JOURNAL OF MATERIALS SCIENCE 12 (1977) 2401–2410

Strategic reinforcement of hybrid carbon fibre-reinforced polymer composites

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A secondary fibre has been used to improve the impact properties of carbon fibre-reinforced composites. Steel wires possessing similar elastic properties to Type III carbon fibres have been added strategically to the composite cross-section. This has resulted in a 100% improvement in the fracture energy provided that the wires were placed in close proximity to the compressive or impacted face. Such a result is achieved with small increases in longitudinal and interlaminar shear strength. Only minor changes in specific properties occurred through the introduction of the high-density wires. The increase in fracture energy occurs because of the elimination of a compressive failure mode, believed to be brought about by the steel wires increasing the resistance to buckling at the impacted face. Hence, more energy-intensive processes, such as multiple delamination, fibre and wire pull out, are permitted to take place over larger areas of the fracture face.

1. Introduction
Attempts have been made to improve the properties of fibre-reinforced polymers by using a mixture of continuous fibres, e.g. glass and carbon, carbon and Kevlar, etc. [1–6]. In the case of additions of carbon being made to a glass-reinforced polymer (GRP) some increase in strength and modulus is achieved, whilst small additions of glass to a carbon fibre-reinforced polymer (CFRP) will increase toughness. The enhanced property level is not obtained without some attendant reduction in some other mechanical property e.g. glass reduces the modulus and strength of the hybrid carbon composites.

In an attempt to increase the resistance of CFRP to impact damage, whilst maintaining strength and modulus, the authors have chosen steel wire as a minority fibre. It has been shown [7] that steel wire (in the cold-drawn condition), at a volume fraction V_f^s of 0.08, dispersed through an epoxy resin matrix containing $V_f^c \sim 0.50$ Type III carbon fibres, was capable of increasing the impact energy by at least 50%. Overall works of fracture approaching $200\,\mathrm{kJ\,m^{-2}}$ were obtained without necessarily increasing the energy required to initiate damage. This has been achieved without a significant change in interlaminar shear strength, longitudinal strength and modulus. However, the introduction of the steel wires increased the density of the CFRP material from 1.58 to 2.06, thus reducing its specific properties by $\sim 20\%$.

It is the purpose of the present investigation to assess the possibilities of placing steel wires strategically in the CFRP cross-section. Such action is intended to bring about a reduction in the volume fraction of wire, thus enhancing the possibilities of improving the specific properties of this hybrid composite. This assessment involves a study of the fracture properties, interlaminar shear and flexural strengths of these materials, as well as allowing an examination of failed testpeices and fracture surfaces, which may provide evidence of the mechanisms of failure of this type of composite.

2. Materials and fabrication
The experimental panels were fabricated from a commercially available prepreg sheet prepared from untreated type III carbon fibres and partially cured HR4C resin (a mechanical dispersion of an epoxy resin and polysulphone). The reinforcing wire was a commercially available high-carbon steel in the hard drawn condition with a 0.15 mm

	(μm)	(GN m^{-2})	(GN m^{-2})	(%)	(%)
Carbon type III (untreated)	8	190	2.40	–	1.10
Steel wire (brass coated)	151	197	2.47	0.92	2.60

nominal diameter. The tensile properties of the wire and carbon fibre are given in Table I. Panels were produced with steel wires strategically placed near one or both surfaces at varying "local" volume fractions of between 0.08 and 0.25.

The introduction of steel wires into the composite was accomplished by a lathe winding process whereby prepreg–wire–prepreg sandwiches were produced. This process has been described previously [7]. The material was prepared from eight prepreg sheets, each with a nominal pressed thickness of 0.30 mm, the wire lying between the first and second, and second and third sheets for panels reinforced in one surface, and between the sixth and seventh, and seventh and eighth sheets for panels reinforced in both surfaces. A press with heated platens was employed, in conjunction with a "leaky" mould with fixed stops, to fabricate the composites. The mould produced panels of dimensions 203 mm x 76 mm, with stops set to give a panel thickness of 2.5 mm.

The cure cycle was as follows:

1 h at 160 ± 5° C
Moulding pressure 3.45 MN m^{-2}
Post cure 2 h at 180 ± 5° C.

2.1. Micro-structural evaluation of as-pressed composites

Transverse sections were cut from each panel and then polished for microscopic examination using conventional techniques. Full thickness micrographs are shown in Fig. 1. In panels with $V_f^s = 0.08$, the wires were evenly distributed, but in the $V_f^s = 0.16$ material there was some evidence of clustering and this was more exaggerated when $V_f^s = 0.25$. A better wire distribution would have been obtained if thinner prepreg sheet had been available, thus allowing more than two layers of wires to be included in the surface regions. The central areas of these specimens had an identical microstructure to that of the unreinforced CFRP with no evidence of porosity.

