Prices for all available BRE publications can be obtained from:
CRC Ltd
151 Rosebery Avenue
London, EC1R 4GB
Tel: 020 7505 6622
Fax: 020 7505 6606
email: crc@construct.emap.co.uk

BR 405
ISBN 1 86081 429 8
© Copyright BRE 2000
First published 2000

BRE is committed to providing impartial and authoritative information on all aspects of the built environment for clients, designers, contractors, engineers, manufacturers, occupants, etc. We make every effort to ensure the accuracy and quality of information and guidance when it is first published. However, we can take no responsibility for the subsequent use of this information, nor for any errors or omissions it may contain.

Published by
Construction Research Communications Ltd
by permission of
Building Research Establishment Ltd

Requests to copy any part of this publication should be made to:
CRC Ltd
PO Box 202
Watford, WD25 9ZW

BRE material is also published quarterly on CD
Each CD contains BRE material published in the current year, including reports, specialist reports, and the Professional Development publications: Digests, Good Building Guides, Good Repair Guides and Information Papers.

The CD collection gives you the opportunity to build a comprehensive library of BRE material at a fraction of the cost of printed copies.

As a subscriber you also benefit from a 25% discount on other BRE titles.

For more information contact:
CRC Customer Services on 020 7505 6622

Construction Research Communications
CRC supplies a wide range of building and construction related information products from BRE and other highly respected organisations.

Contact:
post: CRC Ltd
151 Rosebery Avenue
London, EC1R 4GB

fax: 020 7505 6606
phone: 020 7505 6622
email: crc@construct.emap.co.uk
website: www.constructionplus.co.uk
Contents

Preface v
Acknowledgements v
Abbreviations vi
Chapter 1 Introduction 1

Chapter 2 Properties of materials and manufacturing techniques 3
Resins 3
Fibres 3
Mechanism of reinforcement 4
Methods for manufacturing fibre reinforced thermosetting polymers 5
Processing methods for the manufacture of reinforced thermoplastic polymers 6
Mechanical properties of composites 6

Chapter 3 Designing with polymer composites 9
Which materials to use 9
Guidelines for designing in reinforced polymers 11
Theoretical approaches to design 12
Safety factors 13
Design codes 13
Applications of limit state design principles to composite structures 14
Costs 14
Design for recycling 15
Developments in design using advanced composites 16

Chapter 4 Joint design 19
Adhesive joints 19
Bolted joints 20
Jointing and fixing of GFRP 20

(Continued)
Preface

This book deals with various aspects of polymer composites — properties of the materials and uses to which they are put, design of composites, in-service properties of the materials, and construction and erection of the components. Glass fibre reinforced polymers (GFRP) are the main subject, but uses and potential uses of other polymer composite systems are highlighted. The book will be of particular benefit to those with little or no prior knowledge of polymer composites.

Polymer composites, glass fibre reinforced polymers (GFRP) in particular, are common in construction. The main components are a matrix and a reinforcing fibre which interact to provide the special properties of the composite. Production techniques include hand lay-up, continuous production and matched-die moulding. Properties depend on composition and fabrication (eg resin formulation, fillers, curing, reinforcement, coupling agent, surface finish and workmanship). GFRP composites are used in many applications, such as light-transmitting panels, sandwich panels, modular units, storage tanks, formwork, windows, etc.

Advanced composite materials were originally developed for aerospace and military applications and have superior properties that offer potential benefits to the construction industry. The quantities of material currently used are small, but advanced composites are starting to become established as important materials in all forms of structures. This book describes some of the current uses of advanced composite materials in construction in the UK and overseas.

Polymer composites offer the architect, designer and structural engineer many advantages over traditional construction materials. As the properties of polymer composites are better understood and appreciated, the use of these materials in the construction industry is bound to increase.

Acknowledgements

The Department of the Environment, Transport and the Regions (DETR) funded this project.

