Applications of fibre reinforced plastic composites in the railway industry

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This paper describes the use of fibre reinforced plastics in the railway industry. A description is given of various case studies, including seat shells, temporary overhead structures, pantograph heads, cab fronts and doors, in order to give a practical illustration of the various applications to which such plastics can be put.

The paper also deals with design criteria such as stiffness, strength, flammability, durability and cost effectiveness, quoting comparative figures. Finally, the paper looks at future developments, specifically the use of higher performance carbon and aramid fibres, both of which are discussed, after which a brief description is given of fibre reinforced thermoplastics for performance applications.

1 INTRODUCTION

Composite structures based on glass reinforced plastic (GRP) are well-established within the railway industry in the UK and there are numerous applications to be found. These materials were first used in 1959 for carriage doors on suburban electric stock. GRP was selected for this application on account of its superior fatigue life compared with alternative designs based on cast aluminium and steel cladding on a timber frame. Since those early days, the use of GRP in rolling-stock has increased significantly and the material is now readily accepted by design engineers. The potential of GRP has also been appreciated in other fields and this material has been used for various civil engineering and architectural applications involving lineside structures and buildings etc. (**1**).

In the early 1960s, an experimental coach was produced in which the complete structure above the under-frame was produced from a GRP/polyurethane foam sandwich construction. This 'plastic' coach was about $2\frac{1}{2}$ tonnes lighter than the traditional design of that period and remained in restricted service on the Southern Region for a period of some ten years, during which time it appears to have given a satisfactory performance. However, with the state-of-the-art at that time, the method of construction was too expensive to justify further development.

Glass reinforced plastic is used in a wide range of applications in modern passenger stock. In a modern Mark III vehicle, for instance, the total weight of GRP materials comes to roughly 1.6 tonnes; the figure for a High Speed Train (HST) power car comes to approximately 1.3 tonnes. There are several reasons for this trend:

1. *GRP enhances the quality of the passenger's environment* Designers appreciated the benefit of being able to produce small quantities of components with complex shapes and which were self-coloured, easy to maintain and hard wearing. GRP has thus been used widely for decorative and semi-structural applications.
2. *GRP is cost-effective* As a rule, the railway industry requires only small quantities of any given component; the low tooling and manufacturing costs associated with GRP thus make this material an attractive proposition, particularly where items have complex shapes.
3. *GRP is light* Composite structures can be made lighter, which means that energy costs can be reduced. For example, the original GRP door mentioned earlier weighed only 30 per cent of the weight of the traditional steel/timber model. Similar savings may be expected with many other components, although it must be appreciated that the lack of stiffness in GRP may present problems in certain applications.

Glass reinforced plastic is used in an extensive range of applications, but it is not intended that the full spectrum be discussed within the context of this paper. The authors will, instead, be concentrating on a description of the ways in which a number of components for which the use of composites has proved to be particularly effective were developed. The future potential for composites, including those based on reinforcing materials other than glass fibres, will also be considered.

2 CAB FRONTS

The development of a GRP cab structure for the HST is possibly the most ambitious use of a composite structure on British Railways. There were a number of reasons behind the selection of GRP for this application:

1. *Impact strength* Drivers need to be protected against missiles which might strike the front of the cab. The specification (**2**) calls for a structure which will resist penetration by a 0.9 kg steel cube fired at a speed of 350 km/h and striking the cab front with a corner leading.
2. *Low weight* Preliminary studies revealed that a composite design would weigh up to 35 per cent less than an equivalent steel structure.
3. *Production process* The production technique needs to be suitable for a low volume output. Manufactur-

