Compression strength of hybrid fibre-reinforced plastics

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Pultruded fibre composite rods have been made from polyester resin and mixtures of carbon, Kevlar and glass fibres. The strengths and elastic moduli of the hybrids were not always as predicted by the mixtures rule, moduli in particular often being lower than expected. The addition of relatively little carbon fibre to a Kevlar composite drastically reduces its ductility. Glass has a less significant effect, and some glass–Kevlar composites show a secondary elastic modulus.

1. Introduction

One advantage of composite materials for the designer is that the properties of a composite can be controlled to a considerable extent by the choice of fibres and matrix and by adjusting the nature of the fibre–matrix interface. The scope for this tailoring of the properties of the material is much greater, however, when different kinds of fibre are incorporated in the same resin matrix. A considerable amount of research and development work has been carried out on hybrid composites, and these materials are presently being considered for use in such specialized applications as helicopter blades.

Although a great deal of information is available on tensile [1–3] and impact [2–5] properties of hybrids, little work has been done on compression properties. Compression strength and moduli are important design parameters because composites are frequently used in flexure, and when a composite is bent it can fail as a result of weakness in compression. This is the normal failure mode in the case of flexed Kevlar composites, and it has often been observed in carbon-fibre-reinforced plastics (CFRP).

In a recent paper [6] we discussed the results of an investigation of the compression strength of a wide range of unidirectional composites of polyester resin reinforced with glass, carbon and Kevlar-49 fibres. The composites were manufactured as cylindrical rods by a type of pultrusion method and tested in a very simple manner with close-fitting end retainers. The results of this earlier work showed the effect of fibre type, fibre volume fraction and resin characteristics on the compression behaviour of the composites. "Rule of mixtures" behaviour occurred in glass-fibre–polyester composites up to limiting volume fractions (V_f) of 0.31 for strength and 0.46 for elastic modulus, the compression modulus being equal to the tensile modulus. At a fixed V_f of about 0.30 the strengths of reinforced polyesters were proportional to the matrix yield strength σ_{my}, and their moduli appeared to be governed by an inverse exponential function of σ_{my}. (Recent analysis, being prepared for publication, indicates that the modulus is determined by two independent compliances, one arising from direct compression of the fibres, and the other due to matrix restraint as the fibre buckles under the load.) At the same volume fraction, Kevlar-fibre–polyester composites behaved as though their compression moduli and strengths were much smaller than their tensile moduli and strengths, while carbon fibre composites were only slightly weaker and less rigid in compression than in tension. The results

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TABLE I Volume fractions (V_f) of hybrid composites tested

	Ratio of two types of fibre					
	0/100	20/80	40/60	60/40	80/20	100/0
Glass–Kevlar	0.297	0.305	0.300	0.294	0.302	0.295
Glass–carbon (HMS)	0.298	0.301	0.299	0.298	0.296	0.295
Kevlar–carbon (HMS)	0.298	0.308	0.299	0.303	0.307	0.297
All carbon (HMS–HTS)	0.308	0.294	0.291	0.293	0.295	0.298

obtained in this work gave no support to the currently accepted theories of compression strength of Rosen [7] and Hayashi and Koyama [8].

The experiments now to be discussed represent an extension of the earlier work to include the effects of mixing different species of fibre in the same resin in hybrid composites.

2. Experimental method

2.1. Specimen manufacture

The technique used to produce the pultruded rods was described in detail in the earlier paper [6]. The fibres, in the form of roving or tow, were wound on a former to make skeins containing the number of fibres required for a given volume fraction of reinforcement. The skeins were then soaked in resin, and pulled into flared glass tubes where the resin was allowed to set prior to post-curing at 80° C for 3 hours. The matrix resin used in this work was a conventional isophthalic polyester resin, Crystic 199, supplied by Scott Bader, with a compression strength of 127 MPa, a yield strength of 87 MPa and a Young's modulus of 3.7 GPa. The fibres used were Pilkington's E-glass, Du Pont's Kevlar-49, and Courtauld's high-modulus (HMS) and high-strength (HTS) carbon fibre (both surface-treated).

