions this can be done by **deep drawing** techniques. For example, panels at the Federal Technical College, Lausanne, Switzerland (architects: Zweifel and Strickler), were drawn into a three-dimensional shape

by Schmidlin (Fig. 5.11). The 1.8 m × 1.2 m pressed panels for the Sainsbury Centre were produced by TIC Superform by deep-drawing them round a shape using a special alloy of superplastic aluminium.

This proved to be a costly and difficult operation because of the depth of the panels (100 mm), and similar panels at Gatwick Airport North Piers and the Financial Times building, London, were produced with smaller reveals (20–40 mm) (Fig. 5.12).

Profiled metal cladding and roof decking

Definitions

Steel Construction Institute, previously Constrado, (1980) on profiled steel cladding defines **cladding** as:

> The external envelope of the building which normally carries no loading beyond its own weight plus the loads imposed by snow, wind and during maintenance. It is the term used when the steel sheet (coated or uncoated) is exposed to the elements. Cladding for walls is sometimes

5.7 Stamping of metal in one operation, normally associated with automobile industry.

5.8 Stamped panels at Milton Keynes.

5.9 Stamped aluminium panels 2.4 m × 1.2 m at Herman Miller extension, Bath.

known as walling or siding and cladding for roofs is generally known as roof sheeting or roof cladding.

and **roof decking** as:

> The part of the envelope, on the roof, which supports insulation and waterproofing plus its own weight, plus imposed loads resulting from snow, wind, maintenance and sometimes access. The steel sheet usually forms the inner layer and is not exposed to the elements, unlike roof cladding.

Profiled steel and aluminium sheets are available in sinusoidal, symmetrical and asymmetrical trapezoidal profiles. According to the PSA Method of Building Guide (1979), these can be defined (Fig. 5.13) as:

— **sinusoidal** – where crests and troughs are symmetrical and have the shape of a sine curve;

'Unistrut' support

Nut with spring

Neoprene gasket should allow for any lack of alignment of 'Unistrut'

Cladding panel

Holokrome M12 recessed socket button head bolt with s/s lockwasher, s/s washer amd black neoprene washer 3 mm thick
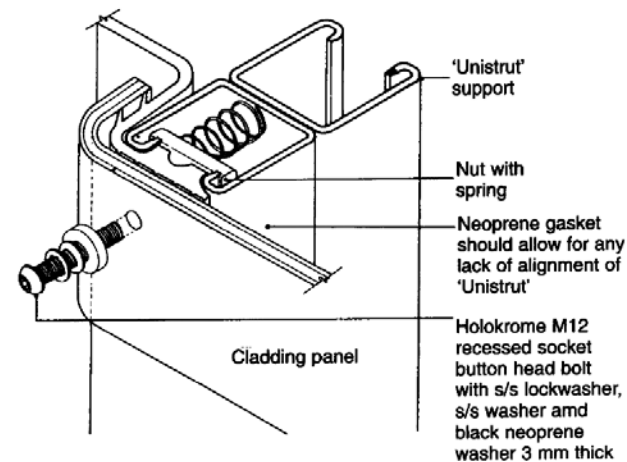
5.10 Detail of panels at Herman Miller, Bath.
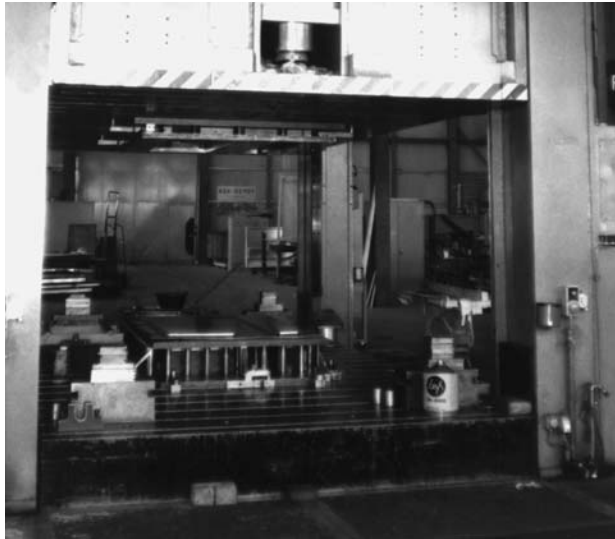
5.11 Deep drawing of complex sections and trays.

5.12 Panels by Superform Aluminium at Financial Times building.

–   **symmetrical trapezoidal** – where crests and troughs are the same width, and the sloping sections are at a constant angle;
–   **asymmetrical trapezoidal** – where crests and troughs are unequal in width. The section can be used with either surface outside provided the organic coating is on the correct side.

The industry

Steel profiled cladding

Coiled steel sheet is manufactured in the UK only by CORUS, which supplies it in three main versions:

–   organic coated on a galvanized substrate as in Colorcoat and Stelvetite;
–   galvanized;
–   undercoated (black steel) for others to apply their own metallic or organic coatings.

Although CORUS has its own fabricating works at Aycliffe, Darlington, in most cases it supplies the coiled sheet for rolling into profiles by other manufacturers. Most manufacturers sell their rolled products to specialist fixing contractors.

Some manufacturers claim to roll profiles of steel, taking advantage of modern steel processing methods, to attain a higher yield strength of 320–550 N/mm^2. However, high-tensile steels do not reduce deflection for any given profile or loading, and therefore the spans cannot be increased for deflection-controlled sheets. Thus if deflection is the criterion then high-tensile steel offers no real advantage, but if strength is the criterion then spans can be increased.

Although in the UK coiled steel, with its factory-applied finish, comes only from one source, it can sometimes be confusing to the specifier that the same finish, e.g. Plastisol, can be called by different names, e.g.

Colourclad or Everclad, depending on the fabricator's description of its particular product range.

Similarly, in considering finishes, it is not always clear which coatings are applied before forming (e.g. Plastisol) and which are applied after forming (e.g. Bacocolour – aluminium sheets only), and what are the advantages and disadvantages of each.

Aluminium profiled cladding

Both steel and aluminium offer a wide variety of sharper (trapezoidal) profiles, and can be used horizontally or vertically with patent bending processes available for specially formed corner junctions. The use of horizontal metal sheeting at the IBM offices at Greenford (Fig. 5.14) (architects: Foster Associates), for example, encouraged other architects to use profiled metal sheeting in a similar manner. The selection of

either steel or aluminium may be a personal choice. Aluminium is nominally more expensive but, on the other hand, is lighter and therefore, in theory, needs less framing. In practice, because the actual difference is 1.5 kg/m^2, this makes no difference to the framing in most cases. Maybe the specifier is influenced by steel being, in theory, more susceptible to rusting at the edges of the sheets. In truth, the choice probably rests on the types of finishes available or even the standard of technical back-up service provided by the manufacturers.

Sinusoidal

Symmetrical trapezoidal

Asymmetrical trapezoidal

5.13 Terminology of profiles.

5.14 IBM offices, Greenford (architects: Foster Associates).
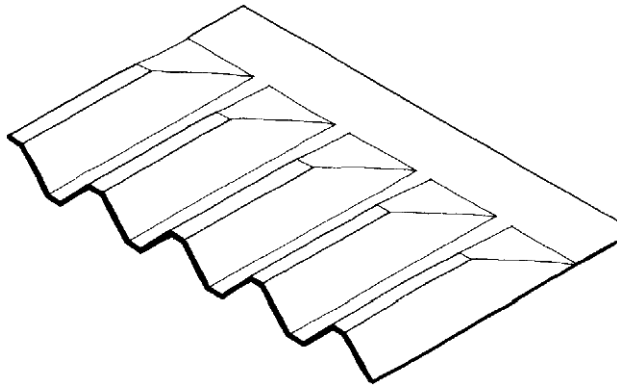
5.15 Tapering close-profile flashings available in aluminium.

Profiles

Profiled aluminium sheets to BS 4868 are produced in depths of 8–38 mm and 38–50 mm; however, there are many more trapezoidal profiles produced between 8 mm and 90 mm profile depth, as illustrated in the manufacturers' catalogues.

Profiled steel sheets are available up to about 13 m long with cover widths up to 100 mm in stock lengths. Trapezoidal sections are usually made in lengths to order. Sinusoidal sections are available in stock lengths. The profiles of sinusoidal sections are defined in BS 3083 and CP 143: Part 10.

Sinusoidal profiled steel sheets to BS 3083 are produced in depths of 19 mm. However, there are many more trapezoidal profiles produced up to 100 mm deep, as illustrated in the manufacturers' catalogues.

Architects often require a tapering closed profile section (Fig. 5.15), particularly where sheets abut window details. These can easily be produced in aluminium, but are more difficult in steel. Some steel tapering pieces are available, but they are normally small profiles and may be limited in cover width.

Corner flashing details and profiles are also an important consideration. Some curved eaves and round corners are now available in metal to match the main sheeting (Fig. 5.16).

There has also been an increased interest shown by architects in recent years in the curved forms possible in profiled sheets. Trapezoidal aluminium profiles can be fully or partly curved in their length by British Alcan to a minimum radius of 3000 mm. Tighter radii can be produced using crimped profiles such as those developed by Ash and Lacey as Floclad.

Design guidance

As well as the manufacturers' own design manuals with specific data provided on such factors as loadings, there are a number of publications offering guidance on the specification of profiled cladding. These include the following.
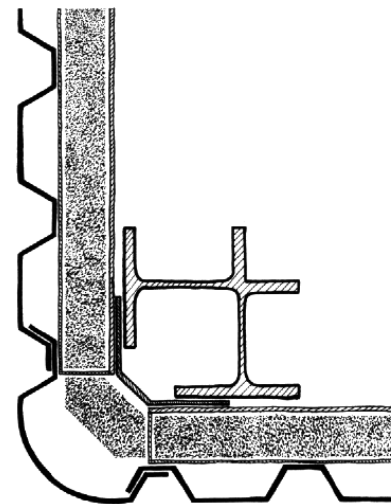
5.16 Typical curved eaves and round corners.

CEGB Guide

This includes recommendations on construction, weatherproofing, fixings, loadings and strength, appearance, durability and other performance factors (CEGB, 1970).

Metal Roof Deck Association

This gives codes of design and technical requirements of roof decking (Metal Roof Deck Association, 1970).

Method of manufacture

In the UK, aluminium is produced by the electrolytic reduction of alumina, from which two types of alloy are made, principally with magnesium, silicon and manganese. These can be hot or cold rolled to form flat sheets or coils.

Steel is made from iron, which is processed with additives such as carbon and manganese to give it added toughness and durability. It is rolled into flat sheets or coils, and is usually given a protective zinc coating in a hot-dip bath. The sheet may then be profiled or cut for site painting or, more usually, given a liquid or bonded coating before profiling and cutting.

Sheet steel and aluminium coil are supplied to the rolling mill for coating and rolling (Fig. 5.17). A typical coating line for sheet steel would consist of the following parts:

Galvanizing plant

Black steel is de-coiled, continuously cleaned and pretreated prior to zinc coating. A thickness of zinc coating is controlled to the requisite tolerance by means of high-pressure air, which removes the excess zinc. After galvanizing and cooking, the strip is re-coiled.

Coating line

De-coil strip. To maintain continuous operation successive coils are stitch welded; strip is held in a catenary form to give maximum area for vaporization of the solvents to occur. Time to allow this operation to be completed is provided by means of an accumulator system at the feed ends of the line.

Pretreatment

Remove oil, grease and surface residues by degreasing and zinc passivation with intervening water wash and scrub.

Precoating

A solvent-based primer is applied to both sides of the strip by means of a reverse roll coater.

First oven

The sheet is now suspended (under tension) in a large oven (temperature 260°C), in which it moves at a maximum speed of 30 m/min. Electronic signalling ensures a nearly constant catenary for the strip so that the vaporization of solvents from the coatings can take place. These solvents are incinerated to prevent atmospheric pollution. The heat generated from the combustion of these solvents is returned via a heat exchanger to preheat the fresh air circulating in the ovens.

Base coat or top coat application

The principal coating is now applied using rubber rollers if both sides of the sheet are to be painted. A second oven then cures this coat. Electronic signalling of the approach of the stitched joint enables the operative to raise the paint applicator rolls to avoid damage to the roller surface by the joint.

The speed of the sheet through the second oven controls the overall speed of the line. It is dictated by
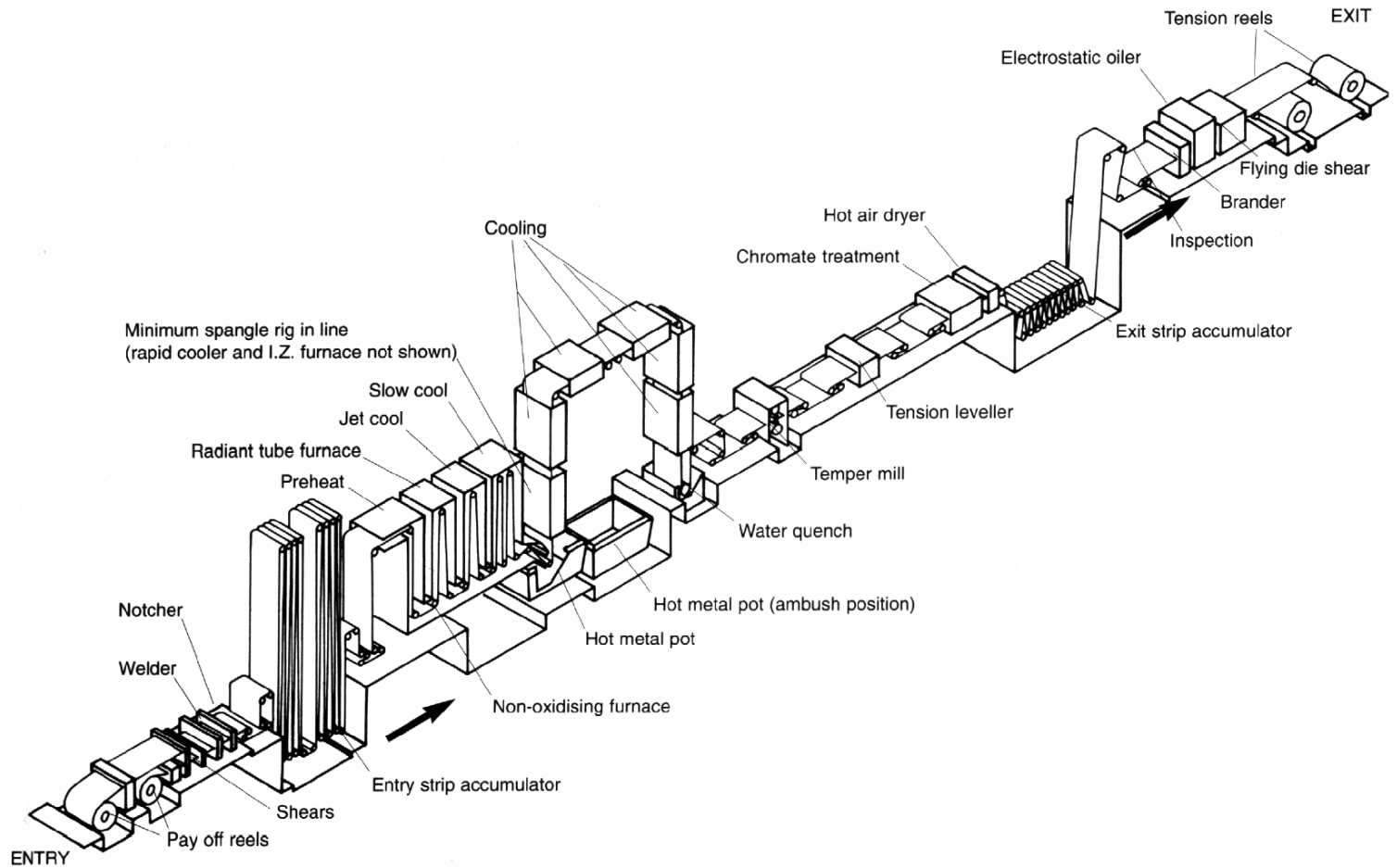
5.17 Typical steel rolling and coating plant.

tensioning rollers, which control the catenary in the second oven to ensure that the sheet is suspended correctly and is evenly heated on both sides of the sheet.

An accumulator allows a 1.5 min delay at the end of the line, and a steering mechanism is provided to ensure that the sheet is straight in the line. A back-tension device allows re-coiling of the sheet, and at this stage prepainted sheets can be fed into the line for embossing if required. Sheets are re-coiled prior to being fed into the rolling mill.

Roll form line

The rolling mill consists of a series of adjustable rollers through which the flat sheets are progressively formed into profiled forms. In some cases it is possible to

provide lateral profiling by means of a special roller (Fig. 5.18). Sheets can be cut to length before or after profiling. Typical manufacturing deviation on the width of the sheet is ±2 mm.

In forming the painted steel or aluminium strip some faults can occur, such as micro-cracking, fluting, bows or twists. Fluting is a pattern of kinks that occur at the ends of the sheet during rolling. Pre-cut sheets of high-tensile steel are vulnerable to this problem. It can also be caused by excessive amounts of nitrogen in the rolled strip, which may need stretch levelling prior to rolling. Bows and twists can also occur with poor rolling.

To avoid micro-cracking, MacGregor (1981) recommends that the minimum bend radius should be four times the sheet thickness for aluminium and eight times for galvanized steel.

Finishes for metal sheeting

Sheet steel

Profiled steel sheet is available with a variety of finishes. The principal types for cladding are as follows.

Hot-dipped galvanizing

This is a zinc finish, which may be spangled or matt.

Hot-dipped zinc/aluminized steel

This is a coating (aluminium finish) consisting of an alloy of approximately 55% aluminium/45% zinc, normally sold as Galvalume, Zincalume or Aluzinc. It is slightly more expensive than galvanizing, but offers better corrosion resistance.

Polyvinyl chloride on hot-dipped galvanizing

PVC Organasol is no longer in widespread use, and the more common finish is PVC Plastisol, which can be liquid applied or used as a bonded laminate. The
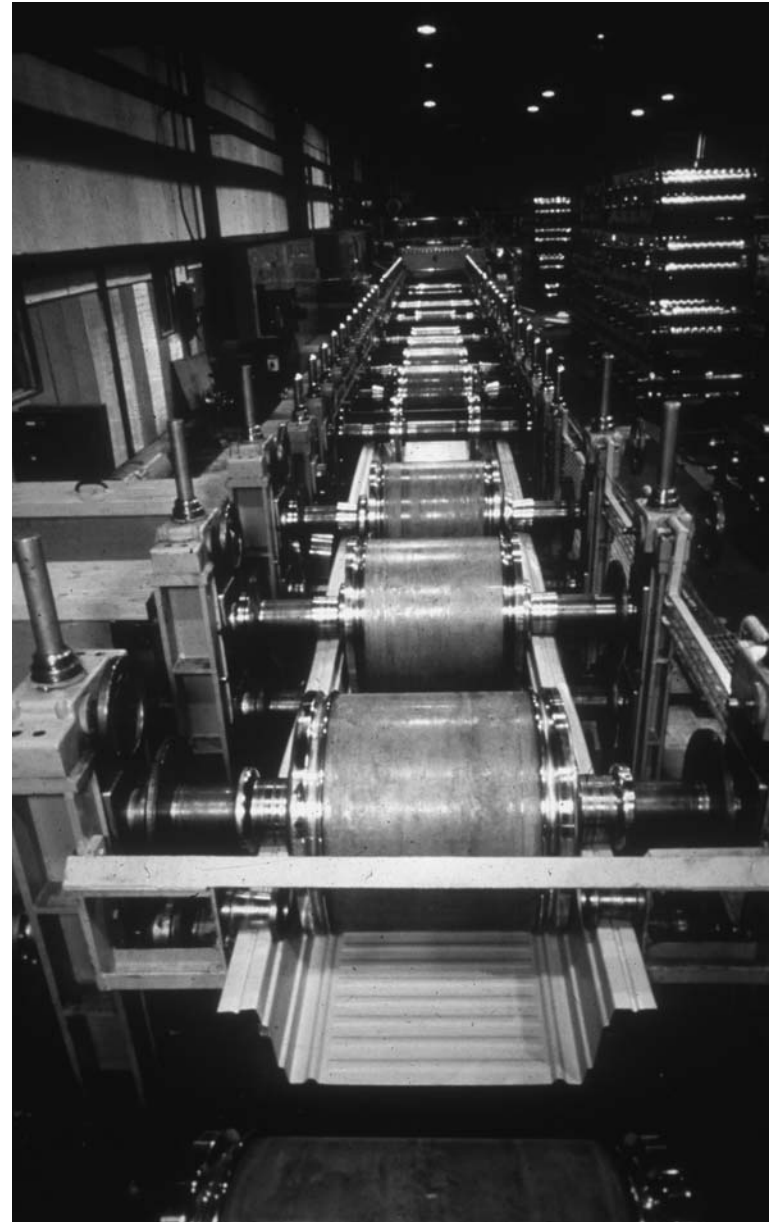
5.18 Lateral profiling can be produced by means of a special roller.

surface will invariably be textured or embossed. This can be considered as a 'thick' coating material with typical nominal thickness of 200 μm.

Acrylic or silicone enamels on hot-dipped galvanizing

Typically 20 mm with a smooth texture, this offers a different colour range from PVC. Siliconized versions of acrylics are also available, and modified silicone and acrylic finishes are now being used, particularly in the USA, as thin 'premium' coatings.

Fluoropolymers on hot-dipped galvanizing

Polyvinylidene fluorides, PVF and PVF_2, are also in widespread use as thin coatings (typically 20 mm), which offer good resistance to weathering. They are usually a mixture of PVF_2 and acrylic and their performance will depend on the particular formulation applied.

Acrylic-modified polyester resin over bitumen/asbestos bonded to steel

This is a very thick coating (overall thickness 555 μm), which is heavily textured, e.g. Galbestos (not now available).

Acrylic-modified polyester on an epoxy base

This is a very 'thick' coating offering good weathering characteristics (e.g. H. H. Robertson's Versacor).

The thicker PVC coatings (Plastisol) offer a better resistance to wear and abrasion than the thinner fluoropolymers (PVF_2) and silicone enamels; however, the PVC colours are not so stable, and tend to fade in ultraviolet light. A general rule might be to use PVC in areas where surface wear might be expected, e.g. roofs, and to use the fluoropolymers where colour integrity is important for reasons of appearance, e.g. walls.

In order to prevent discoloration and deterioration of the organic paint finish, particularly with PVC coatings, it is important that the temperature in use should not exceed the safe temperature ranges of the finishes used (Fig. 5.19). Typical safe temperature ranges for different coatings are:

PVC (inc. Plastisol)	50°C	to	79°C
acrylics	50°C	to	100°C
fluoropolymers (inc. PVF_2)	50°C	to	120°C
acrylic polyester	50°C	to	70°C

Sheets of dark colour, such as chocolate brown, cause the most problems in heat build-up, particularly those with an insulation layer immediately behind the sheet. In general, black and dark colours can be expected to reach temperatures of 80°C during summer conditions, medium colours 65°C and white or bright aluminium 50°C.
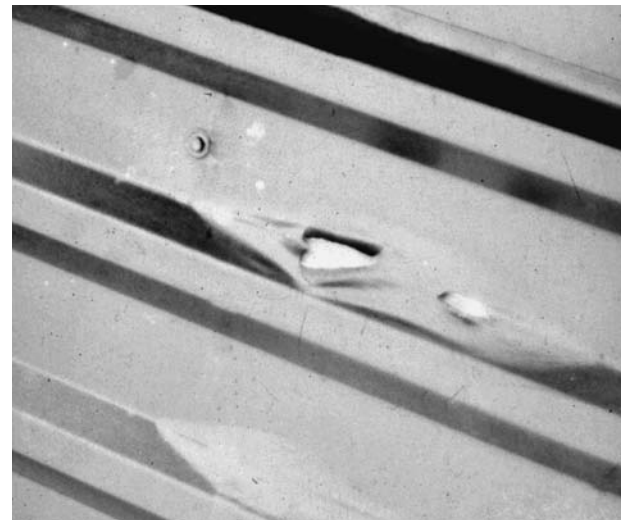
5.19 Delamination of outer paint finish due to safe temperatures being exceeded.

At the Second International Conference on the Durability of Building Materials and Components at Washington, USA, 1981, D. A. Thomas explained that it was generally recognized that organic coatings are permeable to water and oxygen, and also to ions, so even a defect-free coating could not be expected to give permanent protection in sufficiently active environments (Thomas, 1981). Thus the quality of the primer coating is critical to the durability of the paint finish. At the same conference, C. Christ showed the results of tests carried out on two paint systems: an acrylic and a modified fluoropolymer with various types of zinc and aluminium substrates (Christ, 1981). The aluminium-coated substrate was rated better than all other painted substrates at three or four exposure sites. The thickness and weight of the primer are also critical. BS 3083:1959 defines the types of zinc coatings and tolerances on the sizes of sheets for determining the weight of zinc. In general, sheeting with the heavier zinc or aluminium coatings beneath the paint films will suffer from less overall deterioration than those with lighter metallic coating weights.

Guarantees

Corus now offers twenty-five years guarantee in their 'Prisma' finish on steel, including the cut edges. Architects concerned with green issues are now requesting paints without AOC (Active Organic Content).

Aluminium

The aluminium industry has always insisted that its material does not need painting, as it has its own built-in protective surface coating of aluminium oxide, which forms immediately on exposure to the atmosphere. However, in order to compete with the colours of paint finishes available for steel cladding, manufacturers have produced a number of organic-coated colour finishes for aluminium sheets. Colour anodizing is limited in that it only really offers black, grey, gold or bronze finishes.

Thus profiled aluminium sheet is available with mill finish, anodized, or with an organic coating. Mill finish is a natural oxidized surface, which darkens with age. Anodized finishes are generally about 25 mm thick according to BS 3987: 1964 and BS 1615: 1972. There are five different methods of colour anodizing:

– organic dyes, which do not penetrate deeply into the anodic film and are therefore vulnerable to abrasion; many of these are as light fast as inorganic pigments, but some start to fade within two years;
– inorganic pigments, which are used for gold and bronze finishes;
– electrolytic colour, which is deposited deeper than organic dyes to produce black, bronze and grey finishes that resist ultraviolet radiation and abrasion;
– integral or hard colour, where organic acids produce results similar to the electrolytic process;
– special alloys, which produce a grey or gold finish during anodizing.

Aluminium sheeting can be either supplied as pre-coated fluoropolymers or post-coated as alkyd finish.

The important thing to realize is that the stoved-on alkyd finish has to be applied after forming. Because PVF_2 and acrylics are precoated, they are supplied to the fabricator as finished sheets for forming. Alkyd finishes have to be stoved on after forming.

The safe temperature range for aluminium is −80°C to +100°C, above which gradual loss of strength occurs. Above these temperature ranges the colour coating will also discolour and deteriorate.

Some colours reflect or absorb heat more than others, and dark colours are more likely to reach much higher surface temperatures than light colours. It is important to obtain assurances from the manufacturer on the relative durability, colour fastness and temperature limitations of the various colours available.

For both aluminium and steel profiled sheeting, colour matching between batches of sheet and flash-ings is often a problem. Samples of the limits of colour change can be approved before ordering, but some mismatch of colours on a large job is inevitable. The selection of neutral colours for sheeting or contrasting colours for flashings is a way of overcoming this difficulty.

Performance criteria

The acoustic, thermal, strength, and fire behaviour criteria are compared for steel and aluminium in Table 5.1. In general, the mean value for airborne sound reduction through profiled sheeting is not better than 28 dB unless additional insulation is provided with a back-up construction of mineral wool, in which case it is possible to achieve 36 dB. With such a construction, U-values of $1.8 \, \text{W/m}^2\text{°C}$ are normally possible (Table 5.2).

In considering strength, steel and aluminium profiled sheeting can be designed to withstand a deflection of span/90 (span dimension divided by 90; Fig. 5.20). Because the performance of cladding is often determined by the deflection criterion, the limit chosen is important. Most manufacturers now consider that a limit of span/90 does not represent good roofing practice, and is likely to lead to troubles from leaks developing at laps. Thus moves are being made to introduce more stringent controls for roof sheeting.

Resistance to hard body impact is another important characteristic of metal cladding systems, and manufacturers should be asked for results of impact tests (Fig. 5.21).

Installation

Most manufacturers include guidance in their trade literature on the method of handling and storage of their material on site. All the manufacturers of profiled
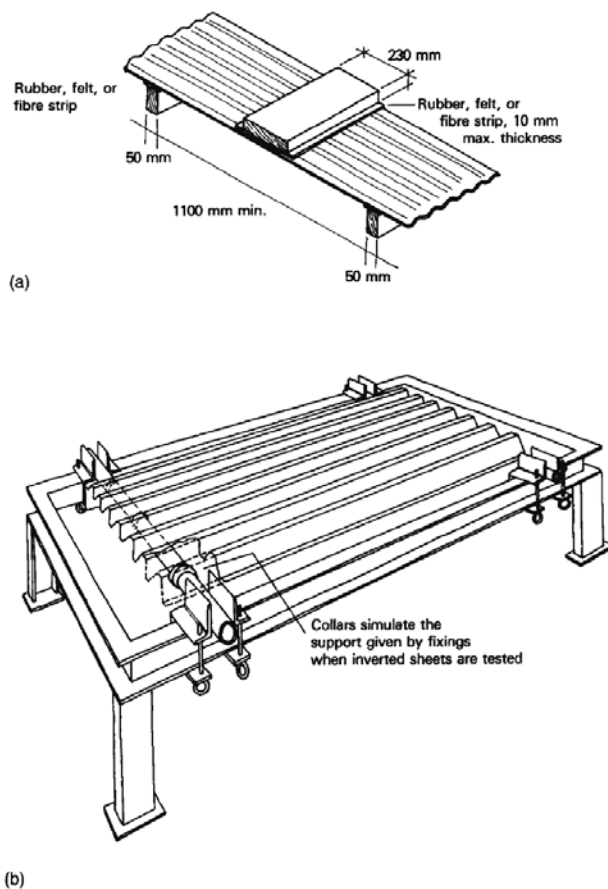
5.20 Test rigs for measurement of the strength of metal profiled sheeting.
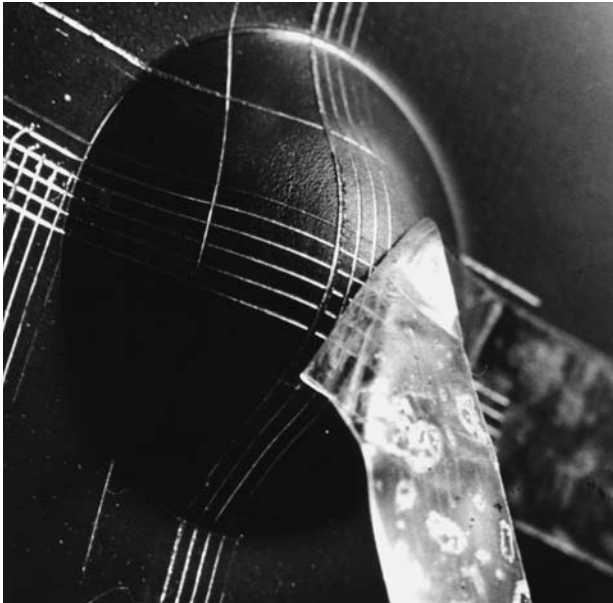
5.21 Hard body impact test for steel sheeting.

metal depend upon nominated subcontractors for the detailed design and erection of their cladding. The quality of workmanship on site, particularly at the edge of sheets and the method of fixing, are important factors in the proper assembly of profiled sheeting. Edges of sheets crumpled in handling can look unsightly. The present vogue of using profiled metal horizontally (Fig. 5.12) imposes an even greater requirement for care in the assembly and fixing of flashings and trims.

One of the advantages of profiled sheet metal cladding is that, with care, the fixing subcontractors can adjust the setting out of their sheets to take account of inaccuracies in the structural framing. Fixers prefer to pull on rather than bend sheets to fit an overall dimension, and thus the mean size of the sheets in manufacture is normally below the target size.

Although sheet cladding is subject to very close dimensional control during manufacture, the designer cannot assume that no tolerances are necessary, as spreading of sheets can cause cutting or use of infill pieces on corners and junctions. Fixing contractors need guidance from the designers on where tolerances have been allowed for in the design.

One method of controlling the setting out of profiled sheeting is to use setting-out or spacer jigs mounted on the supporting framework.

The minimum height of stacking profiled sheets on site can be important in reducing the effect of spreading of the overall width of those sheets at the bottom of the stack. Even the way in which the units are lifted on and off the lorry can affect the dimension if they are not crated correctly.

Effect of temperature change on fixings

The external surface of aluminium sheeting will have to withstand a maximum daily temperature range of 50°C if mill finish or light coloured, and up to 70°C if dark coloured. As the coefficient of linear expansion of aluminium is 23×10^{-6}°C, these temperature ranges mean that an 8 m long sheet will expand about 10 mm and 13 mm for light- and dark-coloured sheets respectively. It is necessary to accommodate this movement on dark-coloured sheets by oversize holes or non-rigid fixings, but no special requirements are necessary for light-coloured or mill finish sheets. For sheets over 8 m in length, non-rigid fixings should always be used. There is no need to provide expansion joints across the width of the sheet, because the profile will accommodate movement. For steel sheets, the coefficient of linear expansion of steel is 12×10^{-6}°C, which means that an 8 m long sheet will expand 5–7 mm. The inherent flexibility of the material can accommodate this, but over 8 m non-rigid fixings should be used.

