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The compression strength of unidirectional carbon fibre reinforced plastic

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A simple compression test, suitable for quality control measurements on unidirectional carbon fibre composite, is described. The specimen, a plane bar, with aluminium end tabs attached, is compressed by applying shear forces over the ends. With either type 1 or type 2 treated fibre the failure mode is one of shear over a plane at approximately 45° to the fibre axis. With untreated type 1 material failure is due to delamination. The variation of the compression strength of treated material with fibre volume loading is linear, the values being considerably below those predicted by buckling theory. Increasing void content causes a steady decrease in compression strength, and off-axis strength values are above those given by the maximum work criterion. The present work supports the recently proposed view that the compression strength of unidirectional carbon fibre composites at room temperature is not governed by fibre buckling but is related to the ultimate strength of the fibre.

1. Introduction

This work involved the study of a simple quality control test to measure the compression strength of unidirectional carbon fibre reinforced plastic (CFRP) specimens. The effects of unsupported specimen length, waisting in depth, fibre type, surface treatment, and loading, the void content of the matrix and the angle between the fibre and the compression axis were all investigated. A study of the microscopic aspects of failure was also made to try to deduce the physical processes occurring in failure.

2. Previous work

Detailed accounts of the practical and theoretical work on the compression properties of composites are given by Orringer [1] and Greszczuk [2] and only the pertinent aspects will be described here. Several methods have been suggested for calculating the compression strength of a composite material. Rosen [3] believed that failure occurred due to fibre microbuckling, and calculated the compression strength of a two dimensional array of fibres in a matrix, noting two cases, out-of-phase buckling, the extension mode, and in-phase buckling, the shear mode. The former applied at low fibre volume fractions and the latter at higher ones. For a large number of buckling wavelengths the stress at which failure occurs in the extension mode, σ_{ce}, is given by

$$\sigma_{ce} = 2\left[\frac{V_f E_m E_f}{3(1 - V_f)}\right]^{\frac{1}{2}}, \qquad (1)$$

while for the shear mode the stress, σ_{cs}, is given by

$$\sigma_{cs} = \frac{G_m}{1 - V_f} \qquad (2)$$

where V_f is the fibre volume fraction, E_f and E_m are the tensile moduli of the fibre and matrix respectively, and G_m the shear modulus of the matrix. Both equations are modified by the addition of an extra term if only a few buckle wavelengths are considered.

Sadowsky *et al.* [4] gave a rigorous analysis of the buckling of a round fibre and Herrmann *et al.* [5] dealt with the situation in which the fibres are initially deformed, but neither piece of work is directly applicable to practical composites as it was necessary to consider very low fibre volume loadings in order to be able to ignore the effects of mutual interaction between fibres.

Evidence of microbuckling has been supplied by Rosen for a glass fibre embedded in resin, though the deformation was due to differences in thermal expansion between the glass and resin setting up stresses on cooling, and not a direct compression load. Chung and Testa [6] observed buckling in glass fibre reinforced composites, with fibre resin moduli ratios of 810 and 1100:1, when these were loaded in compression, and de Ferran and Harris [7] showed that a, possibly, helical type of buckling occurred when a steel wire set in a polyester resin was compressed. With a carbon fibre in resin they observed a regularly spaced series of fractures, part shear and part lateral splitting. Greszczuk suggested that fibre buckling took place in this case but that the fibres being brittle, shattered. Experimental measurements of composite compression properties have been made by Lager and June [8] on boron/epoxy, and by Ewins [9] on carbon fibre/epoxy material. Both obtained strengths well below those given by Equations 1 and 2. The former authors suggested that a numerical coefficient which allowed for the three-dimensional nature of the reinforcement be introduced into Equation 2, while the latter thought that the discrepancy was caused by real composites having a three-dimensional nature, the irregular spacing of fibres especially at low loadings, initial deformation of the fibres, and poor bonding.

Orringer modified Rosen's theory by using tangent moduli, and by using it together with the overall composite modulus (from the law of mixtures) to obtain the minimum strain at which buckling occurred. Finally he suggested that transverse stress concentration in the matrix influenced failure. Greszczuk carried out experiments on constant volume fraction model systems, consisting of relatively thick carbon rods or steel wires in an epoxy resin. He obtained higher values of compression strength than predicted by Equation 2 even when this was modified by the addition of an extra term to allow for a small number of buckle wavelengths. He also showed that initial deformation drastically reduced compression strength.

