GRP and buildings

A design guide for architects and engineers

Alec Leggatt BSc, FICE, FIStructE
Director, NCL Consulting Engineers

The Author wishes to acknowledge the considerable help given by his partner Geoffrey Pinfold BSc, DIC, FICE, FIStructE, particularly with the sections on Manufacturing and Structural Analysis.

Butterworths
London Boston Durban Singapore Sydney Toronto Wellington

First published 1984

British Library Cataloguing in Publication Data

Leggatt, Alec
GRP and buildings.
1. Building materials 2. Glass reinforced plastics
I. Title
624.1'8923 TA455.P55

ISBN 0-408-00368-5

Library of Congress Cataloging in Publication Data

Leggatt, Alec.
GRP and buildings.
Bibliography: p.
Includes index.
1. Glass reinforced plastics. 2. Plastics in building.
I. Title. II. Title: G.R.P. and buildings.
TA455.P55L44 1984 693'.9923 84–1775

ISBN 0-408-00368-5

Photoset by Butterworths Litho Preparation Department
Printed in England by The Garden City Press Ltd, Letchworth, Herts

Preface

This book is written by a designer, but it would be a mistake to expect an esoteric 'back-room' treatise, crammed with mathematical equations and chemical formulae. In fact it has been a deliberate policy to keep these two features to the very minimum.

The function of a designer in the construction industry is all embracing. He must take full account of all aspects of the product from physical and chemical composition, stress analysis, cost, weight, manufacture, erection, finished appearance and most important of all, performance in use. To paraphrase the military dictum – 'there are no bad materials – only bad designers'. No conscientious designer can escape responsibility in a general sense for every aspect of the nature of the product he is designing. This is particularly true in the case of GRP where expert knowledge abounds but tends to lie in separate unconnected channels. The book sets out to bring all these threads together, tackling them in a sequential order and showing links which the designer should maintain through the total design process.

It is not only the designer who will find interest in the book. The raw material supplier, the manufacturer, the builder and, of course, the end-user will all have a better understanding of this exciting material if they see their particular function in the context of the whole development of the product from conception to functional operation.

A. J. Leggatt

Chapter one

Introducing you to GRP

1.1 What do you know?

Even the most distinguished expert started as a complete ignoramus in his subject. It is sometimes difficult for the complete newcomer to a technology to find the sort of information, written or oral, which will take him easily and securely from his zero of complete ignorance into the upward curve of learning. So often he is confronted by a person, already far up that curve, who has forgotten the early lessons and has difficulty in understanding that persons with zero knowledge of the technology, could exist!

Full or partial experts can skip the next few paragraphs but we suspect that most of such fortunate people will steal a glance at what we have to say to the absolute beginner.

1.2 What is it?

GRP stands for Glass Reinforced Polyester. More loosely, but not erroneously, it is sometimes held to stand for Glass Reinforced Plastic. The materal is also known as Resinglass, Glass Fibre and Fibreglass. The last two terms refer strictly to the reinforcement used in the material but are often used loosely to describe the whole composite. In French and German the material is often called simply 'Polyester'.

GRP consists of two primary ingredients – a resin and some glassfibre which adds considerably to the strength of the composite material. The nature and variety of these two basic ingredients are treated in considerable detail later in this book, as are various subsidiary ingredients which can be added to achieve different characteristics for the finished GRP.

Let us stay with these two basic ingredients for the time being and consider them separately and in combination. Polyester resin is a manufactured product and is a liquid. By adding small amounts of other substances, known as catalysts and accelerators, the liquid resin can be made to set or solidify into a very tough material not unlike the natural resin used by violinists, although much stronger. The speed at which the resin sets can be controlled by the selection and quantity of catalyst and accelerator. The resin can be formulated in various ways chemically and other ingredients can be added to the mix, all of which enable a great variety of colour and other physical properties to be achieved.

But let us concentrate for the moment on the principal ingredient – resin. It is the physical behaviour of resin that dominates the nature of the finished composite material. The other ingredients, glassfibre, etc. play vital roles but they are there mainly to enhance and extend the inherent properties of the resin itself. Therefore resin can truly claim to be the basic ingredient of GRP.

Perhaps the most important property of resin is that it starts life as a liquid. In that state it will, by definition, assume exactly the shape of its container. Provided an appropriately shaped container or mould is available, the resin can be formed into any desired form or shape. In this respect it should be noted that unlike concrete for example, resin is a true liquid, the largest single particle being the molecule. Thus the minutest detail (and defect!) present in the mould will be reflected in the resin.

In practice resin can be forced, under the influence of pressure or vacuum if necessary, into the most tortuous shapes without difficulty. The difficulty comes very often in extracting the set resin from the mould if the latter is not to be destroyed. Practical moulding techniques are discussed later in the book. Not only does the liquid resin flow easily into the desired shape, but the setting process normally occurs without the need to apply heat or pressure; thus the mould can be a simple lightweight container. No heavy or complex plant or machinery is required in normal GRP manufacture. The comparative ease with which GRP manufacture can be started has been a blessing to the producer, but occasionally a curse to the consumer. More of that later.

Although GRP can be moulded into bulky shapes such as those commonly used for concrete, the ingredients of GRP are costly by comparison with concrete and iron and it is necessary to use the GRP sparingly and in the form of thin sheets or laminae. The methods used for 'laying up' such laminae are described later.

The economic necessity to form GRP into thin surfaces has fitted in admirably with the requirements of the building and boatbuilding industries. The basic requirements of a boat hull is that it should prevent water falling into the hole form by its presence. A curious definition you may think, and one not likely to appeal to most sailors, but it demonstrates the need for a surface to form the desirable interface between the sea and the occupants. In the case of small boats the geometry of the hull is complex and GRP has been adopted as the pre-eminent material for boats up to some 20 metres in length.

Buildings too, are much concerned with surfaces. Apart from insulation, nearly all the functional purposes of a building are served by surfaces. Surfaces to walk on, surfaces to keep out the rain, surfaces to look through or at. To go to the basic thinking applied above to boat building, one could imagine that if wall paper and carpets could be made infinitely rigid there would be little use for structural slabs, beams and columns as we now know them. Impractical? Yes perhaps, but we already have buildings which are made up only of surfaces. The Nissen Hut was a tentative but brilliant step in that direction but now we have air-supported membrane structures which are nothing but surfaces. Inherently stable forms of membrane structures such as cones and domes are commonly formed as surfaces and precious little else.

So far, GRP has been used in building primarily as cladding, that is to say the external evelope of a building or sometimes internally, to conceal less presentable parts of the building or as walls, partitioning, etc. For the architect, GRP has immense appeal in this context because of its infinite range of colour and, above all, because of its mouldability into any free shape the designer requires. It is also light and strong. But it also has problems, principally an inability to sustain continuous high stress and, a matter which must be taken very seriously indeed, the resin, under certain circumstances, can be burned.

Out of all this, perhaps the basic point to remember about GRP is that the designer has almost unlimited freedom to use a surface in any shape that his whim or the functional requirements indicate.

1.3 History

The history of plastics stretches back well over a hundred years, but before the 1940s their development was very largely a laboratory matter, their presence being felt by the outside world only in such forms as 'Bakelite' and 'celluloid'. Glass fibre has an even longer history but it was only in 1942 that an effective combination of glass fibre with polyester resin giving GRP, was produced. Pioneering work was done in the United States and Britain and under the pressures of the technological demand of the Second World War, rapid progress was made and the first practical uses of GRP emerged in the form of aircraft components. After the war during the late 1940s progress was rapid although GRP was still an expensive material. The basic attraction of GRP, the ease of moulding complex shapes, was quickly recognized by designers of boat hulls and vehicle bodies.

1.3.1 Boats

With increasing demand and increased production of the basic ingredients, the cost of GRP relative to comparable materials fell markedly and during the 1950s, building designers began to consider that GRP may be cheap enough to use in the large quantities required for roofing – or even complete buildings. The attractions for the small boat builder were much more tempting. Until the advent of GRP, timber was virtually the only suitable material for the geometrically complex shapes of small boats. The very high input of skilled labour required in the building of a timber boat and the continuous maintenance of the hull made it an expensive article in the post-war economy. The GRP boat hull allowed rapid repetitive casting of boat hulls from the one mould, high skill being required only for the making of the mould itself. By the late 1950s and early 1960s nearly all

Figure 1.1 17 ft high-speed rescue boat. Moulded in GRP sandwich construction

small boats were being made of GRP. Although the passing of the timber hull is to be regretted aesthetically, the contemporary spread of the leisure boat industry (and the mass enjoyment thereof) owes almost everything to the availability of GRP (*Figure 1.1*).

1.3.2 Buildings

The building industry has been a tempting field for the GRP industry for a long time. Translucent GRP sheeting, as a standard product has been available since the early 1950s but very little bespoke design for particular

Figure 1.2 John Piper murals moulded in GRP, *circa* 1960. Carnwath Road, Fulham, London

buildings emerged until the early 1960s. The Author's firsthand experience of GRP started with some decorative panels for the Gas Board research headquarters at Fulham (*Figure 1.2*).

These panels were designed by the artist John Piper and their colours are still bright and fresh after twenty years in a somewhat adverse atmosphere. The Greater London Council were among the first in the field with some GRP cladding panels for tall blocks of flats. The 1960s produced a number of interesting GRP applications, many of which are reviewed in the 'Case histories' section of this book (Chapter 10). At about the same time it was realized that GRP was a most useful material for reproduction of decayed

Figure 1.3 GRP mouldings replacing cast iron decorative work on Tower Bridge, London

or damaged classical architectural such as church spires and finials, the originals of which were made in masonry, lead or bronze (*see Figures 1.4* and *1.5*). These parts of buildings could be produced with fidelity and at a fraction of the cost of using the original materials. Even parts of the cast-iron decoration to the beloved Tower Bridge in London have recently been replaced with GRP mouldings (*Figure 1.3*).

1.3.3 New techniques in an old industry

GRP as a practical material, had an almost non-existent childhood and a very short adolescence. In comparison with modern technologies this is nothing unusual but in the sphere of the art and craft of building it is quite revolutionary. The development of common, and still widely used building materials and techniques has been evolutionary in the true sense. Almost any materials that came easily to hand has been used at some time or other in building. Certainly there has always been great emphasis on those materials that have been locally available. Materials and techniques which have stood the test of weathering, erosion, corrosion, fire, damp, rot and infestation, survive in good building practice and many of the others still

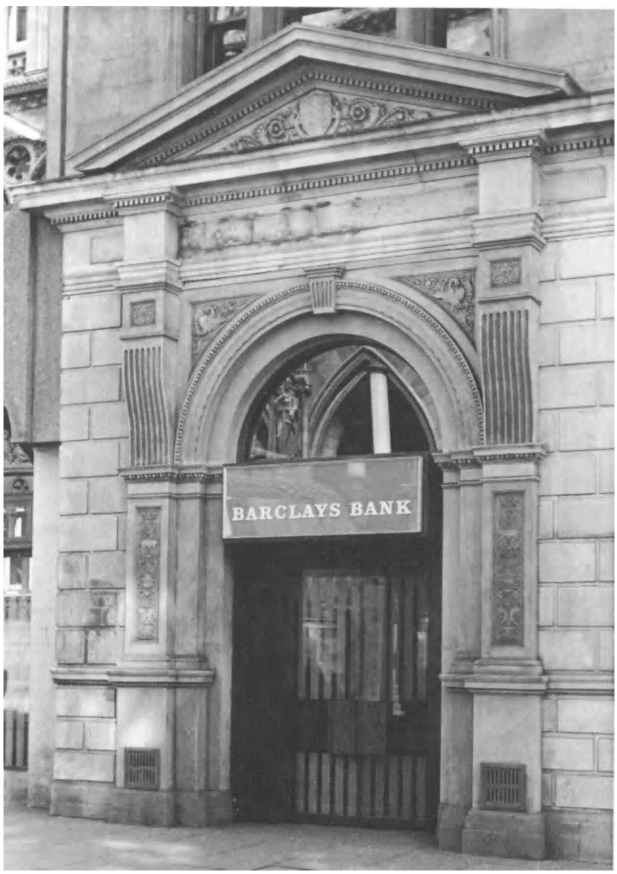


Figure 1.4 The arch and doorway is moulded in GRP, the mould has been taken directly from the original masonry which exists at the other end of the same building

survive in inferior building practice! Even the contemporary housing estate, with its timber-joisted floors, hand-laid brickwork, and timber trussed and tiled roof is only slightly removed from the traditional building methods reaching back through centuries.

It is hardly surprising therefore that GRP, with so many of its qualities unprecedented in traditional building materials, provided some difficulties for building designers. This has resulted in some performance failures of GRP building units and nearly always these failures have been due to an

Figure 1.5 The 9 m diameter GRP dome on the Great Equatorial Building, Greenwich Observatory. The dome replaces the iron-framed papier maché original which wās erected in 1895 and destroyed in the Second World War

inadequate understanding, either by the 'building designer' of the properties of GRP, or conversely by the 'GRP designer' failing to appreciate the requirements for a successful building component. It is the basic purpose of this book to attempt the synthesis of the traditional essentials of building with the new technology of GRP.

Chapter two

GRP uses other than for buildings

As we have seen from the last few paragraphs of the history of GRP, the material passed its childhood in special military applications and came to full maturity through the boat-building industry. The building designer should study established applications of GRP in other fields so that he may better understand its nature and performance in a range of applications.

2.1 The small boat industry

Almost all boat hulls up to 20 m in length are now built from GRP. Steel, aluminium and ferrocement offer some competition for the large boat in this range but the timber boat is, alas, virtually a collector's piece. At the lower end of the range, some very small dinghies and surf boards are now injection moulded using polypropylene but only where long production runs justify the cost of the moulds. For the vast majority of leisure boats, both sail and power, and for work-boats in the range, GRP reigns supreme.

As with most GRP production, the boat-building process is simple. First an exact replica or 'plug' of the desired hull shape is built up in timber or a combination of timber and plaster. At this stage the naval architect is able to adjust the hull shape fairly easily and fine down the lines by eye on the three dimensional plug. The plug does not need to be of great stregth but should be of sufficient rigidity to enable further GRP moulding to be taken from it without distortion. When the geometry of the hull plug is finalized, a GRP mould is cast from the plug, but this of course is a female mould, made normally of suitable thickness and stiffened with deep ribs, sometimes of steel, on the outside. This mould will be the working mould for producing a run of GRP hulls. It is normally split along the longitudinal centre line of the hull.

When this mould is finished and mounted on suitable cradles, the boat builder already has his means of mass producing a large number of hulls of that form. It should be noted that no heavy plant, or even a crane, is involved so far and the capital investment in materials is very low. Similar moulds are prepared for the GRP deck unit and any further smaller units which are to be incorporated in the boat interior. Nearly always the boat hull is cast as one GRP unit and the deck as another. After curing they are assembled together and a bolted or resined seam made round the edge of the deck. Cockpits and other sinkings in the deck are cast integral with the deck unit and thus add considerably to the weather proofing of the finished boat.

Early GRP boat designs tended to follow the traditional timber construction of an outer skin stiffened by curved vertical ribs on the inside of the hull, the ribs being formed by 'top-hat' sections built in GRP laid up over a suitable hollow former. More recently, with the rise in cost of the raw materials and increased experience of GRP boat behaviour, designs

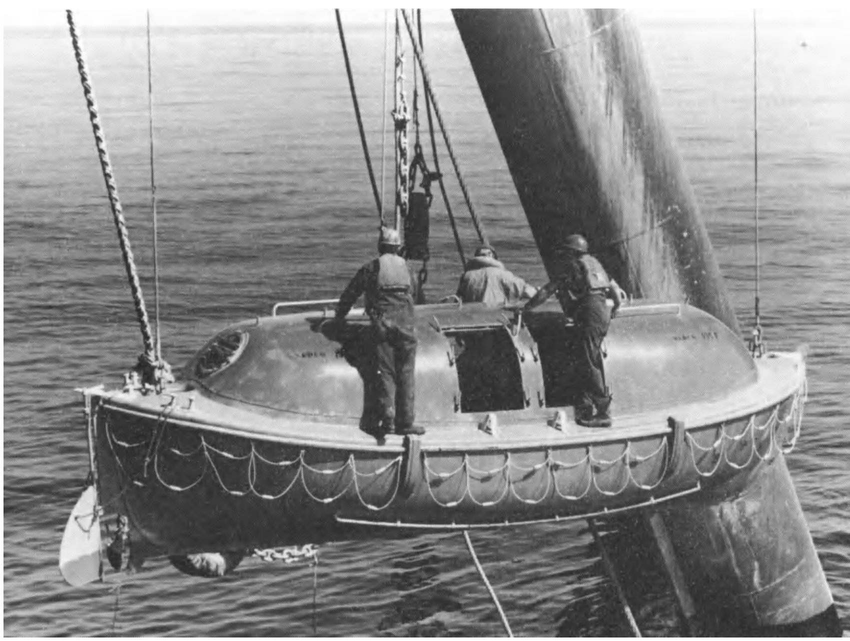


Figure 2.1 A 26 ft GRP self-righting survival craft, designed specially for oil rigs, tankers and gas carrying ships. The boat is totally enclosed to protect up to fifty people from fire and weather

now tend to be much more integrated and make use of bulkheads and other internal fittings to give the necessary hull rigidity. Typical skin thicknesses range between 8 and 12 mm, depending on the size of hull and the location within the hull. Thus the thicknesses below the water line are normally greater and local strengthenings at the bow and other critical points are easily incorporated. Local strengthening for cleats, winches and engine bearers are also incorporated in the GRP design. The GRP boat hull, straight from its mould, although beautifully precise and shiny, has a lack of rigidity which can be alarming to the newcomer, quite large hulls being distorted easily by hand. But when bulkheads are inserted and the deck unit or the 'lid' fastened on, the story is very different. The modern GRP hull, though light, forms an extremely strong and rigid vessel. There is hardly a known instance of any GRP hull failing in the most severe storm (*Figure 2.1*).

The GRP boat has many other virtues of course. Permanent colour? Well, almost. Virtually any colour can be incorporated in the pigmented gel coat but white is by far the most serviceable and most popular. Some colours do fade after a number of years and there is in the long run a surface degradation manifesting itself in loss of gloss due to ultra-violet light. In practice the well-made GRP boat will look like new after eight or ten years if given an occasional wax polish. When cosmetic deterioration has gone too far for the owner's peace of mind, re-coating with polyurethane will restore it's original appearance. A GRP hull, being of seamless impermeable construction is remarkably dry, but a particular defect has been experienced, particularly in the earlier days of GRP boat-building. The trouble was caused by small pockets of styrene being left in the GRP after it had cured. Sea water slowly migrated through the resin skin of the pockets into the stronger styrene solution by the mechanism of osmosis. The styrene pockets were thus enlarged and resulted in blistering of the outer GRP surface. Now that the problem is understood, manufacturers are taking the necessary precautions to prevent the inclusion of styrene pockets and the problem is now becoming quite rare.

2.2 Vehicle bodies

For the vehicle body designer GRP has many attractions but it has not usurped the position of pressed steel in high volume car body production. The reluctance to use GRP in the car industry cannot be put down to mere traditionalism. Steel is a cheaper basic commodity than GRP but requires heavy capital investment in the giant presses needed to form car bodies. But the cost of these presses and the associated equipment can be spread over such a large number of units that it is a worthwhile process. This situation perhaps points to an upper limit of the use of GRP under the present regime of relative costs of raw materials and labour. But nevertheless, for low- and middle-volume production, GRP is a popular material for vehicle bodies and many examples can be seen in trucks, railway wagons, small-volume car production and specialist vehicles. Less total energy is required to produce a ton of GRP than to produce a ton of steel. If and when fuel costs rise even higher than they are at present GRP may find more favour with the large-volume car producers.

Examples of GRP in vehicle bodies can be found in the complete bodyshell of Reliant cars, Scimitar cars, and invalid motor tricycles, and in motorcycle fairings, cab-shells for lorries (*Figure 2.2*), complex parts for coach and van body work – often in combination with aluminium sheet which is used for the flat and single curvature panels. On railways too, GRP is used for certain components of passenger carriages doors, seating units, etc., (*see Figures 2.3* and *2.4*). Many of these applications are everyday sights but go unrecognized as GRP since the high-gloss finish is not easily distinguished from the paint finishes that are normally applied to metal body components.

Figure 2.2 A truck cab with GRP panels

Although the main criteria for choosing between GRP and steel for vehicle body work are concerned with the economics of production as mentioned above, the two materials do have other differences which are relevant in this context. GRP is of course rustproof so small nicks and scratches do not deteriorate further. More extensive damage can be fairly easily repaired *in situ* but a good deal of care and hard labour has to go into restoring the original finish. Due to its elasticity, GRP is probably better at

Figure 2.3 British Rail high-speed train with driver's cab made from impact resistant GRP foam sandwich

absorbing minor impact but in a major collision the energy absorption properties of the modern steel car are considerable and this aspect of design has not so far been developed to the same extent with GRP bodies. The GRP body is lighter than its steel equivalent and this will become of increasing importance with the growing necessity to save fuel.

GRP is often used for the construction of liquid containers in road and rail transport, i.e. tankers, the light weight, resistance to corrosion and easil of cleaning making it attractive. An interesting fire test was carried out on petrol road tankers by the Ministry of Defence. Three vessels made

Figure 2.4 Train seats cold press moulded in GRP

respectively of steel, aluminium and GRP were subjected to a full-scale fire engulfment test. Each vessel was filled with petroleum and sealed in the normal way. Each tank was surrounded by a pool of petroleum which was then ignited. Temperature measurements of the inside of the tank were taken and the behaviour of the tank noted. The GRP tank performed markedly better than the metal tanks both in respect of slowness of temperature rise to the contents and in the final state of the tank and its contents. Despite the fact the GRP is basically combustible, it provides greater thermal insulation than metal. The petrol inside the GRP tank was able to stay cooler for a considerably longer period whereas in the metal tanks the petrol boiled at an early stage in the fire and the resulting vapour pressure blew off the sealed cap thus exposing the escaping vapour to the conflagration.

2.3 Industrial and general uses

GRP is used extensively for the construction of tanks, pipes and ducts (*Figure 2.5*). The material is particularly attractive where the contents or the ambient conditions are corrosive. Domestic sized open-topped water cisterns are mass-produced in GRP and custom-built large tanks are made either entirely in GRP, or GRP is used as linings to concrete or steel enclosures.

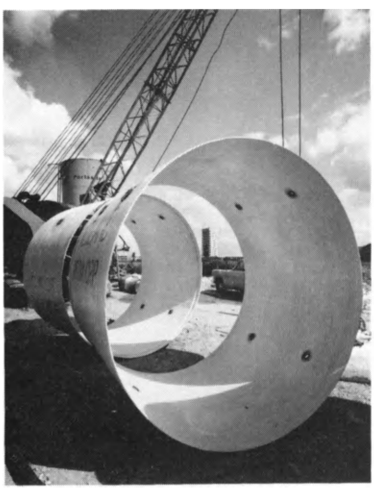


Figure 2.5 Filament wound GRP pipes

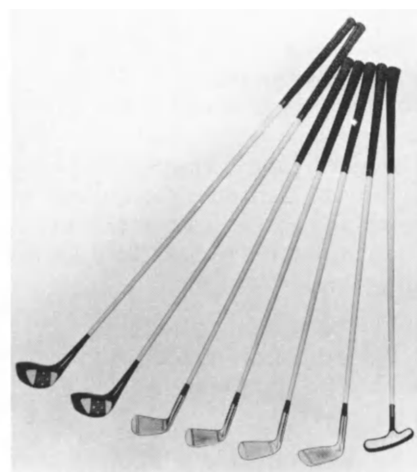


Figure 2.6 GRP shafts for golf clubs

Chimney flues are not normally constructed of GRP although resins are available that would withstand the normal operating temperatures in a number of chimneys. Nevertheless, the possibility of furnace malfunction with a consequent increase in flue temperature renders GRP unsuitable. (But see 'GRP chimney at Hendon', section 10.4).

Street furniture nowadays shows many examples of GRP usage in the form of litter-bins, seating units, road signs, etc. In sports equipment, the lightness, strength and flexibility of GRP is used for fishing rods, skis, spring boards, tennis rackets, etc. (*see Figure 2.6*).

Chapter three

Deciding to use GRP

After this chapter, the book gets down to details, but before doing so, we would like the would-be designer to pause for a moment, so that we may point out a few salient characteristics of GRP which would be fundamental to his decision to proceed with a design involving GRP. If, after considering these basics, it is found that any one of them is likely to cause significant difficulty, then it may be better to put GRP aside for the time being and consider an alternative building material.

The three basic characteristics which should be considered from the start are:

1 The personality of GRP.
2 It's structural limitations.
3 The fire situation.

There are of course many other characteristics that have to be considered carefully and these, together with a more detailed study of the three matters just mentioned, are given in the following chapters. But the other characteristics rarely prove incapable of solution and rarely provide great difficulty, so let us look a little more deeply into the three main factors.

3.1 The personality of GRP

This phrase obviously needs explanation. We do not think it is too fanciful to talk of the 'personality' of any building material and, to attempt a definition, we would say the term means the architectural use, particularly with regard to shape, colour and texture, into which the material fits comfortably and economically. The dominant factor involved here is undoubtedly the shape. It is the ability to form GRP into bold three-dimensional curved surfaces, with considerable benefit in economy and structural ridigity, that marks out GRP from other materials (*Figures 3.1, 3.2, 3.3, 3.4* and *3.5*). Having said that, it must be admitted that GRP can be a ready imitator of other materials and their 'personalities', but this rather specialized use of GRP is dealt with later.

To sum up this point, the designer should consider whether the building he has in contemplation would allow for the visual personality of GRP to

Figure 3.1 GRP detail from American Express building, Brighton. Although there is a strong influence here of pre-cast concrete, the geometric precision, colour and texture, could be obtained only with GRP. Note the moulded-in non-slip walking surface for window-cleaners

be expressed and whether he can honestly assess his own willingness to recognize and utilize in his design, the very different shapes and colours which GRP can so easily provide. If the answer to this question is 'no', then to proceed with GRP could well lead to difficult design and construction problems and possibly even to great disappointment in the end.

Figure 3.2 GRP house in Finland, *circa* 1965

3.2 Structural limitations of GRP

This is altogether an easier question to contemplate than that of personality. For reasons which are explained in a later chapter, GRP although very strong, is not really suitable for continuous load-bearing of high intensity, but intermittent loading, such as wind loading, maintenance access and short duration snow loading, are quite manageable and thus GRP is eminently suitable for roofing and the side cladding of buildings.

A subsidiary matter to be considered at this point is the practical size of units that can be handled both in the factory and on site. *In situ* production of GRP is not really practical at the present stage of development so complete continuous structural shapes such as large domes or arches would be difficult without jointing and primary supporting structures.

Figure 3.3 'House of the Future' in GRP, *circa* 1962, Disneyland

The questions for the designer under this leading are self-explanatory and the answers may lead to an acceptance or rejection of GRP as a suitable material, or perhaps to a modification to the extent of use of GRP in the design from that originally conceived.

3.3 Fire situation

We deliberately use the term 'fire situation' rather than 'combustibility', 'fire rate', etc. as we believe that the rational approach for the designer is to consider the total fire situation, i.e. the effect of a major fire on – first and foremost – the inhabitants of the building and then on the building itself and on neighbouring buildings if any. But first there are a number of routine matters to be considered and satisfied, namely the standard fire tests concerned with flammability, flame penetration and surface spread of flame. Although the relevance of some of these tests to the situation of an actual fire may be argued, very often it is a statutory requirement that they should be satisfied. Beyond compliance with the statutory requirements,

Figure 3.4 GRP cladding to multi-storey car park. The uniformity of shape, colour, texture and weathering gives clarity and meaning to repetition of a simple geometry

Figure 3.5 A store in Bedford. Bold and innovative use of GRP. Clearly the design does not relate to any other building material

the designer owes a duty to the owner of the building and its occupants to consider what is the likely situation in the case of a major fire. All aspects of the problem will have to be thought out, e.g. fire loading of building contents, alarm systems, means of escape, smoke handling, rate of fire spread, access for fire-fighters, etc. Much theorizing about the fire hazards of GRP has been done, but in fact there is very little hard evidence of any unusual hazard arising from GRP used on the outside or on the roof of a building (although there is much evidence concerning some other plastic materials). Nevertheless the truth is that GRP is combustible and thus must be considered along with other materials such as timber when contemplating the fire situation of a building.

3.4 But don't worry

Although this chapter may make discouraging reading to some, the designer should carry on to read the rest of the book so that he can know in more detail the nature of the problems he has to consider and there is little doubt that GRP can be used in some part or other in a great number of buildings. Armed with his detailed study of the material, he will be in a better position to recognize the opportunities when they occur.

Chapter four

The material itself

4.1 Composite materials

The principle of using two materials in conjunction with one another to form a composite material of altogether different properties was used in antiquity and has been ever since. From the use of straw and clay in bricks and in adobe construction, to the use of reinforced concrete and glass-reinforced plastics, composite materials have shown their advantage in building construction for a very long time. Neither glass fibre nor cured resin would suit the purposes to which glass reinforced plastics can be put. In the composite material, glass fibres provide stiffness and strength while the resin provides a matrix to transfer load to the fibres, gives them stability and provides a relatively impermeable and chemical-resistant surface.

4.1.1 Plastic matrix

The plastic part of the composite in glass-reinforced plastics consists of a liquid resin, which, when combined with a chemical catalyst and accelerator sets into a comparatively rigid material. There are two main types of resin which can be hardened in this way, namely polyester and epoxy-based resins. In glass-reinforced plastics we are concerned mainly with the polyester types of resin for which glass reinforced plastics is the major application. The resin itself may have fillers, plasticisers and pigments incorporated in it. The remainder of this section deals in further detail with resins, their curing and their properties.