Quantitative analysis was carried out on a "Quantimet" image analyser. The carbon fibre volume fractions V_f^c, measured in the central areas of the specimens are given in Table II, where it can be seen that they lie close to the nominal pressed value of 0.60. It proved impossible to

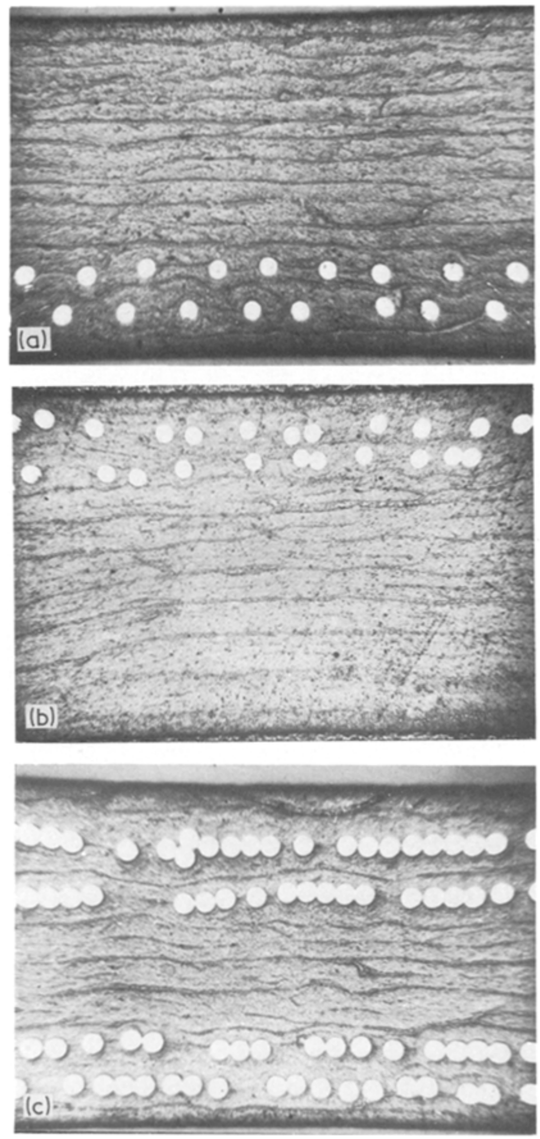

Figure 1 Micrographs showing the full thickness of experimental panels. (a) $V_f^s = 0.08$ near one surface, (b) $V_f^s = 0.16$ near one surface, (c) $V_f^s = 0.25$ near both surfaces. Total panel thickness = 2.5 mm.

TABLE II Carbon-fibre volume fractions in strategically reinforced panels

Code	Wire type	Nominal wire V_f^s	Strategic position	V_f^c carbon fibres
SH 23	0.15 mm Hurst	0.08	One surface	0.59
SH 24	0.15 mm Hurst	0.08	One surface	0.55
SH 25	0.15 mm Hurst	0.08	Both surfaces	0.61
SH 26	0.15 mm Hurst	0.16	One surface	0.57
SH 27	0.15 mm Hurst	0.16	One surface	0.56
SH 28	0.15 mm Hurst	0.16	Both surfaces	0.57
SH 29	0.15 mm Hurst	0.25	Both surfaces	0.57

measure the local wire volume fraction, since the extent of the surface layer in which the wire was incorporated was ill defined. However, experience with panels containing wire evenly distributed throughout had shown that the target and measured V_f^s valued were very close, and therefore it seemed unlikely that the nominal "local" volume fractions of wire were significantly in error.

3. Mechanical test methods and results

In all the different types of tests, the results from the surface-reinforced specimens are compared with results obtained from the straightforward CFRP, and with hybrid composite containing $V_f^s = 0.08$ of wire, generally distributed throughout the sample.

3.1. Short beam interlaminar shear strength (ILSS)

Testing was carried out in a three-point bend fixture with 6.4 mm diameter rollers, mounted in a servohydraulic test frame. The samples, of nominal dimensions 20 mm x 6.4 mm x 2.5 mm were tested at a cross-head speed of 1 mm min^{-1} with a span L to thickness d ratio maintained at 5. In panels containing wires in one surface only, tests have been carried out with specimens orientated so that the wires were positioned at either the outer (tensile) surface or inner (compressive) surface. At least eight duplicate tests have been carried out, and the results are given in Table III.

