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Interfacial cracking of a composite

Part 3 *Compression*

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Interfacial cracking has been studied in a composite body compressed along the interface direction. Two possibilities were considered; a purely compressive debonding; and debonding as a result of compression-induced bending. The energy balance theory of brittle fracture allowed failure criteria to be obtained for these situations in terms of the interfacial fracture energy of the composite. These criteria were then verified by experiments using polymethylmethacrylate model laminates.

1. Introduction

When a composite structure is compressed along the interface direction, failure can arise by a number of mechanisms. Perhaps the most common type of compressive fracture is brought about by interfacial failure (Fig. 1a) where cracks propagate between the phases of the composite to cause "splitting", "brooming" or "debonding" [1–3]. This is the type of failure which is treated here.

Some other modes of compressive failure of composites have, of course, been noted in the literature. For example, elastic buckling of the reinforcing elements has been observed as shown in Fig. 1b [4–6]. Buckling seems to represent the upper limit of compressive strength [7] since theory predicts rather high values of buckling stress except when low volume fractions of reinforcement are used. Another failure mechanism, familiar to woodworkers [8], is that of kinking (Fig. 1c) which can occur in large deformation bands across the specimen. Again this is prone to arise at high stresses when splitting has been inhibited by lateral forces [2].

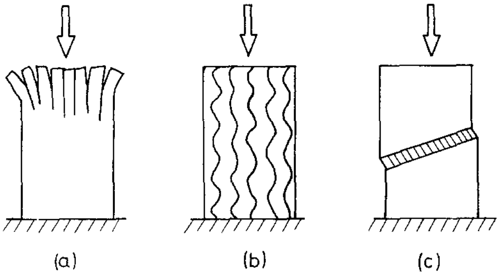

Figure 1 Three mechanisms of composite failure in compression: (a) interfacial failure; (b) elastic buckling of the reinforcement; (c) kinking failure.

Such higher stress modes of compression failure may not be observed in practice because debonding occurs first at a lower load. The object of this paper is to explain how interfacial cracking can give rise to these premature failures. First a model system is described and a theory of interfacial failure developed. It is shown that debonding may arise in a purely compressive situation or may also be due to a compression-induced bending. Finally experiments using polymethylmethacrylate composites support the theory.

2. The model

The model adopted for compression studies was essentially similar to that used in the tension and bending experiments reported previously [9, 10]. Two sheets of polymethylmethacrylate were pressed together at 110° C to form an adhesive interface between them. Cracking of this interface could then be observed under compressive loads.

The geometries studied are shown in Fig. 2. In the first (Fig. 2a) the compressive force was applied assymmetrically to the composite block, but parallel to the interface. This loading caused a crack to propagate along the interface in the same direction as that of the applied force, that is at right angles to the ordinary Griffith direction

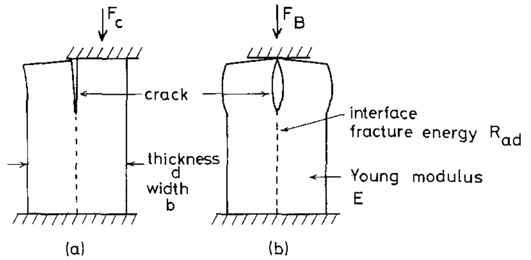

Figure 2 Two modes of composite debonding in compression: (a) compressive failure; (b) compression-induced bending.

[11]. Initially, it may seem surprising that a crack can travel in this way. However, on reflection, this mode of cracking appears little different from that observed, albeit under tension, in lap shear joints [12] and in tensile debonding of a laminate [13]. The prime purpose of this paper is to show that for the configuration of Fig. 2a, tension and compression failure are equivalent. Interfacial cracking, in this case, occurs at the same force whatever its direction.

By contrast, the model illustrated in Fig. 2b failed quite differently in compression and in tension. Tension did not produce debonding until a Griffith crack had been propagated from the outer surface, as demonstrated earlier [9]. In compression, however, a crack could be seen travelling along the interface from the point of load application (Fig. 2b). Obviously, tension and compression were not equivalent in this instance. It appeared that, under compression, bending of the material could occur and this was dominant in causing interfacial cracking. For this reason the phrase "compression-induced bending" has been used to describe the failure. The theory of this mechanism, which causes the structure to be weaker in compression than tension, is treated in the next section.