I acknowledge the following for their advice and contributions:

Mr David Kendall, CETEC Consultancy Ltd
Dr Paul Hill, DML Devonport
Mr Ted Kay, Halcrow Group Ltd
Mr John Cadei, Maunsell Structural Plastics
Dr Sam Luke, Mouchel
Mr Tony Sheehan, Ove Arup & Partners
Dr John Nixon, Scott Bader
Dr Stuart Moy, University of Southampton
Professor Len Hollaway, University of Surrey

Kevlar is a registered trademark of DuPont.
Twaron is a registered trademark of Akzo.
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCS</td>
<td>Advanced composite construction system</td>
</tr>
<tr>
<td>AFRP</td>
<td>Aramid fibre reinforced polymer</td>
</tr>
<tr>
<td>BMC</td>
<td>Bulk moulding compound</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon fibre reinforced polymer</td>
</tr>
<tr>
<td>DMC</td>
<td>Dough moulding compound</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre reinforced polymer</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass fibre reinforced polymer</td>
</tr>
<tr>
<td>SMC</td>
<td>Sheet moulding compound</td>
</tr>
<tr>
<td>TMC</td>
<td>Thick moulding compound</td>
</tr>
<tr>
<td>UHM</td>
<td>Ultra-high modulus</td>
</tr>
</tbody>
</table>
About 30% of all polymers produced each year are used in the civil engineering and building industries[1]. They offer many advantages over conventional materials, including lightness, resilience to corrosion and ease of processing. They can be combined with fibres to form composites which have enhanced properties, enabling them to be used as structural members and units. Polymer composites can be used in many different forms ranging from structural components in the construction industry to high technology uses in the aerospace and space satellite industries.

Polymer composites were first developed during the 1940s for military and aerospace applications. Considerable advances have been made since then in the use of this material and applications have been developed for the construction sector. Loadbearing and infill panels have been manufactured using composites.[Figure 1] Complete structures have been fabricated where units manufactured from glass fibre reinforced polyester are connected together to form the complete system in which the shape provides the rigidity.[Figure 2] Glass fibre reinforced polymers (GFRP) have been used successfully in many other applications including pressure pipes, tank liners and roofs.[Figure 3]

In contrast to the design procedures used for the more traditional construction materials, those for polymer composite materials in structural applications require greater development effort and a wider understanding of the material. The material properties of the final component are the result of a design process that considers many factors which are characterised by the anisotropic behaviour of the material, and cover micro-mechanical, elasticity, strength and stability properties. These properties are influenced by manufacturing techniques, environmental exposure and loading histories. Designing with composites is therefore an interactive process between the design of the constituent materials used, the design of the composite material and an understanding of the manufacturing technique for the composite component.
In the last decade, polymer composites have been used in bridge repair, bridge design, mooring cables, structural strengthening and stand-alone components. These materials are often referred to as advanced composites and have properties considerably superior to those of earlier composites.

In advanced or high-performance composites, fibres with high strength and stiffness are used in relatively high volume fractions, whilst the orientation of the fibres is controlled to enable high mechanical stresses to be carried safely. In the anisotropic nature of these materials lies their major advantage. The reinforcement can be tailored and orientated to follow the stress patterns in the component, leading to much greater design economy than can be achieved with traditional isotropic materials.

The reinforcements are typically glass, carbon or aramid fibres in the form of continuous filament, tow or woven fabrics. The resins confer distinctive properties such as resistance to heat, fire and chemicals, and may be chosen from a wide spectrum of thermosetting or thermoplastic synthetic materials; those commonly used are polyester, epoxy and phenolic resins. More advanced heat-resisting types such as vinylester and bismaleimides are gaining use in high-performance applications, and advanced carbon fibre/thermoplastic composites are well into a market development phase.

Construction industry applications traditionally require low-cost fibre composites. Early economically viable production was by either hand lay-up of low numbers of items or mechanical production of high-volume items. Increased production volumes using automated techniques have enabled the costs of both fibre and resin components to be competitive with those of more traditional building materials. This has made composites, particularly GFRP, more attractive for use in construction applications.

The last decade has seen the introduction of higher grade products to the construction industry. However, the advantages that advanced composites offer, such as free-form and tailored design characteristics, outstanding strength-to-weight and stiffness-to-weight ratios, and a high degree of chemical inertness in most environments, have often been outweighed by high material and manufacturing costs. This has been particularly true in comparison with conventional structural materials such as steel, concrete and masonry[2].

Several developments have changed this picture over the past few years.

