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The compression strength of composites with kinked, misaligned and poorly adhering fibres

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Experiments carried out on pultruded fibre reinforced polyester resins show that, at moderate fibre volume fractions, the compressive strength of aligned fibre composites depends linearly on the volume fraction. The strength falls off when the fibre volume fraction, $V_f = 0.4$ with Kevlar and high strength carbon fibres. The effective fibre strength at $V_f < 0.4$ is much less than the tensile strength but it is close to the tensile strength with E-glass fibres and high modulus carbon fibres. Poor adhesion between fibres and matrix reduces the compressive strength, as does kinking the fibres when the fibre radius of curvature is reduced to below 5 mm. Misalignment of the fibres reduces the compressive strength when the average angle of misalignment exceeds about 10° for glass and carbon fibres. However, with Kevlar no such reduction is observed because the compression strength of Kevlar reinforced resin is only a very little better than that of the unreinforced resin.

1. Introduction

Piggott and Harris [1] showed that the matrix yield stress is an important factor controlling compression properties of aligned fibre composites. Both strength and modulus are much reduced when the matrix is soft, which suggests that the fibres may be imperfectly aligned and curved, and consequently able to buckle relatively easily in response to loads. Chaplin [2] has indeed shown that when the composite is carefully made, so that the fibres are as straight as possible, the composite is much stronger than when no such care is taken. Thus fibre straightness may be an important factor in determining the compressive strength of composites.

Another important factor is the adhesion between fibres and matrix. When this is poor the composite is weaker in compression than when adhesion is good and the effect is more pronounced at high fibre contents than at low ones [3].

The studies described here were undertaken with the intention of investigating these effects by deliberately introducing fibre curvature and misalignment and by reducing the adhesion between the fibres and the matrix.

2. Experimental method

Composites with different volume fractions of four varieties of reinforcing fibre were made by the modified pultrusion technique described by Piggott and Harris [1]. The fibres used were from the same batches as those used by these authors, Courtaulds HMS and HTS carbon fibre, Silenka E-glass fibre and Dupont Kevlar 49. Full details of the basic preparation process and of the fibre properties are given in the earlier paper. A series of aligned composites containing each type of fibre and a range of fibre volume fractions, V_f, was tested to provide base-lines for the study. Subsequently sets of composites with $V_f \simeq 0.30$ and 0.50 were produced with deliberately kinked fibres and the effects of misalignment were studied in a series of composites with $V_f = 0.30$.

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In order to study fibre misalignment, the tows of fibres were twisted before being introduced into the resin, and for a given length of composite the number of twists per tow gives an angle of deviation, θ, of the fibres from the composite axis. There are two inconvenient consequences of this procedure. First, twisting tends to introduce a range of fibre orientations, increasing from the rod axis to its circumference and the values of the angle θ referred to in our results are therefore only notional, mean values, obtained from solid geometry. Despite this disadvantage, the method is preferable to testing samples cut at angles from well-aligned plates because (a) it introduces no clearly identified planes of shear weakness and (b) it avoids introducing effects from fibres intersecting free or cut surfaces. The second disadvantage is that it is impossible to prevent some bunching of the twisted tows near the rod axis and V_f therefore varies from centre to circumference. Macroscopic load levels are therefore less easily correlated with local stresses leading to macrofailure. For both reasons, our results for fibre misalignment must be regarded as purely qualitative, but the conclusions that we draw are still valid in the context of the purpose of this investigation.

Specimens with kinked fibres were produced by drawing glass fibres into polyethylene tubes which had their wall thickness reduced to < 0.3 mm, at 6 cm intervals, by the use of a silicon carbide saw. While the resin was still soft, the tube was clamped in the fibre kinking jig shown in Fig. 1. This produced a controlled amount of kinking by pressing 0.24 mm thick steel blades into opposite sides of the rod at 6 cm intervals. The severity of kinking was controlled by the distance the blades were pressed into the rod. (Their positions coincided with the regions where the wall thickness of the tube was reduced and their edges were rounded.) Four values of the indenting distance were used: 0.4, 0.8, 1.2 and 1.6 mm. The internal diameter of the tubes was 6.0 mm, i.e. the same as the glass tubes used in the work described by Piggott and Harris [1].

