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Three-dimensional deformation mapping of Mode I interlaminar crack extension in particle-toughened interlayers

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ABSTRACT

This paper presents the first use of Digital Volume Correlation (DVC) on Carbon Fibre Reinforced Plastics (CFRPs) to quantify the strain fields ahead of a Mode I delamination. DVC is a relatively novel tool that can be used to measure displacements and strains occurring inside materials under load. In conjunction with Computed Tomography (CT), the technique has been applied to porous materials, with results providing strain data for validation of Finite Element (FE) models. However, the application of the technique to laminated materials has been limited, with studies often requiring fiducial markings required for volume correlation. In this work, crack propagation steps were captured at a 325 nm voxel resolution using Synchrotron Radiation Computed Tomography (SRCT). The material systems investigated featured different crack bridging mechanisms such as; particle-bridges, resin ligaments, and fibre-bridges. An assessment of noise and sub-volume size on the strain measurement determined that the optimal sub-volume size was 150 voxels with 50% overlap. This provided a spatial resolution of 48.8 μm for strain and a corresponding strain resolution ranging between 220 and 690 με for the repeated reference scans. A rigid body translation study confirmed that specimen movements perpendicular to the fibre orientation support the 'real' physical displacements. However, along the fibre direction, the correlation was poor, with correct displacements being detected only within the particle-toughened interlayers. The study demonstrates that strain measurements can be made perpendicular to the fibre direction across the interlayer, which could be used to validate future FE models of these poorly understood particle-toughened interlayers.

1. Introduction

Carbon Fibre Reinforced Plastics (CFRPs) are increasingly used in primary aerospace structures due to their desirable strength- and stiffness-to-weight properties. However, low velocity impacts that may occur in service can cause significant loss in mechanical properties without producing easily identifiable surface damage [1]. The dispersion of secondary-phase particles within interlaminar regions has been developed to suppress the spread of sub-surface delaminations caused by impacts via toughening of the interlayer [2–4]. Micromechanical understanding of delamination processes in these complex particle-toughened interlayers is not well established, with corresponding uncertainty in where added toughness arises. Through the use of Synchrotron Radiation Computed Tomography (SRCT), *in situ* non-destructive identification of micro-mechanisms is possible within the bulk material, maintaining mechanical constraint conditions and allowing time-series experiments to capture crack growth under controlled loading conditions [5,6]. With such data, the DVC technique can be used to quantify the displacements and strains inside the material between the load steps.

Traditionally, strains can be measured using strain gauging, Digital Image Correlation (DIC), shearography, speckle interferometry, Thermal Stress Analysis (TSA) and reflectrometry. However, these techniques can only provide surface measurements of strains at modest spatial resolutions [7]. Internal strains have been measured with diffraction approaches (X-ray and Neutron methods) [8,9], but are complicated especially when handling non-linear or yielding processes. Through the use of CT, and associated *in situ* experimental approaches, it is possible to capture this form of damage progression in sufficient detail to apply the DVC technique. Image correlation of volumetric datasets was first implemented to determine continuum-level displacement and strain fields in trabecular bone [10,11], and helped validate FE models [7], [12]. With CT resolutions now routinely reaching below the micrometer range, 3D volumes of internal micro-architecture can now be generated with ultra-high resolution micro-focus CT systems [13,14], and via SRCT [6,15]. DVC uses the naturally occurring texture in the material to track 3D displacements of a small sub-volume

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of interest between two load steps, which can be translated into local strain measurements [11]. Due to the relatively recent uptake of the technique, further investigation is required into the validity of the displacement data produced since it relies heavily on the specimen's internal architecture and CT results (repeatability of contrast-to-noise, spatial resolution, and imaging artefacts). Previous DVC studies have investigated materials such as bone [16], rock [17], synthetic foams [18], wood [19] and sand [17], which all offer high contrast in volumetric datasets. Less contrasted materials, such as laminates, have not been explored with DVC. The only known work that used DVC to assess strains within a laminate required fiducial markings, in the form of copper particles, to track displacements during a three-point bend test [12].

In the present study, Mode I delaminations are studied in particle-toughened CFRP laminates with the aim to (a), quantify the strain generation at and ahead of a Mode I delamination tip, which can be seen as the most critical loading condition [20], and (b), to assess the accuracy and validity of the DVC technique. Since this is the first use of the technique to investigate interlaminar strains using SRCT data at such high resolutions, the first section of the paper investigates the strain resolution and the optimal sub-volume parameters via a noise study. This experiment was conducted using stationary and pre-determined physical translations of the specimen in order to provide an assessment of the scan repeatability and interpolation errors from the correlation algorithm. The strain resolution is defined as the minimum strain value that can be extracted from the data and regarded as a result of material behaviour and not due to noise in the data or systematic artefacts due to the imaging or signal processing [7]. These known displacements were also used to validate the displacement data from the DVC analysis. The second section of the paper identifies the strain behaviour at the crack tip, with the three different particle-toughened systems displaying dissimilar crack bridging mechanisms. Crack propagation in these complex microstructures is highly discontinuous, with no clear 'crack tip' [21]. However, for the first time, interlayer-scale strain measurements have been made that can be compared to micromechanical FE models. The work is intended to support material development and increase the understanding of the fundamental aspects of comparable particle-toughened interlayers that are widely used in modern composite aircraft structures.