A different type of model was proposed by Foye [10] who showed that shear instability, and hence overall failure, occurred if the compression stress equalled the shear modulus of the composite. Using a series model to give the composite shear modulus in terms of the component properties, and assuming that the fibre shear modulus is much greater than that of the resin, his result reduces to Equation 2. Hayashi [11] extended the work by pointing out that the shear modulus of the matrix would be a function of the compression stress and proposed that failure occurred if

$$\sigma_m = G_m(\sigma_m) \tag{3}$$

where σ_m is the compression stress on the matrix and $G_m(\sigma_m)$ the shear modulus of the matrix when the stress is σ_m. The compression strength, σ_c, of the composite is then given by

$$\sigma_c = \sigma_f V_f + \sigma_m(1 - V_f) \tag{4}$$

where σ_m is the stress on the matrix at which instability or yielding first occurs and σ_f is the fibre stress, calculated from Hooke's law, at the strain at which matrix instability occurs. This approach accounts for the results of Lager and June, but as Ewins and Ham [12] point out, if the critical matrix strain is independent of and less than that of the reinforcement, the compression strength of a type 1 carbon fibre composite will tend to be greater than that of the type 2 composite, in contradiction to what is observed.

Another approach is due to Argon [13] who suggested that buckling failure gives an upper bound to compression strength and that in real specimens areas of misalignment undergo kinking and initiate failure. If the angle between the local fibre direction and compression axis is ϕ the compression strength, σ_c, is given by

$$\sigma_c = \frac{\tau}{\phi} \tag{5}$$

where τ is the interlaminar shear strength. This decreases with increasing fibre volume loading and so presumably should ϕ, but it is not possible to say exactly how σ_c will vary with fibre content, making verification of Equation 5 difficult.

Measurements of compression strength on steel wire/polyester or epoxy, boron/polymide, and carbon/epoxy composites reported by de Ferran and Harris, Sierakowski *et al.* [14], Orringer, Argon, and Ewins and Ham, all show that the first sign of compression failure in a uniaxial specimen is the formation of a broad band of shear damage at approximately 45° to the compression axis. This indicates that in many cases failure is due to shear rather than buckling.

Ewins and Ham recently described some interesting experiments in which they showed that for carbon/epoxy composites the longitudinal and constrained transverse compression strengths, and modes of failure, are very similar at room temperature. Since buckling cannot occur in the latter case, this work offers strong support for the idea that compression failure may be initiated by a shear mechanism.

3. Experimental work

Ewins [15] considered the design of composite compression specimens and noted that unless the ends were supported, failure often started there by transverse delamination. The design he recommended was a bar specimen waisted in depth with the ends supported by cementing into aluminium alloy blocks with accurately machined parallel ends.

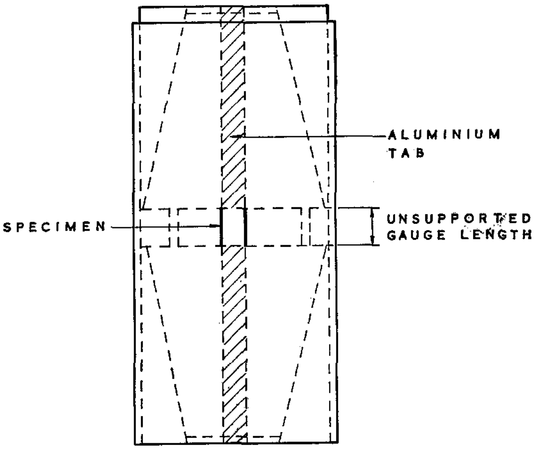

Figure 1 Compression jig.