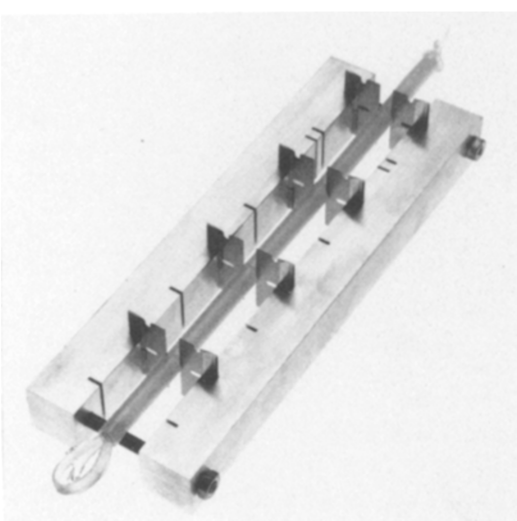

Figure 1 Fibre kinking device used, with pultruded rod specimen inserted.

The adhesion between fibres and matrix was also varied. The glass fibres used in the adhesion experiments had the appropriate surface treatment for the polyester resins used. The adhesion was reduced to a limited extent by soaking the fibres in carbon tetrachloride or water and acetone for 30 min and was severely reduced by heating the fibres to 600° C for 10 min to burn off the silane coating.

Testing was carried out on a floor model Instron with a cross-head speed of 0.5 mm min^{-1}. The end confinement method described by Piggott and Harris was used. In this method the ends of the specimen fit snugly inside holes in steel end pieces.

3. Experimental results

3.1. Strength–volume fraction effects

Fig. 2 shows the variation of compression strength with fibre volume fraction for the four types of composite investigated, in the well-aligned state. The results at $V_f = 0.30$ are in good agreement

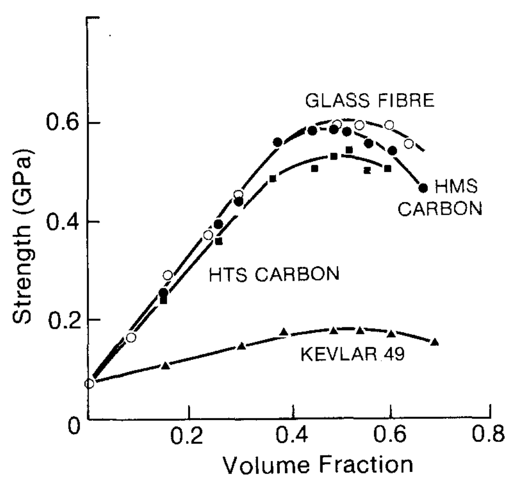

Figure 2 Compression strength of aligned fibre reinforced polyester resin against fibre volume fraction.

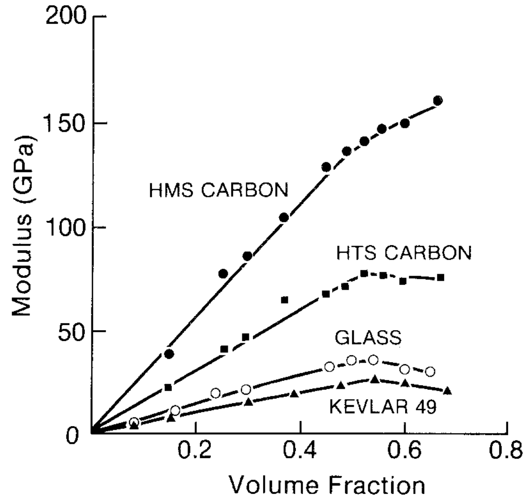

Figure 3 Young's modulus in compression of aligned fibre reinforced polyester resin against fibre volume fraction.

with earlier values at this V_f reported by Piggott and Harris. The variability of these materials was high, as indicated by Piggott and Harris, with coefficients of variation of approximately 9% within any given rod, rising to about 12% between batches. All data points represent the mean of at least four samples from a single rod.

The elastic moduli of these composites vary in similar fashion with V_f (up to the limiting value, about 0.5, which presumably reflects a change in mode of deformation), with the expected reasonable agreement with the mixture rule (Fig. 3). As before, only the curve for Kevlar composites does not extrapolate to a reasonable value at $V_f = 1$.

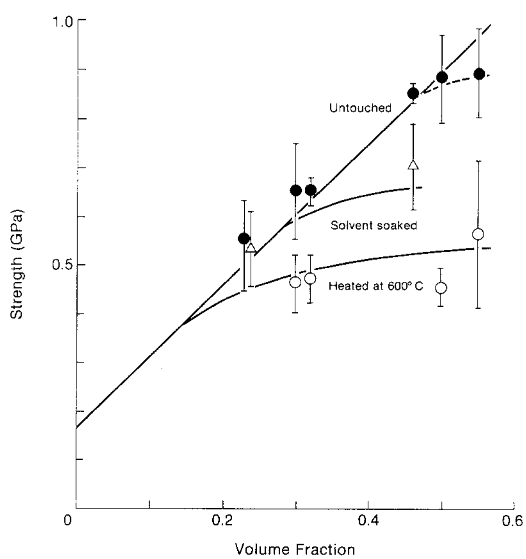

Figure 4 Effect of various fibre treatments on the compressive strength of glass fibre composites.

