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Influence of voids on damage mechanisms in carbon/epoxy composites determined via high resolution computed tomography

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ABSTRACT

A multi-scale computed tomography (CT) technique has been used to determine the material structure and damage mechanisms in hydrostatically loaded composite circumferential structures. Acoustic emission sensing was used to locate macroscopically regions of high damage under load to inform the computed tomography. The resultant images allow direct three-dimensional analysis of voids, fibre breaks and cracking, for which a high level of confidence can be placed in the results when compared to other indirect and/or surface-based methods.

Ex situ analysis of loaded samples revealed matrix cracking in the longitudinally wound plies, whilst fibre breaks were observed in the circumferentially wound plies. The matrix cracking within the longitudinally wound plies is shown to interact directly with intralaminar voids. The correlation of voids with fibre breaks in the circumferentially wound plies is less distinct. A three-dimensional tessellation technique was used to analyse the spatial distribution of the voids and to compare with single fibre break locations. Whilst there was no first order correlation between fibre break densities and void volume fractions or void dimensions, a distinct correlation was found between voids and nearest neighbouring fibre breaks, where 2.6–5 times more fibre breaks occurred immediately adjacent to a void than would be expected for randomly distributed breaks.

1. Introduction

Voids are a common microstructural feature in composite materials, particularly when non-autoclave manufacturing processes are used, resulting either from entrapped air during the manufacturing process or from volatiles arising from the resin during the cure stage [1]. Studies have attempted to determine the effect of these voids on composite mechanical properties, for example [1–6]. Such studies show that void content is detrimental to a variety of material properties including: interlaminar shear strength, longitudinal and transverse modulus and flexural strength, longitudinal and transverse tensile strength and modulus, compressive strength and modulus, and fatigue resistance. Analysis methods have been predominantly limited to two dimensions, however in more recent years CT has been used to characterise the meso-structure of composites including void segmentation in 3D [7–9]. Quantitative micromechanical analysis are largely lacking however, particularly in terms of failure initiation processes, where experimental tools to capture failure within bulk material at high resolutions have been largely absent to date.

In the current study multi-scale computed tomography has been used to provide a direct three-dimensional analysis of the material micro-structure and damage mechanisms of a composite hoop structure when loaded to failure. This provides information of the whole structure geometry and large scale features down to the micro-structure at the individual fibre level. Relationships between the void micro-structure and damage mechanisms have been determined in an essentially novel manner, including a modified tessellation approach to void–fibre break correlation mapping.

2. Experimental methods

Hybrid composite hoop structures were manufactured via filament winding including voids within the composite layers. The experimental structures consisted of an internal aluminium liner, filament wound with carbon/epoxy (CFRP) and glass/epoxy (GFRP). The outer diameter of the structures were approximately 90 mm, with a total wall thickness of ~4.15 mm. The approximate thickness of each material layer is shown in Fig. 1. The circumferential layers were wound at ~90° to the axis of the structure and the longitudinal layers at ~20°. After a three stage cure the samples were autofrettaged to deform the liner plastically.

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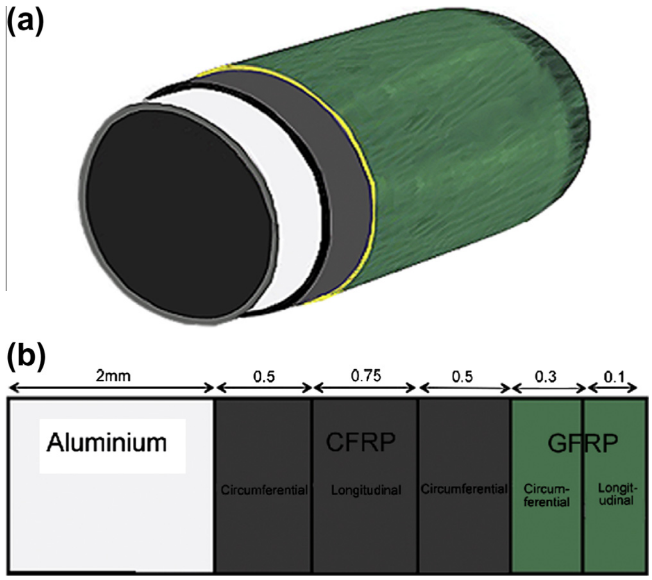

Fig. 1. (a) Cutout image of the experimental structure and (b) schematic cutout section illustrating the material layup (all dimensions are in mm).

