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Interfacial cracking of a composite

Part 2 *Bending*

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Interfacial failure as a result of bending has been observed in a beam containing an interface along its mid-plane. The energy balance theory of fracture was applied to this system and a debonding criterion deduced. This was experimentally supported by studies of interface fracture in polymethylmethacrylate laminates. Results showed that interfacial crack propagation due to bending could be predicted from a knowledge of beam geometry, elastic properties, and interface fracture energy. There was no need to introduce "interlaminar shear strength" in this model situation.

1. Introduction

Bending of a composite beam (Fig. 1) often stimulates interfacial cracking of the structure [1, 2] usually along the mid-plane and sometimes under stresses which are small compared to the tensile strength of the material. Conventional wisdom tells us that such interfacial fracture is caused by shear stress at the beam axis. When the shear stress reaches a sufficient magnitude, known as the "interlaminar shear strength", cracking should occur [3]. This idea is the basis of a well-known test for reinforced plastics [4].

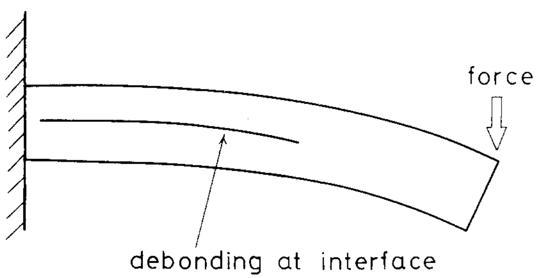

Figure 1 Interfacial debonding in a bent composite beam.

It is the purpose of this paper to demur from this established view. Instead, a new theory of bending failure is presented and supported by experiment. This new theory differs from the old in two respects. First it considers only the propagation of delamination; initiation of debonding is specifically excluded. Second, rather than adopt a stress criterion for debonding, it applies the energy balance theory of brittle fracture [5, 6] to the cracking at the interface. A novel criterion is derived for bending failure, involving the interface fracture energy in place of the interlaminar shear strength. Finally, the theory is verified by experiments using polymethylmethacrylate composite beams. This model may have relevance to cracking in conventional, more complex, composite systems.

2. Theory

Consider a thin bent beam (Fig. 2) where an interfacial crack has propagated a distance x causing separation into two thinner beams which bend independently of each other. Imagine the crack propagating a further small distance dx through a region where the bending moment Fx is essentially constant. This system may be treated according to the theory of brittle fracture, where energy expended in deforming the beam is converted exactly into fracture surface energy at the crack.

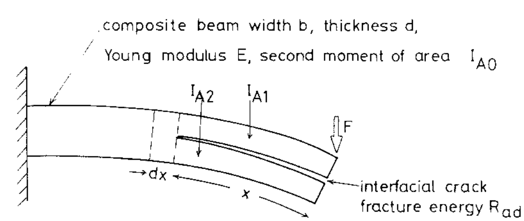

Figure 2 Propagation of a long crack along an interface in a composite beam.

There are three energy terms to be considered. First, energy is absorbed by the creation of new free surfaces. If the energy required to fracture unit area of interface is R_{ad} then the surface absorption term is $R_{ad}bdx$, b being the width of the beam. Secondly, energy is needed to increase the strain in the split beam. Prior to debonding the strain energy in the element dx is [7] $F^2x^2\,dx/2EI_{A0}$, E being Young's modulus and I_{A0} the second moment of area of the original beam about its neutral axis. After splitting, this strain energy rises to $F^2x^2\,dx/2E(I_{A1}+I_{A2})$. The net increase in strain energy is thus

$$\frac{F^2x^2\,dx}{2E}\left[\frac{1}{I_{A1}+I_{A2}}-\frac{1}{I_{A0}}\right].$$

All the energy needed for these two terms is supplied by the third energy term, the work done by the constant force F deflecting the beam as the crack proceeds. This work is twice the strain energy term [8].