The skeins were made without attempting to separate single fibres or groups of fibres from the roving or tow, since this could have caused damage to the fibres, with consequent weakening. The nominal volume fraction of 0.30 could not therefore be reproduced very precisely from specimen to specimen, as shown in Table I. Final volume fractions were thus 0.30 ± 0.01 and in the hybrid composites the proportions of the different fibres were kept as close as possible to the ratios 20/80, 40/60, 60/40 and 80/20. The tows and rovings were intermingled so as to make the fibre mixture as uniform as possible, but the intermingling was clearly of the tows rather than of the individual fibres.

2.2. Compression testing

Prior to testing, the pultruded rods were cut into 30 mm lengths, and their ends polished smooth and perpendicular to the rod axis. They were tested in an Instron machine with their ends supported and confined by discs 7 mm thick which had holes in them which fitted tightly around the specimen ends, as shown in Fig. 1. These end fittings were inserted into the larger hollow platens shown in the figure. The tests were carried out at a cross-head speed of 0.5 mm min^{-1}. The rationale and validity of this simplified testing procedure have been discussed in the earlier paper [6].

2.3. Determination of elastic moduli

The Young's moduli of composites reinforced with the separate species of fibres (other than Kevlar) at $V_f = 0.30 \pm 0.01$ were measured by the normal

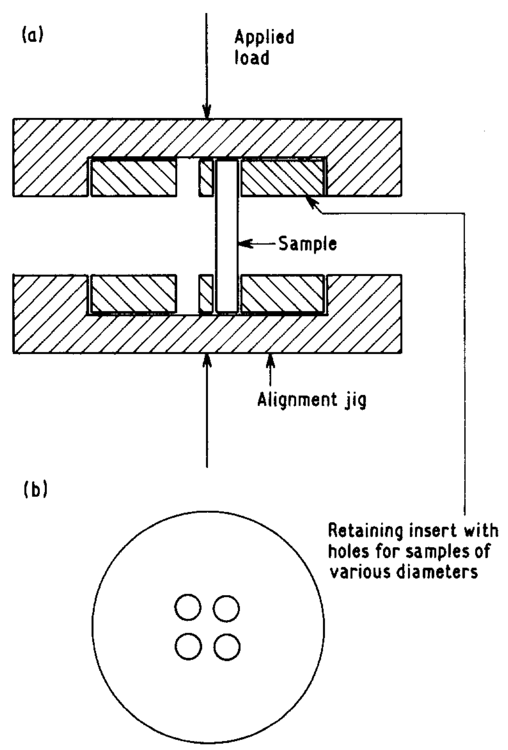

Figure 1 Compression testing arrangement: (a) section through supports with sample in place, (b) view of the upper side of lower specimen grip.

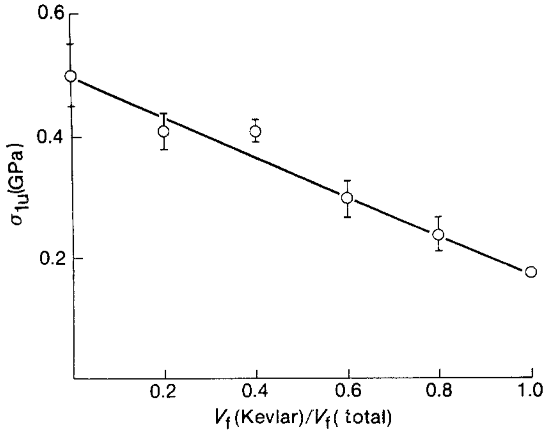

Figure 2 Compression strength of hybrid Kevlar-49–glass composites.

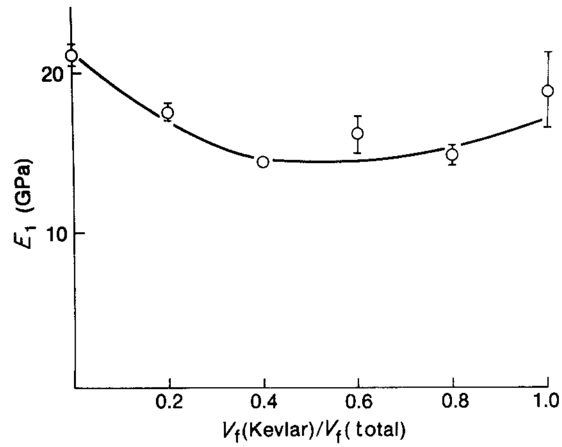

Figure 3 Elastic modulus in compression of hybrid Kevlar-49–glass composites.

method of testing a long rod, reducing its length slightly and retesting, and so on, as described in [6]. The slope of the resulting compliance versus length plot gives the modulus directly. The measured values were 23 GPa for E-glass composites, 92 GPa for HMS carbon fibres and 52 GPA for HTS carbon. The carbon values are significantly less than those predicted by the mixtures rule, assuming that the compression modulus of the fibres is the same as the tensile modulus.

