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THE MODE II INTERLAMINAR FRACTURE TESTING OF GLASS FIBRE REINFORCED THERMOSET COMPOSITES

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ABSTRACT

This paper presents the result of setting up the end notched flexure (ENF) testing to determine the Mode-II interlaminar fracture toughness on various forms of E-glass fibre/thermoset based composites. The materials tested are unidirectional, woven roving and chopped strands mat with polyester and epoxy resins and were manufactured by hand lay up technique. The preparation process, testing procedure and data reduction scheme of the ENF specimen are described in details. To verify the result of this work, the Mode-II critical strain energy release rate, G_{IIc}, for the tested materials is compared to those found in other publications. This study successfully demonstrates the simplicity and effectiveness of the ENF specimen in evaluating the Mode-II fracture toughness of E-glass fibre/thermoset based composites.

Keywords: *Interlaminar fracture, mode II, E-glass fibre/thermoset based, end notched-flexure (ENF), critical strain energy*

1.0 INTRODUCTION

The interlaminar fracture or delamination is associated with the failure of the weakest components of the composite material, i.e. the matrix and the fibre-matrix interface [1]. This failure is often the limiting factor in the use of fibrous composites for structural applications as it leads to losses of stiffness and deterioration in the structural performance. Therefore, the measure of the material resistance to delamination crack propagation is needed. From the literature review, it was found that the popular approach for characterizing this parameter is through the application of the linear elastic fracture mechanics (LEFM), which enables the critical energy release rate of fracture energy, G_c, to be determined [2]. Unlike homogeneous metallic or polymeric materials, the fracture of continuous fibre composites may not be modelled by a single linear elastic fracture parameter, G_c.

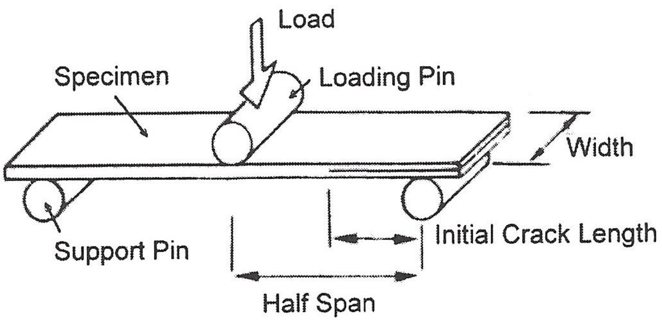


Figure 1 ENF test fixture

Various modes of failure may be identified in fibre composites, which are highly anisotropic materials i.e. Mode-I (opening mode), Mode-II (in-plane shear) and Mode-III (anti-plane shear). Therefore, there has been a considerable interest in determining values of G_{Ic}, G_{IIc}, G_{IIIc}, which are based upon the application of interlaminar fracture mechanics concepts. Due to the emergence of new material systems exhibiting superior Mode-I fracture toughness [3], emphasis has now shifted to understanding the Mode-II and Mode-III fracture toughness and damage tolerance. In this work, the Mode-II interlaminar fracture of various forms of E-glass fibre/thermoset resin based composites was investigated. For this purpose, the End Notch Flexure (ENF) specimen [4,5,6], as shown in Figure 1, was studied and prepared. This paper describes the specimens' preparation process, the testing procedure and the test result discussion.

2.0 TESTING PROGRAMME

2.1 Specimen Materials and Fabrication Process

In this study, three different forms of E-glass fibres are used, i.e. unidirectional, woven roving and chopped strands mat, which are embedded in the thermoset resins, i.e. polyester and epoxy. The epoxy resin utilized is Sikadur$^{@}$-330 and the polyester resin is a general-purpose orthophotalic resin. A 600 mm long and 270 mm wide composite panel (Figure 2) was fabricated by using hand lay up technique for each test sample [7]. The panel's code, number of plies and fibre to resin ratio are specified in Table 1. Laminates thickness in the range of 3 mm to 5 mm had been produced to ensure that the deflection effect is not large [8]. To define a starter crack, a 40 μm thick, folded mylar plastic (starter film) was inserted between the plies at the midplane of the laminates during fabrication. These test panels were left at the room temperature for two days to complete the curing process.

