FE MODELLING OF DELAMINATION GROWTH IN DCB SPECIMENS WITH MATERIAL VARIABILITY OR GEOMETRIC IMPERFECTIONS

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This paper reports on the application of a recently developed finite element (FE) model for delamination growth in composite components. The FE analysis has been applied to composite Mode I interlaminar fracture toughness specimens to investigate the sensitivity of results obtained using various data reduction techniques. Two types of double cantilever beam (DCB) specimen have been studied; the conventional DCB specimen and an edge-delaminated version of this specimen. The investigations have included sensitivity to material property variations and geometric imperfections which might occur in an actual test specimen. The results of the investigations have shown that some of these effects can lead to distortion of the true interlaminar fracture toughness.

INTRODUCTION

A finite element based delamination growth modelling facility is currently being developed at Imperial College so that problems of delamination growth in real components can be tackled. To evaluate the performance of the software studies of simple delamination growth have been performed. This paper reports the results of one such study in which the sensitivity of results from Mode I DCB tests was investigated.

INVESTIGATION DETAILS

Specimen types, material and models

Two types of DCB specimen were investigated; the conventional DCB specimen, Figure 1a, and the edge-delaminated version of this specimen, Figure 1b. (The edge-delaminated version has been used to investigate the interlaminar fracture toughness between off-axis reinforced plies[1].) In these investigations the behaviour of the specimens has been analysed for a unidirectional carbon epoxy system (Ciba-Geigy's T800/924) with the fibre direction parallel to the longitudinal direction of the specimen. Table 1 shows the composite material stiffness properties which were used in the FE analyses.

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TABLE 1 - Stiffness properties used in FE analysis

E_{xx}=155 GPa	E_{yy}=9.5GPa	E_{zz}=9.5GPa
ν_{xy}=0.270	ν_{xz}=0.270	ν_{zy}=0.6
G_{xy}=4.6GPa	G_{xz}=4.6GPa	G_{zy}=4.6GPa

The FE models used in the majority of the investigations consisted of 8 or 9-noded Mindlin plate elements. Taking advantage of symmetry, either one arm or one half of one arm of the specimen was modelled. Typical meshes used in the analyses are shown in Figure 2. Twenty-noded 3D brick element models were used for some of the cases to verify the results of the plate models.

Delamination growth modelling technique

Details of the technique for modelling of stable delamination propagation have been given in [2]. In this technique, the delamination profile, for 3-D planar delaminations, is sought so that a constant strain energy release rate (G) equal to the critical value (G_c) is achieved along the delamination front for a given applied load or displacement. Therefore the analysis reduces to the solution of a system of non-linear equations which relate the location of delamination front points to the G at each point. An efficient moving mesh algorithm is also used in the iterative solution procedure. The effect of contact, found to occur between the arms of edge delaminated specimens, is included in the models where appropriate [4].

Sensitivity parameters

The baseline case for each DCB specimen type was that of a constant G_{Ic} of 270J/m^2 throughout the specimen with no geometrical imperfections. The sensitivity of the fracture toughness specimens was investigated for the parameters described below.

a) Conventional DCB specimen. Geometric imperfections (Figure 1a): a skew initial crack front at 6° to the ideal position; the applied load offset from the specimen centreline by 1.67mm. Material imperfections: input G_{Ic} varying linearly across the width from 250J/m^2 at side 1 to 290J/m^2 at side 2.

b) Edge-delaminated specimen . Geometric imperfections: none. Material imperfections: input G_{Ic} varying linearly along the length of the specimen from 230J/m^2 at zero crack length to 310J/m^2 at a crack length of 150mm.

Investigation procedure

The investigation procedure was the same for all specimens. The FE analysis was used to determine the crack front shape for a given applied displacement. The load, applied displacement and crack position were recorded and the process repeated for further increments in applied displacement. (The crack position is that which would be observed at the edges of the specimen.) The load-applied displacement-crack length data was then treated as if it were experimental data. It was processed using the modified beam theory (MBT) method[5] which in its basic form gives

$$G_{Ic}=P\delta/2B(a+\chi h) \quad \text{...}(1)$$

where χh is the correction to the crack length. χh is determined by fitting a straight line to $(\delta/P)^{1/3}$ vs. a. The intercept on the crack length axis is, after a change of sign, the value of χh. (Note that this is the basic form of this equation. A more refined form [5] was used in the data reduction here.) The calculated G_{Ic} was then compared with the input value.

