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A comparison of multi-scale 3D X-ray tomographic inspection techniques for assessing carbon fibre composite impact damage

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ABSTRACT

Tomographic imaging using both laboratory sources and synchrotron radiation (SR) was performed to achieve a multi-scale damage assessment of carbon fibre composites subjected to impact damage, allowing various internal damage modes to be studied in three-dimensions. The focus of this study is the comparison of different tomographic methods, identifying their capabilities and limitations, and their use in a complementary manner for creating an overall 3D damage assessment at both macroscopic and microscopic levels. Overall, microfocus laboratory computed tomography (μCT) offers efficient routine assessment of damage at mesoscopic and macroscopic levels in engineering-scale test coupons and relatively high spatial resolutions on trimmed-down samples; whilst synchrotron radiation computed tomography (SRCT) and computed laminography (SRCL) offer scans with the highest image quality, particularly given the short acquisition times, allowing damage micromechanisms to be studied in detail.

1. Introduction

Impact damage resistance and damage tolerance have been concerns in the development of carbon fibre composite materials, particularly in aerospace structures [1]. Various damage assessment techniques have been employed to achieve a better understanding of CFRP impact damage and to develop toughening strategies [2,3]. Ultrasonic C-scans [4] and thermography [5] are widely employed, for example; these are non-destructive testing (NDT) techniques but lack micrometer resolution and the ability to track the interaction of various damage modes within the material microstructure. Ultrasonic time of flight (TOF) scans can provide 3D representation of damage through the thickness of a laminate [6], but the nature of the scans means overlapping damage goes undetected. To achieve very high levels of detail to study the material microstructure, traditional materialographic sectioning followed by microscopy can be performed [7,8]. However, as a destructive technique, the sample is effectively lost, risks introducing new damage during sectioning, and observed damage/displacement conditions may become non-representative due to the disturbance of residual stresses at the sectioning plane. Furthermore, physical sectioning is commonly restricted to two-dimensions (2D) on exposed surfaces; whilst this technique has been adapted to perform automated 3D analysis in the case of cross-sectional fractography [9], this is time consuming and has not been widely adopted. The focus of this paper is to examine and assess several non-destructive X-ray tomographic techniques for the 3D examination of impact damage in composite laminates, and considers issues of resolution, sample preparation and length scales.

Considering the anisotropic properties, heterogeneous microstructure and multi-mechanistic, multi-scale nature of failure in CFRP laminates, it is relevant to take into account the 3D behaviour of the material without affecting its integrity for subsequent testing, particularly so with compression after impact (CAI) analysis. What is desirable is a technique that offers high resolution to study the internal micromechanical damage in 3D, without the issues of destroying the sample or introducing new damage. To achieve this, synchrotron radiation computed tomography (SRCT) [10–14], and in more recent work synchrotron radiation computed laminography (SRCL) [15,16] have been successfully used to study composite materials at voxel resolutions in the order of 1 μm and below. In comparison, laboratory microfocus computed tomography (μCT) offers routine moderate resolutions, typically several micrometers and above [17–22]. These techniques have allowed key features such as micro-cracking, voids and fibre breaks within the material's structure to be assessed in considerable detail.

Recent studies have used μCT to study impact damage on composite laminate materials and have detected interlaminar and intralaminar damage within the through-thickness. In some cases contrast agents are used to detect the presence of damage [19]; this however has a limitation requiring interconnectivity between all cracks to absorb the agent which cannot be guaranteed [17].

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Other studies have successfully captured 3D damage without the use of contrast agents [23–25]. A major challenge in standard μCT imaging using a large-area, (e.g. flat panel) detector is that for reaching high spatial resolutions (e.g. 10 μm and less), flat specimens cannot be fully turned due to collision with the X-ray tube housing which effectively limits the angular acquisition range. In most studies the specimens are hence cut to smaller sample sizes. To our knowledge, no work using SRCT or SRCL to study composite impact damage has been published so far.

SRCL, SRCT and μCT operate on similar principles: a large number of 2D radiographic projections are taken as the sample in question is rotated. These radiographs undergo an inverse Radon Transform via a variety of possible methods to form a 3D volume. The two key differences between these techniques are the X-ray sources – use of synchrotron vs. micro-focus tube – and the axis of rotation for scan acquisition; this is perpendicular to the X-ray beam in computed tomography (CT), and tilted to less than 90° in computed laminography (CL). Key benefits of synchrotron imaging include fast acquisition speed with high signal-to-noise, convenient exploitation of phase contrast effects particularly propagation methods for enhanced edge detection [26], and sub-micrometer resolutions, when compared to conventional micro-focus sources [27].

