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Partial volume correction for approximating crack opening displacements in CFRP material obtained from micro-focus X-ray CT scans

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ABSTRACT

This paper presents a partial volume correction technique that applies a measurement weighting based on grey scale intensity values, allowing crack opening displacements (CODs) to be better estimated in micro-focus computed tomography (μCT) scans. These were tested on 3D data obtained from two separate μCT scanners on particle toughened and non-particle toughened carbon fibre material subjected to low velocity impact. Direct comparisons of COD estimations were made with higher resolution measurements obtained using synchrotron radiation computed tomography (SRCT) scans taken at the European Synchrotron Radiation Facility (ESRF). In this study, partial volume correction is reported to improve the accuracy of these measurements to within 20% of SRCT measurements, whereas measurements based on counting interconnected voxels representing a detectable crack are reported to consistently overestimate crack openings by up to 500%. Scatter in estimations was dependent on material type, noise, and artefacts associated with μCT volumes.

1. Introduction

Industrial CT scanners have made it possible to routinely extract 3D damage features in structural materials such as carbon fibre composites [1]. Common operating voxel resolutions of the order of 5 μm have been used in previous studies on impacted composites [2–7]; the significant limiting factor affecting resolution is the X-ray focal spot size and specimen size [8]. Whilst this resolution is useful for identifying the components of composite damage, quantification of key features, such as crack opening displacements (CODs) within impacted carbon fibre materials requires a higher fidelity. Informed use of the partial volume effect provides a means so that sub-resolution features may still be detected and quantified [2]. Crack opening and crack shear displacements are important parameters in micromechanical modelling of composite damage and failure. Accurate experimental measurement of these parameters in three-dimensions (3D) is enabled by computed tomography, and allows the validation and calibration of models [9] and to calculate effective stress intensities at the crack tip [10].

The partial volume effect occurs when two or more phases with differing density are represented within a single voxel leading to an effective averaging of attenuation coefficients; this is typically critical if the object or region's dimensions are at the voxel resolution or less (assuming other forms of unsharpness are undersampled by the voxel dimensions) [11–13]. Depending on the contrast difference between the two phases, this has an influence on the smallest detectable feature. For the detectability of cracks in composites it has been reported that openings down to 20% of the voxel resolution in CT scans can be detected, and by using contrast enhancement agents, this may be further reduced to 5%. Contrast agents require all cracks to be interconnected up to the surface of the material to allow full penetration of the dye [2]. For internal damage, such as that sustained in impact loading, this is often not the case. Furthermore, in cases for which *in situ* load-stepped CT experiments are combined with digital volume correlation (DVC), the detectability of cracks can be greatly improved by quantifying the mechanical effects of cracking in addition to direct physical imaging [14,15]. However, these rely on comparisons between multiple scans rather than a single volume.

The partial volume averaging effect may lead to inaccuracies in the estimation of object sizes due to the dependence on the feature's location on the image grid. Fig. 1a and b shows schematically how this affects crack opening measurements. Since a crack that partially fills a voxel may be treated as occupying a full voxel when interconnected measurements are taken, overestimations in measurements occur [16–18]. This phenomenon is particularly noticeable at phase boundaries that fall within a voxel, leading to intermediate voxel intensities dependant on the percentage of "fill" between both phases [16,19,20].

Where the crack openings approach the limit of detectability, in reported cases down to 20% of the voxel resolution, measurements of counting interconnected regions will overestimate the crack opening by up to ten times. If the smallest detectable crack were

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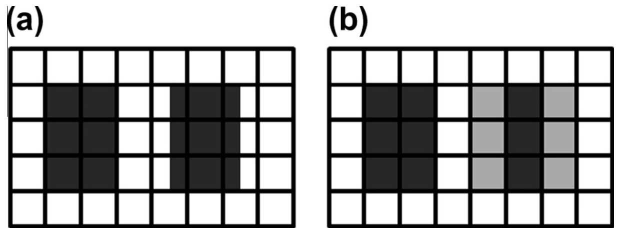

Fig. 1. Schematic showing (a) positions of an actual crack relative to the image grid, (b) corresponding rendered image. The crack boundaries that partially spill over and fill neighbouring voxels are rendered with less intensity at the edges and result in an inaccurate width estimate, this leads to consistent overestimates when measured by counting interconnected voxels.

to partially fill two neighbouring voxels, measurements would include the crack as fully occupying both voxels leading to a large overestimation. Scanning at higher voxel resolutions does reduce these errors [16], however the trade-off between resolution and field of view [8], and the high barriers to entry to equipment capable of higher resolution such as synchrotron radiation computed tomography (SRCT) often limits this option.

