Developing a four point bend specimen to measure the mode I intralaminar fracture toughness of unidirectional laminated composites

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Abstract

The use of a four point bend test is investigated for the measurement of intralaminar toughness of unidirectional carbon fibre composites. A key element of the investigation is the process of producing a sharp pre-crack and the effect of this on the measured toughness. A method is presented in which the pre-crack is produced during the layup and cure process and this is shown to cause minimal distortion of the plies of the laminate. The test results show good consistency and low scatter.

Key words: B Fracture toughness, Intralaminar

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Fig. 1. Transverse and longitudinal intralaminar crack growth

1 Introduction

This paper is concerned with the measurement of a particular intralaminar toughness of unidirectional laminated composites. This toughness is the resistance to a crack growing in the thickness direction of the laminate, labelled ‘transverse intralaminar crack growth’ in Fig. 1. It is important for material characterization and for numerical modelling. Currently, there is no standard test to determine this property.

Different testing methods have been used to measure the intralaminar fracture toughness of laminated composites. The test methods most commonly used are the centre-notched tension [1], surface-notched tension [1], Compact Tension (CT) [1–5], Three Point Bending (TPB) [1,6,2,7], Four Point Bending (FPB) [8,9], double edge notch [7], double cantilever beam [10] and the wedge insert fracture [11]. Investigations into size effects for the CT specimen [1] and for the FPB [9] concluded in both cases that the effect of specimen dimensions did not affect the fracture toughness appreciably. Furthermore, Garg [1] compared the fracture toughness obtained using TPB and CT specimens, and observed good consistency.

The intralaminar fracture toughness is expected to be of the same order of magnitude as the interlaminar fracture toughness as in both cases the fracture process involves failure of the matrix. However, at the microscopic level, the failure processes are different and therefore it is only by measuring the intralaminar fracture toughness that a detailed comparison can be made. Regarding the intralaminar fracture toughness, two different modes can be distinguished (see Fig. 1): when the crack propagates parallel to the fibres (longitudinal), and when it propagates normal to the fibres (transverse). When it propagates parallel to the fibres, the fracture toughness can depend on the angle of the fracture plane relative to the plane of the laminate (90° in Fig. 1, left). If the laminate does not exhibit perfect transverse isotropy, then it is expected that the longitudinal intralaminar fracture toughness will depend on this angle. In the current study, the focus is on measuring the *transverse* intralaminar fracture toughness.

An important characteristic exhibited by some unidirectional composites is an increasing R-curve in the intralaminar toughness which has been attributed to fibre bridging [7,10]. In such cases, it is usual to take the initiation toughness value for use in design as this is conservative. The accurate measurement of the initiation toughness is therefore a key requirement of an intralaminar toughness test and it has been shown that a poor initial pre-crack can lead to an artificially high initiation toughness [3]. However, it is more difficult to introduce a sound and sharp intralaminar pre-crack than to introduce an interlaminar one, due to the layered structure of the material; the manufacture of specimens with pre-cracks formed during the layup and the cure process presents some technical difficulties, while the introduction of a pre-crack after manufacture of the laminate can cause damage around the intended crack tip.

In order to introduce an intralaminar pre-crack into a cured composite, breaching tools [4], wire-blade saws (0.1 mm thick) [7], jeweler saws (0.35 mm thick) [1] and razor blades (0.06 – 0.1 mm thick) [3,5,9,12] have all been used. However, it has been found that introducing the crack mechanically after the composite has been cured provokes damage ahead of the crack tip, which can compromise the toughness values obtained [9,12].

