FIBRE REINFORCED PLASTICS

BY

R. DUKE, B.SC., PH.D., M.A.I.A.A.
(*Admiralty Materials Laboratory*)

Introduction

Reinforced plastics of various types show promise as structural materials if proper use can be made of their unique properties and if their shortcomings can be successfully overcome. In this paper an attempt is made to review the properties, advantages and disadvantages of fibre-reinforced plastics as we know them today and to suggest areas in which they might be developed.

Available Materials

Table I summarizes the properties of the most commonly used fibrous reinforcing materials. The wide variation in properties is immediately evident even among fibres of the same material. This variation may arise from various sources, the range of glass fibre strengths is due to the effects of mechanical damage caused during handling and in general the more the fibre is handled the lower the strength. The range of properties of carbon fibres on the other hand arises from the processing which can be controlled so as to give various combinations of strength and stiffness. The bulk of reinforcement used at present is glass and only glass fibre is available in so many different forms; rovings,

TABLE I—*Reinforcement Properties*

	Specific Gravity	Tensile Strength MN/m²	Tensile Modulus GN/m²	Typical Fibre Diameter μ
Glass	2·55	1800–3500	70	10
Carbon	1·9	1800–3000	200–400	7
Steel	7·8	2700–3100	210	250
Asbestos	3·2	3200	190	0·1
Boron	2·3	3500	400	100

TABLE II—*Resin Properties*

	Polyester	Epoxide
Specific Gravity	1·11–1·45	1·11–1·40
Tensile Strength MN/m²	40–90	30–90
Tensile Modulus GN/m²	2–4	1–4
Compressive Strength MN/m²	90–250	100–200
Shrinkage %	4–8	1–4
Heat Distortion Temperature °C	60–200	40–300

chopped fibre mat and woven fabrics, although efforts are being made to provide carbon fibres in similar forms. Economically, glass also has an advantage, being of the order of 4*s*. per lb, while the exotic carbon and boron fibres are two or three orders of magnitude higher.

As glass fibres form the major part of the reinforcement so polyester resins form the bulk of the matrix material due largely to cost and convenience. For specific applications the special properties of other resins may merit the expenditure and particularly with epoxide resins there is great scope for tailoring the matrix to have specific properties. TABLE II shows some of the properties of these two types of resin. Again a wide variation of properties, dependent upon precise formulation and processing, can be seen. In general polyesters have a distinct price advantage, being of the order of 5*s*. per kilogram compared with epoxides which range from 10*s*. per kg up to many pounds.

The common factor in these matrix materials is the low modulus and while this ensures that the load is carried by the fibres, it has a deleterious effect on the overall stiffness of the composite. Attempts to increase the resin modulus usually result in brittle materials with low strain to failure in tension which is also most undesirable. The second major limitation is one of temperature since the resins undergo a transition at some temperature in the range 50–200 degrees C depending upon the cure schedule used. In addition the resins are viscoelastic and suffer from time dependent deformation which is also strongly affected by temperature, and this behaviour is carried through to the composite where the resin is used to carry load. When the reinforcement and matrix materials are put together to form a composite the properties depend very much upon the way the reinforcement is distributed and TABLE III shows typical values for a range of glass- and carbon-reinforced plastics.

TABLE III—*Composite Properties*

	Fibre Content %	*Specific Gravity*	*Tensile Strength* MN/m²	*Tensile Modulus* GN/m²	*Comp. Strength* MN/m²
Unidirectional Glass Epoxide	60–90	1·7–2·2	550–1750	30–65	300–500
Satin Weave Glass Polyester	50–70	1·6–1·9	250–400	15–25	200–300
Glass Woven Roving Polyester	45–60	1·5–1·8	230–350	13–17	100–150
Glass Random Mat Polyester	25–40	1·4–1·5	60–150	6–12	100–150
Glass Filled Moulding Compound	5–25	1·8–2·0	35–70	10–14	140–180
Unidirectional Carbon Epoxide	50–70	1·5–1·6	1000–1750	150–300	
Bidirectional Carbon Epoxide	50–70	1·5–1·6	500–900	75–150	