All the surface-reinforced panels have a slightly greater ILSS than the CFRP-only samples. However, the increase appears to depend on the wire content e.g. mean values for samples with $V_f^s = 0.16$ at single and both surfaces were always greater than those containing $V_f^s = 0.08$. There were also small differences due to the positioning of the wires for example, specimens tested with wires in the compressive surface had a higher ILSS than those with wires in the tensile surface, but the same ILSS as those reinforced in both surfaces.

3.2. Flexural bend strength

The flexural strength was determined using specimens of nominal dimensions 125 mm x 6.4 mm x 2.5 mm tested at a crosshead speed of 5 mm min^{-1} in three-point bending over a span of 100 mm, i.e. $L/d \sim 40$ (no attempt was made to compensate for the effect of slight variations in specimen thickness on this ratio, for provided $L/d > \sim 30$, the ratio has little effect on the measured flexural strength). The results are shown in Table III; an insufficient number of tests were carried out to allow calculations of standard deviations.

Measured values of flexural strength showed two interesting features. Values obtained on specimens having wires positioned in the compressive surface only were in excess of those measured on specimens with wires in the tensile surface only. There was also an increase in flexural strength with wire content in each group of tests, i.e. in both the single and double surface wire-reinforced samples.

In the specimens with wires positioned in the tensile surfaces only, the initial failure was compressive, and the wires did not prevent complete separation of the sample into two pieces. With wires in the compressive surface, whether or not there were wires near the tensile surface, the initial failure was always tensile and complete separation of the sample did not occur across its section.

3.3. Impact testing

Impact tests have been carried out on specimens of nominal demensions 50 mm x 2.5 mm x 2.5 mm using a Hounsfield Plastics Impact Testing machine. In each case the direction of impacting was normal to the panel surface (with the 50 mm dimension parallel to the fibre direction) and the results given in units of kJ m^{-2}, representing the energy absorbed per area of cross-section. The results are given in Table III. It is worthwhile noting that the impact tests were carried out at an effective L/d ratio of 15. According to Bader and Ellis [8], low values of this ratio produce increased amounts of

TABLE III Mechanical properties of reinforced panels

Panel code	Strategic reinforcement	Interlaminar shear strength ($MN\,m^{-2}$) Panel mean	Standard deviation	Material mean	Standard deviation	Mean flexural strength ($GN\,m^{-2}$)	Impact strength* ($kJ\,m^{-2}$) Panel mean	Standard deviation	Material mean	Standard deviation
Base CFRP	–	–	–	57.9	1.5	1.39	–	–	104.7	18.1
CFRP + 0.08 steel wire in general distribution	–	–	–	59.9	2.6	1.40	–	–	147.4	22.8
SH 23	0.08 Tensile surface	60.6	1.5			1.20	109.9	19.9		
	0.08 Compressive surface	65.3	0.5	61.0 (Tensile)	2.2	–	123.7	–	101.5 (Tensile)	23.3
SH 24	0.08 Tensile surface	62.8	2.0	63.7 (Compressive)	2.5	–	88.0	–	129.0 (Compressive)	24.5
	0.08 Compressive surface	63.0	1.3			1.23	135.6	12.8		
SH 25	0.08 Both surfaces	63.7	2.6	–	–	1.28	157.0	26.9	–	–
SH 26	0.16 Tensile surface	63.6	3.6			1.30	125.4	26.7		
	0.16 Compressive surface	66.7	0.7	63.7 (Tensile)	3.1	–	214.2	23.0	125.6 (Tensile)	26.6
SH 27	0.16 Tensile surface	64.4	0.8	66.1 (Compressive)	1.9	–	126.0	26.4	203.5 (Compressive)	37.2
	0.16 Compressive surface	66.0	2.1			1.48	200.0	31.2		
SH 28	0.16 Both surfaces	66.5	3.1	–	–	1.52	199.7	35.5	–	–
SH 29	0.25 Both surfaces	64.8	2.4	–	–	1.61	213.2	41.3	–	–

*Impacted normal to test panel surface.

shear damage and thereby raise the impact energy. Bradley [9] has carried out tests on CFRP composites with general wire reinforcement at higher ratios than 15 and has shown that the impact results did not change significantly.

In the single-surface wire-reinforced samples, higher impact values were measured when the steel wires were placed in the impacted surface i.e. where it underwent compressive loading. As the local volume fraction of these wires in this position increased from 0.08 to 0.16, the mean impact values increased from 23 to 94% above the level obtained on non-wire-containing samples. The positioning of wires in the tensile side increased the impact values only where the volume fraction was equal to greater than 0.16. Wire reinforcement in both surfaces was more effective than single surface reinforcement only at low V_f^s values.

