ON THE MODE II TESTING OF CARBON-FIBRE POLYMER COMPOSITES

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In this paper the contribution of friction to the mode II delamination toughness of fibre-reinforced laminates has been assessed. It is shown that the conventional analyses used for the determination of $G_{IIc}$, i.e., the compliance method and the corrected beam theory method require correction for friction, and that both of these analysis methods over-state the value of $G_{IIc}$. It is shown also that the failure to include friction in the analysis results in a deviation between the values of $G_{IIc}$ deduced via the experimental compliance method and the values deduced from corrected beam theory. It is shown that friction corrections are significant, and in the case of a tough matrix composite (APC-2) and a glass-fibre epoxy composite may actually lead to the value of $G_{IIc}$ being equivalent to the value $G_{IIc}$, the mode I fracture toughness.

INTRODUCTION

There has been much interest recently in the mode II delamination testing of fibre-reinforced polymer composites. However, progress towards an International Standard for measuring the mode II delamination toughness, $G_{IIc}$, has been slow and there remain a number of critical issues which need to be resolved before any testing standard can gain International acceptance.

Firstly there is the issue of choice of test method. A recent round-robin coordinated by VAMAS (Versailles Agreement on Materials and Standards) compared three experimental methods across an International platform. Labs in Europe, USA and Japan performed mode II tests using the ELS (end-loaded split), ENF (end notched flexure) and SENF (stabilised end notched flexure) test geometries. More recently, another version of the ENF test using four point bending has been proposed and is currently being assessed in a second round-robin. The final decision on the test method will likely be determined on the grounds of crack stability, repeatability, reproducibility and ease of use. Secondly, there is the issue of specimen calibration. In the ELS test, for example, different values of $G_{IIc}$ are typically deduced depending upon whether the experimental compliance method or corrected beam theory methods of analysis are employed. Friction in the mode II test will influence the calibration of the specimen and will lead to discrepancies in the values of $G_{IIc}$ deduced via the experimental compliance method and the corrected beam theory method. Finally,

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there is the issue of the mechanism of crack growth under mode II loading conditions in composites. In a recent review article by O'Brien (1) it was suggested that under mode II loading, the crack does not grow in a continuous manner as previously assumed, but grows via the formation and subsequent coalescence of microcracks ahead of the main crack tip. This mechanism creates a characteristic hackle pattern on the fracture surfaces which in turn causes a locking of the sliding surfaces. This stress induced matrix microcracking was recently analysed by Lee (2) and such a mechanism could explain the high degree of scatter noted in mode II test data and in mixed-mode test data where the loading is predominantly mode II.

In the present paper, the role of friction in the mode II ELS test is investigated. An analysis based upon the assumption of a uniform shear stress acting on the cracked surfaces is presented and results for this case are given. A second analysis is also considered for the assumption that the shear stress is not uniform, but reaches a sharp peak at the crack tip. It is also indicated how the ELS test may be modified to allow the form of the shear stress distribution to be determined.

**FRICTION IN MODE II**

**Background**

A number of studies have previously been reported on the influence of friction on the measured values of $G_{IC}$ in the mode II ENF test. Gillespie et al. (3) included the contact problem into a two dimensional FE model of the ENF test, and found that the assumed friction reduced the beam compliance and $G_{IC}$ values by up to 1% and 5% respectively. In an experimental study using the ENF test, Davies (4) found that for thick specimens, the values of $G_{IC}$ measured from specimens without a PTFE film separator between the crack surfaces were 20% higher than when PTFE film separators were used. Thus, the additional friction had caused a 20% overestimation of the fracture toughness. In the following section, the effect of friction on the measured $G_{IC}$ values in the mode II ELS test will be considered.

**Assumption of uniform shear stress**

The mode II ELS test geometry is shown in Figure 1. The analysis derived previously by Williams (5) for this mode II test ignores the frictional stresses acting on the crack faces. If we now include shear stress in our analysis and assume that it is uniform along the crack length, i.e. $\tau = \tau_0$, then the displacement of the beam shown in Figure 1 is given by:

$$u = \frac{3}{2Ebh^2} \left[ P \left( \frac{1}{3} + a \right) \right] + \frac{4}{3} \tau_0 bh a$$  \hspace{1cm} (1)$$

