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Compressive strength of aligned steel reinforced epoxy resin

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Experiments were carried out to determine the effect of fibre strength on the compressive strength of aligned fibre reinforced composites. The steel reinforcing rods used in this work were hardened to different degrees to control their strength. The compressive strength of composites made with these rods was governed by the Rule of Mixtures, and was a linear function of both volume fraction and fibre strength. The failure strain of the composites was less than one sixth of the matrix yield strain, and failure appears to have been initiated by plastic collapse of the fibres while being fully supported by the matrix.

1. Introduction

The compressive strength of fibre composites is a very important property because of its influence on the flexural strength of the material. With some composites, failure in flexure is initiated on the compressive side of the specimen [1].

The compressive strength is difficult to measure because of the many different modes of failure that are possible. For example, when the fibres are aligned, and the ends are not suitably confined, failure can occur at low stress due to splitting of the specimens at the ends. In order to avoid this type of failure either a waisted specimen is used [2] or the ends of the specimen are confined by special loading pieces [3, 4].

The composite strength is not easily related to fibre and matrix properties since the compressive strengths of the components, especially of the fibres, are usually not known, although values for a stiff carbon (1.3 GPa) and strong carbon (2.5 GPa) have been determined [5]. Experimental results overwhelmingly support a linear relation between compressive strength and volume fraction, V_f, (except for large values when $V_f > 0.8$) [6, 7]. However, the most widely recognized theory gives an inverse relation between compressive strength and volume fraction [8]. This is in marked disagreement with the deviations from linearity observed experimentally that show that at high V_f the strength falls below the linear relation observed at low V_f. In the case of carbon–epoxy composites this effect appears to be due to poor adhesion [9].

It has been suggested that the composite fails at the matrix yield strain, ϵ_{my}. Thus the compressive strength for aligned fibre composites, in the fibre direction (the 1 direction), σ_{1u}, is

$$\sigma_{1u} = (V_f E_f + V_m E_m)\epsilon_{my}, \qquad (1)$$

where E's are the moduli and the subscripts f and m refer to the fibre and matrix, respectively [10]. This expression gives the required variation of strength with V_f, and whilst it fits some reinforced polymers the relation tends to underestimate the strength of reinforced metals (which have very low yield strains).

Equation 1 suggests that the fibre compressive strength has no effect on the composite strength and therefore that it can only be applied to composites with strong fibres. Kevlar, which has poor compressive properties, gives composites which, by comparison, fail at low stresses [11], due to the low fibre strength.

It is likely that there are a great number of possible failure processes, each of which will have its own governing equations. This study was carried out to determine the effect on failure processes of fibre properties, and is an extension of the work of Moncunill de Ferran and Harris [12]. Steel wires were used as reinforcement so that a wide range of fibre strengths could be obtained by appropriate heat treatment.

2. Experimental method

The composites were manufactured in the form of

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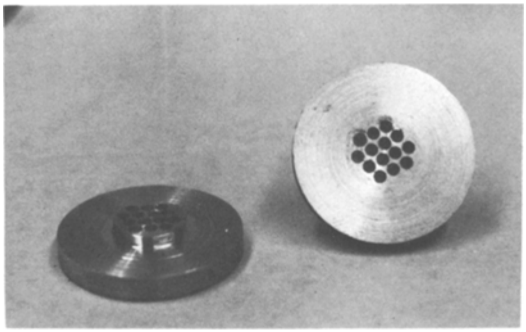

Figure 1 Aluminium guides used to align wires in the mould. The diameter of the flanges is 2.5 mm.

round bars 10 mm in diameter, using an aluminium mould. The steel wires were held in aluminium guides at the top and bottom of the mould, and the composite was made by liquid infiltration.

For most of the tests Shell Epon 815 resin with V40 curing agent was used in the ratio of 3:1. After mixing, the resin was centrifuged for at least ten minutes to remove trapped air.

