Carbon fibre and glass fibre hybrid reinforced plastics

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A review of the literature on carbon fibre and glass fibre hybrid reinforced plastics is presented. There are indications that the incorporation of both fibres into a single matrix sometimes leads to better properties than would be expected from consideration of the rule of mixtures. The incorporation of glass fibres in cfrp appears to improve impact properties and to increase the strain to failure of the carbon fibre in tension. The addition of carbon fibres to the surface of grp beams markedly increases the flexural modulus. A system of nomenclature for the diverse types of hybrid composite lay up is proposed.

The incorporation of two or more fibres within a single matrix is known as hybridisation and the resulting material is generally referred to as a 'hybrid' or 'hybrid composite'. A variety of reinforcing fibres and matrices are used to form hybrids, but this review deals solely with carbon fibres and glass fibres in a polymeric resin matrix. Carbon fibres provide a strong, stiff and low density reinforcement but are relatively expensive, while glass fibres are relatively cheap and have better fracture strain and fracture stress but lack stiffness. By combining the two fibres within the same resin matrix it is possible to achieve a balance between the properties of all-carbon fibre reinforced plastics (cfrp) and all-glass fibre reinforced plastics (grp); as knowledge of hybrid systems progresses it will be possible to design the material to suit particular requirements, especially where properties are required which differ with the direction of the material.

The existence of composites of hybrid construction with properties better than the sum of the components, the 'hybrid effect', is still controversial.[1] The lay-up of hybrid composites is almost exclusively such that the fibre sequences are symmetrical with respect to the neutral axis, otherwise thermal contractions would lead to bending-stretching coupling and cause undesirable warping.[2]

Several forms of hybrid construction can be identified,[61] and these are principally;

(a) those in which the two fibres are intimately mixed throughout the resin, with no intentional concentration of either type of fibre;

(b) those in which the material is formed as discrete layers of a mixture of the individual fibres, for example by the use of hybrid tapes (see Fig. 1) which may be woven or knitted from the constituent fibres;

(c) those in which each layer is a sequence of plies, each of a single type of fibre, mirrored by the neutral axis of the composite;

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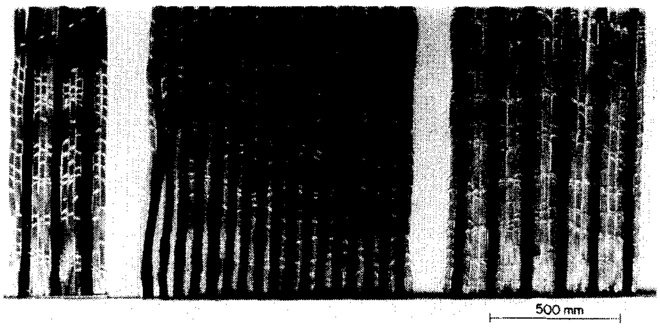

Fig. 1 Examples of hybrid tapes (Ministry of Defence photography)

(d) a specialisation of the type (c) in which the core of the composite is composed entirely of one of the constituent fibres, and the shell (outer ply) is of the second fibre. This is commonly referred to as the sandwich composite;

(e) a further refinement of type (c) in which stiffness is achieved by a selectively positioned carbon fibre web, or rod, on a continuous grp base.

In all cases the resulting material is anisotropic, and the properties are dependant on the constituent materials and on the structure of the component due to the lay-up sequence The matrix resin is generally an epoxy, although Harris and Bunsell[3] and Dukes and Griffiths[4] have used polyester, and Golding[5] and Marshall[6] used Derakane 411-45 vinyl ester.

APPLICATIONS

One of the earliest reports of the use of both carbon and glass fibres in the same matrix was for the Ford GT40 racing car body in which the use of 1.4 kg of a carbon fibre web allowed a reduction of the weight by 27 kg to only 42 kg, yet simultaneously increased the stiffness and so maintained the aerodynamic shape at high speed, eliminated roof vibration and 'drumming' and increased the life of the car body.[7,8] The Morris Nunn Ensign MN01 Formula One racing car has a grp body stiffened by Grafil ribbon.[9]

The torsional stiffness of the rotor blades in the Aerospatiale SA360 helicopter is provided by a structural skin of carbon fibre over a glass and carbon fibre framework[9,10] (Fig. 2).

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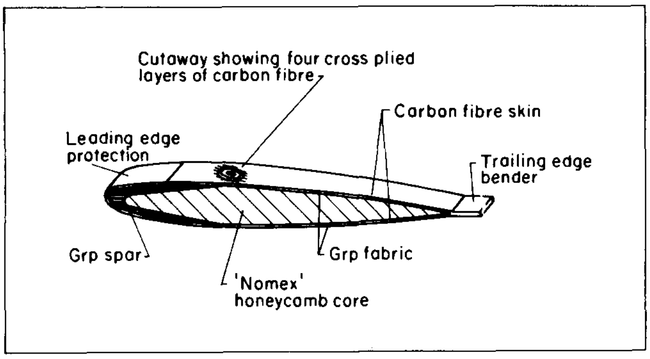

Fig. 2 Grafil carbon fibre reinforced blade construction of the Aerospatiale SA 360 helicopter (see also *Composites* 4 No 5 p 144)

Fig. 3 The Saab MFI 15/17 trainer and multi-role light support aircraft; Grafil carbon fibres, in a knitted glass fibre ribbon, have been used in the engine cowling and wing tips, resulting in substantial weight savings (see also *Composites* 4 No 5 p 194)

Fig. 4 Pentti Fabritus during the World Record Power Boat Drive in Tampere, Finland in October 1972; the grp hull is further reinforced with a knitted hybrid ribbon (see also *Composites* 4 No 2 p 52)

A twin beam composite helicopter rotor blade has also been reported by Salkind.[58] Knitted hybrid tape is used in the engine cowling and wing tips of the Saab-MFI 15/17 trainer and multi-role light support aircraft, resulting in substantial weight savings[59] (Fig. 3). Aeromodellers have also realised the benefit of mixed fibre structures and a fuselage[11] and propellor[12] have been reported.