Park [16] described a jig in which plane bar specimens were loaded in compression by applying a shear force over tabs of aluminium or fibre glass attached to the ends of the specimen. An approximately full size sketch of the jig is shown in Fig. 1. It consists of two cylindrical split collets, at the top and bottom, which fit snugly into hollowed out end pieces. The plane bar specimen with end tabs is fitted into a groove running down the centre line of each split collet. The collets are clamped onto the specimen by hand and two metal rods protruding from either half of the top collet engaged in holes in the bottom one such that there is an unsupported section of specimen between the two collets. A 5 mm thick piece of square cross-section metal rod is used to keep the collets apart while the hollowed out end pieces are slipped over the top and bottom. An outer metal sleeve, with a hole in the centre to allow access to the specimen, is then pushed over the whole assembly, though the top split collet and enclosing metal end piece project above the sleeve as shown in the figure. To carry out a test a preload of 10 to 20 kg is applied several times to the jig in order to bed the collets onto the end tabs. Finally the metal spacer is removed and the jig compressed until the specimen breaks.

This method was adopted here since standard bar specimens already produced for other quality control work, could be used with a minimum of extra preparation. The specimens were 110 mm × 6.3 mm × 1 mm with end tabs extending over approximately a 50 mm length of either end.

Unidirectional specimens were made by a wet lay-up technique from type 1 treated and untreated (1T and 1U) and type 2 treated (2T) carbon fibre, and a liquid bisphenol A resin. The resin mix consisted of 100 p.b.w. resin, 80 p.b.w. methyl nadic anhydride hardener, and 2 p.b.w. benzyldimethylamine accelerator, cured for 2 h at 120°C. Specimens produced by this method normally contain less than 0.5% voids, and to make specimens with increased void content the fibres were soaked in acetone before being saturated with resin, and then heated at 80°C for times between 1 and 30 min to drive off some of the acetone before pressing.

The void content of several of the higher voidage specimens was determined from a knowledge of the densities of the fibre, resin and composite and the weights of fibre and resin in the latter. The relationship between composite density and void content was linear, thus allowing the percentage of voids in all specimens, especially those containing only 1 or 2%, to be determined. Some pure resin specimens were also made and machined.

In order to have a compression rather than a Euler buckling failure, it was necessary to determine the unsupported gauge length (the length of the specimen between the ends of the aluminium tabs, and also the split collets – see Fig. 1) to give a constant failure stress. The results for 60 vol % fibre composites and pure resin, loaded longitudinally, are shown in Fig. 2. Provided that the gauge length is less than about 6 mm, the stress is constant for a given type of specimen and a compression rather than buckling strength is measured. It was assumed that the gauge length was the same for other volume loadings. This is supported by the similarity of the results for pure resin and 60 vol % composites. In all experimental work unless otherwise stated, a gauge length of 5 mm was used.

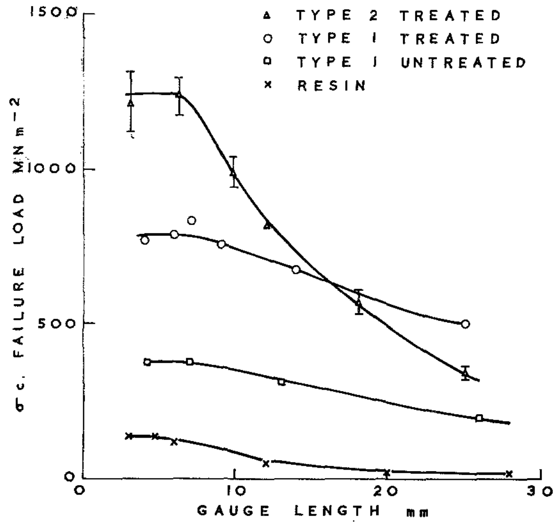

Figure 2 Failure load as a function of gauge length for 60 vol % carbon fibre composites.

When failure was due to buckling, the mode of failure was shear at approximately 45° to the long axis, for gauge lengths between 5 and 9 mm, while for longer lengths the break was similar to that noted in a flexural test.

The effect on the compression strength of waisting standard bar specimens to a depth of about 0.67 mm, with a radius of curvature between 2 and 125 mm, is shown in Fig. 3. Below a radius of curvature of 10 mm failure was always due to shear in the shoulders, but above this a 45° shear break in the centre of the waisted region was obtained. No measurements were made for waisting radii between 10 and 125 mm. It was observed that in unwaisted specimens though failure very often occurred at or near the tip of one of the end tabs the compression strength and nature of the break were the same as with a 125 mm radius of curvature specimen. Because of this, and the added simplicity, plane bar specimens were used throughout this work. It was also of interest to note that compression strengths measured here are very similar to those reported by Ewins [15], and Purslow and Collings [17] using much larger, waisted, specimens supported in aluminium alloy end blocks.