Steel drill rods 1.59 mm in diameter were used as reinforcement. They were cut into 90 mm lengths, heated to 950° C and quenched in oil to harden them. They were next tempered in a salt bath for various lengths of time to obtain five different hardnesses. Then the rods were cleaned in a commercial cleaner containing formic acid, rinsed thoroughly in water and acetone, and dried by heating to 100° C for several hours. Finally they were tested for straightness by determining whether they would roll freely down a slope of 10° from the horizontal under their own weight. Any that failed this test were rejected.

The rods were assembled vertically in the mould and, after infiltration with the epoxy, and after being allowed to set for about sixteen hours, they were then cured for 1.5 h at 100° C. Fig. 1 shows the aluminium guides used to align the fibres in the mould.

For all tests, the bars were cut into 20 mm lengths and their ends were polished. (Their aspect ratio was 2:0.) They were tested in an Instron machine at a cross head speed of 2 mm min^{-1}, using hardened steel plates at each end of the bar, to protect the surfaces of the machine driver and load cell plates. Lateral supports at the ends of these specimens were found to be unnecessary, since they showed no tendency to split at the ends.

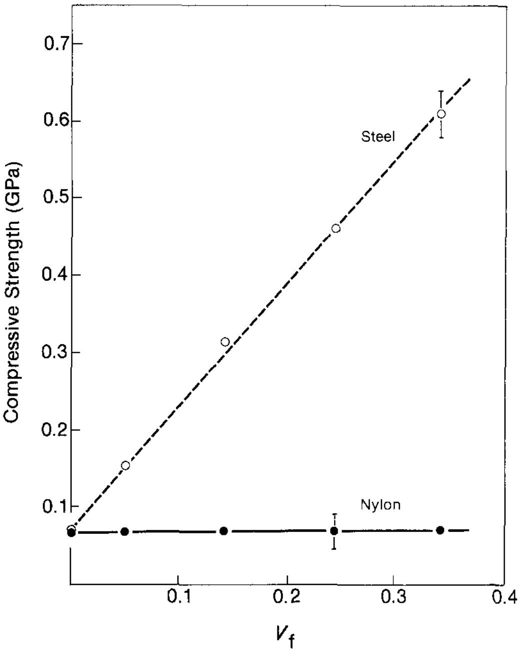

Figure 2 Variation of composite compressive strength with volume fraction for hard steel and nylon reinforced epoxy resin.

3. Results

The compressive strength of the specimens varied linearly with volume fraction for all steel hardnesses tested. Fig. 2 shows a typical result. The experimental points, each of which is the average of four tests, showed, for steel, increasing coefficient of variation as volume fraction was increased

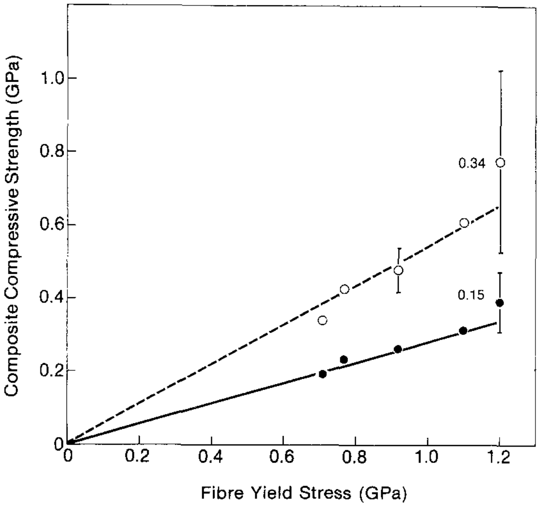

Figure 3 Variation of composite compressive strength with yield stress of steel reinforcement, for $V_f = 0.15$ and 0.34. Error bars indicated correspond to twice the standard deviation of the results. Where there is no error bar the standard deviation was very small.