The use of carbon fibres in large grp structures has been proposed[13] as a means of accelerating the cure by electrical resistive heating, and further applications such as domestic heated water tanks are also suggested. Use of carbon fibres in grp parts (used a replacement for metal parts) can restore some of the electrical properties sacrificed by the change.[61]

Tentative proposals for the use of mixed fibres in boat constructions were discussed as early as 1969,[14] but it was not until 1972 that the advantages were practically demonstrated by the West German four man sculling team at the Olympics. They won a gold medal in a boat equipped with oars and sculls of lightweight construction, strengthened and stiffened with a knitted Courtaulds hybrid tape.[15] Also in 1972, hybrid ribbon made possible a 30% saving in the shell weight of the Avenger 21 power boat,[16] and helped to achieve a new world record for power boat drive with a flying start,[17,18] by P. Fabritus (Fig. 4).

The following year Chay Blyth's yacht 'Great Britain II' was launched and the use of mixed fibre fabric in the reinforcement was claimed to increase hull-life because of reduced vibration with only minimal weight increase.[19] The worlds largest grp ocean racing catamaran 'British Oxygen' was launched in 1974 with 'Carboform' hybrid tape stiffening the hull and nacelle mouldings,[20] and in her first major test she came in ahead of the field in record time, despite encountering force eight gales, to complete the 1900 mile Round Britain Sailing Race.[21] A brief outline of the design considerations and construction details of the EP46 sailing sloop has been reported.[22]

The top hat section frames[23] of the grp minehunter 'HMS Wilton' used only a few percent of carbon fibres in a woven roving polyester composite to increase stiffness. Three percent of carbon fibre was found to double the modulus of the laminate and introduce a pseudoyield behaviour,[4] but because of the high labour costs a considerable expenditure on carbon fibre did not markedly increase the cost.[24]

IMPACT BEHAVIOUR

It is generally agreed that the impact behaviour of cfrp is improved by the inclusion of a percentage of strong fibres with a greater strain to failure than carbon, and Hancox and Wells[25] have suggested that E-glass, S-glass and Kevlar 49 are suitable. Simon,[26] Hancox and Wells[27] and Chamis et al[28] have conducted Izod impact tests, Bradshaw et al[29,30] used dropweight tests and Simon[26] has also devised an impact test in which NOL rings are moderately impacted and then tested for compressive strength. Adams[31] and Adams and Perry[32] have presented scanning electron micrographs of the failure surfaces of impacted specimens.

The properties of the constituent materials and the lay-up sequence determine the mode of failure, but several energy absorbing mechanisms have been proposed[5,29,30,33,35,36] notably the tensile modes:

- cleavage of the resin parallel to the fibres
- cracking of the resin transverse to the fibres
- debonding of the fibre from the resin
- delamination of the plies, dependent on lay-up sequence
- fibre pullout
- filament fracture,

and the compressive modes:

- ply buckling
- fibre microbuckling
- shear crushing

Glass fibre cloths were used as the reinforcement instead of uni-directional fibres in some tests.[32,33,34] The improved impact resistance of cfrp due to the addition of glass fibres has been attributed to the increase in the area of new surface created by the increased number of fracture modes[29,30] and to the increased capability to store strain energy in a glass fibre core in a sandwich composite.[29] Golding considers the fibre pullout mechanism to be the dominant contributor to hybrid toughness, but Novac et al[36] consider the stress/strain behaviour of the reinforcing fibre as the most important factor. Notched impact specimens are reported to behave almost independently of notch dimensions,[3,37] although Golding[5] has observed changes in the failure mode related to notch characteristics. Doubts have been cast on the influence of specimen geometry[5,33] and on the rate of impact.[33]

Bradshaw et al[29,30] consider the toughness of the resin matrix to be insignificant, but feel that a stronger resin matrix with a stronger bond would be beneficial. Hancox and Wells[27] have reported an increase in impact energy by a factor of 2.5 for ERLA 4617 epoxy resin and by a factor of 5.0 for DX 209 epoxy resin on changing from an all-carbon composite to a 50 : 50 carbon: glass sandwich structure, but they found no change in the energy level at which initial damage occurs. The range of values obtained by workers in this field is shown in Figs 5 and 6.

COMPRESSIVE PROPERTIES

A marked increase in the compressive modulus is reported to result from only a small addition of carbon fibres to grp.[4,38] Kalnin[38] further reports non-catastrophic failure consisting of progressive debonding of both fibres from the matrix, followed by cumulative local buckling of the graphite with a consequent decrease in the load carried. The modulus of glass rich hybrids was found to be much better than that predicted by the law of mixtures, the initial modulus remaining constant to only 0.15% strain after which a progressively lower secondary modulus is observed up to maximum load, which results from delamination. A rapid decrease in first fracture strain follows from incorporation of carbon into grp. Perry and Adams[37] have examined the compressive strengths of a variety of fibres in hybrid composites. Youngs modulus in compression[4] was found to double with the addition of only 4.7% of carbon fibres to 50% weight fraction grp. The range of values reported is shown in Figs 7 and 8.