- Advances in the manufacture of polymer matrix composites in pultrusion, resin transfer molding and resin infusion type processes, as well as filament winding and the automated or semi-automated manufacturing of large components, have significantly reduced costs.
- Reduced demand for advanced composite fibres such as carbon and aramid in the defence industry, expansion of a highly competitive market for these advanced fibres in the sporting goods industry and prospects for large-volume applications in the civil sector, have led to new low-cost manufacturing.
- Designs of new materials in conjunction with conventional structural materials rather than individual component replacement or complete advanced composite designs, have shown that technical efficiency can be achieved within competitive cost constraints.
Composite materials consist normally of two discrete phases—a continuous matrix, which is often a resin, surrounding a fibrous reinforcing structure. The reinforcement has high strength and stiffness whilst the matrix binds the fibres together, allowing stress to be transferred from one fibre to another and producing a consolidated structure. Composites offer the designer a combination of properties not available in traditional materials. It is possible to introduce the fibres in the polymer matrix at highly stressed regions in a certain position, direction and volume to obtain the maximum efficiency for reinforcement; then, within the same member, to reduce the reinforcement to a minimal amount at regions of low stress. Other advantages offered by the material are lightness, resistance to corrosion, resilience, translucency and greater efficiency in construction compared with more conventional materials.

**Resins**

There are two main types of polymer used for resins: thermosets and thermoplastics[3]. For structural applications some degree of flame retardance is mandatory. Fire retardants are usually incorporated in the resin itself or as an applied gel coat. Fillers and pigments are also used in resins for a variety of purposes: fillers principally to reduce costs, and pigments for appearance and protection.

**Thermosets**

A thermosetting polymer is formed by a two-stage chemical reaction. In the first stage a substance consisting of a series of long-chained polymerised molecules is produced; in the second stage the chains become cross-linked. This reaction can take place either at room temperature or under the application of heat and pressure. The resulting material will not flow and cannot be softened by heating. The thermosetting polymers commonly used in the construction industry are the polyesters and the epoxides.

**Polyesters**

The three main types of polyester used in laminating are orthophthalic, isophthalic and ‘HET acid’ based resins. Orthophthalic types are used as general-purpose resins, isophthalic for better weathering and chemical resistance, and HET acid in many instances where flame-retardant characteristics are required. Proper curing of the resins is an important factor in their performance and, in general, the higher the degree of cross-linking, the better the weathering. The stress which may be imposed on the fibre-resin bond by the increase in hardness related to cure is not significant.

**Epoxides**

A range of epoxy resin formulations is also available for laminating, their characteristics depending on the resin constituents and choice of hardeners. Manufacturers are able to advise on appropriate formulations for particular applications.

**Thermoplastics**

Thermoplastic polymers consist of linear molecules that are not interconnected. The chemical valency bond along the chain is extremely strong, but the forces of attraction between the adjacent chains are weak. Because of their unconnected chain structure, thermoplastics may be repeatedly softened and hardened by heating and cooling. There are many thermoplastic resins used in composite manufacture: polyolefins, polyamides, vinylic polymers, polyacetals, polysulfones, polycarbonates, polyphenylenes and polyimides[3].

**Fibres**

A wide range of amorphous and crystalline materials can be used as a fibre[4,3]. In the construction industry the most commonly used is glass fibre. Carbon fibre can be used separately or in conjunction with glass fibre as a hybrid to increase the stiffness of a structural member, or an area within a structure. Aramid fibres may replace glass fibres to give increased stiffness to the composite.
Glass fibres
Glass fibres are manufactured by continuously drawing molten glass from an electrically heated furnace through platinum bushings at high speed. The filaments cool from a liquid state at about 1200 °C to room temperature in approximately 10^{-5} seconds. On emerging from the bushings, filaments (from a few hundred up to 6000) are bundled together and bonded to one another by a lubricant or 'size'. This process is known as sizing and has four main functions:
- To reduce the abrasive effect of the filaments rubbing against one another
- To reduce the damage to fibres during mechanical handling
- To facilitate the moulding process
- To improve chemical compatibility with the intended resin system

There are four main types of glass fibre:
- E-glass, of low alkali content, is the most common and is used widely in the construction industry, especially with polyester and epoxy resins.
- AR-glass (alkali-resistant glass) has been developed as a fibre for reinforcing cements, mortars and concrete. It is highly resistant to alkali attack.
- A-glass, of high alkali content, has been used in the aircraft industry but is now going out of production and is rarely used for fibres.
- High-strength glass fibre is produced for extra high strength and high modulus applications in aerospace technology and space research.