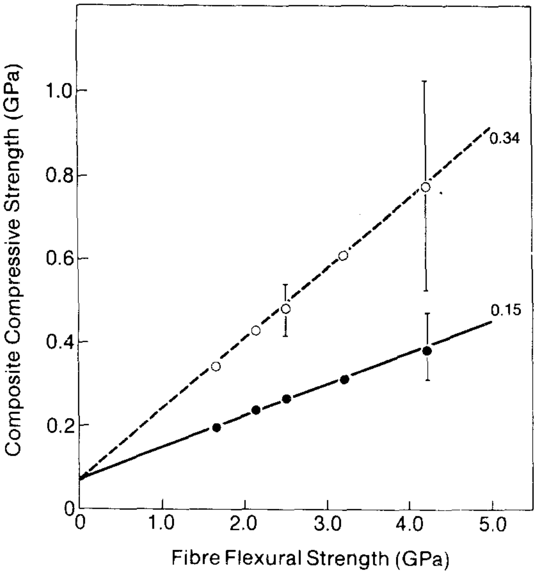

Figure 4 Variation of composite compressive strength with flexural strength of steel reinforcement, for $V_f = 0.15$ and 0.34.

from about 1% at $V_f = 0.05$ to about 10% at $V_f = 0.34$. The mean values fit the straight line with great fidelity; the correlation coefficient is 0.999. Control specimens made using nylon rods instead of steel, showed very little change of strength with change of V_f (Fig. 2).

At each volume fraction tested, the composite strength did not fit a straight line very well when plotted against the yield strength of the steel, as estimated from the hardness. The plot is shown in Fig. 3. It can be seen that the hardest wires produced composites of variable strengths, while the softer wires gave quite reproducible composites.. The hardness was measured by the Rockwell method, and converted to yield stress as recommended by Tabor [13]. The compressive strength of the composite did fit a straight line very well when plotted against the flexural strength of the steel. Fig. 4 shows the same set of strength results as Fig. 3, plotted against fibre flexural strength, instead of yield stress. The intercept with the y-axis corresponds quite closely to the matrix compressive strength.

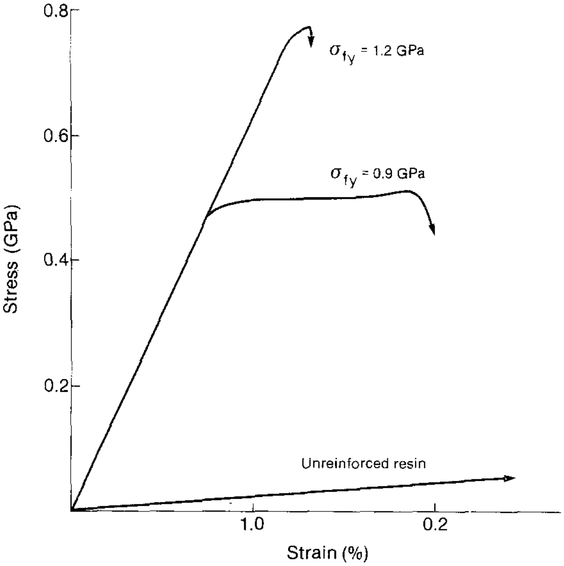

Figure 5 Typical stress–strain curves for composites with $V_f = 0.34$ using steel having yield stresses of 0.9 and 1.2 GPa. Unreinforced resin also shown.

Figure 6 Fragments from hard steel reinforced epoxy after compression test.

The stress–strain curves (Fig. 5) indicated that when the steel was relatively soft the composite had some ductility. This ductility progressively decreased as the steel hardness was increased, as is also shown in Fig. 5. This figure also shows the stress–strain curve of the reinforced epoxy resin. The specimens with the hardest steel failed suddenly; the rods disintegrated, and pieces of them flew away at high speed. Other rods were sharply bent. Fig. 6 shows pieces of such a failed specimen. The rods that disintegrated failed along planes at an angle of about 45° to the rod axis. The specimens containing the softer rods failed by plastic buckling, as shown in Fig. 7.

