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Interfacial cracking of a composite

Part 1 *Interlaminar shear and tension*

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The interfacial cracking, or debonding, of a composite has been studied both in tension and interlaminar shear, the fracture force being applied parallel to the interfaces in both cases. Application of the energy balance theory of brittle fracture has provided theoretical criteria for debonding failure. These equations have been verified experimentally using polymethylmethacrylate models. There were three conclusions: (1) interfacial cracks can propagate along the direction of the applied force in a theoretically predictable manner; (2) these interfacial cracks must be triggered by flaws, either edge cracks or internal defects; (3) it is wrong to characterise brittle interfacial adhesion by means of an interlaminar shear strength. Instead, the interfacial fracture energy should be used.

1. Introduction

Failure of composite materials may often occur by a debonding process, separation taking place at the interfaces between the two phases form the structure [1, 2]. If the composite is transparent, this debonding may be rather dramatic as cracks are observed shooting along the interfaces.

Two particular examples of this process might be mentioned for composites stressed along the interface direction, these interfaces themselves all being parallel. In the first example, illustrated in Fig. 1a, deep cuts are made in the edges of the sample before pulling. This geometry is often used to test the interlaminar shear strength of the composite [3, 4], i.e. the strength of the interfaces between the phases. Debonding starts at the cuts and causes a failure of the type shown in Fig. 1b, a so-called shear failure, similar in many respects to that of a lap shear adhesive joint [5].

A second sort of interfacial failure occurs in tension (Fig. 1c). Debonding starts in the bulk of the composite prior to a tension failure (Fig. 1d) where pulled out layers are seen projecting from the fracture surfaces.

There are a number of difficulties associated with these observations. Why, for example, should the interfacial cracks propagate along the direction of the applied force? Gordon [6] doubted that cracks could propagate continuously in this direction. Ordinary Griffith [7] cracks, of course, travel

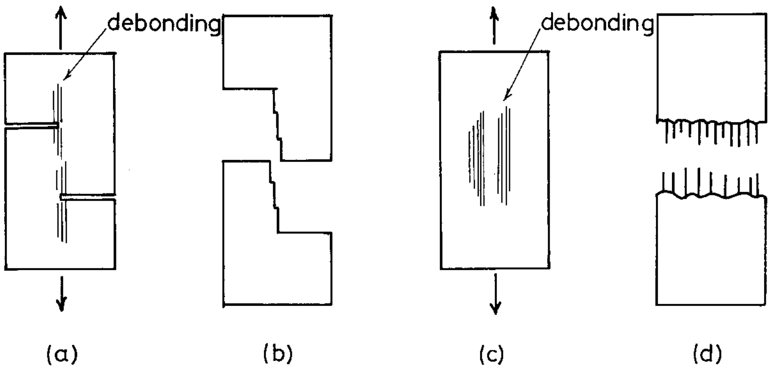

Figure 1 Two types of interfacial failure in a composite: (a) debonding leading to (b) shear failure; (c) debonding prior to (d) tension failure.

in a plane normal to the tension. It is the prime purpose of this paper to delineate the conditions under which cracks may propagate perpendicular to the Griffith direction.

Again, it is not easy to define the differences between the geometries of Fig. 1a and c, those of interlaminar shear and tension. In both instances debonding occurs, although at different loads in each case. In this report it is demonstrated that both tension and shear failure are essentially similar, the only difference being the nature of the flaws triggering off the interfacial debonding.

Finally, there is the problem of the degree of adhesion at the interface. It has become commonplace to express this adhesion in terms of an interlaminar shear strength measured typically in the geometry of Fig. 1a. This paper points out that such a definition lacks meaning for a brittle interface since the shear strength measured in this way depends not only on the interface but also on the geometrical and elastic properties of the test piece. It is shown that a better parameter for characterizing interfacial bonding is the adhesive fracture energy.

In the first part of this report, an ideal model composite is described and a theory of interfacial failure presented for both shear and tension fractures. This theory is then verified experimentally by direct observation of interfacial cracking in the model.

