CRACK LENGTH DETERMINATION DIFFICULTIES IN COMPOSITES- THEIR EFFECT ON TOUGHNESS EVALUATION

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ABSTRACT

The occurrence of damage in front of delaminations in composite laminates leads to difficulty in defining crack length. This is particularly so in mode II but can be significant in mode I in some materials. The effect of these ‘errors’ is to give spurious, usually high, modulus values when corrected beam theory is used to analyse the data. In addition, it is of interest to know whether increases in toughness can be implied which are not real. A scheme is described to overcome these problems by first measuring the true modulus and hence deriving true, or effective, crack lengths. These may then be used in conjunction with the measured values to define a crack length correction which may additionally be used to define a damage factor and the real toughness. Examples of the use of this scheme in both modes I using a glass-fibre epoxy composite and II using a carbon fibre epoxy composite are given.

1 INTRODUCTION

Recent efforts [1, 2] have attempted to derive additional parameters from the mode I composite DCB test [3] to describe fibre bridging stresses at the crack tip, and the damage to the composite arm caused by microcracking. These efforts required accurate values of the beam root rotation correction, Δ, to be known . The available test data, obtained from a large number of laboratories revealed considerable scatter in this correction term and additionally, considerable scatter in the values of flexural modulus back-calculated by beam theory. Such scatter appears to originate from an uncertainty in the position of the crack tip and is most severe when fibre-bridging and microcracking are present. A new scheme was proposed [2] to obtain more reliable values of this correction. There are similar problems in mode II, when the difficulties in defining the location of the crack tip are even more severe. The analysis scheme is extended to mode II in the present work, and an attempt is made to define the true crack length, the appropriate clamp and crack tip length corrections for the end loaded split (ELS) test and the R-curve.

2 ANALYSIS

2.1 Mode I procedure

In the mode I DCB test, the load, P, the displacement, δ, and the crack length, a, are determined simultaneously during stable crack growth [3]. The compliance, C, (where $C=\delta/P$), is then determined as a function of a, and the mode I energy release rate is determined from:

$$G_{IC} = \frac{P^2}{2b} \cdot \frac{dC}{da} \tag{1}$$

where b is the width of the specimen. Beam theory can also be used to determine G_{IC} and the simple beam analysis is corrected for the effects of transverse shear and deformation beyond the crack tip via the addition of a length correction, Δ, to the measured crack length. The compliance of the beam can therefore be expressed as:

$$\frac{C}{N} = \frac{8}{E_1 b h^3} \cdot (a + \Delta)^3 \tag{2}$$

where h is the arm thickness and N is a finite displacement correction to account for the effects of the bonded-on loading block [4].

In the standard scheme [3], the analysis proceeds by plotting $(C/N)^{1/3}$ versus a to yield an average value of E_1 for the specimen from the slope and an average value of Δ from the intercept. G_{IC} is then determined via:

$$G_{IC} = \frac{3P\delta}{2b(a + \Delta)} \cdot \frac{F}{N} \tag{3}$$

where F corrects for potential large displacement effects. Confidence is given to the data analysis scheme when values of E_1 and Δ are close to the expected values i.e. when the values of E_1 are close to the known, or independently measured values of flexural modulus and the values of Δ are close to the values calculated from an elastic analysis [5]. However, for various laminates, the values of E_1 and Δ obtained by this procedure have not been as expected. Large variations in E_1 and Δ have been observed [1, 2] and these variations appeared to correlate highly with each other. Such variations have been noted when micro-cracking or fibre-bridging occurs ahead of the main crack. Under these conditions, there is an uncertainty in crack length measurement, and an associated difficulty in defining the *true* crack length.

