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Measurement of the in situ ply fracture toughness associated with mode I fibre tensile failure in FRP. Part I: Data reduction

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ABSTRACT

The fracture toughness associated with fibre tensile failure was measured for a T300/920 laminated carbon/epoxy material system using the compact tension specimen configuration. Six methods of data reduction were investigated for calculation of the toughness with the aim of finding the best technique, in terms of reproducibility of results and simplicity. The calculated fracture toughnesses were found to correlate well, though varying amounts of scatter were produced by each method. An optimum method was proposed that does not rely on the use of an optically measured crack length.

1. Introduction

The fracture toughnesses of a fibre reinforced polymer (FRP) play a key role in determining the damage tolerance of a composite structure and response during damage propagation. To characterise damage tolerance in composites, there is a need for reliable experimental procedures to obtain these properties; results need to be reproducible and the test method itself should not introduce scatter.

Numerous studies have measured the translaminar fracture toughness of composite laminates [1–5]. A range of approaches in terms of both specimen configuration and data reduction schemes have been used. Perhaps the most commonly used specimen is the compact tension (CT) configuration, which also exists as a recommended configuration for fracture toughness characterisation of metallics [6]. The use of the CT specimen for toughness measurement in composites has previously been disregarded, as longitudinal splitting perpendicular to the notch tip was observed in highly orthotropic laminates [4]. The results of this study favoured an extended compact tension (ECT) specimen configuration, and subsequently led to the creation of the ASTM E1944 "Standard test method for translaminar fracture toughness of laminated and pultruded polymer matrix composite materials" [7]. The standard recommends the use of the ECT and calculation of the laminate critical stress intensity factor using a finite width correction factor developed for isotropic materials. For the measurement of toughness at fracture initiation, the finite width correction factor has been deemed valid for a wide range of composite laminates. However, the standard only covers measurement of toughness for fracture initiation and so the full *R*-curve behaviour cannot be determined.

There have been few studies that have specifically attempted to measure the fracture toughness associated with fibre tensile failure. In 1997, Vaidya and Sun [8] developed a fracture criterion based on the 0° plies in a laminate; the authors stated that the critical stress intensity factor for fibre failure, K^0_{Ic}, is a material constant and should be independent of laminate configuration. The initiation values of K^0_{Ic} measured using the centre-cracked tension specimen geometry, calculated using a finite width correction factor developed for isotropic materials, were found to be approximately equal for the range of laminates tested.

The CT specimen is the another configuration that has been used to measure fracture toughness associated with mode I fibre tensile failure [9]. The critical energy release rate of the fibre tensile failure mode, G^0_{Ic}, at both fracture initiation and propagation were calculated using a finite element (FE) based method of data reduction; fractographic analysis of the test specimens indicated that the measured values may be lay-up dependent.

The work presented in this study aims to take a step towards defining accurate methods for measurement of the toughness of mode I fibre tensile failure. Part I investigates six methods of data reduction that have been used throughout the literature to calculate toughness. Part II investigates the effect of specimen geometry and laminate stacking sequence on the measured initiation and propagation values of fracture toughness associated with mode I fibre tensile failure.

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2. Materials and manufacture

The material system used in this study was a T300/920 unidirectional carbon/epoxy prepreg. The material properties used for the data reduction were obtained using standard tests and are presented in Table 1 in the principal material axes.

Composite panels with a lay-up of $[(90/0)_8/90]_s$ were manufactured using the hand lay-up method and cured to the prepreg manufacturer's instructions. A wet saw was used to cut the rectangular plates to the geometry shown in Fig. 1; the 8 mm holes were made using a carbide tipped drill.

A three-step procedure was followed to obtain a sharp crack tip in the CT specimens: (i) a ~4 mm notch of approximately 30 mm length was machined using a diamond coated disk-saw, (ii) the notch was then extended to 40 mm using a 0.2 mm thick razor saw, and (iii) finally, a 0.1 mm thick razor blade was used to further sharpen the notch-tip in a sawing motion.

Prior to testing, a scale with a 1 mm increment was drawn on the CT specimens in order to optically measure crack growth and the individual specimen dimensions were measured and recorded.

3. Test method and experimental setup

Six CT specimens were tested using an Instron machine with a 10 kN load cell; each specimen was loaded under displacement control at a rate of 0.5 mm/min. Measurements of load and crosshead displacement were recorded using a data logger. After the test, the values of crosshead displacement were corrected to account for the test machine compliance.

A CCD camera and monitor was used to view a magnified image of approximately 12 mm of the area of the specimen containing the crack-growth scale. This magnified image was used together with an event marker connected to the data logger to monitor crack growth.