2. The model composite

To facilitate both the theoretical and experimental study, the simple composites shown in Fig. 2 were constructed. The objective was to produce transparent specimens allowing debonding to be easily seen. Only a small number of interfaces were to be introduced, again to ease the observation of debonding. For the same reason, plane interfaces were used. It was hoped that these simplifying features, introduced for experimental convenience, would not vitiate the general applicability of the conclusions.

Sheets of polymethylmethacrylate (ICI Perspex) 2 cm wide and about 1 m long were cut from a sheet 1.6 mm thick. These strips, after washing with soap and rinsing with water, were dried and then joined together over a distance of 20 cm at one end. The flat faces were pushed together in a press at 110° C for 30 min under a load of 10 tonnes. Such conditions were found to give sufficient adhesion between the smooth polymer surfaces, the interface being quite transparent and free from defects. The remaining 80 cm of strip were left hanging free and were used to measure the interfacial adhesion by a method to be described later.

In the type of model shown in Fig. 2a the interface was perfect. This geometry was to be used to study the effect of an interface on the fracture of the polymer. The model shown in Fig. 2b con-

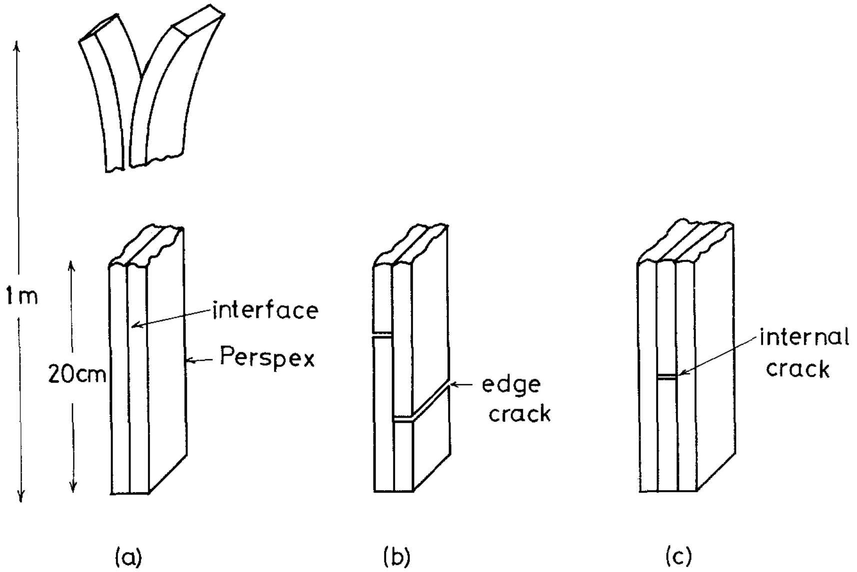

Figure 2 Model composites used to demonstrate interfacial failure: (a) perfect interface, (b) shear failure specimen, and (c) tension failure specimen.

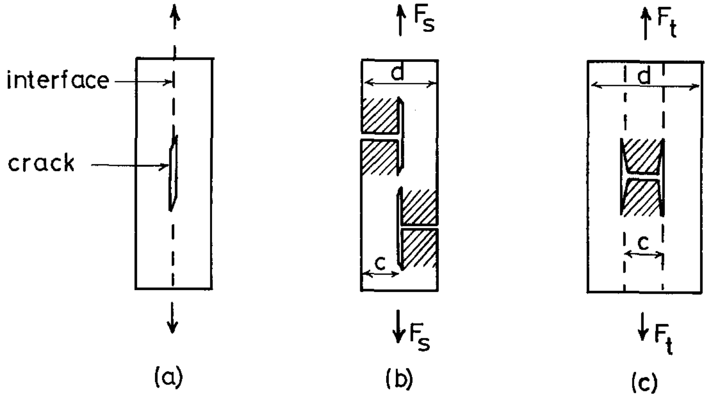

Figure 3 Release of elastic energy as a result of interfacial failure.

tained edge cracks and was meant to simulate the shear failure pictured in Fig. 1a and b. The model of Fig. 2c contained two interfaces between which there was a break in the central lamination. This was meant to represent a composite with an internal flaw from which debonding could occur in tension.

