MIXED-MODE FRACTURE OF ASYMMETRIC INTERFACES

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A problem of evergrowing importance, crack propagation at interfaces between dissimilar materials, has been studied analytically, numerically and experimentally. An asymmmetric double cantilever beam (ADCB) has been used where a composite is bonded against a composite or aluminium base. For such a configuration, crack propagation is governed by a mixed-mode state of stress (modes I and II). The ratio of crack opening (mode I) and in-plane shear (mode II) changes with specimen configuration and crack extension. The present study is primarily concerned with the problem of mixed-mode fracture, especially where such failure occurs along a plane of potential weakness such as a bimaterial interface.

The interfaces found in almost all load-bearing engineering structures often represent the most critical element in the structure. It is well known that interfaces behave differently under different modes of loading. This behaviour is complicated by the fact that certain materials are tougher under mode I (opening mode) loading than mode II (shear mode) loading whereas others are more fragile. Thus C. F. Shih [1] used complex variable theory to develop solutions for problems involving cracks at interfaces. M. Charalambides [2[examined a number of mixed-mode fracture problems relating to bi-material interfaces. A. J. Kinloch [3] identified the importance of residual stresses at the interface.

1. Experimental Description.

In the first phase of this study, a review was undertaken in order to assess the viability of the currently available mixed-mode specimens and determine their suitability regarding crack stability and mixed-mode ratio. It was decided that none of the geometries commonly used were fully suitable for characterising a wide range of mixed-mode loading conditions. Instead, an asymmetric double cantilever beam (ADCB) specimen similar to that frequently used for evaluating the mixed-mode fracture toughness of long fibre composites was selected and adapted. A schematic representation of the loading jig is shown in Fig. 1.

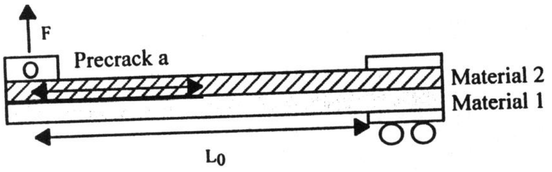

Fig. 1 Schematic representation of the asymmetric double cantilever beam specimen for the investigation of mixed-mode fracture.

Essentially, the test specimen consists of two parts, the upper and lower portions being made from different or similar materials (composite/composite, aluminum/composite and aluminum/aluminum). A 50 mm length of mylar foil is placed at the interface between the two materials at one end of the specimen for a total length L_0=150mm. The other end of the

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specimen is clamped on a steel base which is free to move during the test. A load is applied through an aluminium block glued to the free end forcing the mylar pre-crack to open and a crack to propagate at the bi-material interface. During the course of the test, the load, the load point displacement and the crack length are measured.

According to the approach used, results have been obtained in three different areas: in the derivation of an appropriate analytical solution for the mode I and mode II fracture energies during interfacial fracture, in the evaluation by finite element analysis of the essential parameters involved in crack propagation, and in the experimental investigation of crack propagation and of the toughness of different bi-material systems.

2. Analytical evaluation.

Based on the analysis of J.G. Williams (4), we have first developed a closed form analytical solution in which the modes I and mode II fracture energies during interfacial fracture of an ADCB specimen can be shown to be:

for constant load;

$$G = \frac{F^2a^2}{2B}\left(\frac{1}{\chi_a} - \frac{1}{\chi_b}\right) \qquad (1)$$

for constant displacement;

$$G = \frac{9\delta^2a^2\left(\frac{1}{\chi_a} - \frac{1}{\chi_b}\right)}{2B\left[\frac{L^3}{\chi_b} + a^3\left(\frac{1}{\chi_a} - \frac{1}{\chi_b}\right)\right]^2} \qquad (2)$$

where $\chi_a = \frac{E_2Bh_2^3}{12}$ and $\chi_b = \frac{B\left[\left(-h_1^2E_1 + h_2^2E_2\right)^2 + 4E_1E_2h_1h_2\left(h_1 + h_2\right)^2\right]}{12\left[h_1E_1 + h_2E_2\right]}$

B: specimen width

h_1: lower beam thickness. h_2: upper beam thickness (loaded arm).

E_1: lower beam Young's modulus. E_2: upper beam Young's modulus.