To produce a pre-crack during layup, previous work [8] has investigated applying a PTFE spray onto a cut made along the fibre direction in the pre-preg assembly (not to the full thickness of the pre-preg assembly), prior to cure. However, the PTFE spray failed to prevent the sides of the pre-crack from sticking together in the cured laminate, because of small movements of the plies during the cure process. A plastic release film placed into a cut in the prepreg assembly was later tried [12,9,13] instead of the PTFE spray, but the resulting pre-cracks were not straight and resin pockets often occurred at the crack tips. Finally, the use of a razor blade coated with a release agent, which was inserted into the pre-preg assembly and held in that position during cure, was investigated [9]. The pre-crack obtained was straight and sharp, but considerable distortions in the layered structure of the composite were present, as a result of the introduction of the blade and the mechanical constraint imposed by the blade during the cure.

In this work, the FPB test is used to measure the intralaminar fracture toughness, because of its simplicity and accuracy. The test method is briefly described and the investigations conducted into the manufacture of a sound, embedded pre-crack are presented. The tests carried out are then described and the results are presented and discussed.

Fig. 2. Four point bending test specimen and loading

2 Test method

The FPB test, adopted in previous work [8,9,13,12] to determine the intralaminar fracture toughness of laminated composites, is used here. The test specimen, together with the loading conditions, is presented in Fig. 2. The test specimen is composed of a unidirectional laminate, with fibres aligned in the width direction of the specimen. The nominal dimensions of the specimen are 140mm in length, width $w = 10\text{mm}$, and thickness $h = 3\text{mm}$. The distances L and c in Fig. 2 are $L = 60\text{mm}$ and $c = 30\text{mm}$.

The critical stress intensity factor is defined as [14]

$$K_{Ic} = \frac{3Pc\sqrt{\pi a}}{wh^2} f(a/h) \quad (1)$$

where P is the total applied load at failure (the crack growth is unstable in this test), a is the length of the initial pre-crack, and $f(a/h)$ is defined by

$$f(a/h) = 1.12 - 1.39 \left(\frac{a}{h}\right) + 7.32 \left(\frac{a}{h}\right)^2 - 13.1 \left(\frac{a}{h}\right)^3 + 14.0 \left(\frac{a}{h}\right)^4. \quad (2)$$

Assuming plane stress, the critical energy release rate is obtained from the critical stress intensity factor at the onset of crack propagation as

$$G_{Ic} = \frac{K_{Ic}^2}{E_2} \quad (3)$$

where E_2 is the transverse modulus of the unidirectional laminate.

3 Manufacture

3.1 *Material systems used*

Two different carbon-epoxy unidirectional pre-preg systems were used. The system HSC/ SE84LV (produced by SP systems) was used for most of the tests and T300/ 913 (produced by Hexcel), was also used to confirm that the process to insert the crack into the laminate could be replicated with other materials. Both materials were cured according to the instructions from the respective suppliers. For the first material system, a consolidation cycle was also performed in some instances (as detailed later), and this also followed the instructions from the supplier.

The single material property needed for the data reduction is the in-plane transverse Young's modulus, which was determined using standard tests: $E_2 = 8200\text{MPa}$ for the SE84LV/ HSC, and $E_2 = 8800\text{MPa}$ for the T300/ 913.

3.2 *Manufacture of the test specimens*

Laminates with dimensions $200\text{mm} \times 200\text{mm}$ were manufactured by laying up 24 layers of prepreg. The thickness of each panel was nominally 3mm. Depending on the method to introduce the pre-crack into the pre-preg assembly, some panels were manufactured by first stacking up together two or three sub-assemblies. All laminates were unidirectional, with the pre-crack running

at the mid-length position, parallel to the fibres.

From the panels, specimens for FPB tests were cut using a wet saw. As noted earlier, the nominal dimensions of the specimens were 140mm in length, 10mm in width, and 3mm in thickness, with the fibres and the pre-crack oriented along the width. The actual width and thickness of each specimen, necessary for the data reduction, were obtained by averaging three individual measurements.