The relative simplicity of these models allowed easy theoretical interpretation of the interfacial failure.

3. Theory

Theoretical analysis makes use of the energy balance theory of brittle fracture. According to this idea [7], cracking produces new surface, and the energy required for this is derived from the mechanical energy in the system. Fracture, therefore, first requires the energy of the system to be reduced by propagation of a crack. Secondly, this reduction in mechanical energy must be sufficient to equal the energy of the new surfaces revealed.

Consider the application of these principles to the composite of Fig. 3a where a perfect interface separates two equal strips of material. Imagine a hypothetical crack propagating along this interface. No mechanical work can be done in this operation, providing there are no tractions across the interface. The conclusion is that debonding cannot occur in the situation of Fig. 3a.

For debonding to take place, some mechanism or trigger must be provided to allow the strain energy in the system to change as the interface fractures. The edge cracks shown in Fig. 3b provide such a trigger. When debonding starts from these edge cracks the strain energy in the shaded regions is reduced to zero and this supplies the driving impetus for interfacial cracking. Applying the energy balance method to this geometry leads to the debonding criterion giving the force F_s necessary to propagate a long crack [8]

$$F_s = b\left[\frac{2R_{ad}}{cE_1}\right]^{1/2}[E_2(d-c)(cE_1+(d-c)E_2)]^{1/2} \qquad (1)$$

with the nomenclature of Fig. 4. In this equation R_{ad} is the adhesive fracture energy of the interface, that is, the energy required to fracture unit area of interface. According to the energy balance theory only surface energy is created, so that the total energy expended in this debonding is U where

$$U = R_{ad}A, \qquad (2)$$

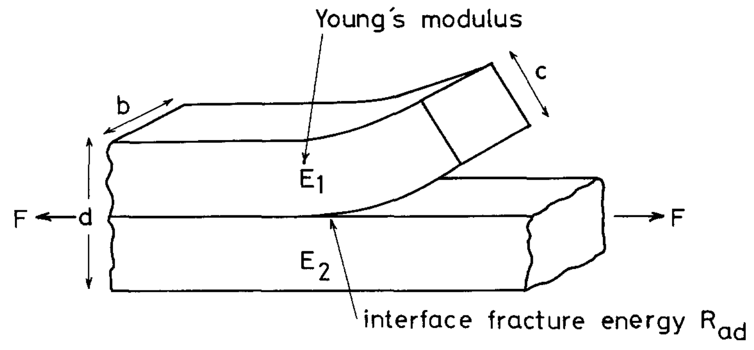

Figure 4 Nomenclature used in the interfacial failure theory.

A being the area of interface debonded.

For the simple situation of Fig. 3b, the elastic moduli E_1 and E_2 were equal and the thicknesses $(d-c)$ and c were the same, so Equation 1 reduced to

$$F_s = b\,(2R_{ad}Ed)^{1/2}. \qquad (3)$$

Similarly, in Fig. 3c, an internal crack supplies the trigger for the interfacial debonding, the strain energy in the shaded material being converted into surface energy as before. There are now two interfaces to deal with so that [8]

$$F_t = b\left[\frac{4R_{ad}}{cE_1}\right]^{1/2}[E_2(d-c)(cE_1-(d-c)E_2)]^{1/2} \qquad (4)$$

and again, if the moduli are the same and c equals $d/3$, the debonding condition is

$$F_t = b\,(8R_{ad}Ed)^{1/2}. \qquad (5)$$

A number of conclusions may be drawn from this theoretical analysis. In the first place, no interfacial cracking should occur in tension unless triggered by edge or internal flaws. After initiation by such flaws, interfacial cracking should proceed continuously, there being a definite mechanism for propagation parallel to the applied force. Moreover, since there is no crack length dependence in the equations, the interfacial cracks should travel at constant speed under a steady load. In principle there turns out to be no difference between propagation from an edge flaw and that from an internal flaw. Therefore, tensile failure and shear failure as defined in Fig. 1 are essentially similar except for a numerical factor. Finally Equations 3 and 5 show clearly that interlaminar shear stress is not the critical factor governing debonding. Indeed, this quantity does not appear in the theory at all.