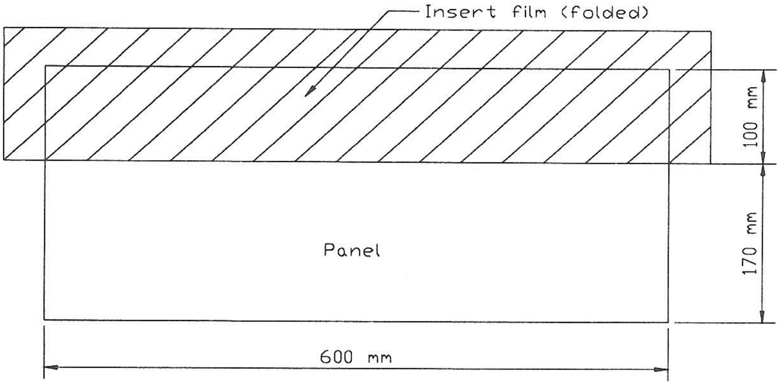


Figure 2 The test panel geometry

Table 1 Number of plies and fibre to resin ratio used in the test sample preparation

Panels	Code	Number of plies	Fibre to resin ratio (By weight)
Unidirectional glass fibre/polyester	UNIP	6	1:1
Unidirectional glass fibre/epoxy	UNIE	6	1:1
Woven roving glass fibre/polyester	WRP	6	1:1
Woven roving glass fibre/epoxy	WRE	6	1:1
Chopped strands map glass fibre/polyester	CSMP	4	3:7
Chopped strands map glass fibre/epoxy	CSME	4	3:7

2.2 Specimen Preparation

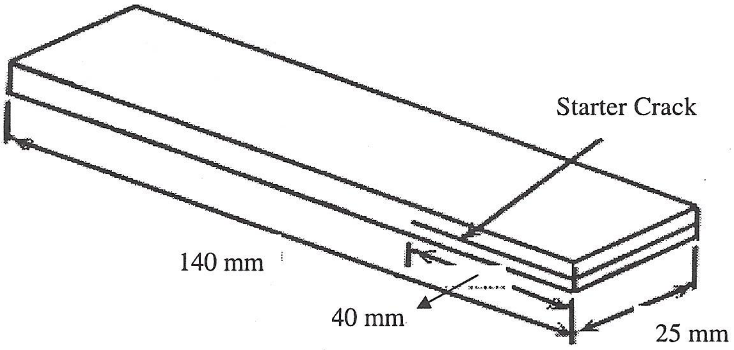


Figure 3 The ENF specimen dimension

After removing the starter film from the cured composite panels, at least six ENF specimens with the dimensions given in Figure 3 were cut from each panel, using a diamond cutting saw. To produce flat and smooth surfaces, the edge on both sides of the ENF specimens were polished by using sandpapers from grade 500 to 2000. Pressurized dry air spray was then used to clean the specimens from the cutting dust. As the result of the folded starter film placed at the mid-plane of the specimen during processing, a small resin rich region (Figure 4), which blunts the crack tip and yields higher G_{IIc} results [6], had been detected. Thus, the specimens must be precracked before the testing is conducted. Two types of precrack method were found in literature, namely 'Mode-I' and 'Mode-II' precrack. The 'Mode-II' precracked is produced by loading a specimen in the three point bending fixture to attain a stable crack growth until its arrests at the centre load point bend fixture. The 'Mode-I' precrack was chosen in this studies after finding that the 'Mode-II' precrack is time consuming and not suitable for some materials that produce multiple crack propagations during loading.