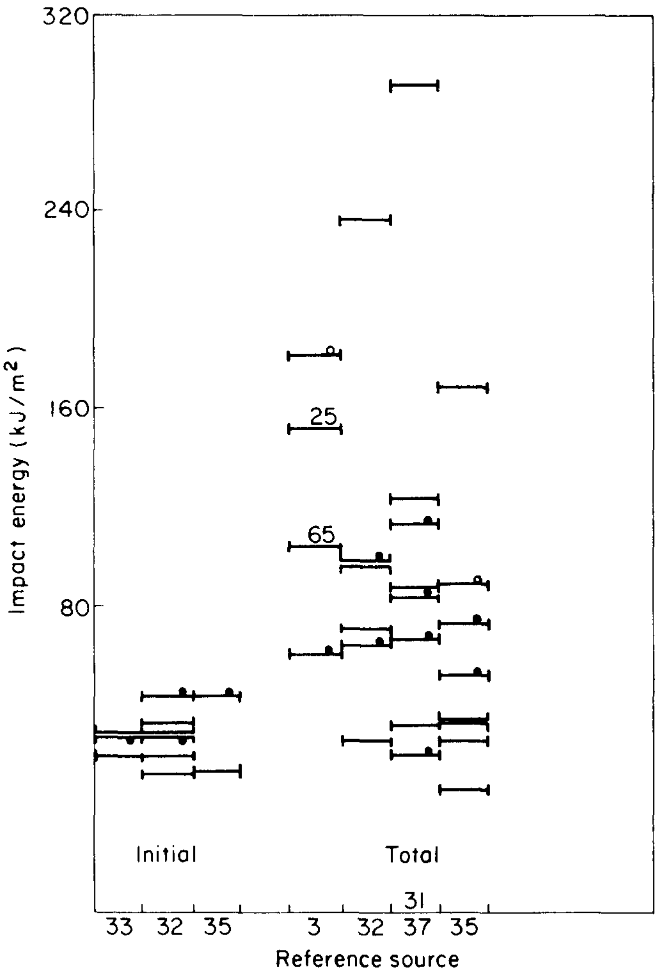

Fig. 5 The range of values reported for impact energy using the Charpy test; a solid circle indicates a value for an all-carbon composite and an open circle indicates a value for and an all-glass composite, where a number occurs this shows the volume percentage of carbon fibres in the composite relative to the sum of the carbon and glass fibres; the number at the foot of each column indicates the source of reference; the components and lay-up sequences are listed in Table 1

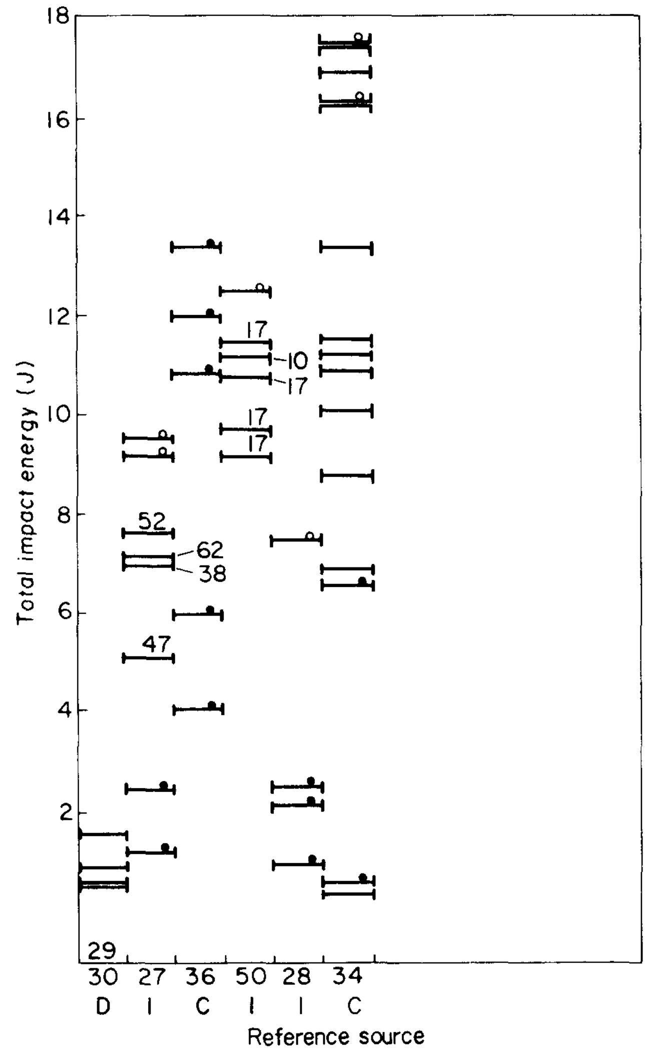

Fig. 6 The range of values reported for total impact energy (C = Charpy test, D = dropweight test and I = Izod test), (solid circle = all-carbon composite, open circle = all-glass composite; where a number occurs, this indicates the percentage of carbon fibres in the composite)

TENSILE PROPERTIES

In tension, hybrid composites perform in a manner similar to that when in compression and failure is again non-catastrophic with the transfer of load to the glass fibres on failure of the carbon fibres.[38] The initial Youngs modulus[47] shows a remarkable linear increase (Fig. 9) with the addition of carbon fibres to grp and a progressively lower secondary

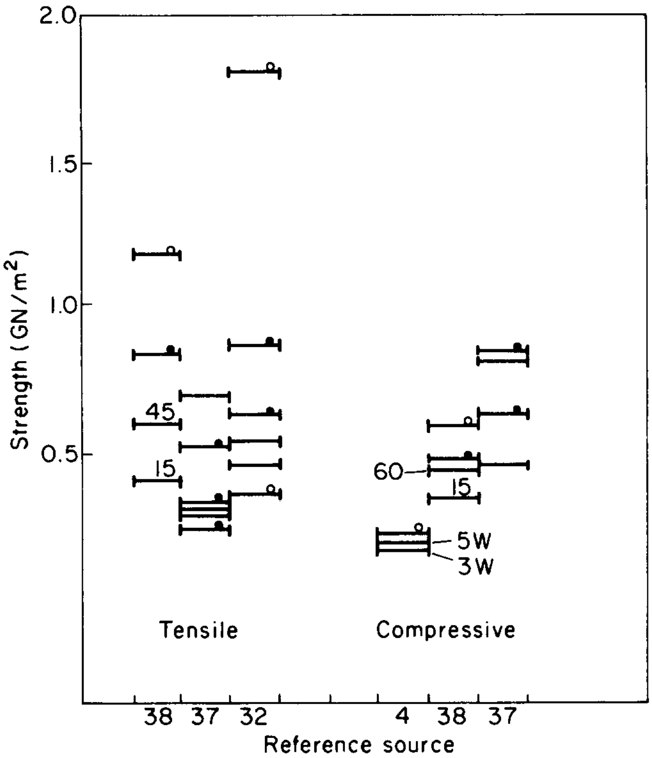

Fig. 7 The range of values reported for tensile and compressive strength (solid circle = all-carbon composite, open circle = all-glass composite, where a number occurs, this indicates the percentage of carbon fibres in the composite), the data from Reference 4 are weight percentage since absence of density data made conversion to volume percentage impossible

modulus after failure of the carbon fibres. Dukes[4] reports that there is no change in the stress level at ultimate failure relative to a glass-only composite but Kalnin[38] reports a linear increase in fracture stress and initial modulus with increasing carbon content. The tensile modulus of glass rich hybrids is found to exceed the value predicted by the rule of mixtures,[38] an increase of 5% by weight of carbon fibres increases the tensile modulus by 100% with an estimated 50% of the load carried in the carbon fibres.[4] Transfer of load to the glass fibres on failure of the carbon produces a net loss of stiffness, and at higher carbon fibre contents (10% by weight) redistribution of the load occurs too rapidly and the glass fibres fail with no rapid increase in strain. The fracture strain due to the addition of high modulus graphite to grp is reported to be reduced by a factor of ten by Kalnin,[38] but to increase linearly with the increasing carbon content according to Hayashi.[39]