3.3 Introduction of the crack tips

Two different approaches to introduce the pre-crack into the laminates were investigated. In the first one, a plastic non-stick film was used to separate the two sides of the crack (Fig. 3(a)) and in the second one, a metal blade coated with release agent was used (Fig. 3(b)). The plastic film was a fluoroethylene polymer film, with a thickness of 0.0125mm, and the metal blade was composed of a row of steel razor blades, with nominal thickness 0.08mm (the thickness of the blade at the sharp tip was considerably smaller than 0.08mm). For the metal-blade approach, two aluminium plates were used, which held the razor blades so that part of the blade was left protruding, see Fig. 3(b). Two different depths of the protruding blade were used: 0.625mm in one case and 1.00mm in the other.

In previous work [8,9], the film and metal-blade approaches have not consistently produced good quality cracks. In the current study, several variations of both approaches were investigated in a systematic way to identify the best method to produce pre-cracks of good quality. A description of all methods

investigated to introduce the intralaminar pre-crack is now presented.

It should be noted that the accurate manual positioning of the films, assemblies and sub-assemblies is crucial for obtaining accurate results and with low scatter. While the processes are described in detail in this section, the quality of the pre-cracks obtained is dependent on the skills of the operator, and ideally, for industrial characterization, an automated process to replace the operator would be preferable. A measure of the precision achieved can be assessed by analysing micrographs of the cured laminate, as it will be shown later (see e.g. Fig. 4).

Method A This method uses the plastic-film approach. From the 24 layers that constitute the final laminate, part of them are stacked together in one sub-assembly, and the remaining are stacked together in another sub-assembly (the number of plies in each sub-assembly depends on the required depth of the pre-crack). The first sub-assembly is cut at the mid-width position, along the fibres, using a scalpel. One half of it is then positioned carefully on top of the second (uncut) sub-assembly, allowing the non-stick film to be positioned as shown in Fig. 3(a). The positioning of the film requires great care to avoid wrinkles of the film at the crack tip, and to obtain a crack of uniform depth. The second half of the first sub-assembly is then very carefully positioned next to the film. Care in positioning the second half of the first sub-assembly is essential to avoid gaps adjacent to the film.

Method B This method uses the metal-blade approach. From the 24 layers that constitute the final laminate, part are stacked together in one sub-assembly, and the remaining are stacked together in another sub-assembly.

Fig. 3. Methods to introduce a pre-crack to a laminate: (a) method A, (b) method B, (c) method C, (d) method D, (e) method E and (f) method F

The first sub-assembly is cut in the middle, along the fibres, using a sharp scalpel. Both halves are then carefully positioned on each side of the metal blade on the aluminium plate, as shown in Fig. 3(b). Attention must be paid to avoid, as much as possible, any gap between the laminates and the blade. The second sub-assembly is then positioned on top, taking care not to move the two halves of the first sub-assembly.

Method C This method also uses the metal-blade approach. The 24 layers are stacked together to form a single pre-preg assembly. The pre-preg assembly is then positioned on top of the aluminium plate holding the metal blade as shown in Fig. 3(c). Very carefully, pressure is manually applied on the pre-preg assembly to force the blade to penetrate it, and the upper part of the rig is finally positioned on top.

Method D This method is another variation of the metal-blade approach. From the 24 layers that constitute the laminate, two sub-assemblies are laid up. In order to create the pre-crack, the first sub-assembly is cut at the mid-width position, parallel to the fibres, using a scalpel as shown in Fig. 3(d), but the two halves are not separated. The second sub-assembly, with the remaining layers, is then placed on top of the first sub-assembly. Since the two halves of the first pre-preg assembly were not separated after they were cut, this process leads to a very small and uniform gap between the two halves, dependent on the thickness of the scalpel only. Fixing the first sub-assembly to the working surface before performing the cut facilitates the operation, as it prevents the relative movement of the two halves of the first sub-assembly. A small pressure can be applied on top of the second sub-assembly to improve the adhesion to

the first one, and this also results in a reduction in the width of the gap created by the blade. The pre-preg assembly is then lifted off the lay-up surface and is bent gently so that the gap created by the cut is widened and this is carefully positioned over the razor blade held in the aluminium plate, as shown in Fig. 3(d). The upper plate is then positioned on top.

