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Influence of the Mode Mixity Ratio and Test Procedures on the Total Energy Release Rate in Carbon-Epoxy Laminates

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Abstract

In this work, the fracture behaviour under modes I, II and different mixed mode I/II ratios has been studied for a AS4/3501-6 carbon fibre epoxy resin laminate.
Mixed Mode tests were carried out by means of two different procedures: MMB (Mixed Mode Bending) and ADCB (Asymmetric Double Cantilever Beam). ADCB specimens, in which the crack plane is out of the laminate midplane, are simple and useful test configurations to produce a mixed mode load state at the crack tip of the samples. The ADCB test is not still covered by international standards, so the calculations were performed by means of the Finite Element Modelling (FEM) and analytical formulation developed in previous works.
FEM was used in order to analyze modes I, II and mixed I/II and to compare the experimental and numerical results.
It was found a good agreement between ADCB and MMB tests. On the other hand, it was also observed that the critical energy G_c increased as the mode mixity ratio G_{II}/G_c increased.
Finally, experimental and numerical results showed a good agreement as the differences obtained from both procedures were generally lower than 10%.

Keywords: delamination; fracture; mixed mode; MMB; ADCB; FEM

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1. Introduction

Delamination is the mode of failure most frequently found in composite laminates due to the laminate nature of this kind of materials. Delamination is a complex process where more than one failure mode is usually present giving rise to a mixed mode mechanism. There are several experimental methods documented in the literature in order to determine the mixed mode fracture toughness in laminated composites.

The procedure most widely used is the MMB method (Mixed Mode Bending) [1-4]. This test method allows the application of different percentages of mode I / mode II load at the crack tip.

On the other hand, ADCB test is an interesting alternative to the MMB test. This test configuration is similar to the DCB (Double Cantilever Beam) tests. Nevertheless, in ADCB samples the crack plane is out of the laminate midplane.

Due to this asymmetric configuration a mixed mode load state is produced at the crack tip. This test configuration is much simpler than the MMB.

Mangalgiri et al. [5] were the first to apply the ADCB test. Other studies can be found in references [6-9].

In this work, MMB and ADCB test procedures were compared for carbon epoxy laminates. On the other hand, both experimental procedures were analyzed by means of FE models in order to compare experimental and numerical results.

There are several methods documented in the literature to compute the energy release rate *G* by means of FE methods: the Virtual Crack Closure Technique (VCCT), the Two Step Extension Method, cohesive elements, etc. [10-12]. In this work, the Two Step Method has been used.

2. Experimental procedure

2.1. *Material and samples*

The material used in this study was a 32 ply carbon fibre reinforced epoxy laminate denoted as Hexply® AS4/3501-6 RC37 AW190.

The material properties of this laminate are shown in table 1.

Table 1. Material properties of the AS4/3501-6 laminate

Material Property	Value (MPa)
E_{11} (Longitudinal elastic modulus)	131,000
E_{22} (Transversal elastic modulus)	8,900
G_{12} (Shear elastic modulus)	5,090
σ_{11} (Longitudinal tensile strength)	1,954
σ_{22} (Transversal tensile strength)	24.0
σ_s (Shear strength)	79.3

The specimen thickness was 6 mm for both tests.

2.2. Test procedures

The ASTM D 6671-06 standard [4] was followed to perform MMB mixed mode tests. This procedure allows the calculation of G_c, G_{Ic} and G_{IIc} for different mode I/mode II ratios. Figure 1 shows the MMB configuration. The load is applied to the sample trough hinges bonded to the end of the sample that contains the non-adherent insert and by means of a rod in the centre of the sample in order to generate a three points bending configuration.

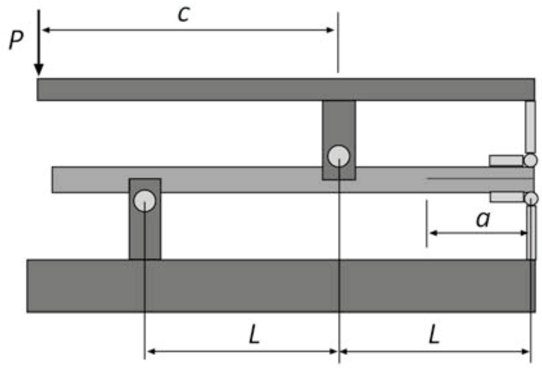

Fig. 1. MMB test

The initial crack length of the MMB samples (a) was set to 25 mm. The arm length (c) (see figure 1) was set to 58 mm and 47 mm in order to obtain two different mixity ratios (G_{II}/G) of 31% and 43% respectively.

ADCB test is an interesting alternative to the MMB test (figure2). This test configuration is similar to the DCB (Double Cantilever Beam) tests. Nevertheless, in the ADCB samples the crack plane is out of the laminate midplane. So, a mixed mode load state is created at the crack tip (figure 3). In this test configuration, the position of the crack plane controls the mode I /mode II load ratio at the crack tip.

