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Compressive fracture in undirectional glass-reinforced plastics

C. R. CHAPLIN
Department of Engineering and Cybernetics, University of Reading, Whiteknights, Reading, UK

The shear mode of compressive failure in unidirectional fibre composites is discussed. A mechanism is described in which the shear deformation is restricted to a band of material inclined to the plane normal to the fibre axes. The relationship between the orientation of the failed band of material and the limiting shear deformation in the band is explained in terms of volumetric strains. Tests are described which demonstrate that, in GRP, this type of failure can propagate from a notch and this notch sensitivity is put forward as an explanation for the apparent inadequacy of the theoretical model. The sequence of events in the propagation of compressive failure is studied by examining serial sections of an arrested failure. It is found that fibre fracture at the boundaries and interlaminar failure within the band follow as a result of increasing shear deformation in the band.

1. Introduction

The low compressive strength of unidirectional fibre composites has been a problem for some time. The expressions for micro-buckling were first published by Rosen [1] but these theoretical strengths have only been approached under carefully controlled conditions with samples prepared in such a way as to give near perfect alignment and distribution [2] and even then the measured strengths are nearly 40% below the theoretical values. This difference was explained by the geometrical differences between the two-dimensional model and the three-dimensional real material with cylindrical fibres.

In the course of work (to be published) on compressive failure of CFRP, some attention was also given to GRP. The *modus operandi* of this programme was to take a fracture mechanics view of compressive failure, an approach which has shown some success. The essence of the approach is that low compressive strength can be attributed to sensitivity to defects from which local failure can propagate across the material. This paper is the result of an attempt to understand the compressive behaviour of glass-reinforced systems in this light.

2. The shear mode of composite failure

Of the two theoretical failure modes described by Rosen [1], the buckling mode and the shear mode, in any composite with a realistic fibre volume fraction over 15% and a plastic matrix which ensures a modulus ratio of at least 20:1, then the shear mode will give the lower bound for strength [3].

If we assume that shear deformation in the reinforcement is small compared with that in the matrix, then the critical compressive stress for the shear mode depicted in Fig. 1a is given by the expression:

$$\sigma_{\text{crit}} = \frac{G_{\text{m}}}{(1 - V_{\text{f}})} \tag{1}$$

where G_{m} is the matrix shear modulus and V_{f} the fibre volume fraction.

In practice, this mode has a somewhat different appearance to that shown in Fig. 1a. Fig. 1b shows a typical failure in GRP. Note that the shear deformation is restricted to a band of material with sharply defined boundaries at a characteristic angle to the reinforcement direction.

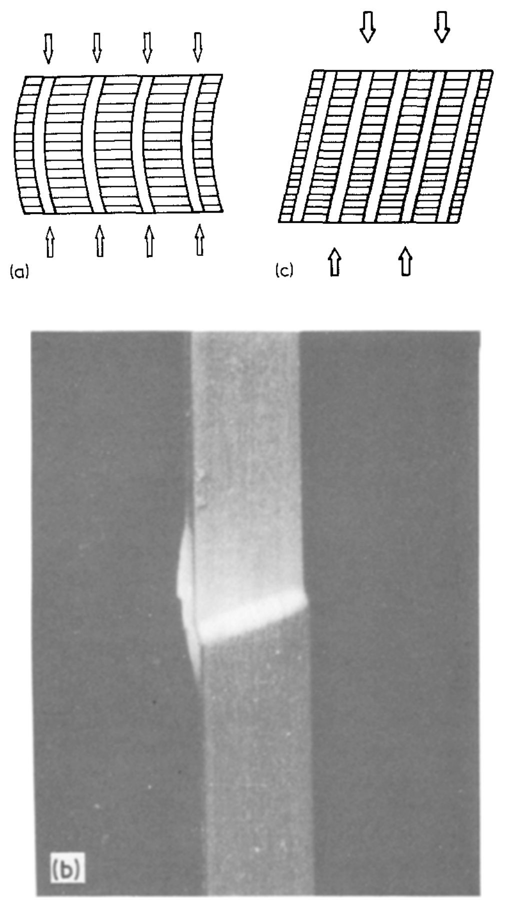

Figure 1 The shear mode of compressive instability. (a) Rosen's model; (b) failure in GRP × 8; (c) an alternative model for gross shear instability.

