MODE I FRACTURE TOUGHNESS TESTING OF FIBRE-REINFORCED POLYMER COMPOSITES: UNIDIRECTIONAL VERSUS CROSS-PLY LAY-UP

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Mode I DCB tests have been conducted on a carbon-fibre epoxy composite utilising three different cross-ply lay-ups as part of a European round-robin exercise to investigate the procedures necessary to test cross-ply and woven fabric laminate materials. In this first round-robin, the procedure developed for unidirectional laminates (currently ISO CD 15024) has been followed with the objective to identify whether this procedure requires modification before it can be successfully applied to laminates with cross-ply lay-up. This paper reports on some initial results from the round-robin exercise and discusses the fracture behaviour of the three materials tested and describes some of the problems posed when stick-slip crack growth is observed.

INTRODUCTION

The development of fracture mechanics tests for fibre-reinforced polymer matrix composites has led to the standardisation of fracture toughness measurements for unidirectional (UD) laminates under mode I loading. At the time of writing, this standard is in ISO Committee Draft form (1). The main standardisation effort has in the past been directed towards laminates with UD fibre reinforcement because these materials have been shown to yield the most conservative values of the fracture toughness, G_{IC}. However, there is a need for values of G_{IC} from laminates with cross-ply or arbitrary lay-ups, since these "real" engineering materials are widely used in industry.

The European Structural Integrity Society (ESIS), through its Technical Committee 4 on Polymers and Composites recently initiated a round-robin exercise to investigate the behaviour of laminates with cross-ply lay-up. The principal aim was to investigate whether the testing standard for UD lay-ups could be extended to cover non-unidirectional lay-ups without change in procedure or, whether the test procedures would have to be revised or even rewritten entirely. A substantial amount of data has been reported in the literature on mode I testing of non-unidirectional laminates. For

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example, Russell and Street (2) investigated delamination along three interfaces; 0°/0°, 45°/45° and 90°/90°, Nicholls and Gallagher (3) investigated delamination along a number of +θ°/-θ° interfaces and more recently Robinson and Song (4) reported on a modified version of the DCB specimen to constrain the crack to the intended interface. However, the authors are not aware of any inter-laboratory round-robin studies on this subject. Ten laboratories are participating in this round-robin and, as a first step, we report on the initial results of tests from two cross-ply laminates (alternate 0°/90° plies) and one woven fabric.

EXPERIMENTAL

Many studies e.g. (5) have reported the importance of fibre lay-up orientation in the DCB specimen, particularly the partial symmetry of each arm of the beam and the total symmetry with regard to the defect plane. In this first round-robin, it was decided that, as a starting point, partial symmetry of the arms of the DCB would not be imposed, but total symmetry with respect to the defect plane would be imposed in two of the three lay-ups chosen. Some insight could then be gained as to the importance of total and partial symmetry in DCB testing of laminates. Mode I DCB tests were conducted according to the latest version of the ISO mode I Committee Draft (1). The material investigated was supplied by Fiberite and consisted of an epoxy matrix, 970, reinforced with T300 carbon-fibre. The lay-ups were as shown in Table 1.

TABLE 1- Details of the fibre lay-ups employed in this study.

Code	Description	Detailed Lay-up
TYPE I	Symmetric cross-ply laminate	$[0/90]_6$ insert $[90/0]_6$ or $[0/90]_{6S}$
TYPE II	Unsymmetric cross-ply laminate	$[0/90]_6$ insert $[0/90]_6$ or $[0/90]_{12}$
TYPE III	Woven fabric laminate	$[0/90]_4$ insert $[90/0]_4$ or $[0/90]_{4S}$

The insert material was a PTFE film. Due to limited material availability the film thickness was 25 microns. This was greater than the maximum thickness of 13 microns recommended in (1). The experimental procedure which the participating labs were asked to follow included a drying cycle at 80°C for twenty-four hours. The other main procedures to be followed were: (i) precracking the samples in mode I, extending the crack ahead of the starter film by 3-5 mm, (ii) fully unloading the specimens before reloading from the mode I precrack, (iii) propagating the crack at least 50mm ahead of the mode I precrack before fully unloading the beams and (iv) conducting five repeat tests for each material. Constant loading rates of between 1-5 mm/min could be used.