Where $E$ is the axial modulus of the beam. If we now define a parameter $\alpha$ which is the ratio of the frictional shear stress to the applied shear stress or:

$$\alpha = \frac{\tau_0}{\tau}$$  \hspace{1cm} (2)$$

Then it can be easily shown that for the ELS test:

$$\alpha = \frac{4 \tau_0 bh}{3P}$$  \hspace{1cm} (3)$$

Then the compliance of the beam may be written as:
\[ C = \frac{u}{P} = \frac{3a^3}{2Ebh^3} (1 - \alpha) + \frac{L^3}{2Ebh^3} \]  

Equation (4)

Therefore, including this frictional term we can write:

\[ G_m = \frac{P^2}{2B} \frac{dC}{da} = \frac{9P^2a^2(1 - \alpha)}{4Eb'h^3} \]  

Equation (5)

And noting that when we do not consider friction, the value of \( G_{nc} \) deduced via beam theory (BT) is:

\[ G_{nc}(BT) = \frac{9P^2a^2}{4Eb'h^3} \]  

Equation (6)

It is noted that equation (5) is equivalent to the value of \( G_{nc} \) which is determined from the compliance method of analysis, because the frictional shear stress, \( \tau_r \), influences the calibration of the test, i.e. the plot of \( C \) versus \( a^3 \) from the ELS test will yield a gradient, \( m \), which has been altered by friction. Hence we can describe the value of \( G_{nc} \) determined from equation (6) as \( G_{nc}(BT) \) and the value determined from equation (5) as that obtained from the elastic compliance method of analysis or \( G_{nc}(ECM) \). However, it can be shown that the exact solution for \( G_{nc} \) obtained by considering the shear stress contribution to the bending moment at the crack tip, is given by:

\[ G_{nc}(TRUE) = \frac{9P^2a^2(1 - \alpha)^2}{4Eb'h^3} \]  

Equation (7)

Therefore, in the ELS test, both beam theory and the elastic compliance method will overstate the value of \( G_{nc} \), but by differing amounts. Beam theory yields the higher value and the exact solution yields the lower value. They are related via equation 8:

\[ \left \{ \frac{G_{nc}(ECM)}{G_{nc}(BT)} \right \}^2 = G_{nc}(TRUE) \]  

Equation (8)

As usual, equations (5) to (7) require correction for shear deflection and rotation of the crack tip and this may be achieved by adding a term \( \Delta \) to the crack length. The results presented later are corrected in this way, i.e. \( G_{nc}(BT) \) is the corrected beam theory.

Assumption of non-uniform shear stress

The analysis above assumed that the frictional shear stress, \( \tau_r \), was uniform along the entire crack length. In practice, the shear stress distribution probably has a more complicated form. If we now assume a shear stress distribution of the form:

\[ \tau = \frac{\tau_r x}{a} \]  

Equation (9)

Then we can proceed as before and write the exact solution for \( G_{nc} \) as:
\[ G_{\text{nc}} = \frac{9P^2a^3}{4Eh^3} \left(1 - \alpha \right) \left[ 1 - \frac{2\alpha}{(1+n)(2+n)} \right] \]

The dependence of the shear stress distribution upon the parameter \( n \) is shown in Figure 2. When \( n = 0 \), we revert to the uniform shear stress assumption above. A high \( n \) gives a sharp peak to the shear stress at the crack tip. One possible method to determine \( n \) and \( \alpha \) would be to measure both the vertical displacement \( u \) and also the horizontal sliding displacement between the lower and upper beam. In the present work however, the assumption of a uniform shear stress will be made.

**EXPERIMENTAL**

**Procedure for uniform shear stress**

The parameter \( \alpha \) can be deduced from the ELS test and the experimental procedure is described in an ESISS protocol (6). The parameter can be deduced by comparison of the values of \( G_{\text{nc}} \) determined via beam theory and via the elastic compliance method, as will be shown later. The values of the crack length require correction by the addition of \( \Delta t \) as specified in (6). The materials tested contained folded PTFE insert films up to the initial crack length, \( a_c \).

**Results assuming a uniform shear stress distribution**

The parameter \( \alpha \) and the corrected value of \( G_{\text{nc}} \), termed \( G_{\text{nc}} \) (TRUE), was deduced by comparison of the two data reductions methods, namely the elastic compliance method and beam theory, i.e. by equations (7) and (8). Test data which had previously been obtained from tests on: (i) a carbon-fibre epoxy composite, (ii) a carbon-fibre PEEK (APC-2) composite and for comparison (iii) a glass-fibre epoxy composite were reanalysed and typical results are shown in Table 1.