Now this shear mode is an "elastic" instability and it is therefore not determined by strength considerations. It involves shear instability in a volume of material – not failure on a plane due to a resolved stress. The same theoretical result is obtained by considering a failure of the type shown in Fig. 1c. But, discounting any lateral dilation, if this mode is to involve any deformation in the direction of the applied stress, it must necessarily involve a reduction in volume. Therefore, this failure mechanism is impossible here. However, if we consider the same type of instability but in a slice of material inclined at some angle α to the end faces, as in Fig. 2, then omitting the effects of any changes in axial stress and considering only the effects of shear rotation within the band, the volumetric strain in the sheared slice is given by

$$\epsilon_{\text{vol}} = \frac{\cos(\alpha - \gamma)}{\cos \alpha} - 1 \qquad (2)$$

where γ is the shear strain. Therefore, for $\alpha > 0$ the volumetric strain will initially be positive, returning to zero when $\gamma = 2\alpha$. This angular relationship is the same as that noted by Weaver and Williams [4] who observed a similar mechanism in CFRP, but derived here from a volumetric strain argument. The argument is dependent on assuming that as the shear deformation increases, the angle of the band and the length of fibres within the band do not change. This is in contrast to the mechanism proposed by Weaver and Williams who, likening the process to the development of kink bands in zinc, suggest that as the shear deformation increases the band rotates, thereby maintaining a constant relationship, $\gamma = 2\alpha$, throughout. The validity of this assumption is examined below for a propagating band.

In a unidirectional fibre composite under axial compression, once there has been any significant amount of interfacial failure, then there will be little resistance to a large positive volumetric strain. However, in the presence of a hydrostatic stress component or reinforcement in a direction such that it restricts lateral expansion, then the expected effect of this extra constraint would be an increase in compressive strength.

Thus there is a limit set on the longitudinal compressive displacement associated with a shear failure in terms of the inclination of the shear zone α and the associated maximum shear strain 2α. If we think in terms of a propagating shear failure, then a maximum of strain energy will be released

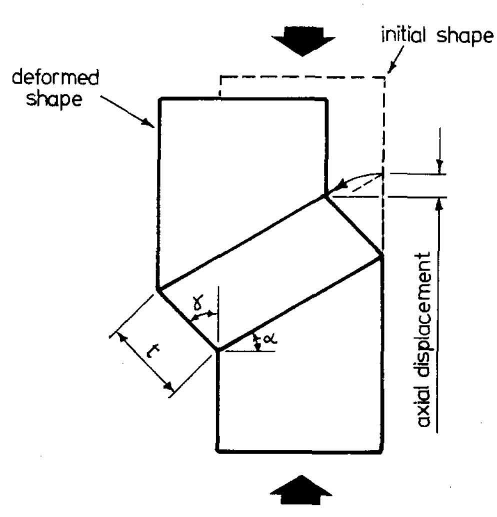

Figure 2 Geometry of a shear band, showing rotation of elements within the band and the associated axial displacement.

when there is no axial stress in the fibres in the failed region. This condition will be met when the longitudinal compressive displacement associated with the shear deformation ($\gamma = 2\alpha$) and the longitudinal recovery due to the fall in stress both within the collapsed band and to some distance on either side, are equal. In other words, the material can relax without any net increase in length. Thus for a failure band of thickness t, complete relaxation over a distance kt and an assumed local stress just prior to collapse given by Equation 1,

$$t(1-\cos 2\alpha) = \left(\frac{G_m}{1-V_f}\right)\left(\frac{kt}{E_f V_f + E_m(1-V_f)}\right).$$

For composites where $V_f E_f \gg E_m(1 - V_f)$ this simplifies to give

$$\sin^2 \alpha = \frac{kG_m}{2(1-V_f)V_f E_f}. \quad (3)$$

Substituting typical values into this equation suggests that to obtain the right sort of value for α, k will then approach 10. With $t \approx \frac{1}{2}$ mm this may seem excessive, although in highly anisotropic materials, such as we are considering here, stress will be relieved over a much greater depth from a transverse crack than in an isotropic material [5]. This is also confirmed by compliance measurements in edge notched compression specimens of CFRP (to be published).