Table 5.1 Relative performance of steel and aluminium cladding

	Steel	*Aluminium*
Acoustic	A mean value for airborne sound reduction through 1.6 mm mild steel sheet is 28 dB. Additional insulation can be provided by a back-up construction. An insulated cladding, such as 9 mm plasterboard, 25 mm mineral wool and profiled steel sheet has a mean sound index of 36 dB. The same construction without mineral wool has 30.9 dB reduction. A steel lining tray with 12.5 mm urethane in place of plaster-board and mineral wool insulation and foam sealing strips offer 32.9 dB.	A mean value for airborne sound reduction through 1.6 mm aluminium sheet is 18 dB.
Thermal	The conductivity (k) for carbon steel is 50 W/m°C. Typical U-values for steel sheeting given in Table 5.4.	The conductivity (k) for a typical aluminium alloy is 160 W/m°C. To calculate thermal transmittance (U) see BRE Digest 108 Standard U-values. Aluminium foil increases insulation only if it faces a cavity.
Strength	Figures published in manufacturers' trade literature are not necessarily comparable. Plannja, for example, use high tensile steel for their profiles which increases the permissible span across supports. Manufacturers should be asked to explain the basis of their calculations.	The tensile strength of the two main aluminium alloys used in the UK is: BS 1470-Ns 3-1 175 N/mm^2; BS 4300/6-NS31-H6, 185 N/mm^2 (BS 4868). Thin aluminium may damage easily on-site, particularly from ladders or equipment.
Behaviour in fire	Profiled steel cladding has no fire resistance as defined in BS 476 : Part 8. Where fire resistance is required, steel sheet can be suitable fire-resisting lining. Profiled steel sheet is classified as 'not easily ignitable' (p) to BS 476 Part 5 and 'non-combustible' to BS 476 Part 4. Profiled steel sheet without a finish can be graded as Class 0 surface spread of flame classification. For classification of sheets with proprietary coatings, the manufacturer should be consulted and if required a test certificate obtained.	Profiled aluminium sheet cladding has no fire resistance as defined in BS 476 : Part 8. It is classified as 'not easily ignitable' (p) to BS 476 Part 5 and 'not combustible' to BS 476 Part 4. Aluminium sheeting with mill finish can be graded as Class 0 spread of flame. For classification of sheets with a proprietary coating it would be necessary to obtain a test certificate from the manufacturer concerned. Obviously it can be used as a total fire-resistant construction with a suitable back-up material.

Table 5.2 Thermal performance – typical U-values

Material	Construction	U-value (W/m²°C)
Steel	1. Plastic-covered steel sheet	5.7
	2. As 1, but with cavity and aluminium foil-backed plasterboard lining	1.9
Aluminium	1. Bright surface inside and outside	2.6
	2. Dull surface outside, bright surface inside	2.8
	3. As 1, but with cavity and aluminium foil-backed plasterboard lining	1.8
	4. As 2, but with cavity and aluminium foil-backed plasterboard lining	2.6

Position of fixings

Using metal sinusoidal sheeting, primary fixing should be made through the crown of the corrugations. However, using trapezoidal metal sheeting, fixing in the crown of the profiles can cause spreading of the sheets and damage to the metal, and thus it is normally advisable to fix in the troughs (Fig. 5.22). Maximum fixing centres are 450 mm or every third corrugation, whichever is the less.

Secondary fixings secure one sheet to another so as to exclude wind and rain and provide continuity from sheet to sheet for the dispersion of applied loads. For wall claddings the shear strength of fixings in the centre of the crown is usually adequate, provided that they are no further than 500 mm apart. In some cases it may be possible to provide secret fixings at the side laps between sheets (Fig. 5.23).

Types of fixing

Primary fixings attaching metal cladding to steel rails are commonly self-tapping screws (Fig. 5.24).

Blind light rivets are usually used for secondary fixings in metal claddings. For steel sheeting, cadmium-plated Monel metal rivets should be used, not cadmium-plated mild steel. Rivets in aluminium sheeting should be aluminium alloy (Fig. 5.25).

Cartridge-assisted fasteners, as shown in Fig. 5.26, are used to secure metal roof deck units, but are not used where watertightness relies upon careful tightening against a washer seal, such as is required when fixing roof and wall cladding sheets. Welded or screwed stud fixings for impaled sheets should not be used for metal sheet cladding.

For the aluminium roof sheeting at Stansted Airport the sheeting was fixed to the supporting steelwork on the ground. Because of the improved
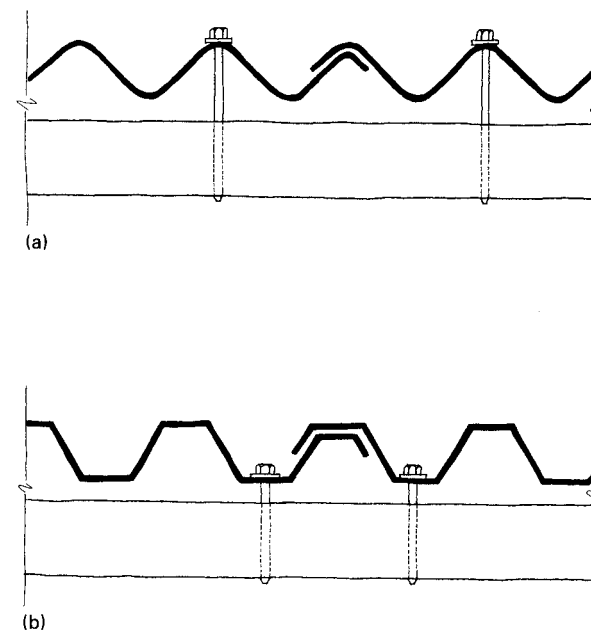
5.22 Fixing positions using steel or aluminium sheets: (a) crown fixings for sinusoidal sheeting; (b) trough fixings for trapezoidal sheeting.

(a)

(b)
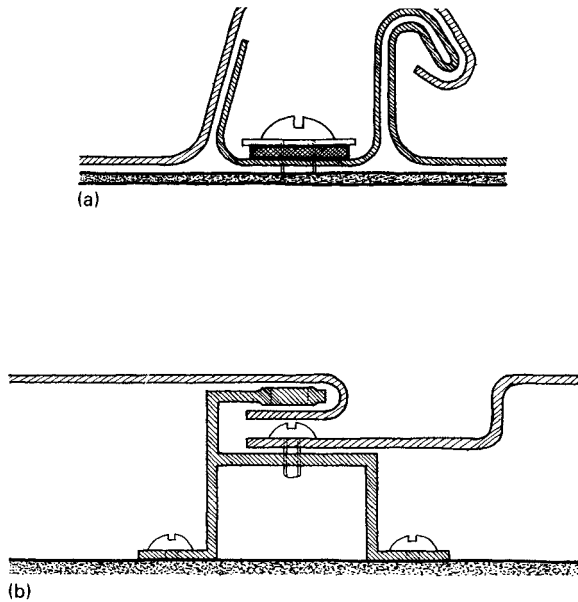
5.23 Examples of side-lap joints with secret fixings: (a) fixings without accessory section; (b) fixing with accessory section.

(a)   (c)

(b)   (d)

5.24 Examples of self-tapping screws: (a) 12 point plastic head type 'Z' cone-pointed screw with sealing ring to BS 1494 Part 1 17; (b) modified version of (a) with load-spreading head; (c) modified version of (b) with spacing collar; (d) self-drilling screw.

quality control available with visual inspection at ground level, fixing through the trough of profiles was possible (Fig. 5.27).

Sheet cladding may fail at the fixings, either by pull-through or by failure of the fixing itself. Fixing should therefore be specified to include nuts, washers and weather-seal devices, all preferably from the same manufacturer.

Compatibility with other materials

Compatibility with other materials is also an important consideration, particularly when using aluminium.

Aluminium is particularly susceptible to electrolytic corrosion with dissimilar materials. With an organic coating, it is liable to attack if pierced or cut, and anodized aluminium is as susceptible as the untreated metal. There is no corrosive action between aluminium and zinc or between zinc coatings and galvanizing.

Aluminium sheeting, whether organically coated or not, suffers attack from many building materials. Direct contact should be avoided by good detailing and efficient drainage to prevent water run-off. If unavoidable, the protective measures listed in Table 5.3 can be taken.

Hot-dip zinc-coated steel suffers moderate attack from copper alloys, iron, steel, some timbers, cement, concrete, plaster, asbestos cement, copper-bearing paints and stainless steel, particularly if water run-off from material onto this cladding occurs. Direct contact should be avoided by good detailing, and efficient drainage will prevent run-off.

Rivet in drilled hole
before drawing

Rivet after drawing
and stem snapped

(a)

(b)
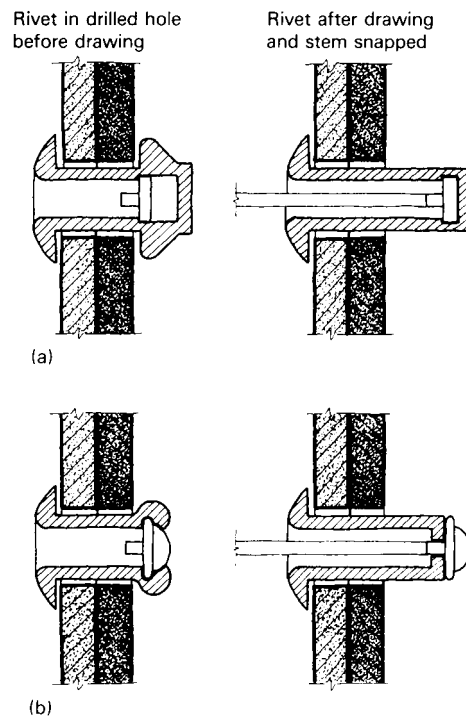
5.25 Rivets for secondary fixings in metal cladding: (a) pop rivet; (b) sealed-end rivet.

Table 5.3 Protective measures for aluminium sheeting

Copper alloys	No protective measure possible; avoid direct contact and water run-off from copper onto aluminium, unless organically coated.
Iron and steel	*Direct contact.* Unless organically coated, use non-aggressive protective paint, e.g. zinc chromate. Avoid copper-bearing paints. In industrial and marine atmospheres, use non-rotting chromate insulating tape. *Water run-off.* Paint iron, galvanize and paint steel (non-copper-bearing, non-aggressive paint).
Lead	Unless organically coated, avoid contact and run-off.
Timber	Compatible non-copper-based preservative (see CP 1430) bituminous paint or felt or building paper.
Boards	Moisture barrier, such as building paper or polythene.
Concrete, plaster, asbestos cement	Bituminous paint and felt insert between contact surfaces.

Organic coatings on hot-dip zinc-coated steel are unaffected by all common building materials, unless they are cut or pierced, when they behave similarly to hot-dip zinc-coated sheet.

Joints between sheets

Side laps of one corrugation will generally prevent driving rain passing through the outer cladding, but when exposure is 'severe' (e.g. in areas with a driving rain index of 7 or more) an increased lap may be needed (Fig. 5.28).

Side laps may sometimes need to be increased locally to avoid cutting sheets at corners and openings.

Plastic washer compressed when screw is tightened into plunged hole

Snap-on plastic cap

5.26 Cartridge fasteners for metal cladding.

Such laps are easy to increase with regular profiles, but are difficult with irregular profiles and sheets with bonded insulation.

End-lap joints on walls will normally be 100 mm, and on roofs 150 mm, but when exposure is severe the end-lap should be increased to 200 mm.

Sealing of lap joints with mastic is generally not used in vertical sheeting for weather protection. However, sealed side-laps are required for pitched roof-cladding below 15° pitch (Falconer, 1981). Swedish building practice HusAMA also recommends weather seals for profiled sheet roofing for pitches below 14°, and requires side-laps to be joined with screws with washers to protect from leakage, or rivets maximum centre-to-centre 500 mm. Corner details are an important design consideration. Figure 5.29

5.27 Aluminium roof sheeting at Stansted Airport, fixed on the ground and lifted into position as complete assembly.

(a)

(b)

(c)
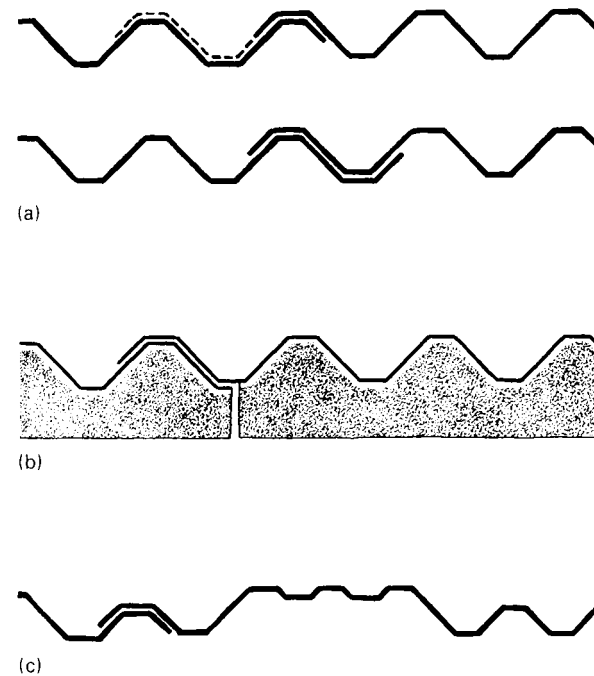
5.28 Side-laps between sheets. (a) Maximum flexibility in side-laps is provided by sheets with uniform troughs and half-corrugations. (b) Standard sheets with factory-bonded backings do not permit variations in side-lap. (c) Sheets in which corrugations are not uniform do not allow variations in side lap.

shows various ways of turning a corner using flashings. Over-sheet corner flashings usually need to be wide in relation to the profile of the main cladding and tend to conflict with it in scale. Appearance and weather-
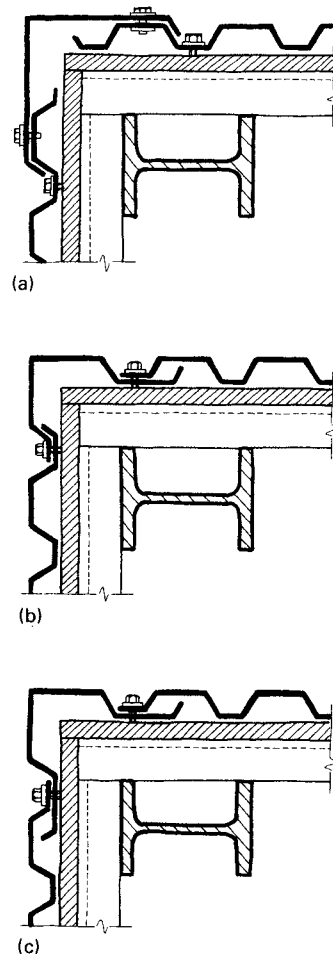
5.29 Various methods of corner detailing using flashings: (a) over-sheet corner flashing; (b) over- and under-sheet corner flashing; (c) under-sheet corner flashing.

ing are improved by inverting the edges of the angle, but this allows little flexibility in positioning the sheets with the profile shown. Curved-over-sheet corner flashings can also be used.

Using over- and under-sheet corner flashings, these can be shaped to match the profile of the main cladding. The upturned lip of the main cladding is also covered, offering a better water check.

With under-sheet flashings, in order to avoid the exposure of an upturned lip, one of the cladding sheets has to be reversed. The length of the under-leg of the flashing offers some tolerance in the assembly. In some cases the sheets are butted against the steel frame and the frame exposed at the corner (Fig. 5.30).

With horizontal cladding, various corner-joint details have been used including welded corners and special GRP closer ends with matching finish, as used at IBM Greenford (architects: Foster Associates). Tolerances in manufacture and assembly are even more critical with horizontal cladding, because any misalignment of the profiles can cause apparent waving. Slip trays can also be used at the joints between horizontal cladding; however, it is sometimes difficult to match the profiles exactly, and the thickness of the slip tray tends to make the edge of the sheet more obvious in appearance.

Profiled sheeting is best used in well-proportioned large areas, to enclose the main structure with the minimum of joints with other materials. Translucent sheets are available to match most profiles. If opening lights or transparent areas are required, sheets of patent glazing are better than small isolated windows, because they relate more naturally to the scale of the main cladding and reduce the problem of jointing around window openings.

Butt-end joints between sheeting and windows are normally made with Z-flashings or propriety neoprene sections (Fig. 5.31).

5.30 Corner detail with exposed steel frame.

5.31 Neoprene flashing at window opening.

Sheeting rails and liner trays

The optimum use of sheeting rails to support profiled cladding is critical to the economic use of the material and its capacity to withstand wind loading. Constrado (1980) shows typical spans of around 2 m for profiled steel cladding, depending upon its profile. Thus sheeting rails are required at intervals up the height of the wall to support the cladding. These sheeting rails must themselves be designed to span between the main support columns (Fig. 5.32).

As an alternative to sheeting rails, liner trays can be used, which when clipped together (Fig. 5.33) act as horizontal rails at 500 mm intervals. The interaction of cladding and liner trays provides a composite lattice effect. Mineral fibre insulation can be pushed into the

5.32 Sheeting rails are needed to span between main supports.
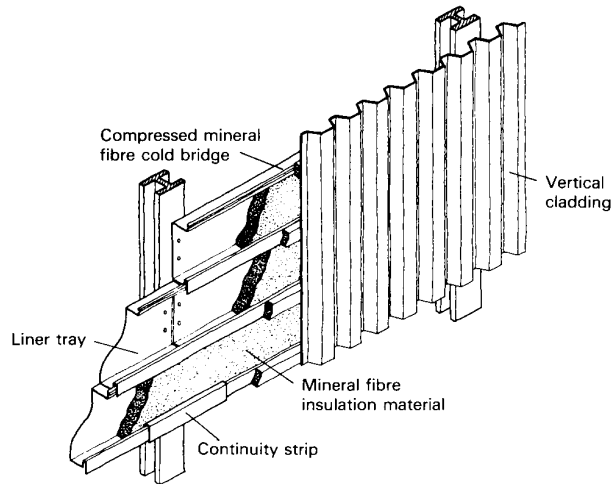
5.33 Liner tray assembly.

liner trays from the outside before the outer profile cladding is fixed. The flat surface of the liner tray, which can be prepainted, then acts as a finished inner lining to the construction. The liner can either be used horizontally as described above, or vertically, used in conjunction with horizontal profiled cladding.

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6

Sheet metal, composite metal panels and rain screens

> The idea is to create a flexible framework, a framework which embraces the floor, the walls and the ceiling so that within that framework the plan is completely changeable.
>
> *Norman Foster (1978)*

Introduction

In architecture the father of pressed metal panel systems, *le panneau*, is undoubtedly Jean Prouvé. Many such panel systems were developed by Prouvé including his early use of metal composite panels at the Aero Club Roland Garros in 1935 and the facade designed for Cours Conception Construction, an industrialized school building system designed in 1963 (Huber and Steinegger, 1971).

In the 1950s the stainless steel clad Airstream Caravan became a twentieth century icon of pre-fabrication. Prefabrication predominantly takes two structural forms: **monocoque shells** and **framed construction**. Renzo Piano's design for the Fiat VSS experimental vehicle (Fig. 6.1) showed the application of a structural frame and clip-on plastic cladding to car manufacture. Most composite cladding systems in building have been developed for use as spanning between framed construction.

Early examples of metal cladding systems, mainly in the USA and France, usually consisted of metal undersill panels mounted into curtain walling assem-
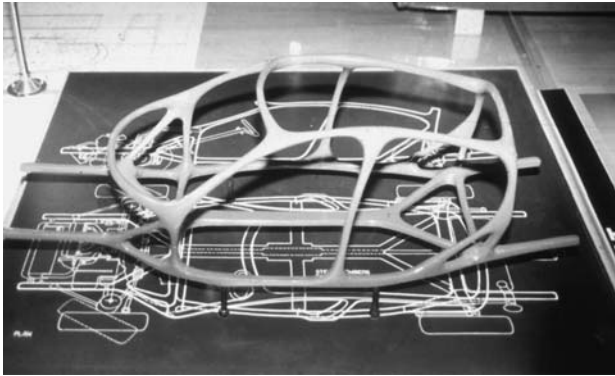
6.1 Fiat car by Renzo Piano.

6.2 Typical metal cladding system in the USA.

blies known in the USA as 'stick' systems, or in France as *la grille*. In this way a continuous curtain wall could be used, with the metal, solid (non-glazed) panels masking the floors and columns. Such infill panels were often small in size (typically 1.75 m long × 0.75 m high), and were often pressed into a decorative or embossed profile. During the 1950s such systems were in widespread use in multi-storey buildings, typified by the rigid chequer-pattern facades produced by the exposed curtain walling framework (Fig. 6.2).

Aesthetic objections to this form of facade, together with improved legislation on energy conservation and insulation, encouraged architects to consider complete panel assemblies, in which the solid, insulation and opening elements are fabricated on subframes in the factory and transported to the site and erected as one unit.

There are essentially four types of sheet metal and composite panel system (Fig. 6.3):

– rolled flat sheet panels mounted onto a supporting framework;

– box-type panels (including proprietary panels), usually with foamed cores;
– laminated panels;
– rain screen panels.

The second and third types can be considered as composite metal panels.

Composite metal panels

A combination of predictable thermal and structural performance quickly led architects to see the benefits of using composite metal panels. Composite construction is the bonding together of layers of materials to form a rigid structure. The Mosquito bomber (Fig. 6.4) was an early example of composite construction in aircraft design. Composite construction is now extensively used in products as diverse as tennis rackets and jet aircraft. The principal form of composite construction is two thin sheets held apart by a lightweight core to which they are bonded. It is the spacing of the two sheets that is mainly responsible for the rigidity of the final composite: the wider the spacing, the greater the spanning capabilities of the finished product. Early developments of composite steel panels in the UK included the panels for the

Foamed Panel

0.7 mm

Rainscreen

2 mm

Laminated Panel

0.5 mm

0.7 mm   Edging

Fabricated Panel

2–3 mm   Loose Insulation   Weld
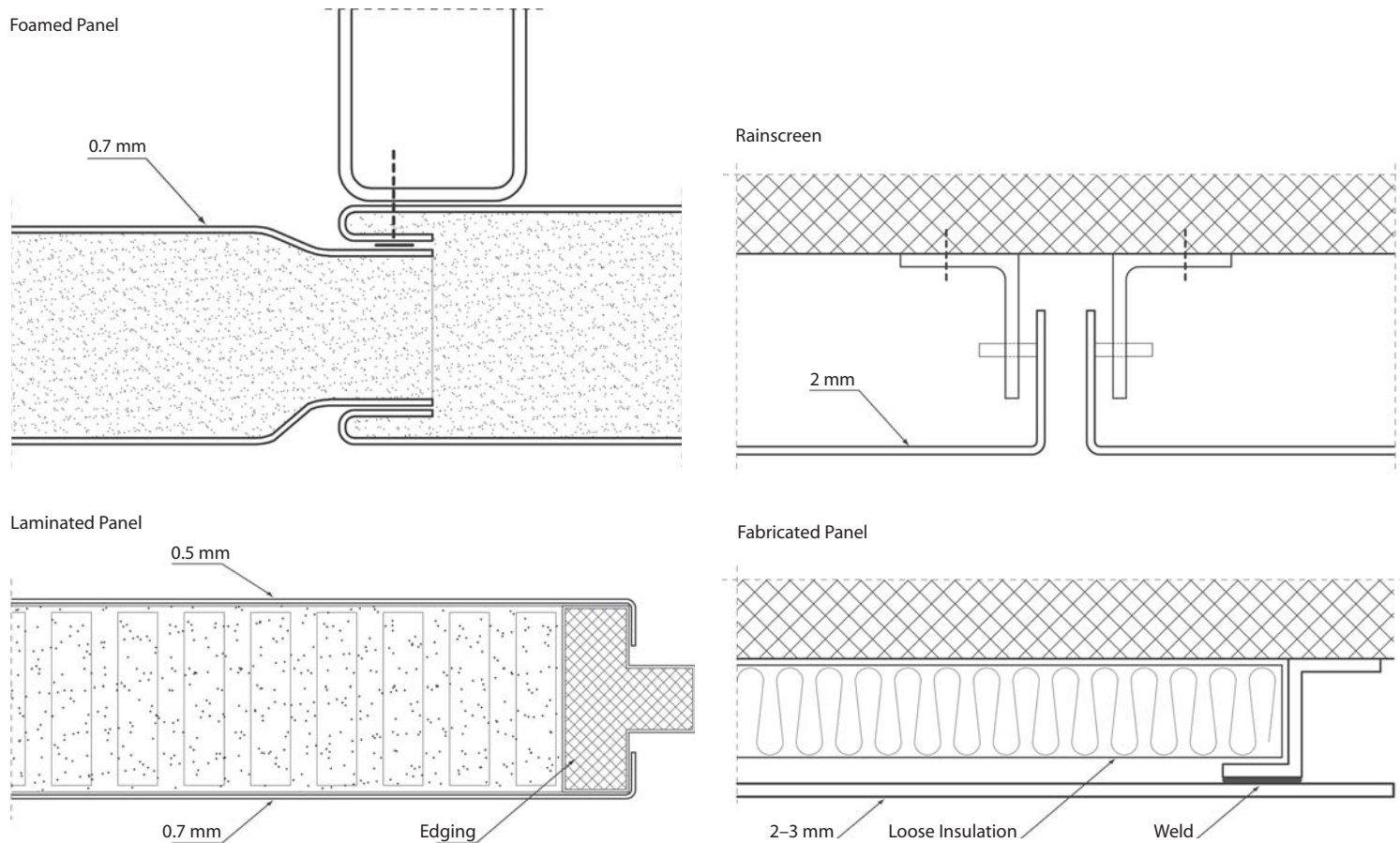
6.3 Types of metal cladding system.

6.4 Mosquito bomber.

Oxford Regional Hospital Board System, 1963–73. A gasket joint designed by Jan Silva was based on a jointing principle developed by Jean Prouvé in which a neoprene gasket fixed to a steel channel is compressed against the panel profile by bolts at intervals up the height of the panel (Fig. 6.5).

Some difficulties were experienced in the foaming of the polyurethane insulation of these panels and in ensuring the integrity of the skins and the core material. The panel system was later abandoned in favour of a more conventional horizontal profiled high-tensile steel cladding with site-applied insulation.

The economics of using metal composite units depend upon standardization of unit sizes, and it is perhaps not surprising that their use tends to be associated with a system of coordinated dimensions. For example, during the 1970s, development in open system tendering by local authority consortia schools programmes, such as the South Eastern Architects Consortium (SEAC Mark 4), encouraged the

6.5 Oxford Regional Hospital Board joint (plan and section).
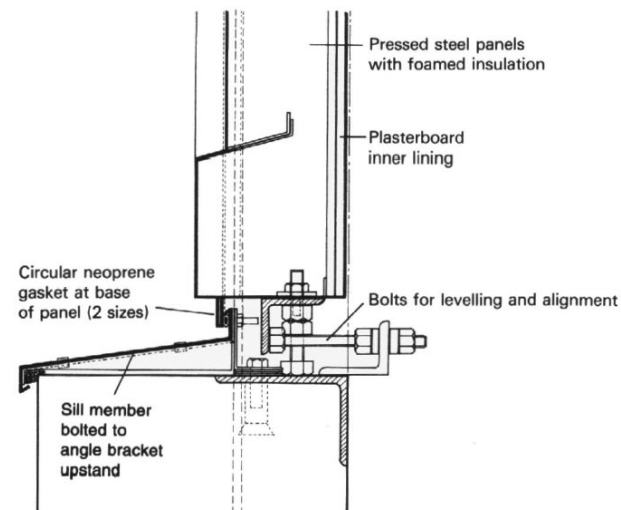
production of pressed metal panels mounted within a steel 'third member' subframe. Such panels were manufactured by Gordon Durham Aycliffe Ltd as Conatus panels, and by Brockhouse Lightform for SEAC Mark 4. These panels are no longer marketed, probably because they proved to be too expensive in comparison with other cladding materials when used for the variety of panel sizes required for school buildings.

The use of proprietary composite panels for industrial buildings has been more widespread, where standard-width panels are bolted back to a simple structural framework, and where the facade has no, or only a few, windows. Typically a facade unit of this type consists of a profiled sheet, thermal insulation and an internal lining, either produced as a composite unit in the factory or assembled separately on site (Fig. 6.6).

The Sainsbury Centre (Fig. 6.7) designed by Foster Associates in 1977 was one of the first uses of Superplastic aluminium for insulated composite panels and, more importantly, was one of the first non-commercial, non-industrial buildings to use an interchangeable panel system. Identical 1.8 m × 1.2 m panels were used for both walls and roof, with the weatherproofing joint detail dependent upon the neoprene gasket being mounted back against an aluminium carrier system.

The panels were manufactured by Superform Metals ITC Worcester using vacuum-forming techniques, from a special alloy patented by the British Aluminium Company. This 'supral' alloy has the advantage over conventional aluminium alloy that it will flow or 'run' at the right temperature, and can be extended to ten times its original length. However, the process of manufacture is slow and costly, and some technical difficulties were experienced at first in forming the corners of the panels. Each outer tray was filled with 100 mm phenelux foam (curved decorative sections

a

b

c
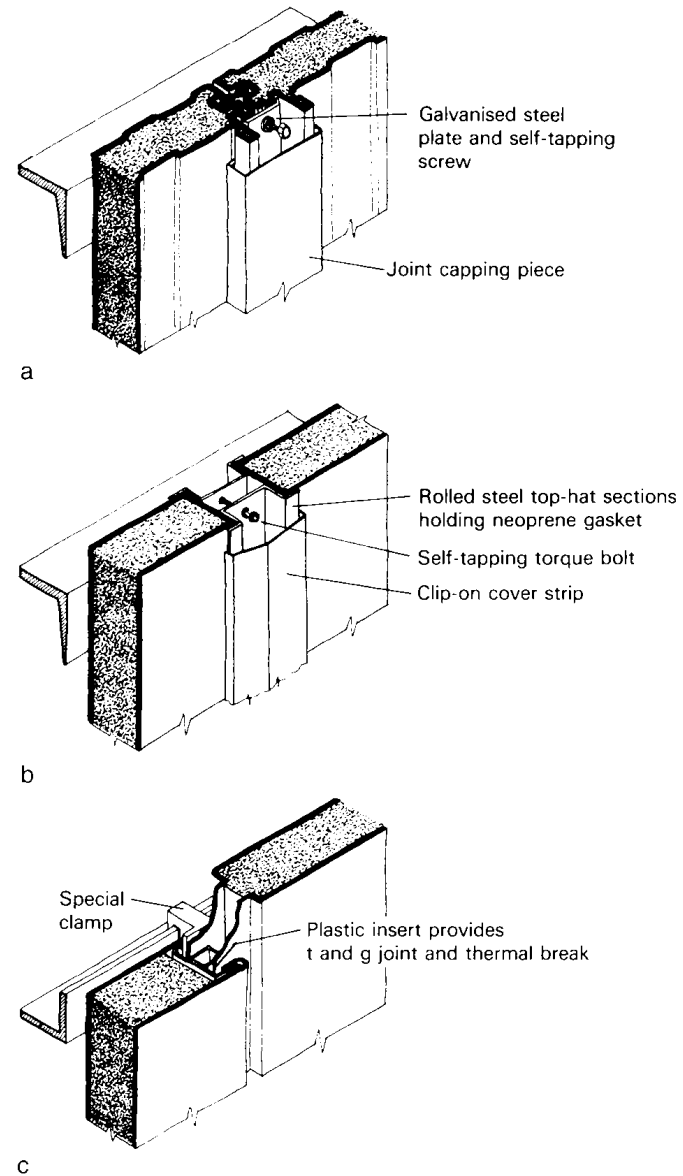
6.6 Early examples of proprietary box-type panel joints: (a) Briggs Amasco Perfrisa; (b) Booth-Murie Simplan 1200; (c) Hunter Douglas Luxalon.

6.7 Sainsbury Centre panels (architects: Foster Associates).

being filled with polystyrene), and the inner skins were then pushed into the outer trays and pop-riveted together through a small section of phenolic foam core, which formed the thermal break at the edge of the panel. Thermal transmission of the panels was $U=0.47$ W/m²°C. For a detailed study of this construction see case study 22 in Brookes (1985).

The aim was to produce a U-shaped one-piece continuous ladder gasket, which fitted into an aluminium carrier system by Modern Art Glass, forming not only the main seal but also the guttering system (Fig. 6.8). These neoprene gaskets were manufactured by the Leyland and Birmingham Rubber Company as a lattice framework with two-way joints at mid-points of the overhang vulcanized on site using portable equipment (Fig. 6.9). In this way an interchangeable system of wall and roof panels was achieved. A similar

principle of continuous neoprene gaskets was later used at Gatwick Airport North Piers (Fig. 6.10).

The original panels on the Sainsbury Centre failed for a number of reasons and have been replaced by a flat composite panel by H. H. Robertson, which does not have the architectural effect of the original panels, nor is the replaced jointing gasket used in the same consistent way.

Composite panels were also used by Foster at the Renault Centre (Fig. 6.11), where 75 mm thick panels span 4 m between the vertical cladding support. The panel system, which was bolted to the vertical cantilevered columns by three fixings at each end of the panel, provided a very low-cost elevation. A large neoprene skirt takes up the deflection at the top of the assembly (Fig. 6.12). For further details of the construction see case study 21 in Brookes (1985).

Aluminium split carrier system bolted to main steel truss structure

Neoprene gaskets double as rain-water channels

Pop rivets

Captive bolt fixes panel back to carrier system

Termal break

Polyisocyanurate foam core

Outside

1800 x 1200 x 75mm superplastic aluminium panels

6.8 Detail of joint at Sainsbury Centre.

6.9 Lattice gaskets used at Sainsbury Centre.

6.10 Assembly of panels at Gatwick Airport North Piers.

There are now essentially two types of composite panel. These are:

foamed polyurethane panels:

—   continuous production;
—   batch production;

laminated panels:

—   continuous production;
—   batch production.