It had been found previously that the compliance of rods containing Kevlar was reduced by a compression test, and that the elastic modulus of this material could not therefore be determined by a series of compression tests in which the length of the sample was gradually reduced for each successive test. It was therefore necessary, since the modulus varied between apparently identical samples of pultruded rod, to estimate the modulus each time a sample was tested to failure. This can be done if the machine compliance is accurately known and the end effects are taken into account. Machine compliance was measured by operating the Instron without a specimen present and was found to be 19.8 nm N^{-1} for loads in the range 10–100 kN, and 22.5 nm N^{-1} for loads in the range 4–10 kN. An estimate of the importance of end effects, which arise from (a) the deformation of the platens due to pressure exerted by the specimen, (b) the higher modulus of the end regions of the specimen (as a result of their being confined), and (c) stress transfer at the perimeter of the holes through friction, suggests that, for our materials and testing system, they affect the measured properties by less than 5% when an interpolation formula of the form

$$E_1 = \frac{10.8T(1-0.223T)}{1-0.362T}$$

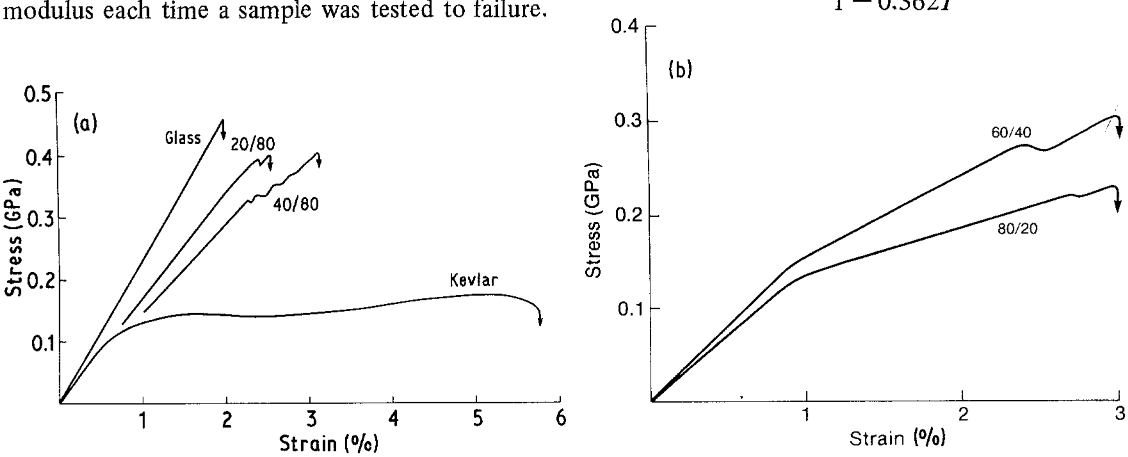

Figure 4 Stress–strain curves for hybrid Kevlar-49–glass composites. (a) Plain glass; 20% Kevlar–80% glass; 40% Kevlar–60% glass; plain Kevlar-49. (b) 60% Kevlar–40% glass; 80% Kevlar–20% glass.

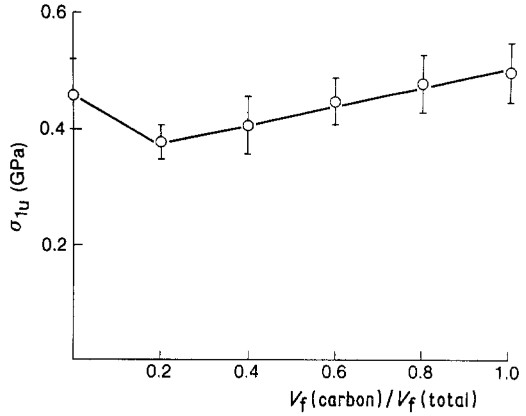

Figure 5 Compression strengths of hybrid carbon (HMS)–glass composites.

is used. In this expression T is the load in tonnes needed to give an apparent deformation of 1 mm, 10.8 is the appropriate scaling factor for the specimen dimensions, the constant 0.362 accounts for the compliance of the machine and gripping system and the constant 0.223 is needed for non-linear effects at the ends (factors (b) and (c) above). This formula was used for all hybrids.