3. Experimental work

A number of tests were performed in the course of this study: some of a straightforward type to establish strength and demonstrate the mode of failure, the others involving notched samples. The objective in the later type was to demonstrate first that failure would propagate from a defect and then to attempt to arrest a failure so as to facilitate a close examination of the material in the region of the tip of the failed zone.

3.1. Samples

The material used in these tests was Shell "Epikote 828"/NMA BDMA reinforced with 60% by volume E glass (Fibreglass Suprewind). The proportions of the resin components were 100:60:1.5, by weight. Composites were cured for 2h at 100° C followed by 10h at 125° C.

In manufacturing samples, a wet lay-up process was chosen in preference to pre-preg as it was thought this would give a more uniform material with the added advantage of being able to vary the volume fraction. The reinforcement was passed through a bath of warm resin and wound onto an open wire frame. After the required number of revolutions the impregnated reinforcement was pressed into a "leaky mould". Keeping the reinforcement on the frame ensured that fibres remained well aligned during the cure. This system was found to give excellent results producing a composite of uniform volume fraction, with good alignment and very low voids fraction.

The type of specimen and the end fixtures were similar to those recommended by Ewins and Ham [6]. The specimen geometry is shown in Fig. 3 and the end fixtures are shown in Fig. 4. The end fixtures were aligned in a jig before the sample was clamped and glued with cyanoacrylic impact adhesive. In designing the loading arrangement great care was taken to make the system as stiff as practicable in order to minimise the energy stored.

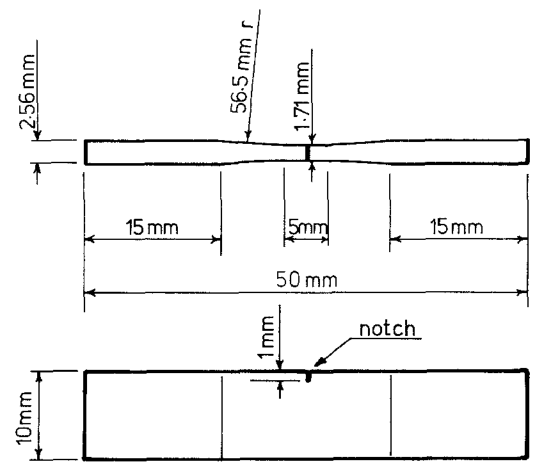

Figure 3 Geometry of test specimen. For testing, the parallel end sections are clamped in the end fixtures.

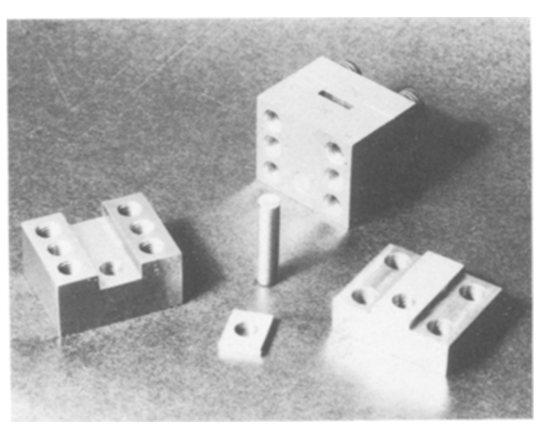

Figure 4 End fixtures.