Insulation cores

Different types and thickness of sheet material and foam can be used for the insulation cores for composite panels. These are:

—   mineral wool;
—   honeycomb paper core;
—   bead polystyrene rigid sheet;
—   IB polystyrene rigid sheet;
—   polyurethane foam (polyisocyanurate is a modified form of polyurethane to improve fire retardancy).

6.11 Panels at Renault Centre.

Polystyrene sheet, which is produced by heating up polystyrene granules and fusing them together with a combination of steam and pressing, is cheaper in material cost than polyurethane foam. However, polyurethane gives better insulation than polystyrene (25 mm thick polyurethane has the same insulation value as 40 mm thick polystyrene; see Fig. 6.13) and it is easier to manufacture. Most manufacturers of box-type proprietary panels prefer to use polyurethane or at least its modified version, polyisocyanurate, which is sometimes used because of its fire retardancy.

The use of any particular type or thickness of core depends upon the stiffness required of the whole panel and the requirements for thermal and acoustic performance. In general, for foamed materials, the

higher the density the stiffer the panel, and the lower the density the better the insulation value. Note that modern foam production is now CFC-free as it no longer uses freon gas as a foaming agent.

Foamed polyurethane panels

The market for foamed polyurethane panels was estimated (1996) as 2.3 million m^2 in the UK, 7 million m^2 in Germany and 12 million m^2 in Italy, of which only a small percentage, say 5%, are made by batch production using vertical or horizontal foaming. The majority are made on continuous foaming lamination lines by such companies as Hoesch (Germany), Elcom (Italy), Forges D'Haironville (France), Kingspan (UK) and Perfrisa (Spain).

Polyurethane and polyisocyanurate foams can be foamed in place during the production, by:

—   continuous foaming;
—   vertical pouring; or
—   horizontal pouring.

Becker (1968) gives more details of methods of in-place foam production and other detailed considerations for sandwich panel design. Profiled sheets of metal with polyisocyanurate backing are often produced on a continuous process (Fig. 6.14). Surfactants are necessary to ensure a closed cell and to maintain the quality of the foam (Fig. 6.15).

Although well-insulated buildings help to reduce energy consumption, and indirectly limit carbon dioxide emissions by decreasing the amount of heating they require, increasing concern over the potential effects on the ozone layer of CFC gases used as foaming agents has led to a review of the materials and their manufacturing processes, resulting in the Montreal Protocol. Now producers of foamed polyurethane offer foaming formulations containing blowing agents

such as HCFC141b. Early use of carbon dioxide blowing agents to reduce the effects of CFCs caused problems due to temperature variations on flat panels. It was also more difficult to use carbon dioxide blowing
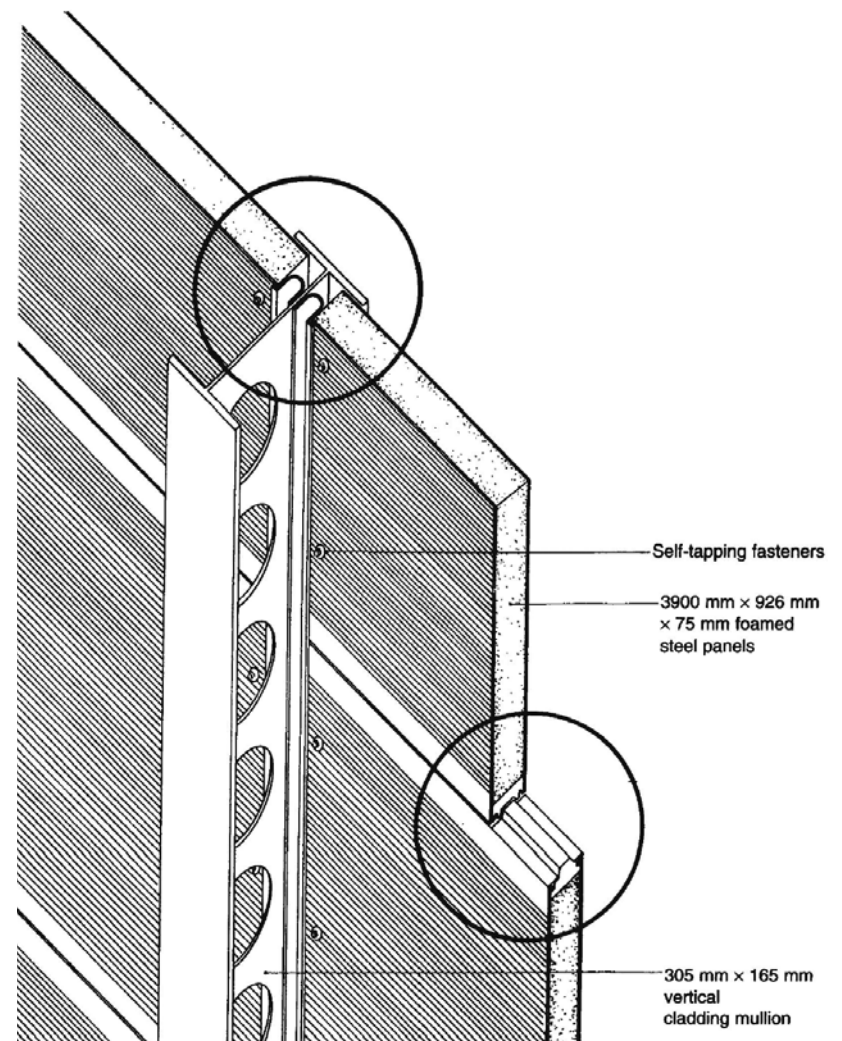
6.12 Detail of panel at Renault Centre.
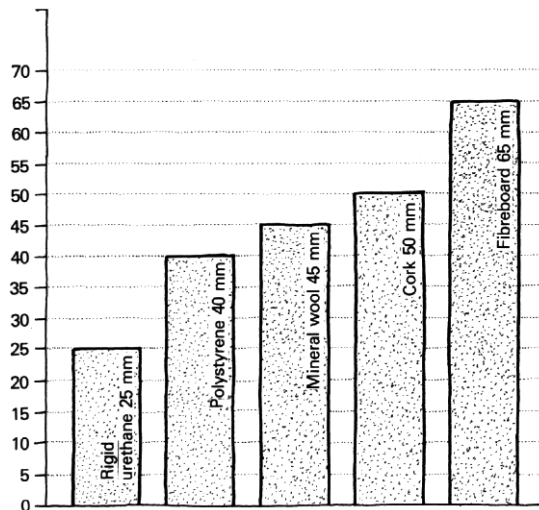
6.13 Relative insulation performance of different core materials.

6.14 Typical continuous foaming line.

agents with polyisocyanurate foams, which had been introduced for their improved fire resistance.

Development work is still continuing on new foam formulations to improve the efficiency of the manufacturing process. One difficulty for the manufacturers of foamed panels in changing the foaming agents used is that these modifications can result in slower production rates and a slight reduction in thermal performance. In theory, panels with modified foamed cores would need to be thicker and therefore potentially more expensive. Inherent in the manufacture of continuous foamed panels is the need to control density to maintain compressive strength. In laminating sheet core materials, it is the adhesion between the core materials and the skins that gives the panel its strength. The bonding therefore has to be undertaken in conditions of strict quality control. In recent years, manufacturers have understood the importance of good bonding, and they now check the temperature, humidity and coat weight of the adhesive

during production as part of their BS 5750 quality management procedures. Following production, checks are made on the strength of the bond to the panel skin, and samples from each production run are tested to destruction.

Foamed panels can also be made by batch production on individual foaming lines (Fig. 6.16), but the most economic production is achieved using a continuously operating line foaming plant. On a continuous horizontal line, which can now produce high-quality panels at a speed of 7 m/s, there is no limit to the length of the panels other than that imposed by the means of transportation and the individual manufacturer's method of fixing and panel configuration. Panels can now be transported on articulated trailers up to 30 m long, and typically panels are 6–12 m long. The width of coils of metal has increased in
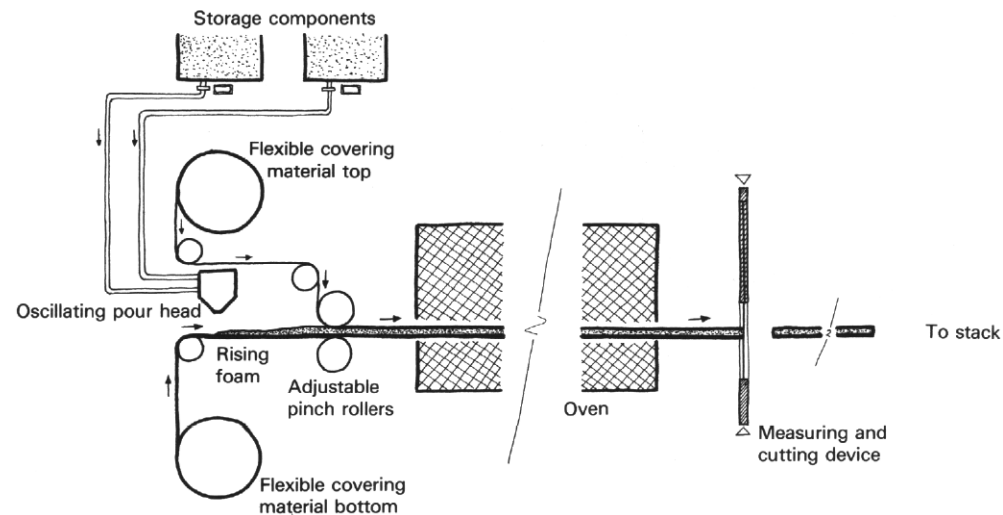
6.15 Diagram of continuous foaming process.

recent years, so that steel panels can now be produced up to 1300 mm wide and aluminium up to 1500 mm. Foamed panels produced in a vertical-injected foaming press are normally limited to 600 mm high to control the density of foam over the width of the panel (Fig. 6.17).

Laminated panels

Laminated panels using sheet core materials of extruded or bead polystyrene are increasingly used on more sophisticated 'architectural' buildings. Integrated systems, including composite panels, are supplied complete with doors, windows and louvres. It is noticeable that the divisions are becoming increasingly blurred as the sectors of the market change shape. Manufacturers with previous experience of volume markets are now asked to provide the management expertise to control all stages of the process, including quality control and transportation, and to offer specific

guidance on the performance criteria, leading to a more accurate specification for their use within the system market. This process relies on changes in attitudes towards technical specifications and quality control, and a requirement for design input from the manufacturers that may be beyond their present resources. Batch-produced sheet core manufacturers using platten presses (Fig. 6.18) and vacuum presses (Fig. 6.19) concentrate on wall panels only.

Large laminated panels (up to 7 m × 2.5 m) can be pressed together under heat using a platten press, on which a number of panels can be made up from trays, sheet insulation, edging pieces and backing sheets, and stacked together before pressing. The typical lamination process is where the outer aluminium sheet is brake pressed and welded into a dish. Into this is placed a honeycomb core with a further aluminium sheet forming the inner lining. The complete assembly is bonded together with a neoprene or timber edging

6.16 Batch production of foamed panels – horizontal foaming.

6.17 Batch production of foamed panels – vertical foaming.

and placed in a large platten press (Fig. 6.18). In this way laminated panels can be produced up to 2.5 m × 7.0 m long.

Vacuum presses (Fig. 6.19) can also be used to press laminated panels, but because the panels are pressed not more than two at a time the production may be slower; producing sandwich panels with either a mineral fibre, polyurethane or honeycomb core up to 1.6 m × 6.0 m long is standard, and larger sizes may be possible after consultation.

Panels can also be laminated using large 'nip' rollers. Using pressing techniques it is possible, with care, to apply a finish prior to fabrication.

Curved panels can be produced, in one direction only, by cold rolling or pressing. Panels curved in three dimensions can be produced by deep-drawing techniques. Curved laminated panels (Fig. 6.20) will inevitably cost more than flat panels, as special forms are required to press the panels, which will increase their cost of production.

Panels using insulation boards have the advantage of batch production, allowing the production of a range of bespoke sizes with variable cores. The laminated cores can include bead polystyrene and extruded polystyrene, polyurethane, Rockwool Lamella and Foamglass. Bead polystyrene, often used in packaging, does not require a blowing agent, and is available in large size sheets, 1.2 m × 8 m nominally. However, it does have disadvantages: its thermal conductivity (k value 0.034–0.037 W/m K), shrinking immediately after manufacture, and its moisture-permeable open cell structure. Extruded polystyrene has a closed cell structure, is moisture resistant, and of a controlled density with a k value of 0.030–0.035 W/m K. Producers of extruded polystyrene now use HCFCs as foaming agent. These materials contain hydrogen and consequently have a much reduced ODP (ozone depletion potential). Polyurethane, which

also has a closed cell structure, uses HCFCs to achieve a *k* value of 0.025 W/m K.

Mineral wool and honeycomb paper core, which normally contain polystyrene inserts within the core, are used for laminated panel production. The honeycomb core has the advantage that adhesive collects in the holes and offers good adherence to the panel skin. Additional acoustic performance, particularly where improved sound reduction at low frequencies is required, can be obtained by increasing the mass of the panel and laminating asbestos cement sheet and high-density mineral wool into the panel.

The integral strength of the metal and core allows the use of a thinner sheet of between 1.2 and 2.0 mm. Often the outer skin of the panel is brake pressed and shaped prior to being pressed, and the edges of the panel are reinforced with edging pieces of neoprene, or timber or even foamed glass. It is not unusual for these sandwich panels to be mounted within a steel or aluminium carrier system, using a capping piece and neoprene gasket to support the panel along its four edges.

The process of pressing these thinner sheets and bonding them to the rigid insulation usually provides a flatter panel than can be produced by rolling the sheet material.

An early use of pressed panels using 64 mm of mineral fibre insulation board sandwiched between two layers of 16 gauge aluminium on 6 mm of asbestos sheet was at the Danish Embassy, London (architects: Arne Jacobsen Dissing and Weitling) (Fig. 6.21).

Laminated sheets can be manufactured as thin infill panelling, 6–10 mm thick, such as Alucobond, manufactured by Swiss Aluminium Ltd, which consists of two sheets of aluminium (Peralumen NS 41), each 0.5 mm thick, bonded to a low-density polyethylene core. The exceptional flatness and stiffness of these thin panels makes them ideal for use with glazing
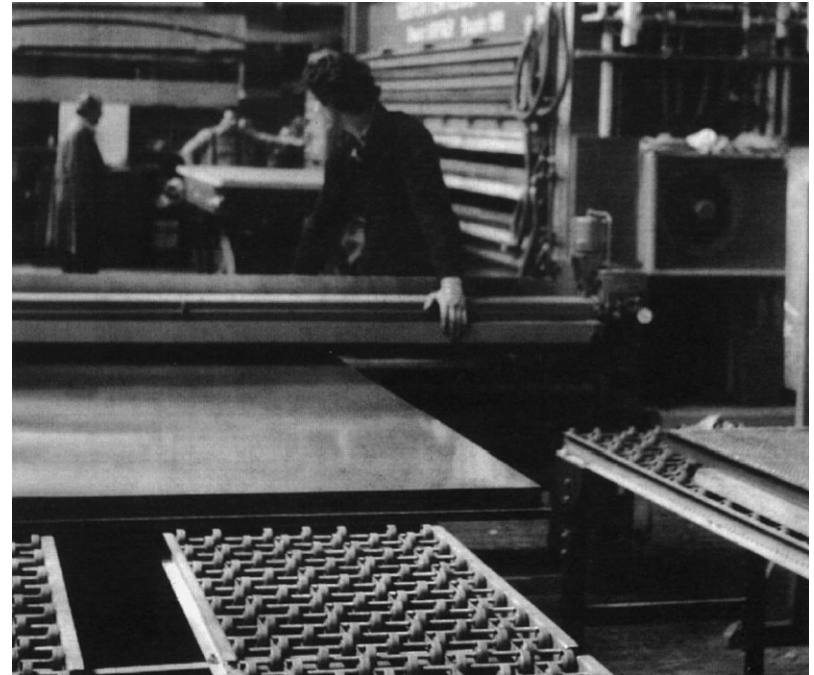
6.18 Laminated panel production using platten presses.

6.19 Laminated panel production using vacuum presses.
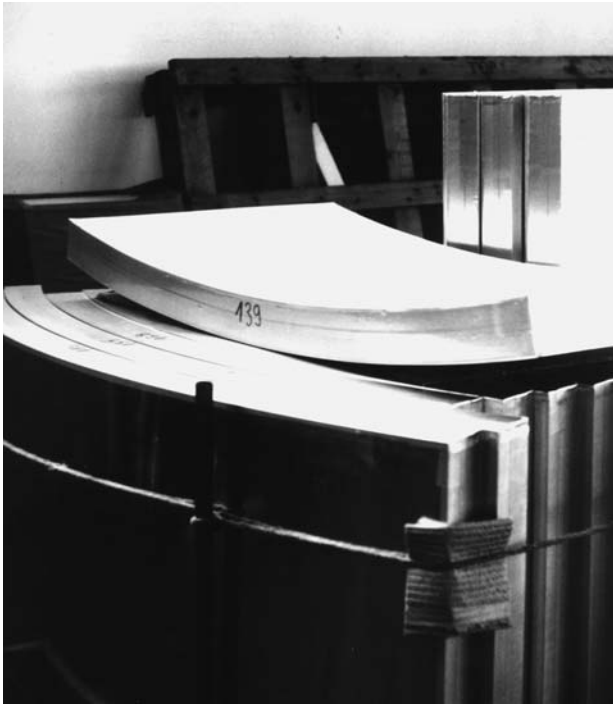
techniques. For example, 2.4 m × 1.25 m panels at Winwick Quay factory, Warrington (architects: Nicholas Grimshaw Partnership) are supported by a 150 mm × 25 mm extruded aluminium presslock system by Modern Art Glass (Fig. 6.22). For a detailed study of this construction see case study 30 in Brookes (1985).

Alucobond can be curved to a minimum radius of approximately 10 times the panel thickness; typical curves are 30–80 mm radius.

Adhesives

Bearing in mind the need to avoid delamination, the architect should seek advice from the manufacturer on the best type of adhesive related to the possible stresses that may be set up between the laminations, and to the requirements for heat resistance. Lap shear strength up to 28 000 kPa is possible with some adhesives. The relative costs of the different adhesives may not be significant relative to the total cost of the panel.

6.20 Curved laminated panels.

Aluminium cover plate

MS flat welded to channel

Insulated laminated aluminium panels

Double glazed unit
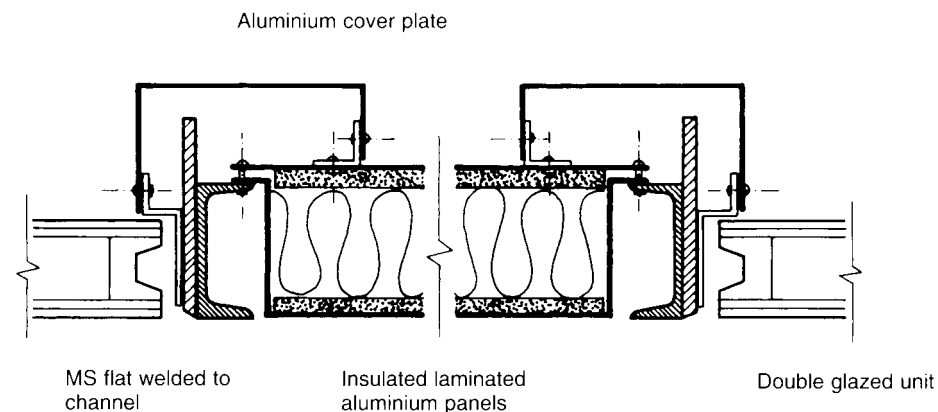
6.21 Plan of laminated panel as used at Danish Embassy, London (architects: Arne Jacobsen, Dissing and Weitling).

There are three types of adhesive in widespread use for the production of laminated sandwich panels:

– neoprene contact adhesives;
– one- and two-part polyurethanes;
– one- and two-part epoxies.

It is sometimes difficult to bond mill-finished aluminium or galvanized steel because of the oxide layer on the surface, which must be removed or strengthened chemically. Although special polyurethanes are available, the problem is better solved prior to application of a thin coat of acid etch primer.

Specification

In the consideration of laminated or foamed production there is a perceived benefit by specifiers, particularly for architectural projects, of the refinement of the joint edge. Batch-produced lamination has some advantage in that a formed edge or adaptor can be introduced on all four sides. However, some manufacturers using continuous foam laminating are beginning to introduce formed stop-ends on their production lines.

Specification of composite cladding is normally carried out by architects/engineers for architectural projects and by engineers for cold store applications. For 'special' projects, cladding consultants or facade engineers are increasingly involved. Generally, there is not enough knowledge by specifiers concerning the types of material used, their performance values or characteristics in use. Specifiers complain of manufacturers' technical data being inadequate. Manufacturers complain that specifiers do not give adequate or informed specifications of their requirements. Users and specifiers increasingly recognize the 'fast track' opportunities of using composite cladding, and are seeking greater variation of products, including their jointing and fixing.

Sound performance is not at present a common requirement, but increasingly manufacturers are being asked to respond to specifications requiring higher degrees of sound performance than 25 dB reduction at 100–500 Hz. Fire performance is becoming increasingly a requirement, led by fire insurance requirements and the Loss Prevention Council. Manufacturers, even of continuous foamed panels, are looking at ways of providing cheap fire-performance panels, while maintaining the same compressive strength and thermal performance as currently required. Test evidence is not normally required by specifiers or users, although most manufacturers would supply evidence of load span tables if required.

In the past, manufacturers conscious of this need for quality have obtained BS 5750 Part 2 registration, and have also obtained Agrément Certificates for products. In some cases they have sought continental certification such as Zalussung certification from the German Institut für Bautechnik. However, with the introduction of new CFC-free formulations, many manufacturers have not sought Agrément certification because of the high cost of testing relative to the small demand for this evidence by the specifier.

Part of the procedure necessary to obtain BS 5750 approval is to show evidence of checking the panels after production, including the bonding of the skins to the cores and the tolerances on size. Typical permissible deviations on dimensions of continuously foamed panels are: length ±4 mm (0–8 mm), thickness ±1 mm, width ±2 mm. Laminated panels, particularly those with PVC-framed edges, can be manufactured to closer degrees of tolerance.

Manufacturers have developed flat panels to meet customer requirements. Curved and cranked
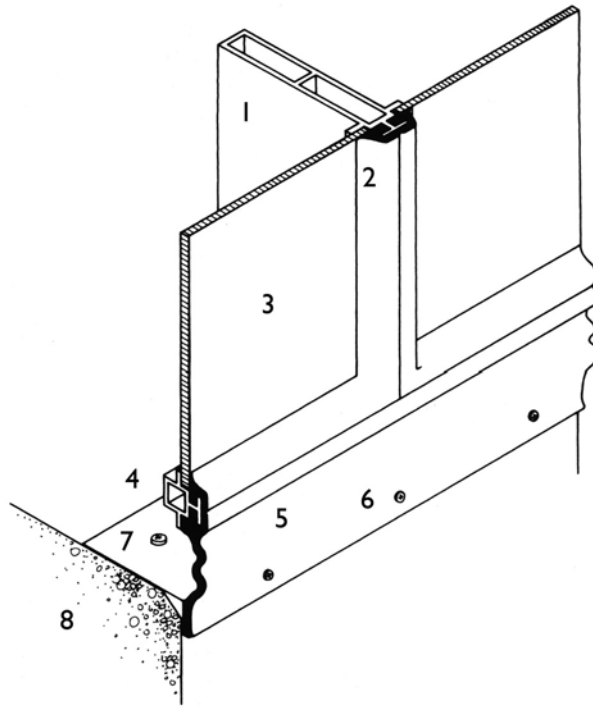
6.22 Alucobond sheets at Winwick Quay, Warrington: (1)
150 mm × 25 mm extruded aluminium cladding mullion spanning
4800 mm vertically; (2) preformed continuous neoprene gasket;
(3) 6 mm anodic silver finished Alucobond; (4) 25 mm × 25 mm
extruded aluminium horizontal cladding rail spanning 1250 mm
between mullions; (5) preformed neoprene tolerance strip; (6) self-
tapping screws fixing neoprene back aluminium sill; (7) aluminium
sill screwed down to concrete slab; (8) 200 mm power-floated
reinforced concrete slab.

shapes are available, allowing freedom of design.
However, no panel can be manufactured perfectly flat.
Variations are caused partly by the foaming or
lamination process. Although it is possible to agree
tolerances for flatness, the degrees of visual flatness can
be minimized by micro-ribbing or embossing of the
panel surface. Some manufacturers of continuously

foamed panels claim to improve flatness tolerance to
0.7 mm over 2 m by controlling the stretch of the
metal skins.

It is the spacing of the metal sheets that is mainly
responsible for the rigidity of the final composite: the
wider the spacing, the greater the spacing capabilities
of the finished product. Typically, a panel with two skins
of 0.6 mm steel and 50 mm of polyurethane insulation
can span up to 4 m. A further advantage is that it can
be used to combine dissimilar materials. Thus durability,
rigidity and insulation can be provided in one product.
It is perhaps disappointing therefore that more con-
sideration is not given to the engineering possibilities
of selecting density in relation to stiffness and per-
missible deflection in the same way that suspended
glass technology (see Chapter 5) has advanced over
recent years.

Delamination

Some composite panels, particularly those with a
foamed insulation core, failed in the past because of
delamination of the outer skin from the insulation to
which they were bonded (Fig. 6.23). This in turn
reduced the spanning characteristics of the panel,
because the materials were no longer acting in a
composite fashion. Tests carried out at the BRE by Dr
R. Thorogood (1979) showed panels that were subject
to this phenomenon, and suggested steps to be taken
to prevent it. Delamination is caused by the sun heating
up the outer skin of the panel, which consequently
expands, while the inner skin remains at a low tem-
perature because of the insulation. An unrestrained
panel will bow outwards to accommodate this exten-
sion, and there will be relatively little stress set up
between the outer skin and the core. However, if such
a panel is fixed to a structure so that its ability to bow
is limited by the fixings, then the stress set up at the
interface of the skin and the core will be considerably

greater, and delamination is likely to occur. The stresses can be reduced if the edges of the panel are free to bend as the panel bows out and are not restrained by the adjacent panels or the method of fixing.

Other factors in design can reduce the effect of this thermal movement, as follows.

- Use light colours on the outer skin to reduce the heat gain on the skin.
- The size of the panel should be taken into consideration. Large panels will deflect more than small ones.
- Fixings in the centre of panels should be avoided.
- The adhesive and type of insulation core should be selected to take account of stresses set up by thermal movement.
- If the inner skin has a higher coefficient of expansion than the outer (i.e. aluminium inner skin/steel outer skin), then the effect of thermal movement will be reduced.

Considerable research has been carried out by reputable manufacturers into the selection of adhesives, insulation cores and specifications of their use. With careful design the issue of delamination can be resolved.

Rolled sheet panels

This type of panel consists of 3–6 mm sheet metal formed into a metal pan on the outside face, either by cutting and welding the metal into a tray or, more usually, by spot-welding angles that form the edge to the tray. The stiffness of the panel thus depends upon the thickness of the metal and the number of stiffening angles (Fig. 6.24).

The panel is supported by a fixing rail or some form of secondary framing, and the insulation is

6.23 Typical example of delamination of composite panels.

6.24 Stiffening angles to rolled sheet panel.

normally applied loosely on site, although in some cases it can be glued to the back of the panel in the factory. The inside face is finished either with another metal sheet or with a conventional interior finish material such as gypsum plasterboard. The essential difference between this type of panel and the other types described is that the insulation and inner linings do not add to the total stiffness of the panel. One problem in manufacturing such panels is that of avoiding the rippling of the surface or 'oil canning effect' and ensuring that the sheet metal is perfectly flat and smooth, which also influences the thickness of the metal used.

In order to allow for thermal expansion of the aluminium rolled sheet, it is now advised that the sheet is not directly connected to the angel framing, but 'floated' onto its supports using Z-section cleats (Fig. 6.25). These cleats are spot-welded to the sheet during fabrication, thus holding it within the frame. Following fabrication, the edges are sealed with a silicone joint. Pins can also be used welded to the back of the sheet onto which the sheets of insulation are mounted.

Many projects in the USA have been constructed using rolled sheet panels. These would include the City-Corp Building in New York (curtain walling by Flour City) and the Richard J. Hughes Justice Complex at Trenton, NJ (architects: the Hillier Group, Princeton), also supplied and erected by Flour City. Such panels were also used at the Federal Reserve Bank building in Boston (architect: Hugh Stubbins), where flanges were welded onto 5 mm plate aluminium, and the Bronx Centre, New York (architect: Richard Meier), where 3 mm aluminium sheet was brake pressed and the corners formed by cutting and welding into a tray. These were mounted onto a secondary framing on site, with insulation and inner linings applied *in situ*. For a detailed description of these projects, see Murphy (1978).

The maximum size of rolled sheet panels tends to relate to the size of sheets available (normally 1.5 mm width maximum), and the weight of units when assembled. Panels at the Bronx Centre, which were mainly 3.45 m wide × 0.75 m, 1.5 m and 1.35 m high,
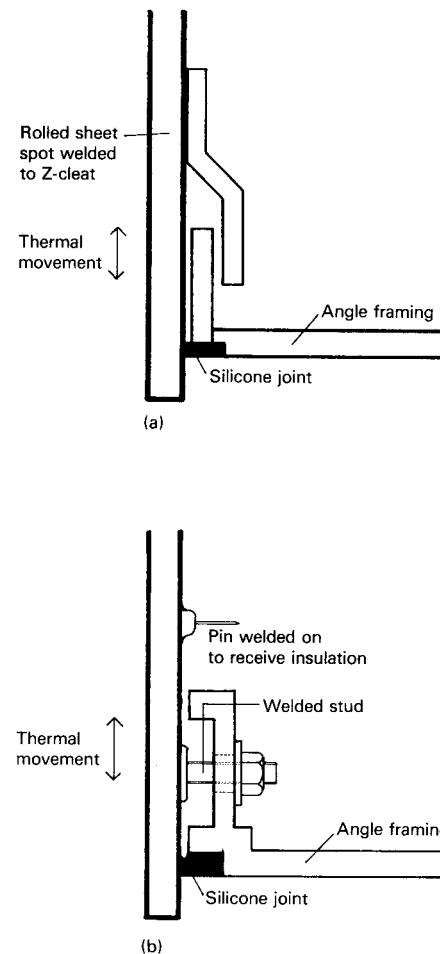
6.25 Alternative methods of fixing angle framing to rolled steel panels: (a) Z-section cleat spot-welded to sheet; (b) welded stud on outer sheet with slotted holes in angle framing.
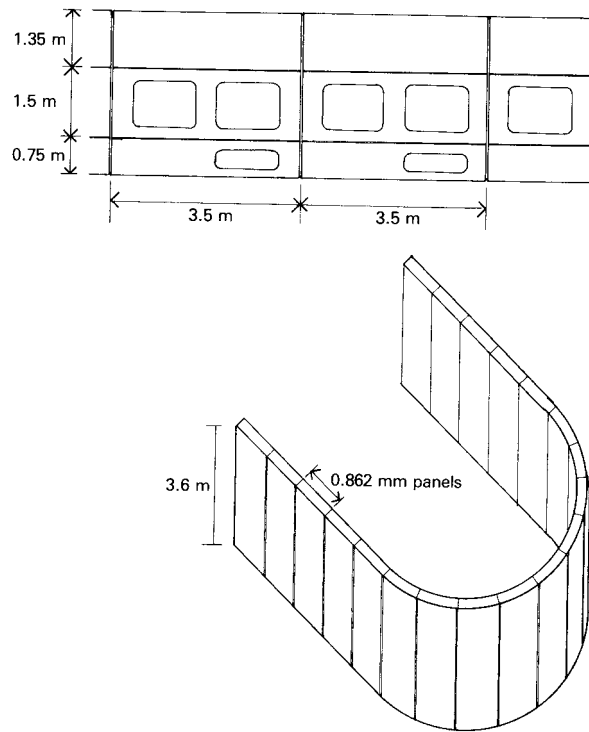
6.26 Dimensions of panels used at Bronx Centre, New York (architect: Richard Meier).

6.27 Horizontal joint detail from Johnson & Johnson building, New Brunswick, USA (architect: I.M. Pei).

made near-maximum use of available rolled sheet sizes. Some curved panels were also used on the projecting staircase enclosures, 3.6 m high × 0.862 m wide (Fig. 6.26). Because of cost, plasterboard linings were selected for this project, and it is interesting to note that the curved corners to the windows had to be made good in plaster on the inside face. Figure 6.27 shows detail from the Johnson & Johnson building, which incorporates a gutter system at the base of the panels to collect any water that may penetrate the sealant (usually silicone) joint system. Weepholes are also provided to discharge the water to the outside face. Also note the method of 'floating' the aluminium sheet

onto the panel framework, using studs welded onto the sheet with slotted holes to permit thermal movement.

