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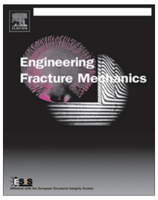

Intralaminar fracture toughness characterisation of woven composite laminates. Part II: Experimental characterisation

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ABSTRACT

The tensile intralaminar fracture toughness of the carbon/epoxy 5HS-RTM6 woven composite material has been experimentally characterised, using the doubly-tapered compact tension (2TCT) specimen. This specimen geometry was found to achieve lower values for the failure indices described in the first part of the article. Two different configurations of the material were considered: one with the warp direction of the material parallel to the direction of the applied load and the other with the warp direction of the material perpendicular to the direction of the applied load. The obtained values for the mode I intralaminar fracture toughness were similar for both configurations. Although some tow splitting took place in the second configuration, from the analysis of the images obtained by DIC, X-ray and C-scan it was concluded that the effect and presence of other damage mechanisms different to mode I intralaminar crack opening was negligible. Consequently, the experimental values obtained were reliable and the 2TCT specimen was useful for its purpose.

1. Introduction

Final failure of laminated composite structures is preceded by different damage mechanisms involving fracture initiation and propagation. The evaluation of damage onset, fracture propagation mechanisms and associated fracture toughness are important parameters in the design of efficient and durable fibre reinforced composite structures. In a composite laminate, fracture can appear either between two plies or within a lamina. In the first case, interlaminar fracture or delamination, the crack causes the separation of two adjacent plies of the laminate. The propagation of the crack mainly involves matrix failure or matrix-to-fibre debonding, although some failure of fibres bridging the delamination may also occur. There are numerous studies addressing this subject in the scientific literature (see [1] for a reference). In the second case, intralaminar or translaminar fracture, the crack is located within the lamina, either parallel to the fibres (matrix crack) or at an angle (with fibre failure). When an intralaminar crack propagates at a certain angle to the reinforcing fibres, the fibres bridge both surfaces of the crack, arresting or reducing further crack opening until the bridging fibres are broken. Even if the energy consumed in fibre fracture is usually much larger than in matrix cracking or fibre–matrix debonding [2], experimental determination of the fibre fracture toughness is important for accurate numerical modelling of composite failures.

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Nomenclature

a	crack length
c_i	fitting coefficients for $G_{\text{Ic-lam}}$ versus a
G_{Ic}	mode I critical energy release rate
$G_{\text{Ic-lam}}$	mode I critical energy release rate of the laminate
K_{Ic}	mode I stress intensity factor
P_{c}	load for critical energy release rate
t	specimen thickness
σ	stress or standard deviation
σ_{xx}	longitudinal stress at the upper and lower edges
σ_{yy}	longitudinal stress at the right edge
σ_{xy}	in-plane shear stress

The intralaminar fracture toughness of carbon fibre laminates has been generally obtained with the CT specimen [2–5]. However, despite the growing industrial interest in the use of woven composite materials, there are still few studies dealing with the experimental determination of their intralaminar fracture toughness. Masters [6] evaluated the translaminar fracture toughness of a warp-knit carbon fabric, with fibres in the 0°, 45°, −45° and 90° directions, infiltrated with epoxy resin. Rokbi and co-workers analysed failure mechanisms in epoxy/woven fabric E-glass composites using CT specimen and Digital Image Correlation techniques [7]. However, the use of the CT specimen was found to be inadequate for woven composites because some other damage mechanisms which dissipate energy and so interfere with the determination of the intralaminar fracture toughness appear [8,9].

In the first part of this two-part article [10], a parametric analysis of different specimens was performed. The considered specimens were the compact tension specimen (CT) and different versions of it.

The study was based on the finite element method (FEM) in combination with the virtual crack closure technique (VCCT). Different failure mechanisms were considered in order to ensure crack propagation prior to any other damage in the specimen: fibre fracture due to longitudinal compressive stress (σ_{yy}) at the right edge of the specimen, fibre fracture due to longitudinal compressive stress (σ_{xx}) at the upper and lower edges of the specimen, matrix cracking due in-plane shear stress (σ_{xy}), bearing in the holes of the specimen due to compressive stress, shear-out in the holes of the specimen due to shear stress and buckling due to the high compressive stresses at the right edge. After comparing the results for all the specimens, it was concluded that the specimen geometry that best ensures crack progression for intralaminar fracture toughness characterisation of woven laminated composite materials is the doubly-tapered compact tension, 2TCT.

This work aims to obtain the intralaminar fracture toughness of a five-harness satin carbon fibre fabric by using a 2TCT specimen, proposed by the authors in the first part of this article [10]. During and after the test, the specimens are inspected with a Digital Image Correlation system, X-ray and ultrasounds (C-scan) to assess for the presence of other damage mechanisms which dissipate energy and so might interfere in the experimental procedure.

2. Material and methods

2.1. Specimen and material

The geometry for the 2TCT specimen proposed in the first part of this article [10] has been used (Fig. 1). A 600 mm × 600 mm panel was manufactured from Class 3, Type 1, Style 6K-150-5HS, five-harness satin carbon fibre fabric, and Hexcel RTM 6 resin using resin transfer moulding (RTM) techniques and cured according to the manufacturer's instructions. The panel was produced using 16 layers of material according to a lay-up $[0–90]_{8s}$, where 0–90 indicates the warp and fill directions of the material, with a nominal thickness of 0.35 mm. A wet diamond saw was used to cut eight specimens from the panel with the geometry defined in Fig. 1 and the dimensions of each specimen were measured. Six of them were cut to be tested with the warp direction of the material parallel to the direction of the applied load. The other two were cut to be tested with the warp direction of the material perpendicular to the direction of the applied load. To ensure a sharp crack tip for the pre-crack, first an approximate 29 mm long notch was cut with a 4 mm wide dry diamond saw. Then, three 0.2 mm thick razor saws with 32, 42 and 52 razor teeth per inch were used one after another to obtain a thin and sharp 5 mm extension of the pre-crack. Finally, a 0.1 mm thick razor blade was used to further sharpen the crack tip using a sawing action.

2.2. Experimental procedure

In order to monitor the specimen displacements and strains during the test with the Digital Image Correlation system (DIC) GOM-Aramis, a speckle pattern was created on one face of each specimen using white ink spray. A 1 mm increment scale was also drawn onto each specimen to monitor the crack length propagation during the test.