For a long crack, the strain energy around the crack tip remains constant and therefore disappears on differentiation. Balancing the energies leads to the delamination condition:

$$\frac{F^2x^2}{2Eb}\left[\frac{1}{I_{A1}+I_{A2}}-\frac{1}{I_{A0}}\right]=R_{ad}. \quad (1)$$

For the cantilever beam where splitting occurs in the mid-plane and the second moments of area are

$$I_{A0} = bd^3/12 \quad (2)$$

$$I_{A1} = I_{A2} = bd^3/96, \quad (3)$$

Equation 1 simplifies to

$$F = b\left[\frac{R_{ad}Ed^3}{18x^2}\right]^{1/2}. \quad (4)$$

This formula, giving the force required for propagation of a long crack down the central plane of a cantilever beam, was to be verified experimentally.

3. Theoretical discussion

The theory propounded above for interfacial fracture under bending illustrates a number of points. In the first place it differs strongly from current theories based on a stress condition for interface rupture. For example Equation 4 shows a dependence of the failure force on beam modulus and on beam thickness to the power 3/2. It is apparent that the "interlaminar shear strength" does not enter the equations. Instead the effect of interfacial adhesion on bending strength is embodied in the interface fracture energy R_{ad}.

Another feature of Equation 4 is its inclusion of a crack length term. As the crack increases in length, the force required for propagation becomes smaller, leading to crack acceleration. It will be observed that this crack length effect is derived from the bending moment variation along the beam. Obviously, by arranging for the bending moment to be constant along the beam, steady speed cracks could be obtained. Alternatively, cracks would slow down on entering a lower bending moment region.

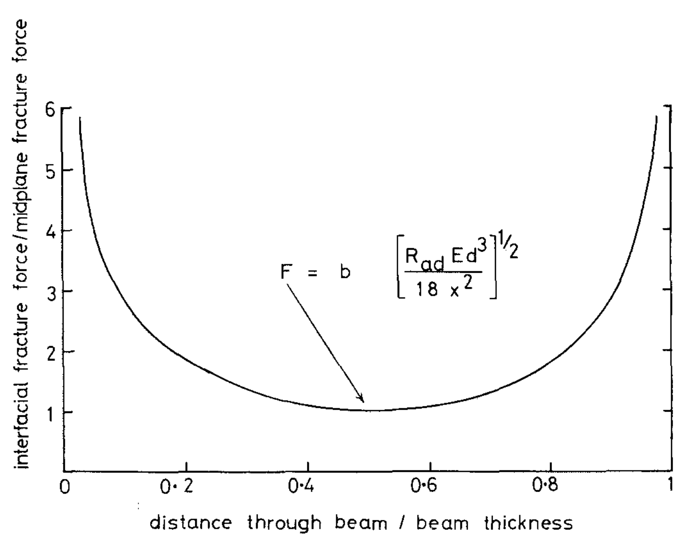

Figure 3 Theoretical rise in interfacial fracture force away from the mid-plane.

A third point to be gleaned from the theory concerns the likely path of the crack. A study of Equation 1 demonstrates that an interfacial crack will favour the mid-plane because this gives a maximum value of $1/(I_{A1}+I_{A2})$ thereby allowing the minimum fracture force. To propagate an interfacial crack on a plane a distance nd from the beam edge, where d is the beam thickness and n a number between 0 and 1, requires a force given by

$$F = \left[\frac{n^3+(1-n)^3}{n(1-n)}\right]^{1/2} b\left[\frac{R_{ad}Ed^3}{18x^2}\right]^{1/2}. \quad (5)$$

This corresponds to Equation 4 at the mid-plane and rises rapidly near the edges of the beam as shown in Fig. 3.

4. Experimental

The experimental objective was to study the veracity of Equation 4. To do this, simple composites were made from polymethylmethacrylate as detailed in [6]. These composites consisted of two sheets of polymer pushed together in a heated press to form a beam with a reproducible adhesive interface in its central plane (Fig. 4a).