European examples of rolled sheet panel construction would include the Hochhaus Dresdner Bank in Frankfurt (panels by Josef Gartner; architects: Becker, Becker and Partners). Here the panels consist of 2.5 mm aluminium rolled sheet outer skin, which is deep drawn into a tray and screwed to an aluminium carrier system. Figure 6.28 shows the junction between two panels where the carrier is in four sections forming the outer and inner parts of the assembly. The aluminium skin is fixed to the outer section of the carrier, which is screwed from the inner section by a thermal
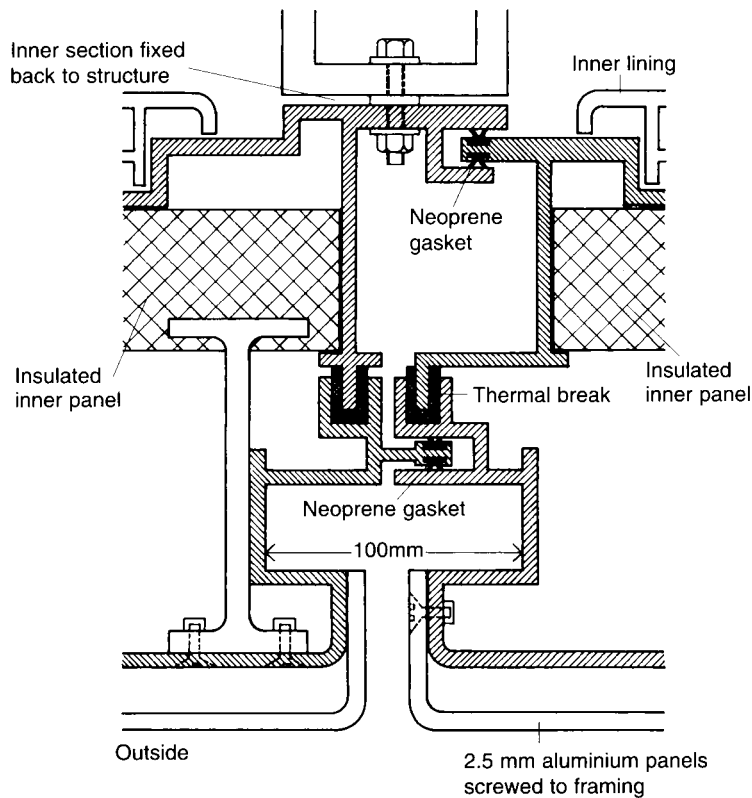
6.28 Plan of joint between panels at Hochhaus Dresdner Bank, Frankfurt (architects: Becker, Becker and Partners).

6.29 Section of panels used at Umschlags AG office building, Basel (architects: Wetterwald and Wenger).

break. The inner lining is bolted back to the main structural framing.

Rain screen panels

This last type of panel is in effect a combination of rolled sheet and laminated panel in which a flat aluminium sheet 4–6 mm thick is mounted in front of a laminated panel, itself designed for weather resistance with a ventilated cavity between the two parts of the construction. As the name 'screen' suggests, these

panels are only a first-stage barrier. The panels behind provide the thermal and acoustic performance, and can be mounted into a carrier system or fixed to secondary framing in the same way as previously described. The joints between the rain screen panels should be 10 mm or more to allow for any thermal movement, and it is also advised that the fixing of the outer sheets to the carrier system should allow for movement. The gauge of the plate panel must also be such as to avoid rippling and distortion of the sheet (in aluminium, 4–6 mm). For a further discussion of rain screen and pressure-equalized wall design, see the AAMA (1971), and Chapter 7 on curtain walling. This system of construction was used at the Umschlags

AG office building in Basel (Fig. 6.29) (architects: Wetterwald and Wenger), where 1651 mm wide × 2060 mm high decorative aluminium panels were deep drawn by Schmidlin and in effect 'hooked' onto the building, with an air gap of 20–30 mm provided between the outer panel and the insulation to ensure ventilation of the rain screen principle. Figure 6.30 shows a UK example of a rain screen, showing the air gap, the method of clipping the rain screen to the carrier, and the thermal break.

The size of the panel is limited only by the maximum size of the sheet metal panel and its ability to span between supports. However, the outside face of the inner laminated panel must also be waterproof, and this may limit the size of the overall assembly if joints in this panel are to be avoided. Rain screen panel principles have also been developed for over-cladding using metal panels mounted onto concrete block back-up walls.

These metal panels (usually powder-coated aluminium) are fixed to supporting mullions fixed in turn back to the external building fabric. A cavity is usually formed between the original and the new fabric, which is insulated, normally with mineral fibre insulation. Panels are normally locked to the supporting mullions by stainless steel pins, either exposed or secret fixed, with the joint forming a rain screen mounted on brackets fixed to the blockwork or brickwork wall behind (Fig. 6.31).

The Knowsley fire in Liverpool (Bolland, 1991) raised questions on fire spreading through cavities within this type of assembly, and the need for fire stops at floor levels and around window openings. There is an essential conflict between the need for horizontal fire stops and the provision of ventilated cavities.

Fire tests on board products undertaken at Cardington (BRE, 1989) indicated that some benefits of fire spread may result from reducing the width of the cavity, but clearly the amount of air movement to ensure proper ventilation of the system to avoid condensation will need to be checked.
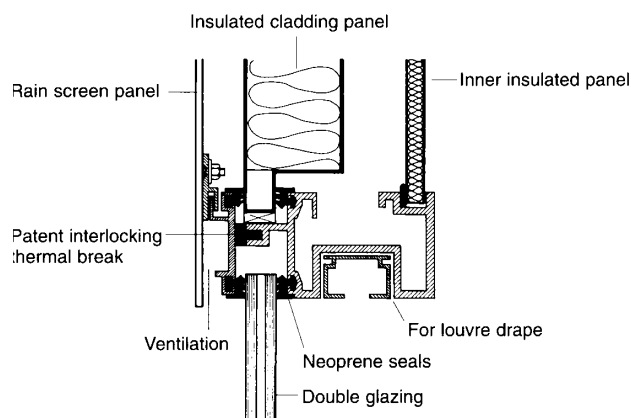
6.30 Typical rain screen detail (section).
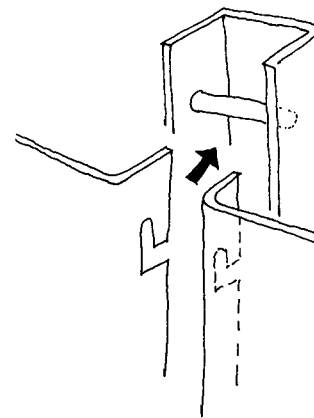
6.31 Typical secret fixing using metal pins for rain screen cladding.

The situation of wind loading on the inner face of the cavity is also not clear. Work by N. J. Cook (Building Research Establishment) on dynamic wind effects on board products with open joints has shown that fluctuations in wind pressure are transmitted through open joints to act directly on the original wall. Manufacturers should be asked to confirm their assumptions on wind loading when specifying the fixings and type of back-up wall.

Finishes

As well as the organic coatings normally associated with profiled metal claddings, such as Plastisol PVC finishes and PVF$_2$ coatings, manufacturers will offer a number of alternative finishes, such as:

- electrostatic powder coating;
- anodizing;
- thin premium paint coatings;
- vitreous enamelling;
- stainless steel.

Electrostatic powder coating

Powder coating is the application of thermo-hardening polyester/polyurethane within an air oven. This process has to be carried out in the factory, and it is therefore necessary to coat matching flashings and trims. Cured coating thickness should not be less than 75 μm.

Anodizing

Advantage can be taken of the oxidation characteristics of aluminium to provide an anodized aluminium finish (Fig. 6.32).

There are essentially three types of anodizing. The first two are **natural anodizing** (silver) and **two-stage anodizing** (bronze colours – the best known example in the UK is Anolok). Both these types of anodizing use sulphuric acid electrolyte to produce an initial silver-coloured anodic film. In the case of silver anodizing this is then sealed. In two-stage anodizing, the film is dyed in a second stage and sealed to give the required shade.

Sulphuric acid produces a relatively coarse-grained pore structure, which is not as resistant to abrasion as the structure produced by **integral anodizing** (golds, bronzes, greys and blacks). This is a one-stage process in which the colour is produced by the alloying constituents in the parent metal combined with the action of proprietary acids (e.g. Kalcolor, Duranodic, Calanodic) and then sealed. This produces a dense anodic film with superior weathering characteristics and resistance to abrasion. Thus, although silver anodizing is produced in one stage by the action of electrolyte on the metal, it does not have the film density of the true integral anodizing using sulphosalicylic type acids, and it is normally recommended that this type of anodizing should be washed down more frequently than the other types.

Anodizing should be carried out using alloys specifically suited for the process according to BS 3987:1974. The minimum required anodic film thickness is 25 μm for external applications.

The European Wrought Aluminium Association (EWAA, 1978) specification for anodizing types includes a terminology of aluminium anodizing procedures. Anodized aluminium panels will need washing down regularly to avoid pitting of the surface, and thus provision of cleaning rails and cradles should be allowed for.

One difficulty is that it is extremely difficult to match the colour of anodizing, which is dependent on the time the panel is in the electrolyte and the type of alloy used. Although it is possible to agree upper and lower limits of colour variation with the manufacturer,
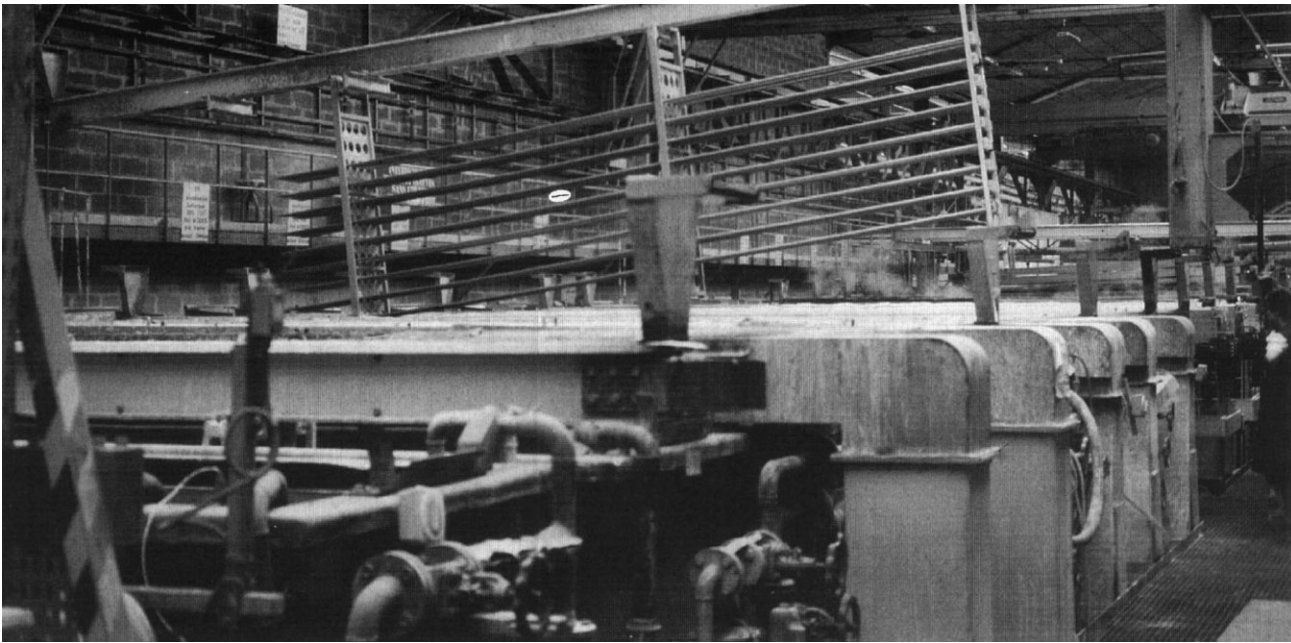
6.32 Typical anodizing bath.

6.33 Panels for Gatwick Airport on Duranar coating line.
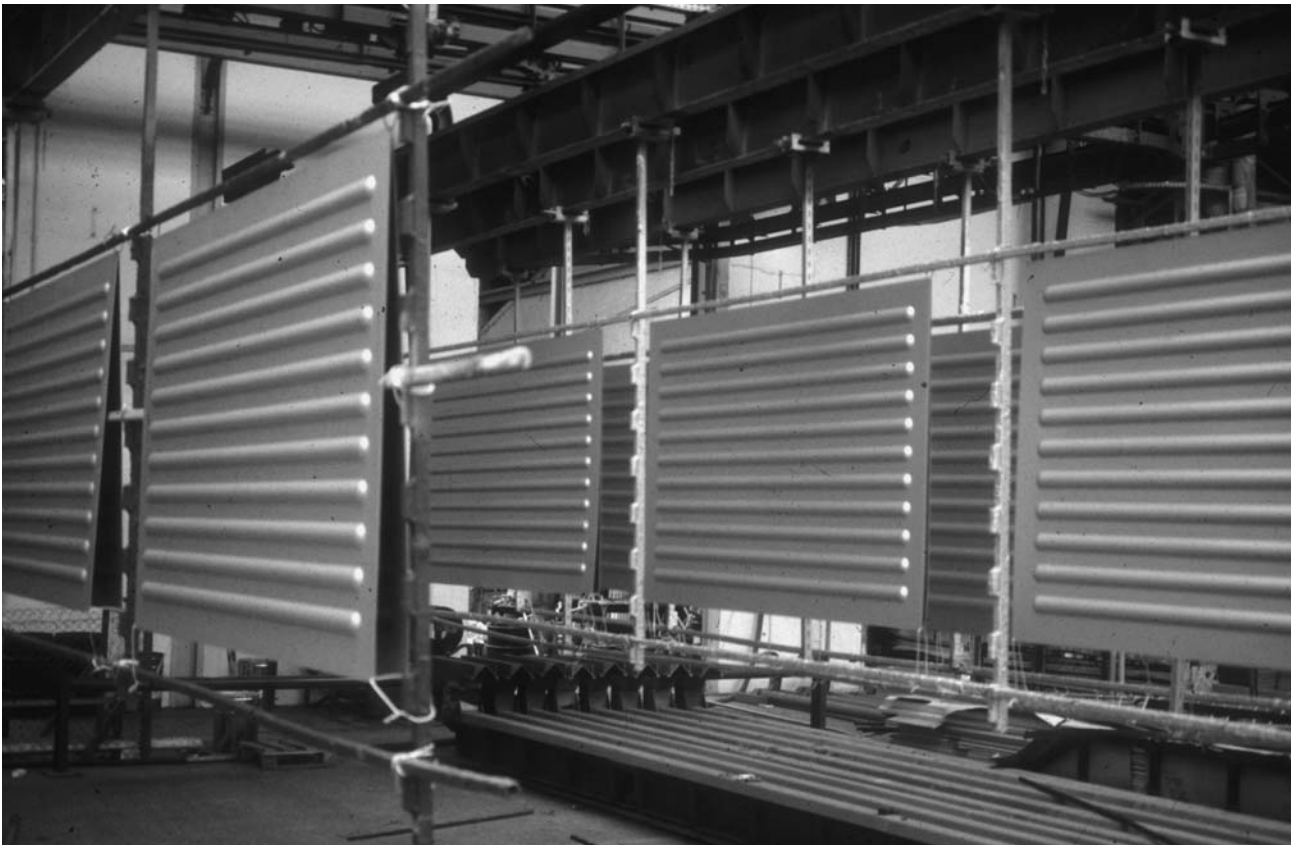
6.34 Patera building systems using panels 3.6 m × 1.2 m (courtesy of Patera Products Ltd).

some variation must inevitably be accepted, depending upon the degree of quality control in the factory.

Thin premium paint coatings

It is this difficulty of maintaining anodizing quality that led to some American architects expressing a preference for more recent paint finishes, such as fluoropolymer coatings (e.g. Duranar from PPG Industries), or acrylic finishes.

These premium, thin (20 μm) paint films are dependent for their performance on the type of substrate used, and, as with all organic coating, long-term durability will be affected by the type of metal pre-treatment used.

Figure 6.33 shows panels for Gatwick Airport being coated with 3 coat Duranar finish.

Vitreous enamelling

Vitreous enamelling is normally associated with steel panels, because it is difficult to ensure proper adherence of the enamel to aluminium sheeting. The zero carbon steel necessary for the manufacture of vitreous enamelled panels is available in widths of up

to 1520 mm, which can restrict the size of the finished panel.

Stainless steel

Stainless steel can also be used for external cladding. For laminate sheets, in which the integral strength of the core allows the use of thinner gauge metal skin, the cost of the stainless steel may not be significantly more than the equivalent stiffness gauge of aluminium with a hard anodic anodizing. The surface finish of stainless steel can vary from a matt descaled finish to a bright, highly polished finish. The choice depends on the use and the cleaning technique to be applied. Number 4 dull polished finish, which is not highly reflective, is suitable for most architectural applications, because it combines ease of cleaning with uniformity of appearance.

Proprietary systems and their fixing

The size of box panels is often governed by the type of press used to produce the box tray. Steel panels produced for the Patera system (Fig. 6.34) were stamped out in three separate pressings for the same panel prior to fabrication into a composite unit using a mineral wool insulation core.

The type of metal used can also influence the maximum size of the panel. Stainless steel, for example, is available from BSC (Stainless) Sheffield in coils up to 1520 mm wide. Similarly, zero-carbon flattened steel, necessary for the manufacture of vitreous enamelled panels, is available in widths up to 1520 mm. Consequently, the size of vitreous enamelled panels is normally restricted in size to 2950 mm × 1450 mm allowing for flange dimension. Panels can of course be assembled into a larger assembly using supporting framing: for example, facade units 3.86 m wide × 4.42 m high at Burne House Telecommunications Centre,

London, were made up from panels less than 1 m wide mounted into a steel channel cladding frame. The construction incorporates a vapour barrier and a conventional inner lining. As well as 'one-off' designs for specific projects, a number of proprietary panel systems are marketed in the UK using box-type construction with both steel and aluminium metal skins. For details of these systems see Brookes and Stacey (1990).

Several early Russian examples of box-type composite panels and their joints are shown in Fig. 6.35. Experience in the use of composite panels in New Zealand is also reported by Sharman and Duncan (1980).

In the same way as some allowance must be made for thermal expansion using sheet metals, similarly for box-type panels consideration must be made for possible thermal movement, particularly

6.35 Examples of joints between foamed composite units developed in the former Soviet Union.
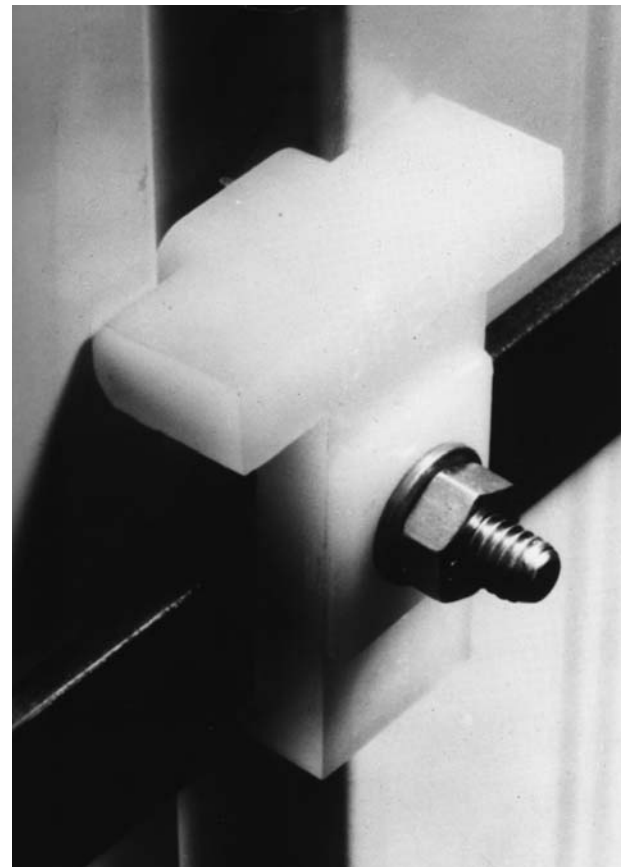
6.36 Proprietary patent fixing device.

when using aluminium. Simple calculation shows that if the interior panel temperature varies by 20°C, then for a 1200 mm wide panel with a steel skin (coefficient of linear thermal expansion approximately 12×10^{-6}°C) the width will vary by 1 mm. An aluminium skin would move twice this amount. Thermal movement is normally allowed for at the joint, and if an overlap H-shaped aluminium extrusion is used, then the legs of the H-section should be long enough to accommodate this movement. It is not good practice to 'gun in' a sealant into these sections to provide a final seal, as this can be squeezed out onto the face of the panel because of thermal movement (Sharman and Duncan, 1980). Vertical movement of the panels must also be allowed for in the design of any top and bottom fixings. Allowance for movement must be made in the panel fixing (Fig. 6.36).

Aspect II

The joining and fixing of metal composite panels is critical to their performance in use. Additional stiffness can often be achieved by the incorporation of UPVC edge profiles, which also act as joint formers to achieve more complex jointing and fixings and to allow interchangeability with other components, such as doors, windows and louvres.

The search for an improved four-way crossover junction without the use of ladder gaskets (as used for the Sainsbury Arts Centre, University of East Anglia and Gatwick North Piers), and the need to avoid the use of site-applied sealants, were fundamental design aims in the design of the new cladding system, Aspect

6.37 Interchangeable facade panels.

II, developed by Brookes Stacey Randall Fursdon, and now manufactured and marketed by Coseley Panel Products (Fig. 6.37).

This system of interchangeable facade components offers the opportunity of rearranging or adapting the building envelope at any stage during the construction process or after the building is occupied. Aspect II allows panels to be interchanged with glazed panels, louvres or doors. Even loading bay doors can be relocated. For a full description of the development of the system, see Anon (1990).

Aspect II achieves the freedom of movement of the components of the building envelope as suggested by the architects of the Hertfordshire Schools Programme in 1948: 'the freedom of movement of a queen on a chessboard as opposed to the limitations of a pawn' (Fig. 6.38). Modular coordination is essential to make this possible.

The method of fixing panels is to fix via an aluminium clamping plate located within the UPVC edge profiles and behind the primary gaskets. The clamping plates are secured with a stainless steel countersunk socket-head machine screw to a rear fixing block, which slides within the vertical rear

aluminium carrier. The Aspect II system is entirely secretly fixed, and avoids any problems of aligning fixings, sealing fixings or panel damage by fixings.

The panels can be easily assembled or dismantled by a skilled fixing team. The clamping plate has been carefully engineered with allowance for thermal movement, rotational effects and tolerance. The interface of the clamping plate and the UPVC edge section has been designed to minimize thermal bowing of the panel. The number of clamping plates is dependent upon the wind loading and panel size.

In Aspect II the weatherseal is formed by the primary gasket framing the perimeter of the panel. The inner seal is formed by a horizontal airseal mounted to the top and bottom edges of the panel. This is clamped against the vertical airseal mounted to the rear aluminium carrier. A still air zone exists between the primary gaskets and the airseal. Drainage continuity is maintained using sealed joints in the rear carrier, normally at 4 m centres, which allow for thermal

6.38 Hertfordshire chess diagram.
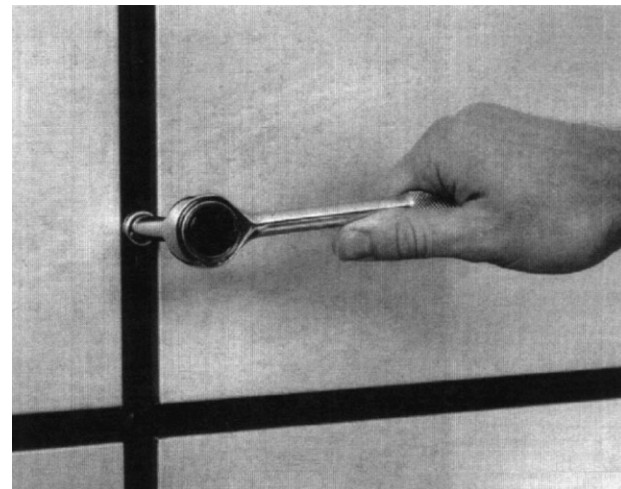
6.39 Panels face fixed using Allen key, then tightened to a specific torque.
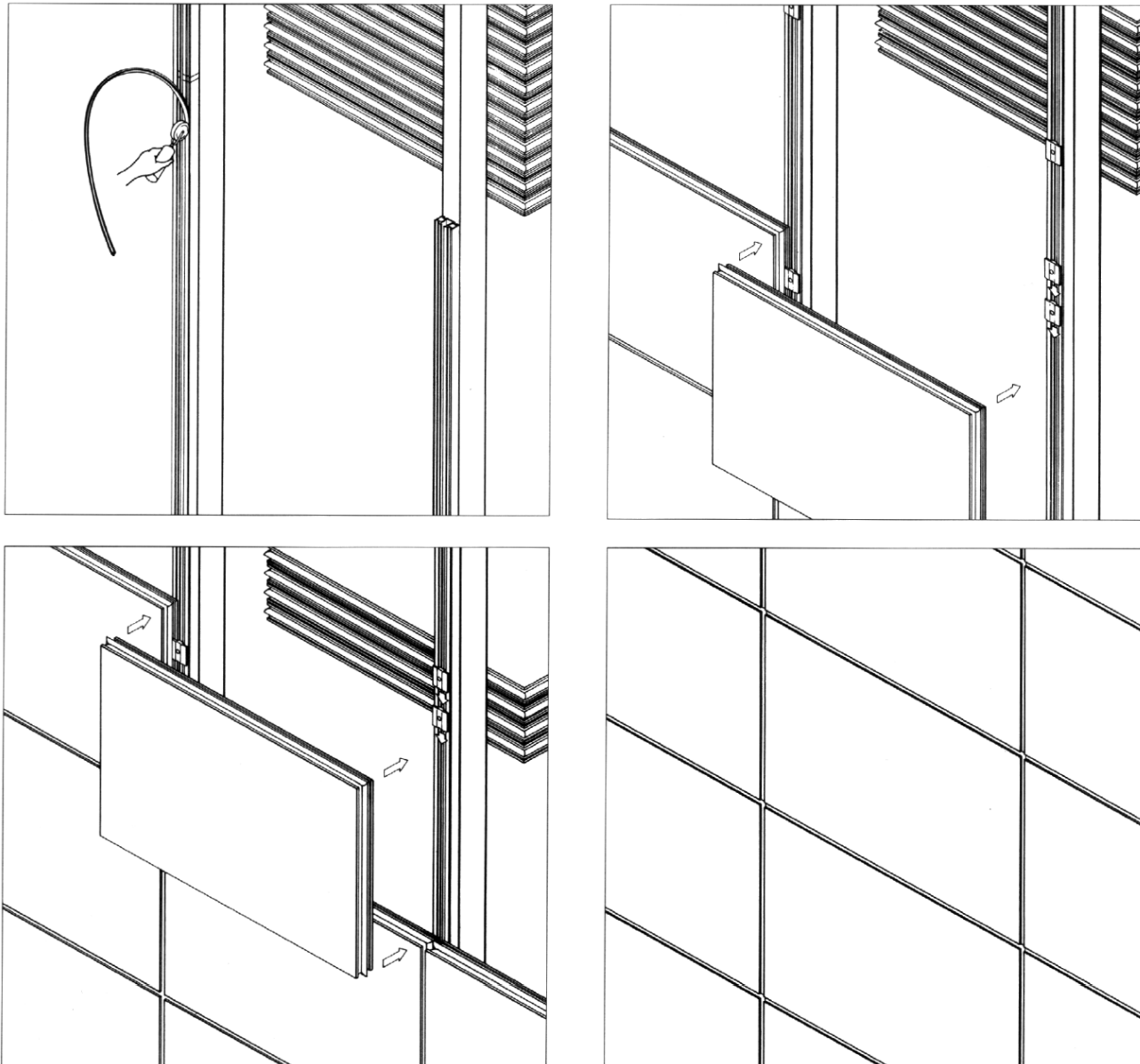
6.40 Sequence of erection.

expansion. The sill detail is designed to drain moisture from within the assembly to the outside.

All components, including windows, louvres and doors, have a common method of jointing, and are secretly fixed. This achieves a system of coordinated components, through their means of jointing, resulting in a coherent assembly of diverse elements. Throughout these elements the finish can be common or highly varied depending on the needs of each project and the requirements of the specifying architect.

The sequence of assembly starts with the aluminium rear carriers, which are fixed back onto the building's substructure and aligned, plumbed and shimmed to a flat plane. The fixings and shims will be determined by the nature and tolerance of the substructure of each project. The vertical airseals are rolled into the locating channels in the front face of the carriers. These airseals run continuously up the elevation, and initially are oversized to allow for shrinkage (Fig. 6.40).
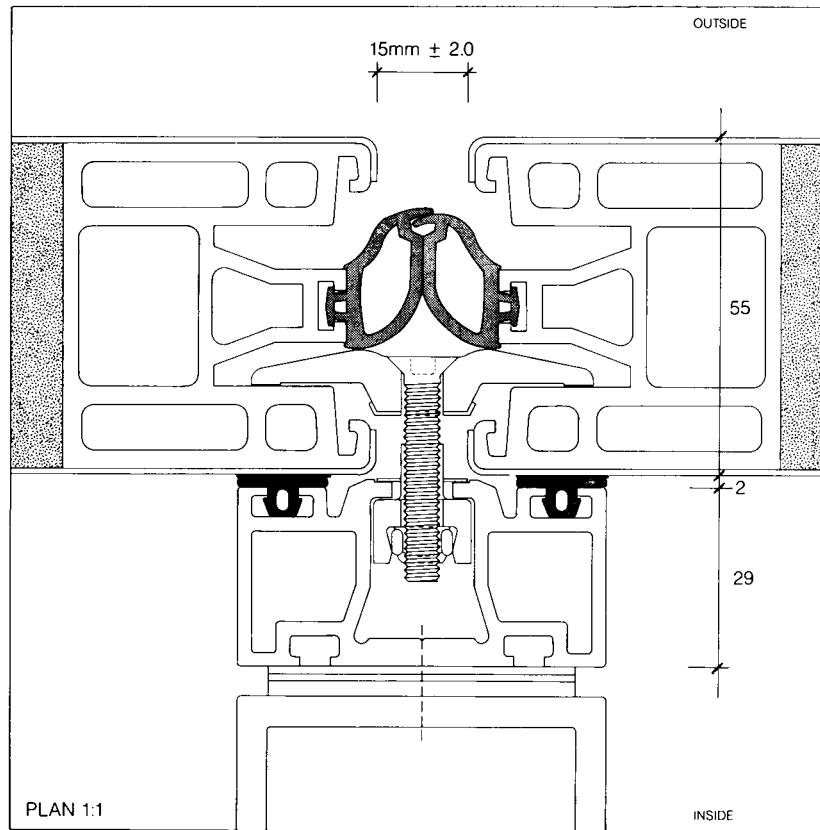
6.41 Plan of joint.
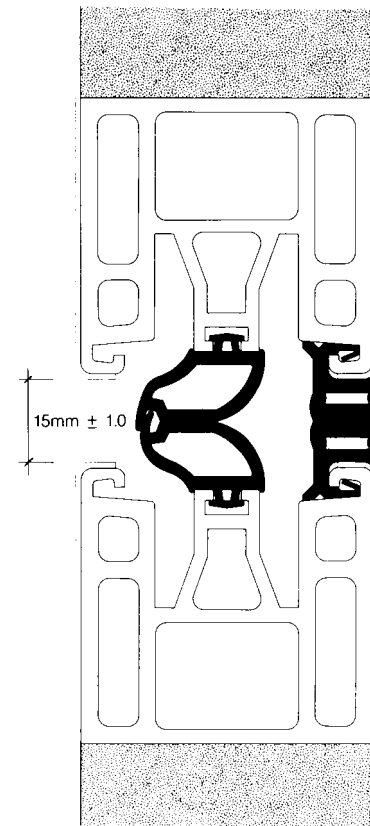
6.42 Section through horizontal joint.

The first panel, complete with its horizontal airseal and primary framed gasket, is offered up to the carrier and restrained by bolting down the aluminium cladding plate onto the aluminium rear block within the carrier. The clamping plate is then partially backed off and the adjacent panel offered up to the carrier. The joint between the panels is compressed to 15 mm (Fig. 6.41). The panel alignment is checked. The action of tightening the clamping plates' socket-head machine screws compresses the panel and the horizontal airseals against the vertical airseals. It is good practice to assemble a bay of panels vertically.

What seems to be required of the structure is something analogous to the freedom of movement of a queen on a chessboard as opposed to the limitations of a pawn.

The weatherseal of the horizontal panel-to-panel joint is formed by the primary framed gaskets, backed up by the panel-mounted horizontal airseals. There is no requirement for horizontal rear carriers or subframes (Fig. 6.42).

To minimize thermal migration, the rear clamping block of the clamp plate assembly has an extended nose section. This ensures that panels are retained
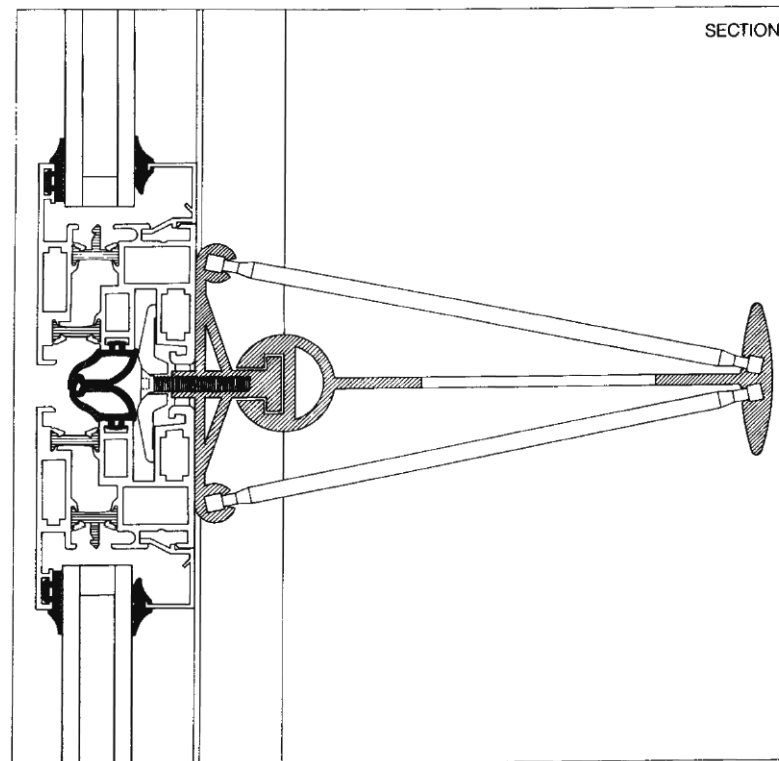
6.43 Horizontal wind stiffener.

