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High resolution tomographic imaging and modelling of notch tip damage in a laminated composite

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ABSTRACT

Synchrotron radiation computed tomography (SRCT) has been used to observe *in situ* damage growth and enable micromechanical damage characterization in $[90/0]_S$ carbon fibre–epoxy composite samples loaded in uniaxial tension to stresses ranging from 30% to 90% of the nominal failure stress. A 3-D finite element model has been constructed to predict crack opening displacements and shear displacements in the 0° plies resulting from thermal residual stress imposed during autoclave cure and from the application of mechanical load. Of particular interest is the demonstration of SRCT as a technique to enable direct, *in situ*, 3-D, non-destructive damage quantification to assist model development and provide model validation. In addition it has been identified that SRCT has the potential for full field analysis of strain re-distributions during damage growth.

1. Introduction

Modelling the behaviour of composite materials is far from trivial due to the complex interactions of multiple damage mechanisms, including fibre–matrix de-bonding, inclusion-matrix decohesion, inter-laminar delamination, intra-laminar cracking and fibre rupture [1,2]. A large number of models have been able to predict successfully the strength of laminated structures for a particular lay-up configuration or loading regime [3–6], however the inherent assumptions and simplifications within these models usually result in a lack of predictive capability when the material system, lay-up or type of loading is modified [7]. Many current models are only successful in their predictions due to empirical fitting to a particular data set. With its limited physical basis, the fitted model will not predict changes in failure processes (lay-up, load case). A homogenised damage mechanics approach to modelling requires an understanding of the interacting mechanisms leading to damage initiation and propagation while a micromechanics approach that captures the physics of fracture mechanics is computationally expensive.

This paper has two principal objectives. The primary aim is to demonstrate the potential of synchrotron radiation computed tomography (SRCT) [8] as a technique to observe the *in situ* initiation and propagation of damage in a $[90/0]_S$ carbon fibre–epoxy composite and to identify the critical damage interactions that lead to laminate failure to assist model development, calibration and validation. Particular damage parameters such as crack opening displacement (COD) and shear displacement have been quantified and used in conjunction with high resolution images of damage evolution to inform the development of a finite element (FE) model of intra-laminar matrix splitting in the 0° plies. The secondary aim is to compare a 3-D FE model with the SRCT results and to determine the extent to which the model of a single observed damage mechanism of a split in a 0° ply has useful predictive capability. In addition, the data acquired from SRCT can be compiled as a library of experimental results that can be accessed for comparison with existing and future model predictions.

2. Materials and methods

Laminated plates of Hexcel HexPly® M21 carbon fibre pre-preg were laid up in a $[90/0]_S$ configuration with dimensions $300 \times 300 \times 1$ mm and cured in an autoclave to the manufacturer's specifications at a single dwell temperature of 180 °C [9]. While the cure process will initiate before this temperature with the accompanying onset of residual thermal stress, this value is considered to represent an upper bound estimate of temperature for the stress free reference state. Double edge notched specimens with the geometry shown in Fig. 1 were machined from the plates using an abrasive waterjet. A comprehensive analysis of tomographic images of the samples prior to loading showed that negligible damage occurred as a result of the waterjet machining process and that all of the damage reported in this paper was a direct result of the applied loading. Aluminium tabs were bonded to the

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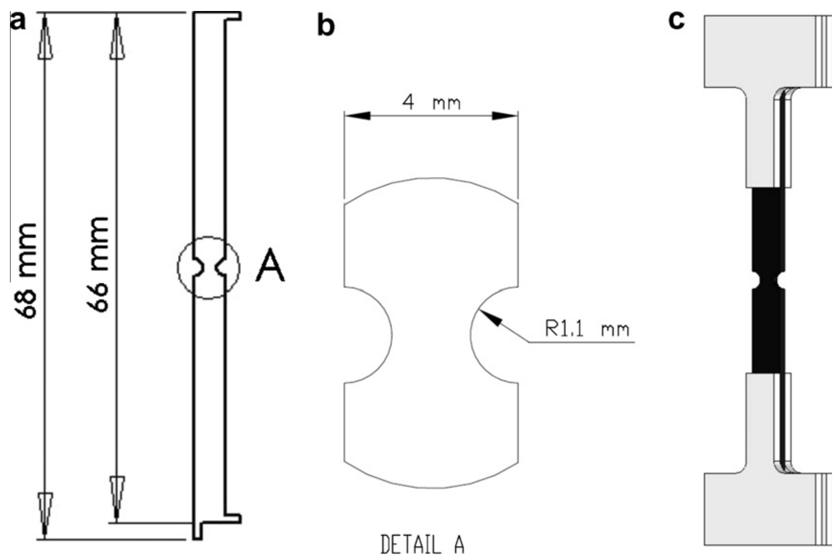