The retardation of failure in the carbon composites is attributed to the greater ductility of a grp matrix relative to a resin-only matrix.[39] Bunsell and Harris[40] reconsidered this result using hybrids in which alternate layers were either bonded or not bonded to one another. Initial fracture was similar in both cases, but in the bonded hybrid the carbon fibre continued to carry load and contribute to stiffness until final failure, which occured at lower extension than in the unbonded or all-grp specimens. It was suggested that extension only takes place in the regions of grp adjacent to the fractured cfrp. Zweben[57] has presented a theory to attempt to explain the 'hybrid effect' and re-examines the above results further within his report.

Aveston and Sillwood[41] proposed that the failure strain of a brittle fibre can be increased if the reinforcing matrix remains intact at the normal fibre failure strain, with sliding frictional bonds leading to higher values, and confirmed this

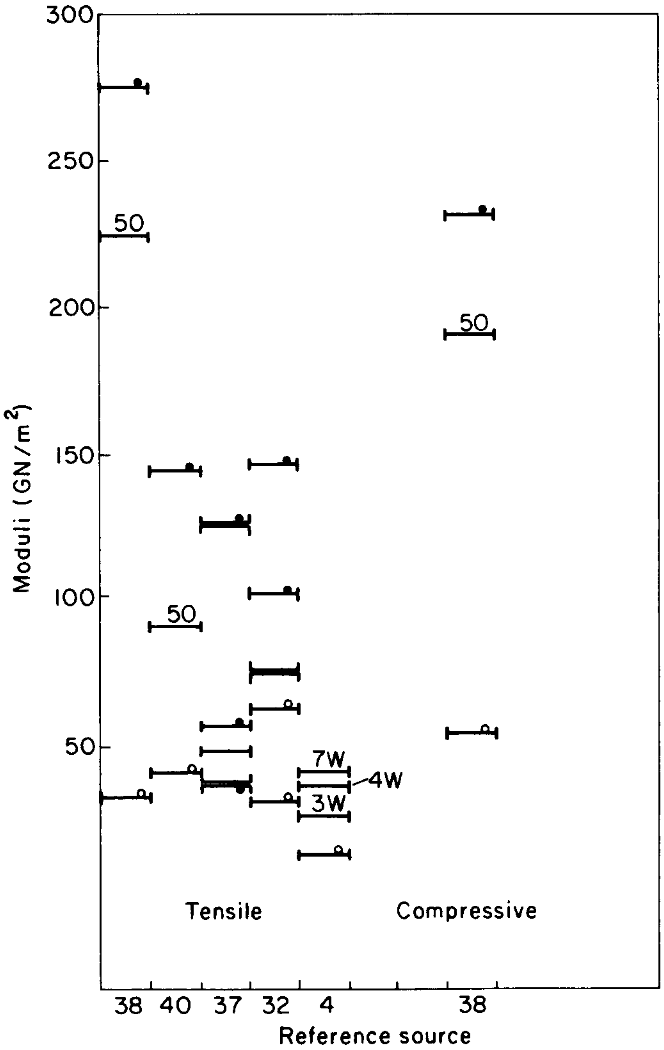

Fig. 8 The range of values reported for tensile and compressive moduli (solid circle = all-carbon composite, open circle = all-glass composite, where a number occurs, this indicates the percentage of carbon fibres in the composite)

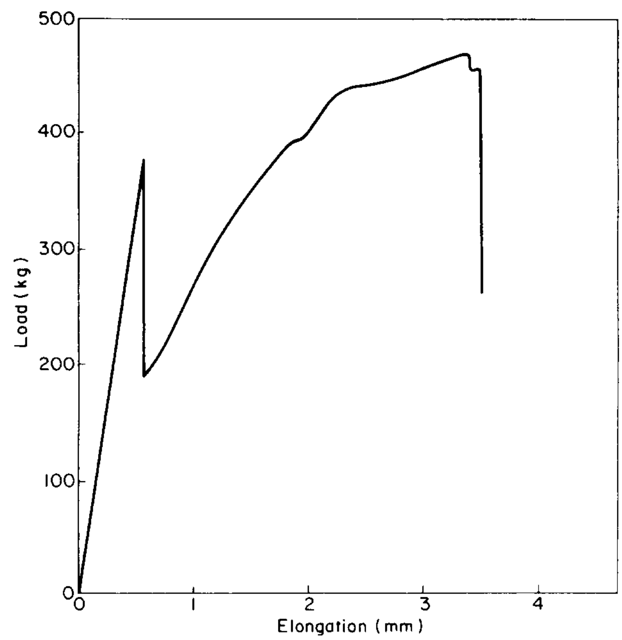

Fig. 9 An example of the load versus elongation plot for a hybrid composite with 40% by volume of carbon fibres in an epoxy resin matrix (from Fujii and Tanaka[47]), solid circle = all-carbon composite. open circle = all-glass fibres in the composite)

in carbon/glass hybrids to an increased failure strain of around 1%, with crack propagation restrained by the glass fibres.

Better load distribution is provided by uniformly distributed interply hybrids than by core-shell systems,[42,43] and this also overcomes the modulus mismatch across the core shell interface which causes high interlaminar shear stresses and early failure. Skudra et al[44] have proposed a mathematical function relating the ultimate deformation of hybrid composites to the proportion of each type of fibre and calculate from it a critical glass fibre content which defines a change in failure mode. Rao and Hofer[43] believe that optimum performance occurs with the glass to carbon ratio between 0.5 and 2.0. The range of values reported is shown in Figs 7 and 8.