4. Discussion

With a specimen aspect ratio of 2, Euler buckling could not account for the specimen failures, and since no brushing was observed at the specimen ends, it is concluded that the true compressive strength of the specimen was being observed. The compressive strengths of the composites containing the hardest steel are almost identical to those for hard drawn steel in polyester resin observed by Moncunill de Ferran and Harris [12] and to

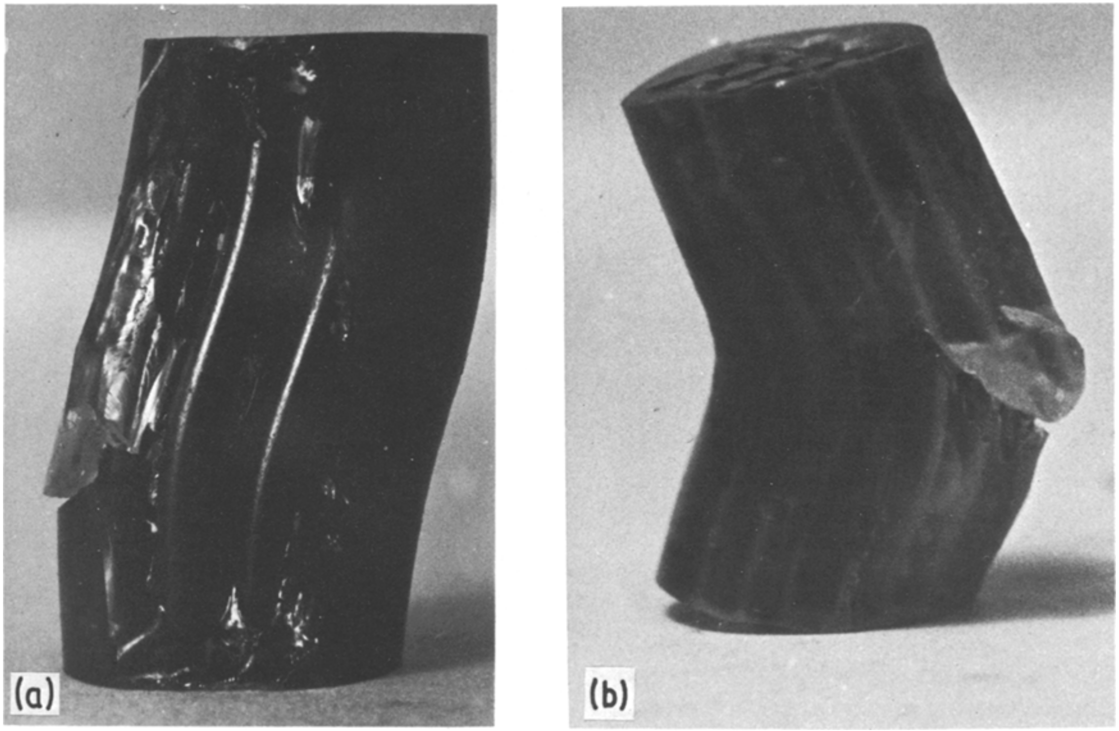

Figure 7 Failure modes for composites.

those for well-adhering strong carbon fibres in epoxy resin, observed by Hancox [9].

The experiments with nylon fibres clearly demonstrate the importance of fibre strength in controlling the composite strength, at least when the fibre is low. For steel fibres the composite strength varies linearly with V_f and obeys a Rule of Mixtures expression

$$\sigma_{1u} = V_f \sigma_{fcu} + V_m \sigma_m , \tag{2}$$

where σ_{fcu} has a value of about 0.55 of the flexural strength of the steel. The flexural test overestimates the strength of the steel because the material can yield in the most highly stressed regions, and the load can be transferred to other regions. Thus it seems likely that σ_{fcu} is close to the compressive strength of the steel. (Moncunill de Ferran and Harris [12] observed results that extrapolated to approximately the tensile strength of steel found in their work.)