Visual examination of the failed test peices indicated that those samples with wires in the tensile side only fractured in a similar manner to the unreinforced samples i.e. a crack initiating from the point of impact, a single major delamination in the region of the neutral plane and some damage at the tensile surface. A tendency was noted for the outer wire-containing layer to delaminate. With wire in the compressive side, irrespective of reinforcement in the tensile side, there was a large reduction or complete elimination of the region of compressive failure, concomitant with an increase in tensile fracture. These specimens did not break completely across the section, hence the material maintained an effective residual strength. When wire reinforcement was present in both surfaces, again there was tendency for the outer tensile layer to delaminate completely from the specimen; even so, the test piece retained some residual longitudinal strength.

3.4. Slow bend tests

Slow bend fracture tests have been carried out in the manner of Tattersall–Tappin [10]. The specimens, of dimensions 50 mm x 2.5 mm x 2.5 mm, with the special isosceles triangular notch were broken over a span of 38 mm at a crosshead speed of approximately 4 to 5 mm min^{-1}. A load versus deflection curve, plotted on an $X-Y$ recorder was integrated to give the energy absorbed during failure. When complete failure did not occur, the energy to give a 5 mm displacement was measured; at such a displacement the load had dropped to ~5% of the maximum hence, the error involved is quite small. The results are presented in terms of energy absorbed per cross-sectional area of the specimen in kJ m^{-2}, as in the case of the impact results.

Because of the triangular shaped notch, it would be expected that only a few wires would remain uncut in the tensile surface, so that specimens with wires in the tensile surface would be almost identical to unreinforced samples. Therefore, the tests were carried out on single-surface samples with wires in the compressive side only.

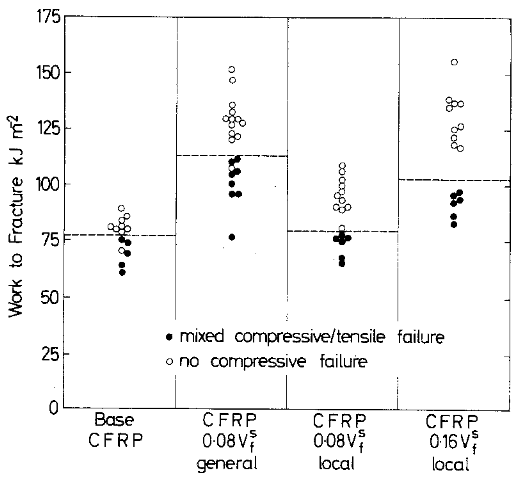

Figure 2 Work to fracture values of hybrid composites as measured by the slow bend tests.

A spread of results was obtained for each category tested, as Fig. 2 indicates. It is maintained that the mode of fracture was responsible for this spread, e.g. if a mixed compressive–tensile failure occurred then a low value was recorded, whilst if a simple tensile crack propagated from the machined notch, values exceeding the non-wire-containing specimens by at least 50%. Examination of the samples which failed at high energy values usually had evidence of limited amounts of delamination.

It was noted that putting $V_f^s = 0.08$ wires generally throughout the section was much more effective than placing them strategically at the compressive surface only. The increase in local V_f^s up to 0.16 did improve the work of fracture above that found in samples containing $V_f^s = 0.08$ surface reinforcement, particularly in those samples that had no evidence of compressive failure.

3.5. Microscopic examination of failed samples

Two different techniques were applied, the optical microscope examination of longitudinal polished sections taken through the fractured region and scanning electron microscopy of fracture faces. In the main impact samples were examined, although checks were run on material that was subjected to the notched slow bend test.

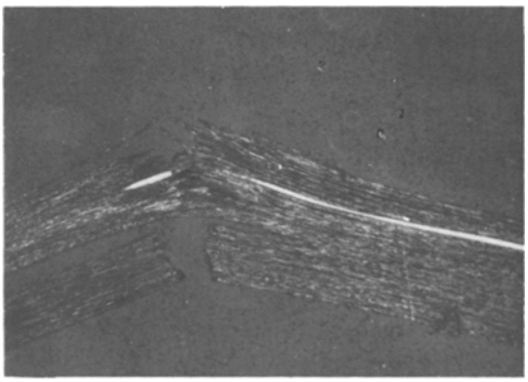

Figure 3 Longitudinal section through an impact sample, showing compressively induced failure at point of impact, major shear delamination, and tensile failure with multiple delamination. The steel wire, shown as the white constituent, has fractured in tension.