RESULTS

The failure path of the crack in TYPE I and TYPE III laminates remained co-linear, i.e. did not deviate from between the central plies which bordered the insert film. However, the failure path observed in the TYPE II laminates, where the crack had been initiated between a 0° and a 90° ply, jumped back and forth through the 90° ply. The initial crack interface and the location of the resulting crack paths are summarised in Table 2. The crack propagation in all tests showed pronounced stick-slip behaviour. Typically, the initial crack jump from the insert film extended about 10mm and was associated with a large decrease in the load. Unloading the samples and subsequently reloading them, as required by (1), failed to render the crack stable and stick-slip crack propagation occurred along the entire length of the beams for all lay-ups i.e. TYPES I, II and III. Figure 1 shows a typical load-displacement trace obtained when testing the TYPE III (fabric) laminates.

The occurrence of stick-slip crack growth in a mode I DCB test poses a number of problems and complicates the analysis. Firstly, it was not possible to obtain a precrack via stable propagation, as required by (1). Secondly, the load-displacement behaviour was linear right up to maximum load and the onset of unstable propagation. The 'non-linear' and 'visual' definitions of initiation were thus not obtained. (Whilst the initial propagation from the film insert may have been influenced by the 25 micron thick PTFE starter film, subsequent initiations are unlikely to have been influenced by the film. However, some new specimens are being manufactured with thinner inserts to verify this.) Thirdly, the accuracy of the compliance calibration was reduced because the number of crack length measurements available was lower than for a stable test. Indeed, it was not possible to control the crack length, so many crack length measurement details prescribed in the Committee Draft (1) couldn't be followed, e.g. it was not possible to measure the crack growth at 1mm intervals for the first and last 5mm of propagation. The crack length measurements were limited to a series of crack initiation and arrest points. These points could be defined from the fracture surfaces after the tests when the specimens had been broken open. This method may be more accurate than trying to observe the crack length during the test with a travelling microscope as recommended, but care was required to correlate the crack initiation and arrest lines accurately with the load-displacement trace. Then there was the question of which points to analyse in the mode I analysis. There were three options: (i) input all initiation and arrest points into the analysis, (ii) input only the initiation values or (iii) input only the arrest values. The Committee Draft (1) prescribes in the Informative Annex (B.8) that in the event of stick-slip crack growth all arrest values should be excluded from the analysis.

TABLE 2 Comparison of initial crack interface and failure path of crack.

Code	Laminate	Interface	Crack Path Co-linear?
TYPE I	Cross ply	90/90	Yes
TYPE II	Cross ply	0/90	No
TYPE III	Fabric	0/90//90/0	Yes

Thus, option (ii) above was followed. Finally, it should be noted that according to the criteria of the ISO Committee Draft (1) for UD materials, no valid G_{IC} results were obtained for these cross ply specimens for two reasons. Firstly, an insufficient number of data points were recorded and secondly initiation did not occur from a stable precrack.

Table 3 shows data from one lab. All the crack arrest points have been excluded from the analysis. The values of G_{IC} in Table 3 have been computed via the corrected beam theory method, as detailed in (1). All data was analysed using a spreadsheet (Version 1.02) developed at EMPA (6). The initiation values from both the insert film and the precrack are shown together with the mean of the subsequent initiations (termed running initiations) obtained at longer crack lengths. The values of G_{IC} measured at crack initiation from the insert film may be questionable due to the film being thicker than recommended. It should be noted also that initiation from the precrack, and all subsequent 'running initiations' were effectively obtained from the condition of initiation from a point of crack arrest. In the current tests, hardly any stable crack growth was observed. It is instructive to compare the scatter in this data to the typical scatter observed when testing UD reinforced carbon-fibre laminates in mode I. Brunner et al (7) reported mean and standard deviation values of G_{IC} for a UD carbon-fibre composite (G40-800, 977-1) measured from a film insert, from a mode I precrack and from a wedge precrack. Converting to coefficients of variation (CoVs), they reported CoVs of 6%-17% for G_{IC} values measured at crack initiation from the insert film.

TABLE 3- Values of G_{IC} for initiation from the insert, precrack and the mean of subsequent initiations; mean values and COVs from 5 specimens

Lay-up type	G_{IC} (J/m^2)		
	Init-Film (Max)	Init-precrack (Max)	Running Inits
(Mean)			
TYPE I	396 (9.3%)	326 (26.0%)	310 (18.9%)
TYPE II	375 (7.8%)	472 (13.8%)	530 (21.8%)
TYPE III	346 (16.0%)	439 (19.4%)	422 (12.4%)

However, from a mode I precrack CoVs of 2%-6% were reported and for average propagation, CoVs of 5%-10% were reported. In the data shown in Table 3 for the three types of cross-ply material, the scatter or CoVs in the G_{IC} values measured from the insert film are of the same order as for the unidirectional results reported in (7). However, the CoVs in the values of G_{IC} from the mode I precrack and from the running initiations are clearly much greater than was reported for the UD material, where stable growth had been observed from the mode I precrack. The TYPE II cross ply laminate with the 0°/90° interface developed the highest values of G_{IC} as would be expected, because crack deviation from the mid-plane was occurred. Figure 2 shows the R-curves (plots of G_{IC} versus crack length) obtained from a single test of each of the three materials. The stronger rising 'R-curve' behaviour of the TYPE II laminate is clearly seen.