3. Experimental results

3.1. Kevlar–glass hybrids

Fig. 2 shows the strengths (σ_{1u}) of these hybrids. Most of the results fall close to the straight line joining the all-glass and all-Kevlar composites, indicating very little deviation from the mixture rule. The 40% Kevlar–60% glass result is high, but still falls within the scatter band defined by results for other composites. Fig. 3 shows the moduli (E_1) of these hybrids. Some cohibitive effects appear to be taking place, since the moduli are generally significantly below the values predicted by the mixture rule.

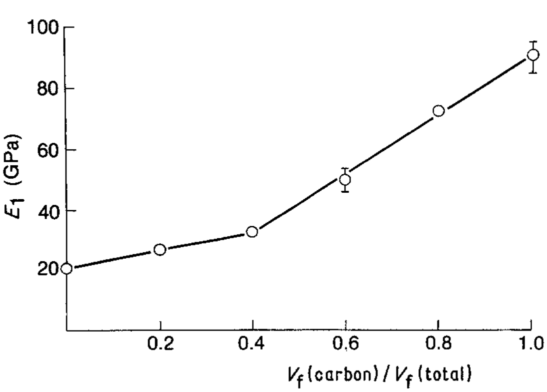

Figure 6 Elastic modulus in compression of hybrid carbon (HMS)–glass composites.

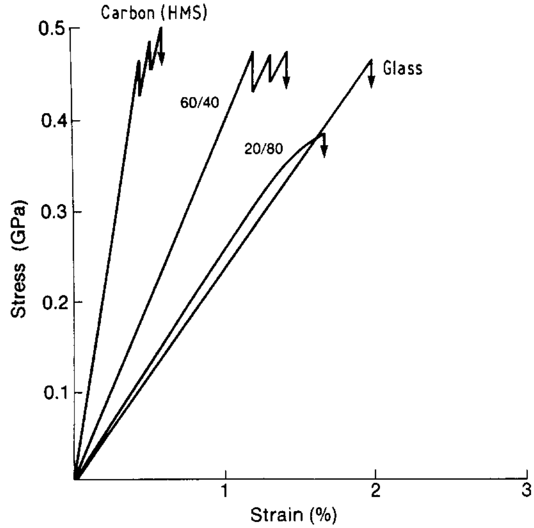

Figure 7 Stress–strain curves for hybrid carbon (HMS)–glass composites: plain carbon; 60% carbon–40% glass; 20% carbon–80% glass; plain glass.

Fig. 4 shows typical stress–strain curves. The 60% Kevlar–40% glass and 80% Kevlar–20% glass stress–strain curves had two straight regions, and the secondary moduli for these two materials are 8.7 ± 0.8 and 5.1 ± 0.5 GPa respectively. These are quite close to the values that would be achieved if the glass alone were present. The dual slopes for the 60/40 and 80/20 Kevlar–glass composites can be seen in Fig. 4b.

3.2. Carbon (HMS)–glass hybrids

Fig. 5 shows that there appears to be a strength minimum in the region of 20/80 carbon–glass for these composites, and the curve of modulus versus composition shows two linear regions (Fig. 6) meeting at about 40/60 carbon–glass. The stress–

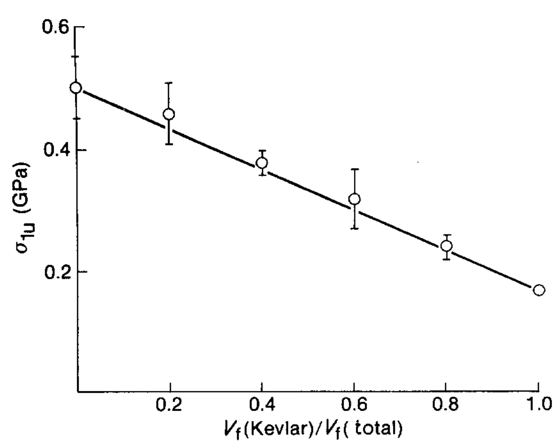

Figure 8 Compression strengths of hybrid Kevlar-49–carbon (HMS) composites.