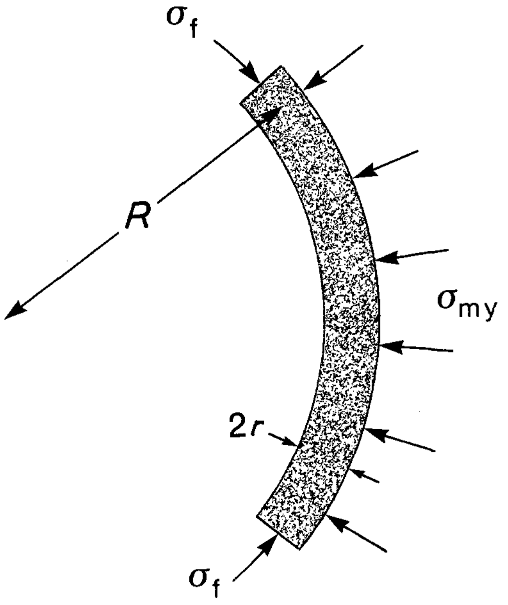

Figure 8 Segment of curved fibre.

The yielding of the steel does not appear to initiate failure; the stress in the steel when the composite failed was about 2.2 GPa for steel that yielded at about 1.2 GPa.

(For the matrix, $E_m \sigma_{fcu}/E_f$ should be used in preference to σ_m, since the failure strain of the fibres never exceeded 0.02. This is much less than the compressive yield strain of the matrix, which is 0.038. However, the matrix contribution to the strength is very small, except at very low V_f, and the results are adequately represented if the matrix ultimate compressive strength for σ_m is used.)

The process of failure initially involves the yielding of the steel. The steel then work-hardens, and the slope of the stress–strain curve is reduced (see Fig. 5). Failure follows the onset of plastic instability in the steel. The matrix can support the steel at the stress levels involved in these experiments, as can be shown by the following simplified treatment.

Suppose that the fibres, of diameter $2r$, are curved to a radius, R, have a compressive stress σ_f, and are supported by the matrix exerting a stress σ_m, as illustrated in Fig. 8. The condition for equilibrium is that

$$\pi r^2 \sigma_f = 2rR\sigma_m \tag{3}$$

It is assumed that σ_m operates over the projected fibre area of $2r$ per unit length. Since, at a moderate V_f, $\sigma_1 \simeq V_f \sigma_f$, then

$$\sigma_1 \simeq \frac{2V_f R\sigma_m}{\pi r}. \tag{4}$$

Providing that the matrix stress in the fibre direction is much less than its yield stress, then σ_m (which is normal to the fibre direction) can increase until it is very close to the ultimate compressive stress, σ_{mcu}. Thus the maximum value of σ_1 is

$$\sigma_{1max} \simeq \frac{2V_f R\sigma_{mcu}}{\pi r}. \tag{5}$$

Results from this work for the hardest steel are $\sigma_{1u} = 0.78$ GPa at $V_f = 0.34$, and $\sigma_{mcu} \simeq 69$ MPa. Thus for $\sigma_{1max} = \sigma_{1u}$, the ratio $R/r \simeq 52$. The rods in these experiments, however, were very straight, with $R/r > 4500$, since 90 mm long lengths would run freely down a 10° slope. For the other steels, R/r would have had to be less than 52 for the matrix to reach the yield stress. Thus it is concluded that the matrix can support the steel at these stress levels. Elastic instability [8] is also not predicted at these stress levels, since the elastic instability theory requires a stress of 1.14 GPa to cause failure of the composite and does not give the linear variation with V_f that is obtained here. The linear variation with V_f is observed with great fidelity, having a correlation coefficient of 0.999.

The hypothesis that the composite fails at the matrix yield strain [10] does not apply to these results, although it does give the correct variation of strength with V_f. In every case here, the composite failure strain was no more than a half of the matrix yield strain.

5. Conclusion

The compressive strength of the fibres play a very important role in the compressive strength of composites when failure takes place at strains which are less than the matrix yield strain. Under these conditions the composite compressive strength is given with sufficient fidelity by a Rule of Mixtures expression which includes the compressive strength of the fibres.

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