An alternative scheme for this analysis is to use the known, true flexural modulus for the beam and the compliance measured in the DCB test to determine a true or effective crack length. From eqn (2), we can define a calculated crack length as:

$$a_c = \frac{h}{2} \left(\frac{E_1 b C}{N} \right)^{\frac{1}{3}} \tag{4}$$

and this can be used to determine G_{IC} in eqn (3) as:

$$G_{IC} = \frac{3P\delta}{2ba_c} \cdot \frac{F}{N} \tag{5}$$

Thus, the resistance curve, R-curve, is deduced using the calculated crack length. It is of interest to note that the true crack length is related to the calculated crack length via:

$$a_c = a_t + \overline{\Delta} \tag{6}$$

where a_t is the true crack length and $\overline{\Delta}$ is the true correction. The true crack length has been observed to be related to the measured crack length, a_m, via:

$$a_t = ka_m + a_o(1 - k) \tag{7}$$

where a_o is the initial crack length and k is a factor representing the proportional error in a. The factor k may be obtained from the slope of a plot of calculated versus measured crack length, and the true correction $\overline{\Delta}$ may be determined from the intercept of these data as:

$$a_c = ka_m + a_o(1-k) + \overline{\Delta} \tag{8}$$

A damage factor ϕ was defined in [1] to characterise the damage incurred at the crack tip due to microcracking, where ($0<\phi<1$) such that the shear and transverse moduli of the laminate, μ and E_2 are reduced by this factor. A ϕ of unity implies no damage and a ϕ of zero implies a total loss of shear and transverse stiffness. For most laminates the value of ϕ may be approximated by [1]:

$$\phi \approx \frac{E_1}{10\mu}\left(\frac{h}{\overline{\Delta}}\right)^2 \tag{9}$$

2.2 Mode II procedure

A similar procedure can be followed in mode II where loading is via the end-loaded split (ELS) test. The draft standard analysis [6] requires an independent value for the flexural modulus, E_1 and corrects the compliance of the beam for the effects of transverse shear and beam root rotation via the inclusion of length corrections to the measured crack length, a, and the specimen free length, L via:

$$C = \frac{3(a+\Delta_{II})^3 + (L+\Delta_{clamp})^3}{2bh^3E_1}\cdot N \tag{10}$$

The correction on L, Δ_{clamp}, should be determined from an inverse ELS test in which the cracked portion of the specimen is held fully in the clamp (such that a=0) and the compliance is measured for a number of different free lengths. Then a plot of $C^{1/3}$ versus L yields the value of Δ_{clamp} from the intercept. The flexural modulus E_1 may be deduced from the slope of these data if the load-block correction, N is determined or E_1 may be deduced from a three-point bend flexural test prior to mode II testing.

The correction to crack length, Δ_{II}, is required for the standard analysis and has previously been determined from an FEA calibration procedure, yielding a value based upon the mode I correction, Δ_{I} [7]. Such a procedure usually yields small values of Δ_{II}, as $\Delta_{\text{II}}=0.42\Delta_{\text{I}}$ was suggested, which is approximately equal to 1.9mm in the tests reported here. In the modified analysis scheme proposed here, Δ_{II} is not required, but can be deduced as described previously for mode I. If the calculated crack length is plotted against the measured crack length, the data will again have a slope of k and an intercept equal to $a_o.(1-k)+\overline{\Delta}$. Thus the true correction can be found by setting $\Delta_{\text{II}}=\overline{\Delta}$.

The standard analysis scheme proceeds by determining G_{IIC} via:

$$G_{IIC} = \frac{9P^2(a+\Delta_{II})^2}{4b^2h^3E_1}\cdot F \tag{11}$$

and in the modified scheme, we replace (a+Δ_{II}) by a_c:

$$G_{IIC} = \frac{9P^2 a_c^2}{4b^2 h^3 E_1} \cdot F \tag{12}$$

In addition, eqn (10) may be re-arranged to determine the back-calculated flexural modulus and this may be compared to the true value from independent flexural modulus tests.

Eqn (12) may be used to determine the true R-curve, being independent of measured crack length. The magnitude of the measured crack length errors can be estimated from the value of a_c-Δ_{II} during crack propagation.

