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, \( G_{\text{IIc}} \), 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, \( G_c \).
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 orthophthalic 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 $\mu$m 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 9 Typical load-displacement response curve for the test specimens

d) WR/E specimen

e) CSM/P specimen

f) CSM/E specimen
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.

![Image](A) a) Specimen placed at testing fixture  
![Image](B) b) Increment of crack about 3 mm  
![Image](C) c) Slow crack propagation  
![Image](D) 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 $\pm 15\%$ [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

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen Type</th>
<th>No. Pies</th>
<th>Average Dimensions (mm)</th>
<th>Fibre Weight Fraction</th>
<th>Precrack Length (mm)</th>
<th>$G_{IIc}$ Max (J/m$^2$)</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Thickness</td>
<td>Length</td>
<td>Width</td>
<td>0.3706</td>
<td>10.0</td>
</tr>
<tr>
<td>1</td>
<td>UNI/P</td>
<td>6</td>
<td>2.98</td>
<td>144.46</td>
<td>25.23</td>
<td>0.3706</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>UNI/E</td>
<td>6</td>
<td>3.74</td>
<td>143.42</td>
<td>25.62</td>
<td>0.2773</td>
<td>8.4</td>
</tr>
<tr>
<td>3</td>
<td>WR/P</td>
<td>6</td>
<td>3.38</td>
<td>144.81</td>
<td>25.16</td>
<td>0.4055</td>
<td>3.6</td>
</tr>
<tr>
<td>4</td>
<td>WR/E</td>
<td>6</td>
<td>4.18</td>
<td>139.66</td>
<td>24.42</td>
<td>0.3581</td>
<td>10.2</td>
</tr>
<tr>
<td>5</td>
<td>CSM/P</td>
<td>4</td>
<td>4.18</td>
<td>142.02</td>
<td>23.57</td>
<td>0.2626</td>
<td>8.0</td>
</tr>
<tr>
<td>6</td>
<td>CSM/E</td>
<td>4</td>
<td>4.70</td>
<td>140.13</td>
<td>24.25</td>
<td>0.1628</td>
<td>10.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Fabrication method</th>
<th>Material</th>
<th>Fibre Volume Fraction</th>
<th>No. of plies / (Thickness)</th>
<th>$G_{IIc}$ (J/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davies P. et al</td>
<td>Hand Lay Up</td>
<td>0 GF/P</td>
<td>0.50</td>
<td>8 (5.5 mm)</td>
<td>470</td>
</tr>
<tr>
<td>[11]</td>
<td>0/90/CSM GF/P</td>
<td>0.60</td>
<td>6 (6 mm)</td>
<td>583</td>
<td></td>
</tr>
<tr>
<td>Ducept F. et al</td>
<td>Hot press prepeg</td>
<td>0 GF/E</td>
<td>0.35</td>
<td>16 (4.97mm)</td>
<td>2330</td>
</tr>
<tr>
<td>[12]</td>
<td>0 GF/E</td>
<td>0.37</td>
<td>24 (6.3 mm)</td>
<td>2779</td>
<td></td>
</tr>
<tr>
<td>Marom G. et al</td>
<td>Hot press prepeg</td>
<td>0 GF/E</td>
<td>0.5</td>
<td>6 mm</td>
<td>1340</td>
</tr>
<tr>
<td>[13]</td>
<td>±15 GF/E</td>
<td>0.5</td>
<td>6 mm</td>
<td>1556</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±30 GF/E</td>
<td>0.5</td>
<td>6 mm</td>
<td>1796</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±45 GF/E</td>
<td>0.5</td>
<td>6 mm</td>
<td>1506</td>
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</table>
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 CVs of the $G_{IIc}$ results to the allowable CV limit, the specimens’ preparation and test procedure set-up in this study are acceptable.

REFERENCES