The samples were pressurised to near failure. Acoustic emission (AE) sensors were used as an aid to locate damage spatially and temporally without seeking to distinguish the damage mechanisms from the AE data itself. This work was carried out in continuation of a study by Kalantzis [10], involving multiple hoop structures taken to failure whilst acoustic emissions were recorded. The previous work Kalantzis [10] has shown that the final failure sites can be located by peaks in the AE signal amplitude and energy.

The analysis has been carried out for the CFRP component of the samples only. The CFRP provides the majority of the strength and stiffness of the structure.

2.1. Acoustic emission

Six AE sensors were applied to each test structure, the structures were then internally pressurised at a rate of 0.5 MPa per second, using a Top Industrie S.A. Banc Hydraulique 2000 bar testing press. The acoustic emission signal amplitude, energy and counts were recorded for each sensor. An event was located when at least four sensors detected an emission, on the basis of the time of arrival at each sensor and the speed of sound in the composite walls. The signals were pre-amplified by 40 dB and band-pass filtered outside the range of 100 kHz–1 MHz to remove the background noise. The AE signals were recorded and analysed with a Vallen AMSY 4 data acquisition system.

Two samples were kept in the post-manufactured state, *i.e.* only the autofrettage pressure had been applied, to provide details of as manufactured micro-structure with little or no damage. Samples were then taken to near final failure (100% of the nominal ultimate failure). The AE signals where used to determine the regions of highest damage for further analysis via high resolution CT imaging. The next section explains the cutting techniques and subsequent imaging of these high damage regions located by the AE signals.

2.2. Multi-scale CT analysis

Micro-focus CT (μCT) has been used to provide images at moderate to low resolutions, shown in Fig. 2(a and b), from whole component samples and sectioned sub-regions. In addition imaging using the European Synchrotron Research Facilities (ESRF), enabled micron scale resolutions of critical regions of interest, shown in Fig. 2(c), providing structural information down to single fibre levels.

μCT images were taken using an X Tek Benchtop 160Xi scanner at the University of Southampton, providing resolutions of ~75 µm (Macro-scale of the whole sample structure) and ~15 µm (Meso-scale of cut out smaller sections, see numbered items 1–3 for further information). In the μCT system X-rays are generated when an accelerated electron beam collides with a metal target (molybdenum or tungsten). A focal spot size down to ~3 µm is achievable. Due to the conical beam of the μCT, a smaller sized sample will achieve higher resolution. At these low geometrical magnifications the resolution is limited by the number of pixels across the detector (~1200 in the benchtop system) and the width of the sample. As such the finest resolution (*i.e.* ~3 µm) is achievable for a field of view of 3.6 mm cross-section, with the largest possible objects (~90 mm cross-section) yielding a voxel resolution of about 75 µm. An electron accelerating voltage of 125–130 kV with a tungsten reflection target and a beam current of 120–190 µA (dependant on sample size) was used. 1905 radiographs were recorded over 360°via a 1284 × 1284 detector.

The SRCT setup at ID19 of the ESRF, was used to obtain a resolution of 1.4 µm for the micro-scale images (although higher resolutions are achievable). In comparison to the μCT, X-rays are generated from very high energy electrons circulating in an accelerator and associated interactions with an undulator device in this case. The high beam flux enables relatively short exposure times, with satisfactory imaging results being obtained for scans in the

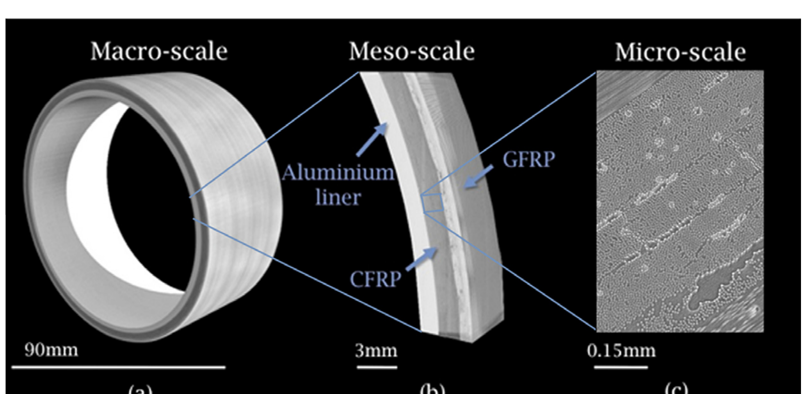

Fig. 2. Multi-scale CT imaging approach of a hybrid composite/metallic structure: (a and b) μCT scans of whole structure and sub-region. (c) SRCT image of plies and local fibre distribution.