RESULTS AND DISCUSSION

Conventional DCB specimen

Geometric imperfection : skew starter crack front. As would be expected, the crack growth is first detected on side 1 of the specimen. However the load does not immediately start to fall with further crack growth (see Figure 3) because initially only a small part of the crack front advances. Crack growth is not observed on side 2 until the whole of the crack front advances. (This occurs after approximately 2mm of growth on side 1.) Two different sets of crack length data are therefore available and both have been processed to give the plots of G_{Ic} shown in Figure 4. (Note that the baseline G_{Ic} derived from the FE data is in good agreement with the input G_{Ic}.) The observations on side 1 yield an apparent initial steep rise in G_{Ic} (i.e. an R-curve) which levels out close to the input value. G_{Ic} based on the crack length observations from side 2 shows good agreement with the input value. If the crack lengths before growth is observed on both sides of the specimen are discarded then the two measures of crack length would be identical and produce G_{Ic} in good agreement with the input value.

Geometric imperfection : offset load. The initial growth is similar to the above case; growth is observed on side 1 first due to the torque applied to the specimen arm by the offset loading. This leads to an initially steep R-curve if data from the side 1 is processed (Figure 5). After growth is observed on both sides of the specimen a1 and a2 remain different but the difference tends to reduce as the crack grows. (The torque in the arm reduces with crack length.) The net effect of this is that G_{Ic} from the 'long' side is higher than the input and that from the 'short' side is lower by almost the same amount. In this case discarding the data before crack growth is observed on both sides of the specimen and using the mean of the two crack lengths would yield G_{Ic} in very good agreement with the input value.

Material property variation : G_{Ic} varying linearly across the width. This variation in the input G_{Ic} produces a similar effect to the previous two cases in that growth will be detected on side 1 first and if the initial crack length data is used it would lead to an apparent initial R-curve. After the initial stages of growth the crack lengths at the two edges differ by an almost constant amount. Using only crack length data available after growth is observed at both sides of the specimen, G_{Ic} from each edge is found to be in good agreement with the mean input G_{Ic} of 270J/m^2.

Edge-delaminated DCB specimen

Material property variation : G_{Ic} varying linearly along the length. For an edge-delaminated specimen the *observed* crack front, a*, is the contact point between the upper and lower arms of the specimen (Figure 6). Since movement of the contact position occurs before any movement of the crack front, the initial a* data before delamination growth should not be considered in the data reduction. Assuming this then for the baseline case of constant G_{Ic}, the MBT data reduction scheme yields a G_{Ic} in good agreement with the input value provided there is a reasonably constant difference between a* and the actual crack length. (This difference is accounted for by the χh correction.) However Figure 6 shows that the baseline analysis yields a value approximately 4% higher than the input. This is because the difference between the actual crack front and a* does not remain constant but reduces with increasing crack length. (This effect is mainly due to the reducing shear force as the crack length increases.) For the linearly varying input G_{Ic} a similar effect is seen and so the output G_{Ic} would be expected to be higher than the input value for a given crack length. However in Figure 6 G_{Ic} has been plotted against the apparent crack length and so the output G_{Ic} plot is additionally displaced to the right with respect to the input value which is plotted against actual crack length. The χh correction could be used to determine the approximate position of the actual crack front but the G_{Ic} would be slightly higher than the input value as observed for the constant G_{Ic} case.

CONCLUSIONS

FE analyses of delamination growth in the conventional DCB specimen have shown that initiation values of G_{Ic} and the initial shape of the R-curve can be sensitive to geometric imperfections and material variability if these give rise to crack growth occurring on one side of the specimen first. The effects are fairly small for the magnitude of imperfections investigated here but will be larger for larger imperfections. If accurate initiation values are to be determined then care must be taken to ensure accurate specimen and loading geometry and the crack growth should be monitored on both sides of the specimen - at least in the early stages of growth. The subsequent R-curve for the cases of starter crack misalignment and toughness variation across the width can be determined adequately from crack length measurements from one side of the specimen provided only those recorded after growth is observed on both sides of the specimen are used in the data reduction. If the resultant applied load is offset from the specimen centreline then the mean readings of crack length should be used, again neglecting readings before crack growth is observed on both sides.

The analysis of the edge delaminated specimen showed that both a constant G_{Ic} and a linearly varying R-curve could be both determined reasonably accurately from the contact position observed at the edge of the specimen. The G_{Ic} values based on this apparent crack length are slightly higher than the input values due to the changing difference between the actual crack position and the contact position observed at the edge.