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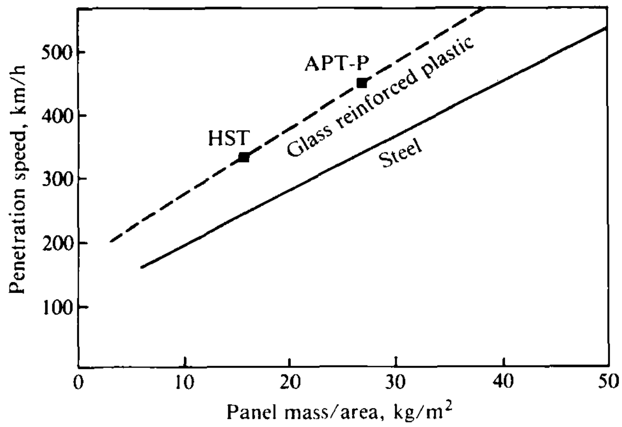


Fig. 1 Impact resistance of cab materials

ing cost estimates for steel and aluminium alternatives were considerably higher.

4. *Streamlining* This was needed in order to reduce drag and to minimize the effect of shock waves. With the use of composites, no difficulty was experienced in producing the complex shape demanded by the designers.

A GRP/polyurethane foam sandwich structure was developed to meet the impact requirements laid down in (**2**). This was to be manufactured by conventional contact moulding methods. Laboratory experiments on test panels had shown that composites would produce far lighter structures whilst maintaining the same impact strength as that found in steel (Fig. 1). Aluminium has a similar impact strength to that of composites, but manufacturing costs are a good deal higher. The outer skin is produced as a single moulding whilst the inner skin is formed from three separate mouldings. The two faces are assembled to form a cavity. Electrical wiring and air conditioning ducting are incorporated at this stage, following which polyurethane foam is injected into the cavity to produce an integral sandwich structure. The cab shell is completed by bonding in a separate GRP floor and bulkhead. The final weight of the complete cab (Fig. 2) is about 1 tonne. This item has proved very successful and over 200 cabs have been manufactured using this method. A similar philosophy was adopted for certain areas of the APT-P cab. Since this train was designed to run at higher speeds than the HST, some of the glass reinforcement was replaced by an aramid fibre in order to give increased impact strength.

Fig. 2 High Speed Train cab

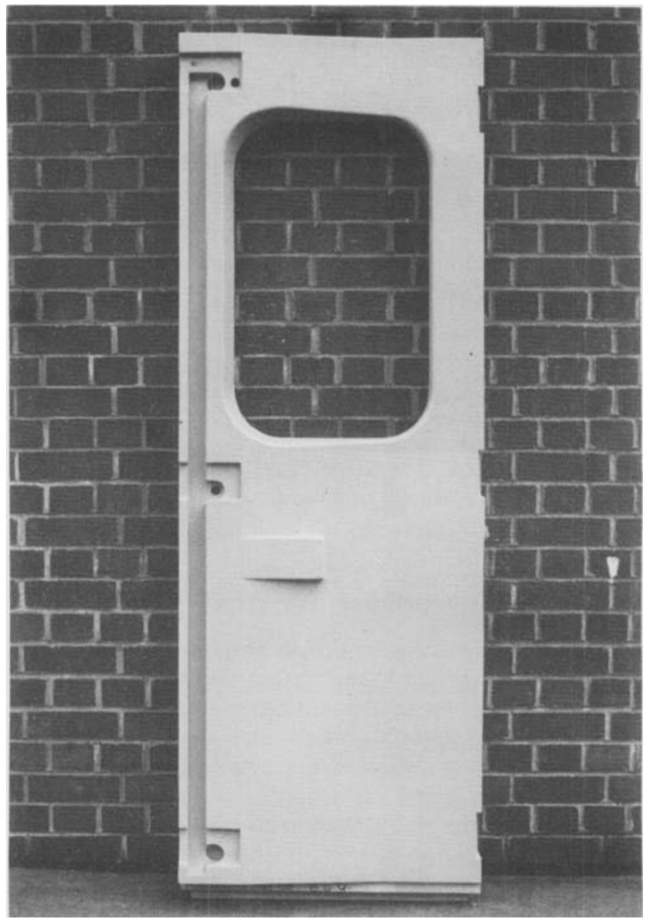
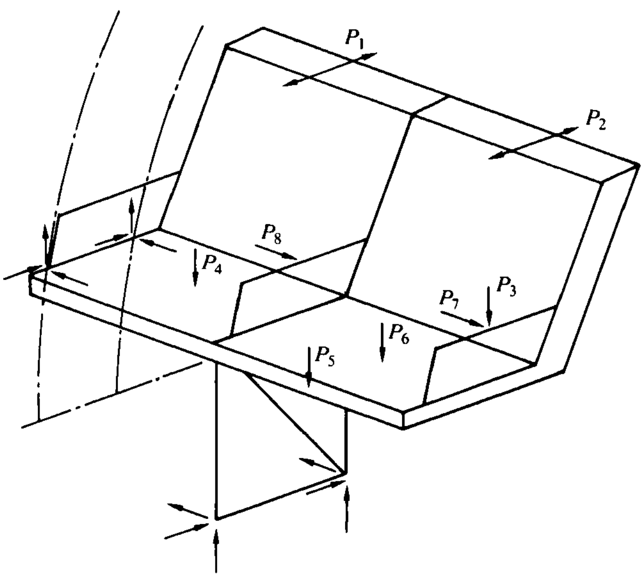