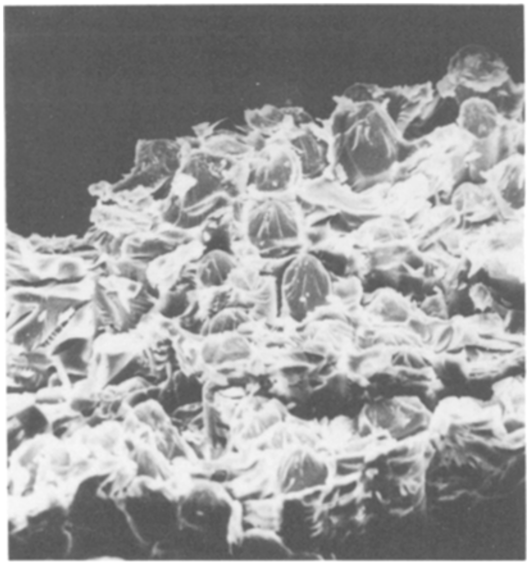

Figure 5 SEM of the surface of a shear band boundary on the undamaged side, × 900.

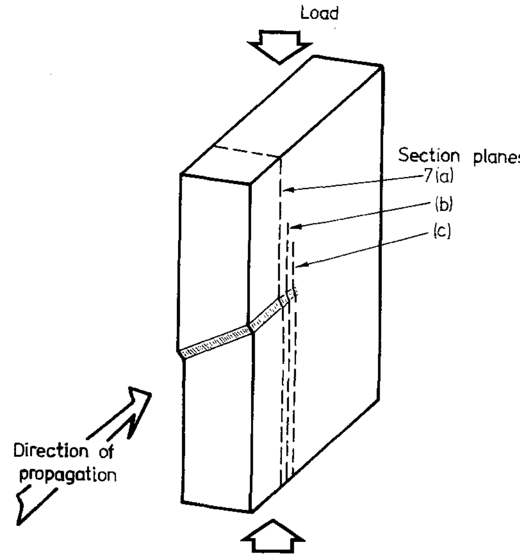

Figure 6 Diagram of a specimen with an arrested failure. An arrow indicates the direction of propagation which is also the direction of viewing the sections shown in Fig. 7. The notch is omitted for clarity.

3.2. Results for unnotched samples

These tests gave strengths of the order of 900 to 1000 N mm^{-2}. Typically there is a well-defined band of sheared material. In this band there is extensive failure of fibre matrix adhesion but the damage is entirely restricted to the band. Fig. 5 shows a scanning electron micrograph of the surface of the shear band boundary on the unsheared side.

3.3. Results for notched samples

In these tests some difficulty was experienced in controlling the fracture to give a stable propagation. There was a strong tendency, as may be expected, for interlaminar shear failures to propagate from the tip of the notch. This tendency was reduced by modifying the resin proportions and cure cycle (details as given above) to give a composite which had a similar interlaminar shear strength but which had a more "ductile" behaviour, i.e. sustained deformation at constant load as opposed to a sharp fall from the maximum. However, once we had got the right mode of failure, the difficulty was then to arrest such a failure. That was largely a problem of reducing the energy available by reducing the average stress applied to initiate failure*.

The criterion used here was that we required to initiate from a notch a failure of the same mode as that observed in the unnotched samples and then arrest it before it traversed the specimen. The desired result was achieved in a small number of samples. Fig. 6 shows diagrammatically how the failure propagated. The failed band is inclined at its characteristic angle of between 20° and 30° to the normal to the applied load but the direction of propagation is in the normal plane.

Having arrested a propagating failure the procedure then adopted was to remove the sample from the end fixtures and mount it for microscopic examination so as to expose sections normal to the direction of propagation, also shown in Fig. 6. Thus successive grinding and polishing revealed sections progressively closer to the undeformed material beyond the tip of the failure. Fig. 7 shows three of a series of such serial sections. The micrographs were taken at low magnification using transmitted polarized light. The specimen was rotated in each case to achieve the maximum contrast between the sheared band and the rest of the sample.