CONCLUSIONS

A full statistical analysis of the data from this round-robin exercise must wait until all the participating labs have reported data. However, from the initial results received, some conclusions can already be drawn. The three different cross-ply lay-ups investigated in this study all exhibited pronounced stick-slip crack propagation behaviour. The mode I UD Committee Draft (1) makes provision for the analysis of this type of data by requiring all arrest values to be excluded. However, this will often leave a rather small number of data points from which to conduct the analysis and this in turn may result in a high degree of scatter in the measured G_{IC} values, as observed in the present work. Whilst the mode I Committee Draft was specified well enough to enable the testing of cross-ply laminates to be performed a number of the criteria were violated. For example, the criteria for the number of data points required could not be met and it was not possible to obtain a precrack from stable crack growth. The next round-robin will resolve many of the issues raised here because a thinner insert film will be used in the cross-ply specimens and a UD laminate with the same matrix and fibre reinforcement will also be tested for comparison.

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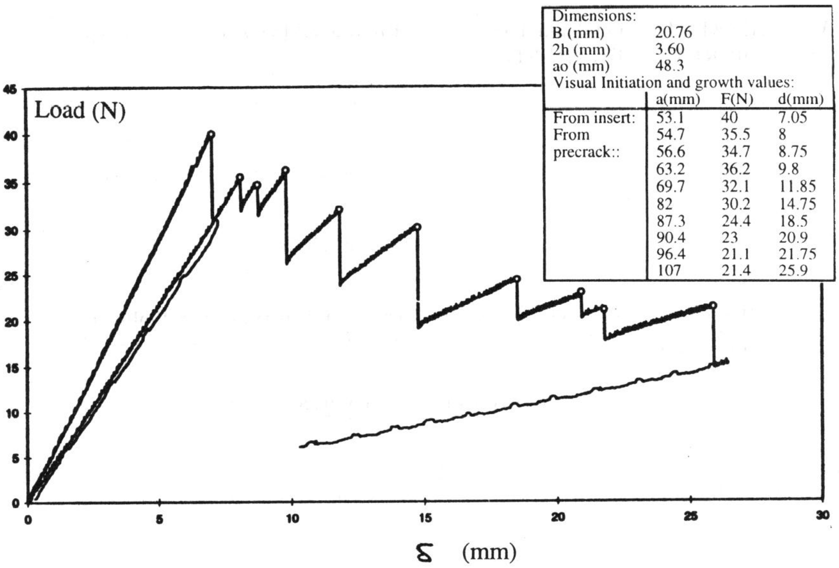

Figure 1 Load-displacement trace for a single test on the TYPE III (fabric) material.

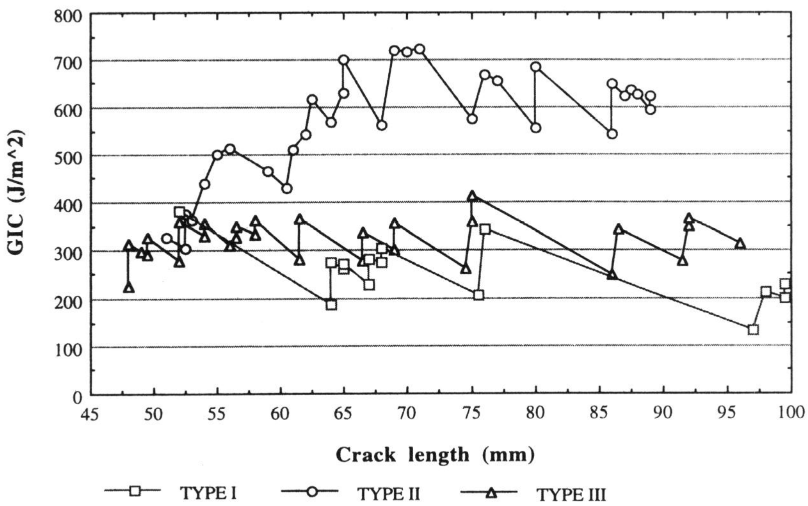

Figure 2 R-curves for a single test on each of the three materials (TYPES I, II and III)