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Some aspects of fracture in brittle fibre composites

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This paper describes some observations on the propagation of cracks through a brittle matrix reinforced with strong, stiff, unidirectional fibres. By means of a model material, observations are made of the interaction of a matrix crack with an isolated fibre normal to the crack. The experiments were extended to cover interaction with a row of fibres. The results of these tests are then compared with the behaviour of a real composite. One interesting observation concerns a mechanism whereby a single initial crack can initiate a series of parallel cracks which enable the opening displacement of the main crack to be distributed among this series of secondary cracks as fracture proceeds through the material.

1. Introduction

Fibre reinforced composites in which both components are brittle when considered individually, can undoubtedly be usefully tough. This is demonstrated by the popularity of glass reinforced plastics in applications like boat hulls, motor-car bodies and furniture; applications where toughness is as important as strength, stiffness and ease of forming. This toughness implies that considerably more work must be performed in fracturing the composite than would be involved in fracturing the component materials separately.

There are several mechanisms which operate to increase the amount of energy dissipated in the fracture process. The complexity and anisotropy of a fibre composite tends to lead to a complex and diffuse fracture: the processes of energy release and dissipation take place throughout a volume extending to either side of the crack and well behind the tip. Indeed, the typical appearance of the fracture is so unlike that of a homogeneous solid that it is evident that the familiar terms of the fracture mechanic, like "crack tip" and "fracture surface area", need to be carefully qualified or even discarded.

Fracture is an energy conversion process whereby elastic strain energy is released from various regions in the vicinity of the fracture, transmitted through the material and absorbed in plastic deformation or by some other means. The process by which the energy is conveyed through the material will be more or less efficient depending on the details of the process. The complexity of fracture in a fibre composite is likely to reduce this efficiency because of the greater distances involved, the interfaces and mismatch between phases. This clearly leads to an increase in the rate of release of strain energy necessary to propagate a fracture.

It is apparent, however, that the two most important dissipative processes in the fracture of fibre composites are associated with the failure of the interfacial adhesion and pull-out of the fibres. A number of authors have considered these different processes both theoretically and experimentally – see for example Cottrell [1], Cooper and Kelly [2], Cooper [3], Kelly [4] or Outwater and Murphy [5]. In calculating composite work of fracture all these approaches assume a planar matrix crack normal to the reinforcement. However, as the tests described below show, it is possible in fibre composite fracture to have several matrix cracks propagating in parallel in a manner somewhat similar to the multiple fracture described by Aveston *et al* [6] and, under these conditions, there will only be a limited amount of pull-out.

2. Experimental observations

2.1. Crack propagation through a model composite

In trying to understand the mechanical interaction between fibre reinforcement and a matrix crack there are certain conceptual difficulties that derive from the three dimensional nature of the problem; any simplification to a two dimensional model is meaningless and even observations of a solid model in two dimensions can be misleading. Because of the requirement to take full account of the geometry, any theoretical analysis would be a formidable task. Therefore this study has been restricted to a series of tests designed to give some insight to the morphology of crack propagation through brittle matrices with unidirectional fibre reinforcement.

The first stage of the investigation was to study the interaction of a slowly propagating crack with an isolated normal fibre. The model used for these tests was a brittle epoxy resin reinforced with two 0.8 mm silver steel "fibres". The type of test used was a slow bend test similar to that used by Tattersall and Tappin in measuring fracture energy [7]. The tests were stopped when it was clear that the matrix crack had passed the fibres and before any significant bending deflections developed.

Fig. 1 is typical of the appearance of the fracture surface in the region of the fibre. There are three points to note from this photograph:

1. The lines of successive arrest of the crack front are clearly visible and indicate how the propagation of the matrix crack has been made more difficult in the region of the "fibre".

2. There is a fissure normal to the primary crack surface and "downstream" of the fibre. This is formed when the two halves of the crack, separated by the fibre, reunite after having moved onto different planes in the course of bypassing the fibre. Associated with this fissure is a step on the fracture surface that was maintained for some distance.

3. On each side of the fibre there is a small crack lying normal to both the primary matrix crack and to its general direction of propagation. These cracks (here called *delaminating cracks*) were not formed in all tests and occasionally were found on one side of the fibre only. However, they appear to be of some importance in the process of crack propagation through a brittle matrix with fibre reinforcement.