Fig. 4 shows the compression strength of plane bars, stressed longitudinally, as a function of the fibre volume loading. Each point represents the mean of up to six readings. In all cases failure occurred catastrophically. For 1T and 2T composites the variation is linear, but for 1U composites the strength does not increase at all above 40 vol %. Also the type of break noted in the latter case, usually massive delamination, was quite unlike the shear break of treated fibre specimens.

Although for any given volume loading the compression strength is usually less than the tensile strength (by about 12 % for the 60 vol % 2T material used here), the variation of compression strength with fibre volume loading is similar to that noted for tensile.

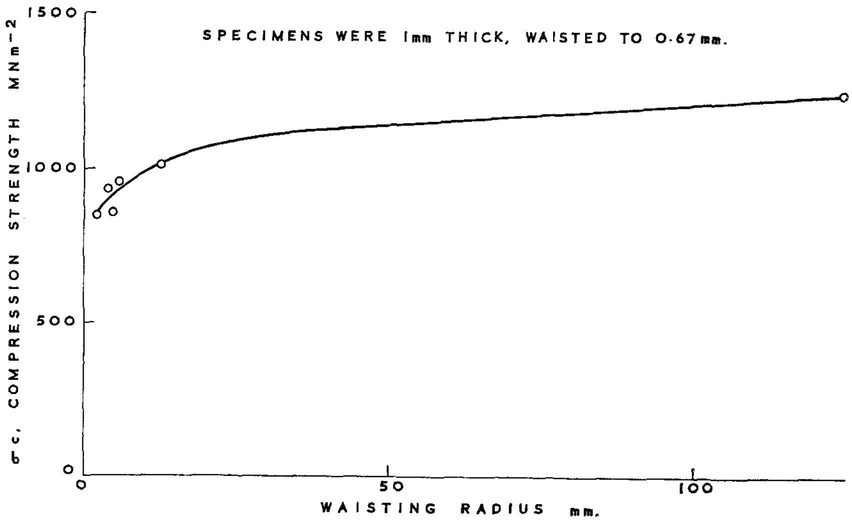

Figure 3 Compression strength as a function of waisting radius for 60 vol % type 2 carbon fibre composite.

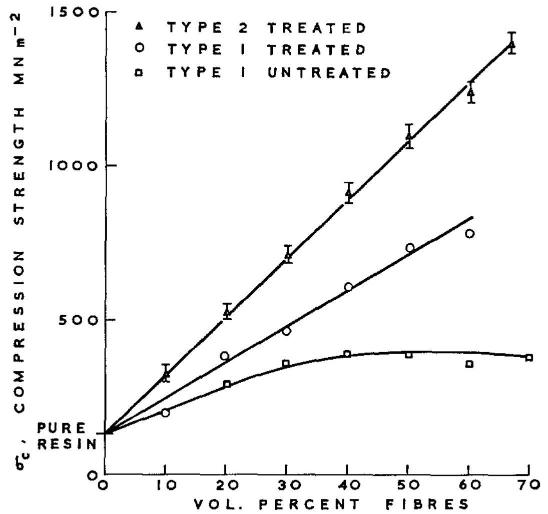

Figure 4 Compression strength as a function of carbon fibre content.

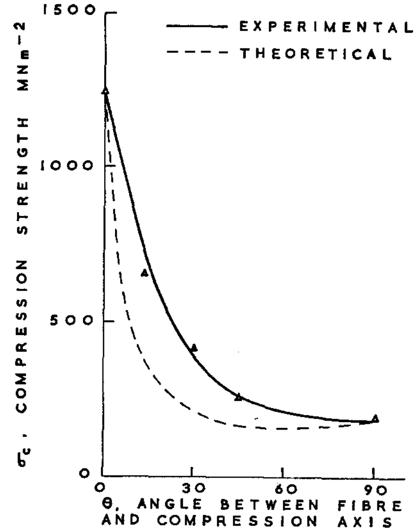

Figure 5 Compression strength as a function of angle between fibre and axis for 60 vol % type 2 carbon fibre composite.