4. Experimental

The experimental aim was to check these theoretical arguments using the Perspex models described previously. In particular, the validity of Equations 3 and 5 was to be investigated.

To do this, the quantities b, d, E and R_{ad} were determined. The width b was 20 mm and the thickness of the Perspex sheets after pressing was 1.5 mm. Young's modulus for the polymer measured in cantilever bend tests was 2.71 GN m^{-2}.

Determination of the adhesive fracture energy R_{ad} was achieved using the peel test shown in Fig. 5. In this configuration, the long arms attached to the model composites were pulled apart on an Instron machine with a force F_{peel}. For this geometry the adhesive fracture energy could then be calculated from the relationship [8]

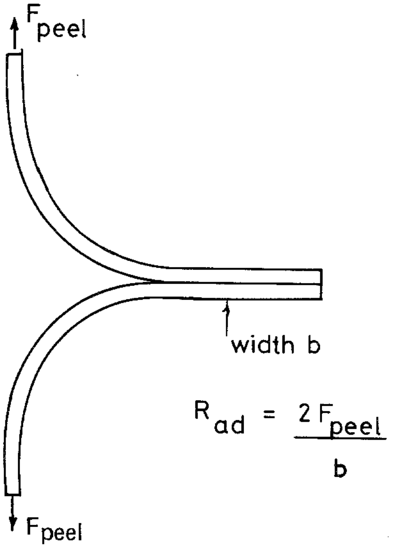

Figure 5 The peel method for determining the interfacial fracture energy R_{ad}.

$$R_{ad} = \frac{2F_{peel}}{b}. \qquad (6)$$

Peeling was carried out in this way at a number of crack speeds and it was observed that peeling force and crack speed were related. As the peeling force was raised the crack speed also increased, as is usual in brittle fracture [8, 9]. The peel results were, therefore, plotted as a function of crack speed, both on logarithmic scales, as in Fig. 6.

The results demonstrated two points very clearly. First the peeling force was quite low, less than 0.5 N to crack a 10 mm wide interface. This was about one fifth of the force required to crack bulk Perspex in this geometry [9]. Secondly, there was some variation in the adhesion results. On any given sample this was found to be ±10%. Between samples the variability was greater than this and it was necessary to determine the adhesive energy by peel testing each sample.

Having measured E, R_{ad}, d and b, it remained to test Equations 3 and 5 by stretching the composite models in a testing machine until debonding occurred. Samples of the geometries shown in Fig. 2a, b and c were tested in this manner.