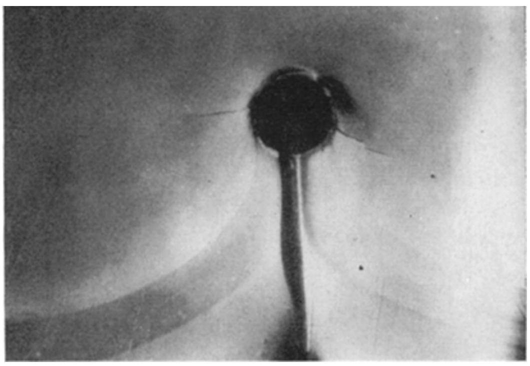

Figure 1 Photograph of the fracture surface showing the interaction of a slowly propagating crack with an isolated normal fibre, diameter 0.8 mm. The matrix crack has propagated from the top downwards.

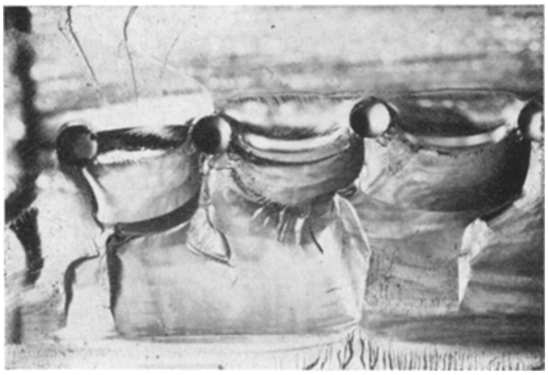

Figure 2 The interaction of a matrix crack with a row of 0.8 mm fibres. The overall direction of propagation of the matrix crack is from the top down.

It is clear trom the position of the crack arrest lines that the delaminating cracks are initiated after the primary matrix crack has been divided and has passed round each side of the fibre. The exact nature of the stress field responsible for the formation of delaminating cracks is not clear nor is the way in which initiation is affected by any other parameter such as volume fraction and modulus ratio. However, it has been observed (see below) that the proximity of the fibres helps both the initiation and propagation of delaminating cracks. In this type of test it is also apparent that they will be helped by the forces set up within the specimen by bending but the fact that similar cracks have been observed in real composites tested in tension indicates that the bending is no more than a contributory factor.

Fig. 2 shows the fracture surface of a specimen with a row of fibres at 3 mm centres. It is immediately apparent that the fibres completely disrupt the planar propagation of the crack. Although a delaminating crack bridges the gap between the two left hand fibres, no other delaminating cracks could be distinguished.

Fig. 3 shows part of the fracture surface of a

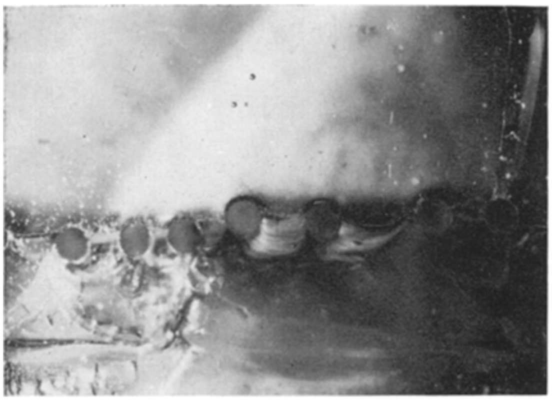

Figure 3 The interaction of a matrix crack with a row of closely spaced fibres.

specimen where the fibres were spaced at 2 mm centres. The individual delaminating cracks can be seen linking all the fibres across the specimen, thus producing a crack in a plane normal to the direction of propagation of the primary crack. To investigate the direction of propagation of the delaminating crack, this specimen was sectioned, polished and photographed on planes that were normal to both the primary crack and the delaminating cracks.