FLEXURAL PROPERTIES

In all cases where the test rig is specified, the flexural testing was carried out on a three-point bend rig. Miyairi et al[51] have reported a substantial increase in the flexural strength of grp when laminated with cfrp and have developed a beam theory approach which predicts these flexural properties. The fracture modes of the hybrid composites differ from those of the all-glass core materials with brittle failure across the carbon fibres in hybrids with glass mat cores and a zig-zag fracture surface in hybrids with glass cloth cores. Core-shell hybrids and basic I-section grp reinforced with cfrp at the extremes show a significant increase in bending stiffness relative to alternate ply hybrids with a consequent increase in buckling load[52] and these lay-ups are thus very attractive for structural components when stressing is essentially flexural.

Hancox and Wells[50] have studied beams with pultruded carbon fibre rods placed symmetrically about the neutral axis of a grp beam and found that the flexural stiffness increased with the number of reinforcing rods and that failure was non-catastrophic, but the overall flexural strength at which the reinforcement failed was lower than that of a grp composite. Wells and Hancox[48,49] have also studied sandwich beams with a core of 'Flomat' glass, unidirectional glass fibre with glass spheres, and with 50% volume of carbon fibre composite the flexural modulus was equivalent to 90% of the value for an all-carbon fibre beam. With 25% of carbon fibre in a similar sandwich beam the transverse flexural strength and modulus are nearly double those of an all-carbon composite due to the reinforcement in this direction provided by the 'Flomat' core. Failure was at the top face by compression, followed by debonding between the core and the carbon fibre layers or by debonding at either interface when the carbon fibre composite is present as less than 30% by volume.

Marshall,[6] using hybrid tapes in a vinyl ester matrix, found an increase in flexural properties with increasing carbon fibre content, and also that the rule of mixtures underestimated the first fracture stress. He suggests that the retardation of failure of the hybrid composite is due to the stiffer glass fibre-resin matrix relative to an all-resin matrix. The resin matrix is reported to have equivalent or better performance than conventional epoxy resins with good adhesion to both fibres. A photomicrograph of the composite reveals that the carbon fibre tows adopt a trapezoidal cross section in the moulding stage (vacuum-box technique) and hence interlock more efficiently with the glass fibres.

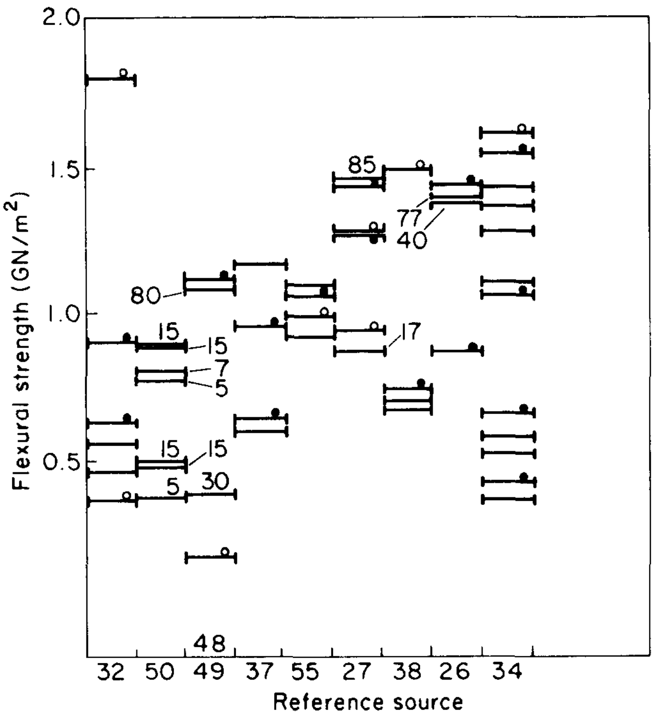

Fig. 10 The range of values reported for flexural strength (solid circle = all-carbon composite, open circle = all-glass composite, where a number occurs, this indicates the percentage of carbon fibres in the composite)

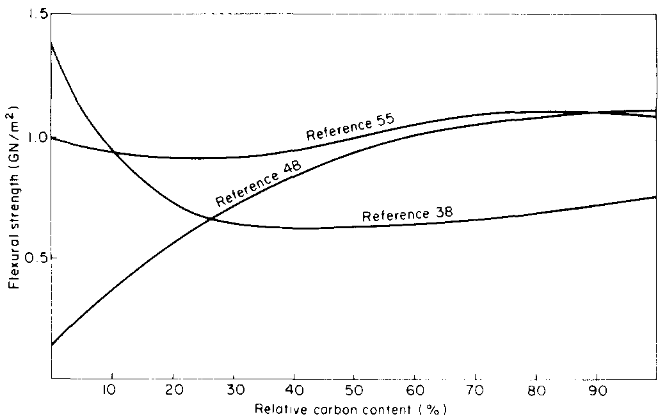

Fig. 11 A comparison of reported flexural strength curves with respect to the relative % graphite content: 38 Kalnin — unidirectional type C and type D hybrids; 48 Wells and Hancox — Flomat core sandwich beams; 55 Shimamura and Furue — unidirectional B type hybrid

Dukes and Griffiths[4] reported a significant increase in flexural modulus from 13.9 GN/m^2 in an all-glass fibre composite to 59.7 GN/m^2 in hybrid material at only 7.2% by weight of carbon fibres with the carbon fibres in the second layer from each surface in an eight-ply unidirectional laminate. Kalnin[38] experimented with a range of fibre ratios in a 12-ply composite with various symmetrical lay-ups, relative to the neutral axis, and approximately 65% by volume of reinforcing fibres. A rapid decrease in flexural strength is reported on addition of carbon fibres to grp composites, followed by an almost constant flexural strength when at least 20% by volume of the reinforcing fibres are carbon. The flexural modulus was found to obey the rule of mixtures when the composite was alternately plied, but with a wide scatter at any single carbon volume fraction depending on the lay-up sequence. (See Figs 10, 11 and 12.)