4.1.2 Choice of plastic matrix

It will be seen that the number of variations of polyester resin/catalyst/accelerator/filler systems is exceedingly large. The choice of system will depend on the durability, fire-resisting, chemical, colour and finish requirements, also how the units are to be manufactured. Resin manufacturers will recommend suitable formulations for particular purposes, given the range of performance requirements and an indication of the manufacturing method to be adopted. The latter will be dictated largely by the size and geometry of the units and the number of each unit to be made, and the surface finish requirements.

In most cases two types of resin would be used, a thin facing resin called a gelcoat and a main laminating resin. The gelcoat would be formulated to impart surface hardness, abrasion resistance and carry any pigments. The main laminate resin can be formulated more to meet the general physical properties of strength and fire resistance that are required without the necessity of compromising on durability and finish. Gelcoats will be covered in more detail in the next section. The following sections describe in some detail the parameters which affect the uncured and cured properties of polyester resin systems.

4.1.3 Resins

Polyester resins consist of a solution of linear polyester in a styrene monomer. It is the co-polymerizing of the polyester with the styrene under appropriate conditions and with a catalyst, which alters the property of the

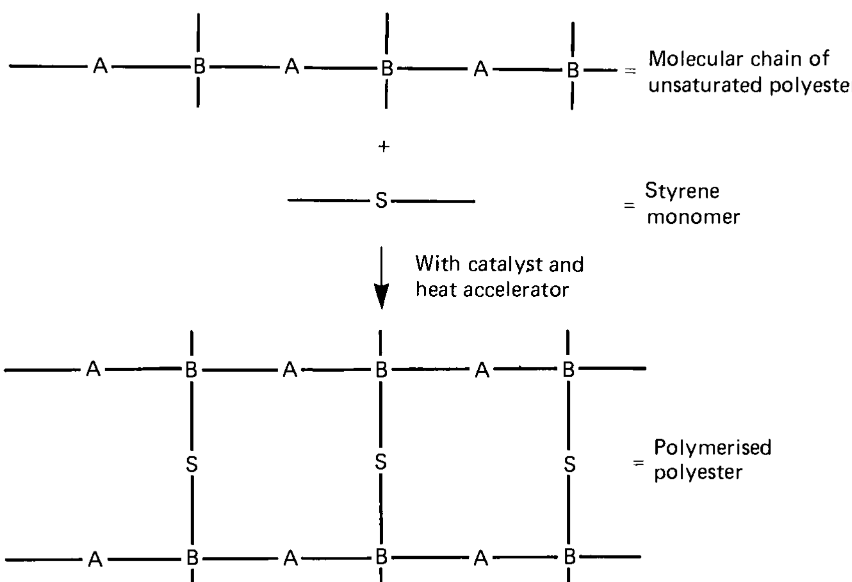


Figure 4.1 A chain of a linear polyester

resin from a liquid to a solid state. The polyesters themselves are formed, for instance, by the polycondensation of dicarboxylic acids (e.g. phthalic, maleic or fumeric) with dihydric alcohols (e.g. glycol). Resins are available in many forms depending upon the raw materials that go into their manufacture and the method of production. Because of this their formulations can be tailored to suit different applications. *Figure 4.1* shows part of a chain of a linear polyester represented by A–B–A–B and the styrene monomer –S– and how the monomer cross-links the polymer chains which then form complex three-dimensional networks.

4.1.4 Catalysts

Catalysts are chemicals which remain unchanged during a chemical reaction, but without which the reaction would not take place. Another common characteristic is that a relatively small amount of a catalyst can cause large amounts of chemicals to react. A catalyst is required for the cross-linking reaction in polyesters whether curing is at room temperature or at higher temperatures. Curing starts as soon as the catalyst is added. The catalysts employed are usually organic peroxides (e.g. benzoyl, cyclohexamine or methylethyl ketone perox). Like most peroxides these are unstable substances and are usually employed dispersed in a liquid, paste, plasticiser or powder. It is important that the type and quantity of catalyst is suited to the resin if the optimum properties are to be achieved. Typically catalyst contents by weight of resin vary from 1% in the case of a concentrated liquid catalyst to 4% for one dispersed in a paste.

4.1.5 Accelerators

The addition of a catalyst will make the resin cure only if it is heated; if curing is required at room temperature an accelerator is required. There are a number of chemical compounds which can act as accelerators but the commonest are based on a cobalt soap or a tertiary amine. As with catalysts, it is essential that the type and quantity of accelerator are correct in order to obtain optimum properties of the cured resin. Typically the proportion by weight of accelerator to resin is from 1% to 4%. In many cases the resin is supplied with the appropriate type and quantity of accelerator already added. These are called pre-accelerated resins and require only the addition of a catalyst to cure them at normal temperatures, although curing is further accelerated if heat is applied.

4.1.6 Curing

Curing is the name given to the reaction which takes place from when the catalyst is added to the resin, to when it has fully hardened. These are the three distinct phases of curing:

(a) Gel time – the period during which the resin changes from a liquid to a gel.
(b) Hardening time – the period during which the resin changes from a gel to a hardness such that it can be demoulded and handled.
(c) Maturing time – the period over which the hardened resin acquires its full stability, physical and chemical properties.

Two other terms should be brought in at this stage. The 'shelf life' of a resin is the useful life of a raw or pre-accelerated resin to which catalyst has not been added. The 'pot life' of a resin is the time during which a catalysed resin should be moulded without detriment to its eventual properties in the matured state. Different formulations have different properties in terms of shelf life, pot life and curing rates which will also vary with temperature. Catalysed resins for hot curing may have a pot life of a week at room temperature, but harden within a few minutes at 95°C to 105°C. Generally with all the reactions the higher the temperature the shorter the time.

Fillers tend to lengthen the gel time but pigments may shorten or lengthen it. The proportion of catalyst and accelerator affects gel time but the latter should be used for control in preference to the former. Bulky shapes cure faster than thin shapes because the curing reaction is exothermic and in bulky shapes the temperature increases more than in thin shapes.

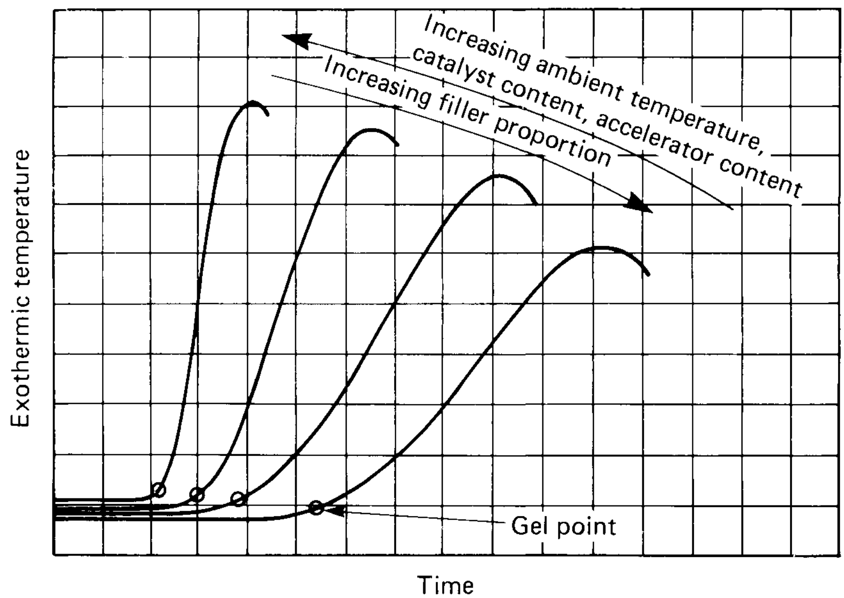


Figure 4.2 Rate of curing dependent on exothermic temperature

Figure 4.2 shows in general terms how curing is affected by various parameters. The exothermic temperature is a measure of the rate of the chemical reaction and hence rate of curing. Because the curves are very generalized and only show trends, no specific ordinates are given.

4.1.7 Fillers and pigments

Fillers are frequently used to reduce the cost, reduce shrinkage and cracking, to assist fire resistance, improve electrical properties or give opacity. Thixotropic imparting fillers are used to improve the uncured properties of catalysed resins to assist layup on vertical or sloping surfaces. Most fillers are powdered minerals of one type or another, such as silica, alumina, china clays, and glass microspheres. Antimony trioxide and chlorinated waxes in combination are used to impart fire extinguishing properties.

Fillers affect both the uncured and cured properties of resins. The setting time is modified in two ways. Physically, the exothermic reaction takes place in a larger mass (because of the mass of the filler) than in unfilled resin, so that the temperature gain and hence rate of hardening is reduced. Chemically, however, the filler can either accelerate or retard hardening so that the net effect is a combination of those two. Generally the quantities of catalyst and accelerator are altered to achieve an appropriate gel time. Minerals such as china clays, very fine silicas and some PVC powders impart thixotropic properties. Most of the inert fillers have little effect on durability under normal weathering but those used in self extinguishing resins can cause pigment colour degradation under ultra-violet radiation. Powdered fillers generally reduce the chemical resistance of the resin.

Pigments compatible with resins can be produced in almost any conceivable colour. Metallic finishes have been produced, but for the most part have not been very successful. Deep colours cannot satisfactorily be produced in a resin which has a high filler content. Normally, however, the colour can be incorporated in a surface gel coat having a different formulation from the body of the laminate.

4.1.8 Viscosity

The viscosity of the liquid resin is important to the moulding process. Different methods of manufacture require different viscosity characteristics to obtain good dense mouldings without surface defects. The properties can be varied a great deal by the formulation of the resin and by the choice of fillers used. Powdered mineral fillers decrease the viscosity and make moulding progressively more difficult as the proportion of filler is increased. Thixotropic properties are essential in most wet layup processes to allow good density and penetration into the glass mat and at the same time limit drainage of resin from vertical and steeply sloping surfaces. Most resins in common use have a viscosity in the range 2 to 20 poise.

4.1.9 Pot life

Most resins used for building applications are pre-accelerated, i.e. they already have the accelerator added, and the pot life after adding the catalyst would be typically between 10 minutes for a fast-gelling resin at high ambient temperature, to 1½ hours for a slow-gelling resin at low ambient temperature. the pot life of given resin is dependent on the proportion of accelerator and the temperature.

4.1.10 Gel time

The gel time is the time between mixing and the setting of the resin to a soft gel and represents the stage at which the exothermic reaction has just started. Gel time is related to pot life in that the resin must be in position before gel commences. It is desirable to control the gel time by the proportion of accelerator, but in pre-accelerated resins it has to be achieved by using a catalyst of the appropriate activity. Some formulations can be made such that they do not gel for a considerably period and then harden quickly, while others can gel early and take some time to harden.

4.2 Glass

4.2.1 General and manufacture

Glass reinforcement used in GRP is formed from very thin filaments which are assembled in different forms of strand, mat or cloth. The strength of finely-drawn filaments is much greater than glass in bulk, having a tensile strength in the range 3250 to 3650 N/mm^2. Glass fibres are dimensionally stable, non-hygroscopic, inert, incombustible, and do not creep.

Two types of basic glass are used, known as 'E' and 'A' types. Glass type 'E' is a boroscilicate glass having a low alkali content, under 1% calculated as Na_2O. It has higher strength, better electrical properties and greater moisture resistance than type 'A' glass. 'E' glass is the type used principally in GRP work. Type 'A' glass has higher silica and sodium contents, lower strength but better acid resistance than type 'E' glass. Comparative typical constituents and properties are as follows:

Composition	*Type E*	*Type A*
% Silica	52	73
% Boron oxide	11	0
% Sodium/potassium oxides	1	14
% Aluminium/iron/calcium/ magnesium oxides	36	13
	100%	100%
Specific gravity	2.55	2.45
Tensile strength of filaments	3650 N/mm^2	3250 N/mm^2
Young's Modulus	76 000 N/mm^2	70 000 N/mm^2
Coefficient of expansion	5×10^{-6}/°C	7×10^{-6}/°C

Before drawing, the raw glass is in spherical 'marble' form. After quality control checks the glass is melted and filaments are drawn from it through special bushes. The filaments are in the range 5 to 14 μm in diameter. Because filaments of this size cannot be handled separately they are combined in various forms suitable for use in reinforced plastic manufacture, as described below.

4.2.1.1 Glass rovings

Glass rovings consist of untwisted bundles of filaments or alternatively bundles of yarns, each yarn being a twisted strand of filaments. They are normally treated with chrome or silane based size to assist interfilament lubrication and to help bond between glass and resin. Rovings are used in the manufacture of rods, filament winding of pipes, for weaving into cloth or direct application with a chopper applicator. British Standard 3691 covers rovings made from type E glass for the purposes of reinforcing polyester and epoxide resin systems. Roving is the cheapest form of glass-fibre reinforcement.

4.2.1.2 Woven cloth and webbing

Woven cloth is made by weaving twisted filament yarn. The type of weave varies and the proportion of glass in each direction can also be varied to meet various requirements. The strength and stiffness of the laminate depends partly on the amount of crimp in the fibres. In simple weave there is a high degree of crimping but with a twill weave (under one and over two) there is less, and in satin weave there is least of all (typically under one and over seven). Woven glass-fibre fabrics for plastics reinforcement are covered by British Standard 3396. Webbing is nothing more than narrow cloth. It is used in insulation tape in electrical application and for edge reinforcement of laminates having other types of main reinforcement.

4.2.1.3 Woven rovings

Woven rovings are cloths made by weaving untwisted rovings almost always in plain weave. They are made in a variety of weights and fineness and may have equal or unequal weights of roving in each direction. Use of woven rovings and woven cloths enables the highest glass contents, and therefore strengths, to be achieved. Resin/glass ratios in the range 1:32½ can be obtained. The cost of woven rovings is higher than that of plain roving by about 50%. British Standard 3749 covers the construction and requirements of ten fabrics made with type E glass for use in polyester resin reinforcement.

4.2.1.4 Chopped strand mat

Chopped strand mat is probably the most widely used form of glass reinforcement in general contact moulding work. Strands of bonded filaments about 50 mm long are themselves bonded to one another in a random pattern to form a mat. Different binders are used to suit different applications, the main variable being the solubility of the binder. As the mat is wetted with resin the binder dissolves, enabling the filaments more easily to take up the shape of the mould where it curves in two directions. The glass content obtainable with this form of reinforcement is considerably less than that using woven materials and resin/glass ratios in the range 2:1 to 3:1 are typical. British Standard 3496 specifies requirements for E glass chopped strand mat for use with polyester resin systems.

4.2.1.5 Surfacing tissue

Surfacing tissue is a little like chopped strand mat except that is is made using much finer fibres and is quite thin. It is used to reinforce moulded surfaces to improve the resistance to cracking or crazing or to form a finer surface on the non-mould side of a layed-up laminate.

Figure 4.3 (*a*) to (*f*) shows the common forms of glass fibre used in glass-reinforced plastics.

4.3 Composites

4.3.1 General

Having reviewed the various forms of the two basic materials it is time to look at the properties of the composite materials formed from them. The

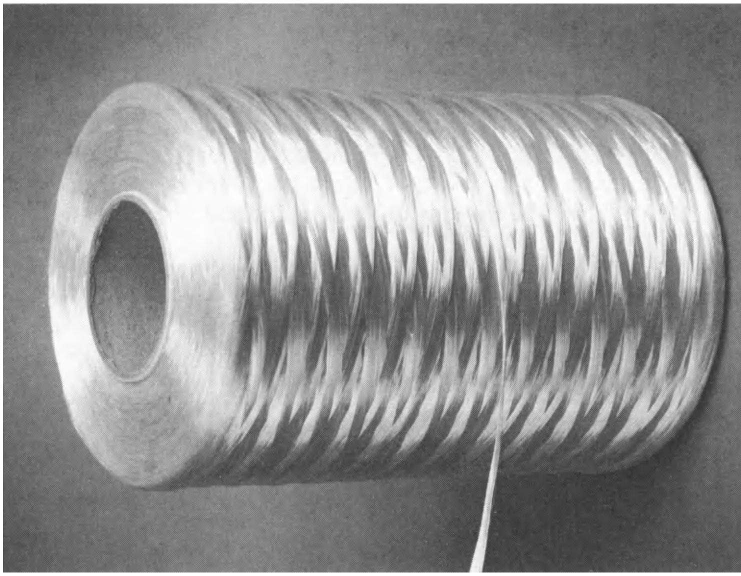


Figure 4.3(a) Roving

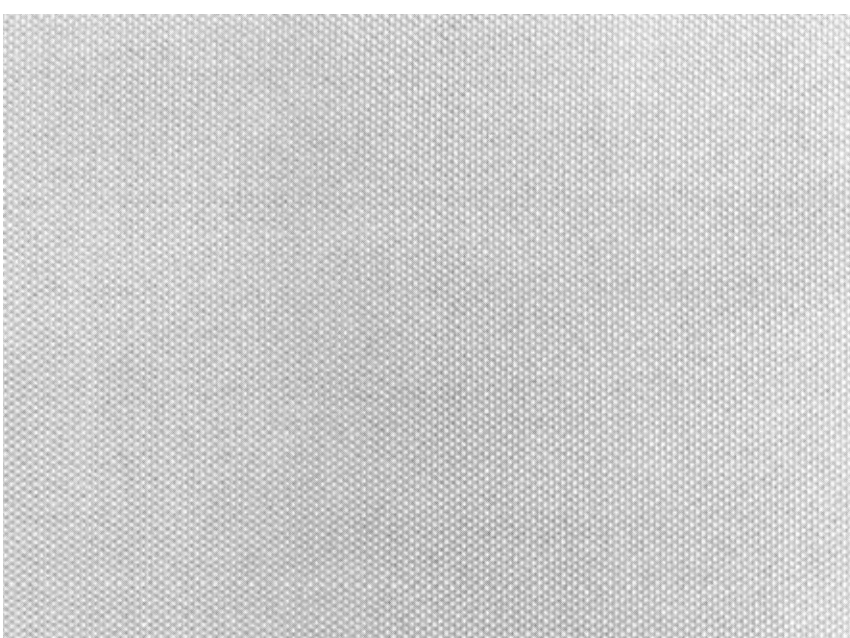


Figure 4.3(b) Yarn-based cloth

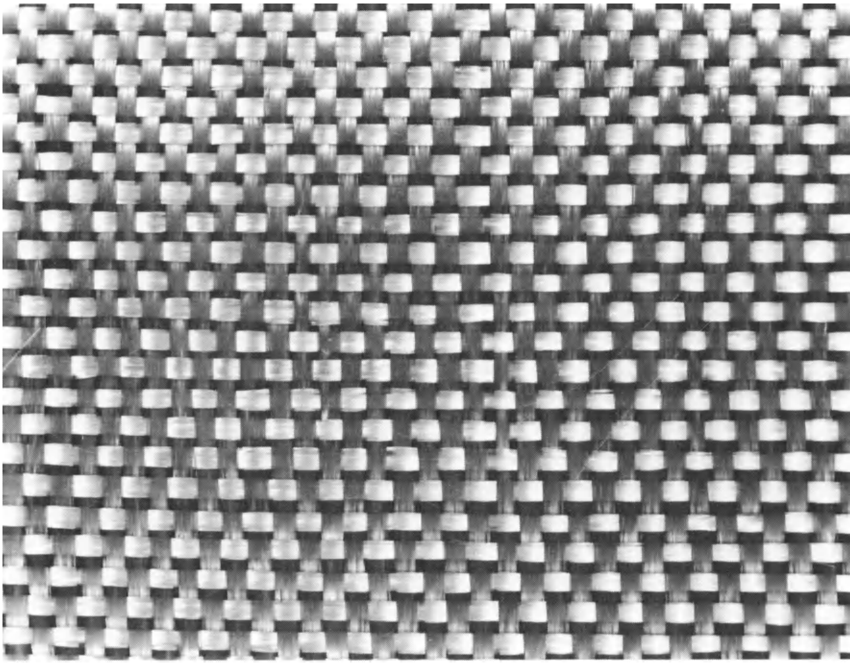


Figure 4.3(c) Woven roving

Figure 4.3(d) Chopped strands (loose)

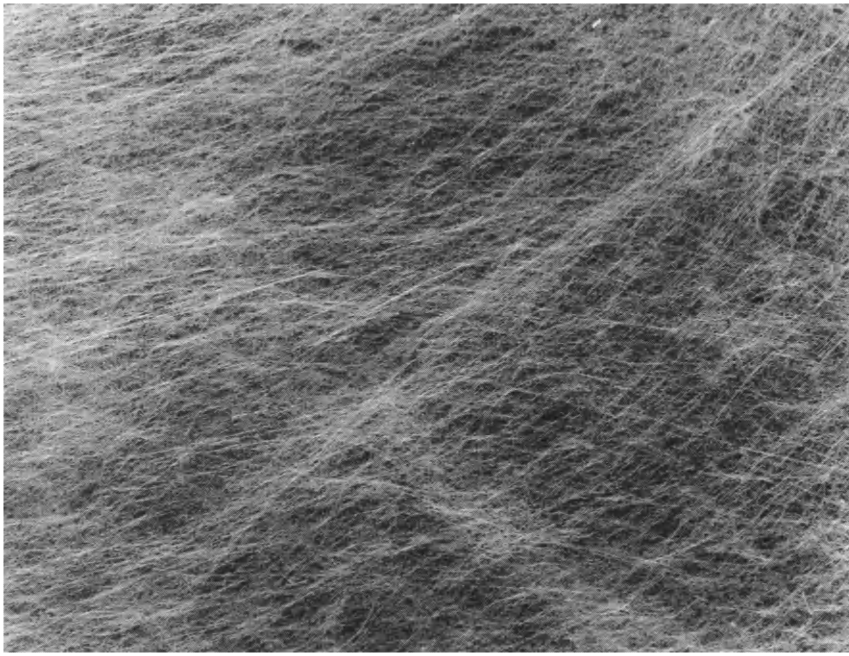


Figure 4.3(e) Chopped strands (mat)

Figure 4.3(f) Surface tissue

forms of laminates used are bound up with their method of manufacture and intended final use. Thus, before looking at specific properties and the parameters which control them, it is useful first to outline the main methods of manufacture, although these will be dealt with in more detail in a later chapter.

Hand layup Wet layup involved laying up layers of resin and reinforcement on a purpose-made reverse mould. A release agent is applied to a cleaned smooth mould surface. This is followed by a thin gel coat, then layers of glass reinforcement and catalysed resin brushed-in to thoroughly impregnate the glass, finishing off with a coat of resin.

Sprayed layup This is similar to hand layup except that instead of hand applying alternate layers of resin and glass they are applied simultaneously with a two-headed gun, one applying catalysed resin as a spray and the other chopping and spraying glass roving on to the surface.

Vacuum/pressure In the two methods described above, one face is a smooth mould face but the other is an unformed layup face. In injection moulding, matched male and reverse moulds are clamped together with the appropriate spacing and the glass reinforcement sandwiched between. A catalysed resin of appropriately low viscosity is introduced under low pressure or suction. The glass content in this type of manufacturing method is generally lower than can be achieved by other techniques.

Wound Cylindrical laminates can be made using this variation of the hand layup method. The mould is in this case a smooth mandrel which is rotated. The glass is wound on to the rotating mandrel having being impregnated with the appropriate quantity of catalysed resin. Glass may take the form of roving or webbing. The webbing can be wound at an angle to the pipe to provide longitudinal strength. Pipes wound with plain roving have high strength to bursting pressures but less resistance to longitudinal pressure forces.

Extruded Long-length, small cross-section members such as rod, tube, angle, channels and tees can be made by drawing through a die. Glass in the form of a number of plain rovings are drawn through a resin bath and then through a heated die of the required shape. Resin/glass ratios of 3:1 can be achieved with this method of manufacture, producing materials with strengths up to 1100 N/mm^2 in the longitudinal direction.

Hot-pressed In hot pressing, heated matched moulds are brought together under pressure. A blank consisting of catalysed resin of putty-like consistency impregnated with glass reinforcement is placed between the moulds before they are brought together. The resin appropriate to this form of manufacture is one having a long pot life at room temperature but which hardens quickly at high temperature.

4.3.1.1 Gel coats

Mention has been made briefly of gel coats and these, being integral parts of the laminates, are now covered in more detail. A gel coat is applied to a mould surface before laying up the main laminate. The purpose is to provide a resin-rich surface which does not show any glass reinforcement pattern and which improves the surface properties of the laminate. Since it is not reinforced it has to be applied in a relatively thin layer of about 0.3 mm, otherwise there would be the risk of crazing and cracking. The gel coat can be reinforced by pressing a surfacing tissue on to the surface before gelation starts. The gel coat should have hardened before laying up the main laminate to avoid the risk of wrinkling. Gel coats are generally thixotropic to avoid draining away from steep parts of moulds. The properties of the gel coat influence weathering, chemical resistance, surface flame spread, colour, abrasion resistance, etc.

4.3.2 Chemical properties

The chemical properties of GRP laminates are controlled mainly by those of the cured resin matrix because the glass is essentially chemically inert and is not on the surface, unless there are drilled holes or cut surfaces.

Compared with most standard building materials, cured polyester resins can be considered to have good chemical resistance, and for most building applications this will be of secondary importance. The chemical resistance depends mainly on the particular glycols and dibasic acids used in making the resin. Each resin manufacturer produces several chemically resistant resins to suit different purposes and manufacturers should be consulted for particular applications. However, it is possible to give a general outline of resistance to chemical attack in a qualitalive way, as follows:

Chemical type	*Resistance at 23°C*	*Resistance at 95°C*
Aromatic solvents	Excellent	Fair to good
Aliphatic solvents	Excellent	Good to excellent
Esters and ketones	Fair	Fair
Non-polar chlorinated solvents	Excellent	Fair to good
Polar chlorinated solvents	Poor	Unacceptable
Strong alkalis	Poor	Unacceptable to poor
Weak alkalis and salts	Good	Good
Strong oxidants	Unacceptable	Unacceptable
Strong acids	Good to excellent	Fair to good

Chemically resistant resins are not attacked by most inorganic or organic acids except for strong oxidizing acids (e.g. concentrated sulphuric acid). They are attacked by strong alkalis that cause hydrolysis. They are attacked by polar chlorinated solvents (e.g. chloroform and trichlorethylene) but not by non-polar types (e.g. carbon tetrachloride or tetrachloroethylene).

In some industrial processes there may be a sensitivity to chemicals given off from the GRP. In the absence of any external chemical effects, GRP will continue to give off minute traces of organic volatiles, mainly styrene and benzaldehyde. These can be eliminated by additional post-curing treatment.

4.3.3 Physical properties

Most of the physical properties with which we are concerned in building work depend upon both the plastic matrix and the glass reinforcement. In discussing individual properties the main parameters affecting that property will be given, but it must be borne in mind that values given must, of necessity, be typical and may vary between manufacturers of the resin and glass used.

4.3.3.1 Specific gravity

The specific gravity of hardened resin is in the range 1.2 to 1.3 and that of glass reinforcement 2.45 to 2.55, thus the specific gravity will vary considerably with glass content, as follows:

Glass content (%)	*S.G.*
0	1.20 to 1.30
20	1.45 to 1.55
40	1.70 to 1.80
60	1.95 to 2.05

4.3.3.2 Strength

In building work GRP is used normally in membrane action in relatively thin sheets. Compression forces are usually controlled by buckling rather than compressive strength. Resistance to impact loading is also important and thus flexural strength and impact strength are the properties which need consideration. Broadly the flexural strength is dependent on the glass content and the type of glass fibre reinforcement; the latter also affects the former.

Type of glass reinforcement	*Glass content (% by weight)*	*Flexural strength (N/mm^2)*
None	0	100–135
Chopped strand mat	32–35	175–235
Woven rovings	60–65	275–290
Plain weave fabric	60–65	345–415
Satin weave fabric	60–65	380–550
Directional weave fabric (maximum reinforced direction)	65–70	620–650
Directional rovings (rod form)	70–75	1050–1100

These apparently high strengths are for short-term loadings; there are considerable reductions occurring for long-term and repeated (fatigue) loadings. These are covered in more detail in sections dealing with creep and fatigue.

4.3.3.3 Elasticity

The short-term Young's Modulus of hardened resins, of the type commonly used in building work, lies in the range 3450 to 5500 N/mm^2, and that of glass filament 70 000 to 75 000 N/mm^2, the modular ratio of the two

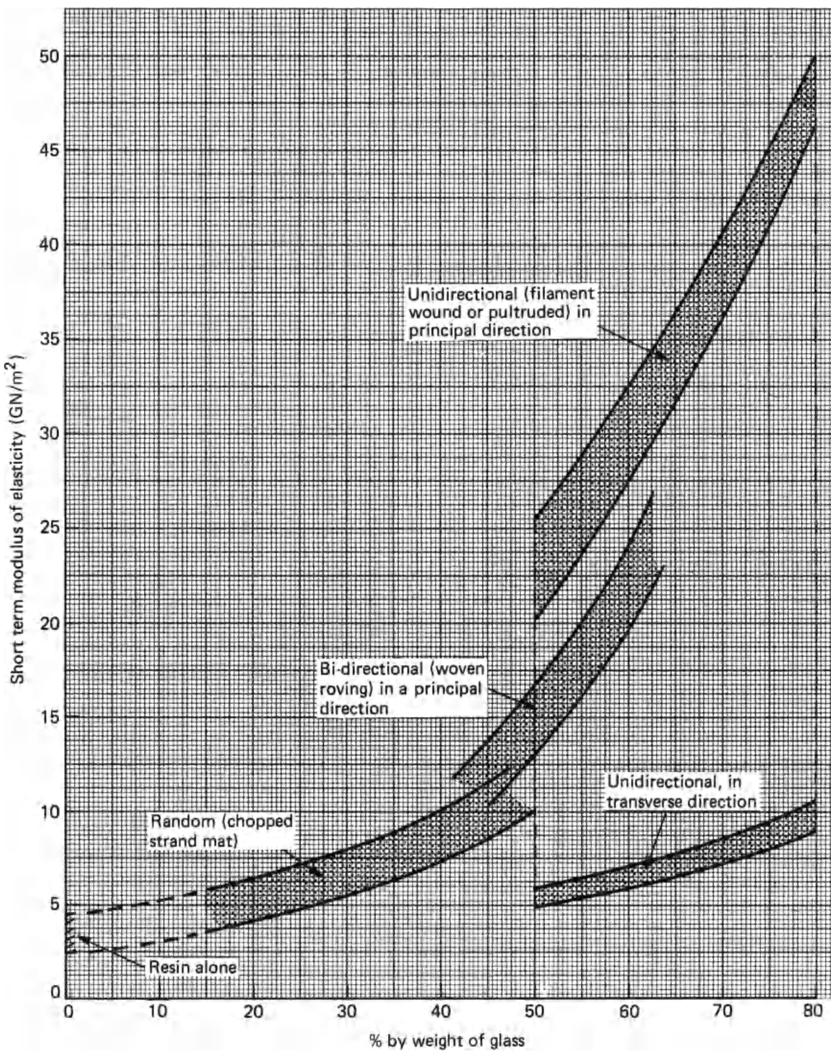


Figure 4.4(a) Typical variation of modules of elasticity (short term) with glass content

materials being, therefore at least 13. The contribution to stiffness arising from the glass is reduced by crimping in fabrics and bond transfer from strand to strand in chopped strand mats. Typical values found are in the range 8000–10 000 N/mm^2 for a resin reinforced with 40% by weight of chopped strand mat, to 22 000–27 000 N/mm^2 for one reinforced with 65% of woven roving reinforcement. In large units used in buildings, where deflections may be critical, the glass content would probably be fairly low – around 25% to 30%, and be of chopped strand form. The modulus of elasticity of such a laminate would certainly be much nearer that of the resin that that of the glass.