The ratio between mode I and II is given by the relation ,

$$\frac{G_{II}}{G_I} = \psi - (1+\psi)\frac{\chi_a}{\chi_b} \qquad (3).$$

where $\psi = \frac{E_2h_2^3}{E_1h_1^3} = \frac{E_2}{E_1}\frac{(1-\xi)^3}{\xi^3}$ and $\xi = \frac{h_1}{h_1 + h_2}$

3. Finite element analysis

The present study was primarily concerned with the problem of mixed-mode fracture. Four different approaches for analysing mixed mode failure were investigated with the F.E. package ABAQUS. The modelisation are done from experimental results on bimaterial

ADCB carbon epoxy composite bonded with epoxy resin against aluminum, loaded on composite.
These concepts are:

- J contour integral method given by the F.E. package (J).
- Crack tip opening displacement method using singular quarter point elements (G_{cod}).
  The stress intensity factor is computed by the crack-opening displacement method using singular quarter point elements. A $r^{-1/2}$ stress (or strain) singularity is represented by an appropriate numerical function.
- Modified crack closure integral applied to F.E. stress contours (G_{mcc}).
  The idea is to use Irwin's concept of crack-closure integral taking a virtual crack extension tending to zero in the limit and admitting that the displacement field ahead of the crack tip can be approximated by the one behind it.
- Energy release rate from beam theory (1) (G_b) equations 1, 2 and 3.

The experimental J-values are designated by J_{ex}.

The calculated and measured energy values and the degree of mode mixity obtained from the different concepts are given in Table 1. It should be noted that the J-values are derived from an elasto-plastic approach whereas the G-values take into consideration elastic deformation only. The difference between J and G_b is relatively small so that we conclude that plastic deformation is highly localised. The same result was obtained by D. Batisse (5) for interfaces in the presence of adhesives. However, the large difference between the calculated values of the ratio of G_I/G according to the different approaches should be noted.

h composite (mm)	crack length (mm)	J (J/m2)	J_{ex} (J/m2)	G_b (J/m2)	ratio $(GI/G)_b$	G_{cod} (J/m2)	ratio $(GI/G)_{cod}$	G_{mcc} (J/m2)	ratio $(GI/G)_{mcc}$
1.4	80	163.5	-	175.5	1	166.4	0.52	192	0.57
2	65	183.1	183	180.2	0.998	189.8	0.57	194.4	0.61
2	85	149.8	150	160.1	0.998	155.4	0.57	195.4	0.62
5.45	80	164.3	-	160.3	0.943	166.4	0.51	-	-

Table 1. Evaluation of Gc and mixed-mode partitioning ratio G_{Ic}/G_c for different approaches.

3. Experimental Results

In the derivation of an appropriate analytical solution for the mode I and mode II fracture energies during interfacial fracture, two concepts of mixed mode partitioning have been proposed so far: (i) a local solution based upon the consideration of a singular field ahead of the crack tip (COD and MCC approach), and (ii) a global solution based upon consideration of the available energy release rate (Beam theory). This notion of local and global solution has been introduced by M. Charalambides [2]. A. J. Kinloch [6] agrees with her and suggests that fracture is governed by the global mode. S. Ramaswamy]7] and J. Y. Shim [8] pointed out the limitation of the mode partitioning proposed by J. G. Williams. They show that the mode-partitioning method which uses a moment decomposition technique is limited to flexural specimens where the geometrical parameter ξ is 0.5 ($h_1=h_2$ and $E_1=E_2$).
In fact latest result shown the validity of the mode partitioning proposed by J. G. Williams (global mode). Also it does work with anisotropic materials as composite. Figure 2. shown

the total energy release versus the mode mixity evaluated by beam theory for two carbon epoxy composite laminas bonded together.

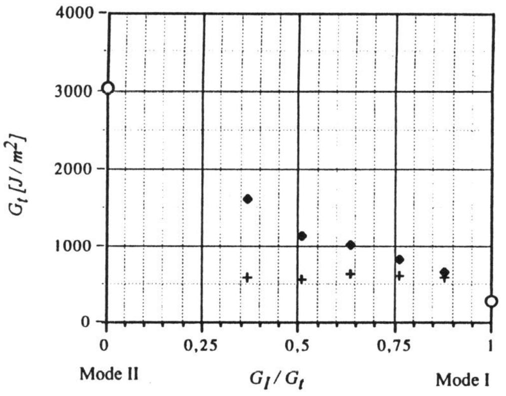

Fig. 2: Mean values of G_t versus G_I / G_t for mode I, mode II and mixed mode tests. The crosses represent G_I values evaluated from G_t.