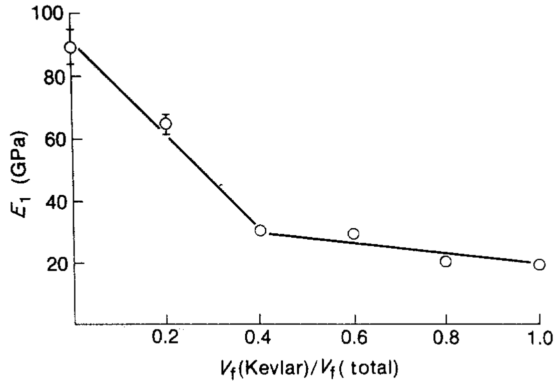

Figure 9 Elastic modulus in compression of hybrid Kevlar-49–carbon (HMS) composites.

strain curve for the 20/80 carbon–glass composition appears to show slight pseudo-ductility (Fig. 7). The other combinations behave in a similar way to that of the composite with HMS carbon alone.

3.3. Carbon (HMS)–Kevlar hybrids

As with glass–Kevlar composites the strengths of these hybrids fall close to a straight line joining the values for carbon–Kevlar composites, see Fig. 8. However, the plot of elastic modulus versus composition again shows two linear regions and values of E_1 fall well below "mixture rule" behaviour (Fig. 9). Unlike the glass–Kevlar composites, these hybrids do not display a secondary modulus, although the materials with higher Kevlar content do appear to have some ductility (Fig. 10).

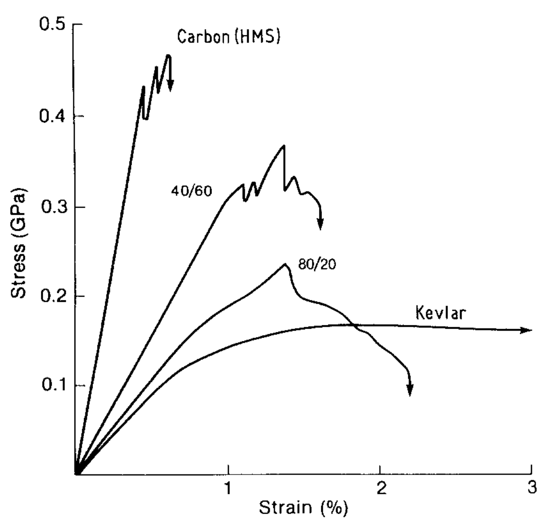

Figure 10 Stress–strain curves for hybrid Kevlar-49–carbon (HMS) composites: plain carbon; 40% Kevlar–60% carbon; 80% Kevlar–20% carbon; plain Kevlar.

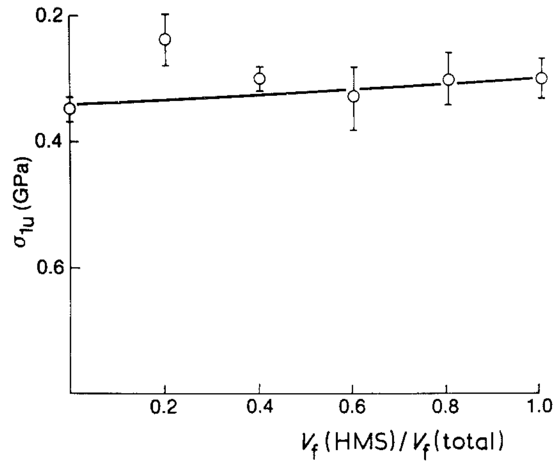

Figure 11 Compression strengths of hybrid HMS/HTS carbon–carbon composites.

3.4. Carbon (HMS)–carbon (HTS) hybrids

The strengths of most of these hybrids falls fairly close to the "mixtures rule" line (Fig. 11), although the 20/80 HMS–HTS value lies above it, and has the highest strength (0.56 ± 0.04 GPa) of any of these composites. The moduli appear to fall on an S curve (Fig. 12). The stress–strain curves obtained for HMS carbon composites are shown in Fig. 13.