Fig. 3 Electric multiple unit door

An interesting variation to this approach has been introduced fairly recently in the Australian XPT, in which the outer skin is produced in the same way as that of the HST, after which foam slab stock is laid in the mould on top of the GRP and then the inner skin is simply formed on top of the foam. The main advantage in using this method lies in the fact that only one mould is needed and this can be light, since it does not have to withstand the pressure generated by the foaming process. Nevertheless, the inner skin may not be so precisely defined, which may pose problems when interior trim is being fitted.

Access doors at the front of Class 312 and Class 317 electrical multiple units also need high impact strength, although the requirement is not so stringent as that laid down for the HST cab. A composite design has been developed, which can be produced using a novel vacuum moulding process developed by British Rail (BR) (**3**). A moulded foam core is first manufactured as a single operation, following which it is encapsulated within the glass fibre reinforcement. Resin is then injected, using a vacuum, into a closed mould containing the glass foam pack. Substantial capital investment is not required for this process, which is particularly well-suited to BR production requirements in respect of items of this nature. There are doors currently in service which have been manufactured using this technique (Fig. 3).

The application of composites in this critical area has



Load, kN \ Load case	1	2	3	4	5	6	7
P_1	2.25						
P_2	2.25	2.25					
P_3			1.7				
P_4				1.7			
P_5					1.7		
P_6				1.7			
P_7						2.0	
P_8							2.0

Fig. 4 Design loads for the Advanced Passenger Train seat

been successful and it is encouraging to see design engineers prepared to adopt fibre reinforced plastics for such stringent performance conditions.

3 SEAT SHELLS

Designers began to appreciate the potential for composites in the manufacture of seat shells back in the 1960s and a free-standing GRP shell, upholstered with foam and covered with moquette, was developed for the experimental XP 64 coach (**4**).

It was possible to produce the curved shape as a single moulding, with a complete, finished surface; this was an important requirement as both sides would be visible to the public. The idea was to produce a light, robust, self-coloured seat which would be easy to install and which would not incur high fabrication and finishing costs. It is, therefore, hardly surprising that such widespread use has been made of GRP seat shells in both suburban and Inter-City stock.

Seating is one of the few applications of plastics in rolling-stock for which a relatively high volume output is required. For instance, a total of 140 000 second class GRP seat shells have been supplied for the Mark III build, which makes the use of hot press moulding techniques to produce the component from sheet moulding compound a viable proposition (**5**). The unavoidable high tooling costs incurred in using this production technique can be justified.