3.5.1. Longitudinal sections

Considerable care had to be taken in the grinding and polishing of these sections, as the steel wires were easily displaced and hence a lower quality preparation of the CFRP regions had to be accepted. Fig. 3 shows a section through an impacted sample with wires placed in the tensile side only. Serious damage has occurred on both the compressive and tensile sides of the specimen and close to the neutral axis a major shear delamination has taken place. On the tensile side, the wire has failed with some evidence of local ductility, and there is an indication of multiple delamination within the CFRP regions. A planar crack emanates from the compressive face and extends across a significant part of the cross section until it reaches the plane of the major shear delamination.

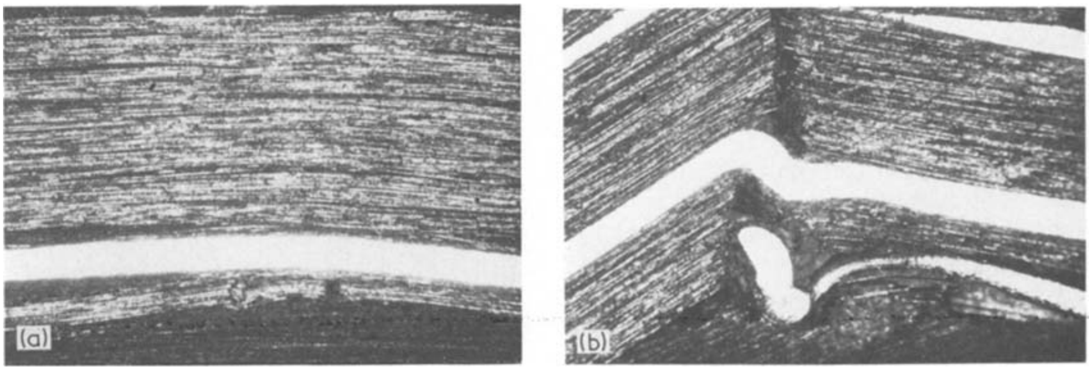

Figure 4 Longitudinal sections through impact specimens (a) Damage at point of impact has been arrested by presence of steel wire reinforcement. (b) Propagation of the damage has caused severe deformation of the steel wires which have not fractured.

With wires in the impacted face, the extent of the compressively induced damage has been greatly reduced, see Fig. 4a and b. In consequence there has been an increase in multiple and major shear delamination. There is evidence, too, of a tensile mode of failure on the compressive side of the neutral axis. In Fig. 4a, the wire placed near the compressive surface has deformed but remains unbroken. A different pattern of wire deformation is shown in Fig. 4b, where the two layers of wire have been displaced perpendicular to the impact blow. Hence, the wires do not run continuously across the section because they have been deformed out of the plane of the section. In the wide range of samples which have been sectioned and examined there has been no evidence of wire failure in the compressive face.

3.5.2. Fractography

At the tensile surface of the impact specimens, varying degrees of multiple delamination and tensile fracture were observed, the amounts depending on the type of sample tested. Examination of the fracture face adjacent to the compressive surface of samples without wires revealed a stepped surface, see Fig. 5a. At higher magnification in this region (Fig. 5b) the carbon fibre showed a distinctive non-planar fracture face. Further it can be seen that the markings on each face are all lined up in the same direction.

4. Discussion

The mechanical test results obtained on the steel-wire hybrid composites show a number of promising features when they are compared with the measurements made on the non-wire-containing material. This situation has been achieved without dispersing the high-density wires throughout the cross-section. Interlaminar shear and flexural bend strengths, together with impact values, increase particularly when the wires are placed in the compressive side of the test pieces and as the local wire volume fraction increases.

It is unlikely that changes will take place in the shear properties of the resin or the resin–carbon fibre interface due to the addition of the steel

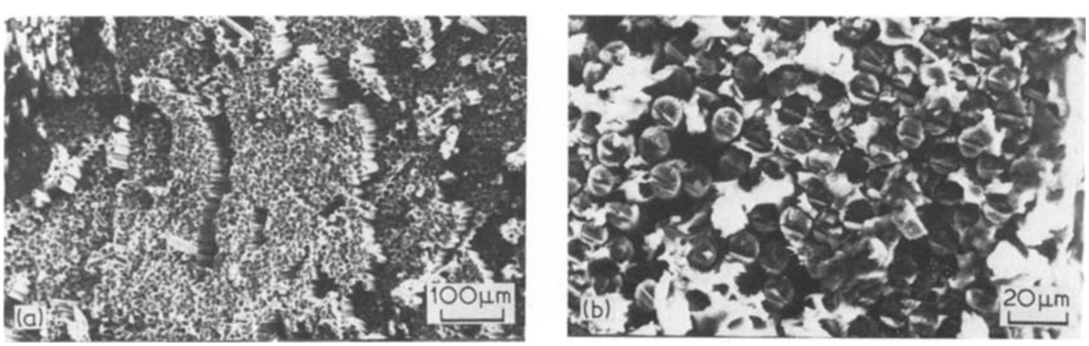

Figure 5 Scanning electron micrographs of fracture faces adjacent to the compressive surface of an impact specimen. (a) Stepped fracture face. (b) Non-planar fracture faces of carbon fibres in the stepped fracture region.