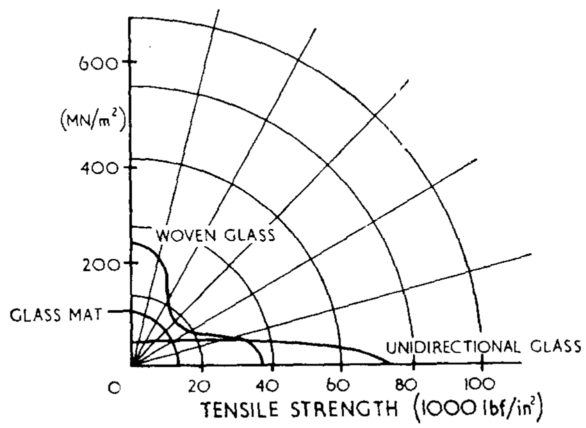

FIG. 1—ANISOTROPY OF COMPOSITES

The two points which appear immediately are the high strengths which can be achieved and, with glass reinforced plastics, the low stiffness. The increased stiffness of carbon fibre composites is also evident.

The increasing properties of GRP are in fact only achieved at the expense of considerable anisotropy, a factor which has not loomed large in engineering before. FIG. 1 shows the increasing anisotropy of strength as the type of reinforcement is changed.

Advantages and Disadvantages of Reinforced Plastics

Most of the remarks in this section will be concerned with glass reinforced plastics simply because of the greater volume of experience with this material. Composites have certain advantages which most common structural materials do not enjoy. First of all they are easily mouldable to complex shapes and secondly there exists the possibility of designing the material at the same time as the structure particularly if the load environment is known in detail as, for instance, with a pressure vessel. On occasions these two advantages cannot be used together since complex shapes are generally difficult to analyse and the precision of fibre placement may not be sufficiently high to ensure that the theoretical requirements can be satisfied. This in fact raises a dilemma which can be met quite often. A very precise lay-up may give the most efficient structure but precision generally means cost so that a less efficient structure may be economically preferable. Additionally, the existence of a flaw would have a significantly greater effect on the high quality composite.

Some other advantages of glass reinforced plastics for naval use are that they are non-magnetic and non-conducting, indeed some of the highest quality GRP is produced for the electrical industry for insulating purposes.

Low maintenance is an often quoted advantage of fibre-reinforced plastics over conventional materials, and it is true that they are not subject to corrosion damage and the like in normal atmospheres. Glass-reinforced plastics are,

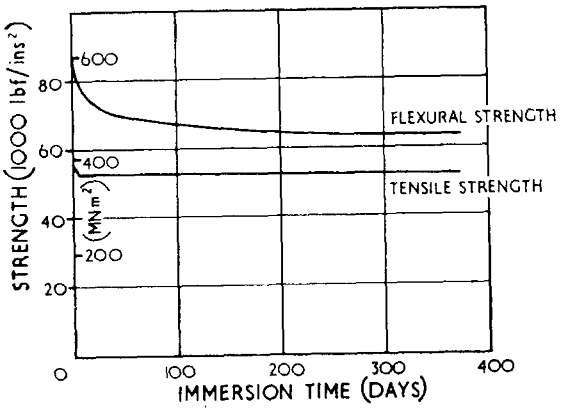

FIG. 2—EFFECT OF WATER IMMERSION ON COMPOSITES

however, greatly affected by the presence of water. The various matrix materials all readily absorb water, and this water, and any which travels along any debonded fibres, tends to degrade the composite. FIG. 2 shows this degradation for flexural and tensile strength of glass roving laminates. The time scale is not too important as it is felt that this may be expanded or contracted, depending upon the degree of protection given to the specimen. The results shown here were taken from a series of tests in which a deliberate attempt was made to accelerate the degradation. The retention of this strength level is typical of what may be expected of the best materials available today. The effect of water is, of course, most important and the combination of load and a wet environment can be quite destructive and this really forms the first problem we have in using glass reinforced plastics as a structural material.

Reference has already been made to the anisotropy of many types of laminates and this can be a problem in that anisotropy is a factor of which most designers have little or no experience. In many cases the same assumptions and formulae which have been used for so long with isotropic materials are applied to composites but as more complex structures are produced with these materials, new design theories will evolve. This particular problem is associated with modulii as well as strength, so that as well as dealing with a material whose strength varies with direction, the designer also has to think in terms of perhaps four or six material constants instead of two. Both of these problems make materials evaluation more difficult and further difficulties can arise from the fact that changes in the lay-up design cause changes in the material properties and constants.

