INTERLAMINAR FRACTURE TOUGHNESS CHARACTERIZATION OF A CARBON-EPOXY COMPOSITE MATERIAL

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Abstract. *The objective of this work is to obtain values of interlaminar fracture toughness (G) for a laminate using 0° carbon-epoxy prepreg fabric plies, at room temperature. Double Cantilever Beam (DCB) tests were performed to evaluate mode I (opening) toughness, Four Point Bend End Notched Flexure (4ENF) for mode II (shear) and Mixed Mode Bending (MMB) for mixed mode I/mode II. DCB and MMB tests followed ASTM standard test methods. 4ENF tests were based on Material Engineering Research Laboratory (MERL) test method. The MMB tests were performed using different mixed mode values of 25, 50 and 75%. Also, the application of the Compliance-Based Beam Method (CBBM) was evaluated for DCB tests. In this method, the delamination length measurements are not required during test. Finally, the relation between* G_I *and* G_{II}*, through the failure locus, and the influences of the laminated fabric on the interlaminar fracture toughness results were assessed.*

Keywords*: composite materials, interlaminar fracture toughness, delamination, carbon-epoxy*

1. INTRODUCTION

Although composite materials have several advantages compared to metallic materials, one of its disadvantages is the relatively low delamination resistance, which is one of the most common failure modes of composite structures. Delaminations may lead to loss of global resistance and, consequently, to a catastrophic failure. Therefore, it is important to evaluate interlaminar fracture toughness, which is normally expressed in terms of the critical energy release rate (*G*). Interlaminar fracture toughness represents the energy dissipated by the material as the delamination front advances through a unit area.

2. SPECIMENS PREPARATION

A rectangular plate was manufactured, using 16 layers of carbon-epoxy pre-impregnated fabric plies orientated at 0° with a PTFE insert at the midplane, from which the specimens were cut. The specimens' width and thickness were measured in 5 points along their length. After that, the edges of the specimens were coated with a white paint. Vertical lines were marked on the edge of the specimens, every 1 mm for the 10 mm before and for the 20 mm after the end of the insert. Thereafter, vertical lines were made every 5 mm up to 70 mm. For DCB and MMB tests, loading blocks were attached to the specimens with an epoxy adhesive.

3. DOUBLE CANTILEVER BEAM (DCB) TEST

The standard DCB test method (ASTM, 2007) consists in applying load to the specimen arms through bonded loading blocks, in order to open the crack (Fig. 1).

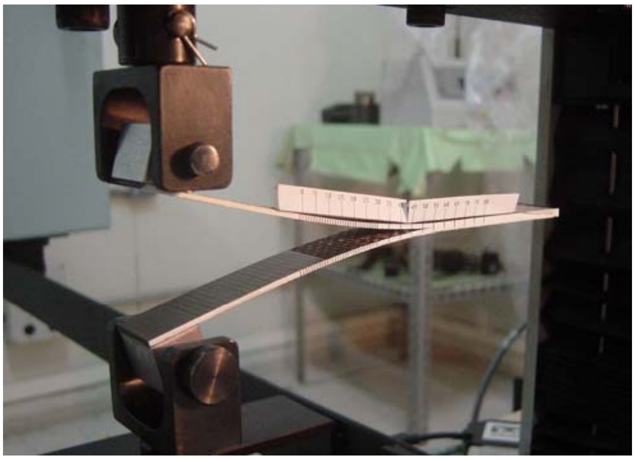

Figure 1. DCB test apparatus

3.1. DCB data acquisition

Crack length was monitored trough a video camera and a crack marker was used to register each time the crack crosses a vertical line marked on the specimen. The load-displacement curves recorded during the test are shown in Fig. 2:

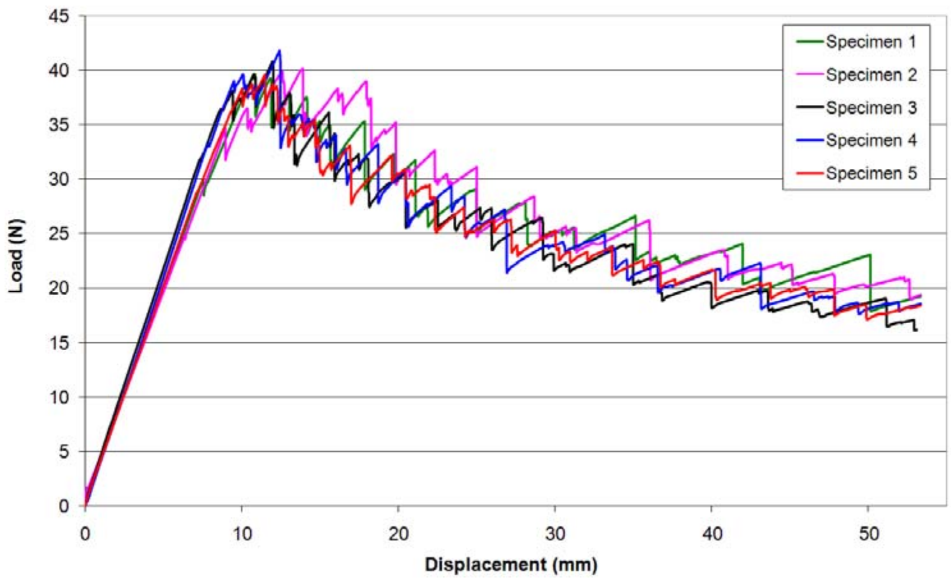

Figure 2. DCB load displacement curves

3.2. DCB data reduction methods

ASTM, 2007 describes three data reduction methods: Modified Beam Theory (MBT), Compliance Calibration (CC) and Modified Compliance Calibration (MCC). A fourth method, described as Compliance-Based Beam Method (CBBM) (Moura *et al.*, 2008), was assessed. In this method, crack length measurements are not required during tests, simplifying the whole test, from specimen preparation until data acquisition.

The basic expression for MBT data reduction method is given by Eq. (1), where P is the load, δ is the displacement, b is the specimen width, a is the delamination length and Δ is defined as the effective delamination extension to correct for rotation of DCB arms at delamination front, which can be calculated from the load displacement curve:

$$G_I = \frac{3P \cdot \delta}{2b\left(a + |\Delta|\right)} \tag{1}$$

For CC method, the basic expression is given by Eq (2), where n is the slope of the plot of $\log C$ versus $\log a$, where C is the specimen compliance, δ/P, and a is the crack length:

$$G_I = \frac{n \cdot P \cdot \delta}{2b \cdot a} \tag{2}$$

For MCC method, the basic expression is given by Eq (3), where C is the compliance, δ/P, A_1 is the slope of the plot of a/b versus $C^{1/3}$, and h is the thickness of DCB specimen:

$$G_I = \frac{3P^2 \cdot C^{2/3}}{2A_1 \cdot b \cdot h} \tag{3}$$

For CBBM method, the basic expression is given by Eq. (4), where a_e is the effective delamination length, E_f is the corrected flexural modulus of the specimen, h' is the half-thickness and G_{12} is the in plane shear modulus:

$$G_I = \frac{6P^2}{b^2 h'}\left(\frac{2a_e^2}{h'^2 E_f} + \frac{1}{5G_{12}}\right) \tag{4}$$

3.3. DCB results

Three definitions for an initiation value of G_{Ic} are described in ASTM, 2007. These include G_{Ic} values determined using the load and displacement measured at the point of deviation from linearity in the load-displacement curve (NL), at the point at which delamination is visually observed on the edge (VIS), and at the point at which the compliance has increased by 5 % or the load has reached a maximum value (5 %/Max). G_{Ic} values are shown in Tab. 1:

Table 1. G_{Ic} values for DCB test

$G_{Ic}(kJ/m^2)$		
NL	VIS	5%/Max
0.436	0.431	0.466

The values of interlaminar fracture toughness for crack propagation obtained using the four different data reduction schemes are listed in Tab. 2:

Table 2. DCB results

Method	$G_I(kJ/m^2)$	Std deviation
MBT	0.587	0.038
MCC	0.584	0.045
CC	0.581	0.040
CBBM	0.617	0.057

4. MIXED MODE BENDING (MMB) TEST

The standard MMB test method (ASTM, 2006) consists of applying load to the specimen arms through a lever mechanism, in order to open the crack (Fig. 3) due to mode I (opening) and mode II (shear), simultaneously at the following mode mixtures: 25, 50 and 75%. The mode mixture of the test is set by modifying the length of the lever arm of the test apparatus.