wires. Even if the steel–resin shear strength is very different from the above it will have little effect on the ILSS for the siting of these interfaces is away from the regions of high shear stress. Therefore, the observed increase in ILSS may have been due to some feature of the test method. It is worth noting that the interlaminar shear test frequently comes under attack, because premature failure can occur at the contact point between central roller and specimen surface. In the current programme, each test was stopped after the initial shear crack had begun to propagate and the compressive surface was examined. This revealed only minor indentation marks. If such local damage is important then the wires might conceivably reduce its level and thereby change the stress pattern in the specimen.

The presence of wires near the compressive surface raises the flexural strength and changes the fracture characteristics, i.e. a clear break does not occur and the sample possesses some residual strength. On the basis of the measured tensile behaviour of the fibre and wire, it is surprising that a consistent increase in flexural strength with wire content has been recorded. The steel wire has a similar elastic modulus to the carbon fibre, but its yield strain is less than the carbon fibre fracture strain. Thus, assuming equal strain in each component, one would predict that after yielding of the wire, the composite modulus would be reduced thereby producing a reduced tensile or flexural strength. The observations may be rationalized, at least in the materials containing the higher wire volume fractions, if thermal stresses introduced during composite manufacture are considered. In cooling from the final curing temperature down to ambient, the steel wire contracts axially to a greater extent than the carbon fibres, thus putting the carbon fibres into compression prior to testing. This means that when the failure is initiated at the compressive surface, the flexural strength is reduced below that of the unreinforced CFRP. However, when the initial failure is at the tensile surface, the effective tensile strain range is increased because carbon fibres are in compression, and hence, the flexural strength is increased.

It appears that this increase in flexural strength above that of the unreinforced CFRP is only seen when the balance between the two opposing effects of the wire, i.e. the reduction in composite modulus close to the fracture strain versus the extended tensile strain range due to thermally induced stresses, shifts in favour of the latter; this seems to occur at wire volume fractions of 0.16.

In the impact tests carried out on CFRP a large proportion of the fracture surface was seen to have been produced by a compressive mode of failure initiating from the point of impact. The energy-absorbing capacity of a compressive failure is not known but it is certain to be small, probably a simple sum of fracture energy of the matrix and fibres over that area. The introduction of steel wires on the compressive or impacted side of the test piece has substantially reduced or even eliminated this type of failure. Examination of test results and broken samples suggests that a local volume fraction of wire of 0.16 is sufficient to inhibit the propagation of compressive failure from the point of impact. In order to interpret these observations it is useful to consider the mechanisms of compressive failure in such materials. Rosen [11] has considered compression failure in high fibre volume fraction composites in terms of an in-phase micro-buckling process. According to this theory, the compression strength, σ_{cs}, under axial loading is dependent on the shear modulus of the matrix, and does not suggest that the introduction of steel wires into CFRP would influence this property. Ewins and Ham [12] and Hancox [13] have shown in axial compression tests that failure occurred by shear on a plane of near maximum shear stress i.e. at $\sim 45^{\circ}$ to the longitudinal stress axis. Further, it was confirmed [12] that the compressive strength was linearly dependent on temperature over a range in which the matrix shear modulus changed appreciably. Eventually a change in failure mode from shear to micro-buckling was found when the resin became too soft to support the fibres. Confirmation of this change was obtained from the appearance of the fracture surfaces.

A more complex stress system exists on the compressive side of impact samples than that considered in axial compression tests. However, it may be suspected that during bending a buckling type of failure would be preferred at some point adjacent to the impacted face. Evidence of this failure mode is given in some scanning electron microscope pictures in Fig. 5. This takes the form of a stepped fracture face adjacent to the compressive surface of the sample and within this region non-planar fracture of the carbon fibres. This bears a close relationship to the fracture surface obtained [12] in axial compression tests on CFRP carried out at elevated temperature i.e. when buckling mode was known to operate. In these circumstances it is possible that the addition of the steel wires to CFRP might reduce the extent of buckling failure because of the wires greater diameter and its limited ability to deform plastically.