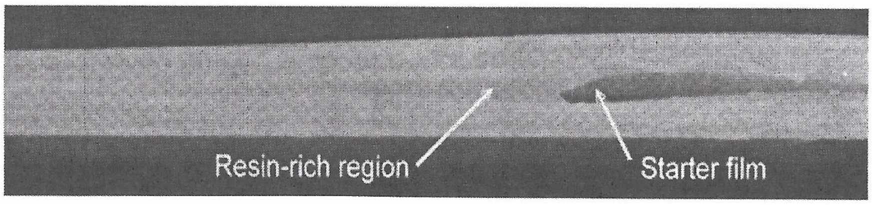


Figure 4 Resin rich region caused by the folded insert film

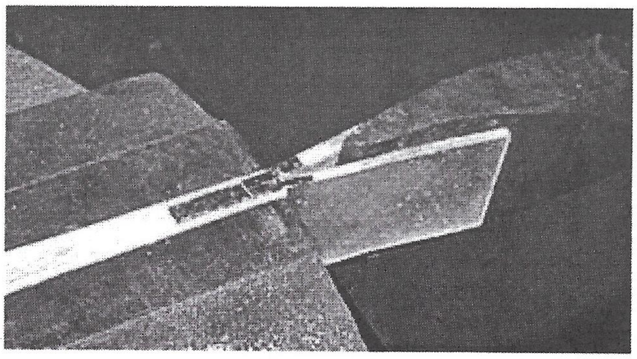
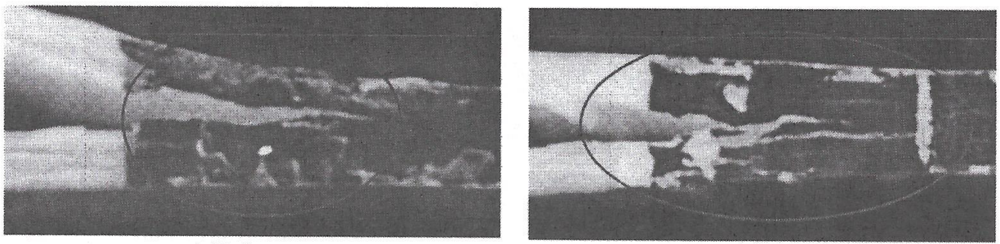


Figure 5 'Mode-I" precracking by forcing a chisel into a clamped ENF specimen

The resin rich zone length was about 10-15 mm long. So, the 'Mode-I' precracking, as shown in Figure 5, was performed by forcing a chisel into a clamped ENF specimen until a length of 8-12 mm crack extension occurred. The crack extension must be kept smaller or equal to the length of the matrix-rich zone in order to avoid fibre-bridging effects [9]. The Mode-I precracking using a chisel had been found successful in producing a single crack extension and sharp crack tip in unidirectional (UNI/P and UNI/E) and chopped strand mat (CSM/P and CSM/E) composite specimens. However in woven roving type of specimens (WR/P and WR/E), multiple crack extensions, which blunted the crack tip as shown in Figure 6 had occurred during precracking process. To overcome this problem, a single unfolded plastic 'mylar' film with the thickness of 40 μm was inserted in the reproduced WR/P panel to eliminate the resin rich area that is caused by the folded film.



a) Polyester

b) Epoxy

Figure 6 Multiple crack extension shown by WR/P and WR/E specimens

For the correct reduction of data it is essential to determine the initial crack length. The position of the crack front was determined by examining each side of the specimen, using the Olympus S2X9 Stereo REA Microscope in the magnifications of 10X. Prior to testing, the edges on both side of the specimen were coated with a white correction pen and then were painted with a black whiteboard marker to create a good contrast for aiding the visual identification of the crack propagation during the testing (Figure 7).

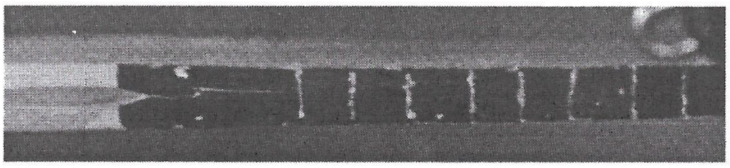


Figure 7 Specimen with precrack and increment markings

3.0 TESTING SET-UP

The experiments were performed in a digitally controlled Instron 4206 static universal testing machine. All experiments were conducted at room temperature of 27 °C at a constant crosshead speed of 1 mm/min. A 5 kN load cell was used in this experiment. The ENF specimen was loaded in a three-point bend fixture (Figure 8) with a distance between the supports, 2L, of 110 mm. The specimen was positioned in the three-point fixture with an initial crack length, *a*, of 30 mm so that the configuration $a/L \approx 0.5$ is achieved. This is to produce unstable crack propagation [10].