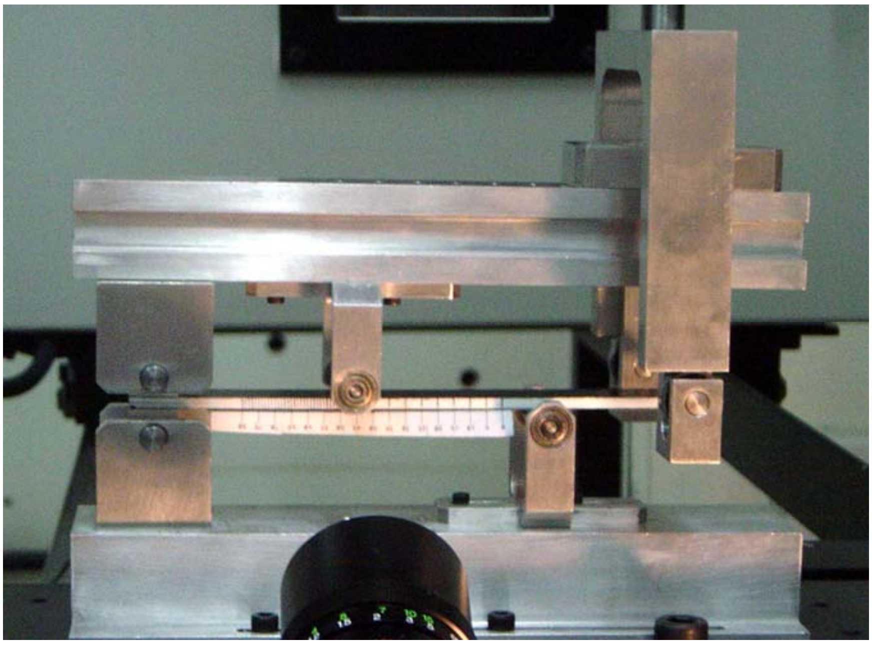

Figure 3. MMB test apparatus

4.1. Calibration specimen

In order to evaluate the compliance of the loading system, a calibration specimen was used. It consists of a rectangular steel bar and it was loaded to approximately 75% of the estimated maximum load. Compliance was calculated using the slope of the recorded load-displacement curves.

4.2. MMB data acquisition

As well as in DCB test, crack length was monitored trough a video camera and a crack marker was used to register each time the crack crosses a vertical line marked on the specimen. The load-displacement curves recorded during the test for the different mixed mode values are shown in Fig. 4, Fig. 5 and Fig. 6, respectively.