A third factor which has a great influence on the use of GRP as a structural material, arises from the inhomogeneity of the material, and its behaviour under load which is unlike anything encountered in metallic materials. If a piece of glass-reinforced plastic is loaded in tension and the stress/strain curve examined, in most cases it is initially straight, provided a reasonable rate of loading is used. However, at some fairly low stress levels, maybe $\frac{1}{4}$ or $\frac{1}{2}$ of the UTS, there is often a kink in the curve and this is indicative of debonding of fibres lying at right angles to the tensile load. At higher stresses this debonding acts as a crack initiator and the surrounding resin matrix cracks. In a cross-plied laminate the original debonding damage often turns at the interface between adjacent plies and produces a delamination which can be of great trouble if a compressive stress has to be carried subsequent to a tensile stress of magnitude sufficient to cause this type of damage. The onset of debonding, which results as a strain concentration caused by the disparity of properties of the matrix and fibre, is very much dependent upon the matrix and it may be possible to produce a resin which will have a sufficiently high elongation to avoid debonding altogether before catastrophic failure. Unfortunately such a resin is likely to have inferior properties in other respects such as modulus.

Debonding may occur under other forms of loading, notably compressive loading when there is a tendency for the matrix to split away from the fibres—again due to the different properties of the component materials.

The purpose of the so-called plastics factor or more simply the large safety factors commonly used with a reinforced plastic structure is to enable the

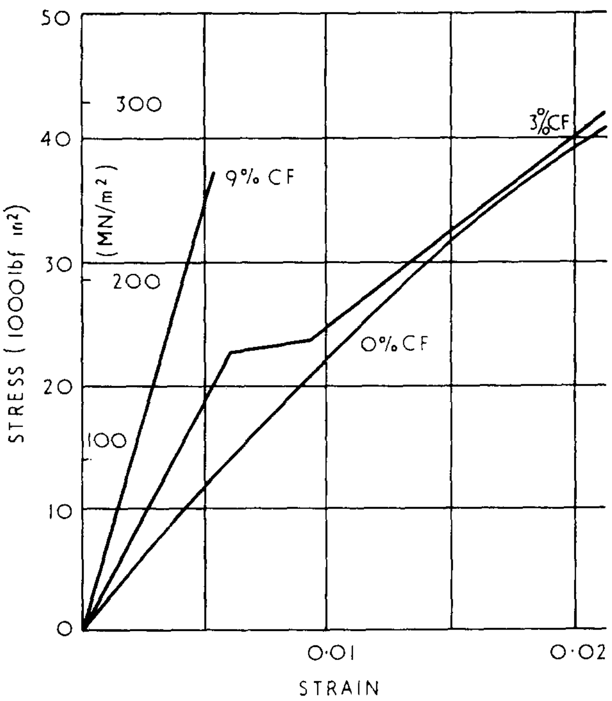

FIG. 3—MIXED FIBRE COMPOSITES

working stress range to be placed below the stress at which significant debonding takes place. Of course the whole problem can be avoided if unidirectional reinforcement can be used but such occasions are comparatively rare. The problems are likely to be much reduced with carbon fibre reinforced plastics due to the much lower overall strain levels which will be found together with the fact that these fibres are anisotropic in themselves, being less stiff across a diameter than along the length so that the strain concentration effect is not likely to be any worse than with glass fibres.

A final factor strongly affecting the use of glass-reinforced plastics, is the low stiffness, typically for shipbuilding composites 2–2·5 $\times$ 10^6 lbf/in^2 which means that in many areas structures are designed on stiffness considerations and not on strength. This problem does not exist with carbon fibre composites.