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SYMBOLS USED

a	= crack length (a1, a2, a* are various measures of crack lengths)
B	= width of delamination front
G_{Ic}	= Mode I critical energy release rate
P	= applied load
δ	= displacement at applied load position
χh	= crack length correction

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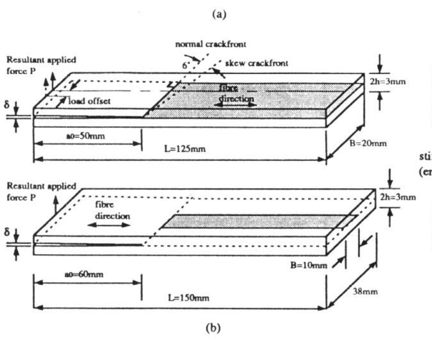

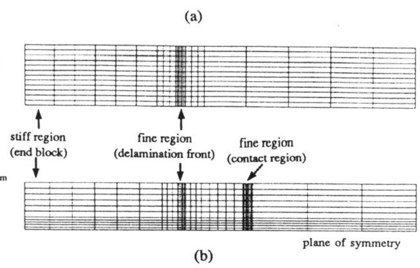

Figure 1. (a)Conventional DCB (b)Edge delaminated DCB

Figure 2.FE meshes (a)Conventional (b)Edge delaminated

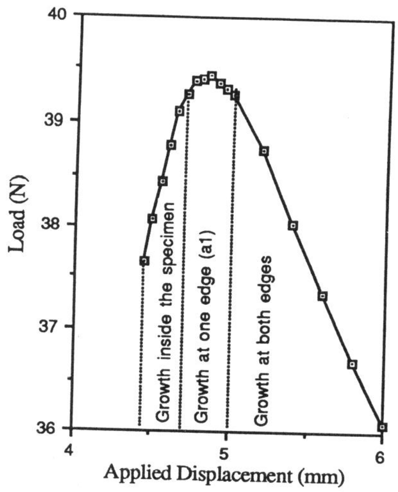

Figure 3. Skew starter crack
Load-Displacement plot

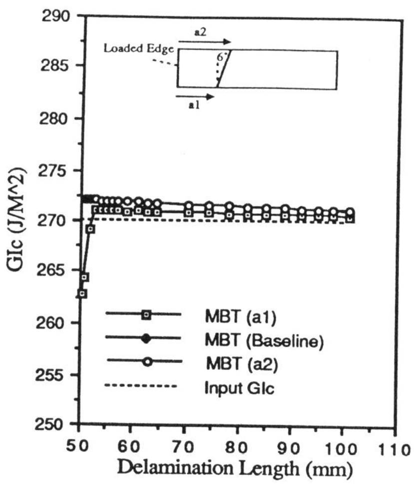

Figure 4. Skew starter crack
GIc-crack length plot

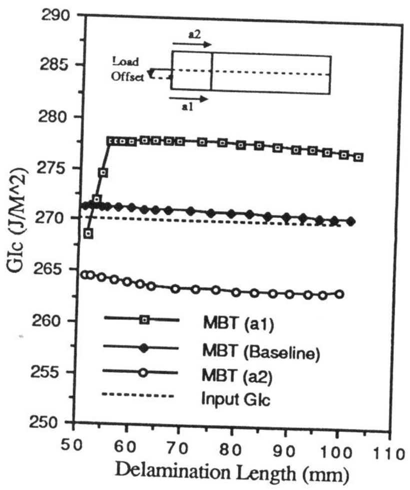

Figure 5. Offset resultant load
GIc-crack length plot

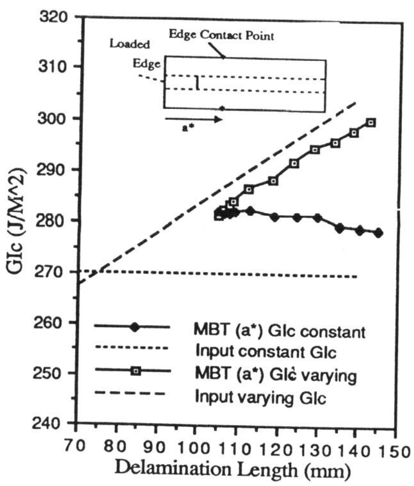

Figure 6. GIc-crack length plot for
constant and linearly varying input GIc