INTERLAMINAR SHEAR STRENGTH

Wells and Hancox[48,49] conducted tests on a sandwich beam of carbon fibre unidirectional sheets surrounding a 'Flomat' core and found that shear failure in the region of the neutral axis occured up to a span to depth ratio of 4.5 to 1, when the carbon/glass interface bond was good. The results are essentially independent of the carbon fibre volume fraction and occur as a scatter around the average value for the core alone. Hancox and Wells[50] also used pultruded rods set in the surface of grp beams with a span to depth ratio of 5 : 1. The interlaminar shear strength for these beams lay between 63 MN/m^2 and 74 MN/m^2 relative to 72 MN/m^2 in an all-glass composite, and failure was invariably due to multiple shear in the glass composite. Kalnin[38] found an increase in horizontal short beam shear strength at room temperature with decreasing carbon content. At 150°C however, the shear strength remained constant and it was therefore suspected that it was being dominated by the resin properties, (see Fig. 13).

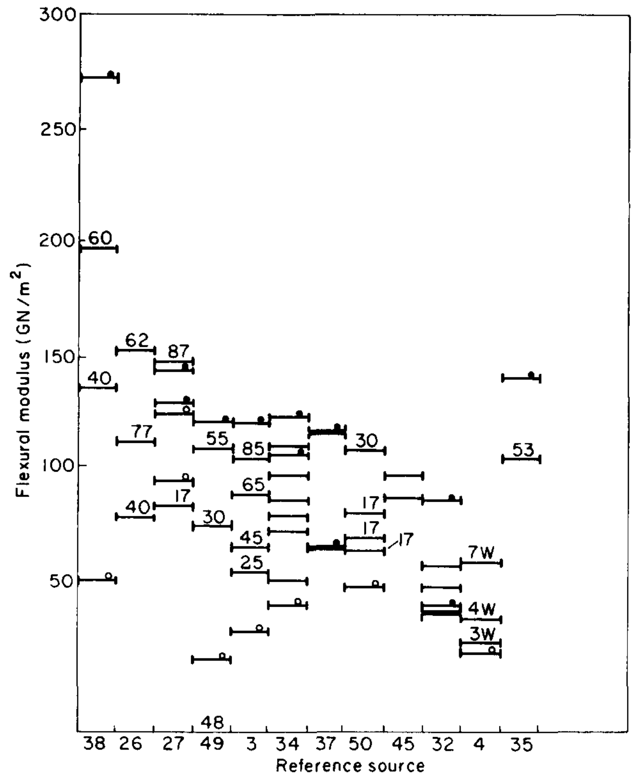

Fig. 12 The range of values reported for flexural moduli (solid circle = all-carbon composite, open circle = all-glass composite; where a number occurs, this indicates the percentage of carbon fibres in the composite)

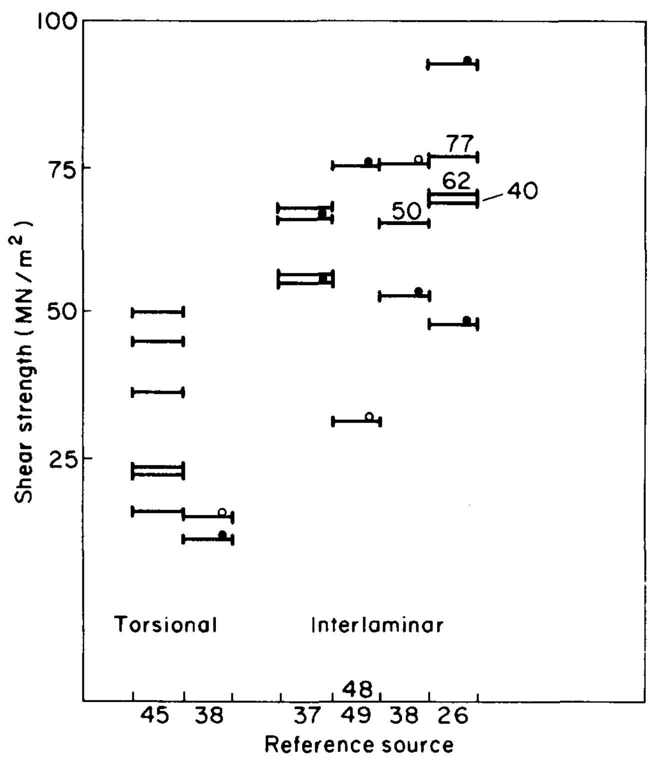

Fig. 13 The range of values reported for shear strengths (solid circle = all-carbon composite, open circle = all-glass composite; where a number occurs, this indicates the percentage of carbon fibres in the composite)

FATIGUE

In tension

Fatigue studies of hybrid composites in tension have shown that the number of cycles to failure at a particular stress level,[1] increases with increased carbon fibre content, (see Fig. 14). The superiority of interply hybridisation is stressed by the fatigue results in a comparative study of interply and core-shell structures.[42,43] The fatigue resistance of the hybrid remains substantial even when 50% of the fibre volume is glass although a greater reduction of fatigue life occurs when S-glass is added to HTS carbon composites then when S-glass is added to HMS carbon composites.

In the case of long term loading, the strength of the three component materials is probably a function of time and is determined by the static fatigue of the high modulus fibres.[44] Salkind,[45,46] has determined permanent changes in stiffness at less than 1% of the total life to fracture in interrupted tensile fatigue tests, and also damage at these early stages by temperature monitoring, ultrasonic monitoring and holographic interferometry. Most of the fatigue specimens which fractured exhibited a rise in temperature just prior to fracture and the line of subsequent fracture could be predicted from colour changes on the temperature sensitive coatings or strips.