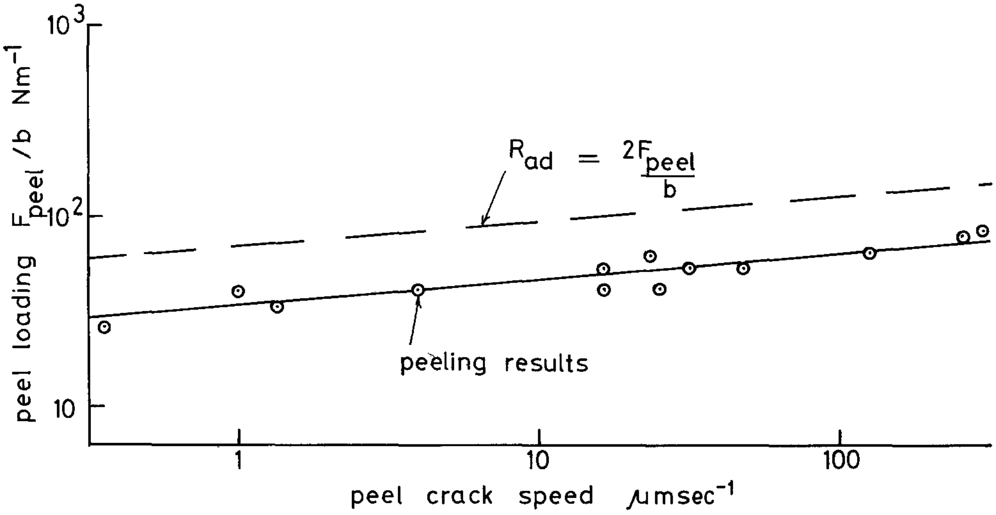

Figure 6 Results for interfacial fracture energy.

5. Results

The sample with a perfect interface (Fig. 2a) did not debond when stressed to 50 MN m^{-2}, almost the breaking stress for Perspex. This result fitted the theoretical argument that a flaw is necessary to trigger interfacial cracking. To test this reasoning the tensile stress was maintained and a slight razor notch 0.15 mm deep made across the wide face of the Perspex sample. Immediately, this flaw propagated through to the interface. Then debonding started from this crack and rapidly spread over the whole interface. Thus, interfacial cracking could occur only if a flaw was introduced to act as a trigger. Additionally, of course, complete fracture of the polymer was prevented by the debonding, and a large amount of energy was dissipated in the adhesive fracture.

For the second geometry (Fig. 2b) debonding was observed starting from the edge cracks as predicted theoretically. Measurements of applied load and interfacial crack propagation speed are plotted in Fig. 7 for comparison with the theory. Reason-

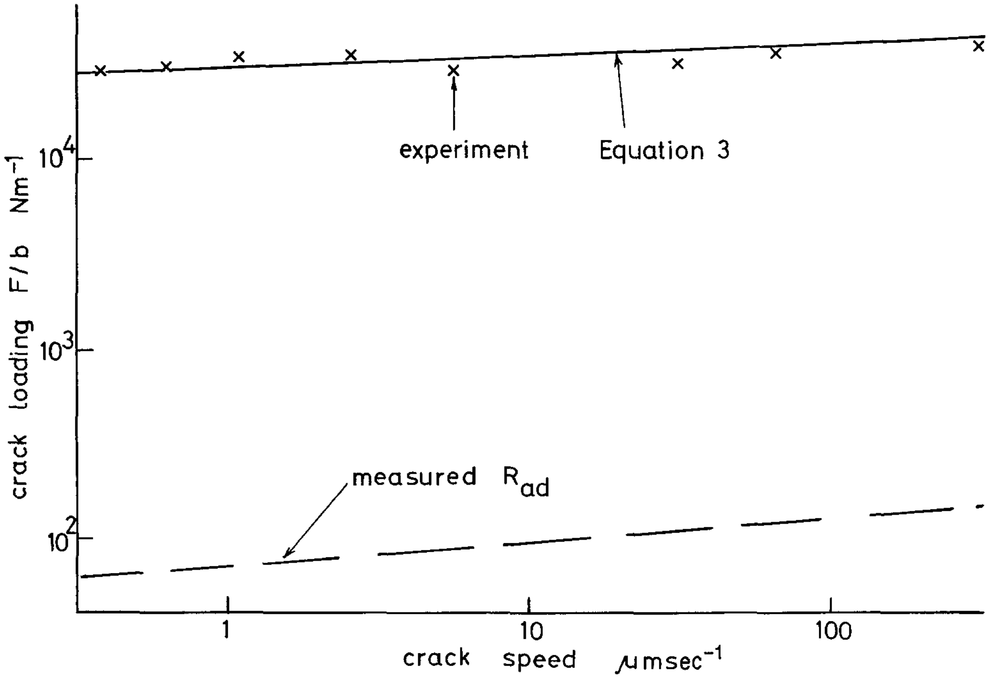

Figure 7 Results for the shear failure model debonding.