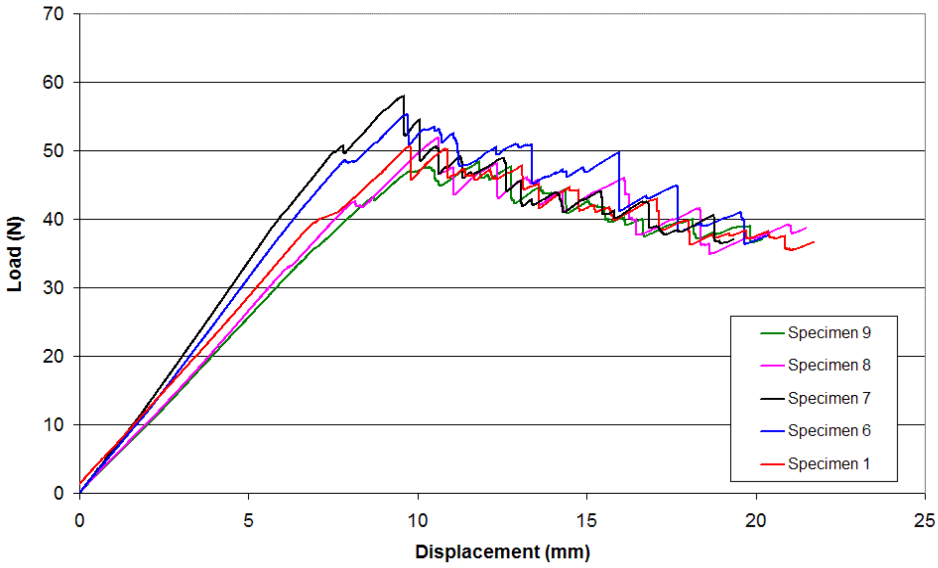

Figure 4. MMB load displacement curves – mode mixture 25%

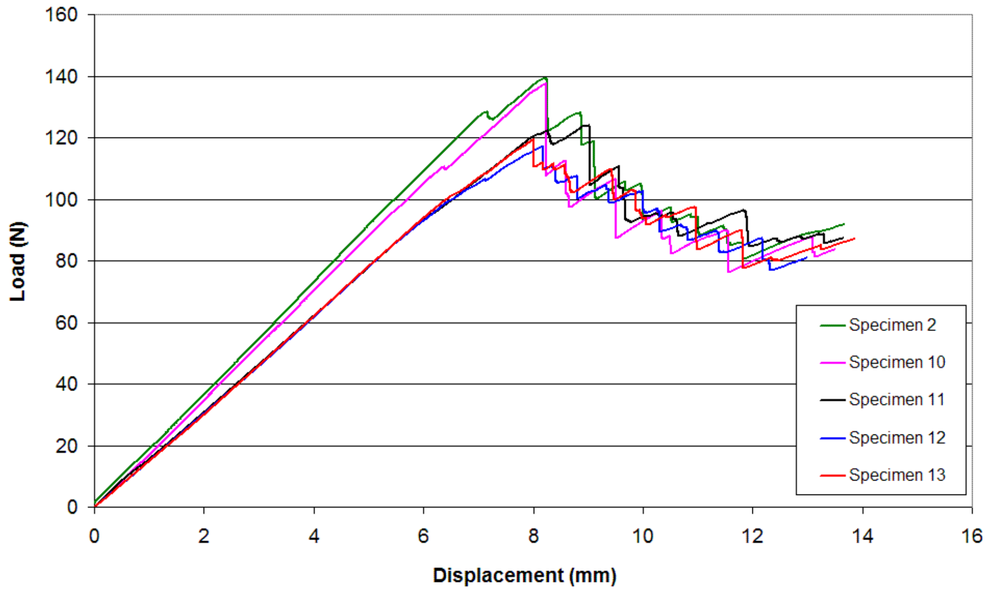

Figure 5. MMB load displacement curves – mode mixture 50%

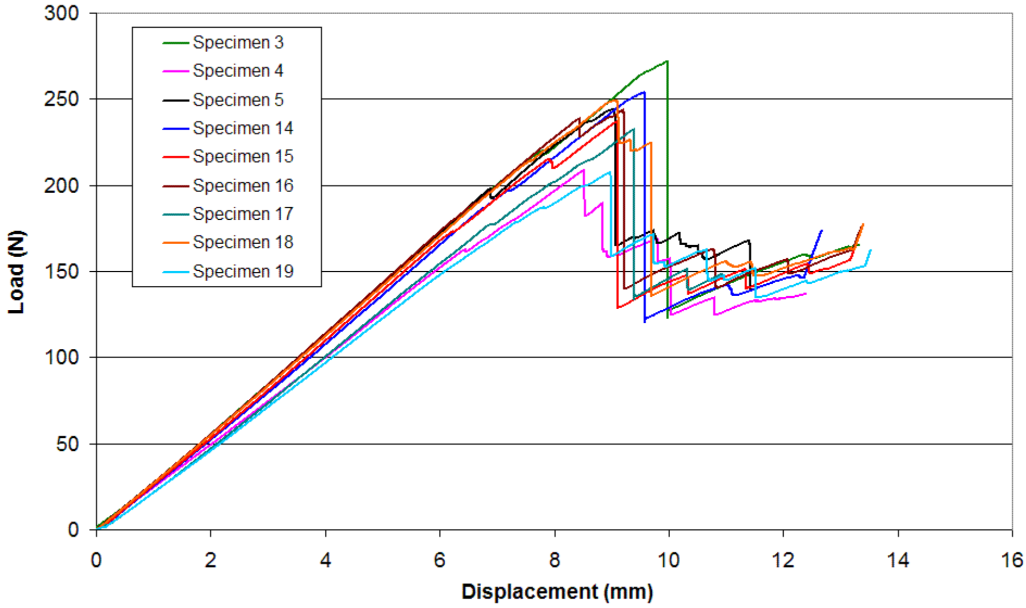

Figure 6. MMB load displacement curves – mode mixture 75%

4.3. MMB data reduction

Basic expressions for interlaminar fracture toughness calculations are given by Eq. 5 and Eq. 6, where *c* is the lever length set to the specified mixed mode values. E_{1f} is the modulus of elasticity in the fiber direction measured in flexure, *L* is the half-span length of the MMB test apparatus and χ is the crack length correction parameter:

$$G_I = \frac{12P^2(3c-L)^2}{16b^2h'^3\,L^2E_{1f}}(a+\chi h')^2 \tag{5}$$

$$G_{II} = \frac{9P^2(c+L)^2}{16b^2h'^3\,L^2E_{1f}}(a+0{,}42\chi h')^2 \tag{6}$$

4.4. MMB results

As in DCB, crack initiation interlaminar fracture toughness values were calculated, and the values are shown in Tab. 3:

Table 3. G_c values for MMB test

Mixture mode	$G_C\,(kJ/m^2)$		
	NL	VIS	5%/Max
25%	0,403	0,493	0,523
50%	0,662	0,678	0,765