A partial volume correction algorithm has been used in previous studies to estimate crack openings on Al–Li fatigue cracks in work by Ignatiev et al. [21] and Guvenilir et al. [22,23]. This work utilised attenuation coefficients to calculate an estimate for the measured fraction of crack opening. Work similar to this by Heckel et al. [19] utilised linear interpolation based on intensity and applied a weighting on the voxel volume at feature boundaries; this has been reported to increase accuracy and repeatability in volume measurements of liver metastases and lymph nodes obtained in CT scans.

The work presented in the present paper uses the same techniques by mapping grey scale intensities to a linear relationship between the material and crack levels to allow an adjusted length to be calculated for that voxel representing a crack opening. To the author's knowledge, this is the first study applying this technique on cracks in carbon fibre composite materials and unlike previous work on this topic, this paper calibrates partial volume correction estimates to higher voxel resolution SRCT scans enabling this technique to be tested more rigorously.

2. Methodology

2.1. Specimens and impact testing

Two carbon fibre reinforced epoxy materials were tested; one with a particle toughened and the other with a non-particle toughened (untoughened) matrix system (exact chemical formulation is proprietary). This allowed different damage morphologies to be examined for crack opening displacement (COD) analysis. The specimens measured 80 × 80 × 1 mm with an eight ply $[+45/0/-45/90]_s$ stacking sequence. Damage was introduced via impact using a drop tower with a 4.9 kg mass with a 16 mm diameter hemispherical tup. The specimens were supported on a base plate consisting of a 60 mm diameter hole following a similar standard to that used in [24]. Specimens were impacted at 0.6 J and 1.3 J for particle toughened and untoughened systems respectively; this was to create a similar projected damage area in each, as measured by C-scan. These were subsequently cut to form 'matchsticks'; i.e. specimens measuring 80 × 4.5 × 1 mm, sized to fit within the field of view of the CT scan at the highest resolutions and to minimise noise and artefacts. To reduce variations in X-ray path length as the sample was rotated during the scan, two specimens were stacked together to form a stack measuring 80 × 4.5 × 2 mm.

Table 1
Settings used for CT scans.

	Benchtop	HMX	SRCT
Energy (kV)	75 (peak)	65 (peak)	19 (monochromatic)
Current (μA)	80	70	–
Reconstruction size (px)	1000 × 1000	2000 × 2000	2000 × 2000
Voxel resolution (μm^3)	5.24	4.3	1.4
Number of radiographs	2000 (360°)	2000 (360°)	1500 (180°)
Exposure time (ms)	2000	2000	100
Scan time (min)	150	150	5

2.2. 3D X-ray tomography

μCT scans on the 'matchstick' samples were carried out at the University of Southampton's μ-VIS Centre[1] using a Nikon Metrology HMX 225 CT scanner and an X-Tek Benchtop CT system. A molybdenum target with no filtering was used. SRCT scans were carried out at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, using beamline ID19, the sample-detector distance being set to 37 mm enabled near-field Fresnel diffraction (edge detection). The settings used for μCT and SRCT are shown in Table 1. These scans were reconstructed using a filtered back projection algorithm to form an 8-bit volume with voxel grey scale intensities ranging from 0–255.

The same specimens were scanned for all three imaging facilities and no penetrants or any other treatment was applied to the specimens. Whilst the full lengths of the cracks were not captured due to the limited field of view, the same regions of interest were obtained with each of the three imaging facilitates. This enabled the same cracks from the same specimens to be directly compared across the different imaging facilities.

2.3. Partial volume COD approximation technique

As the size of the crack opening approaches the voxel resolution, a combination of background material and crack features are sampled and averaged within a voxel. Visually, the crack may appear faint, with a limited contrast against the surrounding material. This effect is shown in the lower resolution HMX scan in Fig. 2c with a higher resolution SRCT scan of the same crack shown in Fig. 2b. Fig. 3 illustrates this behaviour; a line plot across a ~3 μm crack exhibits a dip in grey scale value centred at 23 μm, which is indicative of the presence of a crack. The SRCT scan shows a sharp contrast between the crack and background material over a narrow band of voxels. In the example given in Fig. 2b white fringes are present at the edge of the crack representing the edge detection regime. In this particular case, the fringe was more pronounced on the left hand side of the crack due to slight variations in path length through irregular material which has a control on the interference effect when reconstructed. With the lower resolution μCT scans, the crack intensity diminishes towards the background material mean grey scale, with the dip spread over a wider range of voxels, due to the crack partially filling the voxels.

By taking the grey scale intensity of a voxel partially containing a crack, the percentage of crack and material occupied within the voxel can be approximated as a linear relationship of a combination of grey scales representing the crack (i.e. air) and material. Provided isotropic voxels are used, this calculated percentage can be weighted to the corresponding length of the voxel. A linear relationship between the adjusted length of a voxel and the two grey scale intensity values consisting of the crack (air) and the material is represented by the relationship in the following equation:

[1] http://www.southampton.ac.uk/muvis, EPSRC Standard Research Grant EP/H01506X/1