Although the moduli can appear high, even comparable with concrete, the sections used are comparatively thin and deflection is frequently a controlling factor in design. This is particularly the case where the GRP carries sustained loads when creep effects have to be taken into account (see Chapter 7). *Figure 4.4(a)* shows the typical variation of modulus of elasticity (short term) with glass content, for various commonly used types of glass reinforcement.

4.3.3.4 Coefficient of expansion

In buildings and their cladding, thermal expansion is an important consideration. In the case of cladding, the exposure and low heat mass of the laminate makes it respond very quickly to changes in air temperature or radiant heat. Therefore it is important to estimate and design for thermal effects. The coefficient of expansion of glass reinforcement is 5 to 7 × 10^{-6}/°C and that of the types of resins commonly used about 80 to 90 × 10^{-6}/°C. The incorporation of glass reinforcement into resin will generally reduce the coefficient of expansion to within a range of about 15 to 35 × 10^{-6}/°C. It will be noted that this is 1½ to 2 times that of steel or reinforced concrete.

4.3.3.5 Thermal conductivity

Glass fibre has a conductivity of 0.9 to 1.0 W/m°C and that of unreinforced resin is in the range 0.20 to 0.25 W/m°C. The termal conductivity of laminates may be expected to vary approximately linearly with glass content between these two extremes.

4.3.3.6 Creep

Like most plastic materials GRP is prone to creep and reduced strength under long-term loading. The glass itself does not creep so that creep characteristics depend upon glass content. Other factors which influence creep are temperature (higher creep at higher temperatures) and working

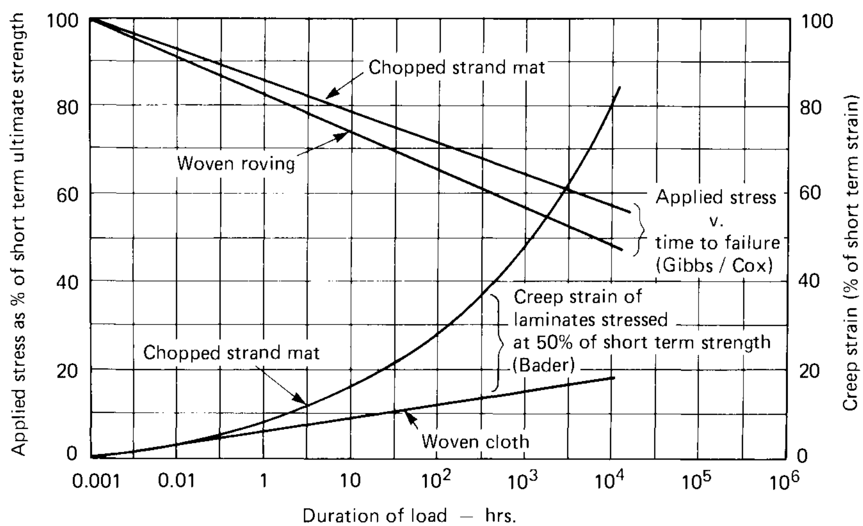


Figure 4.4(b) Typical creep characteristics

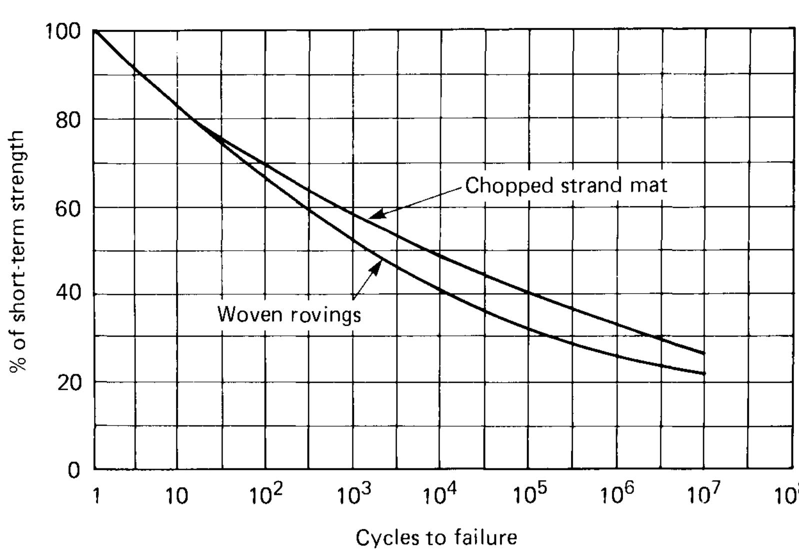


Figure 4.5 Relationship between fatigue strength and time (Gibbs/Hill)

environment (higher creep when kept under water than in air). Regarding loss of strength with time, the strength may be assumed to reduce in proportion to the log of time under stress. At an age of 25 years constantly under stress the strength may be expected to be about 40% of the short-term strength. However, extrapolations from tests have shown expected strengths of between 10% and 60% of the short term-strength.

Creep strains are time-dependent strains which occur in addition to the strain occurring at the time of loading. Their magnitude varies with the type of reinforcement and whether the laminate is maintained in wet or dry conditions. Woven cloth laminates creep less than woven roving or chopped strand mat laminates. *Figure 4.4(b)* shows typical creep characteristics from the point of view of loss of strength and strain for laminates kept in the dry.

4.3.3.7 Fatigue

Glass reinforced plastics reduce in strength considerably with repeated loading. The fatigue strength at one million cycles is approximately 20% to 30% of the short-term tensile strength. The relationship between fatique strength and time is approximately the same for both direct and flexural stress cycling, and is shown in *Figure 4.5*.

4.3.3.8 Fire resistance

So far as fire regulations are concerned in the UK, the relevant fire resisting properties are defined in British Standard 476. Some of the tests are on the materials alone, others are on the assembly concerned. The nature of the tests are described below together with the range of results expected with different types of GRP materials or laminates.

BS 476 : Part 3 – External fire exposure roof test.
This test is applied to sections of roof, rooflight, domelight, etc. and is in two parts, flame penetration and flame spread. Each is reported for flat or inclined surface in four code letters A to D. Code letter A denotes the most time for penetration and least spread of flame. Appropriate GRP formulations for the above applications can normally achieve category A in all cases.

BS 476 : Part 4 – Non-combustibility test for materials.
This test is applied to samples of material and it is designated as being either 'combustible or non-combustible'. GRP, in common with all plastics materials rates as 'combustible'.

BS 476 : Part 5 – Ignitability test for materials.
This test is applied to a sample of laminate 228 mm × 228 mm, and if different resins are used on the two faces, two tests should be carried

out. The result is expressed by one letter 'X' denoting 'easily ignitable' or 'P' denoting 'not easily ignitable'. Suitably formulated GRP would be expected to attain 'P' designation.

BS 476 : Part 6 – Fire propagation test for materials.
The sample for this test is a sheet 228 mm × 228 mm having a thickness up to 50 mm. On side is exposed to heat and the other is a non-combustible backing. The result is expressed as an 'index of performance' 'I'; this is followed by the letter 'P' or 'X' from the tests in Part 5. Typical values of 'I' range from 6 to 40, the higher the figure, the faster the rate of propagation. The reader is referred to *Fire Research Technical Paper No. 25* by B. Rogowski (HMSO).

BS 476 : Part 7 – Surface spread of flame test for materials.
The samples for this test are 230 mm × 900 mm, with a thickness equal to that to be used subject to a maximum of 50 mm. The result is expressed as one of four classes, 1 to 4. Class 1 has least flame spread. Typical results obtainable from GRP materials are:
Class 1 – Low fire hazard gelcoat, intumescent gelcoat, filled low cost, low fire hazard laminating resin, high performance low fire hazard resin systems.
Class 2 – Low fire hazard, light stabilized gelcoat, low cost, low fire hazard general purpose resin, low fire hazard transparent contact laminating resin.
Class 3 – Low cost, general purpose resin.
The Building Regulations define an additional Class 0, broadly speaking a surface complying with Class 1 to Part 7 and having a performance index of under 12 to Part 6.

4.3.3.9 Durability

Durability in connection with GRP applications to building covers resistance to water, light, heat and chemicals. GRP has good water resistance provided there is a good and continuous layer of resin covering all the glass. Once water gets between glass and resin, delamination can start to take place. Where the laminate is to be used for storing water or used in a hot humid environment it is advisable to seek the resin manufacturers advice for an optimum resin formulation.

Light can affect the appearance of GRP. Under ultra-violet light a yellow discolouration of the resin can occur, and this is most important where roofing applications are concerned. Unfortunately good resistance to ultra-violet radiation is not consistent with good fire resisting properties so a compromise sometimes has to be made.

Heat, within the ranges normally expected, does not in itself cause durability problems. The important point is relieving repeated temperature stresses so that stress concentrations leading to delamination do not occur.

4.3.3.10 Light transmission

By selecting appropriate resins and reinforcing, good light transmission properties can be achieved. The notable use of transparent laminates is in the manufacture of corrugated roofing sheeting and for rooflights. For best results the resin and glass should be matched for refractive index; by this means the glass will not be seen in the plastic matrix. Transparent resins are formulated to have a refractive index equal to that of type E glass, the refractive index of type A glass is too low to be matched by any available resin. An unweathered clear laminate will transmit approximately 90% of the light transmitted by glass. After weathering this may drop to 80% or so, with greater attenuation at the shorter wavelengths (violet and blue) than at long wavelengths (orange and red).

Chapter five

Manufacturing methods

In this section the more common methods of forming building components are described. The intention is to give sufficient background to enable architects and engineers to produce designs which are appropriate to the methods of production available. An appreciation of how the components will be made will help in evolving an economical solution in which high standards can be achieved without going to inordinate extents in skill and supervision. More attention is given to hand and sprayed contact moulding than some of the other more special techniques. Contact moulding is often the appropriate technique for the types of purpose-designed components used in building. It will be appreciated that the cost of moulds is very significant and for maximum economy as few basic shapes as possible should be used.

5.1 Wet laying

In most laying techniques the laminate is built up on a mould producing a panel which has one mould and one unformed layup face. The laminate can have incorporated into it fixings, insulation and stiffening ribs.

Normally a batch of units is to be made of a similar pattern and the first task is to prepare a suitable mould. Frequently, also the mould itself is made from glass-reinforced plastics. First a master pattern is made from timber, metal or from a plastered timber framework with a chicken-wire mesh. Porous finishes or plaster surfaces are sealed and the pattern waxed and polished. The mould is formed by laminating on to this pattern a gel coat followed by a reinforced layer somewhat thicker than that of the components to be made from the mould. A thick gel coat gives allowance for rubbing down blemishes and re-polishing.

In order to provide rigidity the mould may be supported in a frame or have stiffening ribs moulded into it as described later. Where moulds need to be jointed a flange joint is normally used. To form a flange a smooth plate is temporarily fixed to the pattern and the mould is laminated up to one side of it. When this has cured, the plate is removed, and after applying a release agent the other half of the mould is laminated up to and on to it. Before removing the mould from the pattern the bolt holes are drilled through the flange. Thus far, a female GRP mould has been made having a smooth internal finish and in one or more parts. When the mould has cured any imperfections are removed by abrasion using, for example, metal polish. Before use the inside of the mould should be polished with a silicone-free wax.

The laying up of the production panel on the mould is now described. First, any dust is removed from the mould, and a release agent is applied, such as polyvinyl alcohol solution or a suitable wax emulsion; *Figure 5.1*

Figure 5.1 Applying release agent to the mould

shows a release agent being applied with a sponge. When the release agent has dried the gel coat is applied as shown in *Figure 5.2*. This is an important stage because the gel coat establishes the visual appearance and durability of the component. The gel coat thickness should be between 0.25 and 0.4 mm. If it is too thin, then the glass fibre pattern from the main laminate may eventually show through. If it is too thick on the other hand, it may craze or become cracked particularly if flexed or subjected to impact. Care

Figure 5.2 Brushing on gel-coat

should also be taken to ensure that the thickness is reasonably uniform. To this end a thixotropic gel coat is advisable where drainage of resin may occur due to the mould shape.

The next step is to start laying up the main laminate. This should be done when the gel coat has hardened but still feels tacky. If the gel coat is undercured, then it may wrinkle but if, on the other hand, it is left too long then poor adhesion of the main laminate on to it may occur. A layer of laminating resin is brushed on to the gel coat and the first layer of glass placed on, pressed in and then consolidated as shown in *Figures 5.3* and

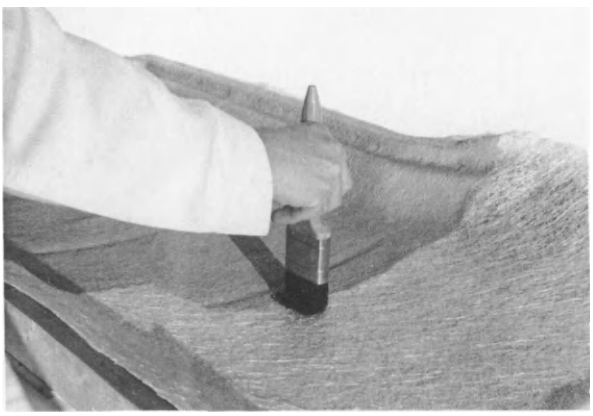


Figure 5.3 Applying glass-fibre mat into wet resin

5.4. The coverage of resin in each coat can be calculated from the design resin/glass ratio using the weight of one layer of glass. Subsequently layers of resin and glass are applied until the design thickness is built up. The rate of laying up may need to be controlled in thick laminates to avoid thermal problems arising as a result of the heat released during the exothermic curing reaction. Once the laminate has gelled the excess reinforcement and resin around the edge of the panel may be trimmed off.

Figure 5.4 Consolidating mat into resin

When the panel has hardened it may be demoulded and set aside to cure. It is important that during curing the panels are not subject to distortion otherwise they will become permanently warped. Curing at room temperature takes several weeks but this process can be hastened by allowing a day or two at room temperature and then briefly post curing at about 80°C.

Where additional rigidity is required, it can be provided for in several ways. The simplest, as in the unit shown in *Figure 5.5* is to form channels in the panel. These show as concave on one side and convex on the other side. Where more substantial ribs are required, or where one side should

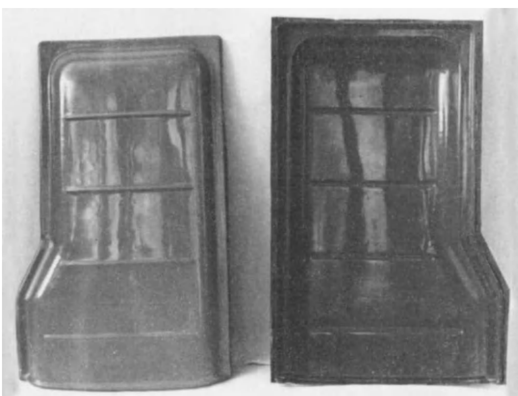


Figure 5.5 Product (left) and mould (right), showing ribs to provide rigidity

be smooth, then GRP ribs can be formed by laminating over a non-structural former. These can be made from formed plastic, paper, rope, plastic pipe or a more rigid material such as timber or metal; essentially the application is similar. The former is layed on the back of the laminate and strips of glass reinforcement are laminated over it and on to the main laminate. Successive layers of glass in different widths produce a transition in thickness of laminate which reduces stress concentration and distortion. If a rigid former is used and if the main laminate is undercured then distortion may occur as the stiffening rib laminate shrinks against the laminate already formed.

Another alternative method by which to increase the rigidity of a panel without adding ribs is to incorporate a core. In this case a laminate say 3–4 mm thick, with a gelcoat is laid up on the mould. Precast core boards are then pressed on to the first layer and laminated over and around the edges to encapsulate the core. Generally the core is non-structural, but where it is to provide strength or stability to the laminate its properties need to be considered, and the bonding of the laminate to it will become important. Core materials can range from 3–4 mm perforated board up to 50–77 mm thick expanded polystyrene or polyurethane foam in an insulated sandwich panel. In many cases only one of the laminate skins is structural and the other may then be a thin nominal skin only. To reduce problems of delamination of the skin from the core, holes can be made through the core and lengths of roving drawn through. The holes are filled with resin as the second skin is being applied and these then form reinforced links between the two skins.

5.2 Sprayed layup

The sprayed layup technique is in many respects similar to the hand wet layup process just described. The release agent is applied in the same way and similarly the gelcoat may be brushed or sprayed on. The main laminate, instead of being laid up by hand is sprayed on. The spray

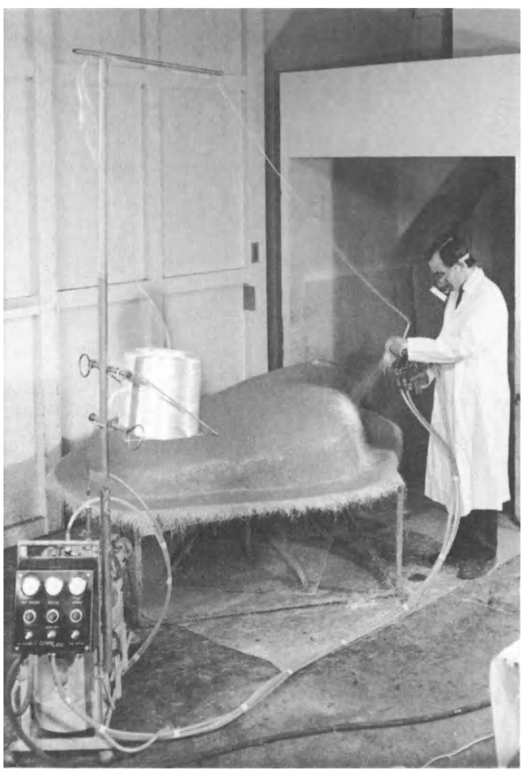


Figure 5.6 Spraying resin and glass on to mould. Resin supply at bottom left. Coil of continuous glass filament centre left

applicator can be used with resin only to wet a mat or fabric which has been hand placed; alternatively it can be used to apply resin and chopped fibres simultaneously at the appropriate resin/glass ratio. *Figure 5.6* shows combined application of resin and fibre.

The glass is in the form of roving which is chopped at the applicator and ejected by compressed air into the resin spray. The resin can be dealt with in either of three ways. First, for short runs, or where the resin needs to be changed frequently, an accelerated and catalysed resin can be made up and sprayed on. The gun then needs to be cleaned out immediately after use to avoid getting blocked with cured resin. In the second method, pre-accelerated resin is sprayed with catalyst added at the appropriate rate at the nozzle. Thirdly, the resin may be divided into two and catalyst and accelerator added to the two halves respectively. This is used in a twin nozzle gun, each nozzle applying resin at the same rate. The laminate requires periodic rolling to consolidate it as with hand laying up. Because the glass is not applied in sheets it is much more difficult to control the laminate thickness than it is when using hand layup.

When reinforcing ribs are to be incorporated, these would normally be hand applied as described in the preceding section.

5.3 Vacuum/pressure forming

This process has particular application where mould surfaces are required on both sides of the laminate. Where there are large quantities of panels and the work is repetitive this method can be advantageous in reducing the works labour content in unit production. Instead of laying up layers of glass and resin by hand or by spray, the glass reinforcement is sandwiched between two moulds and then the resin introduced.

The matching moulds are first coated with release agent and gel coat in the same way as for hand or spray layup. A surfacing tissue may be pressed on to the gel coat to help minimize surface cracking and crazing. A preformed glass reinforcement mattress is then introduced on to one mould and the second mould lowered on and clamped in position. The moulds and clamping are designed to provide a resin-tight mould having the appropriate spacing between the surfaces to achieve the required laminate thickness. A resin of an appropriately low viscosity is introduced at the bottom of the mould and air displaced through a vent at the top of the mould. The introduction of resin may be achieved by vacuum applied at the vent or by pressure applied at the injection points. The moulds need to be designed to withstand the combination of static head pressure and applied suction or pressure without significant deflection; *Figure 5.7(a)* to *(d)* shows diagrammatically the essential stages of this method of production. *Figures 5.8* to *5.11* show a roof panel being fabricated by resin injection.

There are disadvantages with this moulding technique however, First, if the units have large plane areas the moulds must be stiff enough not to distort under the external pressure resulting from application of vacuum. Secondly, there may be air bubbles trapped in the main laminate which do not show because the gel coats may be unbroken over them. Only after some time in service may the gel coat break down and reveal a hole in the laminate.

5.4 Wound laminate

Laminating by winding is a technique used for forming cylindrical shapes such as pipes, ducts, tanks, vessels and the like. A collapsible mandrel is coated with release compound and a gel coat. Reinforcement is applied

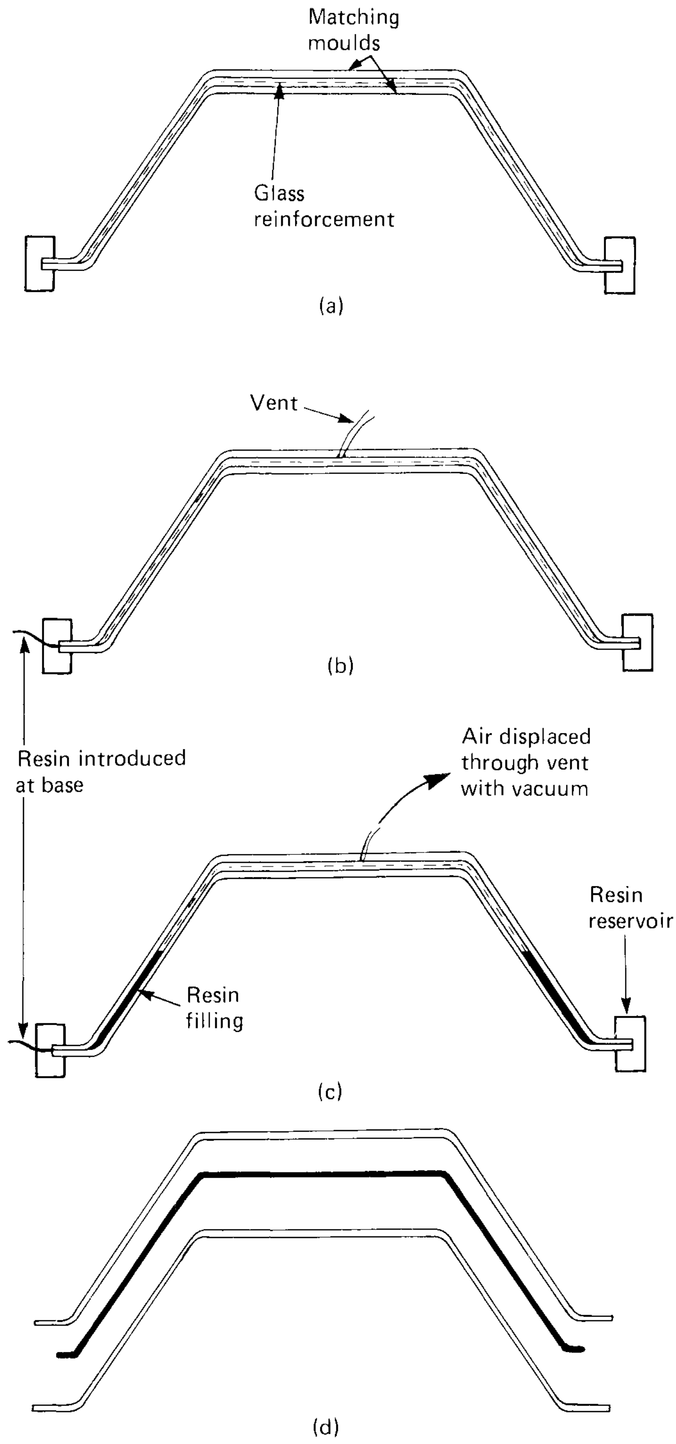


Figure 5.7 Vacuum process forming

Figure 5.8 Assembling reinforcement and insulation slabs on to male mould

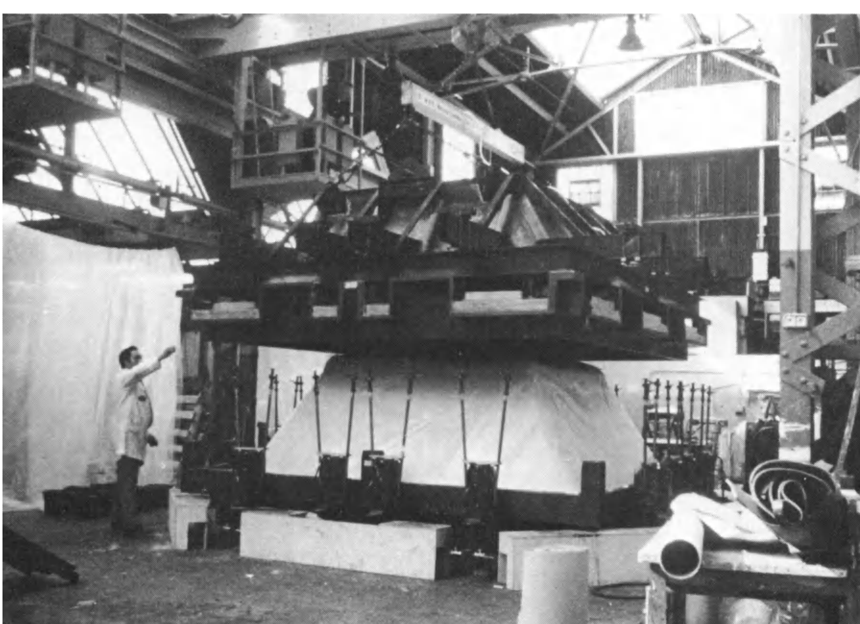


Figure 5.9 Lowering female mould

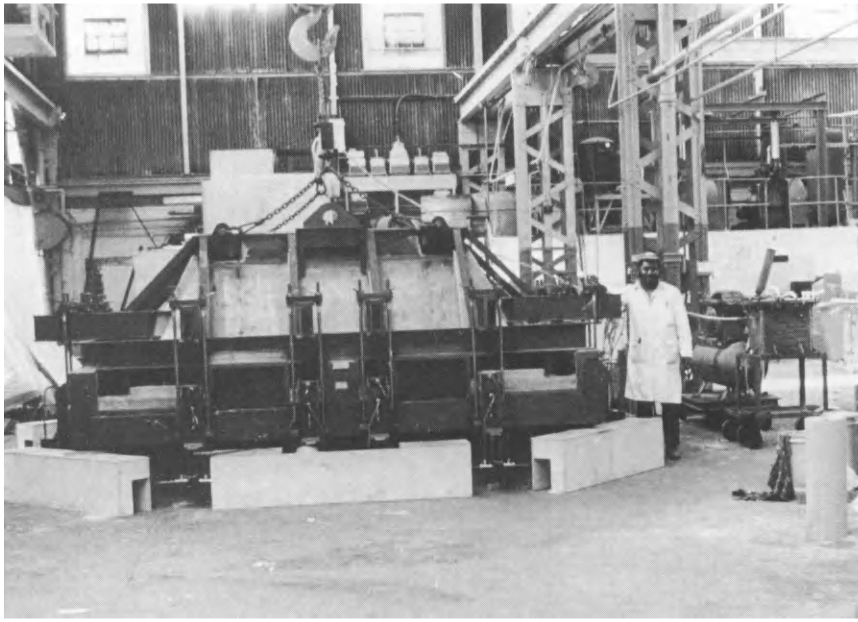


Figure 5.10 Complete mould assembled and clamped

Figure 5.11 Finished mouldings

either in continuous roving or in cloth form. The reinforcement passes through a resin bath before being wound on to the mandrel under tension. *Figure 5.12* shows a pipe being produced by the winding process. At this point in the operation rovings are being applied circumferentially. In addition, it is usual to incorporate longitudinal rovings to provide strength along the axis of the tube. This can otherwise be achieved by helical winding. The external face would usually be given a resin-rich layer to provide durability and prevent water penetration into the laminate.

The internal face may be reinforced additionally with polyester or acrylic fibres chosen for maximum corrosion and abrasion resistance. Pipes manufactured in this way are available up to 5 m in diameter and *Figure 5.13* shows a length of large diameter pipe about to be lowered into a trench.

Pipes will normally have a post-curing heat treatment to minimize future distortion – this is important particularly in the case of drainage pipes if even shallow gradients are to be achieved. Winding is, of course, a technique that lends itself to mass production in a limited range of diameters. In the case of cylindrical tanks additional stiffening ribs can be laminated on to the outsides; this would normally be carried out as a separate hand operation.