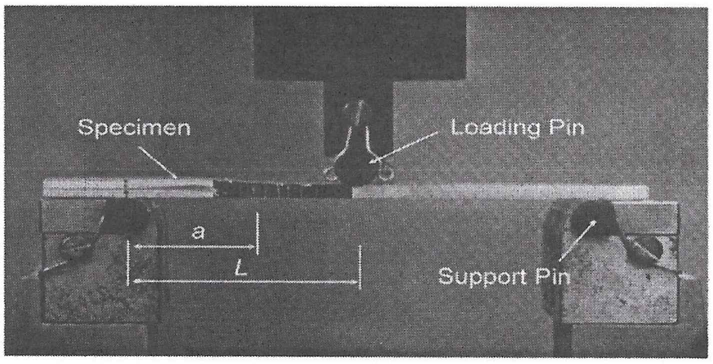


Figure 8 The ENF testing set-up

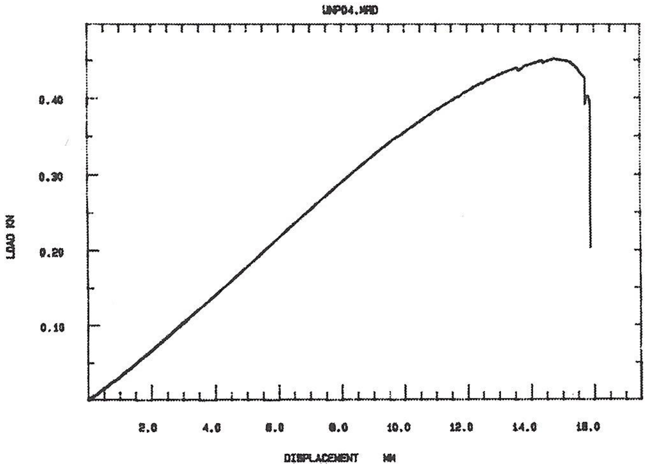
During loading, the crack tip was observed with the help of magnifying glass to detect any stable or unstable crack propagation. The data acquired from the test are the maximum load and the mid-span displacement. This load-displacement response is recorded on a chart recorder. When the crack is observed to be propagating until it reached the centre of the loading point, the test will be stopped and the load-displacement chart will be recorded. Six specimens for each sample were tested in order to produce an average value of the critical strain energy release rate for Mode-II fracture toughness. The beam theory used to calculate the critical strain energy release rate for the Mode-II fracture toughness is given as follow [10];

$$G_{IIc} = \frac{9a^2 P_c \delta_c}{4b(2L^3 + 3a^3)}$$

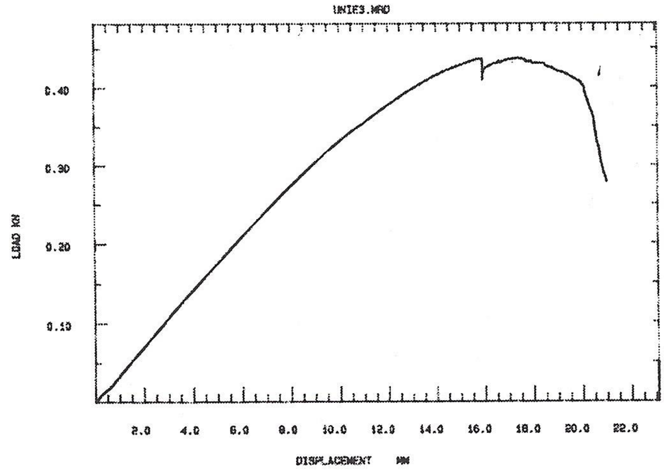
where a is the initial crack length (mm), P_c is the critical applied load (kN), δ_c is the critical central beam deflection (mm), b is the width of the specimen (mm) and L is the half span (mm).

4.0 RESULTS AND DISCUSSIONS

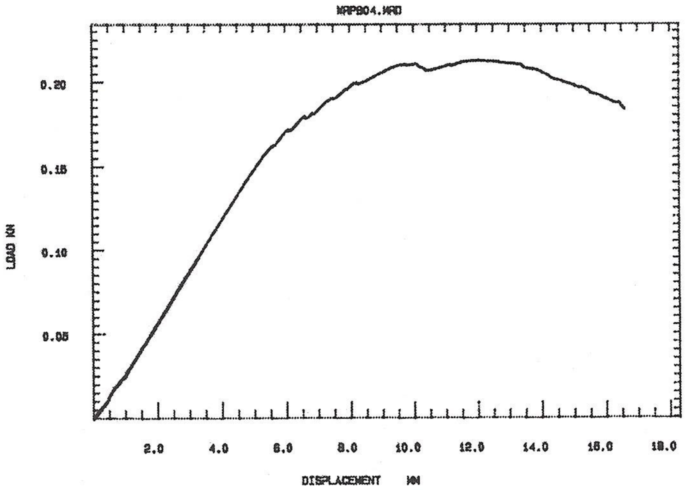
The load-displacement response for each of the tested specimens is shown in Figure 9. All specimens showed a linear elastic load-displacement response during loading but on approaching the critical load, a nonlinear behaviour is observed. This response behaviour is similar with other researchers observation [4,5,6].