The second class APT seat is a good illustration of the use of GRP in this area. The shells are moulded individually and then bolted together at the rear, following which they are fixed, in pairs, to an aluminium pedestal in the centre. The inside seat is secured to the side of the vehicle. The design loads used in the structural analysis are given in Fig. 4. Here, a safety factor of 1.5 has been assumed. A finite element analysis was carried out in order to determine the optimum thickness for the shell. The end product weighs a mere 5 kg and costs approximately £9. The total weight of a pair of seats, including the frame and upholstery, comes to 26.5 kg. This seat design is likely to become the new standard for Inter-City stock in the next decade.

4 CARRIAGE DOORS

British Rail has nearly twenty-five years' experience with GRP doors, which have survived the rigours of service without serious damage. It would be difficult to calculate the exact number of GRP doors which have been installed, but the figure probably exceeds 60 000.

The introduction of large, wrap-around doors for Mark III stock marked a fundamental change in design. These new doors consisted of a jig-welded steel framework clad with a hand-laid GRP skin. The steel framework would take care of the loads whilst the GRP skins constituted, in effect, a weatherproof cladding and had no structural function whatsoever. This approach was subsequently adopted for Mark III stock.

Doors produced to this design have performed satisfactorily in traffic, but are heavy (58 kg) and relatively expensive to produce. The same structural performance could probably be attained through more effective exploitation of the composite's structural properties in order to dispense with the need for a jig-welded framework, thus giving a lighter door. Production costs could possibly be reduced even further by the use of more efficient manufacturing methods.

Since the door had to match the overall profile of the vehicle there was no question of altering its shape, but this was not a serious constraint. A number of load conditions were specified, the worst being 44 MPa evenly distributed over the inside of the door. This represents the crash loading situation with ten passengers in the vestibule and the coach on its side.

The final design proposal consisted of two GRP skins moulded separately, using cold press moulding (**3**); these were bonded together, using a gap-filling adhesive. Blocks of rigid polyurethane foam had to be incorporated in three corners in order to give the box section increased torsional stiffness. These blocks were bonded to both skins in order to give an integral structure.

Laboratory tests have confirmed the results of the structural analysis and have demonstrated that the new design will satisfy the performance specification. The end product weighs only 38 kg, 20 kg less than the original item. It has been estimated that production costs could be reduced by approximately £100. Prototype doors to this design are currently undergoing service trials.

5 FREIGHT APPLICATIONS

Unlike the passenger market, the freight business has seen relatively little penetration by composite materials,

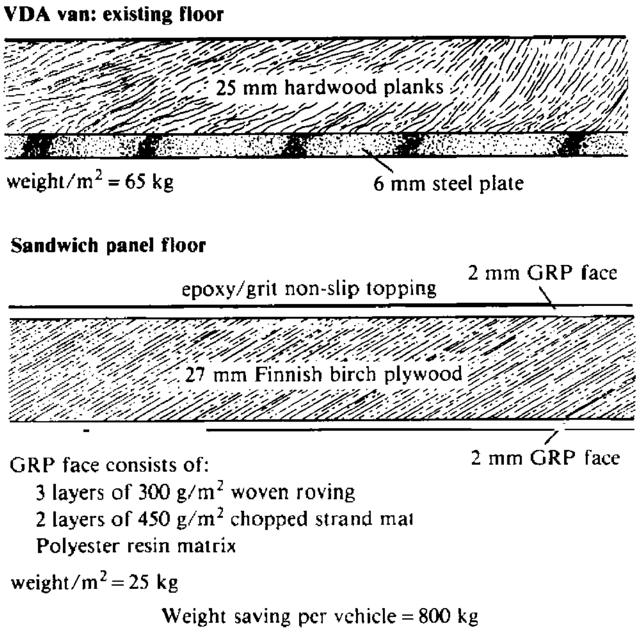


Fig. 5 Sandwich floor construction for freight vehicle

possibly since the benefits of light-weight construction are less significant in freight stock. Energy costs are, however, a matter for increasing concern and engineers are becoming more and more aware of the need to offer freight operators lighter vehicles capable of carrying heavier payloads. There is, therefore, every chance that increased use will be made of composites in this area.