Bundles of filaments are called strands and are usually combined to form thicker parallel bundles called rovings. Assembled rovings are used in processes which involve chopping of the fibres during the production of a composite (eg sheet moulding compound, spray-up and continuous sheet manufacture). Rovings are also manufactured by a direct technique in which all the filaments needed in the final roving (up to 4800) are drawn simultaneously from one bushing. These rovings are called direct rovings and are used in weaving, pultrusion and filament winding. Strands may also be twisted to form several types of yarn. Rovings and yarns may be used either individually or as a woven fabric.

Glass strands for reinforcing thermosetting resins may be used in a range of different forms:
- Chopped fibres can be subdivided into milled fibres (30–3000 µm long), short chopped fibres (up to 6 mm) and long chopped fibres (up to 50 mm).
- Chopped strand mats are manufactured from chopped strands randomly orientated to form a mat. The glass strands are loosely bonded together with a resinous binder.
- Woven rovings are used in composites to produce high directional strength characteristics. Unidirectional roving composites have great strength in one direction. Bidirectional roving composites have high strength properties in two directions at right angles to each other.

Surface tissue is a thin glass fibre mat bonded with a readily wetted medium. It is used where a resin-rich surface is required or where the coarse fibre pattern of a chopped strand mat is to be concealed.

Carbon fibre
Carbon fibre is normally made by heating polyacrylonitrile (PAN) fibre under tension in air at 250 °C. During heating the fibre absorbs oxygen and gains strength. Once it has turned black, it is heated in an inert atmosphere — a process known as carbonisation. By varying the process conditions, mechanical property modifications can be achieved.

There are three grades of carbon fibre:
- High modulus (HM) — the stiffest fibre with the highest modulus of elasticity of the three
- High strength (HS) — the strongest fibre
- Intermediate modulus (IM) — the least stiff of the three with a strength midway between the others

Aramid fibre
Kevlar™ and Twaron™ are aromatic polyamides (from which the generic term aramid derives). Considerable weight savings can be achieved by using advanced fibres such as aramid or carbon. If the structure is designed for stiffness rather than strength then carbon will be lighter than aramid. However, if impact strength is critical, aramid may be lighter. Composites of aramid fibre display good resistance to fatigue, weathering and chemical attack, and give very good impact strength.

To enhance the properties of the composite over single reinforcement systems, aramid fibre can be combined with glass or carbon fibres (or both) in hybrid form.

Mechanism of reinforcement
Reinforcement of a low-modulus polymer with a high-modulus, high-strength fibre uses the plastic flow of the polymeric material under stress to transfer the load to the fibre; this gives a high-strength high-modulus composite. The aim of the combination is to produce a two-phase material in which the primary phase (ie the fibres) is well dispersed and bonded by a weak secondary phase (ie the polymer matrix)[4]. The principal constituents influencing the strength and stiffness of composites are the reinforcing fibres, the matrix and the interface between the fibres and the matrix.

The functional requirements of fibres in a composite are that they should have:
- High modulus of elasticity to give stiffness to the composite
- High ultimate strength
- Low variation of strength between individual fibres
- Stability during handling
- Uniform diameter

The matrix should fulfil certain functions:
- Bind the fibres together to protect their surfaces from damage during the service life of the composite
• Transfer stresses to the fibres efficiently by adhesion or friction
• Disperse and separate the fibres
• Be chemically and thermally compatible with the fibres

Methods for manufacturing fibre reinforced thermosetting polymers

This section briefly describes the main manufacturing techniques used and where they are used. References 1 and 5 give more details.

Open-mould systems
These production methods take advantage of an important characteristic of the resin: it does not require heat or pressure for complete polymerisation to occur. The resins are known as cold-cure resins. There are many variations of the open-mould process so only the principal ones will be considered here.

Hand lay-up process
In this process, only one mould is used. It may be either male or female.

The durability of glass fibre reinforced polymer composite in the construction industry depends upon the quality of the surface exposed to the atmosphere; the fibres on this exposed surface must be protected with a resin-rich coating known as a gel coat. Gel coat thickness should be about 0.4–0.5 mm and be uniform throughout.