Fig. 4 shows a section through the specimen described above. Because the magnification is low and the lighting oblique some of the details of the specimen beneath the surface can be seen through the transparent epoxy matrix. It can be seen that the primary crack has passed round the fibre just below the surface and penetrated the material beyond the fibre before being arrested. A delaminating crack runs away from the primary crack and slightly downwards while propagating between the fibres but, once clear of the row of fibres, it has turned to propagate in a plane normal to the maximum tensile stress. In fact, once a delaminating crack gets out of the space between the fibres, it can propagate forwards (i.e. in the direction of propagation of the primary matrix crack) to the side across the row, or even back between another pair of fibres.

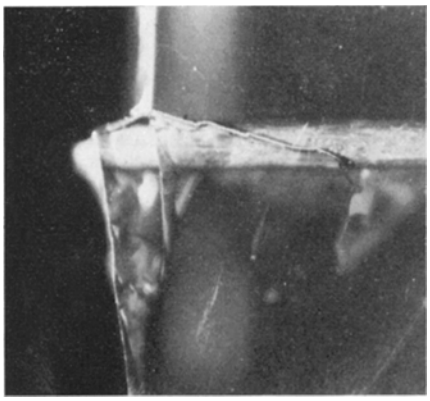

Figure 4 A section through the specimen shown in Fig. 3, showing penetration of the primary matrix crack and propagation of a delaminating crack.

2.2. Crack propagation through a real fibre composite

From these tests on a model system it is apparent that a crack propagating through a brittle matrix, can interact with a group of closely packed reinforcing fibres to initiate a second crack on a plane normal to the direction of propagation of the primary crack. This crack can, in turn, initiate a series of cracks on planes parallel to the primary crack. Because the reinforcing fibres bridge the matrix cracks, they still carry load, a load that will increase as the matrix crack opens, so it is possible for this series of cracks on parallel planes to propagate simultaneously. The load carried by the reinforcement across the matrix cracks also reduces the rate of release of strain energy with crack extension and so increases the overall stress level required for the propagation of the matrix cracks.

The type of specimen used for the model tests has the disadvantage that fracture is essentially restricted to the plane of the notch. While for most fracture investigations on homogeneous materials this is generally acceptable, if there is any tendency for an unrestrained crack spreading through a material to deviate from a direction normal to the maximum tensile stress or to initiate additional systems of cracks, then that tendency will be suppressed. Therefore, for the tests on a real composite system, edge-notched tensile specimens were used. This also ensured that any effects associated with bending were minimized. This is a particularly important point in so far as fibre composites are concerned because the behaviour of fibres bridging the crack will be governed by the crack opening displacements which will be grossly exaggerated in a bend test.

The material chosen for this part of the investigation was a brittle polyester resin reinforced with E-glass rovings at volume fractions between 2 and 15%. Specimens, having a cross-section of 12 mm × 6 mm, were tested in tension after having a notch 1.5 mm deep × 0.25 mm wide cut in the edge. The tests were generally stopped once a fairly severe degree of damage had been done to the specimen.

Some difficulty was experienced in fabricating the specimens in such a way that the reinforcement was uniformly distributed so that, in all the specimens tested, the fibres tended to be grouped closely together in strands where the fibre volume fractions were *locally* quite high, approaching values of 70% in isolated areas. However, these locally high volume fractions seem to play a significant part in the initiation of delaminating cracks.

With fibre volume fractions of about 15% or more a shear failure propagates from the notch tip with secondary cracks penetrating a short way into the load bearing part of the specimen. At the lower end of the volume fraction range, the fracture is effectively restricted to one plane, although, as shown in Fig. 5 the fibres do have some effect on the propagating matrix crack. This photograph shows part of the surface of a fracture which was initiated at an air bubble (visible in the top left) in the matrix of a composite with only 2% of fibres. The material in the region shown is virtually devoid of fibres but those fibres which are present have produced curved temporary arrest lines and wake cracks similar to those observed in the model.