A number of attempts have been made at using GRP in the manufacture of freight stock. During the 1960s, a prototype freight car was produced in North America (**6**) and BR developed an experimental monococque container based on a GRP/polyurethane foam sandwich structure. These were not, however, competitive on a first cost basis, and the ideas were dropped.

Composite technology has progressed since those early experiments and our understanding of the structural capabilities of these materials has improved. Manufacturing technology has also advanced and we would, therefore, expect composite designs to become more economically viable.

The manufacture of GRP tanker barrels using the filament winding process looks an attractive proposition. This is a technique which can be automated in full, thus giving reduced labour costs to offset the higher material costs. There is, at present, a prototype hopper wagon, manufactured using this process, undergoing extensive service trials in North America (**6**). GRP offers a number of benefits which merit consideration:

1. *Weight savings* Recent BR studies indicate a possible saving of 50 per cent.
2. *Low thermal conductivity* In tests organized by the Ministry of Defence (**7**), GRP tankers performed far better than their steel and aluminium counterparts in a fire engulfment situation.
3. *Resistance to corrosion* This eliminates the need for stainless steel or special linings.

There is bound to be increasing interest in GRP rail tankers, and satisfactory designs will become available within the next decade.

One area in which there is currently much activity is the use of composite floors for conventional covered wagons (e.g. VGA and VDA). The authors have recently completed a design study to assess the potential in this area, based on the loading requirements laid down in BS 3951. The recommended design uses a timber core with GRP faces, giving a saving of 800 kg per vehicle (Fig. 5). Costs are estimated at approximately £200 higher (at 1983 prices), but this is more than offset by the increased payload which is offered. In addition, the composite floor can be reversed, thus giving an increased working life and reduced replacement costs. This application is an interesting example of the combination of modern (GRP) and traditional (plywood) composite materials.

A VGA van has recently been fitted out with this new type of flooring and will be assessed in service trials.

6 OVERHEAD STRUCTURES

Accidental damage to overhead electrification structures can lead to serious disruptions to traffic and, in certain circumstances, to complete blockage of the line. Where this occurs, it is imperative that the line be re-opened to traffic with the minimum of delay, which means that some form of temporary structure is needed to support the overhead line equipment until a more permanent structure can be erected. A temporary structure will be required to satisfy all the usual loading conditions and to come up to all the standard safety requirements. Such structures need to be easy to handle for conveyance to the site and for erection on site with the minimum amount of lifting gear. Ideally, equipment of this type needs to be of a light-weight, modular design suitable for use in any of the different situations which can arise in practice. It is helpful if single modules are light enough for one man to carry.

The use of a GRP lattice structure (Mathweb) seems to satisfy many of these requirements. These structures are produced from continuous glass fibres impregnated with resin and arranged in an open, lattice form (**8**). They have a high strength-to-weight ratio (Table 1) and excellent resistance to corrosion. Preliminary experiments have shown this system's potential in a tower and in a portal spanning three tracks (**8**). Since manufacturing jigs were readily available, a triangular section was used for these experiments.

A more detailed study is being carried out for a four-track portal with a width of 18 m and a height of 9 m. A typical loading case is shown in Fig. 6. Vertical deflection has been limited to less than 150 mm. A rectangular 500 × 300 mm section was selected, each 3 m module weighing 30 kg. The structure can be winched into position manually and finally guyed along the track (Fig. 7). This experimental structure was positioned by four men in under two hours.

Static load tests have been carried out in order to simulate the various load cases; results tie in well with predictions. A series of site trials are being arranged in order to allow this novel system to be assessed under real-life operating conditions.