The variation of the compression strength of a 60 vol % 2T composite with the angle between the fibre and compression axis is shown in Fig. 5. The theoretical curve was calculated from the maximum work theory, Tsai [18]. The equation used was:

$$\frac{1}{\sigma_{c\theta}{}^2} = \frac{\cos^4\theta}{\sigma_{cl}{}^2} + \left(\frac{1}{\tau^2} - \frac{1}{\sigma_{cl}{}^2}\right) \sin^2\theta \cos^2\theta + \frac{\sin^4\theta}{\sigma_{ct}{}^2} \tag{6}$$

where $\sigma_{c\theta}$ is the compression strength at an angle θ to the longitudinal axis, and σ_{cl}, σ_{ct} and τ the longitudinal and transverse compression strengths and interlaminar shear strength respectively. This model allows for the interaction between the various failure modes and is applicable to failure under tensile, compressive or shear stresses or a combination of these. Experimental values of σ_{cl}, σ_{ct} and τ were used in the calculation and this accounts for the agreement between theory and experiment for $\theta = 0°$ and 90°. Use of the maximum stress criterion, see Kelly [19] for instance, gave a very similar variation. Off-axis specimens failed in shear on a plane between the fibres.

The influence of void content on compression strength is shown in Fig. 6. The highest compression strength is for a nominal zero void content. It can be seen that there is a steady decline in strength with increasing voidage. The fracture mode rapidly changes from a clean shear break to a ragged failure with considerable delamination. The effects of voids on the flexural modulus and strength and short beam shear strength were determined in three point bending using span to depth ratios of 100:1, 40:1, and 5:1 respectively. To compare the results easily the ratio of the modulus or the appropriate strength, at any void content, to the value at zero void content, expressed as a percentage, is plotted against void content in Fig. 7. As would be expected the modulus is least affected, while above 5 % voids the compression strength is most reduced. The interlaminar shear strength is very sensitive up to 1 % voids. The lack of correlation between the different strength properties indicates that voids have a different effect on each case.

To obtain information on the mechanics of the failure process sections from about 30 specimens were mounted, polished and examined with an optical microscope. In the large majority of cases the failure surface made an angle of approximately 45° to 50° with the fibre axis. Typical pairs of failure surfaces are shown in Figs. 8 to 11. All are for 2T fibre composites, the first with a fibre volume loading of 30 vol %, and the others with a loading of 60 vol %. Fig. 8 shows a clean shear break with a minimum of fibre damage. In the other cases there are

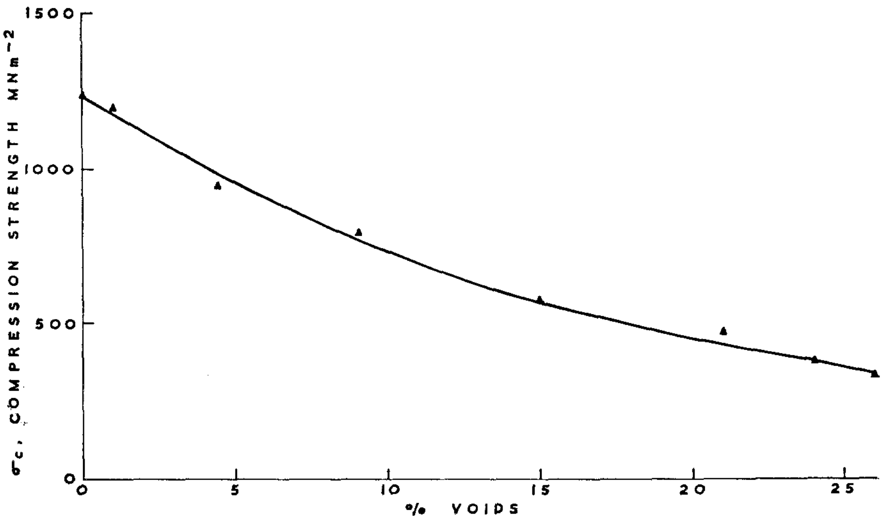

Figure 6 Compression strength as a function of void content, 60% type 2 carbon fibre composite.