The sharp lines at the boundaries indicate the areas of fibre fracture and a difference in contrast

*It is interesting to note that it was found much easier to initiate and control compressive failure in carbon fibre composites. In general failure was iniated at the tip of a notch in a CFRP sample at a lower average stress than in GRP which, coupled with the higher stiffness of CFRP, gives a significantly lower strain energy release rate (work to be published).

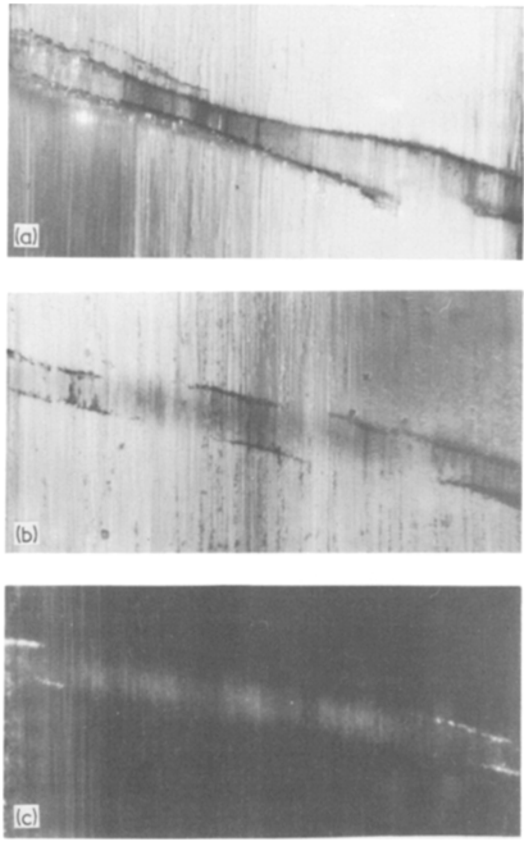

Figure 7 Sections of an arrested failure, normal to the direction of propagation, taken progressively nearer the tip of the failure with transmitted polarized illimination, × 38.

indicates a difference in alignment. It should also be borne in mind that the load has to be removed in order to make this sort of examination and a degree of recovery is inevitable.

4. Discussion of results

Compression tests on samples of the resin (mixed and cured as in the composites) gave a value for Young's modulus, averaged over the first 1% strain, of $4.37\,\mathrm{kN\,mm^{-2}}$ with a Poisson's ratio of 0.33. Thus the resin shear modulus, G_m, is 1.64 $\mathrm{kN\,mm^{-2}}$ which on substituting in Equation 1 gives a critical composite stress of $4.1\,\mathrm{kN\,mm^{-2}}$ at 60% volume fraction. The value taken for shear modulus is not that related to the failure strain of the composite (about 2% in this case). The reason for this is that it is by no means clear that the matrix is unstressed when there is no external load on the composite. The resin is almost certainly pre-stressed in tension due to restrained shrinkage during cure and restrained shrinkage on cooling from the final cure temperature. This tension is probably relaxed by creep but the extent of this relaxation is for the author a matter of conjecture. Any residual axial tension in the matrix will, of course, be reflected in fibre compression but due to the high modulus ratio this can only be small compared to the fibre stress at composite failure. The point is that you do not know what the resin strain is when the composite strain is 2%, except that it is very likely less than 2%.

The strength measured for unnotched samples, 900 to $1000\,\mathrm{N\,mm^{-2}}$, is fairly typical of this class of unidirectional GRP material. It also falls dramatically short of the theoretical prediction given by Equation 1.

The tests on notched samples demonstrate that under appropriate conditions compressive failure can propagate from a pre-existing notch or defect. Fig. 7 shows that in such a propagating failure the sequence of events is as follows:

(1) Shear deformation in a band of material which increases but without change in the orientation of the band itself (Fig. 7c).

(2) As deformation increases there is considerable bending in the fibres at the boundaries of the band which results in fracture along the boundary (Fig. 7a and b). Fig. 5 shows the fractured ends of fibres which all appear to be bending failures starting from the same side of each fibre.