With respect to the axis of rotation in scanning, a significant drawback of CT is that it is best suited to samples with relatively isotropic cross-section shapes, for example circular or square, in cases for which the highest resolutions, signal-to-noise and artefact avoidance are required [15]. The laterally extended geometry of typical engineering-level impact coupons therefore requires regions of interest (ROIs) to be physically cut from the specimen to conform to these geometries. Whilst this can work well [17,19] it clearly obviates the non-destructive character of whole-object CT. CL presents one solution to this limitation in CT for flat objects in its simplest and basic form by maintaining reasonably uniform X-ray transmission at all angles, allowing non-destructive 3D inspection of ROIs within almost arbitrarily extended planar samples at micrometer and sub-micrometer resolutions [28,29]. In various fields of materials science, these resolution ranges render the method particularly adapted to study microstructures [30,31] and their temporal evolution under different loading conditions [32–34].

The present paper specifically explores the use of SRCT, SRCL and μCT on relatively thin (1 mm) impacted coupons of CFRP laminate, to evaluate their uses in a complementary manner. The feasibility of using high resolution SRCL is reported for thicker (4.5 mm) samples conforming to the ASTM D7136M [35] impact standard in addition to local low resolution μCT of complete intact plates. This work differs from previous work by forming a direct comparison of 3D imaging methods on impacted CFRP panels.

2. Materials and methods

2.1. Material

Cytec prototype unidirectional CFRP prepreg material with a layup of $[+45/0/-45/90]_s$ was cut to form 80 × 80 mm coupons with a thickness of 1 mm. The thicker 4.5 mm specimens had a layup of $[+45/0/-45/90]_{3s}$, these were cut to 150 × 100 mm. Particle toughened resin systems were used in this study. The coupons were ultrasonically C-scanned to check for gross manufacturing defects on the mm scale prior to impact.

2.2. Mechanical testing

Impact testing was achieved via a drop tower system to ASTM D7136 standards [35] with a striker mass of 4.9 kg and a hemispherical 16 mm diameter tup. The specimens were impacted at 1.3 J and 30 J for the 1 mm and 4.5 mm thick specimens respectively. In order to accommodate 1 mm thick specimens, a non-standard base plate was used consisting of a circular 60 mm diameter window supported by a ring of the same dimensions as used in [36]. The 4.5 mm samples were supported over a 125 × 75 mm base plate using four toggle clamps. After impact, specimens were C-scanned to measure the overall extent of the impact damage area. Again, the resolution of the C-scan was approximately 1 mm.

2.3. Imaging sample preparation

CT studies were performed on ROIs cut from the panel. For the 1 mm laminate, a low speed diamond cutting wheel was used to cut 4.5 × 80 × 1 mm 'matchsticks' across the damaged impact site as determined from ultrasonic C-scans. The corresponding 'matchsticks' were then stacked in pairs to form 4.5 × 80 × 2 mm specimens to be scanned together in one operation. No specific material preparation was required for samples used in SRCL imaging; regions within the damage area were targeted.

For the 4.5 mm laminate, ROIs were physically cut to 4.5 × 4.5 × 150 mm 'matchstick' for μCT analysis, having already been SRCL scanned in the complete condition. To test the feasibility of locally scanning intact plates using μCT, plates were stacked and scanned in pairs. This was to reduce the width to thickness aspect ratio thus reducing variations in X-ray path length and to fully fill the available field of view in the volume allowing two samples to be scanned at once. The intact plate was scanned at the maximum voxel resolution determined by the clearance between the target and the object to allow a full rotation.

2.4. X-ray tomography

Settings used for μCT, SRCT and SRCL scanning are summarised in Table 1. Two settings were used on the μCT scanner for 'matchstick' specimens and intact 4.5 mm thick plates. Scans were reconstructed via filtered back projection methods in all cases. μCT scans were undertaken at the University of Southampton μ-VIS Centre on a Nikon Metrology HMX 225 CT system, using a molybdenum target without filtration.

SRCT and SRCL scans were carried out at the European Synchrotron Radiation Facility (ESRF) on beamline ID19, providing an intense, parallel, essentially monochromatic and coherent beam that supports simple propagation-based and phase-enhanced contrast,

Table 1
μCT, SRCT and STCL imaging conditions.

	μCT (matchsticks)	μCT (intact plate)	SRCT	SRCL
Energy (kV)	65 (peak) ~24 (mean)	115 (peak) ~40 (mean)	19 (monochromatic)	19 (monochromatic)
Gun current (μA)	70	100	–	–
Voxel resolution (μm^3)	4.3	14.2	1.4	0.7
Number of radiographs	2000 (360°)	1301	1500 (180°)	1500 (360°)
Exposure time (ms)	2,000	1,000	100	100
Total scan time (min)	150	44	5	11