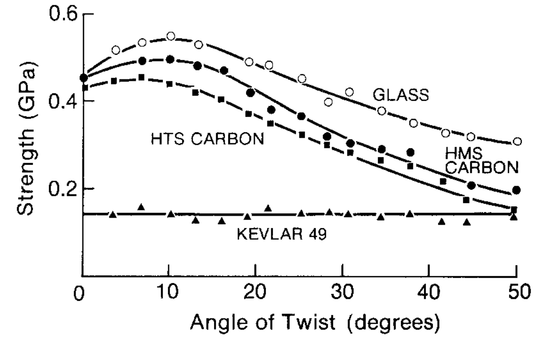

Figure 5 The effect of fibre orientation on the composite compression strength, $V_f = 0.30$.

3.2. Adhesion—volume fraction effects

Fig. 4 shows the strength as a function of fibre volume fraction for fibres having good and poor adhesion. The solvent treatment of the fibres did not affect the compression strength very much, while the removal of the fibre coating by heating to 600° C had a large effect. The effect of the two different solvent treatments was indistinguishable.

3.3. Misalignment effects

Figs 5 and 6 show that misalignment of the fibres relative to the stress axis does not have the anticipated effect. The strength and modulus of the brittle fibre composites are both substantially reduced when the degree of misorientation exceeds 20°, but it is clear that substantial fibre displacements from the vertical can be tolerated before losses of stiffness or strength occur.

Fig. 7 shows the effect on composite strength of fibre kinking at volume fractions of 0.3 and 0.5. There appears to be a linear reaction between the amount of kinking and the strength at both volume fractions.

Fig. 8 shows that the fibre curvature was increased by the kinking process and Fig. 9 is a plot

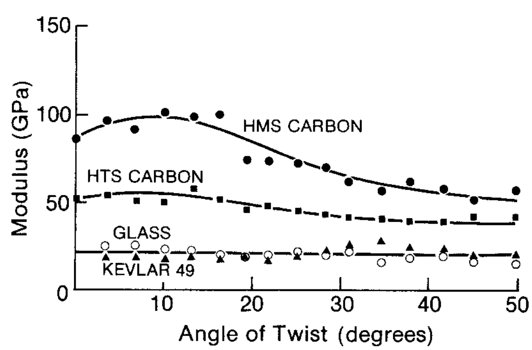

Figure 6 The effect of fibre orientation on the composite Young's modulus in compression, $V_f = 0.30$. The open circles represent the results for the glass.