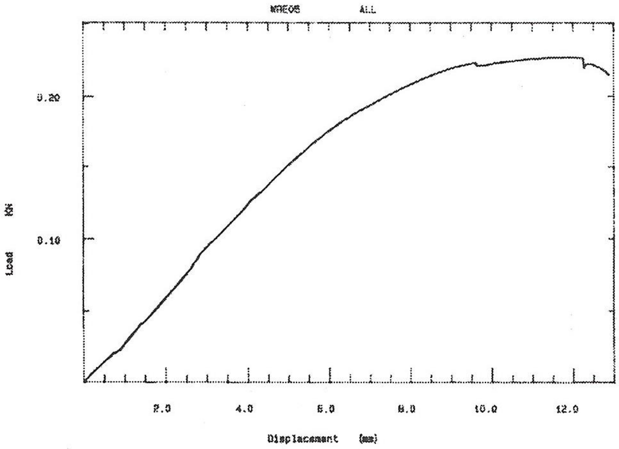
a) UNI/P specimen



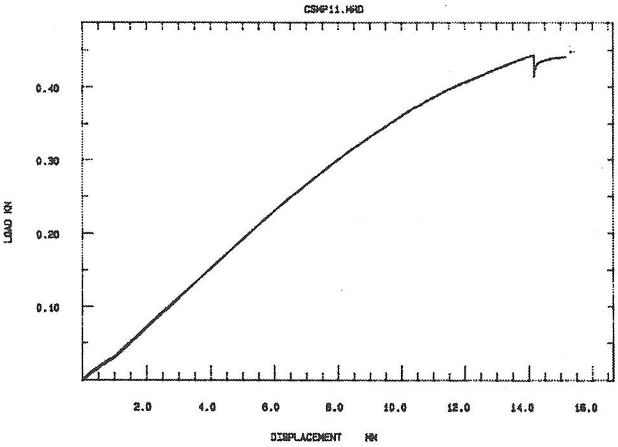
b) UNI/E specimen



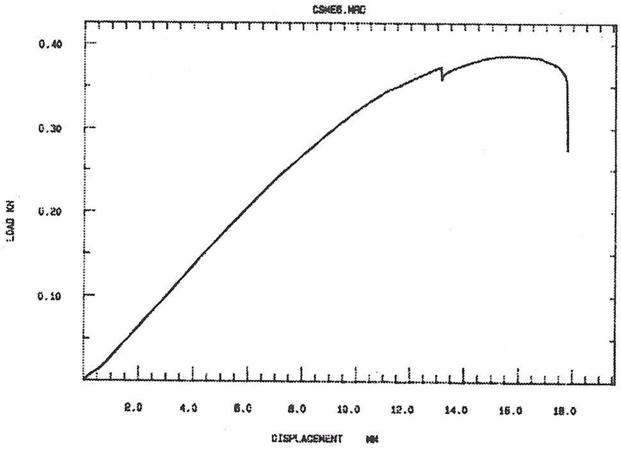
c) WR/P specimen



d) WR/E specimen



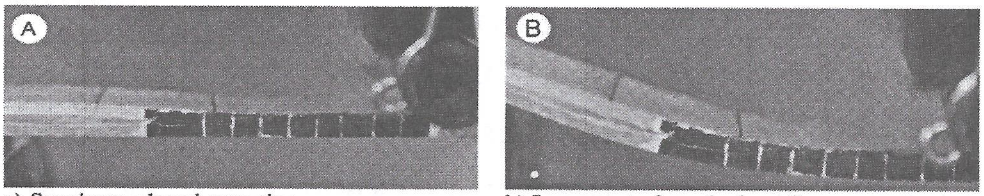
e) CSM/P specimen



f) CSM/E specimen

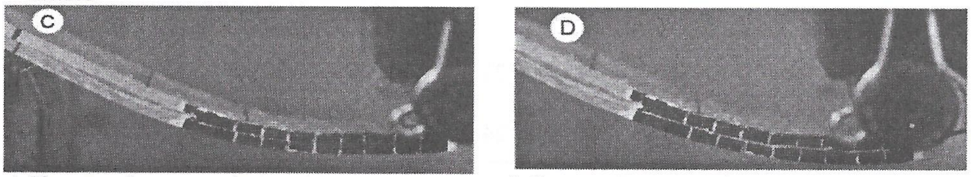
Figure 9 Typical load-displacement response curve for the test specimens

The nonlinear behaviour is caused by subcritical crack growth (slow crack propagation) prior to critical crack growth (fast crack propagation) as shown in Figure 10. The major difference between these specimens is UNI/P, UNI/E, CSM/P and CSM/E specimens exhibit unstable crack propagation while WR/P and WR/E specimens exhibit stable crack propagation during the critical load phase. At the critical load, the crack of the UNI/P, UNI/E, CSM/P and CSM/E propagates immediately to the position beneath the loading pin, which resulted in the sudden drop in the applied load. For the case of the WR/P and WR/E specimen, a longer nonlinear period is observed in the load-displacement due to the multiple crack initiations and failure mechanisms that have occurred before the crack propagation process (Figure 11). Compared to polyester resin specimens, the epoxy resin specimens show a relatively higher degree of nonlinearity behaviour in its load-displacement curve as its crack propagates slower in the stable crack extension manner.



a) Specimen placed at testing fixture

b) Increment of crack about 3 mm



c) Slow crack propagation

d) Fast crack propagation before crack was arrested at the loading pin.

