Mode II interlaminar fracture of carbon/epoxy multidirectional laminates

A. B. Pereira[1], A. B. de Morais[1], A. T. Marques[2], P. M. S. T. de Castro[2]

Summary

This paper reports an experimental study on the mode II interlaminar fracture of carbon/epoxy multidirectional laminates. Selected specimen stacking sequences had starter delaminations in $0/\theta$ interfaces. Their suitability for End-Notched Flexure (ENF) tests was first verified in 3D Finite Element (FE) analyses. The measured critical strain energy release rates G_{IIc} increased with the ply angle θ, a result that disagrees with the ones reported in the literature.

Introduction

It is well known that laminated composites are susceptible to delamination. This damage mode is particularly dangerous, as it promotes localised buckling phenomena and its detection requires sophisticated non-destructive evaluation techniques. Considerable efforts have therefore been devoted to the characterisation of delamination resistance [1,2]. The *Double Cantilever Beam* (DCB) test is nowadays standardised for the measurement of the mode I critical strain energy release rate, G_{Ic}, of unidirectional (UD) $[0°]_n$ laminates e.g. ISO 15024:2001. Where mode II is concerned, various specimens have been proposed but there is no consensus on which is the best one [3]. Nevertheless, owing to the simple set-up, the *End-Notched Flexure* (ENF, figure 1) test has been the most used [3].

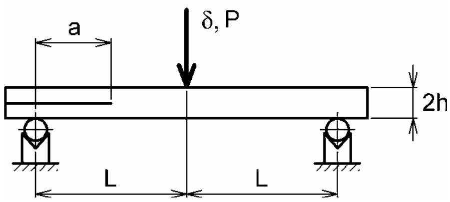

Figure 1. The ENF specimen.

As in mode I, the ongoing pre-standardisation work has been devoted to UD specimens, whose high stiffness and ability to sustain self-similar crack growth conditions are quite convenient for interlaminar fracture tests. However, most applications involve multidirectional (MD) laminates and delaminations occur between plies of different orientations. Unfortunately, fracture tests on MD

[1] University of Aveiro, Dept. Mechanical Engineering, Campus Santiago, 3810-193 Aveiro, Portugal.
[2] University of Porto, Faculty of Engineering, DEMEGI, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.

specimens are often affected by intraply damage and crack jumping to another interface [4-8]. Nevertheless, in most studies conducted on $\theta/-\theta$ specimens (i.e. with starter delaminations in $\theta/-\theta$ interfaces), G_{IIc} values increased with the ply angle θ [4-6]. However, G_{IIc} values of $0/\theta$ specimens have been reported to decrease with θ [7,8], thus suggesting that UD specimens may not give the most conservative results. This was the main motivation for the study herein described.

Selection of specimen stacking sequences

When selecting stacking sequences for MD specimens, excessive elastic couplings that affect G_{IIc} measurements must be minimised. For example, large anticlastic deformations associated with bending-bending couplings lead to highly curved delamination fronts and to a considerable mode III component at the specimen edges [9-11]. In addition, bending-twisting and membrane-bending couplings are generally present in specimens having starter delaminations between differently oriented plies. Such couplings can induce unsymmetrical delamination fronts and significant effects of residual stresses on G_{IIc} measurements. On the other hand, since MD laminates are not as stiff as UD ones, thick specimens should be used in order to avoid large displacements, plastic deformations and, if possible, intraply damage. Considering these requirements, the chosen specimens were $[(0_2/90)_6/0_2//(0_2/90)_6/0_2]$ and $[(0_2/90)_6/0_2//\theta/(0_2/90)_6/0_2]$, where $\theta = 22.5$ to 90 degrees and // stands for the position of the starter delamination.

Selected specimens were evaluated in a 3D FE analysis described in detail in [10,11]. The specimen dimensions were (figure 1) width $B = 20$ mm, span $2L = 100$ mm, crack length $a = 25$ mm [12] and total length 160 mm, while the thickness $2h$ varied from 6.0 to 6.15 mm as a result of the $t = 0.15$ mm ply thickness. The Virtual Crack Closure Technique (VCCT) [13] was employed to compute the strain energy release rate components, G_I, G_{II} and G_{III}. Figure 2 shows distributions of G_{II} along the width of the specimens which are the limit cases of elastic couplings [9,10]. They can be considered fairly uniform, apart from localised edge effects. The 0/45 specimen is clearly the worst, having a less uniform unsymmetrical G_{II} distribution. Nevertheless, the area over which G_{II} differs from the widthwise average value by more than 10 % is less than 1 mm wide. Mode-mixity analyses showed the desired high degree of mode II, as G_{II}/G ratios were always above 95 % [11].