5.5 Continuous forming

Continuous forming is done in two main ways for sections of different types of property. Small compact sections with high longitudinal strength and low resin/glass ratio may be formed by pulling through a die. Wider sheet sections, for example, profiled roofing or cladding sheets can also be made on a continuous basis but they have a higher resin/glass ratio and are produced by a continuous contact moulding method.

The pulling process is commonly known as 'pultrusion' and produces sections typified by those shown in *Figure 5.14*. The rovings are guided through a resin bath and pulled through a special heated die. The profile is formed and the resin cured within the die and the pulling force is applied by means of a moving clamp gripping the already formed part of the section. Some machines inject resin into the die instead of pulling through a resin bath. In the case of hollow sections, cloths can often be used instead of roving in order to give better strength than would be the case if longitudinal rovings only were used. *Figure 5.15* shows a pultrusion machine forming GRP rods; it will be noticed that a number of rods are made concurrently in parallel, and the spools of roving can be seen at the far end of the machine. This method of forming is used to produce sections of the highest strength with glass contents of 50% to 70% by weight being typical.

The continuous contact moulding method is used for making GRP sheeting – commonly profiled, transparent or translucent for roofing as shown in *Figure 5.16*. At the start of a typical manufacturing process a conveyor belt is covered with a release film. On to this is laid liquid resin, then the glass reinforcement followed by a further application of resin. A second release film is placed on top once the curing reaction has

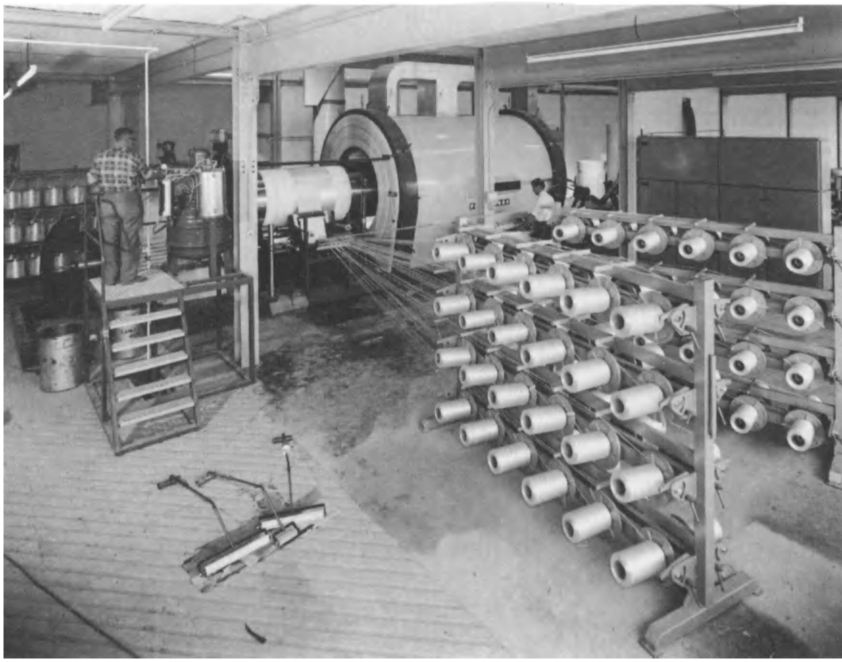


Figure 5.12 Winding GRP pipe

Figure 5.13 Large diameter GRP pipe

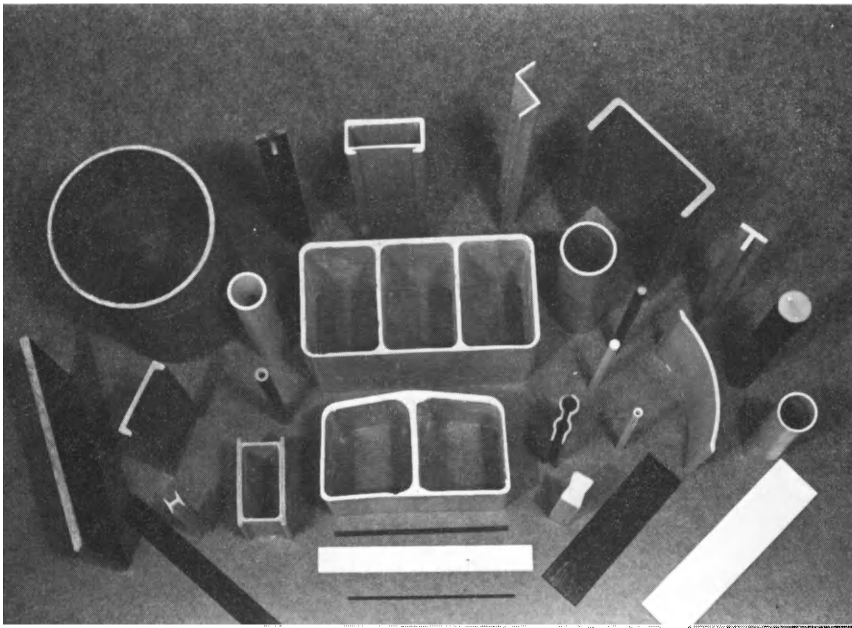


Figure 5.14 Sections produced by pultrusion

Figure 5.15 Pultrusion process

Figure 5.16 GRP corrugated translucent sheeting

commenced. The sheet is then run over heated forms to produce the desired profile and cure the resin. The release films are then removed for re-use and the sheets cut to the required lengths. The resin formulation may include pigments and fillers to suit the type of properties required. In the case of transparent laminates the optical properties of the glass and the resin are matched to make the glass as invisible as possible.

Chapter six

The GRP industry

The commonly used manufacturing processes for GRP units are simple. They involve little capital equipment, the labour required can be trained readily to the necessary level of skill, and many of the operations are suitable for female labour. Nevertheless, production management and supervision have to be of a high order for success. It is a manufacturing process which has made possible the setting up of a number of quite small concerns requiring a mere handful of skilled managers and technicians and the very minimum of capital investment. Many of such firms produce quite excellent GRP products. In addition there are a smaller number of GRP manufacturers who are subsidiaries of much larger concerns and most of the better-known names are in this category.

Thus in choosing a GRP supplier one should pay particular regard to the quality of management and technical supervision rather than the mere size of the firm. The firm's record for quality production is relevant but one has to beware of staff changes at key levels, which can change a firm's quality overnight for the better or for the worse.

Quite a different picture can be painted when it comes to the suppliers of the ingredients of the GRP, namely the polyester resin and the glass fibre. The manufacture of these ingredients involves sophisticated, capital-intensive, plants backed up with very substantial research and development facilities. The history of GRP development and promotion owes almost everything to such large firms, particularly to the resin manufacturers. A reasonable parallel can be drawn with the situation in the steel industry when so much of the development is carried out by the steel mill companies who produce the basic ingredient, which is then fabricated by a large number of firms, some of who are very small.

Provided the resin and glass ingredients are known to be supplied by one of the large and reputable firms, these rarely give cause for trouble. Exceptions occur where a particular resin has been specified which is unsuitable for its application. The resin supplier should always be consulted in case of doubt.

6.1 A typical GRP factory

To give some idea of the manufacturing process let us take a walk around a hypothetical but typical GRP factory. Firms vary in size of course but a typical UK plant may have a total floor area of one or two thousand square metres and may well be found on an industrial estate zoned for light industry.

To follow the movement through the factory from raw material to finished product, first of all there would be storage facilities for the resins, additives and the rolls of glass-fibre cloth. It is not usual to keep a great quantity of resin in store as it is often ordered to a particular specification from the resin manufacturers for any one manufacturing project. On the other hand, for the cladding of a single building, where colour matching is important, it would be usual to order all the pigmented resins for that project at the same time.

Next the resins travel to the mixing room where catalysts, accelerators and other additives, if any, are measured and mixed with the resin. The mixing will nearly always be done by machine but quite small batches are mixed at any one time so the mixers themselves will be quite modest in size and power. The mixing room should be under the control of a conscientious and experienced person. The mixture will be adjusted for the specification of the work in hand and also for ambient temperature conditions which will affect the setting time. An error in the resin mix could not only waste the material itself, which is costly, but could also ruin a work-piece costing a thousand pounds or more. The batches of mixed resin are then handed out to the layup operatives at the correct rate to match their output.

In parallel with the resin mixing room will be a cutting room for the glass-fibre reinforcement. Most of this material is used in the form of a chopped strand mat or a woven cloth, both of which are supplied in roll form. Where appropriate, the reinforcement for large panels is precut in the cutting room and supplied to the layup personnel as required. Other fabricating accessories such as foam insulation, cardboard or other formers for hollow sections and the like are also supplied through the same department.

A further ancillary operation will be the moulding department. Here the full-size replica of the required component will be made, usually in timber, plaster or a combination of both. The designer will be particularly interested in this part of the factory as there, for the first time, his creation will exist in three dimensions. He may well spend several hours with the moulding personnel getting the shape exactly right. An easy and cheap thing to do at this stage, which certainly will not be the case later on! When the replica or 'plug' is satisfactory and finished, a GRP casting is taken from it which will form the working mould for the product. Depending on size and complexity the mould will be split or hinged, stiffened with ribs and perhaps even mounted on its own trolley.

Now we move into the main work area of the factory where the products are 'laid-up'. Depending on the product and the customary practices of the firm, some work may be carried out with a spray applicator, some by injection moulding and in other factories all the work will be carried out by hand layup. In ever factory there is bound to be a certain amount of hand layup work going on. In some firms there may be other processes involved such as dough moulding, rolling to form profiled sheets and 'pultrusion'. These techniques are described in Chapter 5.

Curing of the finished product is an important operation and has to be done with great care in controlled temperature conditions. Some factories have simple curing enclosures or ovens and some simply retain the product in the controlled workshop environment for the requisite amount of time.

The factory as a whole should be clean, warm and well ventilated. Due to the flammable nature of some of the solvents used in GRP work there can be a high fire risk and 'No Smoking' is the general rule. Fire precautions should be to a high standard and the staff trained in fire fighting. Working conditions are generally pleasant.

Usually a considerable amount of storage is required in and around the factory, for finished products awaiting despatch, and for moulds which for the time being are not in use.

From our short tour round the hypothetical factory, you will have noticed that no heavy plant is involved, indeed apart from powered hand tools the biggest capital investment, apart from the factory building itself, would be in injection moulding or continuous forming equipment if such is used. Thus sizeable capital investment is not required to start off a GRP factory and the important ingredients are skill and experience in the technology, plus of course, the ever-important expertise in management and marketing.

6.2 Who should be the designer?

Many of the GRP manufacturers offer a design service and there are a small number of firms, independent from the manufacturers and suppliers, who offer a design service only. There is thus available a wealth of expertise in GRP technology. But before rushing to a specialist with an idea sketched on the back of an envelope, the designer should remember that a GRP building component is primarily *a building component.* No matter how brilliant the GRP technology, if it fails as a building component it will fail totally.

The main body of skill in designing components lies with the architects and engineers – and the skill in GRP technology with the GRP specialists. There are of course exceptions to this general rule. The problem is, therefore, how to combine these two bodies of knowledge in the most effective way.

The author's view (understandably for an engineer) is that it is better to take a little time in studying at least the bones of the technology and incorporate that in the main process of building component design, but nevertheless using specialist guidance to ensure that no mistakes are made on the GRP side.

Assuming no one is so foolish as to imagine that any 'free' design service is really free in the long run, some designers may for various reasons wish to place the design task in the hands of a GRP specialist. As a result it is most unlikely that anything will be wrong with the GRP side of the design, but the building component side of the design, by which is meant compatibility with other parts of the structure, jointing, fixing and the other dozen or so physical characteristics of a building component, should be very thoroughly checked by the architect or engineer. Although smart contract-writing might succeed in putting the legal responsibility on the specialist or the manufacturer, actual failure of a component will certainly result in an unhappy client.

For those architects accustomed to selecting their building components from catalogues, a word of warning – GRP is not that sort of material. True, certain utilitarian GRP components lend themselves to standardization – rain water goods, dome lights and mock-classical porticos, for example – but for the most satisfactory cladding or roof panels, the architect or the engineer will have to get down to the design himself. Certainly he should invoke the assistance of a GRP specialist, a manufacturer and a resin supplier but the major creative work ideally should be in the hands of the person designing the building as a whole and incorporating the sound technology supplied by the specialists.

6.3 Erection

Because of its inherent lightweight and relative flexibility, the erection and fixing of even a large GRP panel should be quite easy, and it is – provided:

1 The jointing and fixing has been very carefully though out.
2 Proper allowance has been made for tolerances, not only in the manufactured panel but in the supporting structure of the building.
3 The erector thoroughly understands the actuality and intention of the design and is familiar with traditional practices in the building industry.

The first two items are primarily the responsibility of the designer and more detailed advice on these matters is given in Chapter 9. For the third item, the designer has a responsibility to communicate his design to the erector through his drawing and specification and, in most cases, to check that the erector really does understand them. Lack of familiarity with life on a building site caused many problems for GRP firms in their early days and they still provide some hard lessons ahead for the newly started GRP sub-contractor. Most of the well-established GRP manufacturers who supply the construction industry, now have their own experienced erecting teams backed up by a management which thoroughly understands the rigours of the JCT and ICE forms of contract. Nevertheless an intending purchaser of GRP components should verify that his supplier is fully aware of his responsibilities in a contractual sense.

One technical point which can be the source of much loss of time and temper is small superficial damage to units during or even after erection. Major accidents to units on site are quite rare and, needless to say, units especially corners and edges should be adequately protected during handling and erection. Nevertheless small scratches and knocks do occur and to replace a complete unit is likely to be very expensive and resisted by the supplier with proportionate firmness. Small blemishes can usually be repaired quite effectively *in situ* at a fraction of the cost of replacement. The contract specification should deal with this matter by specifying the extent and nature of damage which is likely to be acceptable without replacement and also the standard of repair required. Such a contractual position will avoid nearly all tedious site disputes and will enable the GRP supplier to prepare his tender more accurately.

6.4 Estimating

Once the design, specification, jointing and fixing arrangements have been settled, it is not too difficult to estimate precisely the amount of materials and labour required in the factory and hence the cost 'ex-works'. Transport can usually be estimated accurately but the trouble begins when the components are delivered on site. The supplier then enters the rough and tumble of the building industry and particular attention to the points mentioned in section 6.3 on 'erection' is needed. The supplier should ensure that the product can be off-loaded safely and swiftly, securely stored off site, or if very large, can be lifted straight into position.

Probably just as much of the estimator's time and attention should be devoted to the costing after the product leaves the works, than is needed up to that point. Price 'per square metre' is a concept beloved of quantity surveyors and some architects in the early agonies of choosing materials. Manufacturers are often asked for such outline prices and, not wishing to deter a potential customer, give a figure which might bear more relationship to the answer the enquirer would like to hear than the eventual contract price. Experienced GRP suppliers will be able to give prices based on the broad spectrum of their recent contracts but the truth is that the price of GRP cladding and roofing can vary by a factor of two or even three, depending on the design, detailing, size of job and so on. Both the asker and the provider of a price per square metre should keep in mind the following pitfalls:

1 There is the question of geometry. Efficient structural design of GRP calls for deep shaping, and the true developed surface area of the GRP can be one and a half to two times the elevational or plan area of the building covered.
2 There is the off-set saving that might be achieved over a conventional building design, e.g. the GRP component might incorporate benefits such as thermal insulation, rain water disposal and so on (see section 7.5).
3 There is the all-important matter of joints. Careful and skilled design of the jointing will save costs in manufacture and, much more significantly, on site (and even more significantly on maintenance by the owner!).
4 There are the matters referred to previously concerning erection and life on a building site.

6.5 Quality control

Where so much of the design and manufacture of GRP for buildings is bespoke and where a great deal of the manufacture is a hand operation, the opporunities for something to go wrong are almost limitless. Furthermore, because of the precise geometry and uniform colour which are characteristic of GRP, blemishes that do occur are clearly seen. The need for rigorous quality control is therefore more pressing than with some other building materials.

Fortunately it is in everyone's interest to see that proper quality control is exercised. If any of the interested parties, from client through designer and manufacturer to erector, should think it is not really their concern, he should sit down quietly and think out the consequences for himself of poor standards. It is the manufacturer who has the main responsibility for exercising the control but it is the designer who has the opportunity, and often the professional duty to lay down the standards of quality control which should maintained during manufacture and erection. A clearly written and realistic specification enables the manufacturer to price his work economically and give the required standard. Much time, misunderstanding and money can be saved by proper design of the quality-control procedure.

Apart from the routine material tests, many of which are laid down in British Standards, the following points are well worth considering:

1 A record sheet for each unit manufactured, containing a unique reference number, date of casting, mix details, tests carried out, etc.
2 Check weighing of each unit after curing.
3 An established procedure for dealing with minor blemishes and defects discovered in the units at various stages.

It has been the author's practice to provide for these points in the specification on which suppliers base their tenders.

6.6 Institutions

The general advance of plastics technology comes under the care of the Plastics and Rubber Institute, 11 Hobart Place, London SW1W 0HL. The Institute publishes papers and arranges lectures, discussions, etc. Membership of the Institute is open to all engaged in the plastics industry including professionals.

Manufacturers and suppliers are represented by the British Plastics Federation, 5 Belgrave Square, London SW1X 8PH. Although the main object of the Federation is the promotion of the business of its members, it carries out valuable work in the advancement of technology and the dissemination of information. It has a reinforced-plastics section. The National GRP Cladding Federation, 82 New Cavendish Street, London W1M 8AD is concerned particularly with establishing proper standards within the plastics cladding industry and its work is a significant and welcome addition to maintaining and improving the reputation of GRP as a building material. As with most trade organizations, membership implies a certain standard of conduct but it should not be assumed that manufacturers and suppliers who are not members of the Federation necessarily have lower standards.

Chapter seven

Design

7.1 Introducing GRP into the design

The point in the progress of the general design of a building at which the designer starts to consider GRP is all-important. In many ways, the earlier GRP is brought into the design process the better, although it should not be so early that the design of the GRP and of the building itself is distorted to fit a decision to use the material, taken prematurely.

Perhaps the most successful GRP designs occur where the idea of using the material has fallen naturally into place in the early consideration of the primary components of the building design. It is as wrong to say 'let's design something in GRP' as it is to translate into GRP a design concept which has been visualized previously in another material. Ideally, the architect or design leader should have a sufficiently wide knowledge of GRP (as he should of other materials – concrete, brickwork, timber, etc.) that the merits and demerits of the material are to hand in his 'visual vocabulary'. The design leader need not burden himself with knowledge of detailed chemistry or stress analysis, providing he has a broad knowledge of what can be done economically.

7.2 The designer – prima donna or committee?

Anyone who has been involved in the design of buildings will appreciate the significance of the heading to this paragraph. Neither of these extremes is attractive although unfortunately both are frequently found. For design in GRP, a strong sense of three-dimensional form is required, coupled with a knowledge of membrane structures, GRP technology and basic building construction. The theoretically ideal GRP designer would be architect, sculptor, structural engineer, building foreman, plumber and GRP technologist all rolled into one person. Such a multi-skilled genius would be hard to find, but normally successful GRP design can result from a small multi-disciplinary team led by a person with a firm sense of direction and purpose.

At the same time, the leader should be someone who is able to listen with respect to the contributions of the other team members. The 'prima donna' who draws out his design then imagines he can leave the working out of details to others, will be very lucky indeed if the final result is not a failure in some respect or other. As so many skills have important contributions to make in successful GRP Design, it is essential to have the facility for feed-back or reiteration in the design process.

7.3 A plan for the design process

The following plan is a suggested sequence for contemplating the numerous aspects of the design. It is not essential to follow this sequence although it has a certain logic about it, but it is important to check that all the listed elements are given full consideration at some stage, and it is even more important that there should be a free system of reaction of one element on the others. All too often one finds that one element of the design is assumed to be fixed and unalterable (perhaps by the prima donna?) when on further enquiry enquiry it is found that the person laying down the apparently rigid requirement would have willingly altered it if good reasons had been presented to him. The suggested sequence is:

1 Size of unit
2 Functions (i.e. those functions which the design must perform or which may conveniently be incorporated)
3 Rigidity
4 Visual design
5 Stress flow
6 Ease of manufacture

At this point, after considering the foregoing elements, the basic shape of the unit might have evolved – or at least the first attempt at a shape. The reiteration process should now commence and the 'Mark 1' shape tested back through the elements as listed to see what modification or improvement should be made, the whole process possibly being repeated several times again. Having established a reasonably satisfactory basic shape, the designer should proceed to contemplate:

7 Texture
8 Colour
9 Fixing details
10 Thermal insulation
11 Fire performance

Arriving at this stage, having perhaps recycled the design many times to produce a fairly refined version, then after one more step – degree of repetition – an approximate costing can be made.

All the steps in the sequence suggested above, are dealt with in more detail in the following paragraphs.

7.4 Size of unit

As you will see from a later section of the book (Chapter 9), jointing between units forms a major part of the total cost of a GRP installation and furthermore, if the GRP system is going to give trouble in the future, it will almost certainly be at the joints! For these reasons jointing should be kept to the minimum and this means the larger the unit the better. Let us consider the economic aspects of large and small units. There is no basic cost penalty in the material content and labour input per square metre between a large unit and a small unit. A single large mould is obviously more expensive than a single small mould but on a large project, several small moulds may be required in the factory in order to meet the production programme. In such a case the moulding cost for a larger unit may well work out cheaper.

GRP units are relatively light in weight so that handling within the factory and on the site itself does not normally present a problem. Limitations therefore are most commonly imposed by road transport constraints. Units up to 2.5 metres wide and 12 metres long should present no special problems especially if they can be nested within each other during transport. The author's firm has used roofing units as long as 17 metres by 2.5 metres wide. In some cases a module of a certain size will be imposed on GRP design by visual or structural considerations. Even in these cases, the unit size need not be limited to such a module, as two, three or more modules may be incorporated in the same unit. The consequent saving in total length of jointing would be well worth achieving. Such a design decision would not prevent the manufacture of smaller units comprising a smaller number or even a single module. With a little ingenuity the mould designer can arrange for detailed adaptations to the mould so that it can be used for casting a smaller or larger number of modules in one unit. Unit sizes for a number of projects are shown in *Table 7.1*.

Table 7.1. Some unit sizes

Project	*Panel type*	*Max. size*	*Remarks*
New Covent Garden	Roof	4 m × 4 m	Conforms with structural module
Hendon Swimming Pool	Wall	10 m × 1.5 m	Full building height
Morpeth Road School	Roof	17 m × 2.5 m	Full structural roof span
Sharjah Airport	Roof (Dome)	5.6 m × 2.2 m	Constrained by shipping container

All GRP units need to be carefully handled at all stages – in the factory during transport and particularly during site erection. Large units will need large cradles and the like and these will add to the total cost. Nevertheless, within the scale of a particular project, the rule should be – the larger the unit the better.

7.5 Functions

In the early days of building technology, materials tended to be more multi-purpose than of late. For example, thatch roofing provided weather protection and thermal insulation. Mud walls provided weather protection, structure and thermal insulation. Present day building technology tends to use different materials for different functions so that in a modern office block we might find a completely independent structural frame of reinforced concrete or steel; a completely separate weatherproofing system of precast concrete, metal or glass; a completely separate insulation material; a completely separate internal lining system; and throughout and in-between all those varied materials there will be a completely separate services trunking system.

With a material such as GRP, we are given the opportunity to combine a number of functions in the same material and in many cases within the same unit. Although it is not always practical and sensible to incorporate all possible functions into the design of a single GRP unit, the designer should run through the following checklist to see whether some advantage could be gained by incorporating some of these functions or at least the facilities for the functions.

1 *Weatherproofing.* The impermeable nature of GRP makes this function self explanatory.

2 *Rainwater run-off.* The ease with which free-formed shapes can be achieved with GRP makes it easy to incorporate channels, gutters, etc. in the geometry and thus avoid seaprate 'rainwater goods' (*Figure 7.1*).

3 *Snow clearance.* Low-powered electric heating elements embedded in the GRP could provide a useful facility in certain climates.

4 *Solar heat rejection.* The natural gloss finish of a polyester gel coat, combined with white or near white pigmentation, will provide a high degree of solar reflection. Conversely a darkly pigmented textured surface produced by mineral inclusions in the gel coat, would provide a higher degree of solar heating where this is required.

5 *Reduction of wind loading.* The ease with which smooth curved shaping can be introduced into GRP moulding, facilitates the reduction of localized wind forces on the building.

6 *Thermal insulation.* This function is treated in more detail in section 7.13.

7 *Sound insulation.* Although normally associated with lightweight construction, GRP can, if necessary, incorporate dense infills to provide mass damping of sound but a more probable configuration would be the inclusion of a sound absorbent material behind a perforated GRP skin facing into the building for the absorption of internal noise.

8 *Natural lighting.* Polyester resin is naturally translucent and it is easy to make panels, or parts of panels, with a high light transmissivity. The boundaries between translucent and opaque sections are easily made without disrupting the surfaces of the finished unit and without the need for frames or seals (*Figure 7.1*).

9 *Artificial lighting.* GRP units can be moulded to form the support for electric light sources as well as the support and conduiting of the supply

cables. The internal surfaces of the unit can be moulded to form reflecting and diffusing surfaces for the artifical light source.

10 *Air conditioning.* Diffusers and ducting for air supply and venting can be formed internally in GRP units.

11 *Natural ventilation.* Airways can be created through a GRP unit so as to provide natural ventilation in harmony with the visual design of the building. As separate ventilation units are rendered unnecessary, it is possible to disseminate the air inlet or outlet appertures throughout the total design. Suitable weather protection can be moulded in to the unit for the externally exposed end of the air ways and movable louvres or

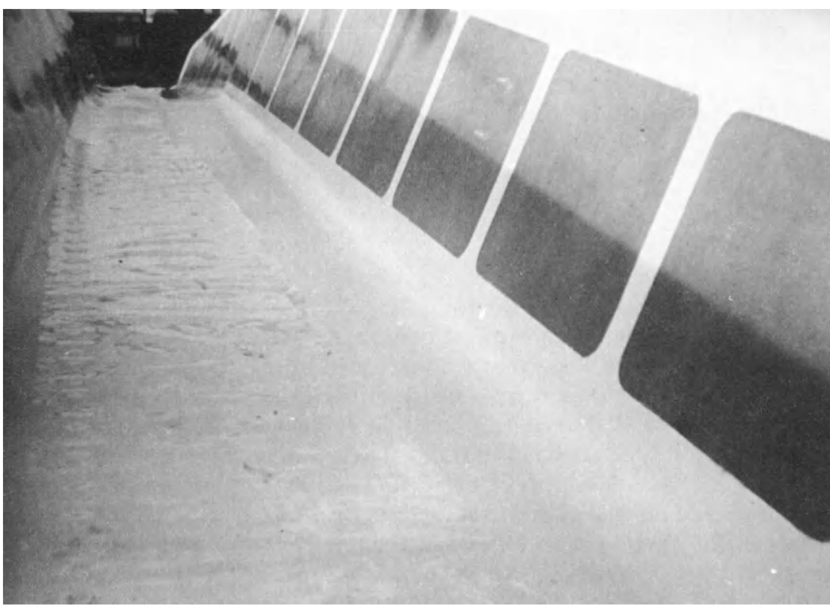


Figure 7.1 GRP roof unit incorporating rain water run-off and, through translucent panels on right, natural lighting (Morpeth School, London)

register plates can be installed on the internal surfaces of the finished unit. The traditional combination of natural lighting and natural ventilation in the one device, i.e. the opening window, can be avoided together with the problems of draught dispersal and the architectural treatment of the heavy double frame required with an opening light.

12 *Services support and ducting.* Ducts and conduits for wiring and pipe services can be moulded into a GRP unit with great ease. It would be preferable to have such moulded passages continuously open on the internal face to be sealed with a 'clip-on' or 'screw-on' cover strip to facilitate installation and revision at a later date. The cover strip can be moulded in GRP so as to provide a visually continuous internal surface.

13 *Access ways.* Doorways, manholes, roof access traps, etc. can be moulded into GRP units without disrupting the primary architectural module and sometimes without even requiring a new mould, merely an adaptation of the standard mould.

14 *Smoke extraction.* As with natural ventilation, airways can be formed in the GRP units and sealed with drop or hinged panels which open under gravity or spring action. Fusible links or other releasing devices can be incorporated.

15 *Self-supporting structures.* This is, of course, a fundamental function and the extent to which it is incorporated depends on the size of the unit envisaged and its position in the building. A fuller treatment of this subject is given in Chapter 8.

The author has not yet heard of a GRP unit which incorporates all the functions mentioned above. Indeed such a unit would be a '*tour de force*' in GRP design! Nevertheless the incorporation of each one of these functions is entirely feasible and these ideas should be allowed to flow through the designer's mind during the initial stages of his work.

7.6 Rigidity

A more detailed approach to the treatment of rigidity is given in Chapter 8, but at present we shall deal with the general nature of the problem and the manner in which the designer's initial concept of shape can provide adequate rigidity without excessive use of material.

GRP is often looked upon as a fairly flexible material. Indeed it is, and when handled in the form of a thin flat sheet, it may appear alarmingly so, although in fact, its modulus of elasticity is somewhat higher than that of concrete and of most timbers. But concrete is never produced in such thin sections as GRP and the comparable thicknesses in timber would be the thinnest plywood grades. Because of its high strength and some of the other physical qualities, GRP can be used in very thin sections and so rigidity becomes a significant problem in the basic design. Rigidity is of much more concern than is normally the case in the design of concrete, where sections have to be much more massive or in steel where the modulus of elasticity is 20 or 30 times greater.

