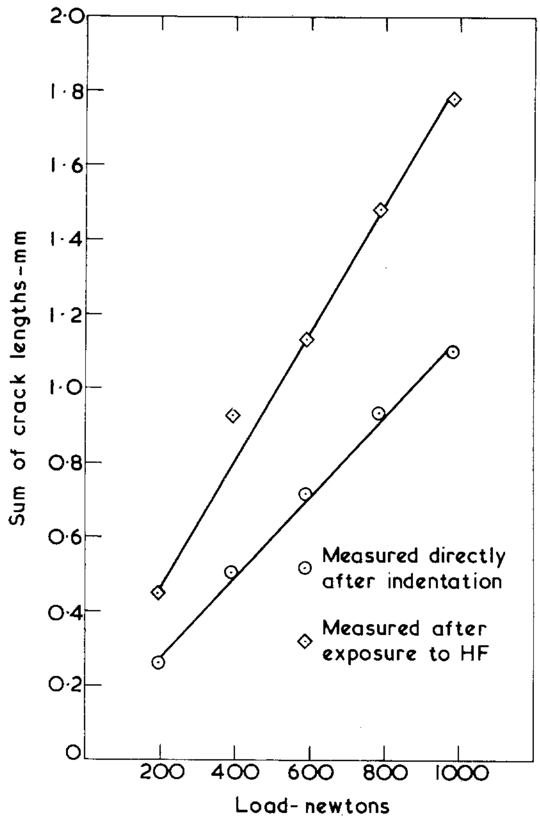

Figure 5 Variation in the average total crack length with load on indenter for 6% Co/WC hard metal specimens before and after exposure to HF vapour.

[6] will be misleading and lead to over-estimates of toughness unless they take into account the possible effects of environment in reducing the fracture toughness of the material.

Finally, the simplicity of the above experiments suggests that an easy and useful test for determining the susceptibility of a low-ductility material to stress corrosion cracking would be to indent the specimen under standard conditions and then measure the length of the radial cracks around the indentations before and after exposure to the suspect environment. The percentage increase in crack length could then be used to compare the effects of different environments.

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Transverse cracking in cross-plied composites

One of the major limitations of high-performance composites, made of aligned continuous strong fibres in a resin matrix, is that the strengths are quite low at substantial deviations from the fibre direction. Consequently, in multi-ply configurations, the layers containing fibres aligned transversely to the imposed loads are apt to fail at low stresses.

The failure takes the form of cracking in the resin between the fibres, with the crack running more or less across the thickness of the ply and parallel to the axis of the fibres. Although the laminate will still be intact, the stiffness decreases and the permeability increases, thus limiting the durability of the component.

The cause of this transverse cracking has been identified by Kies [1] and Schultz [2] as the strain concentration effects of the fibres. Because the fibres are much stronger and stiffer than the resin, most of the longitudinal strain in the transverse ply must be borne by the thin layer of resin between the fibres. Kies estimated that in glass-fibre composites the resin may be subjected, in service, to a strain of about 40%, which is well above the failure strains of epoxide resins normally

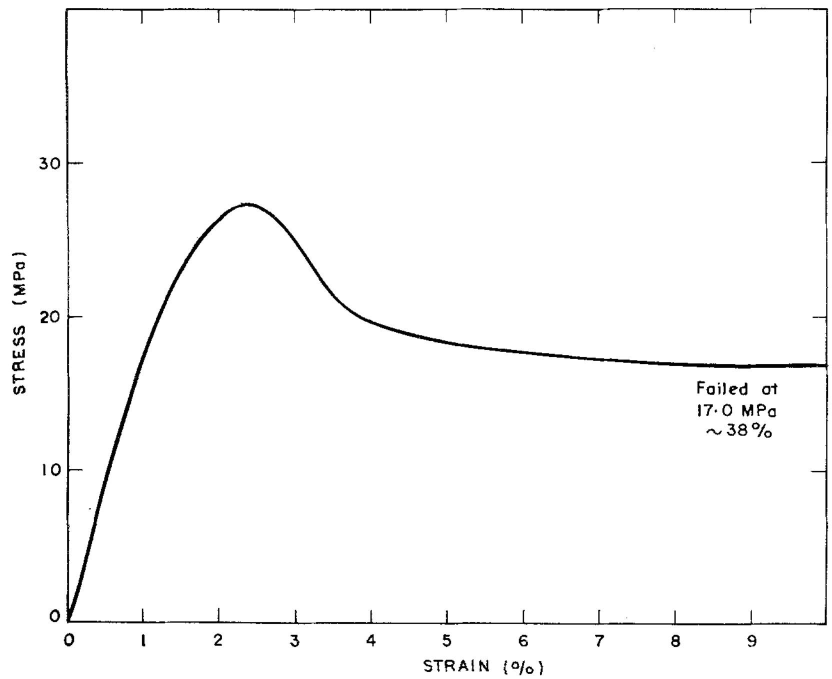

Figure 1 Tensile stress-strain curve of epoxy resin system, (100 parts by weight DGEBA (Araldite F), 77 parts polyoxypropyleneamine (Jeffamine T-403), 25 parts Diba- Geigy Diluent DY-022, cured 3 h, 100° C). Strain–rate 1.48×10^{-4} sec^{-1}, 30° C.

used. In the bi-directional (0°, 90°, 90°, 0°) glass-fibre laminates that we have studied, the transverse cracking commences at about 0.5% strain (about 15% of the ultimate tensile stress), and the modulus is reduced so that the ratio secondary modulus (E_2)/primary modulus (E_1) is in the range 0.7 to 0.8. The problem is not as severe with graphite or boron fibres since their high levels of stiffness limit the strain imposed on the transverse plies and higher stress levels are reached before cracking occurs.