3. Theory

A theory of compressive debonding may readily be deduced from the energy balance concept of fracture. The geometry of Fig. 2a has previously been analysed in this way [9] and gives the force criterion for propagation of a long plane crack of width b

$$F_c = b(2R_{ad}Ed)^{1/2} \qquad (1)$$

where E is Young's modulus of the material, d the composite thickness and R_{ad} the adhesive fracture energy of the interface. This equation, the same as that for tension debonding, was to be experimentally verified.

Compression-induced bending is slightly more complicated and is illustrated in Fig. 2b. The interfacial crack of length x is seen to split the composite into two short struts each supporting a load $F_B/2$ on its inner edge and each bending about a neutral plane $d/4$ from the line of load application. If bending is slight then the bending moment is constant along each strut and is given by $F_Bd/8$ [14].

Applying the energy balance theory of fracture, three energy terms must be considered: the strain energy due to bending of these short struts (the compression energy may be neglected because it remains constant under a steady load), the potential energy in the constant applied load, and the surface energy in the free cracked surfaces. The fracture criterion is then derived from the condition that the sum of these energy terms must remain constant with respect to a small crack extension.

The strain energy of bending in each strut is

$$\left(\frac{F_Bd}{8}\right)^2 \frac{x}{2EI_A}$$

x being the crack length, E Young's modulus and I_A the second moment of area about the neutral axis, in this case $bd^3/96$. The total strain energy due to bending in the two struts is therefore $3F_B{}^2x/(2Ebd)$. The potential energy of the steady load is twice this and negative, that is $-3F_B^2x/Ebd$. The surface energy is bxR_{ad} where R_{ad} is the interfacial fracture energy, the energy required to rupture unit area of interface.

Making the differential of the sum of these terms zero with respect to crack length we get

$$\frac{d}{dx}\left(\frac{3F_B^2x}{2Ebd} - \frac{3F_B^2x}{Ebd} + bxR_{ad}\right) = 0. \qquad (2)$$

Therefore

$$F_B = b\left(\frac{2}{3}R_{ad}Ed\right)^{1/2}. \qquad (3)$$

According to this equation, compression-induced bending failure should occur at $1/\sqrt{3}$ times the load required for pure compressive debonding. This prediction was to be tested experimentally.

4. Experimental results

To check the theory, composite models were made from polymethylmethacrylate as described before

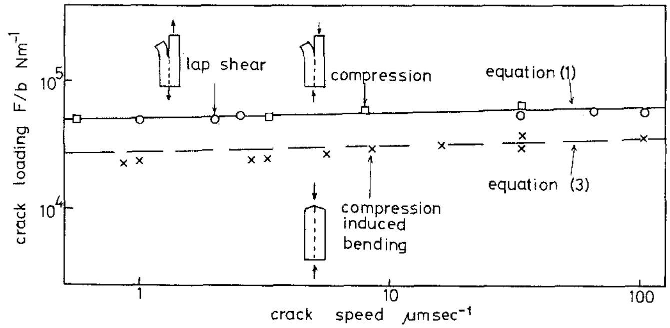

Figure 3 Experimental results. o, lap shear test; □, compressive test; x, compression-induced bending test. As predicted by Equation 1, both lap shear and compressive cracking occurred at the same loading. Compression-induced bending arose at a lower load, in accordance with Equation 3.

[9, 10]. However, the compression specimens were much shorter (6 cm long) and thicker ($d = 1.13$ cm) so that they would not buckle. Because of this, it was impossible to measure the interfacial fracture energies by the peeling test used previously. Instead a lap shear test was used to determine the adhesion, this system having been investigated earlier [12]. Lap forces were applied to the samples using an Instron testing machine and the corresponding crack speeds measured visually through the transparent polymer. The results are shown as circles in Fig. 3.

When the same geometry was compressed in the manner of Fig. 2a, interfacial cracking took place and the results were plotted as squares in Fig. 3. It was observed that the failure force in compression was the same, within experimental error, as that in tension for this geometry. The theoretical prediction associated with Equation 1 was therefore fulfilled.

However, when samples were compressed in the geometry of Fig. 2b, the results depicted by crosses were obtained. The failure force in this compression-induced bending mode was reduced and the measured reduction compared favourably with the predicted factor of $1/\sqrt{3}$.

5. Conclusions

According to the energy balance theory of fracture, compression cracking of a composite loaded parallel to the interface should be similar to tensile failure of a lap shear joint. This idea has been verified by experiments on polymethylmethacrylate composites. Alternatively, compressive forces may induce bending which also leads to cracking along the interface. The theoretical criterion for this failure mode again bears some resemblance towards the lap joint case. Experiment supports this view.

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