75%	0,979	0,884	1,075

The results for crack propagation are shown in Tab. 4:

Table 4. MMB results

Mixture mode	$G_I\left(kJ/m^2\right)$	Std deviation	$G_{II}\left(kJ/m^2\right)$	Std deviation	$G\left(kJ/m^2\right)$
25%	0.544	0.078	0.183	0.027	0.727
50%	0.483	0.050	0.490	0.051	0.973
75%	0.442	0.055	1.031	0.077	1.473

5. FOUR POINT BEND END NOTCHED FLEXURE (4ENF) TEST

There is no standard test method for 4ENF test, so it was followed the test method proposed by Martin *et al.*, 1998. Briefly, 4ENF test consists of applying load to the specimen through rollers in four points along the specimen, as show in Fig. 7. One of the advantages of this method is that the delamination front lies in a zone of constant moment between the upper rollers.

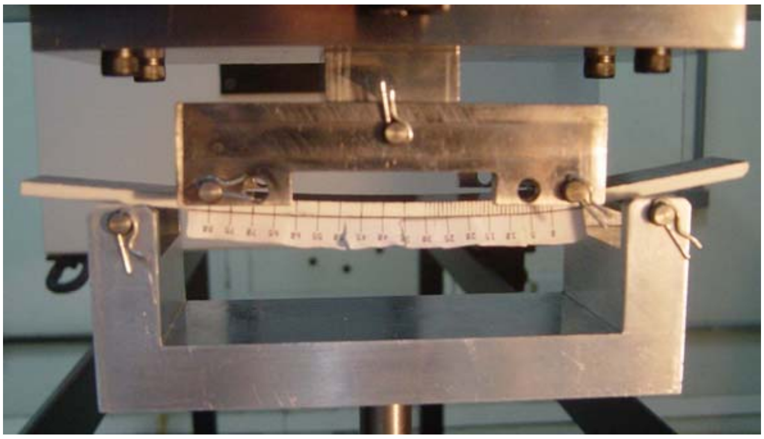

Figure 7. MMB test apparatus

5.1. 4ENF data acquisition

As well as in DCB test, crack length was monitored trough a video camera and a crack marker was used to register each time the crack crosses a vertical line marked on the specimen. The load-displacement curves recorded during the test are depicted in Fig. 8.