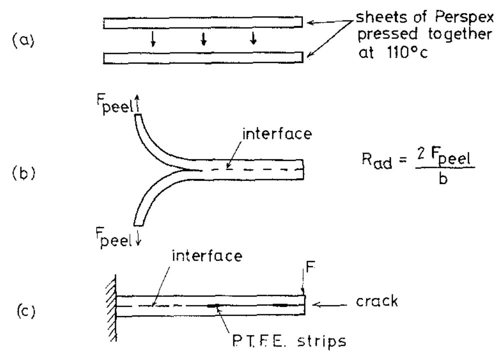

Figure 4 (a) Formation of the beam with a central interface; (b) peel test to determine the interfacial fracture energy R_{ad}, and (c) interfacial crack experiment on the bent beam.

The geometrical and elastic properties required for Equation 4 were readily measured. The Young's modulus was 2.71 GN m^{-2}, the width b was around 20 mm and the thickness d about 2 mm.

Measurement of the interfacial fracture energy R_{ad} was achieved using the peel method [6]. Forces were applied to the long arms attached to the composite beam (Fig. 4b) and the force required to cause peel cracking at a measured speed was determined. This enabled the interfacial fracture energy to be calculated from the equation

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

Finally, a bending experiment was carried out on the composite beam to see whether the interfacial crack propagated as predicted. One end of the beam was clamped and a deflection applied to the other (Fig. 4c), the deflecting force being measured. This caused an interfacial crack to travel along the mid-plane as anticipated. The speed of propagation was noted together with the moment arm x.

Friction between the separated crack faces was found to influence the results considerably. To reduce this, strips of PTFE sheet were introduced into the crack, separating the interfering surfaces.

5. Results

The experimental results are shown in Fig. 5, plotting crack loading F/b against crack speed,

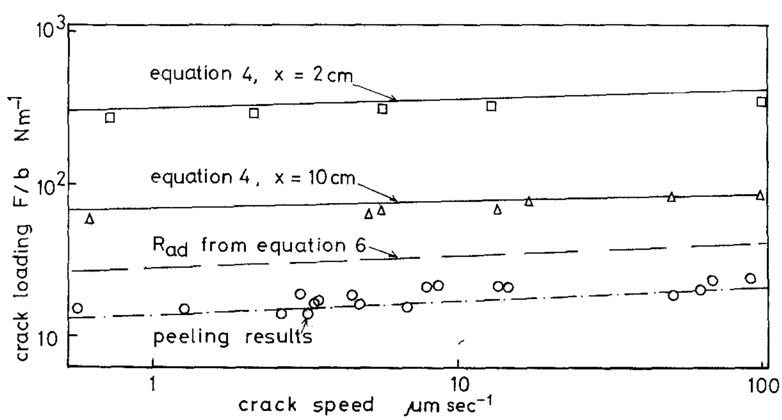

Figure 5 Results from the peeling experiments ○, the derived line — — for interfacial fracture energy, and comparison of bending failure results (□, x = 2 cm; △, x = 10 cm) with theoretical predictions ——— from Equation 4.

both on logarithmic scales. The circles at the bottom of this graph correspond to the peeling experiments used to determine the adhesive fracture energy of the interface. As before [6], the peel loading was low and crack speed dependent, there also being some scatter of ± 10% in the results. From these peeling experiments the interfacial fracture energy was calculated according to Equation 6 and gave the dashed line in Fig. 5.

Above this are the data for interfacial fracture in bending. The triangular points correspond to a moment arm of 10 cm and gave reasonable agreement with the theoretical line derived from Equation 4. It was noticed that there was very little resistance to interfacial fracture for this configuration. The forces were only one hundredth of those needed for debonding in tension [6]. In fact, the force only slightly exceeded that for peeling, itself a notoriously weak geometry.

The uppermost points in Fig. 5 were derived from bending tests with a moment arm of 2 cm. Again, these results gave encouraging support to the theoretical predictions, the splitting force now being five times higher than before.

6. Conclusions

A theory has been developed for propagation of a long interfacial crack along the mid-plane of a bent composite beam. This theory was rooted in the energy balance concept of fracture and differed considerably from the conventional approach based on "interlaminar shear strength". Resistance to debonding, according to this new theory, is related to the fracture energy of the interface and the geometric and elastic properties of the beam. Experiments using Perspex composite beams have demonstrated the validity of the argument.

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