After the gel coat has become tacky but firm, a liberal coat of resin is brushed over it and the first layer of glass reinforcement is placed in position and consolidated with a roller. Subsequent layers of resin and fibre are then applied until the required thickness of the composite is achieved. Curing of the composite takes place at room temperature and normally takes 28 days at 20 °C. For practical purposes curing is essentially complete after a few hours. However, for maximum performance, essentially weathering and water resistance, at least two weeks is recommended.

Spray-up process
The preparatory stages of this process are similar to those for hand lay-up, but the actual technique of applying the resin and fibre to the mould is less labour intensive.

During the spray-up operation, glass fibre roving is fed continuously through a chopping unit and the resulting chopped strands are projected onto the mould together with a resin jet. The glass fibre resin matrix is then consolidated with rollers.

In the construction industry this process and the hand lay-up method are used to form load-bearing and infill panels for buildings and facing materials for sandwich panels.

Vacuum bag moulding
This process is similar to hand lay-up, but final laminate consolidation is achieved by covering the component with a plastic film (vacuum bag) and drawing a vacuum over the component. The pressure differential compresses the uncured composite, forcing out excess resin and drawing out entrapped air. This results in a laminate of higher fibre volume fraction and better consistency than that produced by the hand lay-up process.

Closed-mould systems
For many years fibre/matrix composites have been produced by moulding processes using matched dies. These processes produce mouldings with a good finish on both surfaces of the composite. Compared with the open-mould process, this system enables a higher glass content to be used in the composite, with improved mechanical properties.

Cold-press (low pressure) moulding process
Unheated matched tools, under pressure, are used to impregnate resin throughout fibre reinforcement placed in a mould. A release agent and gel coat are applied to the surface of the mould before the fibre and resin are placed in position. This process is suitable for small batches with good surface finish. It is simple, low-cost and effective, but requires lengthy moulding cycles (usually measured in hours).

Hot-press (high pressure) moulding process
The fibre-filled polymer is confined between heated, matched, polished metal dies (at about 150–160 °C) brought together under pressure (about 15 MN/m²). This process is the highest-volume method for moulding thermoset reinforced polymers, usually reaching an economic output at a level of around 10 000 parts/year. To maintain efficiency, prepared combinations of resin, reinforcement and additives (prepregs) are increasingly used. The most widely used are known as bulk moulding compound (BMC) and sheet moulding compound (SMC).

Resin injection
Resin injection moulding uses a liquid formulated resin which is injected into a closed mould into which the reinforcement has already been placed. It is most often used for parts with smooth surfaces coated with gel coat. The reinforcement is placed in position in the bottom mould. The top mould is then placed over the bottom one and secured. Resin is injected at low pressure (400 kN/m²). Resin injection can be carried out in cold, warm or hot moulds, at up to 80 °C.

Resin injection under flexible tooling (RIFT)
For RIFT, dry fabric reinforcement is laid into a mould and covered with a vacuum bag, the edges are sealed and a vacuum drawn. The vacuum bag is used to draw resin into the reinforcement thus forming the composite component. This process results in a laminate of low void content and high volume fraction. The resin infusion process is well suited to larger components and structures.
and where a closed-mould process is required to reduce emissions. It is ideal for producing low numbers of components.

Resin transfer moulding (RTM)
RTM is similar to RIFT but is suitable where large numbers of components are required. A closed metal mould is usually used (it tends to be more expensive to make but is more durable that the cheaper tooling for RIFT), and the dry fibre preform is laid up within it. Resin is then injected under positive pressure (sometimes with vacuum assistance) to form the final component. The mould can also be heated to accelerate the cure of the resin and so reduce cycle times.

Automated techniques
Filament winding technique
Filament winding is a technique used to produce high-performance hollow symmetrical products such as pipes, tanks, pressure vessels and loadbearing tubes. A mandrel of the required shape is rotated on its axis (usually horizontally, but depending on the size and shape of the object to be produced) and wound with a continuous filament of reinforcement. The fibre angle can therefore be controlled to a certain extent. However, geometry of the part usually dictates the angles that can be achieved (fibres naturally follow the high points on the surface profile). When fully wound with resin-wetted reinforcement, the lay-up is cured, on or off the mandrel.

Pultrusion
A pultrusion machine is designed to produce a continuous length of composite material with a uniform cross-section. Both solid and hollow profiles can be made.