3 RESULTS AND DISCUSSION

3.1 Mode I Results

The results are presented here for a glass-fibre reinforced epoxy laminate. Five repeat DCB tests were performed. These laminates exhibited quite extensive fibre-bridging during crack propagation. Using the standard analysis, values of back-calculated modulus varied from 44 to 55 GPa and the average values of Δ via eqn (3) varied from 5.1 to 9.9 mm. The independent value of E_1 for this laminate was measured via three point bending and was found to be 39 GPa and the elastic value of Δ [5] was approximately 1.7 mm, so the measured values of E_1 and Δ from the DCB tests were all high. Determining values of G_{IC} via eqn (3) indicated strong rising R-curve behaviour with G_{IC} rising from an initiation value of about 350 J/m^2 to about 1,200 J/m^2 over 55mm of crack growth. This data set is a typical example, but more extreme variations in the average values of E_1 and Δ have been reported for other materials [1].

Table 1. Mode I results for a glass-fibre epoxy composite

Test	E_1 (GPa) Eqn (3)	Δ (mm) Eqn (3)	G_{IC} (J/m^2)	k	Δ (mm)	$\bar{\Delta}$ (mm)	ϕ
1	43.8	5.7	285	0.97	4.7	3.1	0.29
2	45.6	5.1	383	0.94	5.5	1.8	0.97
3	53.6	5.9	368	0.93	5.6	2.1	0.65
4	47.3	5.5	380	0.95	5.5	2.8	0.40
5	55.0	9.9	351	0.90	9.0	4.4	0.15

{Notes: a_o=55mm, h≈1.8mm}

The calculated crack lengths were plotted versus the measured crack lengths for these tests, and these data are shown in Figure 1. The slope to these data yielded k, and the intercept Δ. The true correction, $\bar{\Delta}$ was then determined via eqn (8) and the damage factor ϕ via eqn (9). These values are all shown in Table 1 for the five repeat tests. The values of G_{IC} deduced via the standard analysis scheme, i.e. eqn (3) are shown in Figure 2 for a typical test (test 4). Strong rising R-curve behaviour is observed. Also shown in Figure 4 are the values of G_{IC} deduced via the modified scheme, i.e. eqn (5). Although somewhat different values are deduced via the two schemes, the trend of the strongly rising R-curve is common to both.

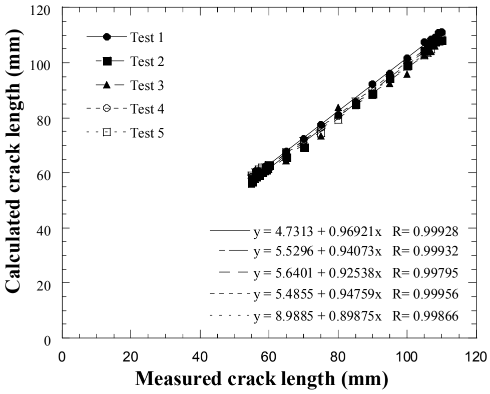

Figure 1. Graph of a_c versus a_m for the glass-epoxy composite.

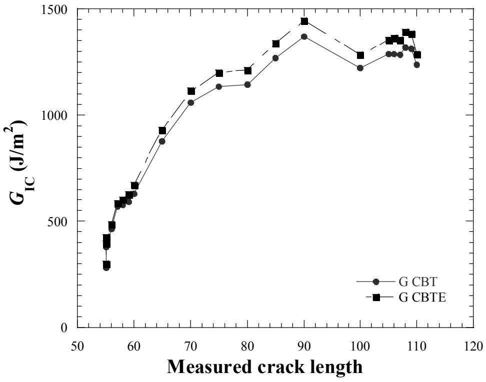

Figure 2. Typical R-curve for the glass-epoxy composite.