For a structural engineer, GRP units are normally so thin in relation to their overall dimensions that they are best reated as 'shells' or 'membrane structures'. The most significant characteristic of a membrane structure is that it cannot carry stress otherwise than in the plane of the membrane itself. It follows that flat membranes are absolutely incapable of sustaining any load applied at right angles to the membrane. On the other hand, curved membranes, even though the curvature may be quite slight, can resist appreciable loads applied at right angles because the curvature of the membrane provides a certain component of its direction in the line of the applied force. This will be self evident to the layman when he presses at right angles on to a flat thin sheet. The sheet will immediately deflect into a curved shape and provided it is adequately restrained at the edges, will support an increasingly greater load the more it is deformed. In the other geometric sense, a flat sheet which is given a slight upward arching shape will provide much increased stiffness against an applied load at right angles to the surface.

7.6.1 Curvature

The simple illustration above gives the clue to the best way of achieving rigidity in GRP units. That is to say, *curvature*. Curvature is the simplest and most economical means of providing rigidity to thin sheet materials. In the case of GRP, it costs almost nothing, or very little, to provide, for in practical manufacture, a mould with curved surfaces takes hardly any more effort to produce than one with plane surfaces.

For the purposes of design, two types of curvature can be considered – one-dimensional curvature and two-dimensional curvature. A sheet with

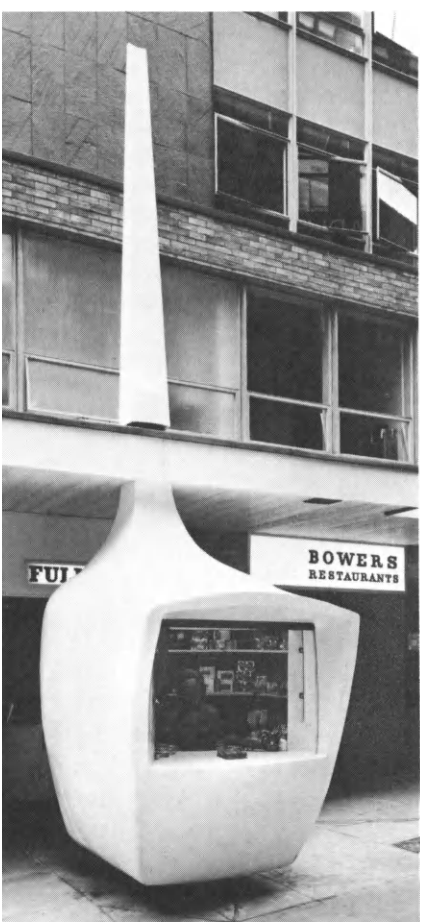


Figure 7.2 A GRP moulding exhibiting two dimensional curvature and 'saddle' curvature. Such units would be extremely rigid in themselves

one-dimensional curvature would produce a curved cross section in one direction but a straight-line cross section in the direction at right angles. The surface of a cylinder or of a cone would be examples of one-dimensional curvature.

A surface with two-dimensional curvature would show curvature in one cross section and also in a cross section taken at right angles. The surface of a sphere would be an example of two-dimensional curvature where both curvatures are in the same sense (e.g. both convex), and a 'saddle' would be an example of two-dimensional curvature with the curvatures having opposite senses (i.e. one convex and other concave). A 'saddle' shape is not so common as a spherical shape but both types of two-dimensional curvature are easily formed in GRP (*Figure 7.2*).

The increase in rigidity achieved by simply forming a flat sheet into a cylinder, is easily demonstrated, but it will be noticed that it is necessary to fix the seams of the cylinder, and in some cases the ends also, in order to achieve effective rigidity. Despite the increased rigidity obtained with one-dimensional curvature, there are still problems under certain conditions with a tendency to buckle (localized instability) and sway (i.e. collapse in a direction at right angles to the applied load). Two-dimensional curvature brings a further leap upwards in rigidity. This form of surface is not so easy for the 'desk-top' experimenter to simulate by bending pieces of paper, etc. but many forms of such surface are all around us. The humble egg-shell is probably the most dramatic illustration of the rigidity of two-dimensional curvature and there are commonplace derivatives such as the construction worker's hard hat and the pingpong ball. An interesting and valuable property of the two-dimensional curved surface is its ability to be rigid in itself, that is to say fixing or constraint of the edges of the surface is not always necessary. This is a most useful attribute for the GRP designer to remember.

There are other devices available to the designer which will increase rigidity.

7.6.2 Troughing

The mechanism of troughing is self evident and perhaps the ubiquitous corrugated-iron sheet provides the most common illustration of the rigidity that can be obtained. It should be realized that the corrugated sheet is in fact an example of single-dimension curvature as a cross section taken along the length of the corrugations would show a straight line. In GRP design, an advance on simple corrugations can easily be achieved by shaping the corrugations in the longitudinal sense so that an element of two dimensional curvature is introduced. The troughs then become more like elongated dishes (*Figure 7.3*).

7.6.3 Ribbing

Ribbing is a form of troughing whereby additional troughed sections are added to one side of a flat sheet in order to give it rigidity. The commonplace corrugated cardboard is a rather feeble illustration of the technique but many examples can be found in articles made from sheet metal. Although the technique is used in GRP design, there are a number of disadvantages to it. Firstly, it is not particularly economical, as two components have to be separately manufactured, i.e. the flat sheet and the trough, and then fixed together either by adhesives or by further laying up of resin, etc. Secondly, there is nearly always a tendency for the ribs to 'photograph' through to the flat surface which is normally to be used as the

Figure 7.3 Dishing, albeit shallow, of these panels imparts considerable natural rigidity

visible surface. Nevertheless it is a useful technique where it is absolutely essential to provide a flat finished surface to the GRP unit and where sandwich construction is inappropriate.

7.6.4 Sandwich construction

For a finished unit which has to have a flat surface on each side, increased rigidity can be achieved by making the panel thicker. Increasing the thickness simply by using more GRP would be a very expensive method, so it is common practice to achieve the required thickness by sandwiching a low-density core between the two outer skins of GRP. Foamed plastic is often used as a core material, but timber (balsa wood) and 'void-formers' fashioned from stiffened paper or cardboard, are also used. These low-weight, low-cost core materials are also of low strength compared with the GRP outer skins. A lower strength for the core is quite acceptable as the bending or 'slab' action which the sandwich panel uses to resist loads applied at right angles to the surface, places most of the stress in the outer layers. Nevertheless, in such bending action the core material plays a vital part in providing shear strength to transmit the tension occurring on one of the outer layers of the sandwich to the compression stresses on the opposite layer. If the core were incapable of transmitting the shear stresses, the sandwich would not develop its intrinsic strength and rigidity and would act merely as two thin sheets of laminate with no more strength or rigidity than as if they had been placed together, with no separating core.

The designer who is contemplating using sandwich action, if he is not himself a structural engineer, should be sure to enlist the help of a person competent to do the necessary stress analysis and strength determination. Beyond that, prototype panels should certainly be tested thoroughly and routine production tests arranged to ensure that the panels are satisfactory, particularly in respect of the bonding between the surfaces of the core material and the GRP outer skins. As well as providing rigidity, sandwich construction provides much increased thermal insulation. Under certain manufacturing techniques, a smooth moulded finish can be achieved on both sides of the finished sandwich panel.

Manufacturing techniques for sandwich panels, by incorporating preformed cores into GRP, are discussed in Chapter 5. There is another technique which does not properly come under the heading of GRP manufacture and it is known as *in situ* foaming. Two preformed outer sheets are held the required distance apart in a jig. The edges of the space separating the sheets are sealed and a liquid mixture pumped into the space. The mixture comprises a liquid polyurethane plastic, the necessary catlysts and setting chemicals and a foaming agent. By careful measurement of the ingredients poured in, the polyurethane foams and sets to fill the entire core space and incidentally forms a very good bond with the inner surfaces of the outer sheets. Although GRP sheets can be used as the outer skins, the technique is more commonly employed in large production runs of wall panels and materials other than GRP are used, e.g. melamine, PVC, plywood, aluminium, etc.

7.6.5 Conclusion on rigidity

Although troughing, ribbing and sandwich construction are widely used to achieve rigidity they are really only expediencies, sometimes necessitated by functional constraints on the geometry of the finished unit, but perhaps more often an indication that the designer has not allowed his imagination to venture into the much more elegant realm of overall curvature of the unit. This is a most convenient point to move on now to the next subject – 'Shape'.

7.7 Shape

It is so easy to form GRP into almost any conceivable shape, that it is not surprising that sculptors are making increasing use of the material for the most imaginative abstract pieces. But not all of us can be a Moore or a Hepworth and the inexperienced designer may be bewildered by such a wide freedom of choice of shape and thus welcome some constraints which will narrow down the choice for him. Although the constraints mentioned here can nearly always be loosened, by some means or other, if the designer wants to give full rein to his imagination, they could be useful starting points for evolving the shape of a unit.

Firstly, there is the constraint of the overall architectural design of the building. This may impose, or at least suggest, a design module in terms of size and perhaps also of shape for the GRP unit. You will remember from section 7.4, 'Size of unit', that the unit size does not necessarily have to coincide with the design module size. A second constraint could be the achievement of rigidity as discussed in the preceding section. This is of course an optional 'constraint' for, as we have seen, even the designer who is, alas, enamoured with dead flat surfaces, can still obtain the desired rigidity of the finished unit. Thirdly, there are other functional constraints such as the need to shed rain water, the avoidance of dirt traps and of course it has to be practical to make and use the mould which will form the shape.

The designer will surely obtain the maximum satisfaction from his work when he achieves a shape which is an elegant synthesis of visual pleasure, rigidity, functional performance and economy of material. It would be wrong to say much more about shape and it is better that the designer is set free equipped only with pencil and sketch pad to work out his own solution. (Incidentally, rulers and set squares should be confiscated from the designer except perhaps when he comes to detail the edges and joints!)

7.8 Stress flow

This may sound an odd term to some readers, but the subject should not be too frightening; it merely concerns the route taken by stresses in carrying an applied load right down to the ground on which the building rests, or in the case of a single GRP unit, to the point where the unit itself is supported. Another term often used is 'load path', but 'stress flow' conveys a more vivid picture of the problem particularly when dealing with shell-type structures.

To become more familiar with the problem, it is necessary to look at the fundamental purpose of a structure. It is axiomatic that the means of support must be fully continuous from the point of application of the load to the support of the unit – otherwise the unit would collapse. But the route which the stresses take in providing that continuous path can be simple and direct or can be complicated indeed. We shall now look at a few common structural forms which will illustrate the point.

In a building structure the main problem is to create stability between the downward gravitational pull of the contents and the upward reaction of the earth below. The simplest (and most economical) solution to that problem is a single compression member joining the load to the ground (*Figure 7.4*). Alas, this is not a useful form of building structure as it allows no space underneath the contents being supported. To create usable space below the load, it is necessary to divert the load path from the most direct route, i.e. the true vertical, either in a curved geometry such as the arch in

Figures 7.5 and *7.7* or by rectangular geometry such as the beam and column in *Figure 7.6*. The beam in *Figure 7.6* is a simplified version but even so you will see that the structural situation has become far more complex, and extra structural material has to be introduced to provide the forces necessary for stability. You will also note that even in this very simple beam arrangement a considerable amount of the material of the beam is used simply to pull and push against itself, which in terms of material economy, is wasteful.

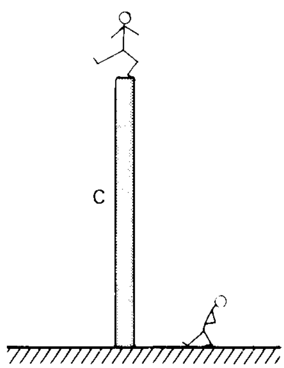


Figure 7.4

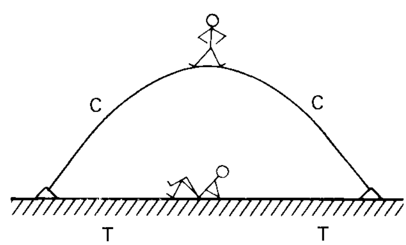


Figure 7.5

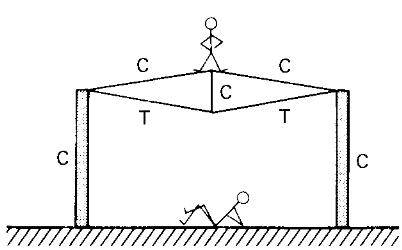


Figure 7.6

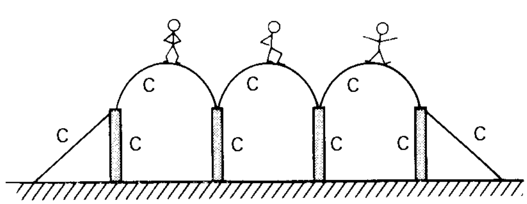


Figure 7.7

You may ask why should the GRP designer have to bother with all these subtleties, when nearly all building structures are made of beams, columns or walls and provided they are properly designed, such systems work perfectly well? The answer lies in the enormous difference in cost 'per particle' between GRP and common building materials like concrete, brickwork, timber (and to a lesser extent, steel). The GRP designer is forced to give very careful consideration to using his materials with the greatest economy and, in terms of structural behaviour, this means using them efficiently. The structure with the theoretical maximum efficiency would be one that carries the imposed loading in the most direct path to the supports and where each particle of the structure is stressed to a point just below failure. Thus the column we contemplated in *Figure 7.4*, if it were loaded almost to the point of collapse, would be highly efficient as a structure but of course quite unacceptable for a variety of reasons. The nearer the GRP designer can approach such theoretical ideas, the more likely he is to achieve an economical design and almost certainly, he will achieve an interesting design.

The dome is a sublime structural form and is a good illustration of a form which approaches the theoretical ideal but remains practical and useful, albeit with obvious limitations in the present manner of building design which is largely based on the rectangle (but see Chapter 11 on 'The future'.) The dome carries any load applied to its surface and of course its own weight, in a fairly direct path down to the support and also has the feature that the stresses imposed by the loading are distributed fairly uniformly through the structure itself. Domes and cones together with shapes approaching those basic forms, are all 'naturals' for GRP moulding and their use often leads to efficient stress flow and economy.

As is often the case in GRP design, it would be wrong to lay down detailed rules. The best shape from the stress flow point of view will depend very largely on the nature and application of the load to be supported and equally on the position and nature of the support for the GRP unit to which the load has to be carried. Nevertheless the general guidance indicated above can be summarized as:

1 Visualize the most direct line or lines between the applied load and the support arrangement for the unit and depart as little as possible from that.
2 Arrange the material of the unit to allow the stresses to be dispersed as much as possible throughout.
3 Avoid stress concentrations such as creases and corners, especially sharp corners, and if apertures are required, locate them where they interfere least with the flow of stress.

7.9 Connections

As a topic related to stress-flow, a special mention should be made of connections between units and from a unit to a structural support. With the technology presently available, most *in situ* connections, for practical purposes, have to be 'mechanical' connections – that is to say, bolts or similar devices such as studs, screws and pins. These are necessarily concentrated points of connection whereas to follow our philosophy of uniform and dispersed stress, a better connection would be a glued continuous seam or, if it were possible to design, some sort of zip fastener! The subject of jointing and fixing is investigated in more detail in Chapter 9, but generally the difficulty of concentrated fixings can be reduced by designing them to be at fairly close centres and with backing strengtheners in the form of plates or ribs which tend to produce a semi continuous clamping action along the joint rather than concentrated points of fixing. The concept of 'stitching units together' is a useful one to keep in mind, rather than 'bolting', even though the stitches turn out to be some form of small bolt.

7.10 Ease of manufacture

Although it should not dominate the design, ease of manufacture should be kept firmly in mind during the development of the design. The principle benefit resulting from attention to this matter is that of economy. Most GRP used in building is manufactured by direct hand layup or by hand-controlled spray machinery. Labour charges are therefore a large part of the total production cost and a design which is easy and quick to lay up will be relatively cheap to make. There is another important benefit to be gained from easy manufacture and that is the maintenance of the desired quality. Complicated details, especially if they involve re-entrant shapes, will not only be time-consuming to manufacture, but will make it difficult to bed down the glass reinforcement and avoid air bubbles in the final product. On the other hand, there is no need to put a total prohibition on re-entrant shapes and they are often very convenient when it comes to detailing effective weatherproof joints between units; but where they are used, fairly generous clearance should be allowed behind the re-entrant to enable hand layup to be carried out quickly and effectively.

Problems of manufacture are not limited to ease of layup, but embrace such matters as mould cost, handling and transport of the units once they have been made. Mould costs per unit are more usually a function of the degree of repetition rather than of their complexity; ease of handling and transport is usually as much a problem of rigidity as it is of size. Guidance for the designer on these problems can be obtained from Chapters 5 and 6.

7.11 Texture

We have seen that GRP can be formed into almost any shape and this characteristic applies right down the scale to the microscopic shape of the mould surface. Thus there is a very wide range of surface textures which can be obtained quite easily by simple contact moulding. As the mould itself can be taken direct from an original surface, exact facsimilies of material such as timber, stone, brickwork and natural rock, can be moulded with ease. Additional surface treatments to achieve a particular finish can be carried out before and after the moulding process. For example, the inclusion of mineral particles such as sand grains in the gel coat will produce a certain effect and post-moulding treatments such as light abrasion and, of course, painting, can all be used.

Such a wide variety of surface finishes is used to great advantage in 'reproduction' GRP work. Some manufacturers have become particularly skilled at simulated finishes and can produce GRP masonry, brickwork, timber, cast bronze, lead, etc. which can deceive even the expert eye.

Although there is a legitimate role to be played by such simulations, the majority of GRP designers will be using the material in its own right and will probably prefer a surface texture which befits the basic nature of the material.

The question of what is the natural textural appearance of GRP would be a fit subject for philosphical debate, but perhaps the basic liquid origin of the resin suggests the hard smooth shiny surface which is commonly employed. The hard gloss surface certainly has some advantages. It is likely to give the least possible problem with dirt retention and in building design, it displays a unique property of the material. Although glazed ceramics, stove-enamelled or plastic-coated steel, can give a hard gloss

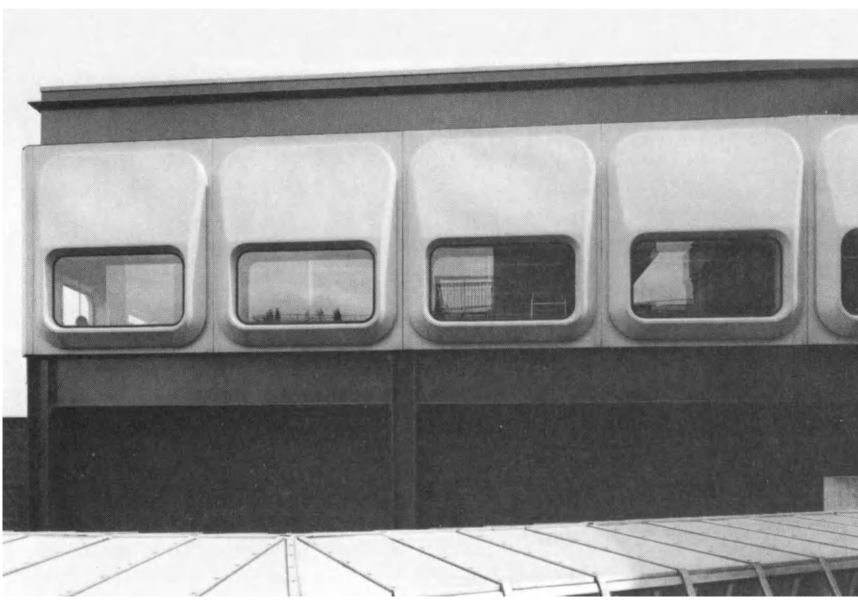


Figure 7.8 The panels at Heathrow Airport. Although not extreme examples, the picture illustrates the effect of clearly defined light and shade areas

surface, none of those materials can combine that finish with a free flowing large scale sculptural shape so easily obtained with GRP. This combination allows the designer to introduce light and shade into a building facade to a degree perhaps even greater than that achieved with masonry in classical architecture. To the conventional repertoire of shadow and relief can be added the quality of reflection. The two dimensional curvature, so strongly advocated in the section on rigidity, enables interesting transition zones to be achieved from light to shade (*Figure 7.8*). The precision of GRP moulding techniques enables highly disciplined repetition of shade patterns to be achieved over a building elevation. Because of the high reflectivity of a hard gloss finish, such patterns are sometimes clearly defined even on an overcast day without direct sunlight.

Some designers prefer to use a departure from the hard gloss finish and use a slightly undulating or dimpled texture (*Figure 7.9*). The advantages claimed are that slight surface blemishes are not so evident (if that can be said to be an advantage!) and that the hard gloss surface will disappear over the years anyway so that a slightly textured surface makes the change less discernible. The loss of gloss from a polyester gel coat certainly does occur depending on the exposure to sunlight, but in well-made GRP in normal conditions the loss is very slow.

Figure 7.9 Heavily textured GRP panels

Another approach to surface texture is to coat the external surface of the units with polyurethane after casting. This is a more expensive treatment than using a self-coloured gel coat but is likely to give a more durable finish. The polyurethane coating will intrinsically have a hard gloss finish but being a thin surface layer, will of course follow any moulded pattern in the base GRP.

7.12 Colour

Yes, any colour you like! But before indulging in this artistic freedom, the designer ought to consider carefully a number of technical points. Firstly, there is the all-important question of colour matching if the designer wishes to have uniformity of colour throughout his building. If, as is usually the case, the colour is to be achieved by a pigmented gel coat, then it is best to ensure that sufficient pigmented resin is produced in one batch to provide the gel coat for all the units to be produced. If this is not practical, very careful colour matching of resin batches is needed and it is important to ensure that samples are viewed under scientifically controlled identical circumstances. The unskilled eye is easily deceived by colour and expert advice would be worth seeking.

Secondly, there is the matter of colour retention. The problem is not severe for internal GRP but as most GRP is used on the outside of a building, the action of ultra-violet light is significant. Most pigments will change to some extent through the years but most colours can be produced nowadays by pigments whose rate of change is so slow as to be insignificant, although some blues and black remain a problem. But it is essential to check that the pigment used has good light stability. The designer should ask to be shown actual samples of pigmented resin which have been exposed outside for a number of years. Most manufacturers now have such samples available. The Building Research Establishment also has been conducting such tests. Fortunately there is now a sufficient number of GRP-clad buildings around which have been in existence for ten to fifteen years and a tour around to see some of those would be interesting for the designer. He should be encouraged by such a visit.

Colour change can also be brought about by yellowing of the polyester resin itself. This was a well-known effect in earlier uses of the material but more light-stable resins are now available. Again, this point should be checked with the resin supplier and, if possible, samples with several years exposure inspected.

Most colour changes go unnoticed provided they are not too violent and more importantly, provided the change is reasonably uniform through the building. Differential colour change can be distressing, although it is a comparatively rare phenomenon in GRP buildings. It is best avoided by careful attention to quality control in the production of the GRP units. Aesthetically, unforeseen colour variation is considered much more objectionable in GRP than in other common building materials such as masonry, brickwork and (particularly) concrete. Perhaps this is due to the unique precision of form which is achieved in GRP which leads us to expect equal precision in colour behaviour; or perhaps the often-heard claim of 'permanent colour' for GRP, leads us to expect just that. Certainly GRP had much stricter standards of appreciation imposed on it than, say, when the most horrid patchiness in concrete is forgiven as a 'natural' characteristic of the material; whereas with careful attention to specification and construction, very uniform concrete can be made.

Although colour matching and colour retention are not significant problems in most good quality GRP work, the risk of them occurring can be reduced by using a polyurethane surface coating rather than a pigmented gel coat. The polyurethane gives a somewhat more durable surface than the polyester resin and it is probably easier in practice to ensure that all the coating comes from the one batch of material. If something goes wrong, and the colour matching of the entire number of units produced is faulty, then they can be recoated! But that is an expensive process.

We have assumed in this section so far, that the GRP units are intended to be the same colour. Indeed most architects, up to the time of writing, seem to have used GRP in monochrome, particularly in whitish colours and pale beige in the early days. More recently, adventurous use has been made of bolder colours such as orange, brown and the darker greens.

Hardly any use has been made so far of the ability to produce cheaply and easily the same basic unit in different colours. The same mould is used and the only change in production is to use a different pigment in the gel coat. By this means alternating colours, or a graded change of tint of the same colour can be used across a building facade.

In its *Guidance notes for the construction of reinforced plastics cladding panels* (1981), The British Plastics Federation suggests pigments which are likely to give good results, and these are repeated in *Table 7.2*. Nevertheless, the Federation recommends that proper tests should be carried out using the selected pigments in the resin system proposed.

Table 7.2. Recommended pigments

Name	*Colour index no.*
Rutile titanium dioxide	White 6
Red iron oxide	Red 101
Yellow iron oxide	Yellow 42
Nickel titanate	Yellow 53
Chrome oxide	Green 17
Phthalocyanine green	Green 7
Phthalocyanine blue	Blue 15
Cobalt blue	Blue 28
Carbon black	Black 7
Iron oxide black	Black 1

In addition to these there is a range of metal complex inorganic pigments that are suitable.

7.13 Thermal insulation

Of all the numerous functions that can be designed into a GRP panel (see section 7.5), thermal insulation is the one which is most frequently used – apart of course, from the basic functions of weather tightness which are inherent in the use of GRP. The reason for this is probably two-fold; firstly, the inclusion of insulating cores or air spaces within a GRP panel is fairly easy to achieve and secondly, the consequent thickening of the finished panel by such inclusions increases the rigidity of the product considerably, especially for flat surfaces. Most buildings require thermal insulation in their walls and roofs and if the building is to be clad in GRP, it is often easier and cheaper to provide the necessary insulation within the GRP panel itself.

Glass-reinforced polyester resin itself is quite a good thermal insulator having a thermal conductivity of around 0.2–0.3 W/m°C, as against the following values of other materials (using the same units). Brickwork 1.2, concrete 1.4, timber 0.14, steel 50. Even so, this property is not a great deal of use in practical design as the GRP is commonly used in such thin sections that the total insulation, which is proportional to thickness, is not great. Nevertheless in considering 'cold bridges' formed through the total thickness of a panel by GRP ribs and in certain joint details, the cold area effect is much less marked than with, say metal-clad panels or even concrete.

In sandwich panels, the greater part of the thermal insulation is provided by the core or by the air space. Commonly used core materials are expanded PVC, phenolic foam and polyurethane foam. Mineral wool in block or slab form can also be used. Polystyrene foam is not used as it is severely attacked by the styrene in the polyester resin. The insulating value of core material depends large on its density but conductivities between 0.03 and 0.1 W/m°C, are common. The choice of core material depends largely on the fire behaviour required of the finished panel. Mineral wool is incombustible and of the plastics, phenolic foam has the best fire performance but it is more expensive than polyurethane foam.

In designing a GRP panel for thermal insulation, careful attention should be given to the matter of the 'cold bridges' mentioned above. The ideal panel would have a constant thermal conductance over every square millimetre of its surface but this is not achievable in practice when it comes to ribs and particularly at joints between panels. The reduced insulation at these points may not be particularly serious in relation to the total heat loss of the building but, under certain conditions, such area of low insulation will cause condensation. Condensation is not so serious in GRP construction as the material is unaffected by moisture and of course will not corrode. Nevertheless metal fastenings and other inserts, which inevitably are more likely to be found at joints, can be affected by condensation and if this is likely to occur, they should be heavily protected or a non-metallic substitute used, such as nylon.

The condensation problem sometimes encountered in certain types of building construction whereby large areas become damp, is due usually to the permeability of the insulating material. The mechanism is that warm, moist, but not necessarily saturated, air from the inside of the building permeates through the insulation and meets the cold external skin of the construction. The moisture in the air then condenses and runs down or drips through the insulating layer causing all sorts of problems such as mould growth, staining, etc. This phenomenon is almost wholly prevented in GRP sandwich construction as the inner surface of the panel is, or should be, quite impervious and no moist air can migrate through to the cold outer surface. In cases where the GRP unit incorporates a single skin of material, or an inset glass window, condensation is likely to occur and the designer should consider how to deal with the condensate. It is comparatively simple to incorporate small gutters or channels at the bottom of such areas to catch the condensate and run it off to the outside of the building or even merely to hold it in storage until the ambient climatic conditions change and the condensate is evaporated again – not perhaps an elegant solution, but one which could be practical where conditions conducive to condensation are likely to be infrequent. Such channels and ducts should be proportioned so that they can easily be cleaned out.

7.14 Fire performance

7.14.1 GRP and fire

GRP is strictly speaking a composite but is generally and justifiably given the family name of 'plastic'. Therefore it has to bear some of the family stigma in relation to fire. The polyester component of GRP is undoubtedly combustible and as the resin commonly forms two thirds or more of the final GRP product, GRP must be taken seriously in any consideration of fire in a building. Although combustible, compared with a number of other plastics its fire behaviour is very good. In this respect it can be likened to the characteristics of cedar wood, which if not the most fire-resistant of timbers, is very widely used in building construction. GRP is not easy to ignite but in certain grades has a fairly high rate of surface spread of flame. The burning is usually accompanied by considerable smoke. The rate of burning does not accelerate much during the progress of the fire and at the end one is left with a charred black mat of the incombustible glass-fibre reinforcement. On the other hand, GRP does not rain flaming droplets nor does it explode, crack or splinter.

7.14.2 A 'real fire' situation

In the context of scientific observation, it is virtually impossible to collect data on the behaviour of building materials in real life situations. The only observers available are the fire fighters and their minds are naturally pre-occupied with the immediate problem of saving life and property. The building designer therefore has to rely on small-scale simulated fire situations from which calibrations of properties, such as rate of fire-penetration and surface spread of flame, can be made. Such measurements have little absolute meaning but can be a useful comparison of the properties of different materials; they can form part of the assessment of what would happen in a real fire but fall a long way short of the total problem.