6.44 Quality control during production.

within the gridlines of the panel modules. The assembly is restrained vertically by stop blocks, which are located in every third horizontal panel joint and carry dead load.

In order to extend the spanning capabilities of the louvre and window sections, increasing the maximum performance to 3.6 m clear span at 1.6 kN/m^2 wind loading, horizontal wind stiffeners have been designed (and patented) by Brookes Stacey Randall Fursdon. An example of one of the more unusual designs shown (Fig. 6.43) comprises two aluminium extrusions. One forms the beam, which is profiled and has holes cut in the web. Depending upon the structural performance required, these holes can change in diameter and shape. The second extrusion forms discrete 60 mm wide brackets fixed into the panel joint at typically 900 mm centres. These two extrusions are linked by 6 mm diameter stainless steel struts.

The composite construction of Aspect II can use various core insulation materials to achieve U values of 0.45–0.35 W/m^2°C.

The Aspect II system of panels and its associated components were produced after a design, research and development programme of mock-ups, prototypes and testing. The panel-to-panel joint, with its patented framed gaskets, has been tested at BSI according to BS 5368 Parts 1–3 for air penetration, weather resistance and wind loading.

Quality control during production and on site is important to ensure the panel's performance in use (Fig. 6.44).

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7

Curtain walling – glazing systems

Definition

Curtain walling may be defined as being non-loadbearing walls, usually suspended in front of a structural frame, their own deadweight and wind loadings being transferred to the structural frame through anchorage points. Usually they consist of a rectangular grid of vertical or horizontal framing with infill panels of glass or some other lightweight panel, but that is not always so, for the term 'curtain walling' encompasses a wide variety of systems (Fig. 7.1):

– patent glazing;
– pressed or extruded metal box framing;
– suspended glass assemblies;
– silicone-bonded glazing.

There are a number of proprietary systems available for each of these types, as described below.

Patent glazing

Nineteenth-century Victorian glasshouses gave many opportunities for the development of dry assembly systems of glass and metal (Fig. 7.2). Many of these are shown by Hix (1995) in his excellent historical study of glasshouse construction. Joseph Paxton's Crystal Palace had wooden glazing bars made on site by sophisticated milling machines, but by the time it was moved to Sydenham it was largely rebuilt using metal glazing bars and a puttyless glazing system, the

recognized advantage of which was illustrated by the abundance of patents taken out at that time (hence 'patent glazing'). Sections of the nineteenth-century patent glazing bars are shown in Guedes (1979). It was the necessity to provide good natural lighting in factories, using north light roof construction in the

1920s and 1930s, that really promoted the commercial development of the large number of types of patent glazing sections used today (Fig. 7.3). Modern patent glazing systems for both inclined and vertical applications were shown in Patent Glazing Conference (1980); however, more recently this type of glazing
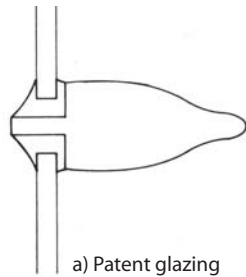
a) Patent glazing
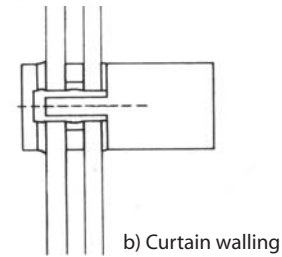
b) Curtain walling
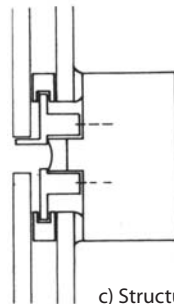
c) Structural glazing
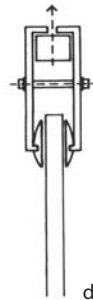
d) Suspended glazing
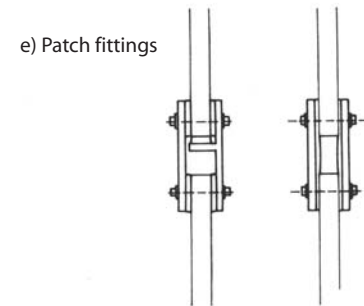
e) Patch fittings
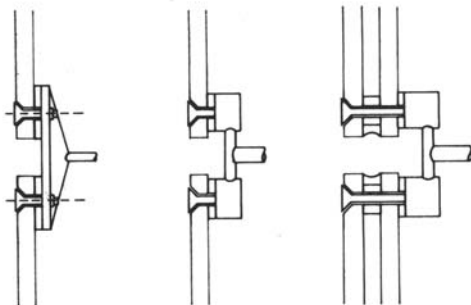
f) Planar fittings
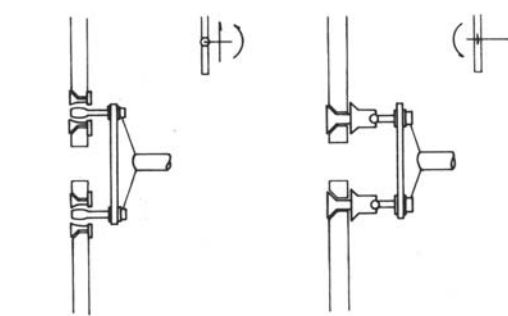
g) Suspended glazing fittings offering greater movement

7.1 Development of glazing systems.

support has fallen out of favour, mainly because of inherent difficulties with thermal breaks and the availability of more sophisticated forms of curtain walling.

Metal box framing

The term 'curtain walling' is most commonly associated with a rectangular grid of vertical and horizontal frame members, introduced from America during the 1950s mainly for use in high-rise office buildings. Two buildings in particular helped the popular aesthetic approval of the framed curtain wall: the United Nations Secretariat (architects: Harrison and others, 1947–50) and Lever House (architects: Skidmore, Owings and Merrill, 1952), both in New York. Important forerunners of these were buildings such as the Gropius factory at Alfeld (1911), the Bauhaus, Dessau (1925–26) and Le Corbusier's Maison Suisse at the Cité Université, Paris (1930–32).

There are two basic approaches to assembling a box-framed curtain wall (Fig. 7.4). Either:

– the component parts of the system are assembled on site, with panels being offered up to a frame (sometimes known as the 'stick' system); or
– the panel system is bolted together, the panels themselves becoming the frame.

Both systems have the advantages associated with a high degree of prefabrication; the first method has more easily handled components, but site construction time may be longer.

7.2 Sections of nineteenth-century glazing bars.
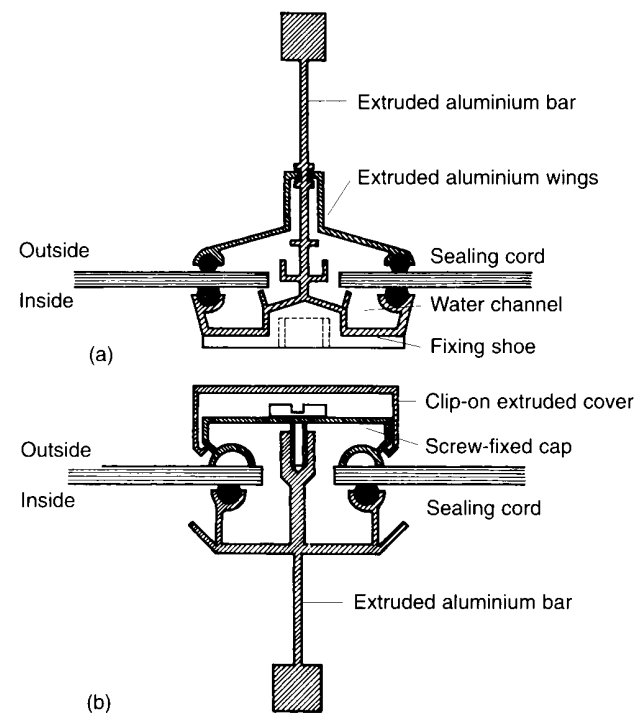
7.3 Two forms of patent glazing: (a) traditional; (b) inverted.

(a)

(b)
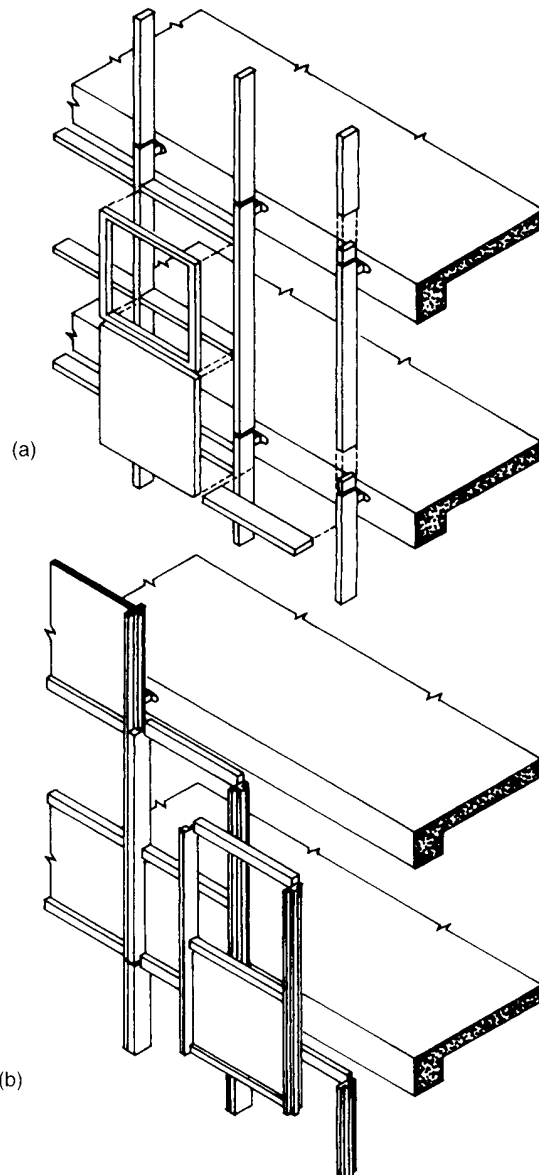
7.4 Basic forms of curtain walling construction: (a) stick system; (b) unitised system.

Means of support

The means of support and the layering of the arrangement can totally change the appearance of the facade. There is clearly an interest in providing diversity in the means of support for a particular project to reduce the visual bulk of the supporting framework or to achieve a particular span requirement. At the YKK M&E Centre in Japan by Roy Fleetwood, the two-storey curtain walling of the ground floor is supported by a transom and mullion of a similar section. However, the mullions are stiffened by the use of a pin-jointed lattice truss. This truss mullion, a combination of cast and extruded aluminium, was developed by YKK Architectural Products (Fig. 7.5).

A similar structural approach was taken by Benthem Crouwel in their extension to Schiphol Airport in The Netherlands, where once again a consistent mullion and transom box is supported by a vertical truss. However, with the truss, the architects have opted for a curved vierendeel beam, very similar to that designed for Stansted Airport (Fig. 7.6).

The curtain walling designed for the British Airways Combined Operations Centre (developer Lynton for Heathrow Airport) by Nicholas Grimshaw & Partners demonstrates the potential of extruded sections, which are more visually interesting than a simple box section and capable of accepting many functions that interact with the building envelope. This is achieved by a family of extruded components (Fig. 7.7).

Renzo Piano, when designing a curtain walling system for Alucasa of Milan, Italy, used cast aluminium sections, which, when bolted together acted as wind bracing between floors, replacing the traditional box extrusion (Fig. 7.8).

7.5 YKK M&E Centre in Japan by Roy Fleetwood.

7.6 Glazed wall at Stansted Airport (architects: Foster Associates).

Typical spans

In metal box framing, the window mullions are the principal members of the grid; horizontal members rarely form the support for curtain walls. Vertical members spanning from floor to floor must withstand axial stresses caused by self-weight and bending caused by wind loads, and it is in this direction that the mullion must have greatest stiffness and strength, a principle also illustrated by the 'fin' section of a patent glazing bar. The depth of the mullion is thus dependent upon its

span and the area of glazing it is required to support (module spacing). Prouvé illustrated as early as the 1930s how the use of a range of proprietary sections could cope with a variety of spans (Fig. 7.9).

The size of the curtain wall grid is determined by the costs of the vertical members, the section size being weighed alongside the number of members required. Proprietary systems offer a module size of between 760 mm and 1200 mm, and according to Elder (1977), where mullion spacings are over 1200 mm, glass costs and mullion sizes increase considerably.
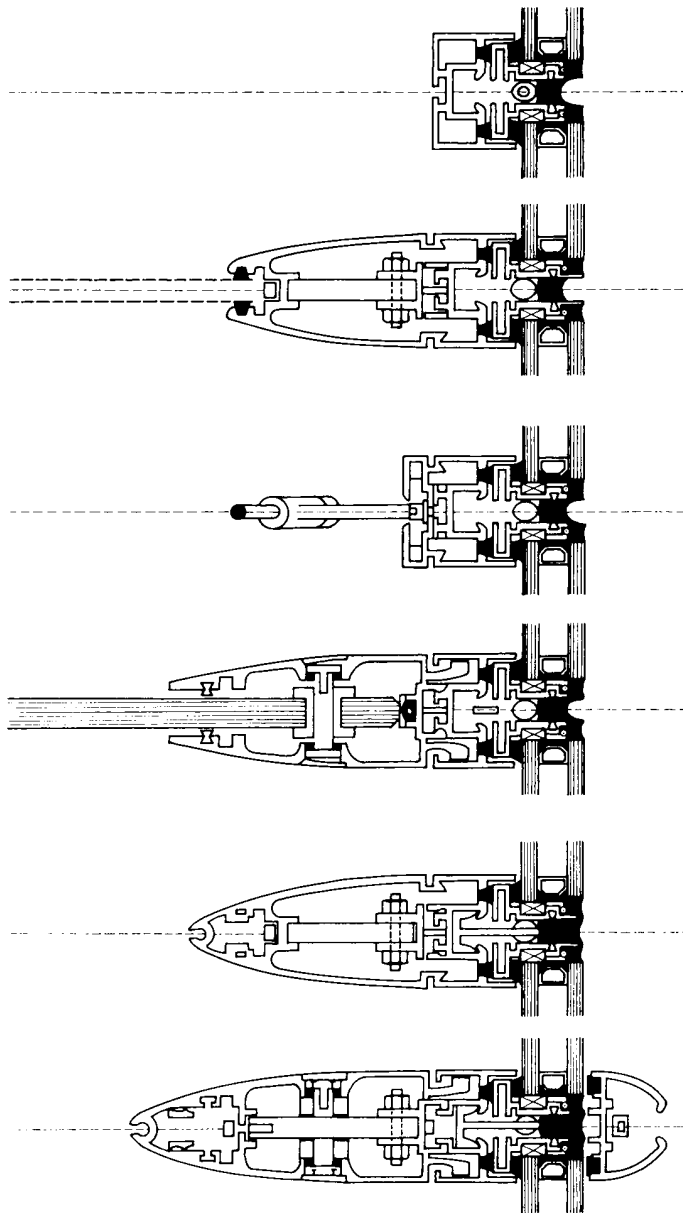
It may be that, with the introduction of designs of glazing systems for particular projects rather than for general use, the sections can be engineered for larger mullion spacings. Float and sheet glasses are now available for use with these larger grid dimensions. Information on maximum sizes normally available for glasses used in curtain walling can be obtained from the various glass manufacturers, including Pilkington Bros, St Helens. BS 6262:1982 *Code of practice glazing for buildings* also gives information on design considerations affecting spanning characteristics of different types of glass.

Joints and connections

The logic underlying the frequency at which prefabricated curtain walling elements are jointed together can be summarized in terms of manageability (both in transportation and in site handling) and reduction of movement per joint, particularly thermal, in the system and between the system and the supporting framework.

Joints to allow thermal movement

The framing members of the curtain wall, which are fixed back at points to the supporting structure, must be allowed to contract and expand freely with changes of temperature. Rostron (1964) shows various methods of allowing for thermal movement (Figs 7.10 and 7.11) between the framing and structure using sliding joints. Reduction and friction at sliding connections is provided by slotted holes and plastic washers.

It is also essential to provide some kind of discontinuity in the frame itself. Frequent jointing within the frame will reduce the thermal movement per joint in the system and between the system and the main structure. There are essentially three types of such joints:

7.7 Mullion section for BA Combined Operations Centre by Nicholas Grimshaw & Partners.
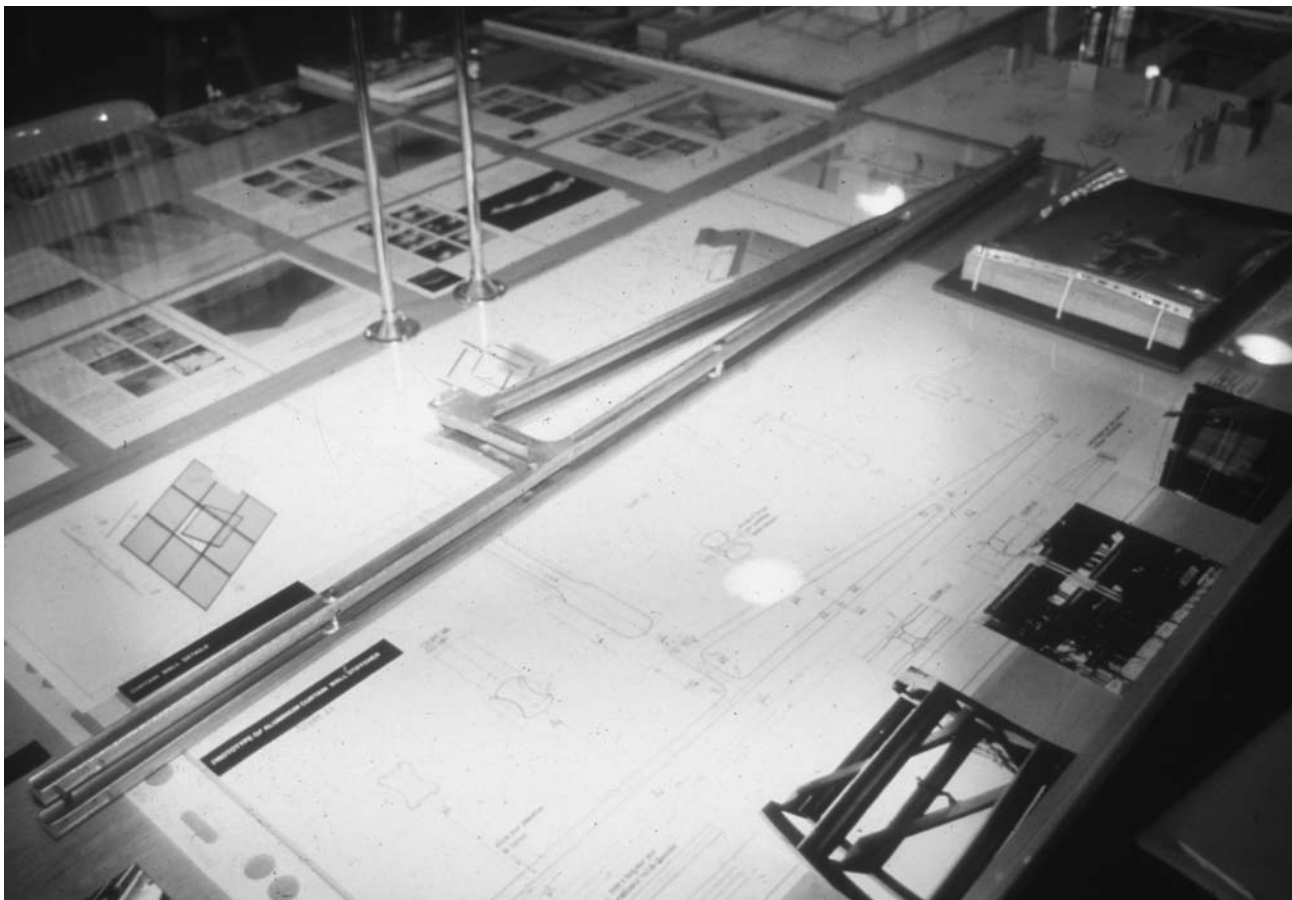
7.8 Cast aluminium truss for 'Alucasa' System by Renzo Piano.

- slip joints;
- butt joints between solid mullions and transoms;
- spring connections between adjacent panels.

Both Rostron (1964) and Schaal (1961) illustrate examples of such joints. Slip joints in vertical framing members, using a loose spigot or a swaged offset, are shown in Fig. 7.12.

Figure 7.13 illustrates the principle of a slip joint in a split mullion, where the male and female sections permit thermal movement between the frames.

Butt splicing between solid mullions and transoms allows a joint thermal movement (Fig. 7.14). Examples of spring joints are shown in Figure 7.15. Flexible metal closure strips can also be used.

Weatherproof joints

Joints between frame and infill panels take the form of beads, gaskets and sealants. The following requirements must be met.

- Joints should be wind- and rainproof (if the inside of the infill panel is sensitive to moisture, the edges should be protected).
- Self-weight of panels and wind loads should be transferred evenly to the frame.
- Panels and framing members should be free to expand and contract independently (if subject to movement; thermal or structural).
- Joints must allow for dimensional and alignment variations between shop and site.
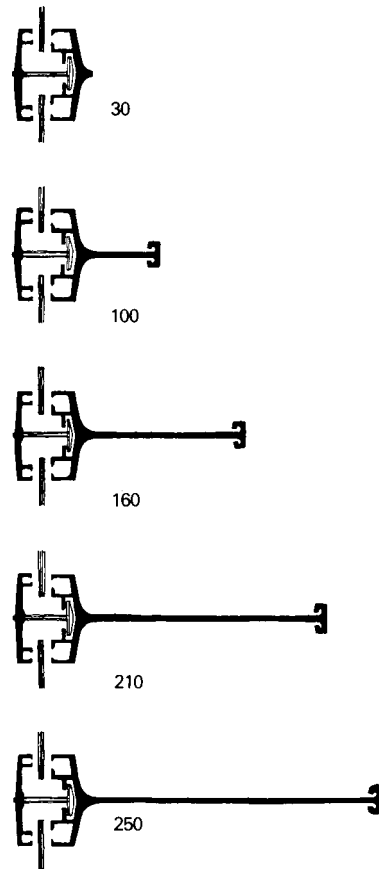
7.9 Range of sections (depth) to cope with a variety of spaces.

7.10 Reduction of friction at sliding connections by using slotted holes and plastic washers and: (a) shoulder bolts; (b) sleeves and standard bolts (from Rostron, 1964).
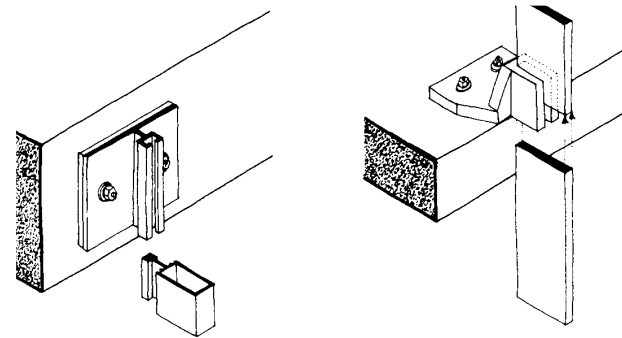
7.11 Allowance for thermal movement in methods of fixing (from Rostron, 1964).

Rostron (1964) describes two main types of joints, open and closed:

– Open joints allow water to enter the joint, control its passage and provide drainage.
– Closed joints form a completely weatherproof barrier.

Open joints have several advantages: they easily accommodate movement, erection is quick, and sub-

sequent maintenance of joint seals is reduced. However, the joint profile tends to be more complicated, and closed joints are more commonly used sealed with either rigid or flexible seals.

Rostron (1964) also defines two main classes of joint shape: integral and accessory.

– In integral joints, members are shaped in such a way that bringing them together forms the joint.
– Accessory joints require additional parts to form the joint.

Each of these joint shapes has three principal forms (Fig. 7.16). The choice of joint shape is determined by requirements for tolerance in assembly, movement, sequence of assembly, performance factors and aesthetics.

The component nature of curtain walling means that there are many joints in the envelope. These joints, at frequent intervals, are necessary to enable components to be of manageable dimensions. Frequent jointing will also reduce the problem of thermal movement per joint. Recent years have seen the development of more sophisticated joints moving away from metal and mastic joints between panels towards patent neoprene gasket designs. Neoprene also helps to accommodate thermal movement between the panel and its framing.

Joints between glass and frame

When glass is the infilling panel the edge cover given to the panel at the joint has to be limited in order to avoid too great a temperature differential occurring between the edge and the exposed surface, which may lead to the glass breaking. Stroud, Foster and Harington (1976) (pp. 170–171) recommend that the edge cover to the glass should be limited to 10 mm, although a dark-coloured frame will alleviate the problem of thermal stressing. A more detailed discussion of glass fracture is contained in T. A. Schwartz's paper to the Second International Conference on the Durability of Building Materials, 1981 (Schwartz, 1981), in which he advises designers to consider the strength-degrading effects of long-term loads, environment and surface defects as part of their glass selection process. At the same conference Zarghamee and Schwartz (1981) reported on a study designed to discover causes for the loss of metal edge bands from insulating glass units during service. Such studies have been carried out as a result of experience with glazing units that have
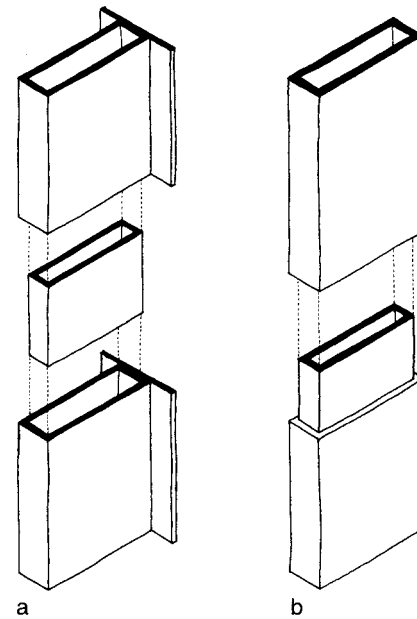
7.12 Two types of slip joint in vertical framing members (based on Rostron, 1964): (a) loose spigot or sleeve; (b) swaged offset.
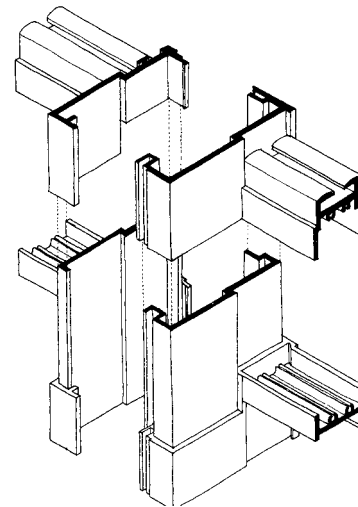
7.13 Slip joints in split mullions (based on Schaal, 1961).
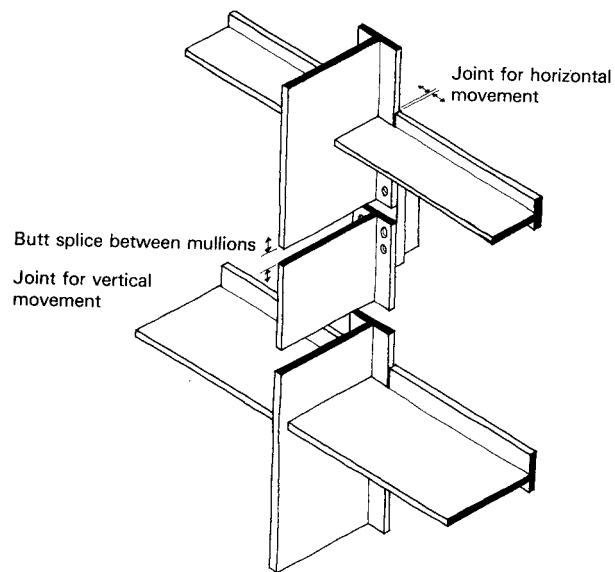
7.14 Butt joints between solid mullions and transoms (based on Schaal, 1961).
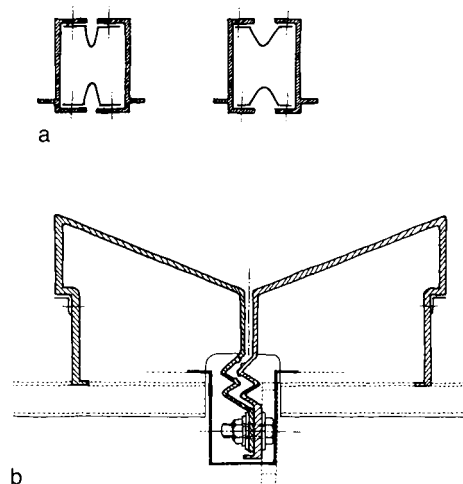
7.15 Spring connections (based on Schaal, 1961): (a) flexible metal closures in the joints; (b) example of a spring joint.

failed either by seal fracture or by glass fracture due to cyclic movement between the glass and the curtain wall. The most dramatic example is that of the Hancock Tower in Boston, where it is necessary to stabilize the main frame in order to reduce the amount of movement.

Edge clearance

Edge clearance should take account of the thickness, strength and spanning capacity of the glass, its deflection, its thermal movement and the condition of the edge of the glass (edge fracture). It is also necessary to take into consideration the strength of the supporting member, its deflection, its thermal movement and the type and characteristics of the weatherseal. The possible creep under dead load and characteristics and correct placement of the setting block must also be taken into consideration.

Some glass manufacturers will offer general guidance, such as the rule of thumb that 'designed edge cover should equal the thickness of the glazing', and most of their recommendations hover around this general principle.

The received opinion from persons within the curtain walling industry is that it is normal that recommendations for minimum edge cover be quoted as **guidance for design**. In setting the measurable minimum to be achieved on site, safety factors should also allow for the particular conditions of use and geometric complexity of the project under consideration.

Some individual manufacturers carry out tests on typical assemblies to take account of variations that occur in practice and any reduction in performance (weathering or strength) that could thus occur. Schuco, for example, in their FW50 curtain walling advise 12 mm as minimum (measured) edge cover governed by the width of the rear airseal.

Integral joints

(a) Butt

(b) Lap

(c) Mated

Accessory joints

(a) Spline

(b) Cover

(c) Frame
     and stop
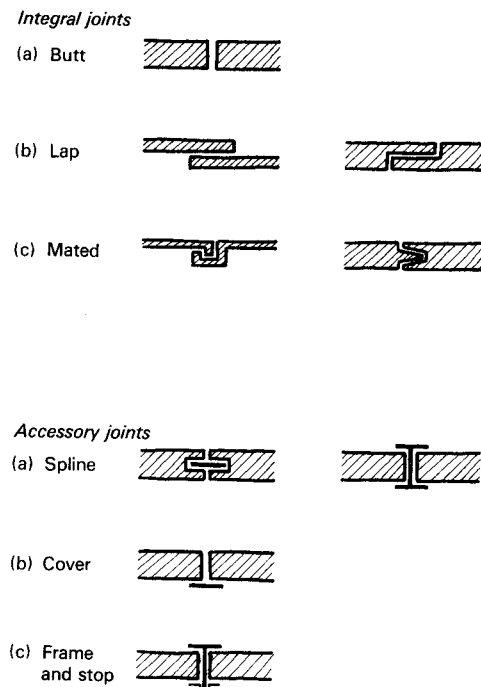
7.16 Integral and accessory joints (based on Rostron, 1964).

The Architectural Aluminum Manufacturers' Association Guide 1979, p. 100, Table C, recommends 9/16 in edge cover for 9/16 in glass.

Insulation and cold bridging

The thermal performance of the assembly is largely determined by the insulating properties of the infilling panel. The nature of the frame, does, however, have some influence upon performance. If the frame is made of metal and is unprotected from the external environment, then it will set up a cold-bridging pathway. The effect can be overcome by discontinuity in the framing members using a patent plastic thermal break (Fig. 7.17). In some systems the metal frame is continuously protected from external conditions by a
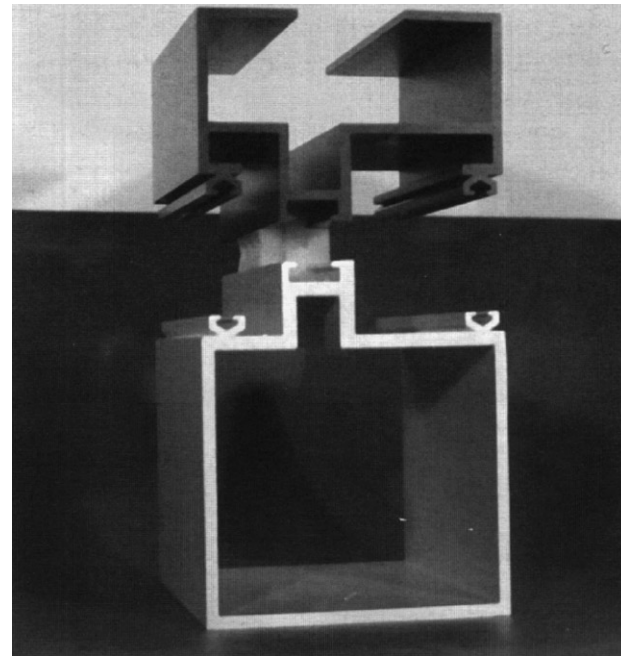
7.17 Patent plastic thermal break.

neoprene gasket, and in this way cold bridging is avoided. If the frame is constructed from timber members then no problems of cold bridging arise.