2. Methods

2.1. Materials

The developmental CFRPs were prepared by Cytec Industries and manufactured and cured according to a standard aerospace autoclave cycle. A uni-directional 16 ply layup (~3 mm thick) was prepared from pre-preg, with a 40 μm thick Polytetraflouroethylene (PTFE) insert at the mid-plane along one edge of the panel to control the initiation of fracture. The primary reinforcement was a proprietary intermediate modulus carbon fibre (~5.4 μm in diameter). The secondary-phase thermoplastic toughening particles were confined to a ~30 μm thick interlayer present at each ply interface. Three different particle systems are presented in this work, with the fibre type, sizing, base resin and particle volume fraction (13%) being consistent between the systems. Material A (Mat. A) is identifiable by its irregularly shaped particles that are 5–20 μm in diameter. Material B (Mat. B) can be identified from a more regular spherical geometry, with particle sizes between 5 and 10 μm. Material C (Mat. C) is a hybrid system, containing both particles featured in Mat A, and another particle type that could not be resolved in the CT data and is suspected to have a high interface strength. The composition of these systems is proprietary and is not important to the key findings of this paper.

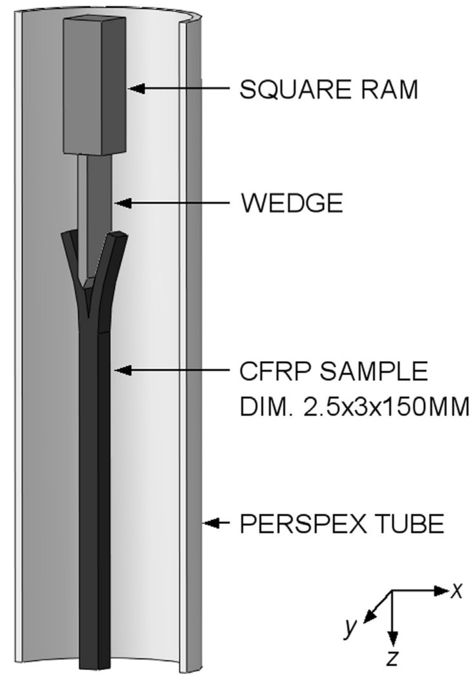

Fig. 1. Schematic of the Mode I wedge-driven loading rig.

2.2. Specimen geometry and loading

In order to provide a uniform X-ray path through all angles of rotation and to maximise the transmission of low energy X-ray photons, a cross-sectional geometry of 2.5 × 3 mm was chosen. The specimens were 150 mm long with a 10 mm long PTFE insert. A purpose built screw-driven (displacement controlled) *in situ* compression rig was used to drive a wedge into the mid-plane of the specimen at the PTFE insert (as seen in Fig. 1). A square ram ensured that there was no torsional loading on the specimen. An initial loading step was conducted to grow the crack about ~ 5 mm prior to conducting the time-series experiments. Following this, the wedge was driven into the crack to achieve a further 200 μm of Mode I crack extension and scanned again in order to capture the crack growth in 3D.

2.3. Synchrotron radiation computed tomography

SRCT measurements were carried out on the TOMCAT beamline at the Swiss Light Source, Paul Scherrer Institut, Switzerland. A detector size of 2560 x 2160 pixels was used and scans were conducted at a beam energy of 14 keV and a voxel size of 0.325 μm. The projection data for each scan consisted of 1601 projections with an exposure of 100 ms for each projection. After reconstructing using the in-house GRIDREC method [22], the bit depth of the volumes was reduced from a 16-bit to 8-bit format in order to achieve faster processing times for the DVC analysis.

2.4. Digital Volume Correlation

Digital Volume Correlation was performed using DaVis 8.1.3 software [23] via a proprietary Fast Fourier Transform (FFT) approach and a 50% overlap between neighbouring sub-volumes. Fig. 2(a) shows the volume correlation process of two neighbouring sub-volumes 'A' and 'B', where following a load step, the new position of each sub-volume centroid is determined. The correlation coefficient measures the similarity in the distribution of grey-levels between the original and displaced sub-volume, with the position