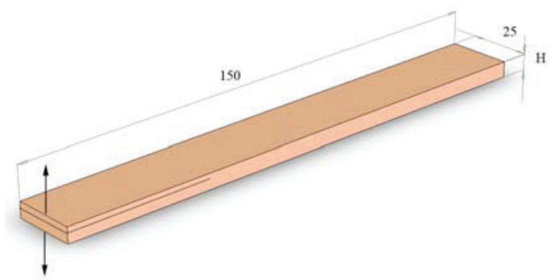

Fig. 2. ADCB test

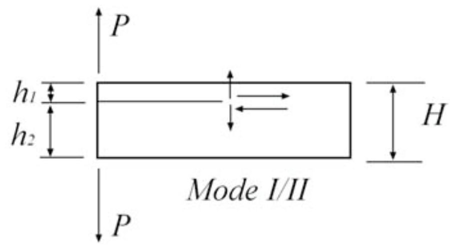

Fig. 3. ADCB test

The analytical procedures developed in the ASTM D 5528-01 standard that allows the calculation of G in DCB tests for pure mode I need to be adapted to the ADCB specimens.

There are some analytical expressions developed in the literature to compute G, G_I and G_{II} [13]. Mangalgiri et al. [5] were the first to apply the ADCB test to study mixed mode fracture. Other studies based on ADCB specimens can be found in references [14-17].

The laminate configuration was 6/d/26. This means that the crack plane was set between the 6th and 7th ply. This configuration induces a mixity ratio (G_{II}/G) of 34% at the crack tip comparable to the 31% mixity ratio of the MMB test.

In order to study the evolution of G as a function of G_{II}/G, pure modes I and II were also tested by means of DCB (Double cantilever beam) and ENF (End Notch Flexure) tests following the ASTM D 5528-01 standard and the ESIS protocol (Protocol for Interlaminar Fracture Testing Nº 2. Mode II May 1992).

3. Numerical procedure

FEM analysis has been used to compare experimental and numerical results. The analyses were performed following the Two Step Method.

In the Two Step Method, the crack path is modelled using pairs of coincident nodes. The forces at the crack tip are calculated in a first step when the load reaches a critical value. The imposed displacement in the sample is then held and the coupled DOFs of the nodes at the crack tip are released in a second step (figures 3 and 4). Displacements are then calculated in this second step. This procedure can be analytically described as follows:

$$G_I = \frac{1}{2B\Delta a} \sum_{i=1}^{n} F_{y1i}(v_{1i} - v_{1'i}) \tag{1}$$

$$G_{II} = \frac{1}{2B\Delta a} \sum_{i=1}^{n} F_{x1i}(u_{1i} - u_{1'i}) \tag{2}$$

Where:

- F_{x1i}, F_{y1i}: forces at the crack tip (nodes 1-1')
- $F_{x1}=-F_{x1'}$, $F_{y1}=-F_{y1'}$
- u_{1i}, $u_{1'i}$, v_{1i}, $v_{1'i}$: horizontal and vertical displacements of the released nodes 1-1'
- B: specimen width
- Δa: crack increment
- n: number of nodes along de crack tip (for 3D models)

The suffix *i* takes into account the extension to a 3D system, where *n* nodes are placed along the crack front.

2D models of the MMB and ADCB tests were developed by means of an ANSYS package. The critical loads obtained in the experimental tests were implemented in the FE models in order to perform the numerical analysis.

4. Results

The results obtained in the experimental tests and numerical runs are shown in table 2.

Table 2. Experimental and numerical results

		Experimental			FEM			
Method	G_{II}/G	G_I	G_{II}	G	G_I	G_{II}	G	Error
DCB	0	90.6	0.0	90.6	95.0	0.0	95.0	-5%
MMB	31	120.3	54.3	174.6	117.4	52.6	170.0	3%
ADCB	34	135.9	70,0	205.9	128.2	66.3	194.5	6%
MMB	43	210.2	159.1	369.3	188.9	152.6	341.5	8%
ENF	100	0.0	943.4	943.4	0.0	951.5	951.5	-1%

As can be seen in this table there is a good agreement between experimental and numerical results as the error between them was always lower than 10%.

Figure 4 shows a plot of G versus the mixity ratio G_{II}/G.

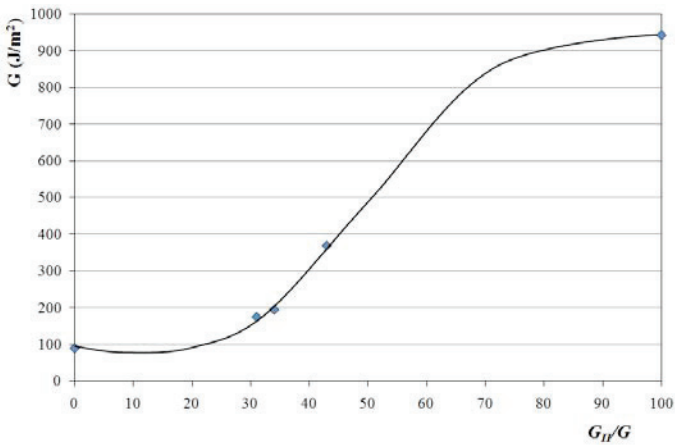

Fig. 4. *G* as a function of the mixity ratio

In this figure we can observe that the ADCB and MMB results for the mixity ratios of 31% and 34% have a good correlation as both values are close and fit the curve in a reasonable way.

On the other hand, as observed by other authors [17], the total energy release rate G increases as G_{II}/G increases

5. Conclusions

In this work it was found a good agreement between experimental and numerical results as differences between results were always lower than 10%.

FE modelling arises as a useful technique in order to study an analyze fracture mechanisms.

On the other hand it was observed a good correlation between ADCB and MMB results as both models fit the global curve of G versus G_{II}/G.

Finally, as observed by other authors, G increases as G_{II}/G increases.

Acknowledgements

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