Fire resistance

A curtain wall has to be regarded as an unprotected area in relation to the transmission of fire to adjoining property. The extent to which an unprotected area is permitted by the fire provisions of the Building Regulations or, if applicable, the London By-Laws is determined by the distance to the wall from the relevant boundary. A common method of reducing the unprotected area, which is acceptable under both sets of regulations, is to provide a non-combustible back-up wall, usually of masonry construction, 100 mm

from the inner face of the infill panel. This approach does, however, invalidate certain advantages of a curtain wall installation, such as saving floor space and light loading of the primary structure.

Suspended glass assemblies

Suspended glass assemblies using glass as the load-carrying material were first developed with Foster Associates in 1973 for the Willis, Faber and Dumas Insurance building in Ipswich (Fig. 7.18). The system consists of two glass components: a **wall skin** formed from sheets for 12 mm toughened glass (armour plate) and **vertical fins** fixed perpendicularly to the skin to provide lateral resistance to wind loads. These are formed from 19 mm armour plate.

The system is constructed from the top down. The topmost glass panels are independently suspended from the main structure using one central bolt, the load being spread across the width of the glass by means of a top clamping strip. Figure 7.19 shows the original sketch of the fixing back to the concrete structure at the head of the assembly.

Subsequent panels are hung from those above using 165 mm square brass patch connectors with stainless steel fixing screws. The height of the assembly is limited by the shear strength of the bolt holes that are drilled through the glass, the maximum height being 23 m.

At Ipswich, the glass fin to resist wind loads is fixed back to the floor structure. Because the wall skin is suspended, the glass expands downwards. In order to allow vertical movement between the wall and the fin, the inside patch connector comes in two parts, one for attachment to the fin and the other to the facade (Fig. 7.20). The two parts dovetail together, allowing the fins and facade to slide vertically independently of one another.

The early design of the dovetail, as shown in the Pilkington design guide (Pilkington, 1975), included a square dovetail, which allowed the two parts of the fins to separate under horizontal movement. Later versions used a rounded sleeve dovetail (Fig. 7.20). At the base of the assembly, a channel section is fitted, which supports the glass laterally and has sufficient depth to accommodate the cumulative downward expansion of the facade.

Joints between the glass are totally exposed to the weather, and rely for their efficiency solely on the

7.18 Willis Faber Dumas at Ipswich.
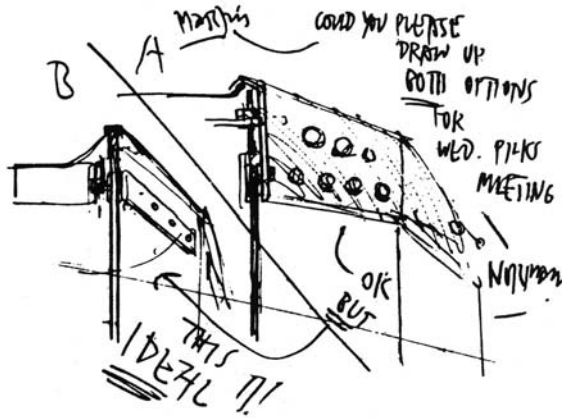
7.19 Original sketch of clamping strip at head of assembly at Willis Faber Dumas.

7.20 Attachment between glass fin and facade at Willis Faber Dumas.

properties of the silicone-based sealant and the correctness of its application.

The whole system was designed to be capable of accommodating errors in the concrete frame of 50 mm in any direction.

Within ten years Pilkington had reduced the means of securing toughened glass to a flush counter-sunk machine screw fitting. This fitting, known as Planar, was first used on Briarcliff House, Farnborough, by Arup Associates and at the Renault Centre by Foster Associates (Fig. 7.21), where 4 m × 1.8 m glazing was restrained using 'spider' connections back to the horizontal steel framing at 1.33 m centres (Fig. 7.22). Later, the span between fittings was increased at Lime Street Station, Liverpool, where 1.95 m × 1.05 m glazing was fixed back to a vertical steel framing at 1.95 m centres (Fig. 7.23 a and b). Generally, a rule of thumb is that Planar fittings should be connected on a grid of pick-up points approximately 2 m square in order to reduce the deflections between the fittings. Fittings for double glazing typically comprising 10 mm outer toughened glass, 16 mm air space and 6 mm

7.21 Renault Centre glazing.
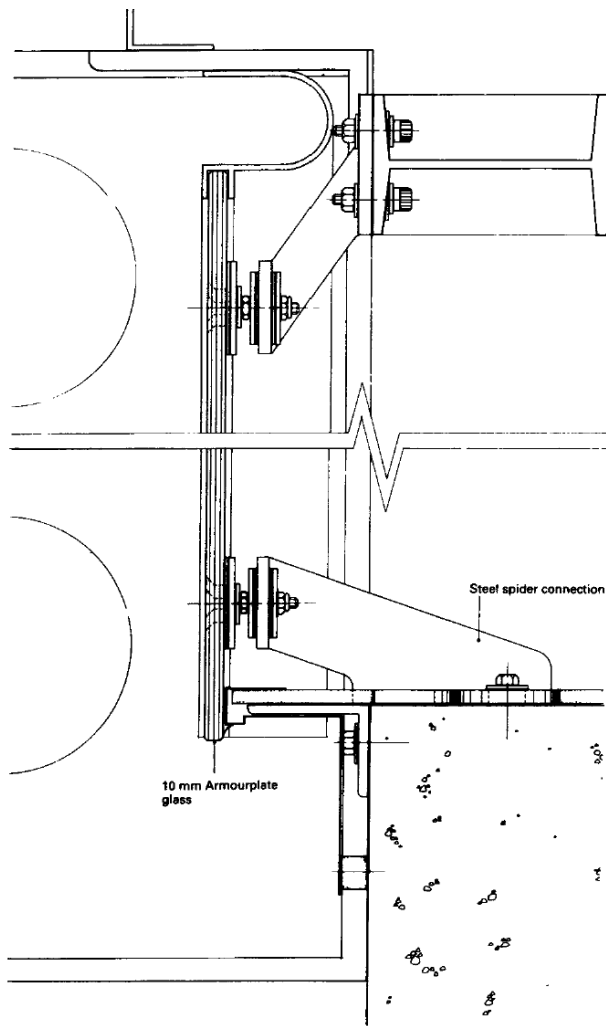
7.22 Detail of glazing fitting at Renault.

Steel spider connection

10 mm Armourplate glass

7.23a Spans of glazing at Parc de la Villette.

inner toughened glass were first used on the Porsche UK Headquarters, Reading, by Dewhurst Haslam Partnership in the form of 4° rooflights.

Later (1989) developments in reducing the number of supports for suspended glazing included East Croydon Station by Brookes Stacey Randall Fursdon

(Fig. 7.24), where cast stainless steel outriggers are used to reduce the effective span of the glass between fittings. Thus the span of the 12 mm toughened glass is reduced from 3000 mm to 2400 mm.

The vertical mast is held at its head and base by stainless steel castings with an articulated head detail, to accommodate the vertical and differential movement between the structure and the vertical
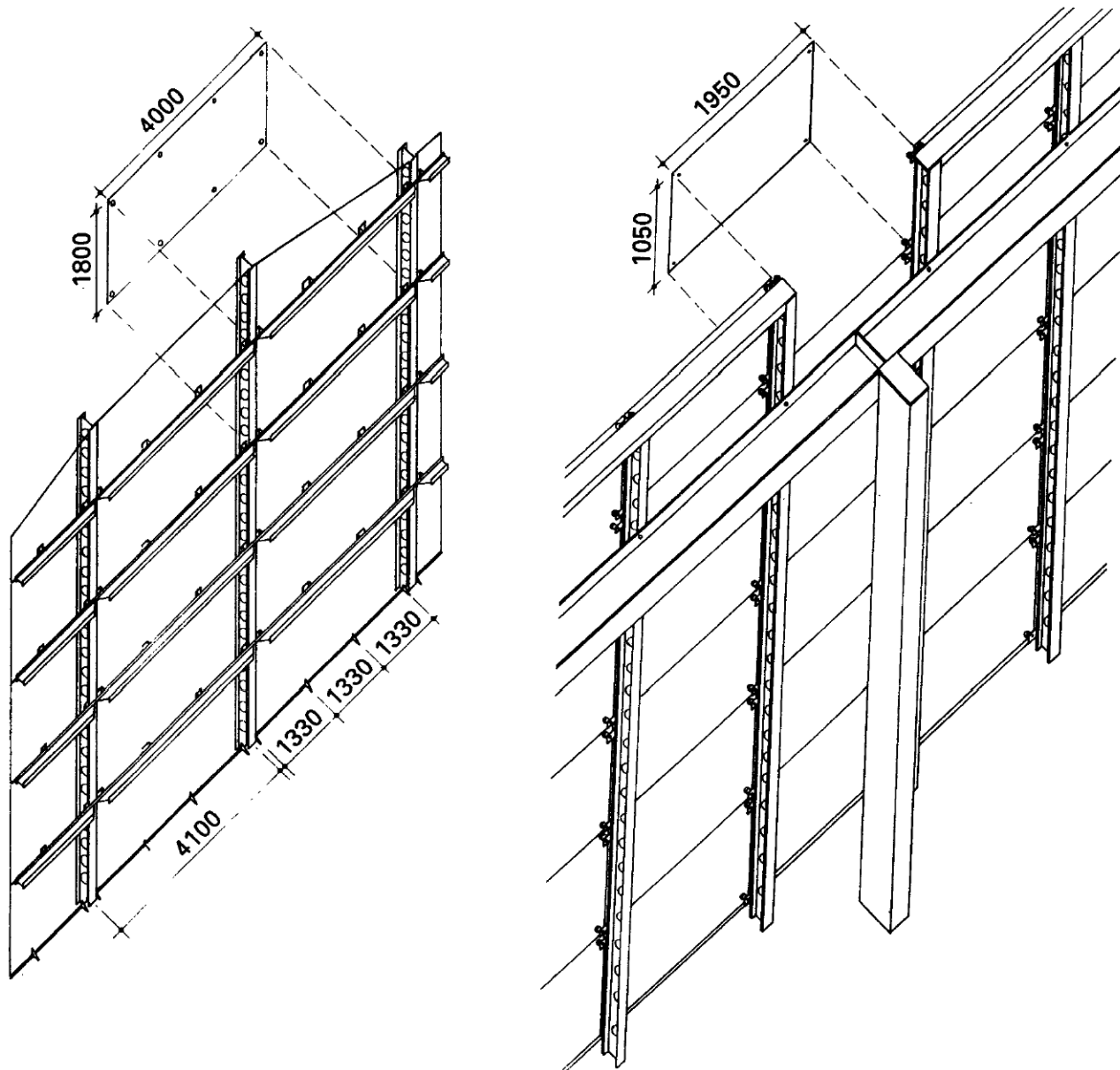
7.23b (contd) Spans of glazing at Renault (left), and Liverpool Street (right).

7.24 East Croydon Station (architects: Brookes Stacey Randall Fursdon).

7.25 Detail at head of glazing.
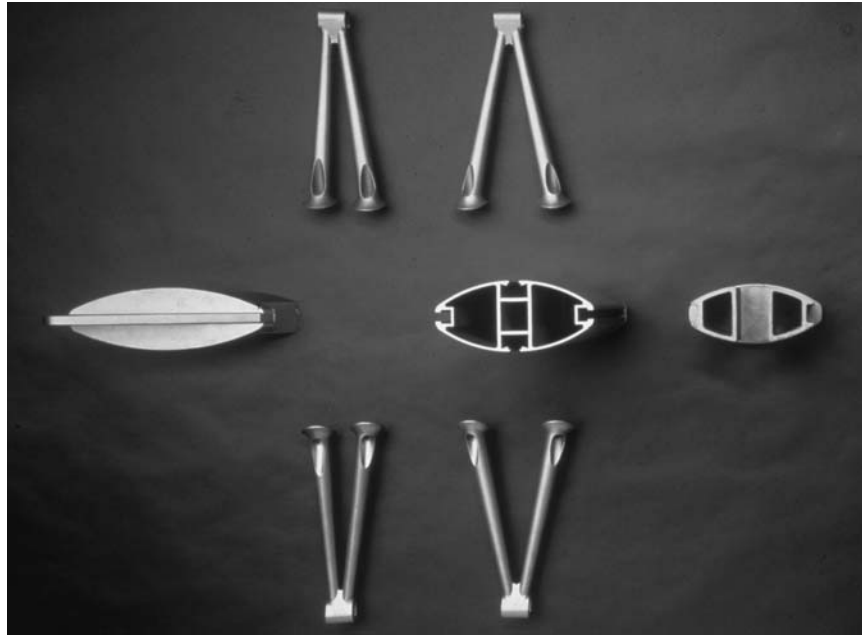
7.26 Cast stainless steel outriggers.
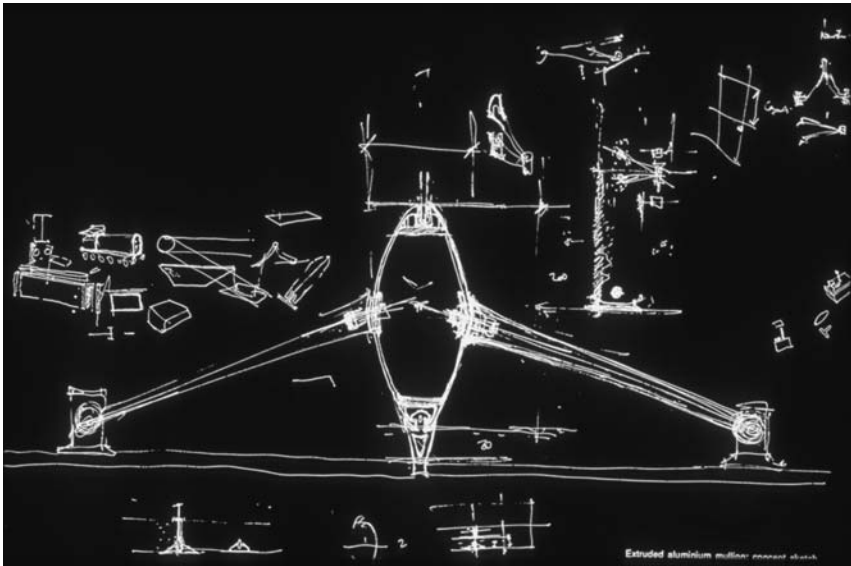
7.27 Plan detail of glazing at East Croydon Station.
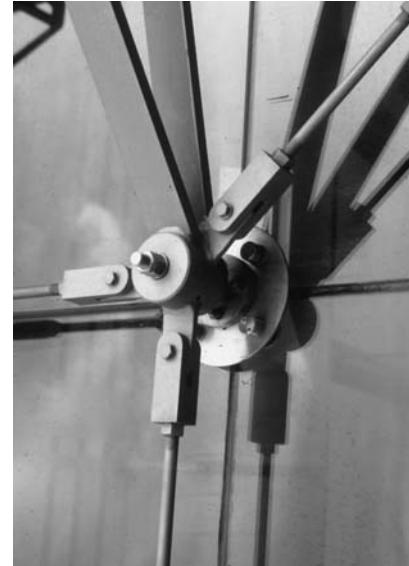
7.28a Financial Times glazing.

7.28b Suspended glazing at Financial Times Building, London (architects: Nicholas Grimshaw & Partners).

cladding (Fig. 7.25). The 10 mm clear toughened glass roof glazing is suspended below stainless steel twin armed castings using 902 mark 2 Planar fittings (Figs 7.26, 7.27).

Other elegant solutions for the problem of picking up the four bolts for the fittings include Nicholas Grimshaw's stainless steel 'dinner plates' at the Financial Times Print Works (Fig. 7.28) and Mark Goldstein's aluminium bronze cast brackets for 111 Lots Road in London.

A refined support system for suspended glazing is the stainless steel wire wind bracing developed for the Parc de la Villette in Paris by Rice, Francis and Ritchie, for Adrien Fainsiber in 1986, where a special detail allowed a span between the main structure of 8 m square, and enabled flexing of the wire-braced intermediate structure and also alignment of the glass (Figs 7.29, 7.30).

An increasing diversity of supply of countersunk and plate patch fittings were then developed. As well as the Pilkington Planar fitting these would include countersunk fittings by Greenburg UK, Marcus Summers UK, MAG Design & Build UK, Seele in Germany, Eckelt in Austria and GME in Belgium (Fig. 7.31).
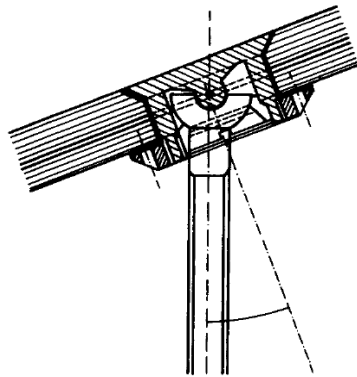
7.29 Detail of Parc de la Villette glazing.
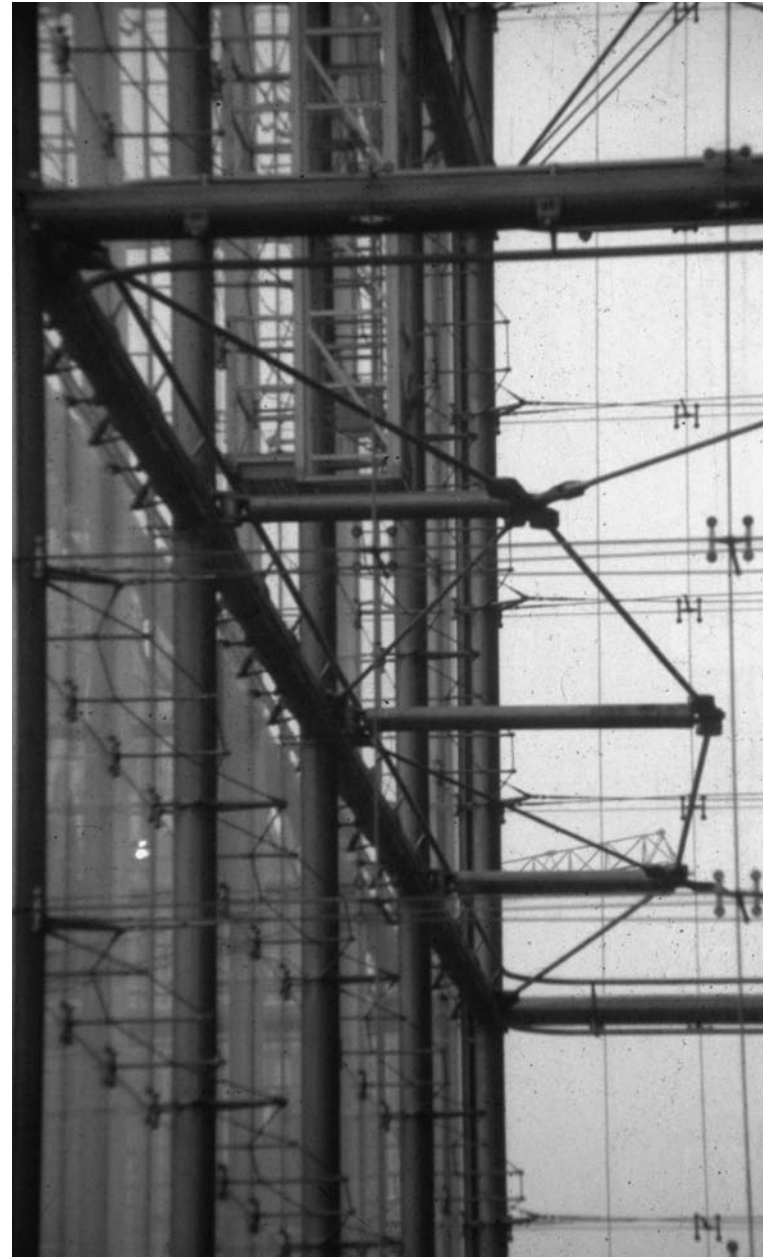
7.30 Parc de la Villette structure support of glazing.
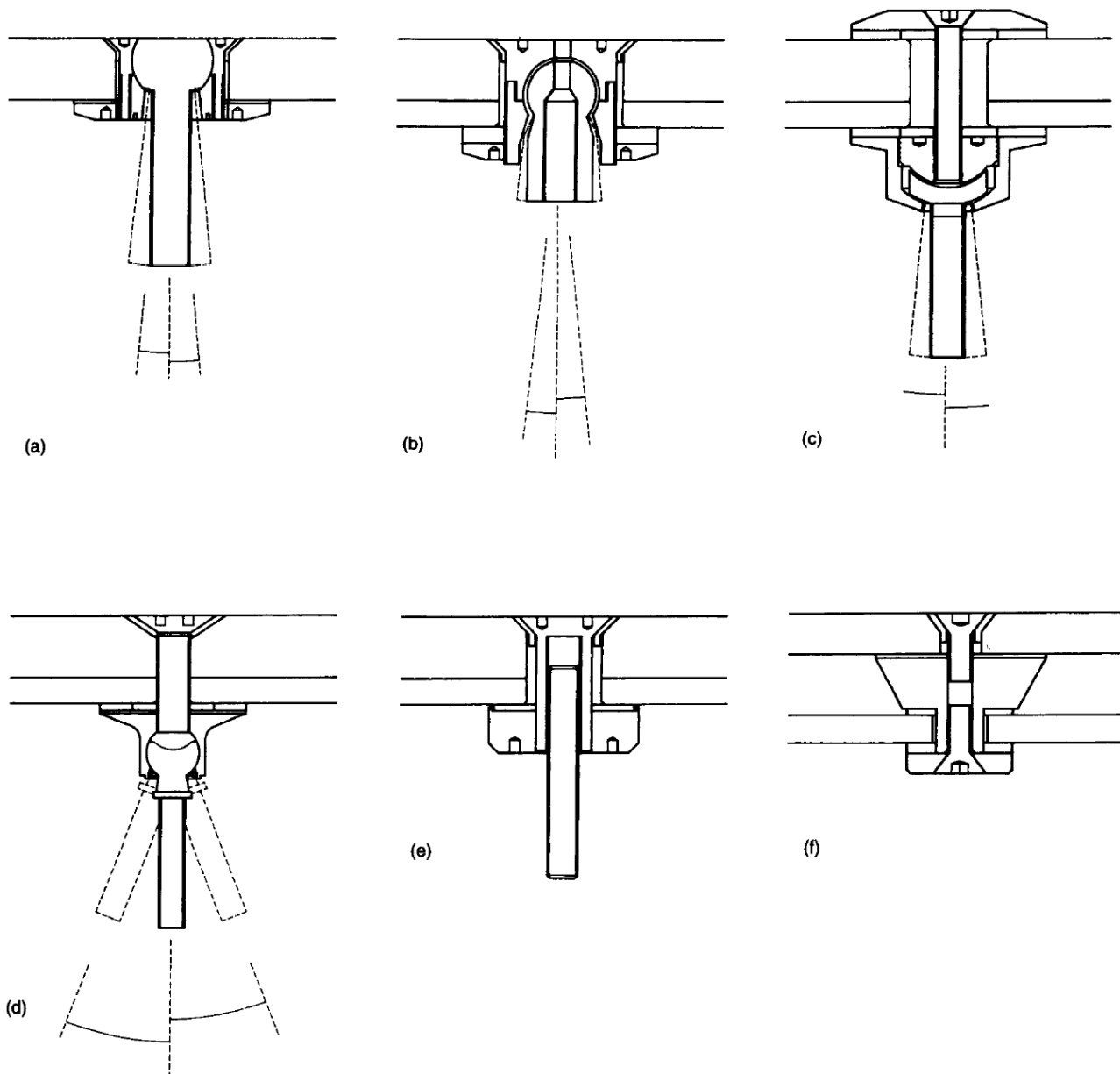
7.31 Variants from Planar and RFR fittings with different degrees of movement: (a) Marcus Summers, UK; (b) GME, Belgium; (c) Seele, Germany; (d) Eckelt, Austria; (e) Eckelt; (f) MAG Design & Build, UK.

At the Montmartre funicular transport station project in Paris, Groupe ALTO developed a new countersunk fitting in conjunction with the manufacturers, SIV. This has a 48 mm face diameter, compared with the 28 mm diameter of the Planar fitting. The 12 mm plus 8 mm laminated glass (not toughened) provides canopies in which the glass is moulded to the desired radius and the fittings are able to accept 22° of rotation (Fig. 7.32).

In most cases the span of the supporting framework is one or two storeys, but at the Reina Sofia Museum of Modern Art in Madrid (architect: Ian Ritchie) the entire glass envelope to each 36 m high tower is suspended by stainless steel rods from roof level. Here, each panel of glass is individually supported. The size of each panel is determined by wind load, economic glass thickness, structural module and heights between floors. Each 12 mm thick pane of toughened glass is 2966 mm wide by 1833 mm high and is suspended from one central panel fitting on its top edge (Fig. 7.33). Flush Planar fittings at each corner provide fixing points for the wind bracing system.

It is noticeable on some projects using suspended glazing that many four-way joints, each nominally 10 mm, are misaligned. Manufacturers are helping to improve this by reducing acceptable variations of the glass size and increasing the accuracy of drilling the countersunk holes. This is being achieved by investment in new automated machinery, which has the added facility of polishing edges.

The maximum available size of glass for use with the Planar system is limited by the need for the glass to be toughened. The toughening process of pre-stressing the skins by heating them to 620°C followed by controlled cooling increases the load capacity of the glass. The maximum size available therefore depends on the size of the toughening ovens at St Helens. The present maximum size for clear toughened glass is 4.2

m × 2.1 m. Some European glassmakers have larger or different aspect ratio ovens and so there is the opportunity for Pilkington to collaborate with them or invest in larger ovens also. Pilkington can combine Planar with body tinted glasses, reflective glasses, double glazing, low-emissivity coatings and even the screen printing of dots or frettings. All these additional processes influence the maximum size.

Of all the types of cladding discussed in this book, suspended glazing and structural glazing are undergoing the fastest development in the application of new systems and environmental control.

Silicone-bonded glazing

Throughout Europe, there has been a considerable growth and development in the use of structural glazing, predominantly to form the non-loadbearing glass envelope of major building projects.

The end walls of the Sainsbury Centre, UEA (Fig. 7.34), installed by Clark Eaton in 1976, remain one of the most elegantly and minimally detailed assemblies of clear annealed glass, 15 mm thick, stiffened by 25 mm, 600 mm wide, full-height glass fins. When Solaglass replaced two units, owing to their size, 2.5 m × 7.5 m, they could only be supplied as 15 mm annealed glass by Saint-Roch of Belgium, edge finished by Solaglas in Coventry. The maximum size of toughened glass is primarily governed by the toughening oven. Pilkington's current maximum size for toughened glass is 4.2 m × 2.1 m. Where larger sizes are required, Plyglass can offer laminated glass up to 6 m × 3.2 m.

It is interesting to note how under BS 6262:1982 it would not have been possible to have replicated the end wall of the Sainsbury Centre, as the standard would have required the first 800 mm from ground level to be toughened or laminated glass. Requirements have changed since its issue, and on 1 June 1992

7.32 Curved laminated glass used at Montmartre funicular.

the revised Building Regulations' Section N: Glazing Materials and Protection was introduced. This specifically recognizes the strength characteristics of annealed glass; it is in effect a relaxation of the requirements of BS 6262. Diagram 2 states the size of annealed glass that can now be used. At 15 mm thick the panel size is not limited by Section N, and the end walls of the Sainsbury Centre are once again a legitimate solution for a building in England and Wales. However, one must remember that annealed glass is not tolerant to local stress build-up of a loadbearing bolted fitting.

The facade glazing of the Sainsbury Centre is restrained against wind suction by a continuous vertical silicone seal only (Adshead Ratcliffe AR1081 translucent). It is designed to withstand wind loads up to 1400 N/m². Overall, the glass is retained by a glazing channel set flush with finished floor level and fin boxes

at the head of the glazing, which are fixed back to the main structure via slotted holes to accommodate tolerance and movement.

In contrast, many current assemblies opt to back up the silicone seal by using a mechanical patch plate or a countersunk fitting. The success of fittings such as Pilkington's Planar has encouraged their use in glass fin assemblies, where it is questionable if in fact they are necessary.

More recent applications of silicone-bonded glazing that have caught architects' imagination include the Sculpture Pavilion at Sonsbeck, The Netherlands, by Benthem & Crouwel Architekten. This pavilion is a direct development of the earlier relocatable house for Jan Benthem in Almere (Brookes and Grech, 1990, p.5). By taking the idea of structural glazing even further, this pavilion is a totally glazed 24 m long, 6.2 m wide,

3.65 m high transparent box (Fig. 7.35). Unfortunately, the museum was designed as a temporary building, and has now been dismantled. A similar proposal was developed by the Faculty of Architecture (course leader Ulrich Knaak) for a pavilion at Aachen University (Fig. 7.36). Such proposals, offering maximum transparency through the use of large sheets of glass and minimizing the apparent means of support, have been adopted

almost as a style of architecture identified with the 1990s. Brookes Stacey Randall Fursdon's use of curved toughened glass and cast stainless steel fittings at the Thames Water Tower, London (Anon, 1996), led the judges of the RIBA Awards 1995 to comment: 'Such is the inspirational nature of the tower that the panel felt its qualities transcended the question – is this sculpture or architecture?' (Fig. 7.37).
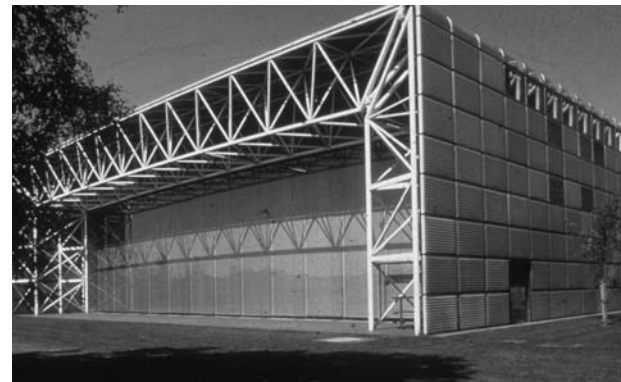
7.34 Sainsbury Centre glazing.
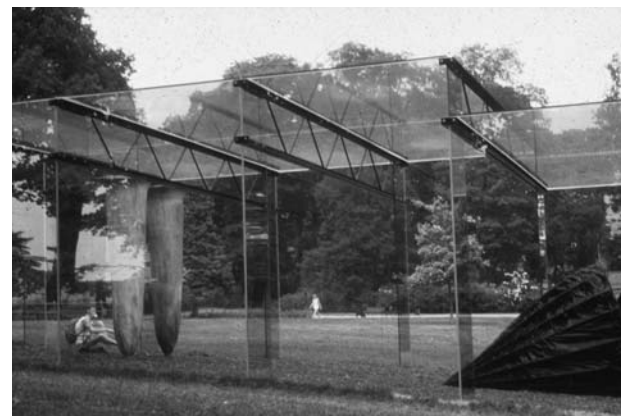
7.35 Sculpture Pavilion, Sonsbeck (architects: Benthem and Crouwel).

7.33 Suspended glazing at Reina Sofia Museum, Madrid.

7.36 Pavilion at Aachen Faculty of Architecture.

7.37 Detail of Thames Water Tower, London (architects: Brookes Stacey Randall Fursdon).

Glass

Finally a few words on the glass itself. There are now many forms of glass and glazing available to provide environmental control and thermal performance. These include:

– variable-transmission glazing;
– liquid crystal laminates;
– electrochromatic glass;
– low-emissivity coatings;
– transparent insulation;
– screen-printed glazing;
– fixed shading systems.

These are described in detail by Brookes and Stacey (1992), pp. 29–41. Also, Button and Pye (1995) summarize much useful technical information.

The weakening effects of nickel sulphide inclusions in glass have been the source of much debate. Annealed glass is unaffected, but in toughened glass spontaneous fracture may occur in use, because of the expansion of the unstable nickel sulphide as it changes phase over time. It is not practical to detect these inclusions by a non-destructive process. However, heat soaking can be carried out after toughening. This is a destructive quality control procedure, as panes with inclusions will shatter during the soaking process, but it is an essential specification requirement.

At present there is no standard method for heat soaking, although it is generally recommended that all toughened glass shall undergo a heat soaking regime to achieve a maximum residual risk of one nickel sulphide failure per 40 tonnes. There is no applied symbol to indicate that glass has been heat-soak treated. It is therefore important that the current Kitemark should be modified to identify when a toughened panel has been heat-soak treated.

In applications where thermal shock is considered a potential risk, but the strength of toughened glass is not required, it is possible to specify a heat-strengthened glass, as it has approximately twice the mechanical and thermal strength of annealed glass.

Research into improving the thermal performance of double-glazed units continues. It is now possible to specify a double-glazed unit which has low-E coatings on surfaces 2 and 3 with a gas-filled cavity between to achieve a U value of 1.1 $W/m^2°C$. Pilkington and BASF have together been carrying out research into a granular aerogel, which provides a transparent insulation layer achieving U values between 0.5 and 1 $W/m^2°C$. This is now supplied by Flachglas of Germany, a Pilkington subsidiary.

Photovoltaic glass, recently considered only an experimental technique, is rapidly becoming a cost-effective option, but it has yet to be seen integrated into a major building facade.

Finally, developments in laminated toughened glass have allowed engineers and architects such as engineer Robert Nijsse, working with architects Kraayvanger Urbis on their own offices in Rotterdam, to build an all-glass bridge using a combination of 10 mm clear toughened glass, PVB laminate and 6 mm Eco-plus low-E glass for the walls and two layers of 15 mm toughened glass bonded with a PVB laminate to form the floor (project architect: Dirk Jan Postel). This is an interesting example of collaboration between engineer architect and fabricator. Having produced this all-glass bridge, Robert Nijsse believes 'it would now be possible to make just a glass tube without the supporting beams' (Fig. 7.38). The challenges of the next generation of suspended and structural glazing are enormous.