Method E This is yet another method which uses the metal-blade approach. The 24 layers that constitute the laminate are stacked together in three different sub-assemblies. The first sub-assembly, shown in Fig. 3(e) is fixed to the table using tape. On its bottom side, a backing sheet is used (with a few layers of tape to reinforce the backing sheet at the intended cut position) to prevent the two halves from separating after the cut shown in Fig. 3(e) is made with the scalpel. As before, the cut is made along the fibres, at the mid-width position. After the cut is made, a backing sheet is positioned on top of the (first) sub-assembly, so that it can be moved more easily without separating the two halves. Very carefully, the two halves of the sub-assembly are detached from the table and turned over. This operation requires particular attention, since the two halves are linked together by the backing sheets (and tape) only. The two halves are again fixed to the table and the backing sheet (with tape) that is now on the top side is removed, so that the second sub-assembly can be stacked on top of the first one. The process just described might seem complex, but it produces a geometry for the cut that more closely matches the shape of the blade in the plate (i.e. the cut is widest at the lower surface and narrower at the crack tip, as indicated in Fig. 3(e), and in contrast to Fig. 3(d)). The same result can, in principle, be achieved more easily, by using equipment that controls accurately the depth of the cut instead of performing it manually. Fig.

3(e) represents how the two sub-assemblies are then bent to facilitate placing them over the mounted razor blades, after which they are fixed to the plate (at the edges, using tape), to avoid any motion between them and the blade. The third sub-assembly is carefully positioned on top, followed by the upper part of the aluminum rig. Using this method, the third sub-assembly does not need to be bent, which is intended to reduce any distortion in the pre-preg layers due to bending. The first sub-assembly has necessarily the required number of layers to produce a notch of the intended depth. The second sub-assembly just needs to have enough plies to provide some integrity during the bending operation; in this work, 2 plies were used. The third sub-assembly has the remaining plies.

Method F This method uses the plastic-film approach, and follows the same steps from method E until the first and second sub-assemblies are stacked on top of each other (i.e. with the first sub-assembly having been cut along the mid-width, parallel to the fibres). The two sub-assemblies are then turned over again, so that the cut is on top. This process is represented in Fig. 3(f), but the ‘turning over’ operations are omitted in the figure for simplicity. The assembly is then slightly bent, to facilitate the introduction of the plastic film in the gap. The third sub-assembly is then added below the second, and the whole is positioned between two aluminum plates. The number of plies in each subassembly is as for method E.

4 Discussion on the suitability of each method to produce satisfactory crack tips

4.1 *Comparing the plastic-film and metal-blade approaches (methods A and B)*

The first goal of this work is to compare the ability of the plastic-film and the metal-blade approaches to produce satisfactory crack tips. For this purpose, two composite plates were manufactured following methods A and B.

A micrograph representative of the pre-crack obtained by method A (film) is presented in Fig. 4(a). It can be observed that the crack obtained is not straight, and the orientation of the crack tip is not in the intended crack direction (i.e. vertical in this figure). The waviness is probably caused by small movements of the plies during the cure process. Resin pockets at the crack tip have been reported in a previous study using the film approach [9], but none were observed in the specimens micrographed in the current investigation. For the laminate manufactured by method B (metal blade), the aluminium plate with a 1.00mm protruding blade was used. The sub-assembly to be cut along the fibres (first sub-assembly) had 8 layers, and the other (second sub-assembly) comprised the remaining 16 plies. When removing the laminate manufactured by method B from the blade fixture, the laminate broke but this did not prevent the micrographic examination of the crack obtained. From the micrograph shown in Fig. 4(b), it is clear that significant movement of the plies has occurred.