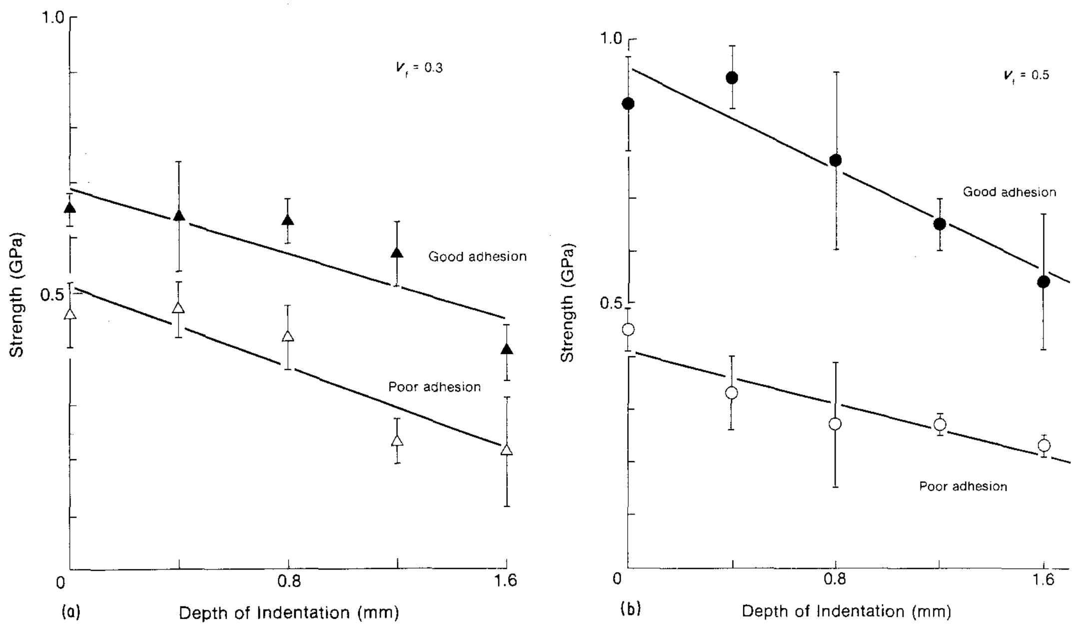

Figure 7 Composite compressive strength against depth of indentation for (a) glass fibre volume fraction = 0.3 and (b) 0.5.

of the minimum fibre curvature (determined by microscopic examination of polished sections) against depth of kink.

4. Discussion

The strength results reflect the insensitivity of the composite compression strength (up to the level where further increases in V_f do not continue to improve the strength) to changes in fibre modulus or strength except in the case of the Kevlar composites. This can presumably be attributed to the known low shear/bending resistance of the organic fibre. The extrapolated fibre stresses at failure, for the brittle fibres glass and carbon, are all in the neighbourhood of 1.4 GPa, as found by Piggott and Harris, and it is significant that while such a value reflects reasonably well the tensile failure stress for glass and HMS carbon, it is less than half the expected value for HTS carbon.

There is marked resemblance between the results for good and poor adhesion obtained with glass fibre composites in this work (Fig. 4), and those obtained by Hancox [3]. Thus when the adhesion is poor the composite strength, σ_{lu}, falls away increasingly from a Rule of Mixtures type of expression

$$\sigma_{lu} = V_f \sigma_{fmax} + V_m \sigma_m \qquad (1)$$

as V_f increases. V_f and V_m are the fibre and matrix fibre volume fractions, respectively. σ_{fmax} represents the maximum compressive stress that the fibre can support in the composite and σ_m is the matrix stress at the failure strain of the composite. (σ_m has the value $E_m \sigma_{fmax}/E_f$ if the matrix is still elastic at the instant of composite failure, where E_m and E_f are the elastic moduli of the matrix and fibre, respectively).

It seems likely that σ_{fmax} is affected by adhesion. Failure occurs by splitting of the specimen. This should be much easier when the fibres are able to separate easily from the matrix than when the two are well bonded. However, there is clearly an interaction between σ_{fmax} and V_f when adhesion is poor.

The increases in strength associated with misalignments of about 10° can presumably be explained in terms of normal geometric arguments relating to resolution of forces and cross-sectional areas. Similar effects are predicted (but not frequently observed) when the orientation dependence of composite tensile strengths are calculated from the maximum stress theory. It is significant that the curves for glass and the two varieties of carbon retain the same relative relationships as θ varies, which implies that the compression strengthening mechanism is similar for all of the brittle fibres. By contrast, the already low strength of the Kelvar 49 composites remains low and quite independent of orientation which is evidence of a completely different deformation mechanism

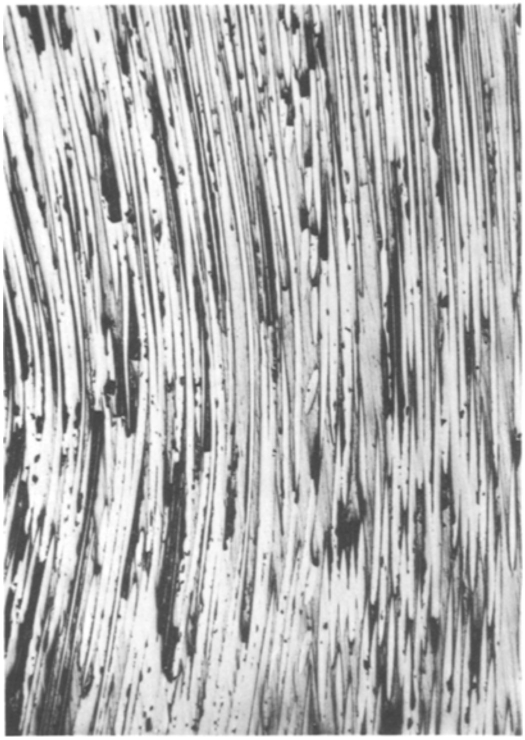

Figure 8 Kinked region of specimen showing curved glass fibres.