Glass reinforced plastic Mathweb portal costs are comparable with those for current fabricated steel structures. These portals may also be suitable for

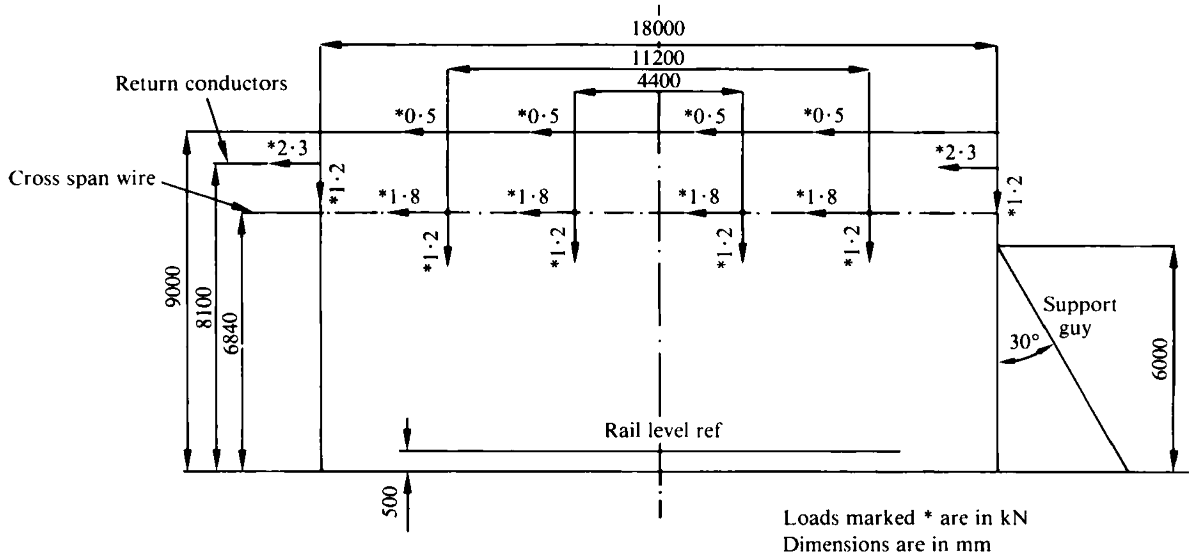


Fig. 6 Typical loading case for overhead structure

Fig. 7 Experimental temporary overhead structure

permanent applications. According to the estimates, the weight of a permanent Mathweb portal would be only 25 per cent of that of an equivalent item in steel, coupled to which there would be scope for significant installation cost savings. GRP does not corrode, which means that little maintenance would be required. At present, fabricated steel structures are painted every seven or eight years.

Clearly, there are strong indications that composite structures of this type can offer significant advantages over steel structures for long-term applications. Such structures may also be suitable for other areas such as signal gantries and lighting towers.

7 FUTURE DEVELOPMENTS

Up to this point only composites based on glass fibre reinforced polyester or epoxy resins have been discussed. Composite technology has advanced considerably during recent years and it is, therefore, appropriate that the potential for alternative materials within the railway industry should be examined.

The introduction of high-strength and high-modulus carbon fibre reinforced plastics (CFRP) in the 1960s created considerable interest in the potential for these light-weight materials in high-performance applications, but in view of the continuing high cost of this fibre, this interest has not been sustained outside the aerospace and leisure industries. Furthermore, design engineers have learned how to make more effective use of glass fibre reinforcement and this has, in certain instances, eliminated the need to consider CFRP. Aramid fibres have also entered the market, with costs pitched between those for glass and carbon fibres; these fibres are, however, like CFRP, used mainly in aerospace and leisure applications.