Continuous strands of reinforcing material, together with any additionally required layer of fabric, are drawn from creels and passed through a resin bath fitted with a constant level device. After picking up an excess of matrix, the saturated fibre is passed through a number of wiper rings and into the mouth of a heated die.

To cure the formed composite it is gripped firmly between rubber blocks and pulled through the die at a predetermined speed. It is then cut to the desired length by a cut-off wheel.

Most forms of geometric sections can be produced by this method. They can be stored and used as structural units when required.

Thermosetting resins are used almost exclusively, with polyester resin being used for most of the production of pultruded composite.

Processing methods for the manufacture of reinforced thermoplastic polymers

Injection moulding technique
The principle of injection moulding is simple. Softened thermoplastics is forced through a nozzle into a clamped cold mould. When the plastics has become cold, the mould is opened and the article is ejected; the operation is then repeated.

Fibre reinforced thermoplastics can be moulded in many ways but injection moulding is the most widely used. The length of fibres used in the various processes is short — about 0.2–0.4 mm; consequently the full loading capacity of the fibre is not developed. Various improvements in recent years have overcome this problem by producing continuous fibre tapes or mats which can be embedded into the thermoplastics matrix.

Film stacking method
The film stacking process is used to produce composites in which the fibres are manually aligned in the desired direction. The process involves interleaving lightly impregnated fibres of fabric with thin films of pure thermoplastics polymer in split moulds. When the required stacking sequence has been achieved, the two split moulds are brought together and heat and pressure are applied. The result is a high-quality laminated thermoplastics composite.

This process is used in the manufacture of high technology composites for the aerospace and space industries.

Mechanical properties of composites

The mechanical properties of composites depend on:

- Relative proportions of fibre to matrix
- Fibre orientation within the matrix material
- Components used to form the composite
- Method of manufacture of the composite
- The fibres’ modulus of elasticity and ultimate strength

Composites formed under pressure will usually have a higher fibre volume fraction than those manufactured by hand. The in-service properties of the composite mainly depend on the physical properties of the polymer matrix.
### Table 1: Typical material properties[^4]

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength (MPa)</th>
<th>Compression strength (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Shear strength (MPa)</th>
<th>Tensile modulus (GPa)</th>
<th>Coefficient of thermal expansion (10^-6/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF/OP CSM (PB)</td>
<td>110</td>
<td>150</td>
<td>190</td>
<td>3</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>GF/IP WR</td>
<td>220</td>
<td>230</td>
<td>270</td>
<td>3.3</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>GF/IP woven cloth</td>
<td>260</td>
<td>210</td>
<td>480</td>
<td>—</td>
<td>17</td>
<td>—</td>
</tr>
<tr>
<td>GF/IP FW/HW 0/90°</td>
<td>650/25</td>
<td>800/120</td>
<td>800</td>
<td>4/—</td>
<td>30/10</td>
<td>—</td>
</tr>
<tr>
<td>GF/IP FW/AP H/A</td>
<td>340/450</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>20/29</td>
<td>—</td>
</tr>
<tr>
<td>GF/IP CSM CM/UD-0/90°</td>
<td>300/25</td>
<td>250/110</td>
<td>—</td>
<td>—</td>
<td>16/7</td>
<td>10</td>
</tr>
<tr>
<td>GF/IP CM/WR-CSM</td>
<td>180</td>
<td>180</td>
<td>320</td>
<td>—</td>
<td>12.2</td>
<td>—</td>
</tr>
<tr>
<td>GF/IP SMC</td>
<td>70</td>
<td>120</td>
<td>140</td>
<td>3.8</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>PF/IP WR</td>
<td>390</td>
<td>86</td>
<td>190</td>
<td>—</td>
<td>24</td>
<td>—</td>
</tr>
<tr>
<td>PF/IP UD</td>
<td>1380</td>
<td>276</td>
<td>620</td>
<td>60</td>
<td>76</td>
<td>—1</td>
</tr>
<tr>
<td>CF UD high modulus</td>
<td>1260</td>
<td>840</td>
<td>1070</td>
<td>65</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>Mild steel</td>
<td>450</td>
<td>430</td>
<td>—</td>
<td>—</td>
<td>330</td>
<td>207</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>300</td>
<td>—</td>
<td>—</td>
<td>180</td>
<td>70</td>
<td>23</td>
</tr>
<tr>
<td>Concrete</td>
<td>2–5</td>
<td>25–60</td>
<td>—</td>
<td>—</td>
<td>25–36</td>
<td>7–12</td>
</tr>
</tbody>
</table>