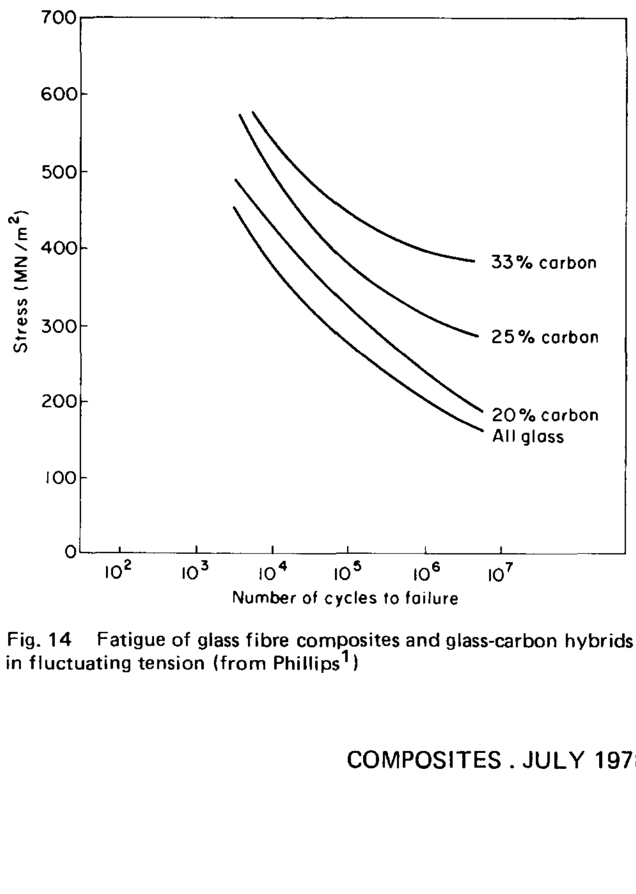

Fig. 14 Fatigue of glass fibre composites and glass-carbon hybrids in fluctuating tension (from Phillips[1])

In bending

The flexural strength and rigidity of grp composites in fatigue tests are improved by sandwich hybridisation and unlike static flexural properties are independent of the type of glass core.[51] Yoshida[53] has established and verified a theoretical analysis of the relationship of modulus of elasticity, composite alignment and dynamic behaviour by resonance vibration testing of hybrids in bending.

Salkind[45] has observed three distinct regions in the fatigue life of these materials; a small initial stiffness change partly due to heating and partly attributed to the failure of weaker fibres and interfaces; a secondary region of very little stiffness change; and a tertiary region of rapidly increasing stiffness leading to fracture.

Miyairi et al[54] examined the flexural fatigue of carbon-shell/glass-core hybrids with both cloth and mat cores and found that in both cases fatigue failure occured by debonding at the core/shell interface with an increased initial breaking strain relative to cfrp alone of between 200% and 250%. Fracture was found to take place transverse to the stress axis with a linear mode in the mat-core hybrid and with a zig-zag mode in the cloth-core hybrid. Shimamura and Furue[55] found fatigue strengths after 10^7 cycles to be reduced to 67% of initial values in all-carbon composites and to around 33% in all-glass composites with a linear transition in both cost and performance for the hybrids, between the two extremes.

OTHER PROPERTIES

The torsional shear character of hybrid composites has been examined by Kalnin[38] who found a transition from yielding without fracture in glass-rich specimens to fracture without yielding in high modulus carbon-rich composites. Salkind[45,46] examined the torsional modulus of hybrids but found that the fibres still carried load when the matrix was damaged because of the $\pm 45^\circ$ lay-up sequence. A straight line relationship was also found[45] between the vibratory torsional stress and the vibratory flatwise bending stress, with little sensitivity to the axial steady stress.

Skudra et al[44] have obtained a linear plot of Poisson's ratio against the volume content of glass fibres in a hybrid composite; Pinckney and Freeman[56] have carried out a series of tests on laminate, sandwich and tube specimens manufactured from mixed modulus carbon and glass hybrid materials to evaluate the compatibility of these materials for the structural and failure mode requirements of helicopter rotor blades, The tests were thermal distortion of asymmetric panels, creep and creep rupture, tube torsion and tube torsion fatigue, tension and tensile fatigue, cantilever deflection and interlaminar shear strength, with post-failure microscopic examination and scanning electron micrography.

CONCLUSIONS

The properties of hybrid composites have often been predicted by application of the law of mixtures, but several authors have presented evidence that the final value for a particular property will be in excess of the value predicted by the law of mixtures, and this synergistic strengthening has been termed 'the hybrid effect'.

The impact properties of carbon fibre composites can be improved by the addition of glass fibres which increase the capability of the composite to store strain energy and introduce a greater diversity of failure mechanisms.

The compressive strength of hybrids is similar to that of the single fibre composites but the compressive modulus of glass rich hybrids shows a marked increase upon hybridisation, greater than that predicted from the component materials.

In tension, failure of hybrids is found to be non-catastrophic in carbon rich hybrids and the elongation at first failure is found to be greater than that for the carbon fibre-only composite. Failure of carbon fibres in the hybrid can result in the load being transferred completely to the glass fibres but this is dependent on the relative proportions of each of the two fibres. Load distribution appears to be best achieved by a uniform distribution of the fibres rather than by

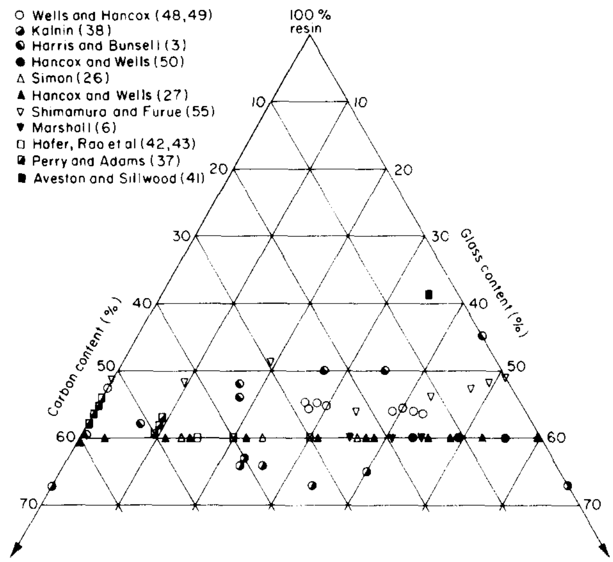

Fig. 15 The volume fractions of the components of hybrid composites reported in the literature

