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Fracture toughness of the tensile and compressive fibre failure modes in laminated composites

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Abstract

The fracture toughnesses associated with fibre tensile failure and compressive fibre kinking in a T300/913 carbon-epoxy laminated composite are measured using compact tension and 'compact compression' tests respectively. The specimen strain fields were monitored using a digital speckle photogrammetry system during the tests. The damage present in the specimens after the tests was investigated using C-scan and optical and scanning electron microscopy. The initiation and propagation values of the tensile fibre failure critical energy release rate were determined as 91.6 kJ/m^2 and 133 kJ/m^2 respectively. For fibre compressive kinking, an initiation value of 79.9 kJ/m^2 was obtained, but no meaningful propagation values could be determined. In both cases, the test results showed low scatter.

Keywords: B. Fracture toughness; Fibre failure; Kinking; Damage

1. Introduction

Fibre breaking can take place during longitudinal tension or compression and, for carbon/epoxy systems, the energy consumed by these failure processes is much larger than for failures involving any matrix or matrix–fibre bond failure. In compression, fibre breaking usually occurs as a result of the kinking process. Experimental determination of the fracture toughness associated with both these fibre failure modes (tensile failure and compressive kinking) is important for material characterization and for numerical modelling. Currently, there are no standards to determine these properties.

Leach and Seferis [1] used three-point bend specimens with a $(0)_{40}$ layup to measure the fracture toughness of the tensile fibre failure mode of a carbon/PEEK composite, and reported a mode I critical energy release rate of 26 kJ/m^2. The technique used to introduce a pre-crack in the specimen was not discussed by the authors. Jose et al. [2] used Compact Tension (CT) specimens (see Fig. 1(a)) made of M55J/M18 carbon/epoxy with layup $(0,90)_{15}$, to determine the fracture toughness associated with tensile failure of the $(0,90)_{15}$ laminate. They created the pre-crack in two steps: a notch was cut with a disc cutter and a razor blade was then used to give a sharp starter, but the authors did not specify whether the blade was tapped or used in a sawing motion. The mode I critical energy release rate reported by Jose et al. for the laminate is 15.94 kJ/m^2. This value corresponds to the mode I critical energy release rate for fibre fracture in the 0° layers combined with matrix crack propagation in the 90° layers. Assuming that those energies are additive (which is to say, neglecting the interactions between the different layers that are failing in different failure modes), and that the matrix tensile toughness is similar in magnitude to the (interlaminar) mode I critical energy release rate (≈0.2 kJ/m^2), the critical energy release rate for the fibre tensile failure mode of M55J/M18 carbon/epoxy is about 31.7 kJ/m^2.

Soutis et al. [3,4] carried out a kink-band propagation test using a centre-notched compression specimen. Different lengths for the notch were used but similar values of

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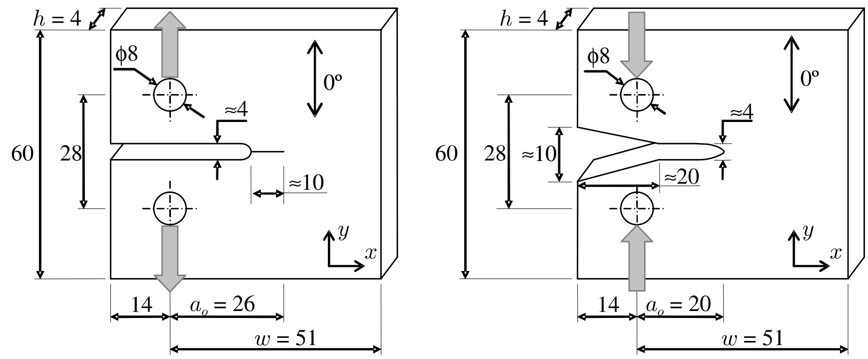

(a) Compact Tension **(b)** Compact Compression

Fig. 1. Test specimen nominal dimensions (in mm) for: (a) tensile and (b) compression fibre-breaking fracture toughness tests.

fracture toughness were observed, which was interpreted as supporting the concept of compressive fracture toughness. For a T800/924C laminate with $(0, 90_2, 0)_{3S}$ layup, the critical energy release rate for the laminate was reported [5] as 38.8 kJ/m^2. Proceeding as before, the value measured corresponds to the mode I critical energy release rate for kink-band propagation in the 0° layers, plus the critical energy release rate for matrix cracking in the 90° layers. Assuming that those energies are additive, and making the simplification that the matrix failure in the 90° layers can be represented by a single mode II matrix crack (with critical energy release rate $\approx$1 kJ/m^2), the critical energy release rate for kink-band formation and for T800/924C is derived from [5] as about 76 kJ/m^2.

Ratcliffe et al. [6] and Jackson and Ratcliffe [7] described the use of Compact Compression (CC) specimens (CC specimens are similar to CT specimens, but used in compression) to measure the compressive toughness of sandwich panels with unidirectional carbon–epoxy facings and honeycomb nomex core. The kink-band length was measured using Shadow Moiré Interferometry. The critical energy release rate for kinking, derived from the tests using the area method, was reported as 36.1 kJ/m^2 [6].

In the work presented in this paper, CT and CC tests were performed with the aim of determining (i) the fracture toughness associated with tensile fibre failure and (ii) the fracture toughness associated with kink-band failure for a carbon–epoxy system.

2. Material system used

Carbon epoxy T300/913 unidirectional prepreg was used for the tests. The material properties needed for the data reduction were obtained using standard tests and are presented in Table 1 in the principal material axes.

Table 1
Mechanical properties of T300/913 unidirectional laminae

Modulus (GPa)			Major Poisson's ratio
Longitudinal	Transverse	Shear	
131.7	8.8	4.6	0.32

3. Test method and data reduction

The geometry of the compact specimens used for the tension and compression toughness tests are shown in Fig. 1(a) and (b) respectively. The notch of the CC specimen, Fig. 1(b), has been widened at the left edge to avoid contact of the notch faces during compression. (Jackson and Ratcliffe [7] found that the stress intensity factor is not affected significantly by the morphology of the opening.) The layup used is $(90, 0)_{8S}$ with the 0°-direction the direction parallel to the loading, as shown in Fig. 1.

The data reduction for CT or CC specimens made of an orthotropic material requires particular attention. Other researchers have used the stress intensity factor approach [2,8,9], often citing the ASTM standard E399 [10] for the determination of the fracture toughness in metals using CT tests [2,8].

According to ASTM standard E399 [10], valid for an isotropic material, the critical stress intensity factor for a fracture load P, is given by

$$K_{\mathrm{Ic}} = \frac{P}{h\sqrt{w}} f(a/w) \tag{1}$$

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 h 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 energy release rate of the laminate can be calculated from K_{Ic} as [11]

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