Using carbon fibre, which is now commercially available, it is possible to construct unidirectional composites with a Young's modulus in excess of 25 $\times$ 10^6 lbf/in^2. This will obviously fall appreciably when the fibre is distributed in more than one direction but a significant advance can still be made on GRP. Strength is at least equal to that of GRP so that potentially CFRP is an extremely attractive material. As has been stated earlier, carbon fibre is currently extremely expensive, 2 or 3 orders of magnitude greater than glass. The obvious solution, is to try to make the best use of a limited amount of carbon by diluting it with glass. The choice then is of how to use the carbon; whether as a separate framework to which is attached a relatively flimsy skin—which need no longer be glass-reinforced plastic—or as a more intimate mixture of glass and carbon. The general strength of materials approach would indicate that in such a mixture the carbon would carry a disproportionate share of the load. However, there seem to be some advantages arising from such an approach. The effect of adding a small percentage of carbon fibre to a glass-woven roving composite is quite startling. The addition of 3 per cent carbon fibre in one direction is sufficient to double the stiffness. The most surprising thing is the overall behaviour of such a composite. FIG. 3 shows the stress/strain curves of a wholly glass roving laminate, a mixed 3 per cent carbon and a mixed 9 per cent carbon laminate. The glass laminate is typical of the shipbuilding material UTS about 40000 lbf/in^2 modulus just over 2 $\times$ 10^6 lbf/in^2. The addition of 3 per cent carbon gives a modulus of about 4 $\times$ 10^6 and at about 0·5 per cent strain complete failure of the carbon fibre, which has a low strain to failure. However, with a low carbon content this failure is not catastrophic and there is in fact a kind of yield behaviour although of course not in the sense that is known in the metallurgical field. With the load redistributed into the glass laminate, the stress strain curve behaves as if the carbon had never existed and failure takes place at around the same stress level as a wholly glass fibre composite. The carbon content can be increased to a point where the load can no longer be redistributed when the failing strain of the carbon is reached and at this point there is no 'pseudo yield' behaviour.

To make use of the increased properties of a mixed fibre composite, a lower factor of safety will have to be tolerated on the carbon fibre, although the overall factor on ultimate failure need not be changed. Most of the failure mechanisms associated with reinforced plastics appear to be strain dependent and currently the working range for a glass-woven roving laminate is 7500 lbf/in^2, or a strain of some 0·3 per cent. Operating at the same strain level, a mixed fibre composite would in fact have an increased load capacity as well as increased stiffness and conceivably the mixture could be adjusted to satisfy both strength and stiffness criteria at the same time.

A more efficient use of carbon fibre is in local panel stiffening where the carbon could be located near the surface of the panels to introduce flexural stiffnesss.

It must be emphasized that this work has not yet progressed very far and better methods of using carbon may be conceived in the future.

A further attraction of carbon fibre composites from the marine point of view is that they are virtually unaffected by water immersion. On the other hand, the conductivity of the carbon allows the formation of cells with metallic materials, with sea water as an electrolyte, and severe corrosion can ensue.

Future Developments

Some of the problems arising in reinforced plastics have been outlined and over the next few years improvements will undoubtedly take place to solve these problems.

Development can be divided roughly into three areas:

(*i*) Materials
(*ii*) Design
(*iii*) Production.

There has been for many years a steady effort by both the resin and glass manufacturers to reduce the deleterious effects of water and this can be expected to continue. At the moment 80 per cent strength retention is regarded as the best that can be achieved although a few years ago such a figure would have been regarded as extremely optimistic. Carbon fibres are obviously going to find increasing use especially as the cost can be expected to be reduced substantially. In the resin field there is now interest being shown in the behaviour of the resin within the composite, which, hopefully, will indicate in more detail the optimum requirements for a laminating resin.

A major step forward is likely to occur in the design field where it is becoming increasingly apparent that there is just not sufficient knowledge to produce efficient RP structures. The trends here have been indicated and quite obviously it is an area open to extensive computerization since optimization of structures and the examination of alternative laminate designs can be carried out very easily once suitable programmes have been prepared.

The third area where progress is certainly desirable is in the development of production techniques which will change the labour intensive nature of industry. Some progress has already been made in the design of impregnating machines to deal with cloth. However, there is still a vast expenditure of labour consolidating the laminate. Further development in this area would certainly make composite materials economically more attractive, and it may be that some loss of properties will arise. The comment was made earlier in this paper that very efficient structures are expensive and the production of high grade composites may not be cost-effective. Ideally, this aspect should be examined during the design process when consideration is given to the type of composite required.

Acknowledgment

The author is indebted to Director, Admiralty Materials Laboratory, for permission to present this paper. The views expressed are those of the author and do not necessarily represent MOD opinion.