The prevention of significant amounts of low energy-absorbing compressive failure by the strategic placement of the wires at the compressive surface does mean that other failure processes can take place. These may include: (a) major shear delamination close to the neutral axis, (b) multiple delamination in the tensile regions, (c) tensile failure with fibre and wire pull out, (d) ductile failure of the steel wires. Of these processes, carbon fibre pull out and plastic deformation of the wire (calculated [7] at $10.7\,kJ\,m^{-2}$) obviously contribute to the total energy but go no way to explain the $100\,kJ\,m^{-2}$ measured increase when $V_f^s = 0.16$ steel wire is added to the compressive surface. The most likely source of this energy increase comes from multiple delamination. The analysis [14] of stresses around a crack tip suggests that a tensile crack will be blunted by delamination rather than propagate if the ratio of composite tensile to shear strength is greater than ~ 14. In the materials tested in this programme the ratio is ~ 23. If it is assumed that the shear fracture occurs in the resin, then the fracture energy of an epoxy resin is $\sim 500\,J\,m^{-2}$; the energy absorbed in forming a single shear delamination of the specimen (shear area = 50 mm x 2.5 mm) is $\sim 6.25 \times 10^{-2}$ J. If this is expressed in terms of the specimen cross-sectional area this represents $10\,kJ\,m^{-2}$. The new surface area generated by the multiple delamination cannot be easily estimated but, as seems likely from the number of layers delaminated, the energy absorbed by multiple delamination can be some multiple of the energy absorbed by a single shear. Bader *et al.* [15] working on several types of CFRP material has shown that high values of impact energy correlate with increased amounts of multiple delamination. However, a span to depth ratio of 6:1 was used in these tests, which latter work [8] has shown favours shear-type failure of higher energy (50% above that at a 15:1 ratio). In the present investigation the use of a 15:1 ratio should not encourage this type of failure. However, when the wires have eliminated the compressive failure, the shear mode has been reintroduced.

Notice may be taken of the increase in composite fracture energy that results from inclusion of $V_f^s = 0.16$ steel wires in the tensile side of the specimen. Despite the incidence of significant amounts of compressive failure the energy has been raised chiefly by intensive multiple delamination on the tensile failure regions. It may be that the wires in tensile regions promotes this delamination by modifying tensile crack propagation. Such modifications may take place, through steel wire pull out and crack bridging phenomena which may modify the stresses at the crack tip.

Results obtained from the Tattersall–Tappin form of slow bend tend to show the same general trends as the charpy impact values with wires being introduced into the compressive surfaces. The energy levels tend to be below those obtained in the impact test and there is a greater variability in results. A correlation was noted between the higher energy values and the incidence of shear delamination when compressive failure was absent.

Finally attention should be drawn to the

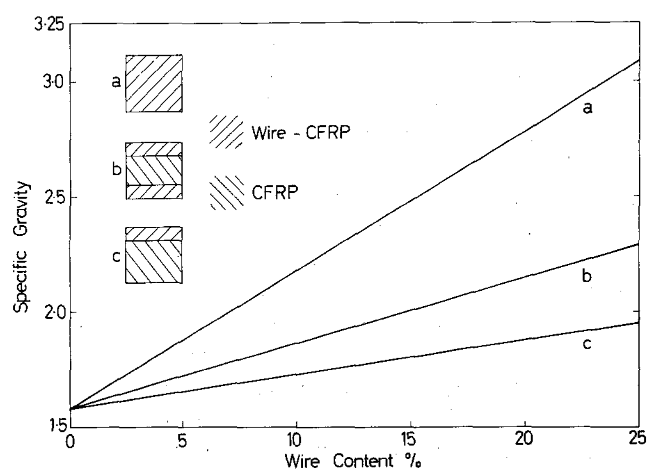

Figure 6 Variation of specific gravity of a hybrid composite of section thickness 2.5 mm with wire distributions.

change in specific properties that occurs due to the incorporation of steel wires into the composite. Fig. 6 shows plots of specific gravity of a series of hybrid composites with different configurations of wire reinforcement. These values have been determined using a rule of mixtures calculation, assuming that the SG of carbon fibre, resin and steel were 1.8, 1.25, and 7.84 respectively, and the total volume fraction of reinforcing fibres (steel and carbon) was 0.6. When wires are evenly distributed throughout the composite, the SG rises rapidly, doubling at $V_f^s \sim 0.26$. With the wire strategically positioned in the surface layers only, the weight penalty is much less severe. In the present work, each strategically reinforced surface region represents ~ 25% of the total cross-sectional area. When the impact values reach an optimum level at $V_f^s = 0.16$ in the compressive surface, an increase in SG of ~ 14% above that of CFRP occurs; with $V_f^s = 0.16$ in both surfaces the increase is ~ 28%. These represent reductions in the specific strength and modulus of 12 and 22% respectively, assuming that such properties are unaffected by the inclusion of the wire. Whilst this assumption is not necessarily true where the wire yields prior to failure, Bradley [9] has shown that measured differences in strength and modulus are small. In thicker sections, where the reinforced regions represent a smaller proportion of the total cross-section, the potential for limiting the increase in SG is even greater, so that large increases in toughness may be feasible with only very small reductions in other specific properties.