Figure 10 Slow crack propagation (Picture B and C) before fast crack propagation exhibited by the UNI/P specimen during testing

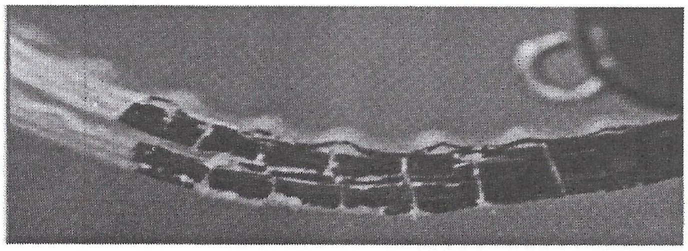


Figure 11 Multiple crack extensions exhibited by WR/P specimen. Noted that buckling had occurred on the compressed surface

Table 2 gives specimens geometries, preparation parameters, the mean value of G_{IIc}, the coefficient of variation, *CV*, (standard deviation divided by mean G_{IIc}) for each UNI/P, UNI/E, WR/P, WR/E, CSM/P and CSM/E specimens. The accepted *CV* of G_{IIc} for the interlaminar fracture toughness testing of composite materials using the hand lay-up method is about ±15% [1]. All specimens show good agreement with the accepted *CV* value. To verify the work of this research, the G_{IIc} results were compared with those found in literature. In comparison, it shows that the method used at here gave G_{IIc} results similar to the other researchers.

Table 2 Three Point Bending Test Results

No.	Specimen Type	No. Plies	Average Dimensions (mm)			Fibre Weight Fraction	Precrack Length (mm)	G_{IIc} Max (J/m^2)	*COV* (%)
			Thickness	Length	Width				
1	UNI/P	6	2.98	144.46	25.23	0.3706	10.0	1151.3	6.07
2	UNI/E	6	3.74	143.42	25.62	0.2773	8.4	1486.7	5.01
3	WR/P	6	3.38	144.81	25.16	0.4055	3.6	514.2	6.80
4	WR/E	6	4.18	139.66	24.42	0.3581	10.2	525.5	5.12
5	CSM/P	4	4.18	142.02	23.57	0.2626	8.0	1068.5	6.19
6	CSM/E	4	4.70	140.13	24.25	0.1628	10.0	1237.1	5.81

Table 3 The toughness value for some of the glass fibre (GF)/ polyester (P) or epoxy (E) composite that found in the literature

Reference	Fabrication method	Material	Fibre Volume Fraction	No. of plies /(Thickness)	G_{IIc} (Jm^2)
Davies P. *et al* [11]	Hand Lay Up	0 GF/P	0.50	8 (5.5 mm)	470
		0/90/CSM GF/P	0.60	6 (6 mm)	583
Ducept F. *et al* [12]	Hot press prepeg	0 GF/E	0.35	16 (4.97mm)	2330
		0 GF/E	0.37	24 (6.3 mm)	2779
Marom G. *et al* [13]	Hot press prepeg	0 GF/E	0.5	6 mm	1340
		±15 GF/E	0.5	6 mm	1556
		±30 GF/E	0.5	6 mm	1796
		±45 GF/E	0.5	6 mm	1506

5.0 CONCLUSIONS

This work shows that the ENF specimen can be used to determine the Mode-II interlaminar fracture toughness of E-glass fibre/thermoset based composites. An unfolded 'mylar' film with a thickness of 40µm is recommended for the starter crack between the midplane of the plies during fabrication. This is to yield more consistence fracture toughness results. The 'Mode-I' fracture precracking made by a chisel is suggested in producing a precrack length that is within the measured resin rich region's length. Based on the comparison of the load-displacement response curve and G_{IIc} values obtained here to other researchers work and also the *CV*s of the G_{IIc} results to the allowable *CV* limit, the specimens' preparation and test procedure set-up in this study are acceptable.

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