The *local solution* shows that at the tip of an interface crack a stress singularity of the order r^λ exists. λ is the complex eigenvalue proposed by M. L. Williams [9] where $\lambda=-1/2+i\varepsilon$ with ε as bimaterial constant, dependent on the properties of both materials on either side of the interface. The presence of the term ε results in an oscillatory behaviour in stresses as the crack tip is approached ($r \rightarrow 0$). Because crack faces can not interpenetrate or overlap each other, a small contact zone has been introduced by J. R. Rice as [10],

$$r_c = 2a \exp(-(\psi+\pi/2)/\varepsilon).$$

where ψ is the phase angle (=0 when only remote tension is applied). This feature suggests that the crack growth is more intimately connected with failure in shear than in the tensile mode depending on the phase angle sign. Improved bimaterial ADCB specimen by post-curing the carbon epoxy composite lamina while bonding it (at 80^0C) to the aluminum substrate using the same resin were tested. The load has been applied on composite and on aluminum for equivalent geometries. This way of loading change the phase angle sign. Two different crack behaviours were observed, Fig 3 (i) cohesive, Fig.3 (ii) adhesive.

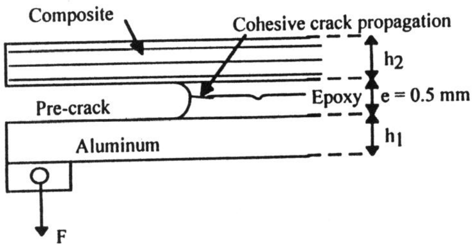

Fig. 3 (i) Loading of an asymmetric double cantilever beam on the aluminum side

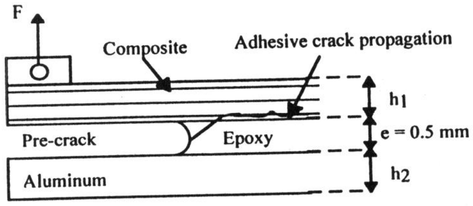

Fig. 3 (ii) Loading of an asymmetric double cantilever beam on the composite side

The results obtained did not shown any correlation between G_t and the mode mixity as in Fig 2. But two levels of G_t appear depending on the loading side Fig 4.

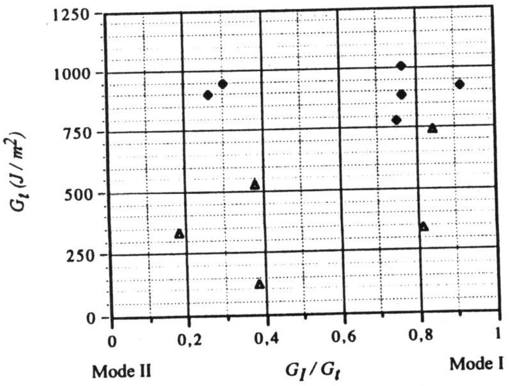

Fig. 4. Mean values of G_t versus G_I / G_t on bimaterial ADCB aluminum-composite specimens. The white triangles dots present composite loading side and the black dots presents aluminum loading side.

On the other hand standard ADCB specimen are used to test experimentally to what extent the *global approach* is valid to determine the ratio of G_I/G for aluminium/composite materials.

Outlook.

The experimental techniques for characterising fracture at bi-material interfaces have been developed and applied with considerable success to a number of problems. In the next phase, tests will be undertaken to quantify local mixed mode zone sizes and mode partitioning. These tests should enable to optimise geometries and the choice of the mechanical characteristics of layers in order to obtain strong, high quality interfaces. It is also intended that the problem of rapid crack propagation across an interface be studied. This is a common problem in the automobile industry, for example, where cracks that initiate in a brittle coating propagate rapidly across the interface causing brittle fracture of the otherwise tough substrate. The numerical study will be further developed in order to examine crack propagation between other types of materials as well as more complex geometries typical of those found in engineering practice. Here a suitable failure criterion will be developed and applied.

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