Increasing the failure strain of the resin to 40% by incorporating long-chain molecules in the cross-linked structure (i.e. adding a flexibilizer) is not a feasible solution because such a resin necessarily has low strength and stiffness which makes it unsuitable for use in composite. Increasing the toughness (resistance to crack propagation) of the resin by the incorporation of elastomer particles (as suggested by McGarry and Sultan [3]) appeared attractive, but we have found that this does not eliminate the cracking in glass-fibre laminates.

We feel that the most promising approach to the problem of transverse cracking is to use a resin system that undergoes yielding and cold-drawing under stress: such a system displays a high modulus yet shows high elongation to failure. The most important benefit, however, is likely to come from the hardening associated with the necking and subsequent stretching of the cold-drawn material, since this mechanism offers a means of relieving the stress concentrations between the fibres.

To test these ideas we incorporated a resin that undergoes pronounced yielding and cold-drawing at 30° C (Fig. 1), in a bi-directional (0°, 90°, 90°, 0°) glass-fibre laminate. Specimens of 50.8 mm gauge length taken from the laminate were strained in tension at 30° C to strains of 1, 1.5, 2 and 3%. As illustrated in Fig. 2, the stress-strain curve was non-linear below about 1% strain with a E_2/E_1 ratio of 0.85. The important point, however, is that cracking was detected (by microscopic fluorescent dye penetrant inspection of the sectioned gauge length) only at the 2% (1 crack only) and 3% strain levels. An increase of at least 200% in the stress or strain level for the onset of cracking was achieved.

Although the resin system used here is not suit-

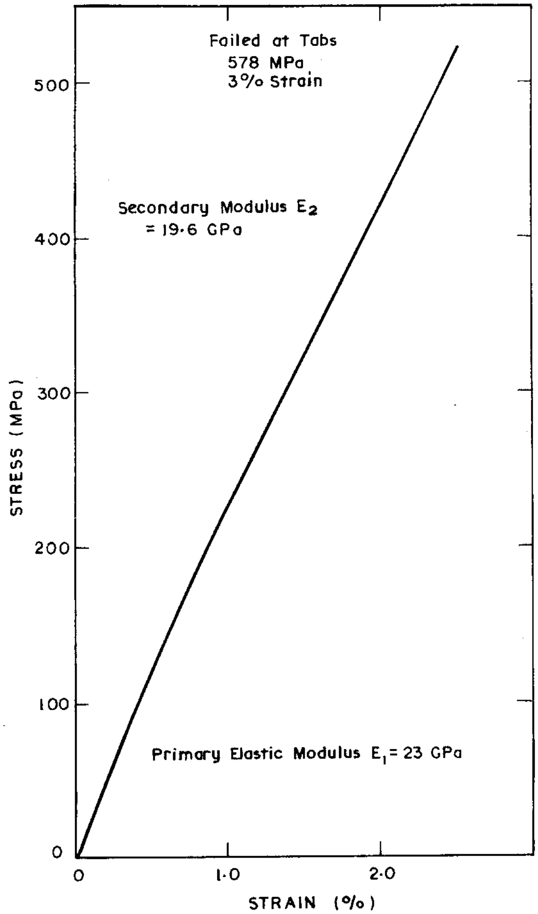

Figure 2 Stress–strain curve of bi-directional glass-fibre/epoxy resin laminate (20 end Ferro Unistrand glass fibre). Strain–rate 1.48×10^{-4} sec^{-1}, 30° C.

able for practical application (low glass transition temperature), the results indicate that resin development along the lines outlined above could result in fibre/resin composites with improved performance in multi-ply configurations.

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Contoured double cantilever beam specimens for fracture toughness measurement of adhesive joints

Contoured double cantilever beam specimens (CDCB) have been often used for fracture toughness (R) measurements and stress corrosion studies in adhesive joints [1–5]. The profiles of the cantilever beams are designed such that for quasi-static crack propagation to occur, the fracture load (X) is invariant in crack length (a) if R is a constant. Thus,

$$R = \frac{4X^2}{Et^2} m \tag{1}$$

where E is Young's modulus of the adherend; t the thickness of the adhesive; and m, which depicts the beam profile, is given by

$$m = \frac{3a^2}{h^3} + \frac{1}{h} \tag{2}$$

with h as the height of the beam at a given crack length (a). It may be realized from Equation 2 that when m is large, the CDCB specimens are slender; and when m is small they become stiff. In many fracture toughness experiments [1–4] for structural adhesive joints, m usually assumes very large values, typically of the order of 90 in.$^{-1}$. (35.6 cm^{-1}). However, in the case of beams with small values of m, say 1 to 4 in.$^{-1}$ (0.394 to 1.575 cm^{-1}), because of crack tip effects and departure from simple beam theory [1], m has to be replaced by m' determined from accurate experimental compliance measurements. In this modified equation,