For the plastic-film approach, it is not obvious how to overcome the waviness

Fig. 4. Pre-cracks obtained using method (a) A, (b) B, (c) C, (d) D, (e-1) E, (e-2) E, (e-3) E and (f) F

of the crack, or how to modify the method to obtain a sound crack tip. On the other hand, it was thought that for the metal-blade approach, modifications in the manufacturing method could lead to improvements on the crack tip quality and so methods C-E were investigated. The distortion of the plies next to the crack was believed to result from two factors: the reduction in thickness due to consolidation during the curing and any gap between the sub-assemblies and the blade, due to the manual positioning, that may have enabled excessive movement of the plies to occur during cure. It was not clear however how much each factor contributed to the final distorted shape of the layers next to the blade.

4.2 Alternative metal-blade approaches

4.2.1 Mounting the blade by pressure (method C)

The effect of the reduction in thickness on the distortion of the layers mentioned in the previous sub-section for the metal-blade approach can be reduced by pre-consolidating the sub-assemblies that constitute the pre-preg—so that the blade might be inserted to a depth that is closer to the final one, and less movement occurs during the curing process. The possibility of a gap between the blade and the layers of composite can be avoided by forcing the blade into the pre-preg assembly. For this purpose, method C was used with pre-consolidated sub-assemblies and the aluminium rig with smaller outstanding blades (0.625mm).

A micrograph representative of the crack tip obtained is shown in Fig. 4(c). It is clear that mounting the blade by pressure resulted in empty regions at

the root of the blade that were filled by resin during the cure, resulting in considerable distortion of the layers.

4.2.2 Mounting the blade by bending the pre-preg assembly (method D)

The distortions obtained when mounting the blade by pressure suggested that it seemed possible to achieve better results if the blade was not forced through the pre-preg assembly. This led to the idea that bending the composite in order to insert the blade could be beneficial, resulting in method D to manufacture the crack. Since the effect of pre-consolidation could not be assessed in the previous trials due to the poor quality of the cracks obtained, two plates were manufactured by this method with pre-consolidation used for one.

The distortion of the plies next to the blade for cracks introduced by method D was found to be reduced but still significant, as shown in the micrograph in Fig. 4(d). Also, pre-consolidating the sub-assemblies did not appear to have a noticeable effect on the crack tip quality.

During the manufacture using method D, it became evident that, due to the profile of the scalpel used to cut the sub-assembly, a small gap would result between the pre-preg assembly and the razor blade, close to the crack tip. This feature is exaggerated in Fig. 3(d) for better understanding. However, it was not clear how much this aspect contributed to the observed distortion of the layers.

4.2.3 Mounting the blade by bending the pre-preg assembly in a modified way (method E)

It was thought that the small gap between the pre-preg assembly and the blade, at the crack tip, that resulted from using method D could be avoided if the cut sub-assembly was reversed before it was mounted on the razor blades. Also, the compression that resulted in the layers away from the crack during the bending process may have contributed to ply distortions. Furthermore, during the bending process, the considerable stiffness of the uncut layers made the bending process more difficult. As a result of these considerations, a modified bending procedure was developed—method E. In this method, only two uncut layers (second sub-assembly) were holding the (first) cut sub-assembly together before it was mounted on the aluminium plate. The remaining layers (third sub-assembly) were stacked immediately afterwards.

This method resulted in the smallest ply distortions obtained so far, as Fig. 4(e-1) shows.

In order to investigate if the same crack tip quality could be achieved with other materials, the same manufacturing procedure (method E) was repeated with another material, T300/ 913. The pre-crack quality resulting for this material, shown in Fig. 4(e-2) confirms that method E is appropriate to systematically manufacture a panel with a sound pre-crack without introducing considerable distortions into the layers of the laminate. A bigger magnification of the crack tip in Fig. 4(e-2) is shown in Fig. 4(e-3). It can be observed that the crack tip is sharp, despite some wearing of the blade in the aluminium plate that occurred during the successive trials.