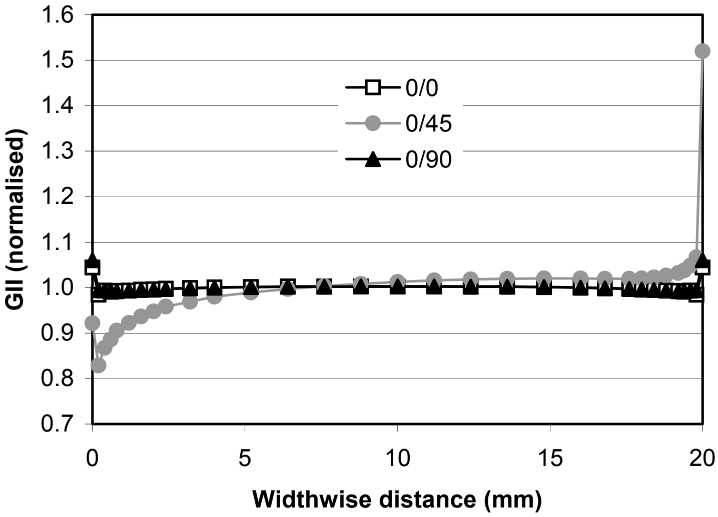

Figure 2. Distributions of G_{II} along the width of ENF specimens. G_{II} values were normalised by the widthwise average.

FE models were also used to assess the accuracy of the compliance calibration

$$C = C_0 + C_1 a + C_3 a^3 \quad (1)$$

leading to [13]

$$G_{II} = \frac{P^2}{2B}(C_1 + 3C_3 a^2) \quad (2)$$

where C_0, C_1 and C_3 are polynomial coefficients, P is the load, δ is the displacement and a = 15 to 35 mm. It was found that equation (1) fitted very well the original FE model compliance data (errors lower than 0.04 %), while the errors of equation (2) relative to VCCT were fairly small (table 1).

Table 1. Errors (%) of equation (2) relative to the original FE and VCCT results.

	a (mm)				
Specimen	**15**	**20**	**25**	**30**	**35**
0/0	-0.28	-0.72	-0.25	0.36	0.93
0/45	-2.73	-2.43	-2.12	-1.47	-0.83
0/90	2.47	2.11	2.25	2.79	3.52

Finally, the effect of residual stresses and friction also proved to be negligible [11]. Therefore, it was concluded that the selected specimens were adequate for ENF tests.

Experimental results and discussion

The laminated plates were prepared from a unidirectional carbon/epoxy prepreg (HS 160 REM) supplied by Texipreg. A 15 μm thick PTFE film was used to generate the starter crack. The plates were manufactured by hot platen pressing according to the recommended processing conditions. The specimens were cut from the plates with the nominal dimensions of the FE models analysed. Tests were conducted at 1 mm/min crosshead speed on at least five specimens of each type. A preliminary set of flexural tests was performed to obtain compliance data for a = 15, 20, 25, 30 and 35 mm. As in [7], $0/\theta$ specimens were positioned on the ENF rig so that compressive stresses acted on the θ-oriented plies. This prevented intraply damage which would invalidate the results. Each specimen was submitted to a first ENF test, which enabled the measurement of G_{IIc} values from the insert and provided the precrack for the subsequent test. Since the exact length of the precrack was not known at this stage, it was assumed that the crack had been arrested below the loading anvil. The true length a was calculated from the measured compliance using equation (1). In all cases, no permanent deformations were visible after unloading. Owing to the difficulties in defining the exact instant of crack initiation, the non-linearity (NL) and the 5 % offset or maximum load criteria (5/M) [1,12] were used.

In general, measured G_{IIc} values from the film were close to those from the precrack (figure 3), the remarkable exception being 0/0 specimens. Similar results were reported in previous studies with UD specimens [1,14]. The most likely explanation is the interference of the film with fibre nesting, which is responsible for the fibre bridging phenomenon commonly observed in mode I tests. It is also worth remarking the small differences between initiation criteria, generally lower than 10 %. This can be partly attributed to the high flexural stiffness of the specimens, since it was shown that the NL point could actually be associated with the onset of large displacements [1,14]. The present results also showed that G_{IIc} values increased with θ, in clear disagreement with those reported in [7,8]. In [8], this trend was attributed to intraply damage in the off-axis ply and therefore the G_{IIc} results cannot be considered truly interlaminar properties. However, Tao and Sun [7] claimed to have avoided intraply damage by positioning the specimens so as to generate compressive stresses in the off-axis ply. A likely explanation for the different results could be the area method used for data reduction, together with the usual unstable a/L = 0.5 specimen configuration [7]. In the conditions of [7], the measured G_{IIc} represent average values over the 19 mm distance between the starter crack and the loading anvil positions. Clearly, this crack growth increment seems too large, making the area method unsuitable.