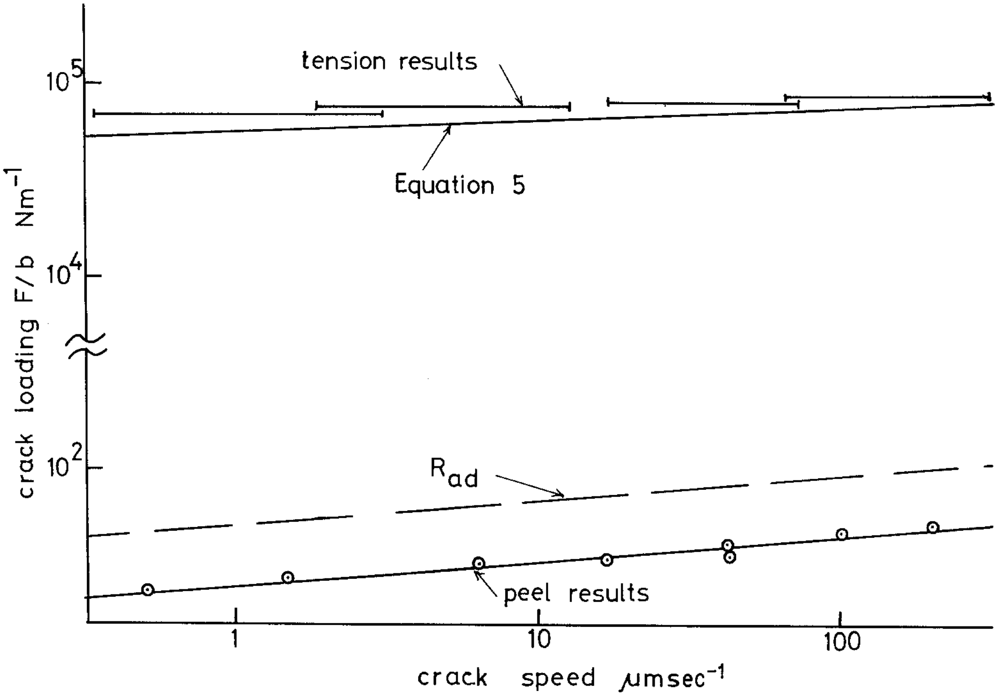

Figure 8 Results for the tension failure debonding.

able agreement was found considering the scatter in the adhesive fracture energy data. It is also noteworthy that debonding in this case required a force three orders of magnitude higher than in the peeling geometry.

Again, when the sample of Fig. 2c was tested in tension, the theoretical mechanism was seen to operate. Debonding took place simultaneously down both faces of the central Perspex sheet (Fig. 3c). However, in this case the propagation was very jerky and it was difficult to obtain good crack speed measurements. This jerkiness was attributed to sliding friction between the debonded surfaces. These surfaces were evidently in close contact as demonstrated by the presence of optical interference fringes at the debonded regions. Also, squeaking sliding noises could be heard. Neverthless, despite this uncertainty in the crack speed measurements, the debonding force proved to be in reasonable accord with Equation 5 (Fig. 8).

6. Conclusions

It has been demonstrated that interfacial cracks may travel in a direction perpendicular to the ordinary Griffith direction. The theoretical criterion governing this debonding phenomena has been presented and verfied experimentally.

For such cracks to propagate, it is not sufficient merely to satisfy the failure criterion. There must also exist certain flaws in the composite to trigger the debonding. It is the nature of these trigger flaws which distinguishes between debonding in "shear" and "tension". A "shear" failure is initiated from an edge crack whereas "tension" debonding starts from an internal flaw. Except for this, both failures are essentially similar.

In addition, the theoretical analysis shows that the brittle interfacial adhesion in a composite cannot meaningfully be related to the shear stress, the so-called interlaminar shear strength, at which debonding occurs. Such a shear strength would be found to change with the dimensions and elastic properties of the composite. Adhesive fracture energy is a better parameter for characterizing interfacial bond strength.

Finally, an experiment involving the propagation of a Griffith crack through a model composite has illustrated how interfacial debonding can deflect a dangerous crack, thereby retarding failure and increasing the energy dissipation.

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