Fig. 1. (a) Geometry of composite samples, (b) detail of notch section of samples, and (c) illustration of sample with bonded aluminium tabs.

samples to allow load transfer in the screw driven load frame shown in Fig. 2. The load frame was used with a calibrated load cell to determine the ultimate failure stress of the samples to be 960 MPa across the notch section.

The samples were tested at the ID19 beamline at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. The experiments consisted of *in situ* SRCT scans under two loading sequences. For the first sequence the specimens were scanned in the pre-loaded state, loaded to a particular stress and re-scanned, and finally scanned in the unloaded state. A comparison of the loaded state (combining mechanical load and residual thermal load) and the unloaded state (purely residual load) allows the separation of mechanical and thermal loads. For the second configuration the samples were scanned in the pre-loaded state then re-scanned at incrementally increasing stresses that ranged from 30% σ_f to 90% σ_f.

To obtain SRCT data each specimen is rotated through 180° in equal angle increments while a 2-D radiographic projection is captured at each position through the rotation. A suitable reconstruction algorithm, in this case filtered back-projection, may then be used to create a representative tomographic volume of the sample from the sequential projections [10]. This technique is similar to conventional micro-focus X-ray computed tomography, however important differences arise in the source of the X-rays and the scale of operation. In contrast to the divergent beam emitted from a micro-focus X-ray source by electron deceleration into a metal target, synchrotron X-rays are the result of electron deflection within a high energy storage ring [11]. In this context, synchrotron

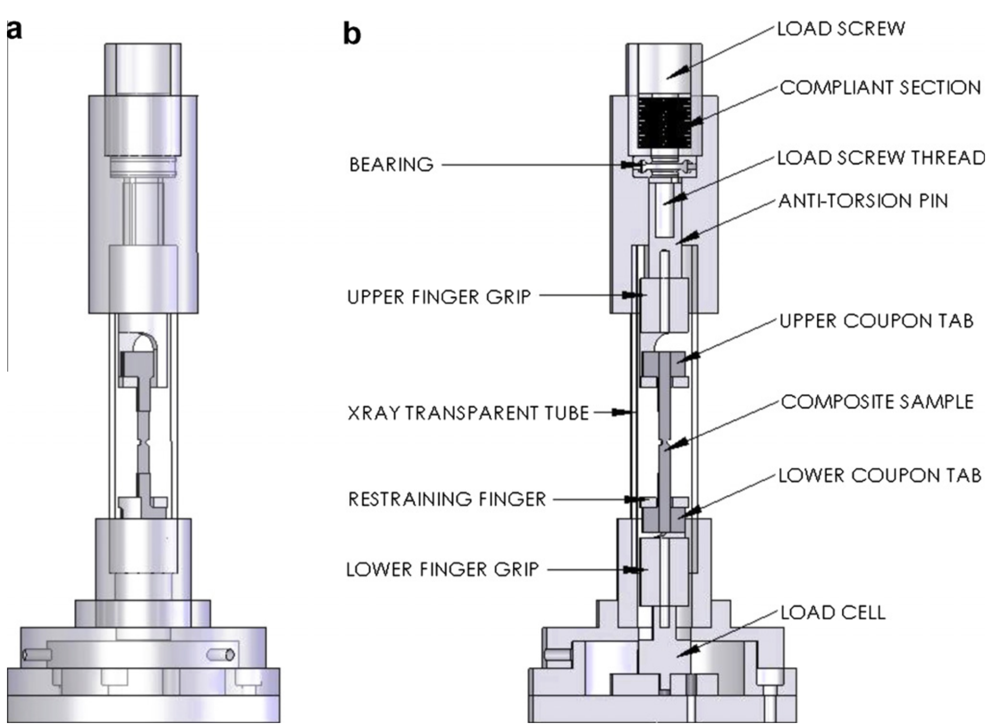

Fig. 2. (a) Semi-transparent schematic of *in situ* load frame, and (b) annotated cross-section of schematic.