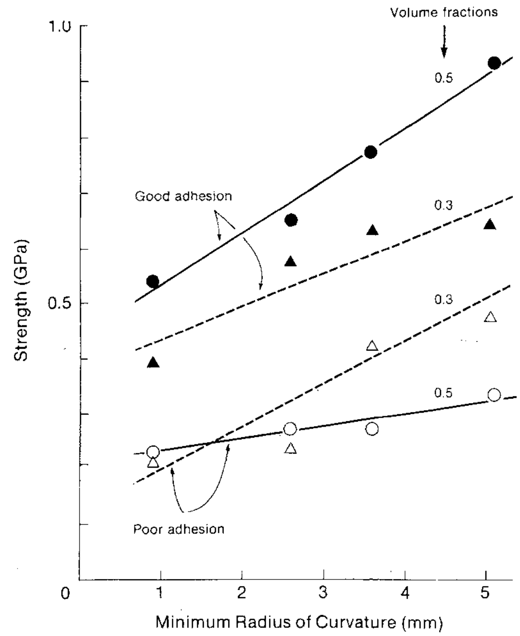

Figure 10 Composite compressive strength against minimum fibre radius of curvature (glass fibres).

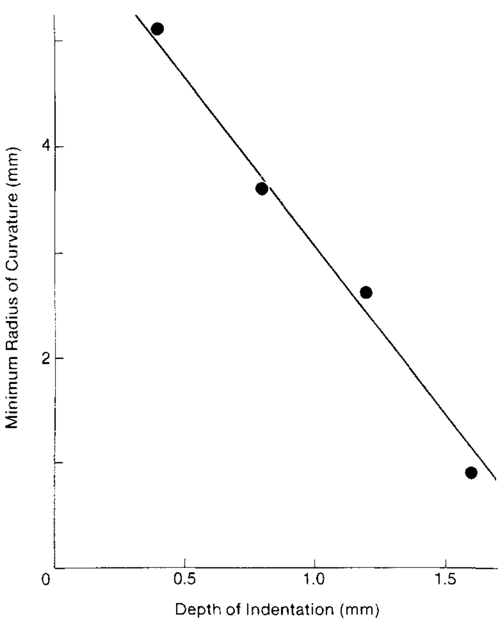

Figure 9 Minimum radius of curvature of glass fibres against depth of indentation.

scarcely affected by the presence of the fibres. It appears from these results that the mean slope for all glass and carbon results in Fig. 2 defines an upper limit to the strengthening that can be achieved with fibres of the order of 10 μm diameter, whatever their properties. There is some evidence, however, that fibre diameter plays a very significant role. For fibres thicker than 10 μm, such as the steel fibres of Ferran and Harris [4], Piggott and Wilde [5] and boron fibres, the upper "bound" in Fig. 2 is exceeded. This is, again, not because of the effect of fibre properties, since Young's modulus of boron and HMS carbon are not too dissimilar and that of steel is much lower than that of HMS carbon. It is also well known that boron–aluminium composites have the highest compression strength/density ratio of any engineering material and this can be only partly on account of the inherent shear stiffness of the aluminium matrix.

The effect on composite strength of kinking the fibres is dramatic and if the results are replotted as a function of R, Fig. 10, instead of depth of indentation, where R is the minimum radius of curvature at the kink, it can be seen that there is a strong correlation between σ_{1u} and R in all cases. (In Fig. 10 the error bars have been omitted for clarity; they are shown in Fig. 7).

The strength of the composite having fibre axes with a radius of curvature of 5 mm is not significantly different from that of the composite without any indentation. Thus we conclude that failure due to fibre curvature only occurs when a limiting curvature is present or when curvature equivalent to 5 mm minimum radius is introduced by the manufacturing process.

The effect of poor adhesion is to lower the strengths at all radii of curvature and the results in Fig. 10 obey the equation

$$\sigma_{1u} = \sigma_0 + bR , \qquad (2)$$

where σ_0 and b are constants.

5. Conclusion

At moderate fibre volume fractions (< 0.4) the compressive strength of composites is linearly dependent on the volume fraction. The strength falls below this linear relationship when $V_f \geqslant 0.4$ and the linear expression does not in general extrapolate to give, at $V_f = 1.0$, a fibre strength equivalent to the tensile strength.

The importance of having good fibre–matrix adhesion when good compressive properties are required has been confirmed by this work. In addition, the fibres should be as straight as possible; the strength increases approximately linearly with minimum fibre axis radius of curvature over the range 90 to 500 diameters. The alignment of the fibres does not appear to be important as long as misalignments do not exceed 10°.

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