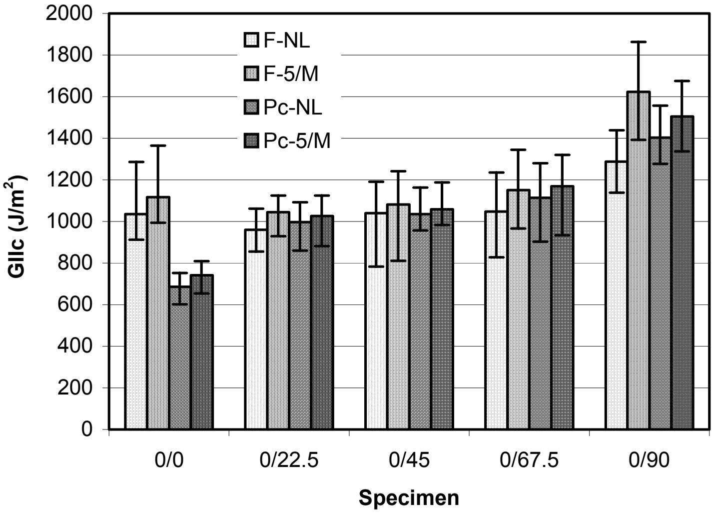

Figure 3. Average G_{IIc} and scatter range obtained from the film (F) and precrack (Pc) using the non-linearity (NL) and the 5 % offset or maximum load (5/M) criteria.

Additional FE analyses were carried out in [11] to assist the interpretation of the interface effect on G_{IIc}. It was found that the increase in G_{IIc} values with θ can be explained by the variations of the level of interlaminar shear stresses ahead of the crack tip inherent to the changes in specimen elastic properties.

Conclusions

An experimental study was performed on the mode II interlaminar fracture of carbon/epoxy multidirectional laminates with starter delaminations in $0/\theta$ interfaces. Specimen stacking sequences were chosen in order to minimise elastic couplings associated problems. FE analyses were performed to evaluate the suitability of selected specimens for ENF tests and to validate a compliance calibration data reduction scheme.

By positioning the specimens so that the interfacial θ-oriented ply would be under compression, it was possible to avoid intraply damage. Experimental G_{IIc}

values increased with θ, a trend that is in contradiction with results reported in the literature. This can be due to intraply damage and to the use of inappropriate data reduction schemes.

Acknowledgements

The authors thank the support of the Portuguese Foundation for Science and Technology (project POCTI/EME/38731/2001, FEDER European Union fund).

References

1. Davies, P., Blackman, B. R. K. and Brunner, A. J. (1998), *Appl Compos Mater*, Vol. 5, pp. 345-364.
2. Tay, T. E. (2003), *Appl Mech Rev*, Vol. 56, pp. 1-31.
3. Davies, P. et al (1999), *Plastics, Rubber and Composites*, Vol. 28, pp. 432-437.
4. Chai, H. (1990), *Int J Fract*, Vol. 43, pp. 117-131.
5. Chou, I., Kimpara, I., Kageyama, K. and Ohsawa, I. (1995), *Composite Materials: Fatigue and Fracture* - 5th Volume, ASTM STP 1230, pp. 132-151.
6. Choi, N. S., Kinloch, A. J. and Williams, J. G. (1999), *J Compos Mater*, Vol. 33, pp. 73-100.
7. Tao, J. X. and Sun, C. T. (1998), *J Compos Mater*, Vol. 32, pp. 1933-1947.
8. Hwang, J. H., Kwon, O., Lee, C. S. and Hwang, W. (2000), *Mech Compos Mater*, Vol. 36, pp. 195-214.
9. Davidson, B. D., Krüger, R. and König, M. (1995), *J Compos Mater*, Vol. 29, pp. 2108-2133.
10. de Morais, A. B. (2004), *Composites Part A*, Vol. 35, pp. 51-57.
11. Pereira, A. B., de Morais, A. B., Marques A. T. and de Castro P. T. (2004): "Mode II interlaminar fracture of carbon/epoxy multidirectional laminates", to be published in *Compos Sci Technol*.
12. *Fracture Mechanics Testing Methods for Polymers, Adhesives and Composites* (2001), ESIS Publication 28. Edited by D. R. Moore, A. Pavan and J. G. Williams. Elsevier Science Ltd.
13. Kaninnen, M. F. and Popelar C. H. (1985): *Advanced Fracture Mechanics*, Oxford University Press, New York.
14. Davies, P., Ducept, F., Brunner, A. J., Blackman, B. and Morais, A. B. (1996), *Proc. of the 7th European Conf. Compos. Mater.* (ECCM-7), Vol. 2, pp. 9-18, London.