Carbon fibre reinforced plastics and aramid reinforced plastics (ARP) are of interest since they combine high strength with high stiffness and a light weight (Table 2). Thus, energy costs can, in principle, be reduced through the greater use of these materials in rolling-stock. However, the cost benefit of energy savings associated with reduced weight are about £2500 per tonne. CFRP and ARP first costs are high, which means that there

Table 1 Physical and mechanical properties of various materials

Material	Tensile		Compressive		Flexural		Impact strength*	Density	Coefficient of linear expansion	Thermal conductivity
	Strength, MN/m²	Modulus, GN/m²	Strength, MN/m²	Modulus, GN/m²	Strength, MN/m²	Modulus, GN/m²	kJ/m²		10⁶/°C	W/m°C
Mathweb element†	500–800	25–35	400	32	715	26	300	1.9	10	0.3
Chop-strand-mat, GRP	100	9	150	7	200	6	60	1.7	25	0.2
Mild steel	450	210	450				100–250	7.8	12	46
Aluminium	260	70	84				30	2.7	23	160
Timber	75	10						0.5–1	4–50	75

† Glass weight 50 to 65 %. * Notched Izod impact test.

Table 2 Mechanical properties of various materials

Material	Specific gravity	Tensile modulus, GPa	Tensile strength, MPa	Specific modulus GPa	Specific strength, MPa
CFRP: type 1 carbon	1.62	186	1330	115	820
CFRP: type 2 carbon	1.53	128	1560	84	1020
CFRP: type XAS carbon	1.5	128	1900	85	1270
GRP	2.1	39	850	19	405
ARP	1.35	74	1270	55	940
Aluminium HE 15 WP	2.8	69	450	25	160
Steel BS 4360 grade 55	7.8	207	625	27	80
*Pure titanium 130	4.54	116	540	26	118
*Titanium alloy 679	4.4	110	1030	25	234

* ICI designations. Volume fraction ~60%.

is not a strong case, in terms of economics, for using these materials in railway applications.

Reductions in unsprung mass are also important considerations, but there does not seem to be any satisfactory technique available for calculating possible cost benefits. It is, therefore, difficult to assess the economics of composite components designed to give reduced unsprung mass.

A number of experimental composite components have been produced with a view to reducing the unsprung mass in wheelsets (**9**), in pantographs (**10**) and in bogies (**11**), but none have passed beyond the development stage. Prototype CFRP axle tubes for the APT-E were tested in the laboratory. The mass of these items was about 30 per cent of that of their steel equivalents; furthermore, static and fatigue design requirements were satisfied, but the composite tubes' impact strength was not acceptable for this application. Significant increases in fracture toughness have been achieved by coating the carbon fibre, using an electro-polymerization technique (**12**), as shown by the results set out in Table 3.

It appears that some of the technical limitations of CFRP can be overcome, in principle, but the economic disadvantages still remain, and are likely to continue to do so in the immediate future.

Experimental ARP pantograph heads have been evaluated in service trials. These composite heads were lighter than their conventional counterparts and gave improved dynamic performance. Carbon collector wear rates were also reduced significantly, but the composite sustained severe damage as a result of arcing under severe winter conditions. The use of composites in the main frame of pantograph assemblies looks a more attractive proposition, since the material would not then be subjected to this arcing problem.

Applications of fibre reinforced plastics in bogie construction are being developed in Germany (**11**) and investigations are in hand in the UK. The purpose of these studies is to reduce bogie mass and, hence, to improve dynamic performance, reduce energy costs and minimize the amount of track damage caused by unsprung mass. Composites are being used more widely nowadays at stress levels associated with bogie applications and an assessment of their potential in this critical area is feasible. A composite bogie frame could incorporate the primary suspension. Preliminary studies indicate that first costs would be competitive, but fresh design concepts will be needed if the full potential of composites is to be achieved in this application.

Fibre reinforced plastic components developed for applications in the passenger environment on British Rail have been based on polyester matrices in nearly all cases. Safety in the event of a fire is absolutely vital and the current philosophy is to specify materials which are difficult to ignite and which are self-extinguishing, with a low spread of flame. Resins have been developed in collaboration with the raw material suppliers in order to meet these requirements. At present, there are no smoke emission requirements in fire specifications, but future developments will consider this aspect of fire safety. Certain underground railway authorities are already including smoke generation in their material specifications, e.g. London Transport, the New York Subway.