4. Data reduction

4.1. ASTM E399

The ASTM E399 testing standard [6], valid for isotropic metals, gives the critical stress intensity factor as

$$K_{Ic} = \frac{P_c}{t\sqrt{w}} f(a/w) \tag{1}$$

with

$$f(a/w) = \frac{2 + a/w}{(1 - a/w)^{1.5}}[0.886 + 4.64(a/w) - 13.32(a/w)^2 + 14.72(a/w)^3 - 5.6(a/w)^4] \tag{2}$$

where P_c is the measured critical load that causes fracture, t is the thickness of the specimen, w is the dimension from the load line to the right hand edge of the specimen, as indicated in Fig. 1, and a is the crack length, whose initial value a_0 is also indicated in Fig. 1. The critical strain energy release rate of the laminate can then be calculated from the laminate critical stress intensity factor as [10]

Table 1
Mechanical properties of T300/920 unidirectional lamina.

Modulus (GPa)			Major Poisson's ratio	G_{Ic}^{delam} (kJ/m^2)
Longitudinal	Transverse	Shear		
135.10	8.88	4.54	0.32	0.456

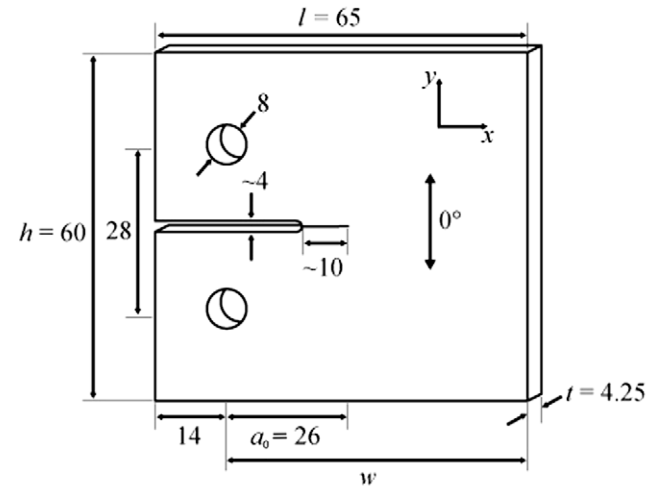

Fig. 1. CT test specimen nominal dimensions (in mm).

$$G_{Ic}^{lam} = \frac{K_{Ic}^2}{\sqrt{2E_xE_y}}\sqrt{\sqrt{\frac{E_x}{E_y}} + \frac{E_x}{2G_{xy}} - \nu_{xy}} \tag{3}$$

where E_x and E_y are the Young's moduli in the x and y directions respectively (see Fig. 1), G_{xy} the shear modulus, and ν_{xy} the Poisson's ratio.

A FE analysis was carried out using the commercial package Abaqus to investigate the accuracy of Eqs. (1)–(3) when applied to orthotropic laminates. A half CT specimen was modelled using uniform square 8-noded elements (S8R5), with side l = 0.5 mm as shown in Fig. 2. Models were 1 mm thick and a 1 N load was applied at the position of the loading pin. Several models with elastic properties equivalent to lay-ups with varying proportions of 0° and 90° plies were run to obtain the J-integral (J) around the crack tip. The obtained J values were then compared with the strain energy release rates obtained from Eqs. (1)–(3) for the same geometry and loading. The results, for ranges of a/w used in this study, are shown in Fig. 3.

It can be inferred that Eqs. (1)–(3) cannot be readily applied to highly orthotropic laminates. For the $[(90/0)_8/90]_s$ lay-up used in this study, the maximum error is 13.2%; this maximum error increases as the proportion of 0° plies increases.

4.2. Area method

The area method is among the simplest methods of data reduction. The critical strain energy release rate can be calculated as

$$G_{Ic} = \frac{1}{2t\Delta a}(P_1 d_2 - P_2 d_1) \tag{4}$$

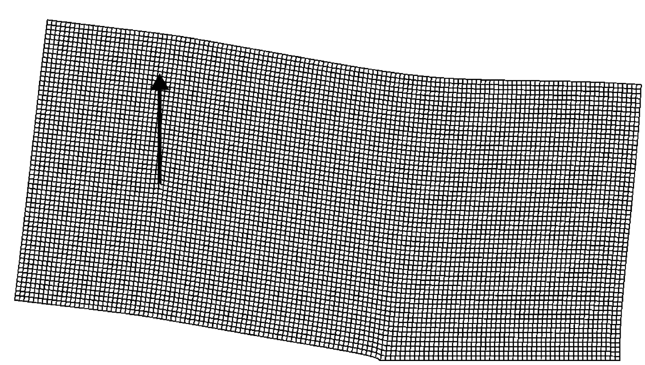
Fig. 2. FE mesh of a half CT specimen.