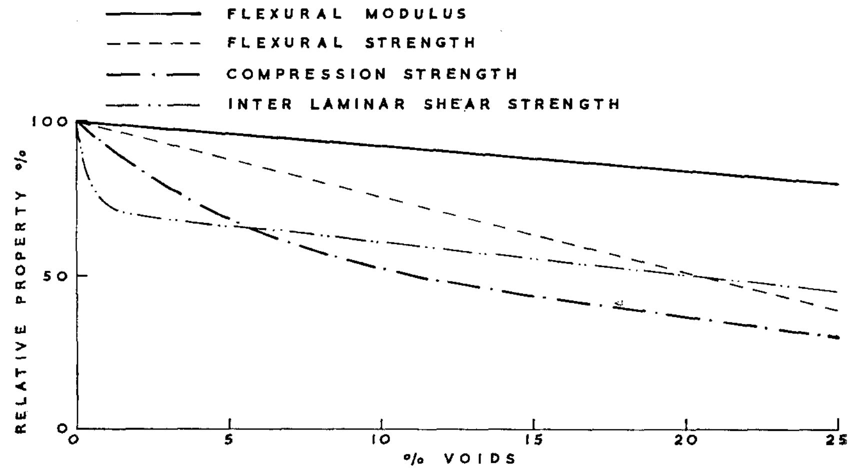

Figure 7 Relative property (i.e. compression strength at given void content/compression strength at 0% voids) as a function of void content for 60 vol % type 2 carbon fibre composite.

varying degrees of fibre displacement indicating the possible presence of a kinked region at some stage of failure. In addition in Figs. 10 and 11 there is evidence of some transverse delamination.

Larger blocks of pure resin failed under a compression stress by shear along a 45° plane, at an average strain of 4.3%. Unfortunately the strain to failure of composite specimens could not be measured because of a slight slippage in the grips. However, most specimens failed after approximately the same amount of crosshead traverse.

4. Discussion

The variation of failure load with unsupported gauge length, shown in Fig. 2, is not unexpected. However, attempts to interpret the curves on the basis of buckling theory were not particularly successful. A fit could only be obtained by assuming that the end conditions changed with gauge length, or for constant boundary conditions, by assuming that the strut was eccentrically loaded. For a 60 vol % 2T composite the eccentricity decreased significantly with decreasing gauge length, while for 1T material the results were more variable.

Of more interest and importance is the type of failure obtained, and the dependence of compression strength on the volume fraction of fibres. The linear nature of the results for treated material is similar to that reported for steel wire/polyester by de Ferran and Harris, carbon fibre/epoxy by Ewins and Ham, and boron/epoxy by Lager and June, though the latter did not themselves fit a straight line to their data. Both in magnitude and form the results obtained here are unlike those predicted by the analyses of Rosen and Foye. The shear modulus of the epoxy resin used was 1.4 GN m^{-2} and putting this in Equation 2 gives compression strengths, independent of fibre type, ranging from 1720 MN m^{-2} at 20 vol % to 3500 MN m^{-2} at 60 vol % – about three times larger than the maximum observed.

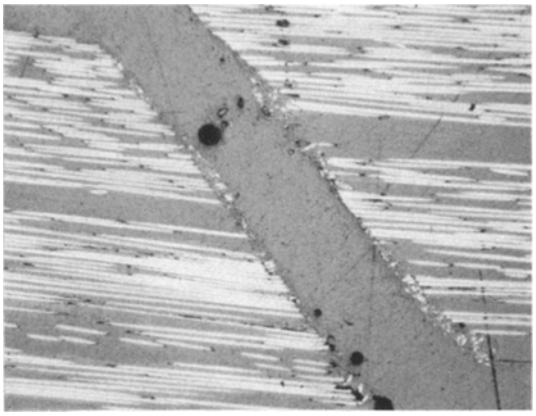

Figure 8 Section through break in 30 vol % type 2 carbon fibre composite, × 50.

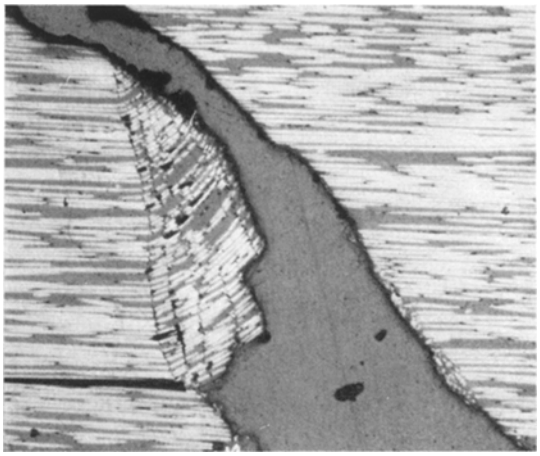

Figure 10 Section through break in 60 vol % type 2 carbon fibre composite, × 50. Note fibre misalignment.