4.3 *Improving the plastic-film approach (method F)*

Method E, which uses the metal-blade approach, proved to reduce the distortion in the layers of the laminate to a minimum, by successfully reducing the empty space between the pre-preg assembly and the blade. The effect of this procedure on the plastic-film approach seemed worth investigating, even though this manufacturing method could not prevent the small ply movements distorting the plastic film during the cure. As a result, method F was developed, which essentially applies the bending method E to the plastic-film approach. A plate was manufactured, using material HSC/ SE84LV, and the corresponding micrograph of the crack is shown in Fig. 4(f). It was confirmed that the plastic film was unable to create a straight crack even with this improved manufacturing process.

5 **Testing**

5.1 *Experimental procedure*

FPB tests were carried in an Instron machine, with a 1kN load cell. The load was applied to the specimens using 6mm diameter rollers. The body containing the upper rollers was free to rotate (about a central horizontal axis parallel to the width direction of the specimen) in order to accommodate eventual minor misalignments and guarantee that both loads applied to the left and right side of the specimen were equal. Rubber fittings were used between the rollers and the specimens, to avoid stress concentrations due to any minor misalignment. The specimens were loaded up to failure at 0.5mm/min. The loading rate

was chosen so as to reproduce quasi-static loading conditions and to lead to a reasonable duration for the test. The failure loads were recorded, and Eqs. 1 to 3 were used to obtain the fracture toughness. The actual pre-crack length was measured individually for each specimen after the tests using an optical microscope.

5.2 Results

The average fracture toughness and coefficients of variation obtained for each method, are presented in Table 1. The features on the fracture surface of failed specimens show features characteristic of mode I fracture, as shown in Fig. 5.

5.3 Discussion

The test results show low scatter on the intralaminar fracture toughness measured for all methods used to create the pre-crack. The mode I interlaminar fracture toughness for HSC/ SE84LV and T300/ 913 have been measured using ASTM standard DCB tests as 235 J/m^2 and 258 J/m^2 respectively, which is found to be similar to the intralaminar values obtained here. This similarity in the fracture toughness values was expected, since the fracture processes are also similar.

The intralaminar fracture toughness values obtained using the plastic-film approach were found to be similar in magnitude to those obtained using the metal blade, provided the ply distortions are reasonably small. This contrasts with previous results [9], where the intralaminar fracture toughness obtained using the plastic-film approach was found to be slightly higher than the one

Fig. 5. SEM images of the fracture surface of a FPB specimen, showing evidence of mode I fracture

obtained with the metal-blade approach. In that previous study, the higher values were attributed to resin pockets at the crack tips, which were not observed here. Possibly, the resin pockets at the crack tip were avoided in this work because the plastic film was more precisely aligned with the end of the pre-cut.

Table 1

Fracture toughness values obtained from the tests

Material	Method	a nominal (mm)	N° of speci- mens tested	Average G_{Ic} (J/m ²)	Coefficient of variation (%)
HSC/ SE84LV	A	1.25	5	208	7.2
	C (pre-cons.)	0.625	7	257	5.3
	D (pre-cons.)	1	6	232	9.9
	D	0.625	5	218	5.6
	E	0.625	7	228	8.5
	E	1	7	222	6.0
	F	1.25	6	213	7.5
	All	-	43	226	9.3
T300/ 913	E	1	13	211	6.4

For the specimens with a pre-crack obtained by the metal-blade approach, those with higher ply distortion appear to produce generally higher toughness values.

6 Conclusions

This work shows that it is possible to manufacture unidirectional laminated panels including straight and sharp pre-cracks, without damage ahead of the crack tip and without causing significant distortion to the layers. This can be

achieved following the process referred to as method E in this paper.

FPB tests were shown to yield values for the mode I intralaminar fracture toughness with low scatter, which are close to the mode I interlaminar fracture toughness.

The results obtained seem to indicate that there is a correlation between ply distortion and an increased measured fracture toughness. However, for the specimens tested (all specimens had sharp crack tips and no damage ahead of the crack tip was present), this correlation is not strong.

Using a plastic film to create a pre-crack does not yield a straight pre-crack, but the fracture toughness values obtained were found to be consistent with those obtained using the metal-blade approach to create the pre-crack.

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