In comparison with other hybrid composites, the wire-CFRP system looks promising. Panels with wires located in one surface only at $V_f^s = 0.16$, have similar impact properties to reported data [2] on 50/50 GRP/CFRP hybrids. This is achieved with only one third of the reduction in specific strength and modulus that occurred in the GRP/CFRP composites.

4. Conclusions

(1) The introduction of steel wires into the surface layers of CFRP composites ($V_f = 0.50$–0.60 Type III fibres) does not reduce the interlaminar shear strength. The data does suggest that this property increases by 5 to 10% when the wire resides in the compressive surface.

(2) Flexural bend strength rises with increasing amounts of wire in the tensile and compressive surfaces. The greatest change (~ 25% improvement) occurs when the wire resides near the compressive face.

(3) Such improvements in flexural strength are explained in terms of the removal, or severe restriction, of the failure initiating on the compressive side of the test piece, and by the possibility of the carbon fibres being put into compression due to differential contraction of steel and carbon during cooling from the resin curing temperature.

(4) Impact tests showed that the introduction of wire in increasing volume fractions significantly increased the fracture energies of these composites without necessarily increasing the energy required to initiate damage. Particularly good results were achieved (~ 100% improvement to 200 kJ m^{-2}) by introducing the wires at a local volume fracture >0.16 in the compressive surface. Unlike the straightforward CFRP material these composites retained some residual strength after test.

(5) Fracture energies obtained from slow bend (Tattersall–Tappin) tests on samples containing wires in the compressive surface gave similar trends to those obtained in the impact tests.

(6) The increase in fracture energy is primarily due to the supression of failure on the compressive side of the sample thus permitting the occurrence of higher energy absorbing processes, e.g. multiple delamination at the resin or at resin–fibre interfaces together with carbon fibre and wire pull out.

(7) Fractographic evidence appears to suggest that a buckling mechanism is possible at the compressive or impacted face of non-wire-containing composites. The introduction of the steel wires (~ 10 × diameter of carbon fibres) probably increases the resistance to buckling.

(8) The higher impact values are achieved with relatively small reductions in specific modulus and longitudinal strength.

Acknowledgements

The authors are indebted to the Science Research Council for providing finance to support this work. They would like to extend their thanks to Professor J. S. L. Leach for providing laboratory facilities and Mr C. E. Jagger for preparing the materials for this investigation.

References

1. I. L. KALNIN, ASTM, STP 497, (1972) p. 551.
2. N. L. HANCOX and H. WELLS, *Composites* 4 (1973) 26.
3. A. R. BUNSELL and B. HARRIS, *ibid* 5 (1974) 157.
4. B. HARRIS and A. R. BUNSELL, *ibid* 5 (1975) 197.

5. J. W. MOORE and D. L. STURGEON, *ibid* 4 (1973) 31.
6. P. W. R. BEAUMONT, P. G. RIEWALD and C. ZWEBEN, ASTM, STP 568, (1975) p. 134.
7. S. J. HARRIS and P. D. BRADLEY, AIME Conference on Composite Materials, Geneva and Boston, 1976, p. 327.
8. M. G. BADER and R. M. ELLIS, *Composites* 5 (1974) 253.
9. P. D. BRADLEY, Ph.D. Thesis, University of Nottingham (1975).
10. H. G. TATTERSALL and G. TAPPIN, *J. Mater. Sci.* **1** (1966) 296.
11. B. W. ROSEN, in Symposium on "Fibre Composite Materials, (ASM, 1964).
12. P. D. EWINS and A. C. HAM, RAE Ministry of Defence Report, TR 73057, (1973).
13. N. L. HANCOX, *J. Mater. Sci.* **10** (1975) 234.
14. A. KELLY, *Proc. Roy. Soc.* **A319** (1970) 95.
15. M. G. BADER, J. E. BAILEY and I. BELL, *J. Phys. D.: Appl. Phys.* **6** (1973) 572.

Received 20 September 1976 and accepted 18 March 1977.