Although Hayashi's treatment gives a linear relation between compression strength and fibre content, it is most unlikely to apply here. The pure resin yielded at 4.3 %, well above the tensile strains at failure of 1T or 2T fibre, and presumably above the compression failure strains. Also unless the yield strain of the resin in a composite is less for the 1T than 2T composite, the failure strength of the former would be greater than the latter, in contradiction to the experimental results.

A study of the type of break noted here for treated carbon fibre shows a fairly typical shear failure straight through the specimen at an angle of about 45° to the compression axis, possibly some delamination, and often small amounts of

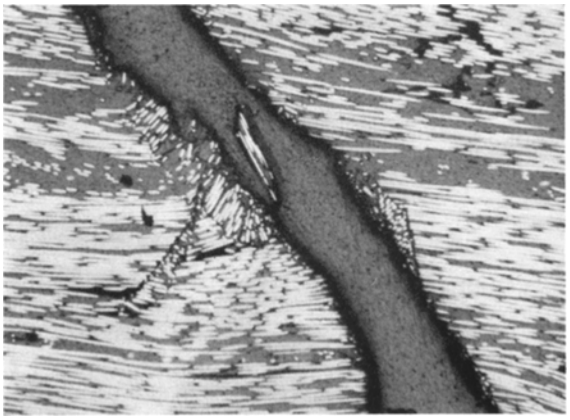

Figure 9 Section through break in 60 vol % type 2 carbon fibre composite, × 50. Note fibre misalignment.

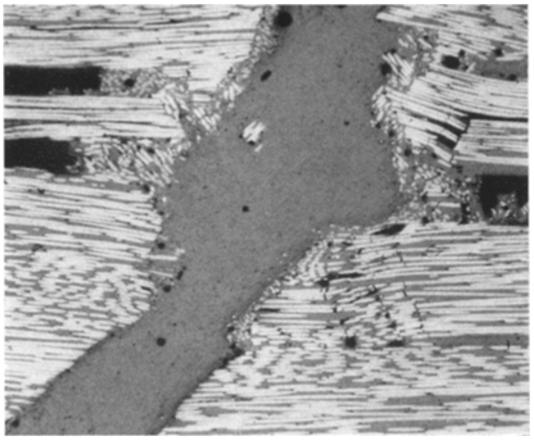

Figure 11 Section through break in 60 vol % type 2 carbon fibre composite, × 50. Note fibre misalignment and delamination.

fibre misalignment and cracking. The latter are not observed in undamaged specimens and may be caused by the relative sliding of the two faces after failure, but the regions of fibre cracking and rotation that can be seen on the left of Figs. 9 to 11 are very similar to the damage noted by Hancox and Wells [20] in short beam shear specimens, and Hancox [21] in impact specimens, where failure was initiated by compression. Hence it seems probable that at least some of the damage observed is intrinsic to the failure process and not caused by sliding. Attempts to calculate the compression strength on the basis of this type of localized failure using some form of energy criterion have been unsuccessful.

In view of the failure of buckling and instability theories to predict measured compression strengths of composites and the similarity between the compression and tensile strengths, it is concluded, in agreement with Ewins and Ham, for treated carbon fibre epoxy resin systems tested at room temperature, that the compression strength of a composite is governed by the same mechanism as the tensile strength and is an inherent property of the fibre. For untreated 1 fibre composites failure is due to transverse delamination, the bonding being too poor for the full fibre strength to be realized.

Voids in the matrix decrease the compression strength markedly. It is probable in view of the delamination type failure observed in this type of specimen that some of the decrease is due to poorer bonding between the fibre and resin. Also at higher void contents serious fibre misalignment was visible in the specimen and this would lower the strength. Foye attempted to calculate the effect of cylindrical voids on compression strength, producing an expression in which Equation 2 is multiplied by a factor including the first and second powers of the void content. Although this did not give correct absolute values it is interesting to note that for a 60 vol % 2T composite it gives, quite accurately the relative decrease in strength up to 10 % voids, but then predicts much lower values.