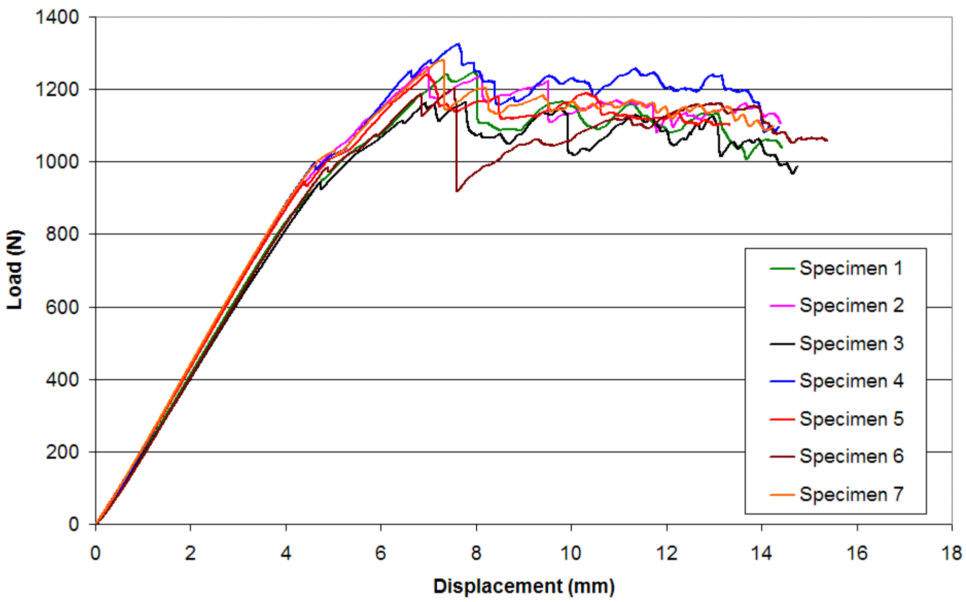

Figure 8. 4ENF load displacement curves

5.2. 4ENF data reduction

The interlaminar fracture toughness expression is given by Eq (7), where m is the slope of the plot of compliance C versus delamination length a.

$$G_{II} = \frac{mP^2}{2b} \tag{7}$$

5.3. 4ENF results

Applying the same definition used for the crack initiation values of the DCB specimens, results for 4ENF test are shown in Tab. 5:

Table 5. G_{IIc} values for 4ENF test

$G_{IIc}(kJ/m^2)$		
NL	VIS	5%/Max
2.052	5.808	3.706

The results of crack propagation are shown in Tab. 6:

Table 6. 4ENF results

$G_{II}(kJ/m^2)$	Std deviation
5.438	1.520

6. FAILURE LOCUS

The results from DCB, 4ENF and MMB tests were compiled into a $G_{II} - G_I$ fracture toughness space in order to define the failure locus. From Fig. 9 it can be seen that the failure locus can be well described using a power law criterion (Mi and Davies, 1998) given below, with $\alpha_{mix} = 0.85$.

$$\left(\frac{G_I}{G_{Ic}}\right)^{\alpha_{mix}} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\alpha_{mix}} = 1 \tag{8}$$