Phenolic resins with far better fire resistance properties are now becoming available for use in conjunction with glass fibre reinforcement. These resins develop a great deal less smoke than polyesters and may well replace these, in the long-term, in GRP components for passenger rolling-stock applications. Suitable manufacturing techniques will, however, have to be developed

Table 3 Mechanical properties of CTBN coated carbon fibre

Coating thickness*, μ	0	0.05	0.4	0.5	0.6	ca 3.5	ca 5
G_C parallel to fibres (DCB), kJ/m^2	0.17	0.85	0.86	1.02	1.33	1.90	9.3
G_C transverse to fibres, kJ/m	29	42	—	34.47	56	—	—
Interlaminar shear strength, MPa	90	65	58	41	30	28	26
Incremental drop weight energy, J	1.75	33	51	55	77	—	—

*Thickness estimated from kinetic experiment. Volume fraction ~50%.

and the long-term mechanical properties of these composites will have to be established before they are widely accepted. Phenolic resins are cheaper than polyesters, but this will be offset by increased production costs. Thus, the final item costs will be similar.

Reinforced reaction injection moulding (RRIM) of polyurethane foam components for panelling etc. has come into increasingly widespread use in recent years, particularly in the automotive industry (**13**). This process involves the mixing of reactive liquids and reinforcement followed by injection into a closed mould, wherein foaming and curing take place. The main advantages of this technique are high production rates coupled with relatively low capital costs. There would appear to be a certain amount of potential for this technique in the manufacture of interior panels in passenger rolling-stock, such as ceiling panelling, walls, partitions and flooring.

Polyurethane composites would not be acceptable for railway applications in view of the fire hazard, but glass reinforced phenolic foams would be satisfactory. Current RRIM processes are not appropriate on account of the high viscosity of phenolic resins, but new techniques are being developed to handle this material.

Phenolic foam composites can be tailored to meet the differing mechanical properties required for each application and significant cost savings can be achieved. It is estimated that the aluminium honeycomb ceiling panels used for certain multiple unit refurbishment schemes (**14**) cost twice as much as phenolic panelling of equivalent weight (density 0.25 kg/m^3). Components could be designed to incorporate ducting for air conditioning etc., thus making for simpler assembly. Clearly, there is significant potential for this type of composite.

The vast majority of plastic composites have been based on continuous or long fibre (> 25 mm) reinforcement in a thermosetting resin. Fibre reinforced thermoplastics have short (< 1 mm) fibre reinforcement and applications in the railway industry have been insignificant on account of the high tooling costs, poor physical properties and relatively poor performance at high temperatures. Recently, Kelly (**15**) has been studying the possibility of using these materials for gears and has concluded that this is feasible for applications up to 10–15 kW. The temperature range can also be extended through the use of newer engineering plastics such as polyethersulphone and polyetheretherketone. Kelly has also shown that although the tooling costs associated with injection moulding are high it can provide a significant cost advantage compared with steel, and that provisioning can be improved as well. Prototype gears based on carbon fibre reinforced polyethersulphone are being assessed in the laboratory.

8 CONCLUSIONS

1. Fibre reinforced plastics offer numerous advantages, including:
   (a) design flexibility;
   (b) good performance, specifically its strength-to-weight ratio;
   (c) a good fatigue life;
   (d) good tooling and production techniques and
   (e) cost effectiveness.
2. British Rail has a proven record in the use of FRPs over the past twenty years. The full benefits of the production techniques and of the performance offered by FRPs were recognized at an early stage.
3. The materials have been developed rapidly, but testing and production design criteria within the plastics industry have not, however, kept pace. This position is now being rectified.
4. With the advent of mathematically based design criteria, the use of FRP in structural applications will increase.
5. Increasing use will be made of high-performance fibres and resins in demanding service environments, which will make these materials more and more competitive.

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