**Abbreviations:**
- AP = angle ply 55°
- CF = carbon fibre
- CM = combination mat
- CSM = chopped strand mat
- FW = filament wound
- GF = glass fibre
- HW = hoop wound
- H/A = direction of stress: hoop or axial
- IP = iso-polyester resin
- OP = ortho-polyester resin
- PF = polyaramid fibre
- SMC = sheet moulding compound
- WR = woven roving
- 0/90° = direction of stress: 0° or 90°
Chapter 8  The future

Applications fit for exploitation

Geocomposites
Geocomposites consist of two or more different polymer structures which are combined together to produce a hybrid material structure. There are a number of different geocomposite material structures possible. One of the major uses of geocomposites is in prefabricated drains comprising a three-dimensional polymer core surrounded by a geotextile filter. The polymer core acts as the drainage conduit along which water flows after it has been filtered by the geotextile skin. Two categories of prefabricated drain are in use: vertical (or band) drains and fin drains\[100\]. There are also geotextiles and geomembranes which are used to reinforce the ground.

Forms for concrete
Reinforced polymers are used in formwork, chutes and various tools; their attraction lies in their ease of handling. GFRP composites manufactured by the hand lay-up, spray-up or matched metal moulding techniques have the advantage of economy due to repeated use of the forms. The glass fibre composite formwork is tough and cannot be easily dented, it does not corrode or deteriorate as steel does and it does not react with the alkaline constituents of concrete. In addition, if the formwork is damaged it can be repaired easily with no visible evidence in the finished concrete\[101\].

Helically wound GFRP composite tubes have been used in column construction for marine structures as a replacement for steel tubes; both types of tube would be filled with concrete. GFRP composite tube is an ideal material to use because the axial load will be entirely taken by the concrete, the expansion of the composite in the circumferential direction is smaller than that of the concrete, and the tensile strength of the composite is high. Consequently, the GFRP casing counteracts lateral expansion of concrete under load and, when used in short columns, the axial strength of the concrete core increases over its uniaxial value and can reach a triaxial failure strength of up to four times the uniaxial strength. It has been suggested that fibre reinforced polymer casings could be used to encase reinforced concrete beams thus improving their strength and ductility in the compression zone and, in addition, providing permanent formwork and corrosion protection.

Resin-bonded systems
Sandwich construction is a form of composite structure using glass fibre (or a hybrid of glass and carbon fibre) in a polyester matrix. Pultruded sections which have exclusively unidirectional reinforcement are anisotropic with extremely high axial and flexural strength but relatively low transverse strength. However, by incorporating hooped strands along a reinforcement core, the hoop strength can be improved. Mats, particularly continuous fibre mats, can also be used to improve the transverse strength. To improve the appearance, corrosion resistance and handling of the product further, glass fibre and polymeric veils can be added to the laminate construction to depress the reinforcement from the surface, providing a polymer-rich surface to the composite. The two most commonly used products are surface tissues of high alkali content glass or chemical resistant glass.

The main properties of the pultruded composite that give it special significance are\[5\]:
- High strength-to-weight ratio
- Dimensional stability
- Corrosion resistance

Prestressing tendons and reinforcement
Three polymer composite materials are commercially available for use as prestressing tendons in concrete.
- Polystal is produced by Bayer AG in association with Strabag AG in Germany\[102\]. The tendon consists of bundles of bars or rods, each containing E-type glass fibre filaments in an unsaturated polyester resin matrix.
Arapree quarters, where there is a strong urge to use materials which are thought to be more friendly to the environment. There is a growing interest in the use of natural fibres in reinforced polymers, not only in the developing countries that produce them, but also in the industrialised countries, where some believe they might help in solving recycling problems. As well as biodegradability, the advantages of natural fibres include low density and cost, better damage tolerance in composites and high specific strength and stiffness. These make natural fibres interesting for housing applications with low load requirements. On the negative side, however, are degradation by moisture, poor surface adhesion to hydrophobic polymers and susceptibility to fungal and insect attack. Properties can be improved by treatment of the fibres.