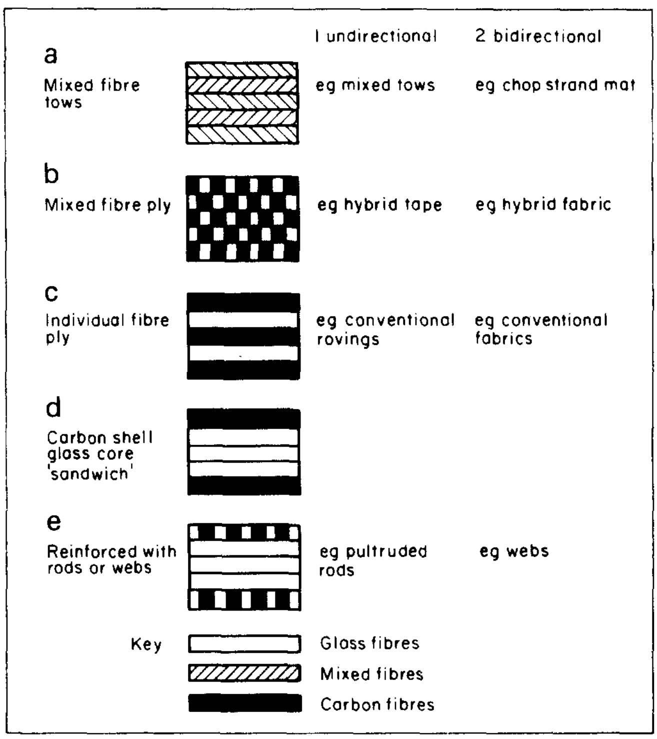

Fig. 16 The lay-up nomenclature used in this review

Table 1 The component materials of hybrid composites reported in the literature

Reference	Authors	Carbon fibres	Glass fibres	Lay-up (see Fig. 16)	Resin system	Cure temperature °C	Properties investigated												
							Charpy impact	Izod impact	Other impact	Tensile strength	Tensile modulus	Tensile fatigue	Compression strength	Compression modulus	Flexural strength	Flexural modulus	Flexural fatigue	ILSS	Torsion
3	Harris and Bunsell	Courtaulds 3	Silenko E	B1	BXL SR17449 Polyester	100	√									√			
4	Dukes and Griffiths			C2	Isophthalic Polyester														
				C2	Bisphenol Epoxy-DDM														
				C2	Epoxynovolac-BF_3-MEA						√		√	√		√			
5	Golding	II (hybrid tape)	E	B1	Derakane 411/45 Vinylester-MEKP-DMA-Co	Ambient	√												
6	Marshall	II (hybrid tape)	E	B1	Derakane 411/45 Vinylester-MEKP-DMA-Co	Ambient													
				B1	Epikote 162 Epikure 113 amines					√	√				√	√		√	
26	Simon	Modmor IIS	S	D1	ERL 2256-ZZLO820		√		√						√	√			
27	Hancox and Wells	HTS	E	D1	Shell DX209-$BF_3$400	170°													
				D1	ERLA 4617-DDM	170°		√							√	√			
28	Chamis et al	Thornel 50	S	C1	ERL 2256-ZZLO820														
		Modmor I																	
		HTS						√											
29, 30	Bradshaw et al	111 untreated							√										
31-33, 35, 37	Perry, Adams et al	Modmor 11	ECG 150- 1/0	C1, C2	Narmco 1004 (Modulite 5206	180°													
			S2 Yarn																
			120 Cloth E				√			√	√		√		√	√			
34	Mallick and Broutman	Thornel 300	E Fibre	C1, C2, D1, D2	Fiberite 934														
		GY70	Style 1534 E Cloth		Ferro CE9006														
					Ferro E293/15S3		√								√	√			
38	Kalnin	Celanese GY70 tape	Ferro S1014	C1, D1	Celanese R350A	120°													
			Ferro S3405G. S24							√	√		√	√	√	√		√	√
39	Hayashi	Torayca P301	Scotchply 0012	D1	Epikote 828-BF_3-MEA	165°				√									
40	Bunsell and Harris	I	E	C1, D1	Ciba Geigy 905 Epikote 828	180°					√								
41	Aveston and Sillwood	Courtaulds I			Ciba MY 753 HY951	Ambient				√	√								
42, 43	Hofer, Rao	HTS (Modmor 11)	S	D1, D2	3M type PR286	180°													
		HMS (Modmor 1)										√							
45	Salkind		E	C2								√				√	√		√
46	Nevadunsky et al		E	C2	DM500 DM101					√	√								√
47	Fujii and Tanaka	Morganite I	E		GY 260-HY 906	180°				√	√								
48, 49	Wells and Hancox	11	Flomat	D2	ERLA 4617. MPD	160°									√	√		√	
50	Hancox and Wells	A U; HM U	E	E1	Epikote 828 DDM 4' Amine														
		HT S; HM S						√							√	√		√	
55	Shimamura and Furue	Torayca T200	ERT 230. 1315 N roving	B1	Epikote 1001-828-DDM	130°									√		√		
56	Pinckney and Freeman	Courtaulds HM S	Owens Corning S	C1, C2, D2	3M-1002 Cyanamid BP907	180				√	√	√						√	√

* Key to cure systems

Co Cobalt naphthenate DDM Diaminodiphenylmethane DMA Dimethylamine MEA Monoethylamine MEKP Methylethylketone peroxide MPD Metaphenylenediamine sandwich systems because of the modulus mismatch in the latter.

The interlaminar shear strength of hybrids has been determined mainly from measurements in the glass core of sandwich composites, which has resulted in values very similar to that in all-glass composites. Kalnin, in a type C hybrid, suggested that this property is dictated by the resin system.

In flexure, the stiffness of grp beams is greatly increased by the addition of carbon fibres, the most noticeable benefit resulting from use of the carbon fibres at the surfaces of the beam.

Because of the diversity of the component materials used and of the lay-up sequences, the work of different authors is not really suitable for direct comparison, although the trends indicated are generally applicable to the range of hybrids considered. This comparison is further limited by the absence of vital information in some papers, notably

- a clear concise indication of lay-up sequence (see Fig. 16);
- the volume fraction and weight fraction of each component fibre relative to both the entire hybrid and the individual ply;
- an indication of the components; resin, carbon fibre and glass fibre along with the relevant properties and trade names of each;
- filament diameter, density and length, tow and tex figures and details of surface treatments;
- resin density additives and the cure cycle of the matrix;
- the extent and nature of any voidage or quality defects;
- the relevant properties of both the single fibre composites, when laid-up in the same way as the hybrids.

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