Nevertheless we must try to do better and accumulate much more data on what actually happens in real fires (*Figure 7.10*). Our knowledge would probably have to be obtained by a synthesis of direct observation of fires, sample testing and the accumulated experience of fire fighters, insurance investigators, medical evidence from fire victims, etc. This is a very long term objective, but one which the whole community would welcome. Certainly the United Kingdom Fire Research Station sees this as an ideal to be aimed for. Perhaps such a development will necessitate the creation of a new category of technologist, the 'fire engineer', but in the meanwhile architects and engineers can take a rational look at the fire situation and it is surely un-arguable that the two principal concerns in order of priority are:

1 The avoidance of death or injury to persons.
2 The minimization of loss of property.

In furtherance of these objectives the matters to be considered by the designer are:

1 Escape of occupants – which includes protection and alarm systems, the type of occupant, his likely physical ability and speed of reaction.
2 The likely contents of the building and their 'fire loading'.
3 Ventilation of a fire.
4 Fire behaviour of the building fabric.

Figure 7.10 'Full scale' fire test on GRP cladding panels. Note: the controlled fire load burning at ground level, the time from ignition (10 minutes) and the unignited curtain fabric in the first floor window. Such full scale fire tests, despite the limited extent of building involved, are quite rare

These four headings have been arranged roughly in order of importance but opinions could differ on this. Whatever the view, it can be seen that the codified fire ratings of the building materials form only a part – albeit a significant part – of the real fire situation.

7.14.3 Standard fire tests

It is an unfortunate truth that all of us engaged in technology tend to seize upon the properties which can be measured and catalogued, and disregard those which are arbitrary, even though they may be more important. Worse still, measurable parameters tend to become exclusively the criteria to be used in design. Thus in most contries, certainly in the United Kingdom, the building designer is presented with a series of strict rules concerning fire – survival periods of building elements, fire penetration and spread of flame measurements, all of which are based on small-scale simulated tests. As far as the regulations are concerned it is a 'go or no-go' situation, but it is possible to design a building which complies with all the regulations and yet is a very dangerous building and no doubt the converse could also be demonstrated. It is not suggested that we throw away our existing fire regulations, they are the best we can do in the present circumstances. Nevertheless the results of the fire tests laid down by the regulations should be viewed objectively and their value assessed in the context of a real fire situation, in so far as we are competent to envisage such. The very diversity of approach in different countries to this sort of fire testing, indicates that there is no universally accepted notion of the precise property which is to be measured.

Present day standard fire tests concentrate on:

(a) The combustibility of the material itself, i.e. does it burn at all? If it does, how slowly or quickly?
(b) Surface spread of flame. This is particularly relevant to building panels.
(c) Fire penetration. Again this is particularly relevant to wall and roof panels.
(d) Fire propagation tests, whereby the products of combustion of the material under test are measured for temperature rise and also sometimes for smoke, and any contribution which the products might make to the fuelling of the general fire.

In the United Kingdom, tests of types (b), (c) and (d) are covered by BS 476. The tests are quite severe and require specialized equipment and skilled handling, but testing houses are available in the UK which conduct such tests as a routine.

Fire penetration tests in the UK (BS 476 : Part 3) apply specifically to roofing. The results of such tests on GRP sandwich panels, depend very largely on the nature and method of fixing of the core material rather than the GRP itself. In buildings which have GRP wall cladding, there is nearly always an inner back-up wall of incombustible material (concrete or blockwork, etc.) which provides the required resistance to fire penetration for the wall as a whole. Thus in a total building design, the fire penetration characteristics of GRP are often not critical and most attention in GRP design is focused on the spread-of-flame characteristics.

Spread of flame in the UK is tested under BS 476 : Part 7 and the results are graded into four categories, class 1 being with the minimum spread of flame and class 4 the maximum. The British Building Regulations allow for a further category, class 0, which covers noncombustible materials, but class 0 can be achieved by a GRP which comes into class 1 of the BS test, provided it is adequately bonded to a non-plastic substrate and that the combination itself meets certain requirements under the propagation-of-fire test. It is therefore possible to design a building using GRP extensively both as an external and internal surface which will satisfy the building regulations. A number of examples exist and a particularly interesting case is that of the access ramps at Heathrow Airport, Terminal 2 – (see Chapter 10, Case histories).

It is not necessary to go to the expense of making these elaborate fire tests for every GRP design, as the building control authority will normally accept a test certificate from the resin suppliers covering previous tests on a particular resin. The manufacturers of proprietary GRP panels will also have test certificates corresponding to fire penetration behaviour but any new or specially designed composite panel will probably have to undergo a fire test.

7.14.4 Practical design for fire

Taking what we do know about GRP and combustion, what can we do to use GRP in the safest possible manner? Firstly we can look at the material itself. Certain additives to the resin can improve the fire performance in test samples but unfortunately all such additives detract from the weathering qualities of the finished surface, often seriously so. As a result it has been the author's policy so far, to avoid additives for external cladding and to attack the fire performance problem by a consideration of the total 'fire situation' likely to occur in the building. One exception to this rule on additives is the use of mineral particles (sand, aggregate) set in the surface of the GRP. Even though such mineral particles would eventually fall out in the advanced stages of burning of the resin, the inclusions can make a dramatic reduction in the rate of fire spread along the surface. Great care must be taken in the design and manufacture of such panels to avoid cracking and crazing of the resin due to the stone inclusions. Frost action on such defects can cause rapid deterioration.

Another method of reducing surface spread of flame is to use a final coating of polyurethane on the GRP surface. This will have other benefits in durability and uniformity of finish as discussed earlier; on the other hand it is a relatively expensive procedure.

Returning to the consideration of the real fire situation, it is worth remembering that GRP is virtually impossible to ignite if it is kept damp and the quantity of water required is quite small. Thus sprinkler and drencher sprays can be very effective.

For external walls there is nearly always a non-combustible inner wall of brickwork or concrete which protects the GRP from an internal fire and the building from fire in the GRP itself. There is normally an air gap between the GRP cladding and the concrete backup wall and it is important that this gap should be partitioned at frequent intervals so as to inhibit air supply to any fire in that cavity. In such external vertical cladding fire penetration is unlikely to be a problem but surface spread of flame is. A GRP wall with window openings therefore requires greater protection than a blank wall with nothing above it.

In the case of roofs, perhaps the most important consideration is immediate and copious venting of any fire that has started. Not only will that inhibit the spread of fire along the underside of the roof but it will also allow the escape of smoke and other combustion products. Some fire authorities consider that the best roof is one which falls out in the early stages of a fire without burning – provided of course that it is light-weight! Although automatic mechanical ventilators are aimed at achieving this effect, they are rarely installed in sufficient numbers to give large, rapid venting – and they are expensive. It would be perfectly feasible to design a GRP panel which would collapse before burning. Such panels set at frequent intervals in a roof would provide an economic smoke-venting system.

To sum up, GRP is combustible but one of the better-behaved plastics from the point of view of fire. There is a great need for a better understanding of the total fire behaviour of the building and the role that GRP components would play in a real fire. Although studies of the intrinsic fire qualities of the material should continue, eventually it is likely to be of greater importance to study the behaviour of the materials as one component in a total building situation.

7.15 Degree of repetition

The GRP designer often will start his work under the threat of heavy costs if his design requires a number of different shapes and sizes of panel to be moulded. It is certainly true that each different mould required will add to the cost of the project. The designer therefore will probably resolve from the beginning to use only one standard panel or at the most perhaps two or three standard designs. Even with these good intentions, he will eventually find that by the time he has catered for corners, internal and external, differing elevations or heights, various types of necessary openings in the façade, left-handed and right-handed units, he may find himself landed with 50 or more different types on his final schedule. Most GRP manufacturers will confirm that the latter figure is no exaggeration. The problem can be reduced in two ways:

1 By actually reducing the number of variations.
2 By adapting moulds to produce more than one shape.

Firstly, the multiplicity of shapes such as is quoted above, usually results when the designer decides to wrap the whole of his building, or the whole of one elevation, in GRP. The aesthetic argument would be that GRP has such a strong individuality that it does not blend easily with other facing materials. Although a legitimate argument, it is perhaps based more on the comparative newness of GRP as an architectural element. Alternatively perhaps the designer is so fascinated, understandably, with the artistic possibilities of the material that he is determined on a 'GRP building'.

Whatever the motives, it is certainly true that some of the most successful examples of GRP use have been based on the concept of a complete GRP wrap of the building. If the designer is prepared to face the extra moulding cost involved then so be it.

The alternative is to use GRP panels only in those parts of an elevation where the truly standard panels can be used. Commonly this would still result in 70 or 80 per cent of the elevation being clad in GRP but where odd corners and difficult geometric intersections occur, then more adaptable materials are substituted such as brickwork, blockwork or *in situ* concrete. There are strong aesthetic arguments for using different materials according to their suitability, in different parts of the building. For example, one does not see facing brickwork used as a roof covering material.

Taking this line of thought a stage further, GRP units can be used purely as an applied decoration on a building. The weather-proof shell of the building is then constructed solely of low-cost but effective materials such as concrete, blockwork or brickwork. The GRP units are then fixed on the face of the building structurally separated from each other and, if desired, visually separated. The multitudinous problems of making weather-tight joints between the panels, as explored in the following section, are thereby avoided. It would not be difficult to make the panels separately demountable so that access to the main building fabric beneath is obtained.

It may be thought that such a noble material as GRP, which is quite capable of providing so many building functions, deserves better usage than being mere costume jewellery. Nevertheless the building can be given most of the visual benefits of the material in this way at a significantly reduced cost. The technique is also of value in the refurbishment of existing buildings.

The second general approach to the problem of reducing mould cost is by designing the units so that variations can be cast from an extension or simple adaptation of one basic mould. Lengthening and shortening of a mould is an obvious example. Other adaptations can be made by the use of removable panels in the mould to form basic units or similar units with window openings, door openings and the like. The designer of the GRP unit should have these concepts firmly in mind and be prepared to adapt his design somewhat using the advice of the mould-maker on what is practical to achieve.

Chapter eight

Structural analysis

8.1 Concepts

Unfortunately, because of the lack of past experience in the use of GRP, the designer does not have established codes of practice to give guidance. Nor is he likely to find, because of the almost limitless varieties of laminate, a relevant worked example in one of the few textbooks available. To a great extent he is out on his own and thus it is very important that he has a good grasp of what the material can do and possibly of more importance, what it cannot. On the bonus side, within the range of stresses that the designer will be working, GRP behaves in theory as a linear elastic solid. Thus most of the accepted methods of conventional structural analysis which have been developed for the more common materials such as steel and timber, can be used.

A word of warning, however – GRP by its very nature is a composite of several different components, often from different sources. Consider also, the human element and the end result may not be the uniformity that is expected. The designer is in fact faced with a material that he may believe to be homogenous but in fact is unlikely to be, the assessment of degree is a matter of engineering judgement. These generalized comments apply to all types of laminate whether they are reinforced in one, two or random directions.

8.2 Properties of GRP relevant to structural design

Before starting structural calculations, the designer should think carefully about the limitations of the material, bearing in mind its physical properties. It will be noted from Chapter 3 that the main properties of GRP which are significantly different from other materials commonly used in building are the high coefficient of thermal expansion, the low stiffness and the susceptibility to fatigue failure. Approximate strength, stiffness and fatigue properties of chopped strand mat laminate are compared with other commonly used materials in *Table 8.1*.

It will be noted that the ratio of strength to stiffness is high, even when fatique strength is taken into account, which indicates that elastic stability is very much more likely to be a design consideration than with other materials. For this reason a section of this chapter has been devoted to elastic stability as it relates to forms commonly used in GRP design.

The coefficient of thermal expansion of GRP is approximately three times that of concrete of steel. Thus a joint detail which may be effective between two pre-cast cladding panels will not be appropriate for use with GRP. In many cases GRP units have been given additional strength by the inclusion of steel sections. Care is required in the detailing to provide for the different thermal movements which may occur and which, if restrained, could cause undesirable stresses or distortions. This is particularly important where temperature differences may be large and/or repetitive. The low stiffness value, coupled with the fact that GRP is normally used in thin sections, requires that particular consideration is given to deflections.

Table 8.1

Material	*Modulus of elasticity – stiffness (kN/mm²)*	*Static strength (N/mm²)*	** Fatigue coefficient (%)*	*Coefficient of thermal expansion/°C*
Mild steel	210	210	65	12×10^{-6}
Structural aluminium	73	160–200	43	22×10^{-6}
Concrete	25	20–25	65	10×10^{-6}
Chopped strand mat GRP	5–10	180–230	20–30	$25–35 \times 10^{-6}$
Stress-graded softwood, species group S2	8–9	40–80		$5–6 \times 10^{-6}$

* Fatigue coefficient, *Fc*, equals fatigue strength divided by static strength.

8.3 Structural calculations required

8.3.1 Overall stability, or Will it stand up?

A check must be made that the structural element(s) will comfortably maintain both position and integrity when subjected to the design loading. By comfortably we mean without exceeding allowable stresses or deflections. This exercise should embrace all fixings to units and the joints between them.

Some of the most efficient uses of GRP are as a three-dimensional membrane, possibly as a thin spherical shell or complex folded plate (*Figures 8.1* and *8.2*). A rigorous theoretical analysis of this latter type of structure is likely to require a considerable input of time and will produce results to a degree of accuracy which is incompatible with the somewhat arbitrary methods which will necessarily be used to determined the

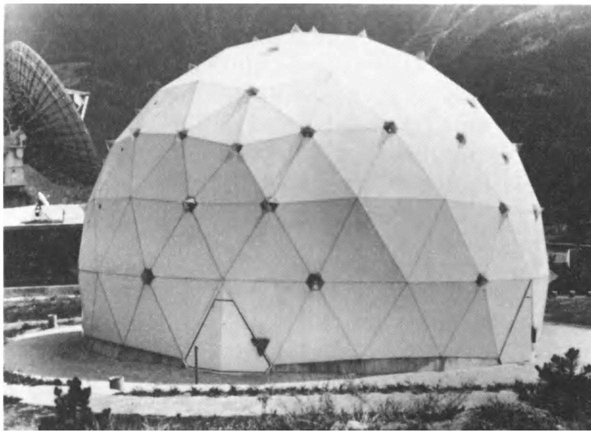


Figure 8.1 Triangulated dome in GRP

allowable working stresses. It is logical, and often the practice, that somewhat empirical analysis is employed when the designer is faced with a complicated structure. This simplified approach is justified if used in conjunction with a prototype load test.

Design loadings tend to be modest, e.g. wind, snow, etc. and hence load testing is normally relatively inexpensive. Indeed many designers in other materials would sleep more easily in the knowledge that their creations had successfully withstood a similar test.

Figure 8.2 Swimming pool enclosure made up of GRP hyperbolic paraboloid modules to form a 'folded plate' structure

8.3.2 Local elastic stability or buckling effects

As mentioned in section 8.2, GRP is a very strong, but also very flexible material and is thus particularly susceptible to local buckling. This type of behaviour can be illustrated by imagining a paper drinking straw subjected to an increasing compressive axial load. As the load builds up, a stage will be reached where the straw kinks and is unable to support any further load. A cursory examination of the kink will reveal that the paper has failed neither in tension nor compression but in a buckling mode. A more theoretical approach to elastic stability is pursued later in this chapter.

8.3.4 Deflections

In Chapter 3 the short-term elastic behaviour of different types of laminate was described. It was noted that the effective modulus of elasticity of the laminate is strongly dependent upon the glass content in the direction under consideration. For the calculation of deflections under transient loadings it appears that the short-term elastic modulus can be used with sufficient accuracy. For medium-term loads such as snow, which may be applied for several hundred hours over the life of the structure, the deflection obtained from the short-term modulus should be multiplied by approximately 1.5. For long-term and self-weight loads the deflection calculated using the short-term modulus of elasticity should be at least doubled in the case of laminates made with chopped strand mat.

Temperature movements should not be forgotten and in the case of large cladding units and 'floating' roofs where temperature movements are concentrated at the edges, the deflection relative to the fixed supports can be considerable.

8.4 Safety factors and allowable stresses

The structural designer, when meeting GRP for the first time, is likely to be already well acquainted with the more conventional building materials, e.g. brick, concrete, steel, etc. However, the designer may be in for some surprises; not only will he find that some of the GRP physical properties are markedly different, but also and perhaps more worrying, that the concept of a finite permissible working stress, which has probably been relied on heavily in the past, has no parallel in GRP design. Some guidance may be obtained from BS 4994 – Vessels and Tanks in Reinforced Plastics, and the principal points relating to allowable stresses (where strength and not buckling is the main consideration) are as follows:

The tensile strength of a laminate is obtained by specified British Standard tests and results in an ultimate unit tensile strength U N/mm per kg/m^2 of glass. The value of U should in any case be not less than 200 N/mm per kg/m^2 for laminates reinforced with chopped strand mat or 300 N/mm per kg/m^2 for those using woven roving cloth reinforcement. The allowable unit loading U_L is defined as:

$$U_L = \frac{U}{3 \times k_1 \times k_2 \times k_3 \times k_4 \times k_5}, \text{ but not more than } U/6$$

k_1 is a factor relating to method of manufacture and varies between 1.6 for handwork to 3.0 for spray application.

k_2 is a factor for long-term behaviour taking into account loss in strength, and should be within a range 1.2 – 2.0 for tanks.

k_3 is dependent on the design temperature and the heat distortion temperature (HDT) of the resin system, and is based on the loss in resin properties with increasing temperature. A value of 1.0 is used for design temperatures up to 40°C less than HDT. The value rises to a maximum of 1.25 at the highest permissible design temperature which is 20°C less than HDT.

k_4 is related to cyclic loading and takes the value 1.1 for up to 1000 cycles, increasing to 2.0 at 1 million cycles.

k_5 is a factor relating to the efficacy of the curing procedure and varies between 1.1 and 1.5, the lower being for full post-cure at elevated temperature at the manufacturer's works.

For well-manufactured and fully-cured components subject to normal environmental loads (e.g. snow, wind, etc.), U_L would be approximately U/6.

Using this value, the equivalent approximate working stresses for two typical laminates would be:

Laminate with 40% chopped strand mat	25 N/mm^2 (for U of 200 N/mm per kg/m^2 of glass)
Laminate with 55% woven roving	55 N/mm^2 (for U of 300 N/mm per kg/m^2 of glass)

Safety factors on ultimate strength that have been used range from 2 for static short-term loads, to 10 for repeated impact loads. A safety factor should not be selected without careful consideration of the nature of the loading, the detail design of the laminate and of the environmental conditions to which the structure will be exposed. Safety factor against buckling modes should be at least 5 to include an allowance for geometrical imperfections.

8.5 Analysis of typical structural forms

This section gives guidance on the stress analysis for a number of commonly used structural forms. Some of the more complex shell shapes could be more conveniently analysed by computer using one of the standard frame or shell programmes. At the end of the section some useful formulae on critical stresses for elastic buckling are given for some of the most commonly encountered situations.

8.5.1 Cylindrical tanks with hydrostatic load (*Figure 8.3*)

Moment in shell at height x per unit length producing vertical stresses

$$M_x = \frac{\gamma h e^{-\beta_x} \sin \beta_x}{2\beta^2}$$

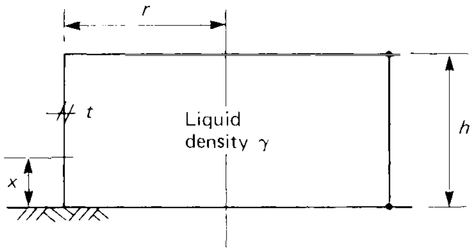


Figure 8.3

Hoop tension per unit height, $N_x = \gamma r(h\text{-}x\text{-}he^{-\beta_x}\cos\beta_x)$

Base shear per unit length, $Q_0 = \gamma h/2\beta$

where $\beta^4 = \dfrac{3(1-\nu^2)}{r^2t^2}$

ν = Poisson ratio, t = wall thickness, r = radius, h = height

8.5.2 Axi-symmetrical shells and domes (*Figure 8.4*)

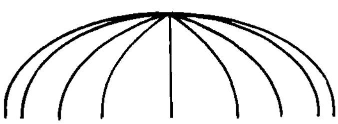


Figure 8.4

Analysis is routine and well-documented in many standard textbooks*. Under normal conditions of uniformly distributed loading, the main stresses to be considered are those due to in-plane tensile and compressive forces. Bending effects are small and usually ignored except when the supports are fixed, when localized bending effects need to be considered. In order to cope with horizontal thrust at the support, a ring beam is sometimes introduced. Where the radius of curvature is very large (a shallow dome) consideration must be given to secondary deflections which may give rise to so called popping effects. A rigorous iterative analysis will then be required which makes allowance for the change in shape as load is applied (*Figure 8.5*).

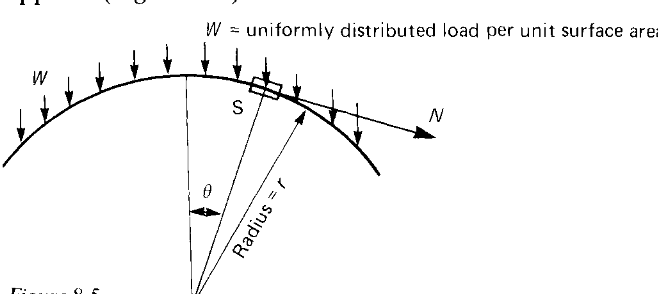


Figure 8.5

T = Horizontal circumferential force in unit strip at S

$$T = Wr\,\frac{[1-\cos\theta-\cos^2\theta]}{(1+\cos\theta)}$$

* *Theory of Plates and Shells*, Timosheinko and Woinourstay-Kruger (McGraw-Hill, 1959).

N = Meridional thrust (acts tangentially) in unit strip at S

$$N = Wr\frac{[1-\cos\theta]}{(\sin^2\theta)}$$

8.5.3 Non axi-symmetrical shells (*Figure 8.6*)

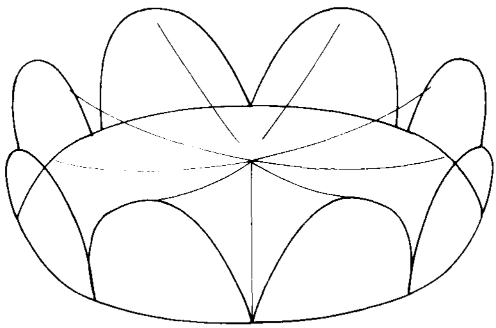


Figure 8.6

Many complex curved profiles do not lend themselves readily to either theoretical or empirical analysis. In such cases, computerized finite element techniques provide the obvious solution.

8.5.4 Faceted cylindrical vault (*Figure 8.7*)

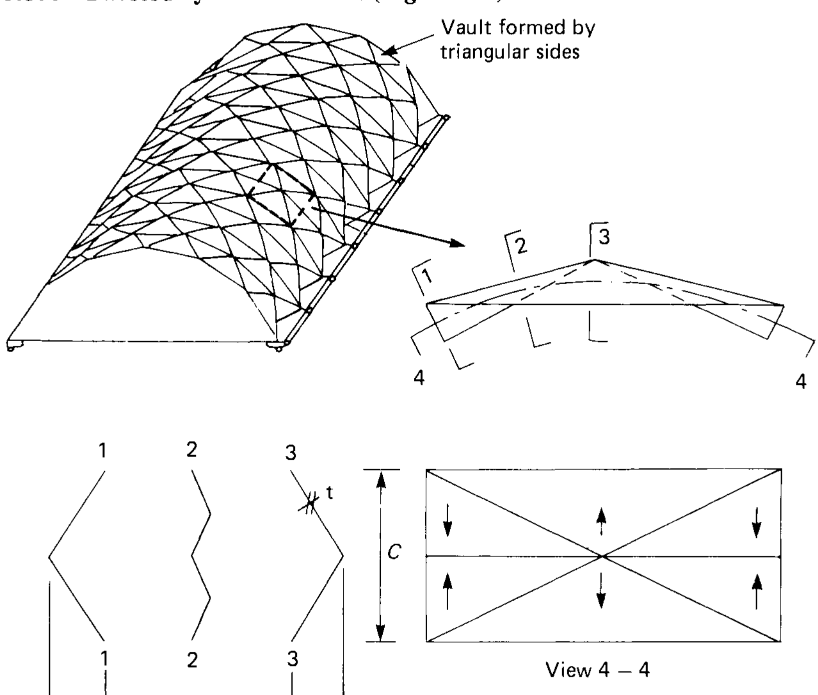


Figure 8.7

Effective moment of inertia for overall bending moment, shear force and deflection calculations.

$$I_{eff} = \frac{tH^2}{12}\sqrt{(C^2 + 4H^2)} \text{ for strip of width } C$$

Minimum section modulus for stress calculations

$$Z_{min} = \frac{tH}{12}\sqrt{(C^2 + 4H^2)} \text{ for strip of width } C$$

The overall analysis of the vault may be any of the standard methods of arches or by computer using an equivalent frame of short cord elements.

8.5.5 Folded plates of uniform section (approximate method) (*Figure 8.8*)

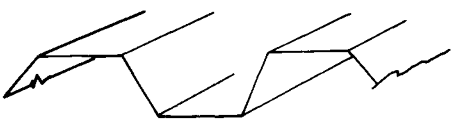


Figure 8.8

1 Resolve self-weight and applied forces into components in the plane of and perpendicular to, each plate.
2 Analyse the cross section of the structure using the forces perpendicular to the plate, assuming the nodes to be pinned. This gives the transverse bending moments and stresses.
3 Calculate the distribution of longitudinal bending stresses in each plate separately due to the forces in the plane of the plate. After this operation there will be incompatible stresses along the lines where the plates join.
4 Apply equal and opposite shear forces along each joint edge of each plate connection to make the stresses in each side of the edge compatible. An edge shear which changes the stress at an edge by σ_s produces a change of stress of $-\sigma_s/2$ on the opposite edge of the same plate. Where adjacent plates have different thicknesses the applied shear force produces stresses in each plate in proportion to the increase of its thickness.

8.6 Sandwich construction (*Figure 8.9*)

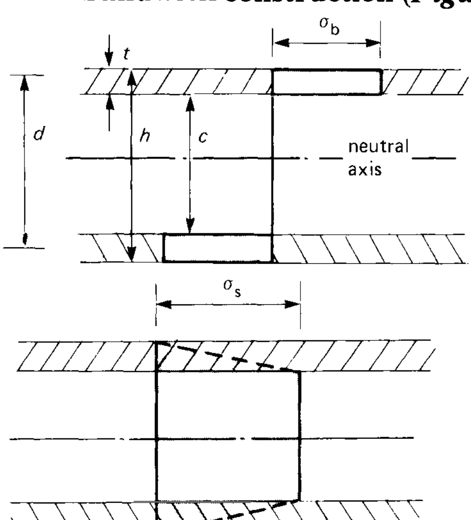


Figure 8.9

Bending stress distribution: simplified (flexural rigidity of core ignored)

$$\sigma_b = \frac{Mh}{btd^2}$$

where M is the applied bending moment, b is the width.

Shear stress distribution: simplified (shear strength of laminate ignored)

$$\sigma_s = \frac{Q}{bd}$$

where Q is the applied shear force, b is the width.

The formulae above relate to the most common arrangement of two GRP skins separated by a thick and relatively weak core. For a more detailed approach the reader is referred to *Design Data Fibreglass Composites*, J. A. Quinn, and *The Use of Plastics for Load Bearing and Infill Panels*, edited L. Holloway (Manning Rapley, 1976).

8.7 Elastic stability

Allowable stresses calculated from section 8.5 may have to be reduced, or stiffening added, in order to guard against general or local instability. Most structural materials in common use are manufactured or formed in standard types of cross section, for which design charts or simple rules for maximum slenderness are available which enable stability to be taken care of with confidence. With a free form material such as GRP it is often necessary to consider elastic stability from a more detailed point of view. It is normal to allow a factor of safety of at least five on buckling calculations to allow for initial deformations and the fact that buckling failures can be sudden.

8.7.1 Struts

The overall buckling characteristics of axially and eccentrically loaded long hollow struts are given in many standard textbooks on structural analysis*, but local buckling of circular sections requires consideration.

The theory is based on small deflections at critical stress levels, for an axially loaded cylinder:

$$\sigma_c = \frac{Ed}{a\sqrt{[3(1-\nu)^2]}}$$

Where σ_c = critical buckling stress, E = Young's modulus, ν = Poisson ration, d = wall thickness, a = radius.

Experiments on hollow metal cylinders have shown that the onset of buckling may occur at levels between 10% and 60% of the critical stress levels*. Lundgren estimates that for practical purposes a lower-bound figure should be used thus:

$$\sigma_c = \frac{Ed}{a\sqrt{[3(1-\nu)^2]}} \simeq \frac{0.2\ Ed}{a}$$

8.7.2 Torsional stability of beams in bending

For I, Z, T and L forms, loaded through their shear centre,

σ_c = Critical buckling stress
M_c = Critical buckling bending moment

* *Analysis of Engineering Structures,* A. J. S. Peppard and J. F. Baker (Edward Arnold, 1936)

Z = Constant depending on shape of bending moment and varying between 1.0 for a uniform bending moment to 1.36 for a triangular bending moment diagram having a maximum value at the centre of the beam
q_c = Euler buckling stress of the beam acting as an axially loaded strut
G = Modulus of rigidity
J = Torsion constant of beam
h = Total depth of beam
d = Distance between centre lines of flanges
s = Width of flanges of Z beam
r_{xx} = Radius of gyration about major axis
A = Area of cross section of beam

For I beams loaded symmetrically in the plane of the web,

$$\sigma_c = Z\frac{hd}{4r_{xx}^2} \times q_c \sqrt{\left(1 + \frac{4GJ}{q_c A d^2}\right)}$$

For Z beams loaded in the plane of the web

$$\sigma_c = Z\frac{hd}{4r_{xx}^2} \times q_c \frac{2N+1}{2(N+2)} + \frac{4GJ}{q_c A d^2},$$

where $N = d/s$

For T and L beams loaded through the intersection of the centre lines of the flanges or flange and web,

$$M_c = Z\sqrt{(q_c AGJ)}$$

Channel profiles have their shear centre outside the section so unless the line of loading is carried out to the shear centre by brackets the beam will be subject to torsion. A channel profile is, therefore, in most cases inefficient as a beam when used with a material such as GRP.