7.38 Laminated toughened glass as used at the glass bridge in Rotterdam by engineer Robert Nijsse.

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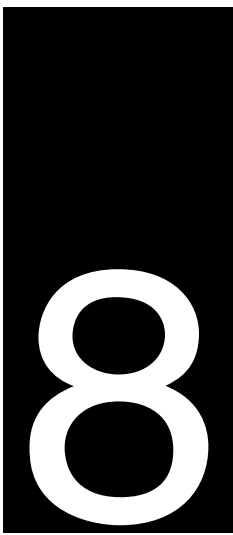
8 Timber cladding

Introduction

As a material for cladding, wood has come back into vogue in Europe only in the past fifteen to twenty years. The modernists used steel, aluminium, glass and concrete not only for their technical qualities, but also for their appearance. The investments involved in wood manufacturing are relatively low, and there are many relatively small factories with moderate capacity throughout Europe. This situation is not beneficial for the research and development of new products and techniques that require big investments. These two factors – the disinterest of the designers and the lack of development – reinforce each other and have led to wood being associated with traditional building in various 'neo-' styles: Neo-Western, Neo-Classical and so on.

Another difference between timber and other materials is the level of knowledge that is incorporated into the cladding system. Many proprietary systems are the result of substantial research, with the knowledge generated used to design the system parts including the fixings. The manufacturer of the system offers a guarantee for fitness for purpose, provided it is applied in the prescribed fashion. Most such systems are erected by specialised facade building contractors, who therefore take responsibility for its correct application. The situation differs in the case of timber, whereby correct installation usually becomes the responsibility of the main contractor, who may not have been chosen for his knowledge of timber

cladding. Moreover, architects cannot rely on the manufacturer of the system, because there is no system.

One of the first examples of the use of wood in eye-catching architecture is Renzo Piano's travelling exhibition pavilion for IBM. Piano did not use wood as a cladding material but did research one of the problems of wood, the connection, and showed how this can be solved in an elegant way by the use of cast aluminium fittings (Figure 8.1). Between 1984 and 1998 Herzog & de Meuron built the Wohnhaus im Hof, in Basel, Switzerland (Figure 8.2), with a timber construction in the gallery and a timber facade. In 1998, David Chipperfield designed the Rowing Museum in Henley-on-Thames, UK. It is a hybrid construction of concrete and steel, with a finely detailed oak cladding. This building is a good example of how timber can be used without the traditional image, and in a crisp, refined way (Figure 8.3).

Wood is still rarely used in tall (high-rise) buildings. Although wood is cheap, it tends to be seen as less durable than concrete, glass, stainless steel or aluminium. If, when necessary, the cladding can easily be replaced, the client can be convinced that wood is a realistic alternative.

The material and its properties

Trees give us the material we call 'wood', also known as 'timber' (or 'lumber' in North America) when used in construction. Wood is derived from two main types of tree: conifers, and the broad-leaved deciduous trees. These two types of wood are often referred to as 'softwood' and 'hardwood' respectively, although by no means all coniferous wood is actually softer than the

8.1 Travelling exhibition pavilion for IBM (architect: Renzo Piano)

8.2 Wohnhaus in Hof, Basel (architect: Herzog & de Meuron)

8.3 Rowing Museum, Henley-on-Thames (architect: David Chipperfield)

hardwood varieties and some hardwoods are much softer. The two main groups comprise many different species of tree, and hence many different types of wood. Moreover, every individual tree is different, depending on the location and conditions of its growth. The differences between groups, species and individual trees account for the differences in the physical properties of the resultant wood.

Where wood is used in construction, a number of properties are particularly relevant. They include its natural 'anistropy' (see below), the effects of changing humidity, vulnerability to biological damage by fauna (insects, crustaceans and termites), fungi and bacteria, flammability and thermal insulation properties in relation to strength.

Anisotropy

Wood is 'anisotropic', i.e. its properties are directionally dependent and vary lengthways, radially and tangentially, with the grain and across the grain. The structural cells of both coniferous and deciduous wood are aligned lengthways, as are (most of) the channels which transport nutrients during the tree's lifetime. The maximum tensile and compressive load is markedly lower in the radial and tangential directions than in the axial direction (Figure 8.4). The tensile strength parallel to the grain or fibre varies from 30 to 140 N/mm^2 according to the type of wood. The compressive strength varies from 20 to 75 N/mm^2. These values depend on the type of wood, its individual grain pattern, the number of 'knots' and the moisture content. All stated values are theoretical, in that they are derived from tests on small, physically perfect samples. The standard values for actual use in construction are much lower, and vary from country to country in practice. The marked variance in strength can be due to the slope of grain, knots or splits in the wood. Major differences can be seen between the
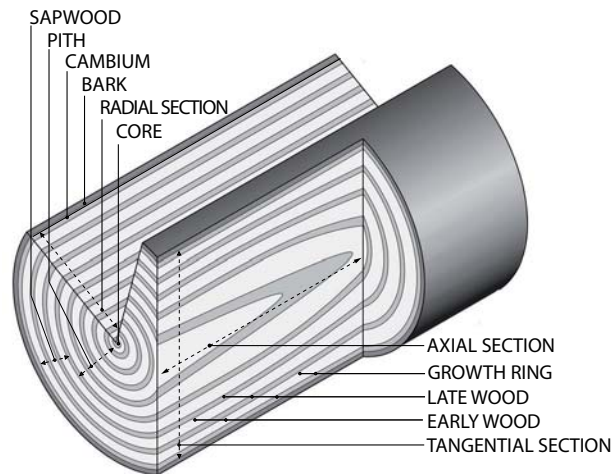
8.4 The treetrunk, structure and terms.

various types of wood, and even between two samples taken from the same tree. The tensile strength (s_{uts}) across the grain is just 5% of that parallel to the grain. This accounts for the propensity of wood to split, and is a major factor to be taken into account when determining the form, number and size of the fasteners to be used.

A significant advantage of wood is that, alongside a good strength-to-weight ratio, it also offers a reasonable degree of thermal insulation. Here too, the values measured parallel to the grain differ from those measured radially or tangentially to the grain.

Sensitivity to changing humidity

Wood swells (expands) and shrinks (contracts) under the influence of moisture content, doing so far more in the tangential or radial direction than in the axial direction. The degree of shrinkage depends on the type of wood; in some species it can be up to 10% in the tangential direction when exposed to a reduction in moisture content from 30% to 12%. In approximate terms, the ratio of shrinkage in the axial, radial and tangential directions is 1:10:20. Expansion and contraction can generate significant forces. Wood can actually fracture a masonry construction in which it has been incorporated. A 2.5 m tall woodframe wall structure (with upper and lower horizontal plates separated by vertical posts) can shrink by 2.5 to 3 mm if the moisture content falls from 20% to 10%. A log wall of the same height can shrink 80 mm when dried down from 20% to 10%.

Durability

'Durability' refers to the material's ability to fulfil its intended function, both technical and aesthetic, over time. A high moisture content reduces the strength of the wood, but within the normal range of variation of moisture content in use, loss of strength is not significant. In the case of exterior cladding, however, the main threats to durability are biological. Many potentially harmful organisms thrive in a humid environment. Exposure to ultraviolet light can result in bleaching, as can exposure to moisture. Loss of colour of unfinished wood by light and water is unavoidable, and indeed is often a desired effect. However, problems arise if some parts of the cladding are more exposed to the elements than others, whereupon loss of colour will be uneven and unattractive. Moreover, because wood has a natural acidity (with a pH value between 4 and 6), mild steel will corrode more rapidly when exposed directly to moisture. Particularly when the wood has a high tannin content, this can lead to severe staining of wood. It is therefore preferable to use stainless steel fasteners.

The useful working life of a wood structure or cladding depends on:

- the natural durability of the wood;
- the environmental conditions;

- the use of preservation techniques and, to a limited extent finishing;
- the detailing of the construction.

Natural durability

Natural durability, measured in terms of the wood's ability to withstand damage by the fungal moulds which cause 'dry rot' and 'wet rot', varies according to the type of wood concerned. Under European Standard EN 350-2, woods are classified into five 'Durability Grades ' (see Table 8.1).

All sapwood timber will fall into category 5.

The wood is tested by means of prolonged embedding in moist humus-rich sandy soil. These conditions are more severe then will ever happen in facades.

Wood is also susceptible to damage by some marine borers, insects and their larvae and termites. No clearcut classification according to durability in this regard exists as yet, but we can state that wood which offers adequate natural resistance to moulds (or which has been treated to protect against moulds) will also be resistant to the other types of biological hazard. Woods used for exterior cladding are shown in Table 8.2.

Table 8.1 Durability according to heartwood's resistance to fungal moulds

Description	Category	Likely useful working life (in years)
Extremely durable	1	> 25
Durable	2	15–25
Reasonably durable	3	10–15
Low durability	4	5–10
Not durable	5	< 5

Environmental conditions

Durability depends in part on the conditions in which the wood is used. Here, a system of 'risk categories' is applied, from 'interior applications' (Category 1) to 'wood in saline water' (Category 5). European Standard EN460 states whether a particular type of wood requires preservation treatment prior to use in a certain risk category (see Table 8.3). When totally immersed in water, and hence isolated from oxygen-dependent harmful organisms), almost all wood varieties are 'durable' (50–100 years) to 'extremely durable' (> 100 years). When wood is exposed to the elements, the moisture content can vary between 13%

Table 8.2

	Durability class
California redwood (*Sequoia sempervirens*)	2
Douglas-fir (*Pseudotsuga menziesii*)	3
European redwood (*Pinus sylvestris*)	3/4
European spruce (*Picea abies*)	4
European larch (*Larix decidua*)	3
Siberian larch (*Larix siberica*)	3
Western red cedar (*Thuja plicata Donn*)	2
Iroko (*Chlorophora excelsa*)	1
European oak (*Quercus robur*)	2/3
Dark red meranti (*Shorea spec.*)	2
Kambala (*Milicia excelsa*)	1
Selangan batu (*Shorea atrivernosa*)	1/2
False acacia (*Robinia pseudoacacia*)	2
Merbau (*Intsia bijuga*)	2
Ukwekan/sapeli (*Entandrofragma cylindricum*)	3
Jatoba (*Hymenaea courbari* L)	1
Tatajuba (*Bagassa guianensis Aubl.*)	1

and 25%. At a sustained moisture content of 21%, wood is at risk of damage by moulds. All sapwood timber (taken from the outer zone of the trunk in which there is still an upwards flow of sap prior to resination) is extremely susceptible to moisture. As the table indicates, only wood in Durability Grades 1 and 2 can be used untreated without risk.

Treatment

The simplest, but not the best, way to extend the useful working life of non-durable wood is to apply a protective coat of paint, varnish or oil, although not all types of wood are suitable to these kinds of products. Paints, stains, etc. have no bearing on the 'durability' of

Table 8.3

Risk category	Durability grade of heartwood*				
	1 Extremely durable (> 25 years)	2 Durable (15–25 years)	3 Reasonably durable (10–15 years)	4 Low durability (5–10 years)	5 Not durable (<5 years)
1 Wood used in interiors, permanently dry environment (relative humidity less than 70%)	O	O	O	O	O
2 Wood sheltered from the weather, some risk of temporary moisture	O	O	O	(O)	(O)
3 Wood used outdoors but not in contact with the soil	O	O	(O)	(O)–(X)	(O)–(X)
4 Wood in permanent contact with soil and salt water	O	(O)	(X)	X	X
5 Wood in salt water	O	(X)	(X)	X	X

- O Natural durability is adequate.
- (O) Natural durability is adequate in most cases, but treatment is advised for some exceptional applications
- (O)–(X) Natural durability may be adequate, but preventive treatment could be necessary depending on the type of wood, its permeability and the application.
- (X) In most cases, preventive treatment is required, although natural durability may be adequate for certain applications.
- X Preventive treatment is always required.

the wood itself, but only reduce moisture gain, prevent bleaching and possible surface deterioration. All such substances demand periodic maintenance and will only extend the life of the cladding for a finite period. Wood can also be impregnated with chemicals which are toxic to biological attack ('chemical modification'). However, such chemicals may pose a threat to human health or the environment during application, use (due to leaching), or disposal (combustion). A number of substances, the best-known being creosote, are now subject to restrictions or have been banned outright. Nevertheless, we can state that the factory-applied methods currently in use are environmentally safe. The production of chemically treated wood is subject to strict control under European legislation, and further restrictions may be forthcoming.

The most effective method of impregnating wood with the protective chemicals is by vacuum and pressure in which the agent is applied to the fully finished (sawn, planed and profiled) wood. The exact penetration required is determined by the usage conditions. Only with full penetration (which is often not possible to establish) is any further working of the wood possible. In all other cases, there is a protective coating around the (untreated) core, which precludes further sawing or planing. The chemicals suitable for use on exterior cladding are:

- organic biocides (e.g. tebuconazole, propioconazole and quaternary ammonium compounds);
- creosote (oil) (This is the oldest known wood treatment substance, in use for well over a century during which time the composition has been perfected. However, it is now banned for use in many applications);
- water-soluble bifluorides;
- boron is the basis of many modern preservatives and is not toxic to flora and fauna.

A further method of treating wood is 'thermal modification', which has been used in one form or another since the Stone Age. Archaeologists have found the remains of foundation piles which had clearly been exposed to flames for some time prior to use. Heat permanently alters the structure of the wood, removing sugars and resins and narrowing the capillary channels. Moisture is then less able to permeate the wood and removing sugars eliminates the food source for moulds and insects. The method is applied on industrial scale in a process which dries low-durability wood (Grade 4 or 5) and then steam-heats it to a temperature of approximately 200˚C. The wood is then cooled by spraying it with water, whereupon the final moisture content is a constant 4%. The resultant product is known as 'Thermowood'. The main points of this process and the resultant product are:

- a permanent modification of the cell structure takes place;
- the weight of the wood is reduced by approximately 10%;
- elasticity and bending strength are reduced;
- any dead knots can become dislodged;
- moisture absorption becomes 40–50% lower than that of untreated wood;
- stability is improved and distortion reduced;
- the colour darkens to a mid-brown;
- durability is increased to (at least) Grade 2 by virtue of the absence of nutrients for moulds;
- wood can still be finger-jointed and/or glued;
- water-based paint adheres as well as to unmodified wood.

Thermowood is suitable for use in manufacturing door and window frames, floors, decking and cladding. The process has not been patented. Another

thermal modification process (which has indeed been patented) is used by the Dutch company Plato. It is a three-phase process in which the wood is not heated to such a high temperature and therefore retains its mechanical properties better than Thermowood. In some cases, those properties are actually improved. The process can transform wood of Durability Grade 4 into Grade 1. Even poplar wood, usually Grade 5, becomes suitable for use with no further treatment.

Detailing of design

Careful detailing of the construction can extend the useful working life of wood considerably. In particular, it is important to ensure that the wood is not exposed to moisture for long periods. The 'end grain' of wood is particularly susceptible to water intrusion, since the vessels which were responsible for the passage of moisture when the tree was still alive are exposed. Because water is retained in joints of up to 7 mm in width (due to adhesion and capillary action), it is essential to design the joints between non-durable wooden elements with a joint of at least 10 mm (7 mm for a minimum joint and 3 mm to allow for the swelling). All joints with a direct, closed joint present some risk. Joints formed by two pieces of wood at an angle to each other ('mitred') are potentially vulnerable due to the differences in expansion and contraction in the axial and tangential directions. The joint can then open, allowing water to penetrate (Figure 8.5).

Strength and thermal insulation

The relatively high thermal insulation quality of wood is due to the large, air-filled pores. However, the greater the moisture content, the lower the insulation index. The weight of the material making up the cell walls is the same in all woods, regardless of species. The difference in volume mass between woods is due to there being a different ratio of pores to cell walls. Light
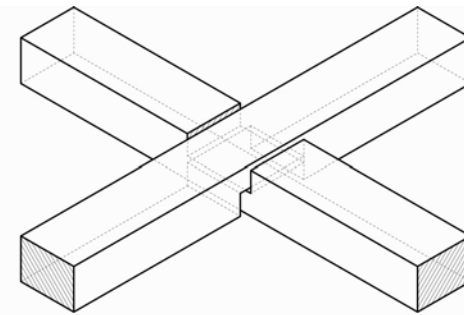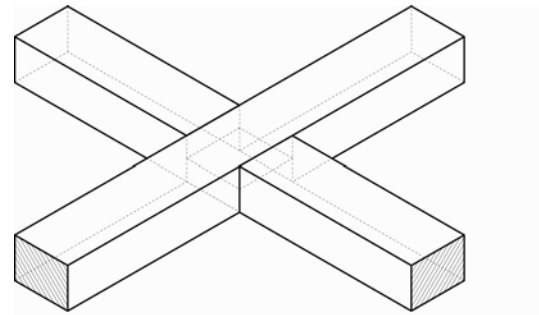
8.5 Joints in wood are vulnerable due to differences in expansion and condition in axial and tangential directions.

woods therefore insulate better but are less strong because there is less actual wood mass per cubic metre. The table below presents some indicative values for comparison.

Flammability

Wood is flammable, yet due to its good heat insulation properties can actually have a flame-retardant benefit. This is particularly true of the charred outer layer which will quickly develop during a fire. In contrast to aluminium or steel, which lose their strength and rigidity at relatively low temperatures, wood will continue to fulfil its structural function even at high temperatures. It burns at the rate of approximately 40 mm per hour, depending on the density of the wood.

Table 8.4

Material	Volume mass kg/m³	Heat conduction coefficient	
		I Dry: m²K/W	II Wet: m²K/W
Swedish pine ⊥grain	430	0.113	0.134
Red meranti ⊥grain	600	0.144	0.162
Merbau ⊥grain	820	0.185	0.22
Plywood	500–800	0.11–0.16	
Mineral wool	35–200	0.04	
Steel	7800	52	

(Source: Netherlands Wood Centre)

The insulation value of the charred layer is some four times greater than that of the wood itself. However, in the case of exterior cladding, which may be only 16 mm thick, these aspects are not relevant.

To reduce the risk of fire spreading via a wooden cladding, this can be treated with a special fire-retardant paint. However, this treatment is not very effective and detracts greatly from the natural character of the wood. A better option is to impregnate the wood with fire-retardant salts. Some woods can then be classified as Grade B flammability (Extremely low flammability). The European fire classification standards relate flammability to density. Most wood types are classed as Grade D (Flammable) when untreated; Western Red Cedar is Grade E (Extremely flammable). A number of dense hardwoods are listed as Grade C (Flammable). This system of classifying various woods and wood products has now been standardized throughout the European Union. However, the exact requirements for exterior cladding vary between member states.

Imperfections

A number of possible shortcomings in the wood affect its suitability as an exterior cladding material.

Knots, slope of grain and the differences in expansion and contraction in the three directions can lead to various distortions (Figure 8.6):

Twist   Cup   Spring   Bow
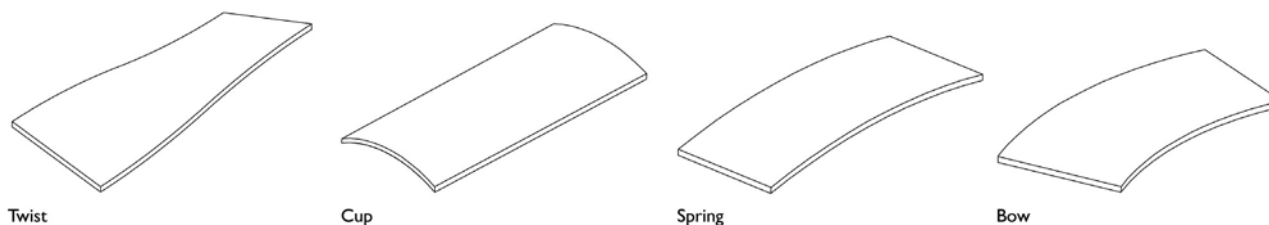
8.6 Possible distortions of wood

- twist (warping): the wood is distorted about the axial direction;
- cup (concave or convex): the sawn section acquires a dish-shaped cross-section. This phenomenon is sometimes known as 'panning';
- spring: deviation of the straight line measured over the smallest axis;
- bow: deviation of the straight line measured over the largest axis.

Elements with a round or rectangular cross-section tend to distort upon drying out, depending on the wood's original position in the tree trunk. Circular cross-sections then become elliptical, square cross-sections become rectangular or even rhomboid (Figure 8.7). The pith of the tree is particularly susceptible to splitting and its use should therefore be avoided. Thin, wide sections will curve inwards towards the heart of the tree. This must be borne in mind as floor, roof and cladding elements are best applied so that any future curvature is always convex to the viewer. This not only improves the appearance but ensures that the joints are more secure. Sections are sawn from the trunk slightly oversized (2–3 mm) on each side (nominal size), and are then planed to the exact (finished) size before actual incorporation into the structure. If the timber is then sawn again, further distortion may occur, especially in hardwoods like iroko. Grooves routed into the reverse of the element may reduce the risk of curvature.

Sustainable forestry

The world's forests are of vital importance to the survival of all organisms which rely on oxygen. Trees convert carbon dioxide into glucose (the building material of the tree itself), oxygen and water. This is the main reason that governments, environmental organizations and the timber industry world-wide have for many decades taken steps to restrict the environmental impact caused by the excessive cutting down of trees, and have been encouraging 'sustainable forestry'. Other reasons include the prevention of soil erosion and the maintenance of biodiversity.

Between 1990 and 1995, the world lost 13.7 million hectares of its total forest area of 3.89 billion hectares. The net loss has now been reduced to 9.4 million, the reduction of 12.3 million hectares in the tropics being offset by 2.9 hectares of newly planted forests in the temperate climate zones. The harvest of wood for commercial purposes accounts for only a very small proportion of the deforestation seen in the tropics. A far greater area is lost due to the expansion of large- and small-scale agriculture, use for firewood, the construction of roads and railways, open-cast mining and new dams. Much forest area is also lost as a result of urban expansion.

Sustainable forestry is important, not only in terms of maintaining the forest areas, but also for the social and economic stability of the regions concerned. Today, approximately 4% of the total forested area and some 25% of the world's managed forests are certified 'sustainable'. There are huge differences between the regions in this respect. The vast majority of forests in the temperate climate zones are managed in a sustainable way. In many tropical and subtropical countries, however, the situation is more precarious. While some countries have introduced certification systems, very few logging companies are actually certified. In other countries, particularly in Africa, even the certification systems have been slow to emerge. In any event, certification efforts have not been enough to address demand.

There are four important organizations responsible for certification. The Forest Stewardship Council (FSC) is responsible for 51.32 million hectares of certified forest, while the PEFC Council (Programme for the Endorsement of Forest Certification schemes) has 57.78 million hectares. The Sustainable Forest Initiative (SFI) has 45.59 million hectares and the Canadian Standards Association (CSA) oversees 47.38 million certified hectares. If we then add the holdings of a number of smaller organizations, a total of 217 million hectares of forest are certified 'sustainable'. Any harvesting of wood which is not conducted according to national legislation is regarded as illegal. In countries with a less stable political and economic system, enforcement of the law can be difficult given the economic relationships, poor infrastructure and 'corruption culture'. The certifying bodies seek to ensure the continuity of ecological functions (such as the forest's bio-regulatory task), the maintenance of biodiversity and avoidance of (or compensation for) the undesirable side-effects of forestry. The continuity of the socio-economic and socio-cultural functions of the forest must also be ensured. A sound management system must be in place, and there must be watertight procedures to ensure that the timber is traceable from source to finished product.

Most of the softwood varieties produced by the well-managed forests of the temperate climate zones are not suitable for use in exterior cladding without treatment. Exceptions are Western red cedar and Californian redwood, both of which are classed as Durability Grade 2. Other woods must be treated or undergo thermal modification. There are few hardwood varieties from the temperate zones which have a high durability and which are suitable for exterior cladding. Those that do exist are relatively expensive. In practice, the choice is limited to European oak (Durability Grade 2/3), false acacia (Grade 2) and sweet chestnut (Grade 2). These woods are more expensive, in short supply or available in a restricted range of sizes. The subtropical and tropical forests offer a far larger range of woods in Grades 1 and 2, but wood from certified holdings is scarce and more expensive than the softwood from the temperate zones. Nevertheless, there is now an increasing import of FSC certified timber from Central and South America, available at competitive prices.

Solid wood and wood products

Solid wood

Once the branches and bark have been removed, entire tree trunks can be used as 'roundwood', but in most cases, the trunk is sawn into boards or battens with a rectangular profile. The trunks can be either 'cross-sawn' or 'rift sawn'. In the latter method, all saw-cuts are parallel, whereby the faces of the resultant planks each have a different angle to the tree's growth rings. In quarter-sawn wood, the rings are all relatively perpendicular to the face of the board (Figure 8.8). Although more expensive to produce, quarter-sawn lumber tends to be more dimensionally stable, while rift-sawn wood is more likely to distort in the ways illustrated previously. Rift-sawn wood shows the typical 'flame' grain which is so appropriate to decorative applications (Figure 8.9). After sawing, the boards are squared (the sides sawn off to produce a straight edge), and sawn again into beams or planks (usually) of standard dimensions. Those standard dimensions differ from country to country. The Northern European lumber sizes are generally applied to spruce and pine, while other woods are subject to the grading rules of the countries of use. In the Netherlands, the Dutch NEN standards apply to much of the timber supplied, although some is subject to the sizing used in other countries, such as the Nordic Timber Grading Rules.
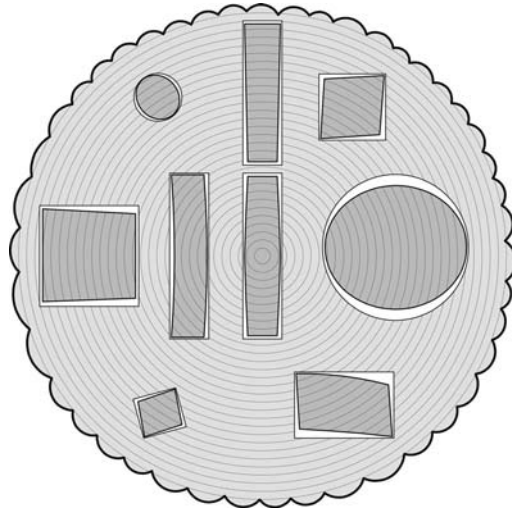
8.7 Deformation of timber according to its original position in the trunk.

8.8 Cross sawn wood.

8.9 Rift sawn wood.

Wood products

As a natural product, wood has a number of properties which need to be taken into account when used for construction or exterior cladding. We have already considered anisotropy and the tendency to warp or distort. In addition, we must think of the finite sizes available, the propensity of solid wood with a larger cross-section to split, the presence of knots, the direction of the grain, and the resulting major variation in strength between different sections. Moreover, much wood is unsuitable for use due to aesthetic considerations (knots and grain). The process of sawing, edging and re-sawing the trunk into boards or lengths results in considerable waste. The remnants of wood which are produced when sawing tree trunks into lengths of solid wood, or entire trunks which for one reason or another are unsuitable for sawing, can be used in the manufacture of wood products. There are now many
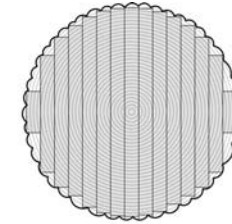
such products on the market, manufactured by taking wood waste (sawdust, chippings or veneer) and bonding them together with resins or mineral-based adhesives. The exact choice of bonding agent will depend on the intended purpose and climatic conditions during use (Fig. 8.10). The resin-bonded products can be classed into the following main groups:

- laminated beams;
- layered products (e.g. plywood);
- products made up of chips or fragments (e.g. chipboard);
- products manufactured from wood fibre.

Brief descriptions of the products that can be used for cladding or in curtain walls are given below. (Source: Ambrozy and Giertlová) They appear in two categories, laminated beams and layered products.

Product   Laminated beams
Structure   Relatively short, knot-free boards with a rectangular cross-section, glued to each other under pressure. The grain of each section runs in the same direction. The boards can also be joined laterally with a butted joint or finger joint, the latter providing the most effective joint.
Wood types   Usually standard spruce or pine, although other woods can be used.
Bonding agent Modified melamine resin, phenol/resorcinol-based resin, polyurethane resins.
Applications   Supporting structures (beams, joists) and in door- and window frames. In facades it can be used for curtain walling.
Dimensions   It is possible to produce pieces with a large cross-section and considerable length which will not split or warp. Curved pieces are also possible. The anisotropic properties remain: swelling and shrinkage according to moisture content, and the differences in permissible stress load // grain and ⊥grain. Because the wood is dried before assembly, the swelling or shrinkage in interior conditions will be very small.
               Lengths 13–40 m, breadth 60–320 mm, height 100–2300 mm.
                                                                          (Source: Ambrozy Giertlova)

Layered products

In this group we shall consider plywood, Laminated Veneer Lumber (LVL), and 3- and 5-ply solid wood sheets. Plywood is by far the most commonly used product in this group. The others are included here by virtue of their relatively recent introduction and their use as an exterior load-bearing element.

Product   Plywood
Structure   Thin sheets (0.5 to 4 mm) are shaved from the tree trunk while rotated on a lathe. It is also possible to cut flat layers from the trunk, which serves to maintain the natural markings of the wood. The sheets, or veneers, are then laid on top of each other with the grain running in different directions, and glued under pressure. The sides are then trimmed and can be tongue-and-grooved. An odd number of layers is always used so that the grain of the outer two layers runs in the same direction. This helps to maintain stability. Many sheets will have a 'good' side and a 'not so good' side. Triplex consists of three layers and comes in thicknesses of 3 to 12 mm. Plywood consists of five or more layers.
Wood types   Many different woods and qualities are used in the production of layered products. The outer, visible layers may be of a different wood than the interior layers.
Bonding agent Phenol, phenol/resorcinol or resorcin resin.
Dimensions   Thicknesses of 6 to 80 mm, in sheets of 2500 × 1220 mm, 3100 × 1530 mm, and 2440 × 1220 mm. In most cases, the grain runs parallel to the longest side. Other dimensions exist, depending on the wood type.

Applications	The number of possible applications is as great and varied as the number of different layered product types available. In exterior wall structures, plywood can be used within a frame of uprights and cross-pieces ('noggins') to form a load-bearing or reinforcing construction. In this case, five-layered moisture-resistant plywood is generally used. For exterior cladding which must meet certain aesthetic requirements, plywood of which (at least) the outer layer is of a high durability wood, in most cases a tropical hardwood, is used. When using plywood in an exterior situation, it is important to ensure that edges and fixing points are properly protected. The edges remain vulnerable because of the exposed end grain even when durable wood types and waterproof adhesives are used because of the risk of delamination. Vacuum and pressure preservation techniques can be applied on plywood.

Product	Laminated Veneer Lumber (LVL), *Furnierschichtholz* (FSH), parallel-grain plywood.
Brand names	Kerto-S, Kerto-Q, Microllam.
Structure	Thin layers glued together with the grain in the same direction (Kerto-S), or with a few layers laid with the grain in the transverse direction (Kerto-Q). The butts of each layer are offset in relation to each other. The advantage of this product compared to plywood is its far greater strength in one direction. In addition, much larger pieces can be produced: 1800 mm in breadth and up to 26 metres in length. Each layer is 3.2 mm thick (Kerto) or 2.5 to 4.7 mm in the case of Microllam.
Wood types	Kerto: European spruce (*Picea abies*)
	Microllam: Douglas-fir (*Pseudotsuga menziesii*); Southern Pine (*Pinus*)
Bonding agent	Phenol resin
Applications	Kerto-S is mainly used as a linear construction element. Its structure gives it a far greater strength lengthways than in any other direction, and it is stronger than plywood. It can be used for timber curtain-walls.
	Kerto-Q is used if load-bearing ability in two directions is required. In sheet form, it is used in roofs, floors and walls with a structural function, and is also used in joists and uprights with high lateral stress. The sheets are extremely level with high stability and good aesthetic properties.
Dimensions	Max 1800 (b) × 26000 mm (l)
	Thicknesses: Kerto-S . . . 27–75 mm
	Kerto-Q . . . 27–69 mm
	In Kerto-Q, one of the five layers is laid with the grain perpendicular to that of the other layers.

Adhesion is necessary

Cutting

Lamination

Rotary peeling

Veneer

Chipping

Long strand

Short strand

Particle

Refining   Fiber

Finger-joint

Finger-jointed lumber

Laminated wood

Cross lamination

Plywood

Parallel lamination

LVL
(Laminated veneer lumber)

Parallel lamination

PSL
(Parallel Strand Lumber)

Parallel orientation

OSL
(Oriented Strand Lumber)

Cross orientation

OSB
(Oriented Strand Board)

Random

PB
(Particle board)

Random

FB
(Fiber board)

8.10 Production methods of wood products.

A construction typology

Wood can be incorporated into outer walls in many ways. A very old but still current construction type is that of the 'log cabin', with tree trunks stacked one on top of the other, providing a load-bearing, water-tight and insulating structure. However, this construction is no longer common, due to the high cost of materials and the limited thermal insulation offered. Today, wood is more commonly used to protect against rain in the form of boards, sheets or tiles which are affixed to a wooden, metal, concrete or masonry supporting structure. It is also used for door frames and window frames, and in curtain walls, possibly with wooden (sandwich) panels.

The stacked log construction

This construction method can be seen in many historic buildings in Europe, Asia (Russia and Japan), and North America. Although still in use, it is generally only applied to buildings which do not have high requirements in terms of energy efficiency and comfort. The relatively high thermal insulation value of wood, combined with the extreme thickness of the walls renders those walls reasonably efficient insulators. Nevertheless, a thickness of 330 mm would be required to meet the current European standards of 2.5 m^2 K/W. The use of secondary walls (interior or exterior) and some form of insulation material is possible, but the swelling and shrinkage of wood as moisture content varies must be taken into account. Any structural supports attached to or within the stacked log wall must allow for the vertical movement of the wall. The moisture content of wooden structures exposed to the elements can vary between 13 to 25%. A 2.5 m high wall of white deal (*Picea abies*) would therefore be subject to shrinkage of between 50 and 55 mm when dried down from a moisture content of 25% to 13%. If no

allowances are made for this, there can be major problems involving the connections with other structural elements like interior walls, which are far less susceptible to movement. The uprights of door frames and columns will account for particular problems, since wood does not expand greatly in the linear direction. The joint between the topmost lintel of the frame and the wall above it must therefore allow adequate space for swelling and shrinkage of the wall. If the wall also supports a floor or roof, it is not possible to incorporate columns into the load-bearing structural system. Although the problem is limited to the initial shrinkage of logs, this effect has to be taken in account in all detailing. Despite this constructional disadvantage, this form of insulation is now common in log buildings.