(3) As deformation increases further the adhesion between fibres and matrix breaks down. Fig. 7a shows the start of this process which eventually leads to the debris which is generally all that remains of the shear band after failure. As the interlaminar failure occurs after the fracture along the boundaries it is arrested at these boundaries.

5. Conclusions

Anyone who has watched a compression test on a material which demonstrates this compression crease type of failure be it fibre reinforced composite, wood or some other natural material, will have noticed that it does not fail simultaneously across the section. The failure starts in one region and propagates, often very rapidly, across the sample.

It is, in practice, impossible to manufacture a material totally free of defects. These defects will operate as stress concentrators. The problem is the classical fracture mechanics one of determining the

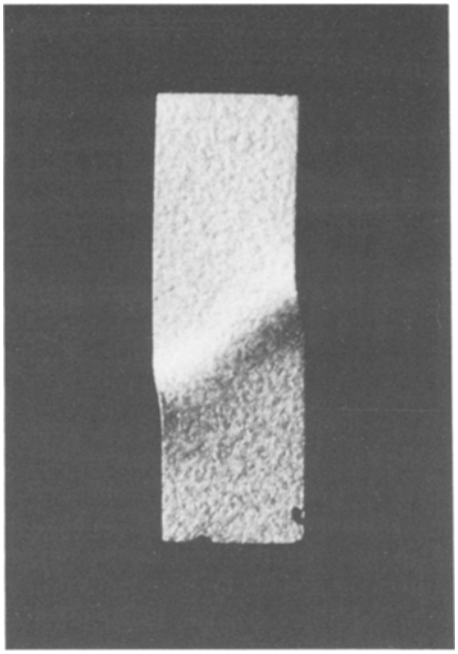

Figure 8 Face of a resin compression sample of square cross-section and with an initial length of 12 mm. The sruface has been sprayed with a matt finish paint to highlight the surface deformation.

extent to which a given defect will affect the load bearing capacity of a component. Under what conditions will a load failure initiate total failure? What factors enter into the energy balance that governs propagation and what are the details of the mechanism? It should be possible to predict the conditions under which the type of failure being considered here becomes unstable. The mechanisms of energy absorption are readily identifiable as matrix shear and interfacial failure. The difficulty lies in making allowance for load carried by the shear band after failure.

In the work described here on unidirectional glass-reinforced epoxy, it has been shown that under an axial compressive load, once initiated, a shear mode of failure can propagate across the material. Attempts to understand and quantify the conditions which govern the initiation of this type of failure have so far been unsuccessful. However, one of the reasons for GRP not reaching theoretical predictions for compressive strength must be a sensitivity to defects.

The failure itself is essentially a shear instability similar to that which occurs in the unreinforced resin, as in Fig. 8, and the term "micro-buckling" would seem inappropriate. The evidence of the observed results points to the inclination of the sheared band being constant throughout the process. Furthermore, once established, the thickness of the band will remain more or less constant as propagation proceeds. The other features of the composite failure follow as a direct consequence of this localised shear deformation. In particular, as the shear strains increase, the increase in volume dictated by the geometry will lead to the development of transverse tensile stresses within the band. These, coupled with the shear, bring about the extensive failure of adhesion. This shear deformation is limited to the point where the volume, having increased, returns to its initial value.

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References

1. B. W. ROSEN, "Mechanics of Composite Strengthening" A.S.M. Seminar, Phil. Pa. (October 1964).
2. J. R. LAGER and R. R. JUNE, *J. Comp. Mats.* **3** (1969) 48.
3. H. SCHUERCH, Compressive Strength of Boron Metal Composites, NASA CR-202. (1965).
4. C. W. WEAVER and J. G. WILLIAMS, *J. Mater. Sci.* **10** (1975) 1323.
5. S. M. BISHOP, R.A.E. Technical Report, 72240. (February 1972).
6. P. D. EWINS and A. C. HAM, R.A.E. Technical Report, 73057. (March 1973).

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