The future for polymer composites in construction

Polymer composites do have a very large part to play in the construction industry. As the advantages of composite materials become appreciated, and the analysis and design techniques for composite laminates are developed, their use in the construction industry will undoubtedly increase. In the design of composites, material and structural designs must be undertaken simultaneously because they are both interdependent. This means that many interesting structural concepts not possible with traditional materials can now be realised. Indeed, some very innovative structural applications have been built recently.

Advanced composite materials have found a market in construction applications. The quantities of material used are small compared with other competitive structural materials, although applications are already becoming less specialised. The future is optimistic regarding the expanding seismic and infrastructure market using advanced composite materials. Market penetration of fibre composites within the construction industry will ultimately be determined by whole life cost. Material cost alone is not the prime consideration for many applications for these materials. Associated production costs must be minimised by ensuring ease of design, manufacturing efficiency, and product availability. Construction costs of handling, jointing and maintenance must be low. Sustainable material sourcing, production energy and production process pollution, off-cut and ultimately demolition waste disposal are additional factors that will need to be considered.

Natural fibres

Natural fibres, for example hemp, jute, flax, sisal and cotton, are receiving increasing attention from some quarters, where there is a strong urge to use materials which are thought to be more friendly to the environment. There is a growing interest in the use of natural fibres in reinforced polymers, not only in the developing countries that produce them, but also in the industrialised countries, where some believe they might help in solving recycling problems. As well as biodegradability, the advantages of natural fibres include low density and cost, better damage tolerance in composites and high specific strength and stiffness. These make natural fibres interesting for housing applications with low load requirements. On the negative side, however, are degradation by moisture, poor surface adhesion to hydrophobic polymers and susceptibility to fungal and insect attack. Properties can be improved by treatment of the fibres.

The future for polymer composites in construction

Polymer composites do have a very large part to play in the construction industry. As the advantages of composite materials become appreciated, and the analysis and design techniques for composite laminates are developed, their use in the construction industry will undoubtedly increase. In the design of composites, material and structural designs must be undertaken simultaneously because they are both interdependent. This means that many interesting structural concepts not possible with traditional materials can now be realised. Indeed, some very innovative structural applications have been built recently.

Advanced composite materials have found a market in construction applications. The quantities of material used are small compared with other competitive structural materials, although applications are already becoming less specialised. The future is optimistic regarding the expanding seismic and infrastructure market using advanced composite materials. Market penetration of fibre composites within the construction industry will ultimately be determined by whole life cost. Material cost alone is not the prime consideration for many applications for these materials. Associated production costs must be minimised by ensuring ease of design, manufacturing efficiency, and product availability. Construction costs of handling, jointing and maintenance must be low. Sustainable material sourcing, production energy and production process pollution, off-cut and ultimately demolition waste disposal are additional factors that will need to be considered.
References and further reading

About this book

Polymer composites, glass fibre reinforced plastics in particular, are common in construction. This book deals with their various aspects — properties of the materials and uses to which they are put, design of composites, in-service properties of the materials, and construction and erection of the components. Glass fibre reinforced polymers are the main subject, but uses and potential uses of other polymer composite systems are highlighted.

Polymer composites offer the architect, designer and structural engineer many advantages over traditional construction materials. The book will be of particular benefit to those with little or no prior knowledge of polymer composites.
Polymers have many advantages over conventional building materials: they are light in weight, resist corrosion and are easy to process. Combining them with fibres to form composites enhances their properties, making them useful for such construction components as structural members, modular units, light-transmitting panels, sandwich panels, storage tanks, formwork and windows.

Advanced composite materials have superior properties that offer real benefits to the construction industry and are becoming established as important materials in all forms of structures. They offer free-form and tailored design characteristics, outstanding strength-to-weight and stiffness-to-weight ratios, resistance to heat and fire and a high degree of chemical inertness in most environments.

Civil engineering and building industries account for about 30% of all polymers produced each year. And as the properties of polymer composites are better understood and appreciated, the use of these materials in the construction industry will increase.

**Polymer composites in construction** deals with

- properties,
- manufacturing techniques,
- design,
- performance
- and the use of these materials in the UK and overseas.

It also includes:

- examples,
- lists of consultants,
- manufacturers
- and materials suppliers.

It is fully referenced and gives useful further reading.