8.7.3 Elastic stability of plates and flanges stressed in their plane

σ_{sc} = Critical shear stress, l = Plate length, b = Plate breadth, t = Plate thickness.

Plate subject to shear only, as in web of plate girder or folded plate (*Figure 8.10*).

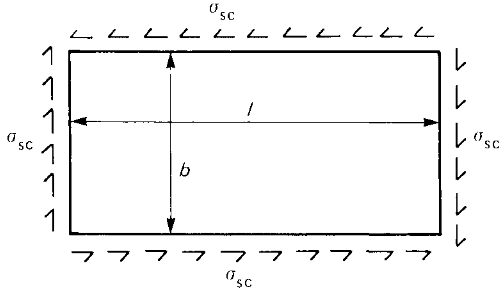


Figure 8.10

$$\sigma_{sc} = 5\left[1+\left(\frac{b}{l}\right)^2\right]\frac{\pi^2 E}{12}\left(\frac{t}{b}\right)^2$$

Plate, simply supported on all sides subject to uniaxial compression, as in top plate of folded plate (*Figure 8.11*).

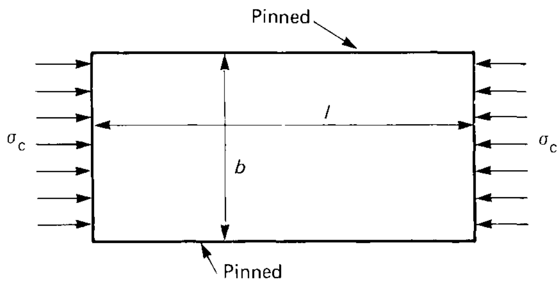


Figure 8.11

$$\sigma_c = \frac{4\pi^2 E}{12}\left(\frac{t}{b}\right)^2, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ for } l > b$$

$$\sigma_c = \left(\frac{l}{b}+\frac{b}{l}\right)^2\frac{\pi^2 E}{12}\left(\frac{t}{b}\right)^2, \quad \ldots\ldots \text{ for } l < b$$

Flange plate simply supported on three sides, free on one side, load parallel to the free edge (*Figure 8.12*).

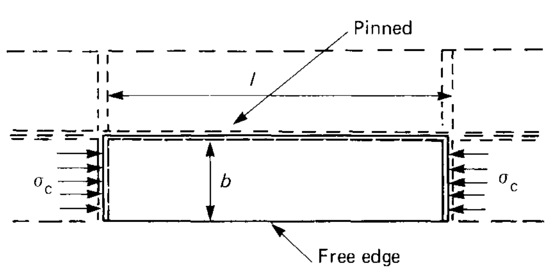


Figure 8.12

$$\sigma_c = \left[0.456+\left(\frac{b}{l}\right)^2\right]\frac{\pi^2 E}{12}\left(\frac{t}{b}\right)^2$$

8.8 Prototype testing

Since the costs of the initial mould construction are likely to form a substantial part of the contract price, it follows that the cost per GRP unit will fall as the production run increases. Thus it is usually worth giving serious consideration to the idea of making at least one sample panel prior to the main run, this can be load tested, to destruction if necessary. Any shortcomings in the original design can thus be corrected, often by a minor modification to the mould or laminate. If significant modifications have

Figure 8.13 Full-scale load test on roof for Morpeth School, London

been found necessary it may be prudent to produce a further sample unit for testing. In this way, it should be possible to enter the main contract manufacturing stage with the knowledge of the future in-service behavioural characteristics (*Figure 8.13*).

The test itself will normally have to be tailored to the particular unit and its design loading. Provided that a competent testing house is used, this should not present a problem. Design loadings are unlikely to be severe and thus a test rig can often be assembled from relatively light members, e.g. Dexion. It is important when assessing measured short-term deflections, that allowance is made for long-term creep effects (see section 4.3.3.6).

Chapter nine

Jointing and fixing

9.1 Joints are important

Yes, joints are very important indeed. Joints make the difference between a successful GRP building and utter disaster. Although GRP buildings normally give less trouble than those with more conventional materials, when trouble does occur it is nearly always at the joints. Trouble rarely stems from the GRP material itself, especially in more recently constructed buildings which benefit from the improvement in the component materials and from a better understanding of the need for high quality workmanship. The author would recommend, from hard experience, that the designer should allocate as much as 50% of his design effort to the joints alone.

This warning may not be popular with those designers who consider it much more interesting to dream up the shapes and contemplate some of the questions raised in Chapter 7 on Design. Certainly a number of the joint failures in otherwise excellent GRP buildings, seem to have occurred through lack of attention from 'the master'. In such cases the joint details may have been taken wholesale from techniques used with other materials such as precast concrete, or worse still, by blindly accepting the claims of proprietary sealant manufacturers (of which more later).

Well, perhaps designing a joint is less exciting than designing the shape of the unit but it is an interesting pursuit in itself and in any event it has to be done properly. Joints in GRP can be designed to be successful, and the starting point of a recipe for success is for the designer to look upon himself as 100 per cent responsible for the performance of the jointing, no matter what materials and techniques, proprietary or otherwise, he may go on to specify.

9.2 Types of joint

There are basically three types of joint used in GRP work – the sealed, the drained and the overlap joint. Some joint details incorporate features from more than one category.

9.2.1 Sealed joint

This can be a very simple joint and comprises basically a sealing material filling a gap between two adjacent GRP panels. The sealing material can be either a compressible foam clamped mechanically between the two GRP surfaces, (*Figure 9.1*), or an adhesive sealing compound which sticks to the GRP surfaces, (*Figure 9.2*). The former can produce a reasonably

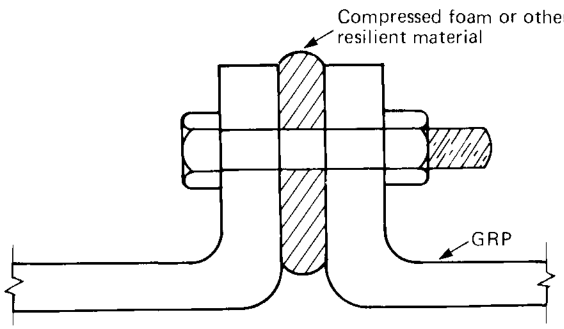


Figure 9.1 Sealed joint using compressible foam between two surfaces

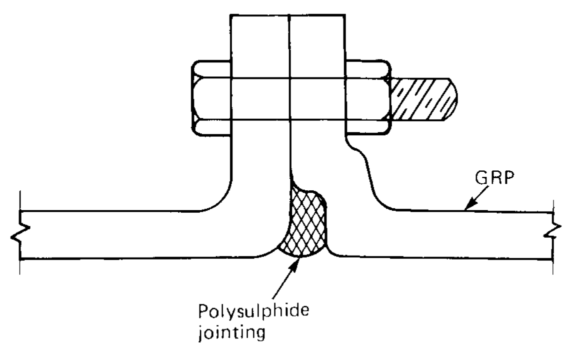


Figure 9.2 Sealed joint using adhesive sealing compound

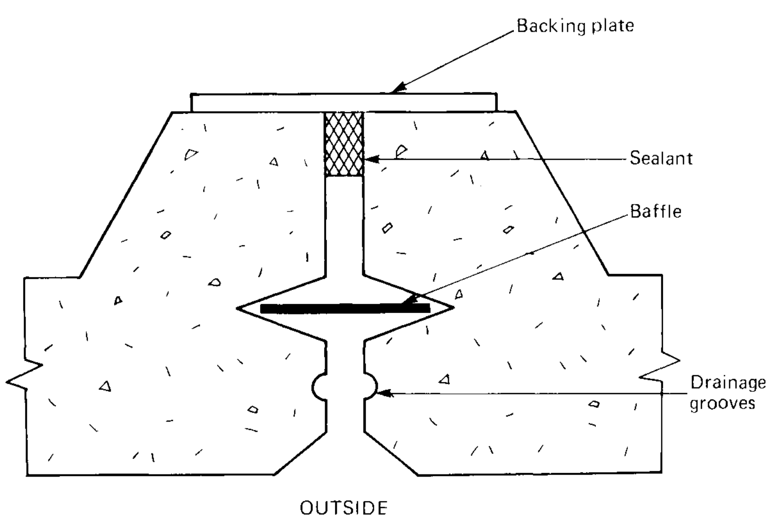


Figure 9.3 Drained joint in precast concrete

reliable joint provided the clamping force is effective throughout the whole line of the joint, but the latter is unlikely to be fully reliable. No sealed joint should be relied upon to be the only line of defence against severe weather conditions.

9.2.2 Drained joint

The drained joint is one in which the designer expects that some rain will pass through the outer barrier of his defence systems but that it will be channelled by gravity, or drained away to a safe place – usually outside the building again. The drained joint was developed in the first instance for precast concrete building panels, (*Figure 9.3*). A similar joint design can be made in GRP. Alternatively the baffle strip can be replaced with a compressed preformed sealing strip or by an adhesive sealer.

9.2.3 Overlap joint

This is simply the joint used for so many traditional building materials such as roofing tiles, slates, corrugated roof sheeting, etc. By simple end-lap or side-lap, often with convolutions, rain is deterred from entering the building. It should be noted that such joints are by no means air tight. This type of joint is rarely used in GRP as it is rather extravagant in the use of material and the complex geometry required for other forms of jointing is fairly easily achieved in GRP. Nevertheless many joint designs borrow from the traditional overlap approach.

9.3 Common problems

There is normally just one type of problem which is encountered with joints in GRP and that is – 'the rain gets in'. Not only does the rain get in but, quite often, it enters in a spectacular way. Not just a slow seepage or even a damp patch but a running torrent, which of course, inevitably turns out to be worse in the boardroom or the Managing Director's office. As we said before, joints are important!

Such embarrassing in-rushes are not due just to the perversity of nature and are admittedly more common in GRP than with conventional building materials. Brickwork, timber, asphalte, etc. tend to let in the water slowly by forming small cracks or pinholes. GRP, having a completely non-absorbant surface, tends to concentrate rain runoff into joints and the joints themselves are often of a type which, when they have failed, create significant lengths of unprotected opening and hence, sadly, a deluge inside the building.

Other problems can occur but are comparatively rare. Air losses through joints of a slightly pressurized, air-conditioned building have been known and occasionally mechanical failure of a joint, or more likely the fixing, has resulted in a panel becoming loose. Such structural failure is rare indeed and of course should never happen at all. No, far and away the most common problem is the rain getting in, so let us look at some of the reasons why this might happen.

9.3.1 Sealant adhesion failure

Polyurethane sealants are widely advertised as providing an ideal weatherproof seal between building components, including between GRP panels. The sealant is supplied in a two part pack, the parts being mixed together on site to form a putty-like material which is then applied between the components to be joined. The sealant cures fairly rapidly to form a permanently elastic but tenacious joint between the two surfaces. Although it is true that an ideal joint can indeed be formed using this material, the same material has resulted in a very large number of failures. The problem is to ensure that the surfaces to which the polysulphide must adhere, are clean and dry. Even an undetectable film of moisture will seriously inhibit adhesion. Attempts are often made to mitigate the problem by using specialists to install the sealant. Such workmen will often warm the GRP surfaces by careful use of a blow torch to make sure they are perfectly dry, but even then, particularly, in the typical British climate, a thin film of moisture can get on to the surface in odd places before the sealant is introduced.

Even the most conscientious (and lucky) workmen will not achieve an absolutely 100 per cent perfect joint and a modest GRP building may have more than 500 m run of jointing. In such a building a 0.1 per cent failure rate will mean 10 or 20 points of ingress of the rain, and at least one of those is bound to be in the boardroom!

It is a pity that polysulphide sealants have this drawback, for in other respects, they have many attractions. They mould themselves to fit the shape and size of the space available between the jointing surfaces and thus can tolerate, within limits, manufacturing and erection discrepancies. They can be pigmented and in many cases can provide a visually neat and compact joint. Although a considerable degree of care and thoroughness is required in their application, no particular skill is demanded. Perhaps with further development some means will be devised of overcoming the problem of adhesion to the adjoining surfaces (see Chapter 11 – The future).

9.3.2 Displacement of jointing strips

Preformed or extruded jointing strips are necessarily of constant cross section and will be able to work properly only within a fairly narrow range of size of joint geometry. The elasticity of the strip material will accommodate some variation in joint size, but manufacturing, and more commonly, erection deviations can allow the jointing strip to escape or work out of the joint. The working out is sometimes caused by a sort of 'ratchet' action due to the diurnal thermal movement of the adjoining panels.

9.3.3 Inadequate rigidity of fixing

Although a fixing system may be quite sufficient to hold a panel on to a building, it may be insufficiently rigid to maintain the confining geometry of a joint within proper limits. This could result in the sort of defect described in paragraph 9.3.2. The problem is concerned not only with the size and spacing of fixings but also the rigidity of the parts of the GRP panels which form and immediately surround the jointing geometry. In situations where there is a joint with no fixings, for example where a glass window pane is set direct into a GRP panel, it is necessary to ensure that there is enough stiffness in the GRP panel surrounding the opening to control the joint geometry.

It follows of course, that the supporting structure to which the GRP is fixed is itself sufficiently rigid. This is not normally a problem where GRP panels are fixed directly to the structural frame of the building.

9.3.4 Poor positioning of joints

Wherever possible, joints should be located in positions remote from concentrations of water. Although in theory, a well-designed and constructed joint should withstand a considerable hydrostatic head, statistically there are bound to be some weak points somewhere in the joint and to have the joint furnished with a copious supply of water is just asking for trouble (*Figure 9.4*).

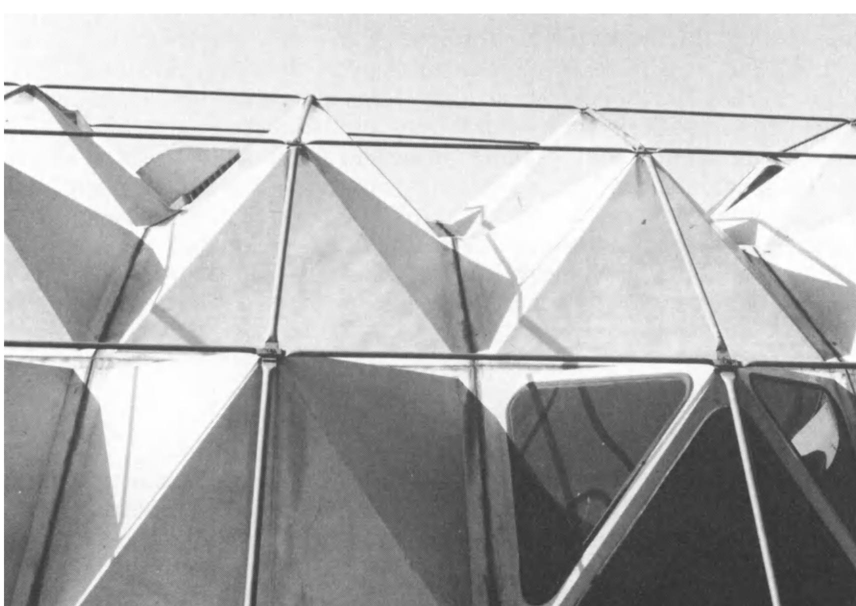


Figure 9.4 Joints placed in gutters and reliance put on simple gunned sealant. Inevitably, continual problems with rain leakage were experienced. Otherwise an exciting and ingenious structural design

Joints on roofs should be placed along ridges and not in gutters. This is fairly easy to arrange with a troughed or folded plate roof such as Morpeth School (*Figure 7.1*) but not so easy for a roof formed by a grid work of pyramidical or domed modules unless each cell of the grid is drained individually such as New Covent Garden roof (*Figures 9.5* and *9.6*). If there are visual objections to the joint on a ridge, it could be placed in say

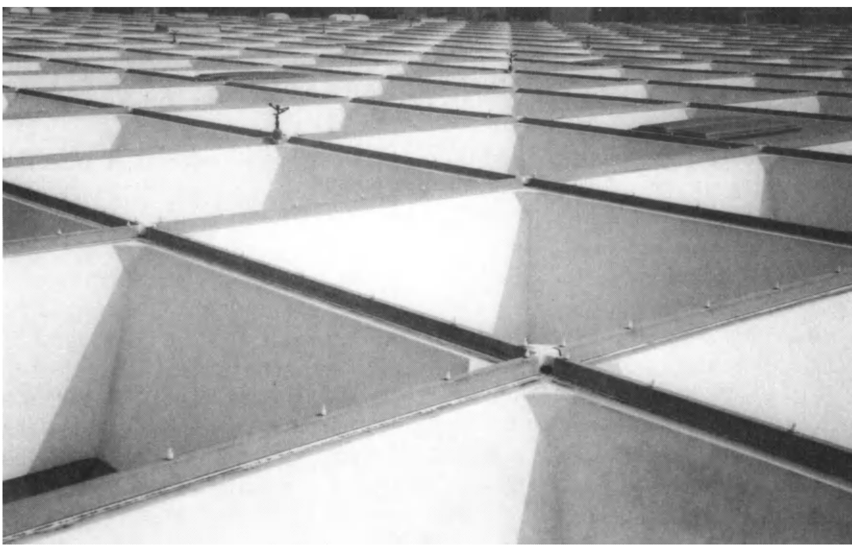


Figure 9.5 New Covent Garden roof showing joints at ridges

Figure 9.6 New Covent Garden roof showing individual drainage of each module

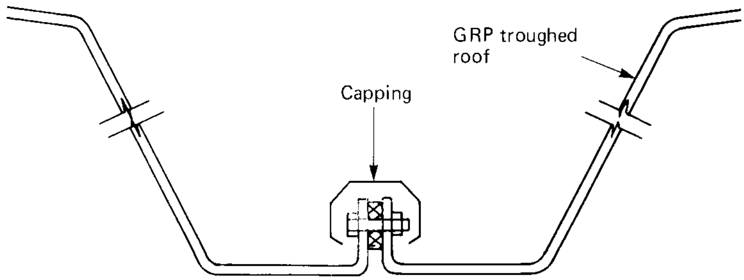


Figure 9.7 Forming the joint by means of two separate troughs

the bottom of a trough provided there is a substantial upstand to form the joint itself (*Figure 9.7*). In effect this device forms two separate troughs on either side of the joint; naturally each half trough will need to be individually drained.

On walling the problem is not so acute as it is much easier to arrange the joint to be fully drained. Even so, joints should be carefully considered from the point of view of wind-driven rain and should not be positioned on the upper surfaces of cornices, ledges, etc.

A particularly common example of poor positioning is at the head of a metal window where it is set directly into a GRP panel (*Figure 9.8*). The upward-pointing metal flange is placed on the outside and defects in the seal will act as a natural drain for the trough formed between the metal

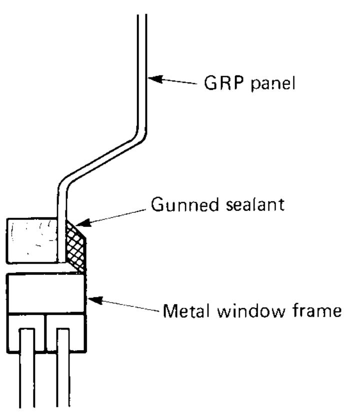


Figure 9.8 A poor positioning of the joint. This is at the head of a metal window where it is set directly into a GRP panel

flange and the face of the GRP. Such an arrangement requires particularly good protection from overhead by means of a ledge or cornice formed in the GRP. In addition, care should be taken to ensure that the proper clamping force is applied to the jointing material. Normal metal window design techniques do not always provide this.

9.3.5 Faulty crossings

Although sometimes insufficient attention is given to the design of a joint in cross section, even less attention is given to the crossing where the line of one joint intersects the line of another. Perhaps this is because a crossing inevitably poses a three-dimensional problem, with its attendant difficulties in drawing; so many designers seem to be trained to think in only two dimensions! Although in theory, a very simple solution to a crossing can be achieved with mouldable materials such as polysulphide, that solution cannot be recommended for the reasons given in section 9.3.1.

Preformed gasket strips can be moulded or welded into a cruciform shape for a crossing but that brings problems of achieving the close tolerances necessary at the meeting of four panels. Also there are inevitably, four more joints to be made in the gasket itself at the ends of the cruciform piece.

The most successful solutions to the crossing problem are achieved by adopting a drained-joint approach. In roofs a good solution is to turn up the ridge joints into a four-part upstand or cusp which can then be capped with a moulded piece. In walls, the corresponding solution would be to bring the upper joint outwards to form a ledge or overhang protecting the start of the lower joint. Both these solutions can have a marked effect on the architectural design of the building and this is yet another reason why close cooperation of all aspects of the design is required from the beginning.

9.3.6 Inadequate seal pressure

Preformed joint strips or gaskets rely for their action on a continuous pressure being applied between the gasket material and the mating surface. This is achieved by compressing the gasket either by a direct clamping action or by inserting the gasket into a space smaller than its uncompressed cross section. Direct clamping action by bolting across the joint and compressing the gasket can be secure and effective. Inserting the gasket into a space formed, say, between two adjacent GRP panels looks fine on the drawing board, but in practice the constant dimension of the enclosing space cannot be guaranteed. Where the space is too small the joint cannot be properly inserted and when it is too large the gasket cannot be sufficiently compressed.

A similar problem – although one that is turned inside out, one might say – arises with the so called zipper gasket commonly used to secure car windscreens. Here the sealing pressure occurs between the insides of the lips of the gasket bearing on to the edge of the panel held between them. The pressure is exerted by first positioning the lips over the panel edge and then a wedge-shaped strip is inserted in the gasket to force the lips together on to the material. Again such a gasket can be extruded to very fine limits and will work very well if the material on to which it is clamping is also made to such fine limits. In the example of the motor-car windscreen, both the glass pane and the sheet-steel frame can be made to close limits and thus the technique works very well. Unfortunately GRP panels, especially hand-layup panels, cannot be made to fine limits of thickness and these zipper gaskets often fail when used in such circumstances. For success, it is essential that special care is given in the manufacture of the GRP to ensure that the finished edge thickness is within the operating range of the gasket.

9.4 The ideal joint

It is not too cynical to say that the ideal joint is no joint at all. There are instances where a GRP building can avoid jointing problems – in so far as they can be without sealed joints – and, following the principle of the traditional roof tile, quite large buildings can be clad. But the majority of GRP-clad buildings will not avoid the use of some sort of sealed joint. Even so the amount of jointing should be kept as small as possible as it is an expensive and potentially troublesome element. Many matters are involved in the choice of panel size (see section 7.4), but reduction of the length of jointing is, or should be, a significant argument in favour of the larger panel.

Assuming, despite the designer's best attempts, that the ideal joint is in fact a joint, then the qualities to aim for are:

1 It should remain 100% weathertight under conditions of:
 (a) Adverse manufacturing and erection errors.
 (b) Repeated thermal movement.
 (c) Repeated load deflection.
2 The joint detail should incorporate a second line of defence so that rain can be prevented from entering the inner fabric of the building if there is a failure in the main joint.
3 The jointing materials should easily be inspectable and replaceable.
4 The joint should have a neat and tidy external appearance. Where the jointing material is exposed, it should be of uniform thickness and colour.
5 It should survive a hose test (see section 9.5).

There is of course some redundancy in these requirements – a second line of defence should not be necessary if the seal is 100% effective – but such is the frequency of joint failure and so unpopular is the result of failure, that it is worth making things as safe as possible at the design stage.

9.5 The hose test

A most effective means of testing a joint is available easily in the form of the local fire brigade. Most fire-fighting organizations willingly provide the apparatus and men to conduct a hosing test – for a small sum, and sometimes free of charge. A fire-fighters' hose is quite powerful but can be used by a skilled operator to simulate various strengths of wind-driven rain. The hose can also be used directly to produce a test far more severe than is likely to occur in a rain storm. The hosing test is simple and direct and should be a normal part of the handing over procedure for a GRP clad building. Naturally, the hosing test should be done immediately on completion of the cladding and its jointing and preferably before internal decoration!

Unfortunately, even the severest hose test is not infallible, because a number of joint defects can develop later in the life of a building due to working of the joint sealer in repetitive movement. Even in those cases, a hose test can be useful to find the precise location of a defect and to test the remaining parts of the building.

9.6 Fixings

By 'fixings' is meant the means of attaching a GRP panel to the supporting structure and/or to its neighbouring panel. Fixings normally do not give quite so much trouble as jointing but nevertheless the proper design of a fixing involves a number of considerations.

9.6.1 Stress flow

As we saw in section 7.8, good design in a GRP unit tends to disperse stress through the plane of the GRP unit and avoids concentration of stress. The difficulty in continuing dispersed stress across a joint or through a fixing line is mentioned in section 7.9 and the wisdom of having fixing points at close centres is explained. Where the fixing devices also provide a clamping action to compress a preformed sealing strip, the need for close spacing is reinforced. The loads to be transmitted by the fixings can be estimated in the normal way by assessing dead weight, wind load, snow load, live load, etc., but particular attention must be given to wind suction and wind uplift forces in view of the unusual lightness of most GRP panels. In the rare cases where there have been fixing failures in GRP buildings, underestimation of suction forces is the most common cause.

In certain cases concentrations of stress cannot be avoided, particularly where GRP is used in a fully structural mode. In roof units and complete small buildings with no other structural framing, there are necessarily substantial loads to be handled at say, the ends of roof units and at the bottom edges of wall units. In some cases the stress concentrations are both handled by incorporating steel inserts in the GRP layup which collect the dispersed load from the GRP panel and bring it down to a steel fixing point or lug. Such metal inserts must be perfectly clean before laying up into the GRP and particular attention must be given to protecting the metal parts from corrosion, especially at the point where they emerge from the GRP panel.

9.7 Movement

A GRP panel will move, or want to move, due to thermal expansion and contraction and due to its elasticity under varying loads. The coefficient of expansion of a GRP laminate is relatively high. It varies a great deal with glass content but a typical laminate with chopped strand mat reinforcing would have a coefficient of linear expansion of $30 \times 10^{-6}/°C$. At the same time GRP has a low modulus of elasticity, which means that it deflects to a relatively large degree under an applied load. Following conventional engineering design, which is founded in material such as steel and concrete, there would be a tendency to make considerable allowance for thermal movement and load deflection in the design of fixings. But at this point we come across a dilemma for the designer, which is, to decide whether or not to make any allowance for thermal movement. The problem is illustrated in the following example:

Example: Flat plate 4 mm thick, 1.5 m long, temperature change, 50°C.

	Steel	*GRP*
Coefficient of linear expansion per °C	10×10^{-6}	30×10^{-6}
Modulus of elasticity (GPa)	210	8
Unrestrained thermal movement (mm)	0.75	2.25
Thermal stress if fully restrained (MPa)	105	12
Shearing load on fixings (tonne/m)	42	4.8

It is worth studying carefully the figures in the table. You will notice that the GRP, if left free to move, will undergo a change in length three times greater than that of steel for the same temperature difference, and yet, the force required to resist that change in length – or to rigidly clamp the sheet – is almost ten times smaller for GRP than for steel. The vast difference in restraining force is, of course, explained by the very much lower modulus of elasticity of GRP. This modulus, which is really a measure of the force required to stretch or compress the material by a given amount, is also a measure of the stress required to prevent the material moving due to a temperature change.

The considerable difference in clamping force illustrates the difference in approach to GRP thermal movement as against conventional notions of steel movement. In practice, a GRP design which makes no allowance for thermal movement is often acceptable, since the restraining forces and the stress in the material itself are both manageable. The advantages to be gained by making no allowance for thermal movement lie in the much simplified fixing and jointing details. Furthermore, as we shall see later, 'rigid' fixings are more likely to behave in the way they are envisaged than fixings which allow for movement.

The example illustrated in the above table is a flat sheet which, in tension certainly, would impose a direct load on the fixing bolts. When the sheet expands, it is unlikely to exert the full outward force on the fixings as some of the movement will undoubtedly be taken up by bowing of the sheet. This will have the effect of reducing still further the load on the fixing bolts. for example, if the same GRP sheet, instead of being flat, had an initial bow one tenth of its width, it would exert only 0.14 tonne/metre on its fixing bolts for the same temperature rise of 50°C. Thus even the slightest curvature or corrugation in a GRP sheet will enable thermal movement to be accommodated without the complication of movement joints. But this applies only to the cross section in which the curvature or corrugations appear. Units which are curved in one dimension will behave only as flat sheets in the other direction, and units which have two-dimensional curvature must be very carefully thought about if the perimeter of the unit is a rectangle – as it nearly always is. In that case, the peripheral 'frame' will comprise straight elements and will not take up thermal movement by bowing (if it did, the consequences on the joint could be disastrous!).