Tree trunks used in this form of construction can be subject to various degrees of preparation, ranging from merely removing the bark and making a notch on one side, to complete planing, squaring-off and incorporation of tongue-and-groove joints. Walls are stable by virtue of the bracing of the cross-walls, forming corners and junctions. The connections between the walls must be such as to prevent the collapse of one wall when under stress, either externally applied or that within the wood itself. One of the methods applied results in the typical structure that we associate with the stacked log cabin, with the logs crossing each other and protruding at the corners (Figure 8.11). If this appearance is undesirable, other measures must be included to ensure stability. Such measures may involve a different design of the connections. The beams are often grooved along the underside to control splitting. When wood dries, it is the outer faces which shrink first. If the outer diameter becomes smaller while the inner core cannot shrink to compensate, there will be splits along the length of the trunk. Some form of profiling can be used to improve the seal between the beams and will also enhance lateral stability.
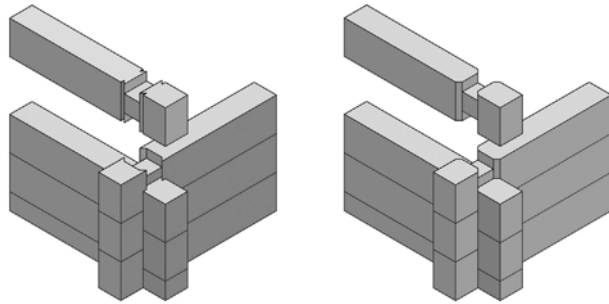
8.11 Typical corner details in stacked log construction.

Stress caused by wind is transferred by the logs or beams to the transverse walls. Where the exterior walls are supporting a floor or roof construction, they will be more stable.

Conradin Clavuot designed his School Hall in St Peter, Switzerland, as a stacked log construction (Figure 8.12). The logs form walls of up to 36 m in length and 7.5 m in height, supporting both the floor and the roof. A cladding system of horizontal boards has been applied to the exterior and a thermal insulation layer has been put into the cavity. The posts supporting the cladding system are attached to the main inner wall by means of sliding connections (Figure 8.13). Because the interior conditions don't change very much during the use of the building, the wall is not very susceptible to movement. Nevertheless, it was considered necessary to incorporate this system, as the wood lost a considerable quantity of moisture immediately following the construction phase and therefore underwent marked shrinkage. Space has also been allowed for movement above the doors and window frames (Figure 8.14). Because the roof sinks as the load-bearing walls shrink, a malleable seal has been included between the roof and the uppermost part of the exterior cladding. The cladding is of larch sections. The joints between them remain more or less open

8.12 School Hall, Conradin Clavuot, St Peter, Switzerland

throughout the year, depending on the weather conditions.

Curtain walls

Curtain walls can be constructed using wood applied in a 'unitised system' as described in 'Metal Box Framing' in Chapter 7 (Figure 7.4). The wooden posts and lintels of the frames are pre-glued in the factory, whereupon they are fixed to the supporting structure on site prior to being sealed. Glass or panels can be placed into the frames in the factory or on site. Where the panels are connected there is always a double post and lintel. In comparison with a stick system this double posts and lintels are less elegant.

When using the 'stick system', the connections between posts and lintels must be made on site. Because wooden connections have to be glued in all exterior structures, and because glued connections
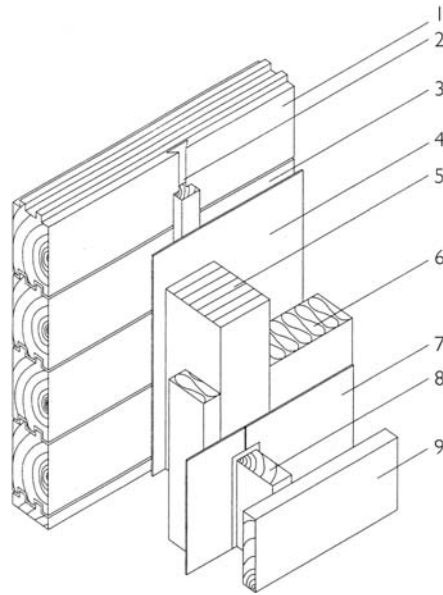
8.13 Wall construction of School Hall, St Peter
1. Load bearing logs. 2. Sliding dovetail connection. 3. Cavity for electrical installation. 4. Air tight barrier. 5. Post. 6. Thermal insulation. 7. Breaker membrane. 8. Batten. 9. Larch cladding.

are difficult to get right in this situation, wood has not been used as a material for the frames of curtain wall systems until relatively recently. However, metal connectors have recently become available, manufactured by companies such as Raico of Germany (Figure 8.15). Depending on the type used, glass weighing up to 700 kg total can be incorporated. The width of posts and beams is the same as that of most metal systems, at 60 mm. In the heaviest type, it is necessary to make a groove in the frame in order to ensure that any torsion applied by the glass to the horizontal lintel is transferred into the upright. The problem of the effective exclusion of water and the mounting of the rubber seals may be solved by using aluminium profiles with rubber strips. The wood provides the necessary
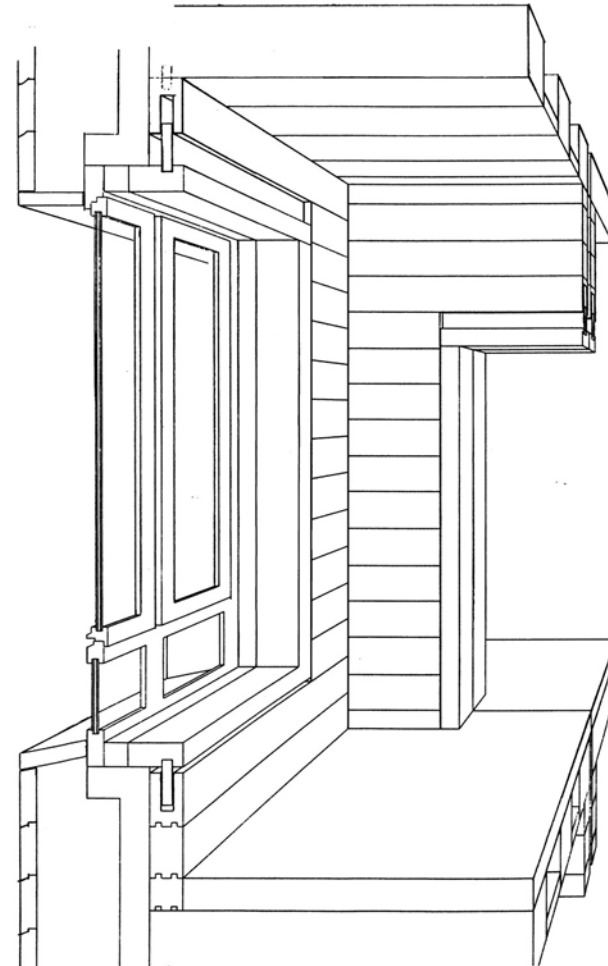
8.14 Sliding connections between window frame and wall in School Hall in St Peter.

strength and rigidity. However, affixing the aluminium profiles to the wooden frames can be problematic: wood doesn't expand lengthways when temperature rises, while aluminium expands rather a lot. This difference in expansion causes problems unless slotted holes are used and enough allowance has been taken

into account. The combination of wooden load-bearing elements, metal connectors and glass panels has been slow to emerge because the manufacturers tend to focus on one particular material. The manufacturer of a combined system must have expertise and production resources covering two or more materials, which demands significant investment. The use of different materials derived from different manufacturers gives rise to problems of liability and guarantees. However, an advantage of wooden frames compared to aluminium is the extremely low thermal expansion coefficient which means that little allowance has to be made for distortion or movement. Besides exterior walls with aluminium ridge-pieces, we now see those with wooden ridge-pieces. An example is the design of Mahler, Günter Fuchs for the University of Wiesbaden (Germany) (Figure 8.16). This usage calls for extremely durable wood (or wood which can be treated to become extremely durable). In most cases, the frames are made of laminated wood, or Laminated Veneer Lumber (LVL). These materials are available in

longer sizes, have high stability and high stress-bearing ability due to the elimination of flaws such as knots and splits, and the constant quality of production.

Wood claddings

Wood and wood products in various forms can be used as an exterior cladding material in all climate zones. The type of wood to be used and the detailing of the construction will depend largely on the climate in the region concerned. In countries which have long, dry winters (with temperatures below freezing point) and dry summers, moisture within the structure has more time to evaporate than in a maritime climate. Cladding which could last many decades in Sweden, Austria, Switzerland or Germany would fare considerably less well in the Netherlands, United Kingdom or Norway. In the dry parts of Canada and the United States, Red Cedar is regularly affixed directly to the supporting structure without any cavity, a practice which is inadvisable in the European maritime climate zones.
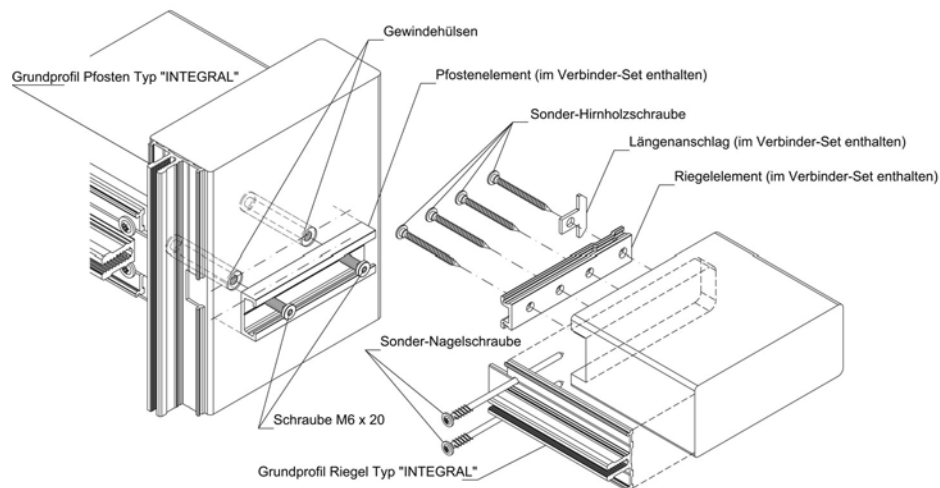
8.15a Metal connectors in timber curtain wall (Raico, Germany)

8.15b The connections between post and beam can be made on site with two screws.

8.16a Horizontal joint in timber curtain wall, University of Wiesbaden (architects: Mahler, Günther, Fuchs).

8.16b Vertical corner joint, University of Wiesbaden.

The cladding may comprise boards applied horizontally or vertically, or may be panels or shingles. A number of cladding options are shown in Figure 8.17. The method of attachment will depend on the dimensions of the wood and the degree to which these change with the weather. Panels which have undergone thermal modification will present fewer problems in this regard.

Table 8.3 shows the suitability of certain types of wood for use in exterior cladding and whether treatment is required. In principle, all woods in Durability Grades 3 to 5 should be treated before use.

Application

When used without a cavity (which is only possible in extremely dry climates and when using woods of Durability Grade 1 or 2), a breather membrame must be applied behind the cladding if the inner sheeting is not waterproof, because external timber cladding can only act as a rainscreen. The structure to which the
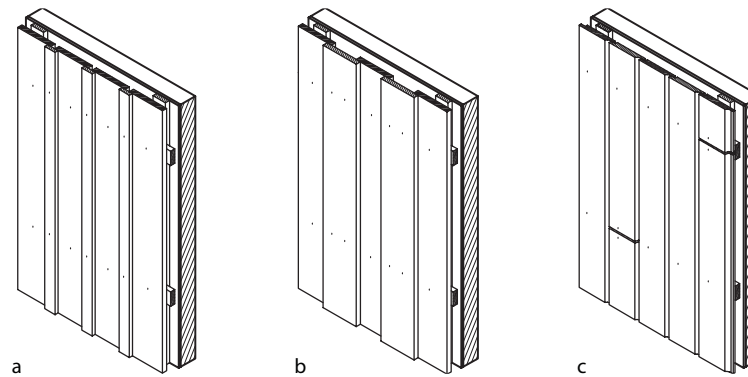
8.17a Cladding types with vertical boards. a. boards and battens; b. boards with lap; c. vertical shiplap.
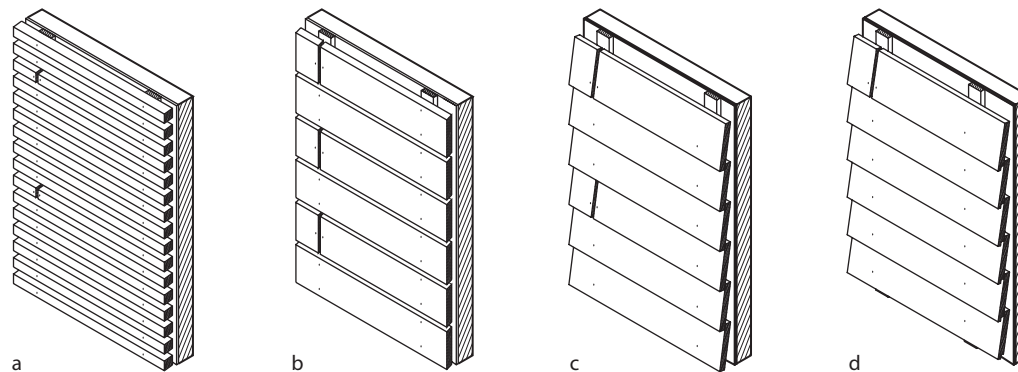
8.17b Cladding types with horizontal boards. a. battens with open joint; b. boards with open joint; c. weather boards; d. weather boards with profiled edge; e. feather edge or bevel siding; f. rebated feather edge/bevel siding; g. shiplap; h. channel siding.

cladding is affixed must be waterproof on the outside and vapour-proof on the inside. Moisture must not be able to accumulate behind the cladding structure. The use of a cavity (of 20–40 mm) is recommended in all cases and is indeed essential in most. This cavity must allow vertical ventilation. An advantage of horizontally laid cladding boards is that ventilation becomes easier to achieve. When the boards are horizontal, the supporting battens are upright, allowing a clear vertical ventilation flow. If the boards themselves are vertical, the battens behind need to be placed horizontally, which will impede the vertical airflow. It will be necessary to provide vertical counterbattens to ensure ventilation up the cavity (Figure 8.18). Horizontal boards also reduce the risk of water permeation. One advantage of vertical boards is that, used unfinished, they will bleach at a more even rate. Moreover, if the length of the cladding boards does not exceed the height of one storey and if a horizontal joint is made on the level of the floor, it is not necessary to include butt joints (since the length of the boards will corres-

pond with the height of each storey) (Figure 8.19). Figures 8.20 and 8.21 show other solutions for a continuous horizontal joint construction.
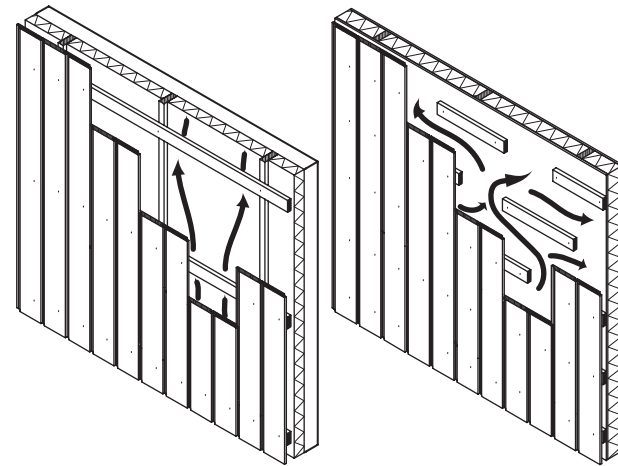
8.18 Two solutions for vertical air flow behind vertical boarding.
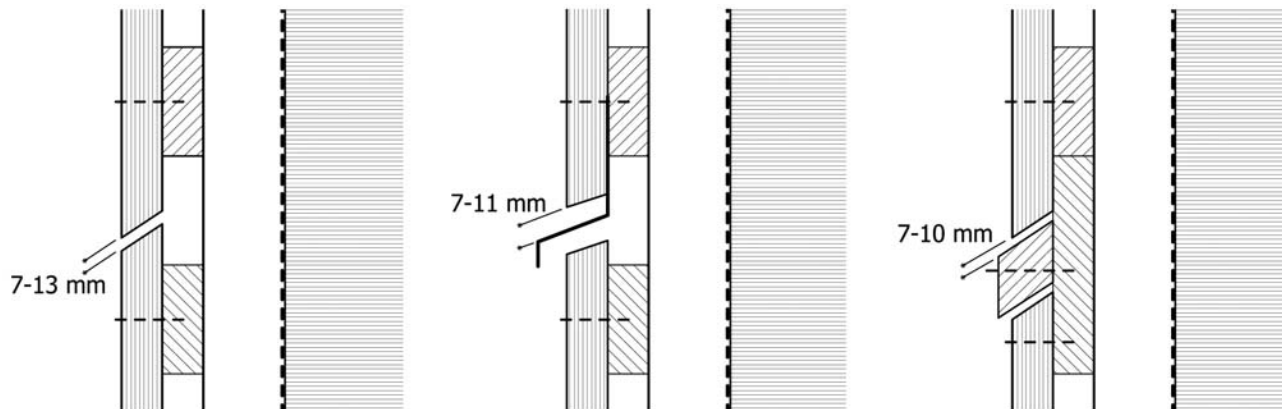
8.19 Typical butt joint in verbal boarding. This joint can be appplied when joints between boards differ in position.

8.20 Horizontal joint between vertical boards with aluminium profile, used when the length of the boards corresponds with the height of each storey.

8.21 As figure 8.20, but with a wooden profile. In this case the joint is not ventilated, which gives a higher risk of rot.

Sizes and relationship with the supporting structure

In most cases, the thickness of the cladding material will be between 18 mm (hardwood and WRC) and 19 mm (European spruce). Boards are commercially available in widths of 75 mm to 225 mm (in 25 mm increments) but boards wider than 150 mm are not recommended due to the likelihood of excessive swelling or shrinking. After planing and the cutting of any edging profile, the boards will be 145 mm. With an overlapping joint, the face width will be some 20–25 mm less again. With open joints, 7 mm must be allowed for the joint itself and 3 mm for tolerance. The face width will then be 155 mm. The centre-to-centre distance of the battens should not exceed 600 mm. Fixing materials such as screws and nails must be used at least 40 mm from the end of the board in order to prevent splitting. Accordingly, if butt joints are used, the battens must be more than 130 mm wide: an extremely uneconomical option. In practice, therefore, the fixing points are generally placed much closer to the edge of the wood, the risk of splitting being reduced by pre-drilling or the use of a single fixing point. A further option is to align all the butt joints and to use two supporting battens. All elements will then be of equal length and there will be a very visible pattern (Figure 8.22). Using this approach, it is also possible to prefabricate larger exterior wall elements which may already have the cladding fitted, or to mount the entire cladding on a frame which can then be affixed to the underlying structure. This is a good option where the cladding consists of battens instead of boards, since accurate placement is difficult on site. Any aberration will be immediately visible and it is therefore preferable to mount the entire assembly in the factory. Usually the boards are affixed to battens of treated softwood.

8.22 Cladding of green oak on the Rowing Museum, David Chipperfield, Henley-on-Thames.

Joints

The joint between the boards can be an open joint, lap joint or mated joint. Butt joints are not recommended because no matter how well the boards are lined up against each other, any unevenness, distortion or mounting space will cause a small chink in which water can be absorbed (by capillary action). The water will then be dispersed by ventilation only very slowly, if at all. The risk of rot is therefore greatest at the joints. Due to the natural swelling and shrinkage of the wood, there will always be a gap at certain times of year, or conversely the boards will press so tightly against each other that they will buckle.

According, open-joint constructions are now increasingly used. A waterproof but vapour-permeable membrane is then applied behind the battens at the back of the cavity, to prevent water from penetrating into the wall construction. The joints are designed in such a way as to minimize the penetration of rainwater and prevent absorption by capillary action. It is advisable to make the joint large enough to ensure that no capillary water remains, even when the wood

reaches its maximum dimensions in damp weather. In practice, this means a joint of 10 to 13 mm, when the boards are applied during the dry season. Open jointed boards should be chamfered so that they overlap and shed water to the outside. A tapered joint, becoming wider on the interior side, will promote drainage and reduce air pressure and thus reduce the amount of water which can pass into the cavity. This will also protect the breather membrane from ultra-violet light. Where boards are applied vertically with open joints, the supporting structure must be designed to ensure proper drainage, and the waterproof membrane must be resistant to ultraviolet light. David Chipperfield's design for the Rowing Museum in Henley-on-Thames (UK) provides a good example of the use of open joints.

The lap joint is seen in the non-profiled weather board, in bevel-siding for horizontal planking and in overlapping planking for vertical boards (Figures 8.17a, 8.17b). Where feather-edged siding (or bevel-siding) is applied, less wood is required and the total package is slightly narrower. If a better seal is required, elements with mated joints can be used (with a simple or 'Swedish' rebate). All edges of the boards must then be prepared accordingly. 'Channel siding' or 'shiplap joint' is a type of cladding joint that is particularly popular in North America. Tongue-and-groove joints are not recommended since they create a closed space in which water can accumulate. Moreover, particularly thick boards are required in order to provide a sufficiently robust tongue.

Mounting

Boards can be fixed with nails, screws, bolts and clips. Where boards wider then 150 mm are applied, especially in the case of open joints, two fasteners at each fixing point are needed. When nails are used, it is not necessary to take the swelling and shrinkage of the boards into account. The nails are flexible enough to follow the swelling and shrinkage of the boards due to seasonal variations in the equilibrium moisture content. At the ends of the boards, it is best to use only one nail, or predrilled holes, to prevent the boards from splitting. The fixing length of the nail should be twice the thickness of the board when annular ringshank nails are used. With ordinary nails this length should be 2.5 times the thickness of the board.

Where screws or bolts are used, and where the boards have a starting moisture content in the region of 16%, holes for screws or bolts should be approximately 2 mm larger then the diameter of the fasteners in order to prevent splitting of the boards. If boards are used with a higher moisture content, as with 'green wood', that diameter should be 4–6 mm. The fasteners should be positioned one quarter of the board's width from the edge. If the holes are much larger than the shaft of the bolt or screw, it is possible that inadequate fixing strength will be achieved, because the screwhead is not big enough unless washers are also used. The use of bolts or screws with an integrated rubber-covered washer will ensure that the screwhead is always centred and that the fixing will remain secure even when the wood shrinks. The screwheads and washers can also be countersunk if desired, but it then becomes important to ensure that enough space is allowed between washer and wood to allow for movement.

Where smaller overlapping boards are used only one fastener is needed at each fixing point. The fasteners should be positioned in the overlapping edge of the board, but allowing the overlapped board to swell and shrink (see Table 8.5).

The number of screws used, their size and their position are not so much determined by the weight of the boards as by the stresses that may be caused by the drying of the wood, and the resultant distortion.

Table 8.5

Distances between fasteners for cladding boards

Non-profiled weather board	30 mm from base
Bevel siding	30 mm from base
Swedish rebate	45 mm from base
Corner rebate	25 mm from base.
Open joints	Boards <100mm: 1 in the centre, Boards > 100mm: 2 pre-drilled (with washers)
Top-mounted	1 in the centre
Channel siding	25 mm from edge

8.23 Stainless steel clips for mounting boards.

Mounting onto the supporting structure will usually rely on stainless steel fasteners and washers. Tannin from woods such as western red cedar and oak will accelerate the process of corrosion in galvanized steel, and the iron will cause unsightly streaks on the wood, particularly if untreated. In principle, aluminium fasteners are also suitable for lighter boards which are not subject to marked distortion, since the maximum permissible load is less than that of the steel equivalent. Stainless steel clips have recently been introduced (Figures 8.23, 8.24) which allow an invisible mounting of rebated elements and allow for considerable shrinkage. The size of the joint is determined by the clips. The use of these clips is particularly advantageous in the case of treated (painted or stained) wood, since it is then unnecessary to perforate the paint or varnish with the fasteners.

Finishing

The boards may be supplied in their sawn state (with a slightly uneven texture) or may have been planed.

Woods of Durability Grades 1 and 2 can be used with no further treatment. They will gradually lose colour due to the effect of ultraviolet light and rain. Careful detailing of the design is essential to ensure equal discolouration. Sections below the roof line or balconies are less exposed to the elements and will therefore weather less quickly. This may result in a distinct contrast between the weathered and unweathered
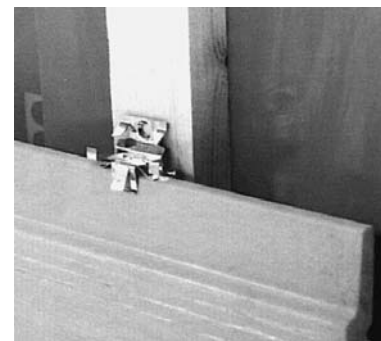
8.24 The application of the clips as shown in figure 8.23.

sections. Planed boards will discolour more evenly, but the planing process must be thorough to ensure no scuff marks or other irregularities, which will be particularly visible in use, especially if the boards are then painted. The adhesion of any finish to the boards will depend on the type of wood and whether they have been treated to enhance durability. A rough texture gives a better adhesion. Some wood treatments (based on oil) greatly reduce paint adhesion, sometimes to the extent that it is no longer possible to apply any form of liquid coating. Generally, substances soluble in water do not affect the paintability of the surface.

Claddings as sheets or shingles

Sheets

Plywood sheets can be used as exterior cladding. However, the risks are greater than in the case of solid wood boards. If anything other than the very highest quality of sheet is applied, and if anything but the greatest possible attention is devoted to the finishing of the edges and to the mounting, there is a substantial risk of 'delamination': the layers of the sheet will become detached from each other. Only plywood sheets with a facing of gaboon (*Aucoumea klaineana*) or sapele (*Entandrophragma cylindricum*) can be finished with a layer of transparent varnish. With all other types, a full-cover coating is required to provide adequate protection against ultraviolet light. Because the edges must also be protected, the sheets are cut to size and treated in the factory. The order dimensions must be extremely accurate since the sheets cannot be sawn again. (Suppliers impose these requirements in connection with the guarantee.)

The vertical joints between sheets must be at least 10 mm, preferably 20 mm. A drainage profile is often fitted to the horizontal joints in order to protect the upper edge of the sheet (in the same manner as in figure 8.20).

Mounting

The sheets can be mounted using staples, nails or screws. The heads of any nails or screws can be countersunk, or screwheads can be fitted with a plastic cap. This solution may be somewhat less attractive, not least due to the risk of streaking.

The sheets can also be affixed to the supporting structure with adhesives. As with all glued joints, this must be undertaken during dry weather, which poses a restriction. The adhesive itself must be thick enough and remain elastic enough to accommodate swelling by the sheets. A good mounting method is to affix the sheets to a wooden frame in a factory and then fit it to the supporting structure. The frame remains adjustable and can be removed if required.

In addition to plywood, there are also sheets of heat-hardened resins, reinforced with wood fibres. These are produced under high temperature and high pressure. The surface can be coloured or have a woodgrain photoprint applied. In effect, these are plastic sheets with the appearance of real wood. The sheets can be sawn into lengths and can be curved. The edges require no special treatment but they will remain dark in colour, which renders them less authentic in appearance than solid wood when subject to close inspection. This effect is exacerbated by the fact that the sheets are only 6 mm to 10 mm thick. The mounting method is the same as that for plywood. Although water permeation at the mounting points does not present any risk, it should be remembered that these sheets will expand and contract more than the plywood equivalents, and a greater tolerance in the mounting holes must therefore be allowed.

8.26 Shakes or shingles nailed on rough sawn boards. This method requires application of woodtypes with a high durability (grade 1–2)

8.25 Shakes or shingles nailed on battens. Counterbattens allow for ventilation of the cavity.

Shakes and shingles

Both are small boards with a size in the region of 50 × 300 mm. The difference between both is that shingles are sawn from a block and shakes have been split from a block. The surface of the first is smoother; the latter has the advantage that the vessels are not cut open, as in splitting the block the cut follows the structure of the wood. This prevents water from penetrating the vessels. The boards are nailed directly to a structure of battens and counterbattens with a ventilated cavity (Figure 8.25) or to a closed timber wall of butt-jointed, rough-sawn boards (Figure 8.26). The boards are applied with a double overlap in such a way that the nails fixing the lower board are covered by the higher board. The vertical joints between the boards alternate. In wet climates shingles and shakes are made of western red cedar, larch, chestnut or oak. In dry climates less durable types of wood have traditionally been used. An outstanding example of the use of shingles is Peter Zumthors' St Benedict's Chapel in Sumvitg, Switzerland (Figures 8.27, 8.28).
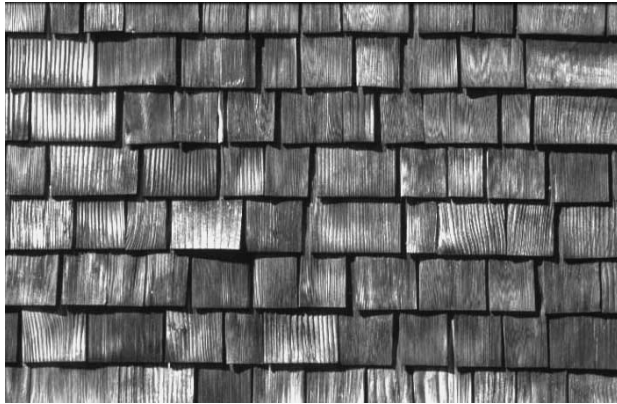
8.27 Shakes applied on St. Benedict's Chapel.

Curved structures

Wood is extremely suitable for use in curved form, although this has not been widely reflected in architectural practice to date. The manufacturers of boats, cars, tools and furniture make extensive use of curved wood. The methods used to curve wood (especially oak) as used in yacht-building may involve heating or burning, which is not appropriate for facade construction since the removal of the charred layer takes too much time and energy. However, alternative methods exist. They include:

- elastic shaping and external fixation;
- elastic shaping and internal fixation;
- plastic shaping distortion;
- sawing the wood into the desired shape.

1. Elastic shaping and fixation in the desired form. In this method, relatively thin boards are bent across a frame and then screwed or glued and screwd into place. The curvature cannot be too great and depends

8.28 St Benedict's Chapel, Sumritg, Switzerland.

on the wood's natural elasticity. The wood will be permanently under stress, which increases the risk of splitting, especially at the fixing points. Over time, the stress is reduced by the process known as 'creeping'. Richard Rogers applied this traditional construction method in his design for the Law Courts in Bordeaux (Figures 8.29, 8.30), representing something of a

8.29 Law Courts (architect: Sir Richard Rogers), Bordeaux.

8.30 Timber construction of the Law Courts in Bordeaux.

departure for his practice. The pear-shaped courtroom is formed by a structure of laminated wooden trusses and posts. This was first clad with 4 mm plywood, sawn to shape. Because the shape includes double curves, while plywood will only curve in one direction, each piece could be of only limited dimensions (Figure 8.30). Insulation has been applied behind the plywood layer, between the laths. Above the plywood is a waterproof skin, and the top layer is of western red cedar boards, mounted diagonally. Although almost every board has to be not only curved but twisted on its axis, the diagonal mounting ensures that the torsion stress is minimized. The top of the 'pear' is truncated diagonally to allow adequate light and ventilation. When boards are used in this way the thickness can be reduced.

2. A second method of producing curved elements involves gluing together thin, curved boards to form elements of greater thickness (lamination). This method is generally used to produce columns and beams. Such columns and beams can then be used as the supporting structure for the curved planks produced using the method described in the paragraph above. It is also possible to use this method to produce curved veneered sheets. We have been unable to find an example, applied as cladding, from architectural practice.

3. Lignin, one of the constituents of wood cells, becomes elastic at temperatures above 170°C. Accordingly wood can be (slightly) bent when heated. Once cooled, it will retain the given form. In this process, wood is accurately cut to length and placed in a steam bath. It is then transferred to a steel mould, the length of the inner side of which is exactly that of the piece of wood to be bent. During the process of bending, it is essential to ensure that the fibres on the outer side of the wood are not pulled apart, since this would result in splitting. The shaping is achieved by pressure applied to the inner side of the bow. Once the wood has cooled and dried, it is removed from the mould whereupon a degree of 'springback' occurs. The size of the wooden elements thus produced is restricted by that of the steam baths and the bending machines. The maximum curvature depends on the type of wood and the thickness of the element. Not every type of wood can be bent in this way, but beech, ash, oak, maple and acacia are among those that can. Of these, oak (*Quercus rubber*) and false acacia (*Robinia pseudoacacia*) are also durable enough to be used for exterior cladding purposes. Bending wood in this way demands great skill and experience.

4. Curved pieces can be sawn from larger, flat sheets of three- or five-ply plywood or solid wood. This technique can be used to produce curved supporting

structures, but is not suitable for the finishing elements of the cladding. Unlike in the bending method described in the foregoing paragraph, in which there is always a degree of 'springback', the exact form of sawn pieces can be determined beforehand. Bending strength will not be the same across the entire length of the element, as it reduces as the degree between the grain and the axis of the pieces increases. The bending strength of wood is always much greater along the grain than across the grain.

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