**TABLE 1**

<table>
<thead>
<tr>
<th>Material</th>
<th>( \alpha )</th>
<th>( G_{\text{nc}} ) (J/m²)</th>
<th>( G_{\text{nc}} ) (BT)</th>
<th>( G_{\text{nc}} ) (ECM)</th>
<th>( G_{\text{nc}} ) (TRUE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF epoxy</td>
<td>0.12</td>
<td>150</td>
<td>560</td>
<td>493</td>
<td>434</td>
</tr>
<tr>
<td>APC-2</td>
<td>0.09</td>
<td>2000</td>
<td>2500</td>
<td>2275</td>
<td>2070</td>
</tr>
<tr>
<td>GF epoxy</td>
<td>0.39</td>
<td>10000</td>
<td>4000</td>
<td>2440</td>
<td>1488</td>
</tr>
</tbody>
</table>

The value of the parameter \( \alpha \) obtained for each material is tabulated. The value of \( G_{\text{nc}} \) measured from a mode I DCB test is shown and the values of \( G_{\text{nc}} \) (BT) i.e. \( G_{\text{nc}} \) from corrected beam theory and \( G_{\text{nc}} \) (ECM) are shown. The final column shows the 'TRUE' or corrected value of \( G_{\text{nc}} \) with the friction term included i.e. from equation (8). It can be seen that: \( G_{\text{nc}} \) (BT) > \( G_{\text{nc}} \) (ECM) > \( G_{\text{nc}} \) (TRUE).

From the above results it is of interest to compare the values of corrected or true \( G_{\text{nc}} \) with the values of \( G_{\text{nc}} \). The rationale for doing this is that if \( G_{\text{nc}} \) was simply '\( G_{\text{nc}} \) plus friction' then the values of \( G_{\text{nc}} \) (TRUE) would be equal to the values of \( G_{\text{nc}} \). The results in Table 1 indicate that for the APC-2 composite, an \( \alpha \) of 0.09 is almost enough...
to reduce $G_{IC}$ to $G_{IC}$. This is shown in Figure 3 which displays R-curve data for the APC-2 composite and it is seen that the value of $G_{IC}$(TRUE) is only 3.4% higher than the value of $G_{IC}$. Also, for the glass-fibre epoxy composite, an $\alpha$ of 0.39 is again sufficient to reduce $G_{IC}$ to $G_{IC}$. However, for the carbon-fibre epoxy composite, an $\alpha$ of 0.12 is clearly insufficient to reduce $G_{IC}$ to $G_{IC}$. These results therefore show that for the APC-2 composite and the glass-fibre epoxy composite, friction alone may account for the difference between $G_{IC}$ and $G_{IC}$. However, in the carbon-fibre epoxy composite, there must be another mechanism occurring which causes $G_{IC}$ to be very much greater than $G_{IC}$. Other studies have shown that this is mechanism is probably microcracking, i.e. microcracks forming ahead of the main crack which then coalesce to leave the characteristic hackle pattern on the fracture surface.

CONCLUSIONS

The contribution of friction to the values of the mode II fracture toughness, $G_{IC}$ has been derived by assuming firstly a uniform friction shear stress acting on the crack surfaces and then secondly by assuming a more complex shear stress distribution, with the stress rising to a sharp peak at the crack tip. By applying the first case, i.e. of uniform shear stress, the friction contribution to mode II test data obtained from the end-loaded split test has been assessed for three different composite materials. The amount of friction deduced from this analysis was significant when related the values of $G_{IC}$. Indeed, when the values of $G_{IC}$ obtained from beam theory were corrected for this friction component, then values very close to $G_{IC}$ were obtained for the APC-2 composite and a glass-fibre epoxy composite. However, for one case (a carbon-fibre epoxy composite) the friction component was insufficient to correct $G_{IC}$ down to $G_{IC}$, so in this case another mechanism may also be operating in mode II to cause $G_{IC}$ to be very much greater than $G_{IC}$. The application of the second case, i.e. with a non-uniform shear stress acting on the crack surfaces may be investigated by performing a modified ELS test in which both the vertical beam displacement and the horizontal sliding beam displacement are measured. Experimental work investigating this modified procedure is at an early stage.

REFERENCES


Figure 1  End-loaded split (ELS) mode II test arrangement

Figure 2  Possible forms of the shear stress distribution

Figure 3  $G_{IC}$ vs crack length for the APC-2 composite