An interesting example of thermal movement in a two-dimensional curved panel is the treatment of the huge GRP domes for Sharjah

International Airport. The largest of these domes is 57 m in diameter and is designed for a generous temperature range of 100°C. The domes are fabricated in panels which are then jointed together on site and supported on an underlying dome of structural steelwork. At first, the author attempted to design and detail joints between each panel which would accommodate the thermal movement and at the same time be weather-tight. With the complication of the spherical geometry and the requirement that no upstands or capping pieces would be allowed, the design of the joints became very complicated indeed. It was then realized that the dome would expand and contract quite happily if it were not restrained in a direction tangential to its surface at any point save one, i.e. the summit. The result is that each of these domes is fixed vertically and

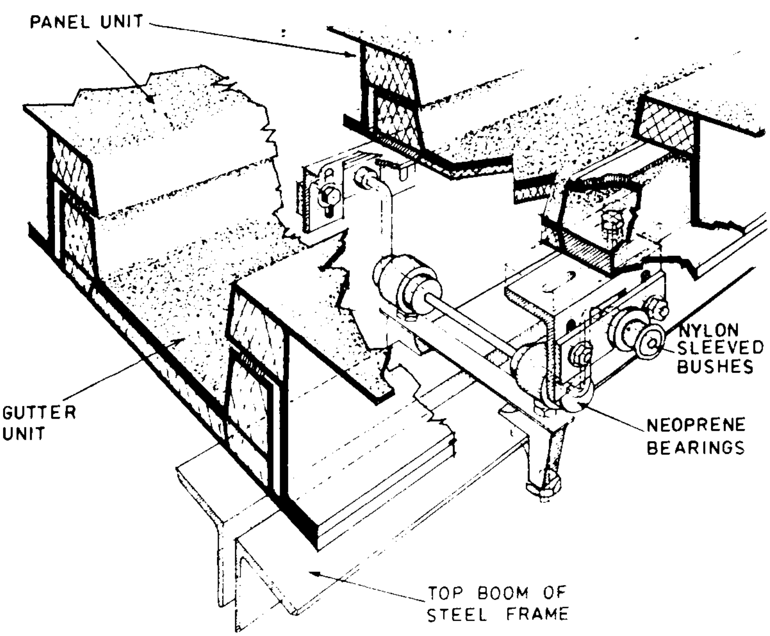


Figure 9.9 Sharjah International Airport domed roof. Detail of rocker support

horizontally at the summit point only. All the other fixings on the dome are of a simple rocker nature (see *Figure 9.9*) which allows the dome to grow or shrink in size with the temperature and yet fully restraining it from other movements. The allowable movement at the periphery of the largest dome is 50 mm. All the joints could then be bolted solidly with a great simplification of detail and reduction in cost, together with much more positive weathertightness. The whole system works perfectly in practice.

Where thermal movement must be allowed for in joints, the detailing has to be carefully considered. The slotted hole with a simple nut, bolt and washer connection, is often thought to be a simple and effective solution, but in practice rarely works as it is intended. To tighten the bolt to allow just the calculated amount of frictional resistance to the movement is well-nigh impractical and the usual result is that the bolt is over-tightened thus preventing any sliding action at all.

To summarize the position on thermal movement, the designer is faced with the question 'to clamp, or not to clamp'. There are warnings to be given whichever route he takes:

(a) *Rigid fixing.* The 'free' movement of the panel should be calculated carefully and, from that, the thermal loads on the fixing bolts and the thermal stresses at critical points within the panel should be derived. Particular attention should be given to thermal stresses at corners and at sharp changes of direction within the panel. Extra reinforcement may be required here.

(b) *Non-rigid fixing.* Here again, the free movement should be calculated and the fixing designed to cover such movement to a generous degree. One has to remember that the panel might be installed on a warm day and subsequently contract, or the reverse might be the case. The total degree of movement to be allowed in a fixing will almost certainly have to encompass other matters such as manufacturing and erection deviations. As was seen earlier, the slotted hole, sliding fixing is uncertain in its action and better details can be obtained by utilizing the shear deformability of sealing strips or – in major applications – some form of rocker mechanism (see *Figure 9.9*).

9.8 Mechanical fixing devices

Most fixing devices used in GRP work are of the nut-and-bolt variety or some derivative of that form. A very useful device produced especially for GRP work is the 'big-head' bolt. This is a threaded bolt shank with a large diameter head in the form of a perforated plate. The plate head is then laid up into the GRP laminate, the large surface area and the holes in the head helping to form a good key and mechanical bond between the bolt and the laminate. Use of this device enables a 'secret' fixing to be obtained, which is useful in some applications. As the position of the fixing bolt and therefore the corresponding hole, cannot be altered once the unit is made, the structure to which the unit is bolted must be capable of adjustment or the holes will need to be site drilled.

Whatever joint detail is derived, metal fastenings must be protected very adequately against corrosion. As such fixings are usually fairly light, it is often worth while to use stainless steel throughout as the extra cost involved is small. If steel fixings are used, the galvanizing protection should be of the highest possible quality.

Chapter ten

Case studies

The examples of GRP usage which follow are all constructed projects many of which have been in service for several years. Most of the projects, but not all, are among those with which the author has been involved personally. This selection is not intended, primarily, as self-advertisement but to enable us to give direct and uninhibited comment on the rights and wrongs of the designs.

10.1 Swimming pool and sports hall for the Metropolitan Police – 1975

GRP application

Vertical cladding panels 10 m high by 2 m wide (*Figure 10.1*).

Design decision

Primarily, provides interest to the otherwise mainly blank-walled building. The buildings (of which this was the latest), forming the large campus of the Metropolitan Police training establishment at Hendon, reflect the order and precision of a disciplined force and this theme is continued by the regular geometry of the GRP Panels. At the same time, GRP reflects the technological advance from the precast concrete and mosaic finishes used during the previous decade of development on the site. Very deep mouldings give rigidity to the panel but were intended primarily to give visual interest to the façade by utilizing shadows and the different intensities of incident light on the curved surfaces. The panels are supported on the main steel frame of the building and there is a blockwork inner wall – thus the panels serve as the weatherproof cladding but perform no primary structural function. The panels are fixed at a point about a quarter of the way down from the top and allowed to expand upwards and downwards from that point.

Design and construction problems

Considerable design effort was spent on detailing the vertical joints and a full-size prototype panel and joint mock-up was pressure tested before acceptance. The panels were formed by the combined resin and glass spray

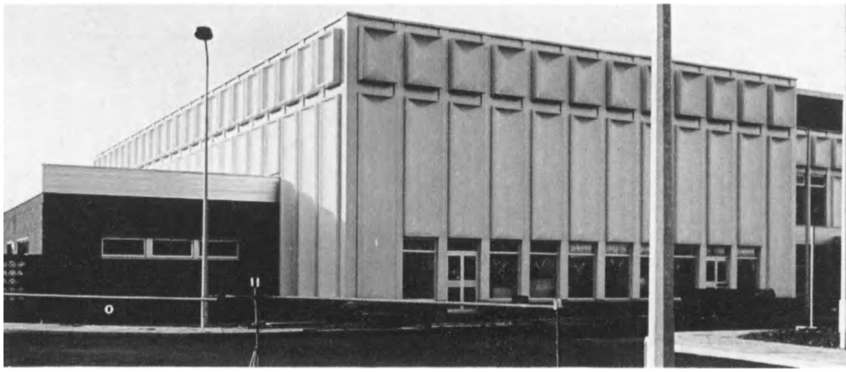


Figure 10.1 Swimming pool and sports hall for the Metropolitan Police. The panels were manufactured in one continuous height from ground level to roof level – a maximum of 10 m

technique and some difficulty was experienced in maintaining the required thickness of laminate especially at the all-important edges of the panel. Some panels required extra reinforcement and some were rejected.

Retrospective comment

This perhaps has been the most successful GRP application in the author's direct experience so far. Certainly the meticulous care taken in the development of detail has been justified.

Architect: Chief Architect, Metropolitan Police.
Consulting engineers (including GRP): NCL Consulting Engineers.
GRP manufacturer and erection: H. H. Robertson Ltd.

10.2 New Covent Garden Flower Market roof – 1972

GRP application

The whole of the cladding of this huge roof, approximately 100 m square, is in GRP. The roof mainly comprises standard inverted truncated pyramids on a 4 m square grid. The base of the pyramid is translucent (*Figure 10.2)*.

Design decision

The geometric form of the GRP units was predetermined largely by the configuration of the supporting steel framework which had been established previously.

Design and construction problems

The design process was complex and protracted, largely because the units were required to perform so many functions simultaneously, e.g. thermal insulation, natural lighting, solar reflectivity and of course, weather-tightness. Several design schemes were pursued but it was found difficult to produce a satisfactory solution using the normal hand layup method at an acceptable cost. The solution was found eventually by using a proprietary injection process which produces a double-skinned unit in one operation.

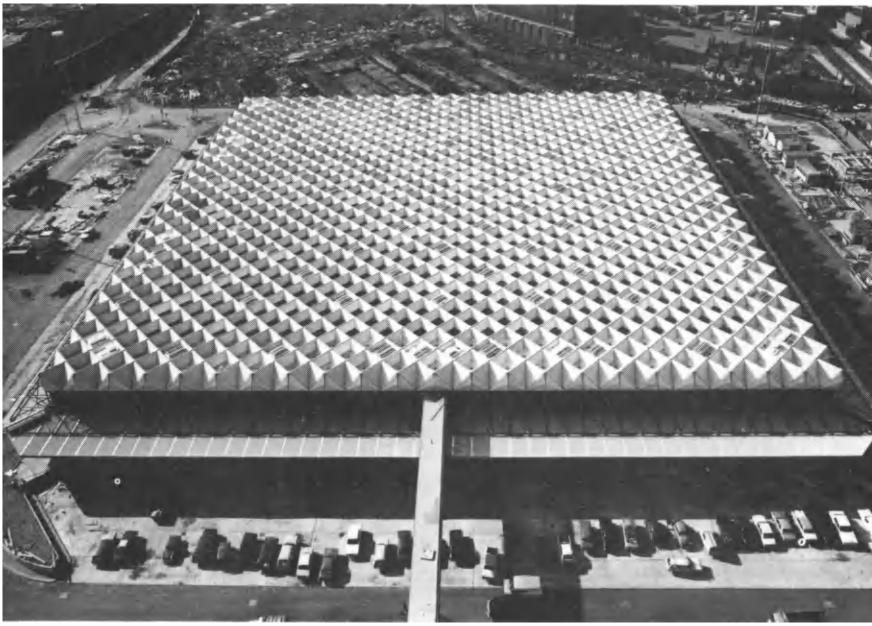


Figure 10.2 New Covent Garden Flower Market roof

Air inclusions caused some problems in the injection process during the early stages of production but generallv a high standard of surface finish and structural integrity was obtained. Meeting the fire requirements involved much testing and discussion. The GLC and the fire authorities were satisfied eventually by the inclusion of a simple smoke baffle arrangement within the roof space and by the provision of an external drencher system which in fact added little to the cost of the roof.

Performance in use

An inspection in 1982 showed a number of short cracks (averagely two or three per unit). These are thought to be due to slight variations in manufactured thickness with consequent resin-rich areas. Otherwise the roof was in good order. Problems have arisen in places due to failure of jointing materials. Some problems which were feared, have not in fact arisen, e.g. obscuring of the transluscent panels by falling leaves, dirt, etc.

Retrospective comment

This roof, particularly the design process, was a GRP *tour de force*. There were times when it was thought that GRP would have to be abandoned although it would have been difficult to have found another material. Many lessons were learned and success achieved in the end.

Architect: GMW Partnership.
GRP consultant: NCL Consulting Engineers
GRP manufacturers: Michelover Transport Co.

10.3 School in Stepney – 1972

GRP application

Full structural roof (*Figure 10.3*).

Design decision

GRP was chosen primarily for its ability to provide a single-span lightweight translucent roof for the gymnasia, assembly halls and workshops, although laboratories and other classrooms are also roofed in the same manner. The design aimed at using GRP as efficiently as possible by making it perform a number or tasks simultaneously, i.e. the primary structure (the units span up to 17 m), thermal insulation, daylighting, weather cladding, and forming part of the artificial lighting system. The main roof units were brought down over the eaves to form window nacelles and thus became a dominant feature of the elevations. Structurally the units behave as a troughed shell, the transparent and opaque areas being parts of one continuous GRP membrane.

Design and construction problems

Under full-scale load testing, the prototype units showed some torsional instability and the transverse ribbing was strengthened. Erection problems arose from dimensional variations in both the GRP and the conventional building structure, particularly around the window nacelle areas.

Performance in use

Some premature deterioration of the resin in the translucent areas occurred and was remedied by the GRP supplier. Solar gain during very hot weather has been a problem in the smaller rooms; some extra ventilation was installed and some of the south-facing translucent areas

Figure 10.3 GRP roof for school in Stepney, London. Note joints at ridge of troughed sections and translucent panels

were obscured. Otherwise the intended functions of the GRP units are being performed very satisfactorily. Weather-tightness has been a particularly good feature. As in other GRP projects, some of the problems that were feared did not materialize, e.g. flutter due to aerodynamic wind effect and noise due to expansion on sunny days. The school authorities carried out a major reassessment of the fire situation (mainly as a reaction from the Summerland disaster, which had nothing to do with GRP) and it was decided to improve the internal spread-of-flame classification by painting the underside of the units with an intumescent resin.

Retrospective comment

This was a bold scheme for the early days of GRP design (1969) and in respect of the exploitation of the multi-function application of the material, it has not yet been surpassed. With hindsight it may been more prudent to restrict that type of unit to the assembly and gymnasia areas. Here the spanning properties of the units yield the full benefit, and the whole performance and appearance of this very light and airy roof excel. If some other form had been found for the smaller classroom areas, the solar gain problems and the extra fire protection work might have been avoided.

Overall, the roof has been very successful in achieving the objectives of the original design.

Architect: GLC Architects Department.
Consulting engineer (including GRP): NCL Consulting Engineers.
GRP manufacture and erection: Anmac Ltd, Nottingham.

10.4 Chimney at Hendon – 1970

GRP application

The chimney is 37 metres high and carries the flues of four large boilers. The four separate flue shafts give an efficient and stable structural form. The structure is entirely GRP except for the actual (non-structural) flue liners which are of steel (*Figure 10.4*).

Design decision

At the time of decision, the GRP chimney was cheaper than the equivalent reinforced concrete structure but more expensive than a simple steel flue arrangement. The GRP design was chosen on grounds of cost and low maintenance. The structural form is followed faithfully to the top 'neck' and the outward splay of the flue shafts above that point is the only strictly non-functional aspect of the whole design. The curved bracing panels at mid height were changed during manufacture to steel plate coated with resin to simplify moulding – a change that was later regretted. The whole chimney structure was erected on the ground and hoisted in one piece by mobile crane in a single day.

Performance in use

Built in 1970, the chimney has been in continuous use but a number of problems, mostly unconnected with the GRP have arisen. Due to a defect

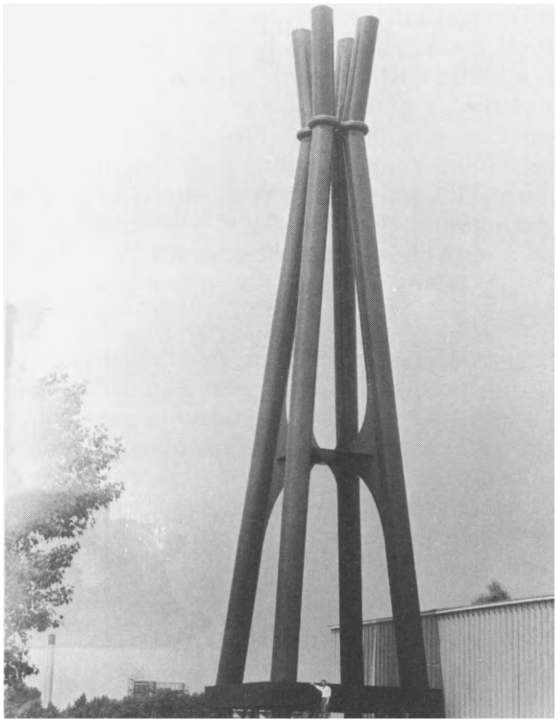


Figure 10.4 GRP chimney structure at Hendon, London

in preparing the steel bracing members the resin coating peeled off prematurely and had to be stripped and re-treated. Some cracking at the junction of the upper (outward-pointing) tubes with their connecting flange at the neck has had to be repaired and reinforced. This is probably due to the thermal expansion effect. The same upper sections were lined, not with mild steel but with GRP and there was considerable surface degradation of this lining. It was replaced with a stainless-steel sleeve.

Retrospective comment

Structurally the design has proved successful but the limited use of GRP as a flue lining has failed in this particular application.

Chimney design: NCL Consulting Engineers.
GRP manufacture and erection: R. Graydon Limited.

10.5 International Airport, Sharjah – 1977

GRP application

Four domes, up to 50 m in diameter, cover the main terminal buildings. The external cladding of all the domes is in GRP (*Figure 10.5*).

Design decision

The client required 'glistening white domes in the desert' and GRP is the ideal material. The domes are spherical and thus all the panels could be cast from the same master mould surface. A structural steel frame supports the GRP cladding and the internal dome ceiling; it also provides a service space.

Design and erection problems

The principle of the drained joint was firmly followed although the easy solution, the upstand flange, was not acceptable due to the interruption it would cause to the smooth spherical lines of the dome. Shallow troughs were formed at the junction lines and a concealed drained joint detailed into the side of the trough. The resulting geometry at jointed sections became complex. Strong hosing tests, simulating heavy wind-driven rain, revealed that the drainage geometry was not effective in all cases and the secondary weather-proofing in the form of silicone rubber compounds was playing a primary role. Several defects in the application of these compounds were discovered and repaired.

It was decided not to attempt to accommodate thermal expansion in the joints and instead the whole dome surface is designed to expand and contract from the fixed summit. The resulting movements inwards and outwards along the spherical surface are permitted by the cladding panels being supported on rocker bearings. In the partly-clad state of some of the domes, the shell action brought about by this expansion system produced some over stressing and distortion in the panels. In the later domes these problems were avoided by greater attention to the erection procedure.

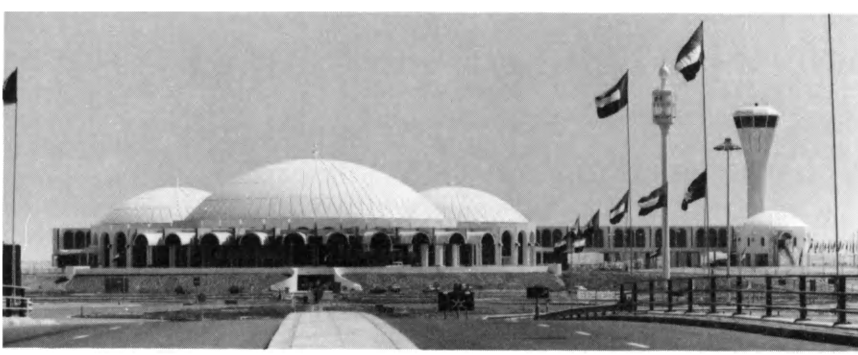


Figure 10.5 GRP domes at Sharjah International Airport

Performance in use

No problem reported so far. The finished appearance of the domes is superb and fulfils the client's original request.

Retrospective comment

The lessons learnt from the erection problems could be incorporated usefully in future designs of this nature.

Architect: Sir William Halcrow & Partners.
Consulting engineers: (including GRP): NCL Consulting Engineers.
GRP manufacturer and erection: Anmac Limited, Nottingham.

10.6 London Airport, Heathrow: GRP ramps to Terminal 2 – 1978

The ramps are a splendid example of GRP design, though their relationship to the surrounding architecture might be questioned (*Figure 10.6*).

Figure 10.6 GRP access ramps at Heathrow Airport

Fire requirements

Apart from their visual interest, the ramps are noteworthy for the designers' treatment of fire behaviour. They form part of the emergency escape system of the terminal building and the design requirements were for a class 0 spread of flame for the inside finish, class 1 spread of flame for the outside finish and a half-hour fire rating for the whole structure against external fire. The spread-of-flame ratings were not difficult to meet but the achievement of the half-hour fire period was ingenious even though to a layman it might appear a puzzling example of 'double-think'. Nevertheless the logic is quite sound.

The construction is double-skinned GRP with an incombustible insulating core between the skins. Each skin is designed to be structurally sufficient on its own and each skin contains at least one layer of heavy-weight woven-glass roving. The theory is that in the event of the structure being exposed to fire, either from the inside or the outside, the exposed GRP surface will burn away leaving a charred but intact glass-fibre roving holding the incombustible insulating core in position and supported structurally by the unexposed GRP lining. Full-scale fire tests of prototype panels proved the theory to be correct and indeed the tests showed that the structure would deserve a one-hour fire rating as against the half-hour demanded. Particular care was taken in detailing the joints and windows to give the overall required fire performance.

Architects: Pascall and Watson.
GRP consultant: R. Pleydell-Bouverie.
GRP manufacturers: Anmac Limited.

10.7 Olivetti Training Centre, Haslemere, Surrey – 1972

GRP application

Complete building evelope in GRP. GRP also used for window surrounds internally. GRP panels were coated with polyurethane finish and panels are alternatively in 'stone' and 'parchment'. According to the published details, vertical joints are sealed by an evacuated tube technique and horizontal joints by compressible polyurethane foam strip (*Figure 10.7*).

Figure 10.7 Olivetti Training Centre, Haslemere, Surrey

Design decision

Olivetti, well known for the high level of industrial design applied to their products, required their training centre at Haslmere to have the same forward-looking design approach. Remembering that the building was constructed in 1972, there is no doubt that their aim was fulfilled. The use of GRP was only one of a number of exciting features about the whole building. Thermal insulation and fire resistance is provided by a mineral wool backing to the GRP and the internal lining of the walls is glass-reinforced plaster.

Performance in use

An inspection ten years after construction showed the GRP itself to be in excellent condition. The surface has lost the high gloss which the original polyurethane would be assumed to have. On the other hand, the colours are very uniform although they have probably faded a little. The owner reports some localized failure of jointing between panels and some problems with ponding of rainwater in the large 'gutter' sections. The façades are hosed down twice a year.

Chapter eleven

The future

In building design, from both architectural and engineering aspects, design techniques and attitudes tend to follow the development of materials rather than the reverse. Although it is becoming increasingly possible to produce a material to fit a specified performance, particularly in the case of plastics, that procedure is followed in only a few special cases. But once a new or an improved material is made available, designers usually react promptly and imaginatively to exploit the new advantages.

Therefore it is appropriate to look first at possible developments in materials but later we shall look tentatively at possible routes along which design might progress.

11.1 Materials in the future

It is undeniable that many building designers consider GRP a difficult material in buildings from the point of view of fire behaviour. This is to a large extent unjustified, as we have seen in section 7.14. Although the intrinsic characteristics of the polyester resin contributes only a part of the total fire behaviour of a GRP panel in a particular building, there would be undoubtedly a ready market for a polymer (polyester or other) which would have even lower combustibility than those presently available. It is possible therefore, that in the future the resin component of GRP will be available which although perhaps not absolutely incombustible, would behave in a manner tantamount to an incombustible material. It seems likely that this would be achieved by admixtures to the polymer rather than by any particular arrangement of the carbon, hydrogen and oxygen structure within the molecule.

Greater resistance to ultraviolet light degradation might be achieved although present standards are good.

An existing, but relatively new development, is the use of catalysts which react only in the presence of ultraviolet light. This enables resin and catalyst to be mixed, stored and used in the manufacture of the laminate with no time restriction, provided that it is not exposed to a light source containing the UV component. When the manufacture is complete and all is ready, a relatively short exposure time to ultraviolet light will set the resin. This is primarily only an advantage in manufacturing but could lead to the use of more sophisticated and complicated construction techniques. It is already of considerable convenience in repair work.

As can be seen from Chapter 9, there is plenty of scope for improvement in jointing techniques and materials. No doubt a great deal of research and development will go into this problem and perhaps a combination of the disposable backing strip and the UV-sensitive catalyst, will enable jointing compounds to be fixed in place in the factory around the edge of a panel so that the jointing compound/GRP interface is perfectly secure. Such panels will then be positioned next to their neighbours on the building and the perfect compound-to-compound joint made by some simple site process.

Although glass fibre has proved to be a most successful reinforcement medium in polyester resin, it is not the only high-strength fibre available. Carbon fibre is already used where particularly high stresses occur and it is possible that composites will be developed using other polymers as the tensile reinforcement. Whether a completely homogeneous polymer can be produced with the physical properties of GRP and its relatively low cost, has yet to be established. Such a uniform mixture would pose difficulties with the hand layup technique, so useful in building work, as the glass-fibre reinforcement stabilizes the wet laminate during the manufacturing process.

11.2 Design in the future

First, let us take a fundamental look at the purpose of a building. The prime requirement is that a building should provide an environment which is an improvement on the ambient condition. That is to say it should provide protection from the rain or the heat or the cold or the arrows of a neighbouring enemy tribe or from radioactive fall out or whatever is the ambient discomfort. In very many cases this primary object can be satisfied simply by the provision of a shell or membrane. Some buildings can produce a worsening of the ambient environment. An important example of this paradox relates to earthquakes. No one is likely to come to much harm during a major earthquake if he sits in the middle of an open field. Buildings of GRP, in so far as they are likely to be very much lighter than conventional construction, have an intrinsic advantage here.

But assuming that buildings satisfy the prime objective, then we come on to the secondary considerations which can be called 'packing and stacking'. Packing, here, is a (perhaps slightly disrespectful) term for the arrangement of space and the planning of a building, usually with the objective of minimizing cost of construction or of land usage. Stacking is an operation derived from packing and is really multi-storey construction. Nevertheless stacking in modern building design has a considerable influence on the choice and use of the structural material. At this point, architect readers may be becoming a little cross if they think that building design is being reduced to a warehousing operation. A building should provide 'delight' but it cannot be denied that the packing and stacking problems have to be tackled and solved if the building is to succeed at all. The enjoyment of the building both visual and occupational, can result from the skill given to the packing and stacking and of course to the expression and or decoration of the solution.

Let us look first at the packing. Nearly all spaces within buildings are basically cuboids (or if you prefer it – rectangular parallelepipeds!). This shape seems to be so basic and obviously right (and so easy to draw with the conventional tee square) that it is never questioned. But should it not be questioned? The gentleman in *Figure 11.1* although often admired, is ignored by the cuboid shape. It is the walking gentleman in *Figure 11.2* who generates the cuboid. In other words the cuboid seems the obvious space to create in a building as it solves the problem of movement both for humans and objects such as furniture and the like. But should a building be planned solely to accommodate movement of translation, i.e. movement involving the complete re-location of the body or object?

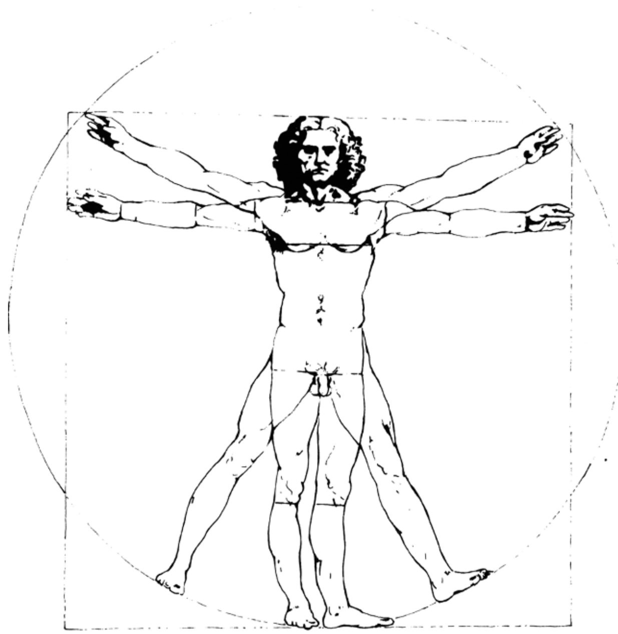


Figure 11.1

For the most part bodies and objects within a building spend a vast majority of their time stationary or at least at the same location. Certainly they have to be able to get in and out of that location but not all the space in a building is needed for translational movement and this could be confined to the necessary passageways. From this it is possible to postulate a building wherein the spaces are largely non-cuboidal, such as spheres or cylinders or some other shape, provided they were linked together by prismatic access ways. Admittedly, it is difficult to find examples of buildings of this form. There is of course the honeycomb and such-like in nature and there are examples in structures where the internal spaces are dominated by the need for a special enveloping shape as, for instance, in boat hulls and aeroplane bodies. There is certainly enought argument and evidence available to establish that the cuboid is not the only form in which the internal space of a building can be arranged.

The point in all this is that the membrane structure (so easily formed in GRP) does not easily provide cuboid space as with the traditional beam and column structure. The beam is not an efficient structural device in normal cases as so much of the material used is not fully stressed. The membrane or 'non-bending' structure is intrinsically efficient.

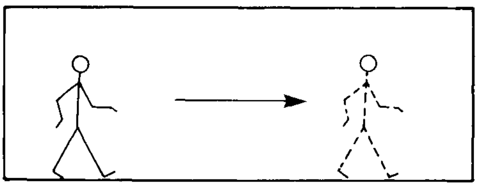
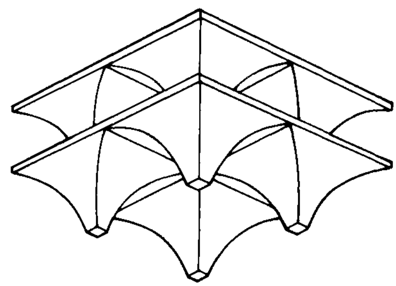


Figure 11.2



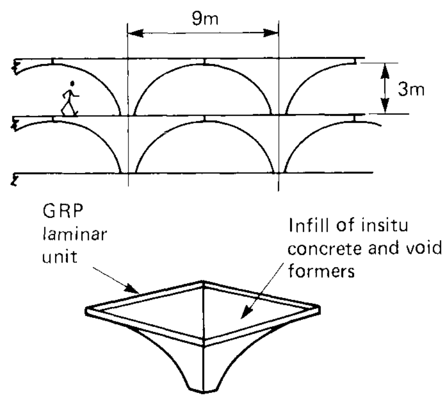


Figure 11.3

To return to practical design, it is perfectly feasible to solve the packing and stacking problems using membrane structures such as GRP provided one is prepared to indulge in a little lateral thinking about the basic conventions of shape within a building. To illustrate this claim a suggested building form is shown in *Figure 11.3*, involving packing and stacking but comprising basically a structural unit of GRP. The building is made up entirely of a single repetitive unit, square on plan at the top and tapering down centrally to a stem. The shell of this unit would be formed of GRP and the inside of the shell would be filled with a combination of *in situ* concrete and void formers to provide a flat and continuous floor surface at each storey level. It is interesting to note that the combination of units automatically provides a structure which is inherently stable against horizontal as well as vertical loading. The details of this type of building can be developed and no doubt improved and the sole purpose in producing this notion is to stimulate further thought.

The final picture presented is that we are only at the beginning of our development of the use of laminar materials and the progress to be made depends largely on the inventiveness of the designer and his willingness to consider departures from the conventional attitudes.

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