3.5. Effect of fibre mixing on failure modes

Longitudinal sections of tested samples were polished for microscopic examination and the following subjective observations made. In carbon–carbon hybrids there was no visible effect of fibre mixing. The failure mode for all compositions was similar to that of unmixed carbon composites described in [6] (Fig. 14a). All failures were brittle in nature with highly localized transverse failure surfaces, irregular but largely perpendicular to the

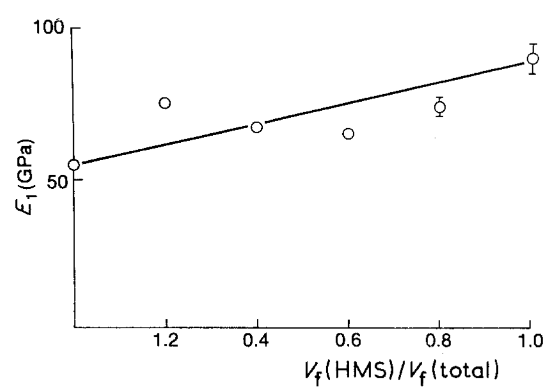

Figure 12 Elastic moduli in compression of hybrid HMS/HTS carbon–carbon composites.

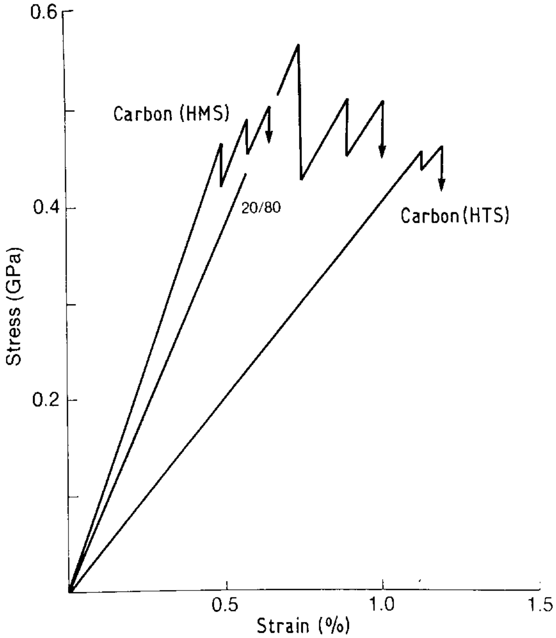

Figure 13 Stress–strain curves for hybrid HMS/HTS carbon–carbon composites: plain HMS carbon; 20% HMS–80% HTS; plain HTS carbon.

load axis. There was no gross distortion of any of these samples and no longitudinal splitting of the composite. In glass–Kevlar hybrids, the incorporation of glass progressively changes the mode of fracture from that typical of plain Kevlar composites, with low general distortion and localized kinking but no longitudinal splitting (Fig. 14b), to that characteristic of plain glass composites. In these, the initial kinking damage is converted to cracking when local deformation of the brittle glass becomes excessive, and these transverse cracks are subsequently diverted to cause longitudinal splitting. Subjectively it appears that the relative amounts of splitting and kinking relate directly to the proportion of glass. An almost identical progression occurs in carbon–glass hybrids, the incorporation of glass increasingly changing the failure mode from the transverse, no-kinks mode typical of plain carbon composites to the kinking–splitting mode characteristic of plain glass composites. In carbon–glass hybrids both fibres are brittle, but cracks are more easily initiated in the carbon-rich regions and the kinking failure mode in adjacent glass-rich regions appears to inhibit the progress of cracks that have initiated in the carbon. Fig. 14c shows this effect in reflected light, but the change of mode at the glass–carbon interface is shown more clearly by the oblique illumination used for Fig. 14d.

In carbon–Kevlar composites the extreme modes of behaviour are more distinctive than those of any other pair. In an 80/20 carbon–Kevlar hybrid there is sufficient Kevlar to permit the initiation of 45° shear kinks, but these pass as 45° cracks into the carbon tows (Fig. 14e and 14f). In this case the Kevlar clearly modifies the natural behaviour of the CFRP component more than any