3.2 Mode II Results

Four mode II ELS tests were performed on a UD carbon-fibre epoxy composite (HTA-12000 carbon fibre in 113 epoxy resin). The flexural modulus, E_1, of each sample was obtained via three-point bending. This was in the range 120-130 GPa. The clamp correction was determined via the IELS procedure to be 8.25mm. The values of effective crack length were then calculated and these values were plotted against measured crack lengths, as shown for tests 1-2 in Figure 3. The slope to these data yielded the factor k and the intercept yielded Δ. The true correction on crack length, $\overline{\Delta}$, was then deduced as $\overline{\Delta} = \Delta - a_o(1-k)$.

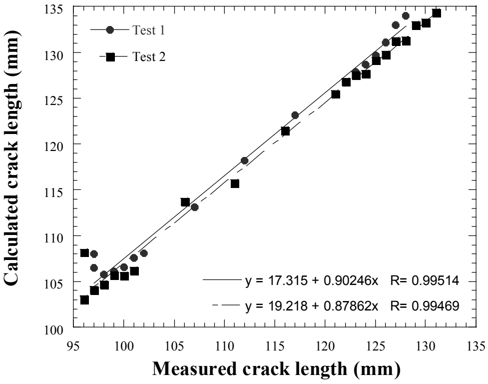

Figure 3. Graph of a_c versus a_m for the carbon-epoxy composite in mode II.

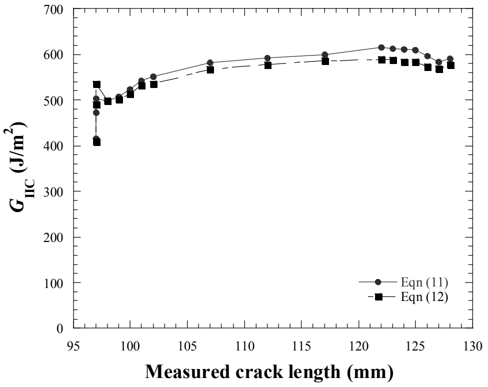

Figure 4. Typical R-curve for the carbon-epoxy composite in mode II.

The values of k, Δ and $\overline{\Delta}$ are shown in Table 2 for the four tests. It is noteworthy that the values of $\overline{\Delta}$ obtained greatly exceeded the value of $0.42\Delta_I \approx 1.9$mm in these tests. The values of flexural modulus were back-calculated using corrected beam theory with the measured values of $\overline{\Delta}$, and these values agree with the independent value of E_1 at initiation as would be expected, but rise during propagation to give an approximately constant error. This is consistent with a measurement error in crack length. The results indicate that this error rises to a maximum of about 5mm at the longer crack lengths in these tests. The values of G_{IIC} were deduced via eqn (11) with $\Delta_{II}=\bar{\Delta}$ and via eqn (12) with the calculated crack length. The two schemes return similar values of G_{IIC} as shown in Figure 4 for the first test, resulting in a very modestly rising R-curve.

Table 2. Mode II ELS Results

Test	E_1 true (GPa)	E_f(GPa)	k	Δ (mm)	a_o (mm)	$\bar{\Delta}$ (mm)
1	128.6	136.2	0.90	17.3	97	7.6
2	122.5	126.9	0.88	19.2	96	8.6
3	130.7	133.2	0.98	10.7	97	8.8
4	121.5	130.5	0.87	20.0	96	7.5

{Notes: Δ_{clamp} (mm)=8.25 mm}

4 CONCLUSIONS

The additional procedure of determining E_1 separately and then calculating the crack length gives considerable insight into the accuracy, and difficulty, in the measurements. The scheme extends well to mode II and permits the calculation of the crack length correction Δ_{II} for each test specimen. It is hoped that this will reduce scatter in measured values of G_{IIC}. The origins of the k factor are not completely clear, but appear in these materials to reflect random errors of about 5% in crack length measurement. The effect on measured values of G_C (both mode I and mode II) of these crack length errors is modest and imply that the standard schemes for determining G_{IC} and G_{IIC} are quite robust.

5 REFERENCES

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