The effect of fibre angle to the compression axis is, of course, considerable, but unlike the case for glass fibre composites the maximum work failure criterion underestimates the compression strength.

Assuming that the basic form of Equation 6 is correct the lower predicted values of compression strength for intermediate angles appear to be due to a low value of the interlaminar shear strength, τ, rather than errors in the longitudinal or transverse compression strengths. The value of τ used here was determined in a short beam shear test and it is possible that because of the complex mode of stressing in this test the value of τ obtained is not suitable for use in Equation 6. In addition the experimental curve between 45° and 90° has been extrapolated and further work might show a dip in this region leading to better agreement with theory.

5. Conclusion

It has been shown that plane bar specimens with tabs attached to the ends can be used in a split collet type jig to give repeatable values of compression strength comparable to values obtained with large waisted specimens. Such a jig and specimen design would be ideal for quality control compression strength measurements on composites. The position of failure in relation to the end tabs does not influence the strength measured. In untreated material failure is due to delamination.

With treated carbon fibre composites the compression strength varies linearly with fibre volume loading and the mode of failure is one of shear at approximately 45° to the loading axis. There is evidence of localized fibre rotation which may occur before or during failure, but following Ewins and Ham it is suggested that the overall composite compression strength depends on the fibre strength.

The compression strength is reduced significantly and steadily by the presence of voids. The off-axis compression strength is greater than that predicted by the maximum work failure criterion.

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References

1. O. ORRINGER, AFOSR TR 71 3098 (1971).
2. L. B. GRESZCZUK, AFML TR 71 231 (1972).
3. B. W. ROSEN, Mechanics of Composite Strengthening, in "Fibre Composite Materials" (A.S.M., Cleveland, Ohio, 1965) pp. 37-75.
4. M. A. SADOWSKY, S. L. PU and M. A. HUSSAIN, *J. Appl. Mech.* **34** (1967) 1011.
5. L. R. HERRMANN, W. E. MASON and S. T. K. CHAN, *J. Composite Mat.* 3 (1967) 212.
6. W. Y. CHUNG and R. B. TESTA, *ibid* 3 (1969) 58.
7. E. M. DE FERRAN and B. HARRIS, *ibid* 4 (1970) 62.
8. J. R. LAGER and R. R. JUNE, *ibid* 3 (1969) 48.
9. P. D. EWINS, RAE TR 70007 (1970).
10. R. L. FOYE, AIAA, 3rd Aerospace Sciences Meeting, N.Y., USA (1966) Paper 66-143.
11. T. HAYASHI, 7th International Reinforced Plastics Conference, Brighton, UK, (1970) Paper 11.
12. P. D. EWINS and A. C. HAM, The Nature of Compressive Failure in Unidirectional Carbon Fibre Reinforced Plastics. To be published.
13. A. S. ARGON, Fracture of Composites, in "Treatise on Materials Science and Technology", Vol 1 (Academic Press, New York, USA, 1972) pp. 79-114.
14. R. L. SIERAKOWSKI, G. E. NEVILL, C. A. ROSS and E. R. JONES, *J. Composite Mat.* **5** (1971) 362.
15. P. D. EWINS, RAE TR 71217 (1971).
16. I. K. PARK, Tensile and Compressive Test Methods for High Modulus Graphite Fibre Reinforced Composites, Carbon Fibres, London, "Plastics and Polymers", Supplement No. 5 (1971) Paper No. 23.
17. D. PURSLOW and T. A. COLLINGS, RAE TR 72096 (1972).
18. S. W. TSAI, Strength Theories of Filamentary Structures, in "Fundamental Aspects of Fibre Reinforced Plastic Composites", edited by R. T. and H. S. Schwartz (Interscience, New York, 1968) pp. 3-11.
19. A. KELLY, "Strong Solids" (Oxford University Press, 1966) pp. 150-55.
20. N. L. HANCOX and H. WELLS, Carbon Composite Technology Symposium (ASME), University of New Mexico, Albuquerque, N.M., USA. 37-53 (1970).
21. N. L. HANCOX, *Composites* **2** (1971) 41.

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