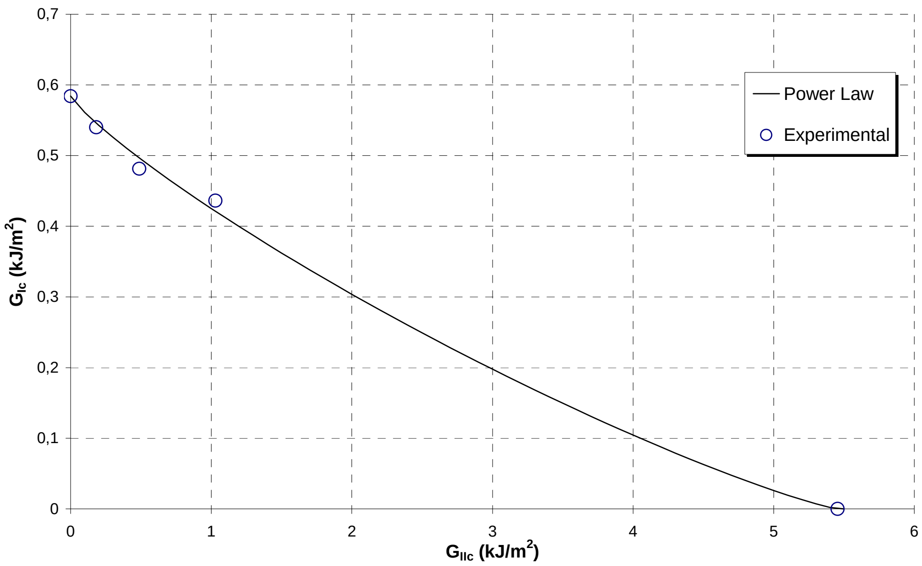

Figure 9. Failure locus

7. CONCLUSIONS

The tests apparatus were well dimensioned and did not affected negatively the results. In general, the results for crack initiation (G_c) were satisfactory, below propagation (G) values. For dimensioning purposes, G_c values should be used, once they are the most conservative values.

The DCB tests were relatively simple to perform, once the crack visualization was facilitated by the opening of the specimen arms. Data reduction methods presented on ASTM, 2007 were equivalent, with very similar results. Data reduction method proposed by Moura *et al*, 2008, however, resulted in non-conservative values. Besides, fiber bridging was not verified in any test.

MMB tests with mixed mode rations of 25 and 50% are similar to DCB test, concerning data acquisition, once the opening of the arms facilitates the crack visualization. However, for a mixed mode ratio of 75% there were difficulties to locate the crack tip, because of the predominant mode II, in which the specimen arms almost do not open. Besides, in some cases, there was unstable crack propagation, invalidating resultant data.

Similarly, there were difficulties in locating the crack tip for the 4ENF test, since there is no opening of the arms at all. Because of the high dependence of the interlaminar fracture toughness with the delamination length, the results might be affected by these imprecise values. Additionally, in both MMB 75% and 4ENF tests, specimens had large deformations, as seen in Fig. 10, and this effect is not considered on the data reduction methods employed in this work.

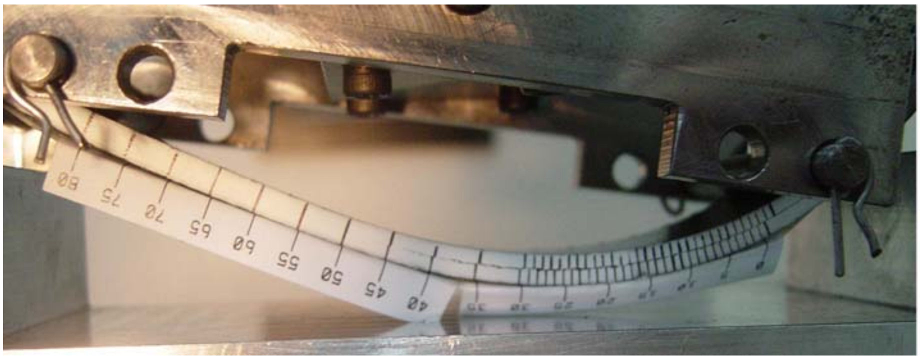

Figure 10. Large deformations on 4ENF test

The effects of the fabric architecture also might have affected the results. Consequently, 4ENF results were not reliable and the high standard deviation may be a result of the stated problems.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

ASTM, 2006, “D 6671/D 6671 M - 06 - Standard Test Method for Mixed Mode I-Mode II Interlaminar Fracture Toughness of Unidirectional Fiber Reinforced Polymer Matrix Composites”, Annual Book of ASTM Standards, USA, Vol 15.03.

ASTM, 2007, “D 5528 - 01 (Reapproved 2007) - Standard test method for mode I interlaminar fracture thoughness of unidirectional fiber-reinforced polymer matrix composites”, Annual Book of ASTM Standards, USA, Vol 15.03.

Martin, R.H., Elms, T. and Bowron, S., 1998. “Characterization of mode II delamination using the 4ENF. Proceedings of the fourth European Conference on Composites Testing & Standardization”, London, UK, p.161-170.

Mi, Y., Crisfield, M.A. and Davies, G.A.O., 1998, “Progressive delamination using interface elements”. J. Composite Materials, Vol. 32, No. 14, p.1247-1271.

Moura, M.F.S.F., Morais, J.J.L. and Dourado, N., 2008, “A new data reduction scheme for mode I wood fracture characterization using the double cantilever beam test”, Engineering Fracture Mechanics, Vol. 75, Issue 13, p.3852-3865.

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