Fig. 6 shows two views under oblique and normal light of a specimen with an intermediate volume fraction of 8%. Here the behaviour is quite different with a series of secondary matrix

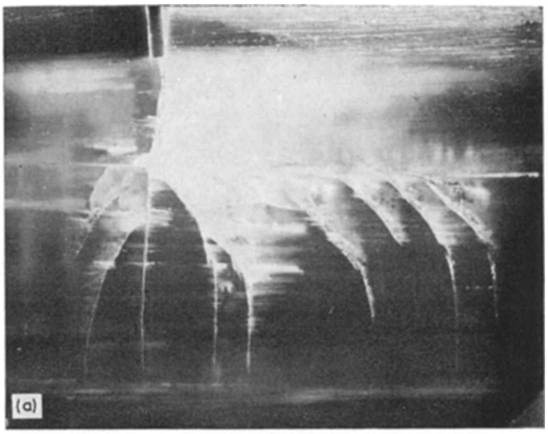

Figure 6 A section through a notched tensile specimen, (a) viewed under oblique illumination and (b) viewed under normal illumination.

cracks running across the material at different levels.

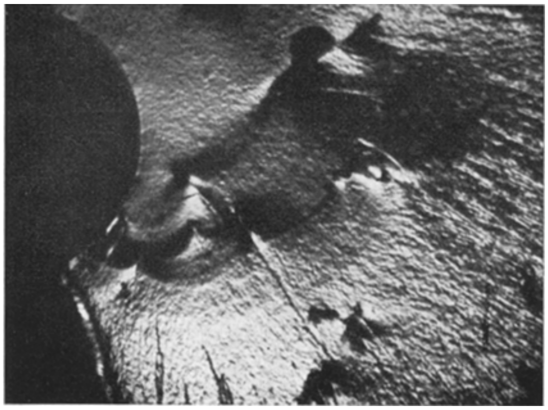

Figure 5 Fracture surface of a tensile specimen of a polyester resin reinforced with 2% by volume of E-glass. The area of the fracture surface shown is virtually devoid of reinforcement.

This secondary system of cracks, parallel to the primary crack, branches out from the shear failure associated with the delaminating cracks between the fibres of a particular bundle. The division of the single primary matrix crack into a number of parallel secondary cracks, brings about an order of magnitude increase in the total area of matrix cracks involved in the fracture.

Because a failure of the fibre/matrix interface forms a new surface which reflects the illumination, it is possible to see from Fig. 6a that fibre debonding takes place on either side of all these secondary cracks. Thus the order of magnitude increase in crack area results in a similar increase in the work involved in debonding as well as the work necessary for the creation of the new matrix surfaces. There will also be an increase in the work done in pull-out but this will not be so great because, although there will be some pull-out associated with each secondary crack, it is only across the final fracture surface, where there is complete separation, that all the fibres will be completely withdrawn from the matrix.

3. Discussion

These observations are all consistent with the behaviour of cracks in the model system with delaminating cracks propagating away from the primary matrix crack and initiating secondary cracks that propagate simultaneously on planes parallel to the primary crack. The secondary cracks are also capable of initiating further delaminating cracks and by so doing, enable a further division of the opening displacement concentrated in the primary crack. The propagation of each of these secondary cracks requires a supply of energy which provides (a) the fracture work of the matrix, (b) the energy dissipated in debonding, (c) the energy dissipated in pull-out.

This multiplication of the fracture surface leads to a substantial increase in the work of fracture over what would be expected when there is a single matrix crack. The difference is largely associated with work done in debonding.

Pull-out is generally regarded as the major component of the work of fracture of a unidirectional fibre composite [4]. However, pull-out can only take place after the passage of a primary matrix crack and after failure of the interface, also any pull-out work must be associated with appreciable opening and, therefore, penetration of the matrix crack. The formation of secondary matrix cracks propagating simultaneously on parallel planes can have two benefits: not only is there effectively an increase in the work of fracture by involving a far greater volume of material in the fracture process but also the opening displacement at the original defect can reach a much higher level for a given amount of crack penetration than would be possible with propagation restricted to one plane only.

An explanation for the propagation of these secondary cracks on parallel planes lies in the way the work required to extend a crack increases as the crack extends. Where the work of fracture is largely the work of pull-out it will increase only gradually as the matrix crack extends. Indeed the matrix crack probably needs to be of the order of 1 cm or more (depending on the geometry and critical length) before the work of fracture is fully developed. This being so, it is possible to see that as a cracked sample of composite is stretched, provided that a suitable mechanism exists, it would be energetically more favourable to open a second crack than extend the first. Once a crack has extended far enough to develop the full work of fracture then, under normal circumstances, it must become unstable and the above mechanism by which secondary cracks can be produced will cease to operate.

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