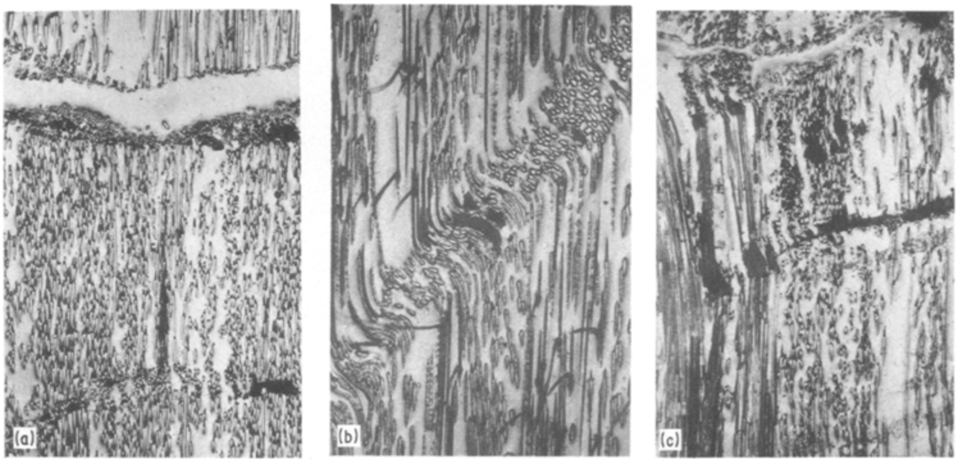

Figure 14 Microstructures of compression-tested samples: (a) typical failure mode in HMS/HTS carbon–carbon samples; (b) highly localized shear kinking band in a plain Kevlar–polyester composite; (c) crack in the carbon rich region of a glass–carbon hybrid which has been stopped by the glass-rich component; (d) showing more clearly in oblique light the manner in which a shear crack in the carbon-rich region is converted into a kink in the glass-rich region; (e) kinking in a Kevlar-rich region of a Kevlar–carbon hybrid associated with a 45° shear crack in the carbon region; (f) the interface in (e) at higher magnification. The compression axis which coincides with the fibre direction is vertical in all cases. Final magnifications may be judged by assuming that the fibre diameters are all about 10 μm.

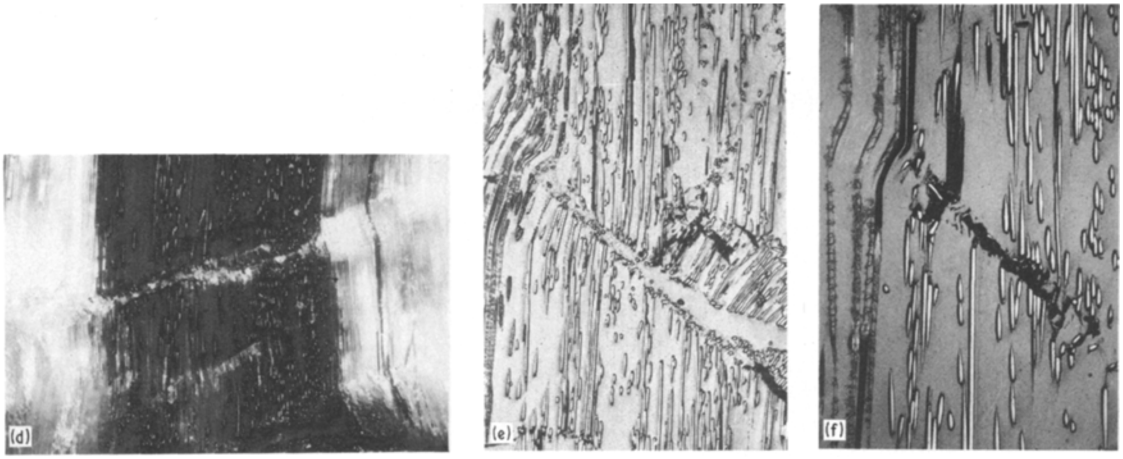

Fig. 14 (Continued)

other second addition, since 45° shear cracking does not occur in any of our plain CFRP samples.

4. Discussion and conclusion

All of these hybrid composites show interactions, in that the measured properties deviate either positively or negatively from linear-addition predictions based on extreme values, although we do not imply here that "rule of mixtures" behaviour is necessarily what would be expected. The observed interactions are more often beneficial (positive) in the case of strength, and harmful (negative) in the case of stiffness. The glass–Kevlar hybrids have a secondary modulus which may be accounted for by the greater failure strain of glass relative to that of the Kevlar and the added element of ductility in the Kevlar after yielding. No such effect is observed with carbon–Kevlar hybrids, where the failure strain of the carbon is less than that of the Kevlar.

The fibres were not intimately intermingled in the hybrid composites, and each roving or tow tended to retain its identity in the composite. There also appears to be a tendency for tows or rovings of the same material to come together, although they were kept separate when the skeins were made.

The stress–strain curves indicate that the addition of small amounts of carbon to a Kevlar composite greatly reduces its ductility while glass additions have a smaller effect.

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