COMPOSITE LAMINATE IMPACT DAMAGE ASSESSMENT BY HIGH RESOLUTION 3D X-RAY TOMOGRAPHY AND LAMINOGRAPHY

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Abstract

Improvements to toughening mechanisms in composite materials have hitherto relied on visual inspection techniques that can be rather limited, especially since the inherent damage behaviour is three-dimensional (3D) requiring high resolution to capture micro-cracks and similar damage. To achieve a better understanding of impact damage behaviour, synchrotron radiation computed laminography (SRCL) and computed tomography (SRCT) techniques were used to capture 3D damage mechanisms with voxel sizes of 0.7µm and 1.4µm respectively. Comparisons between impacted toughened and non-toughened carbon fibre reinforced polymer (CFRP) systems were made in which toughening particles were introduced into the matrix of the toughened material. This study has found that at the macro scale, the overall 3D damage pattern in toughened and non-toughened specimens are very similar, however when studied at the micro level, it is clear that significant differences in damage between the two systems exist.

1 Introduction

Chosen for their high strength and stiffness to weight ratios, carbon fibre reinforced polymers (CFRP) are increasingly used on primary and secondary structures in the aerospace industry. However, one significant drawback to these materials is their poor resistance to impact damage, leading to a reduction in residual compressive strength (damage tolerance). Considering the impact threats present throughout the service life of the aircraft, this poses serious problems to aircraft operators and manufacturers [1, 2].

Impact damage can be particularly difficult to detect. Even at low impact energies, barely visible impact damage (BVID) that appears harmless on the surface can lead to significant internal damage being formed, resulting in reductions to the residual compressive strength of the material. Whilst the presence of this damage can be detected by ultrasonic methods, cost and time limitations result in the majority of in service inspections using visual inspection of the surface, allowing sub-surface damage to go undetected [1, 3]. It is therefore critical that better damage resistant and damage tolerant materials are developed and this requires a better understanding of the damage behaviour.

Traditional damage assessment methods are rather limited. Whilst non-destructive techniques such as ultrasonic C-scan [4] and thermography [5] are excellent for providing information on damage area, they are limited in their resolution and the ability to track the interaction of various damage modes. Destructive techniques such as sectioning followed by microscopy can offer greater detail [6] but risks introducing new damage to the specimen, affecting any residual stresses within the specimens, and are only limited to two-dimensional (2D) cross sections. What is needed is a technique that offers the high resolution required to track internal damage microstructure in 3D. SRCT and SRCL can achieve this, as demonstrated in previous studies [7, 8, 9].

The principal method behind computed tomography (CT) and laminography (CL) are that both techniques allow 3D imaging of materials through the process of collecting a series of 2D X-ray radiographs taken at incremental rotations of an object. These radiographs are then used for reconstruction of a 3D volume. One key problem with CT however, is that to acquire high resolution scans, the size and geometry of the object becomes a limiting factor. This is because the field of view of the detector limits the spatial dimensions of the volume affecting the size of the object that can be scanned, and additionally laterally extended objects lead to large variations in beam transmission as they are rotated leading to artefacts in the reconstructed volume as shown in Fig. 1(a). This essentially means that in order to scan large objects at high resolutions; regions of interest (ROIs) are required to be cut from the object into more conveniently shaped coupons, in most cases 'matchsticks' with square cross-sections. This is clearly a destructive method that is potentially detrimental to damage assessments. To overcome these limitations, CL can be used to acquire high resolution scans of composite plates intact without the need for cutting ROIs. This method essentially works by tilting the axis of rotation with respect to the beam as shown in Fig. 1(b) to allow minimal variation in the X-ray path as the sample is rotated, and is explained in detail in [10].

In this work, a combination of multi-scale imaging techniques consisting of microfocus CT (μCT), SRCT and SRCL are used in a complementary manner to assess impact damage in CFRP specimens. μCT offers larger sample sizes ranging from 4mm that support scanning strategies for SRCT and SRCL techniques [11]. SRCT offers high resolutions in small sections of materials with cross sections in the order of ~2.5mm, whilst SRCL offers high resolution in relatively large (150x150mm) but thin plates with the added benefit of being a truly non-destructive inspection technique at the expense of some imaging artefacts due to the limited angular coverage of the scans.

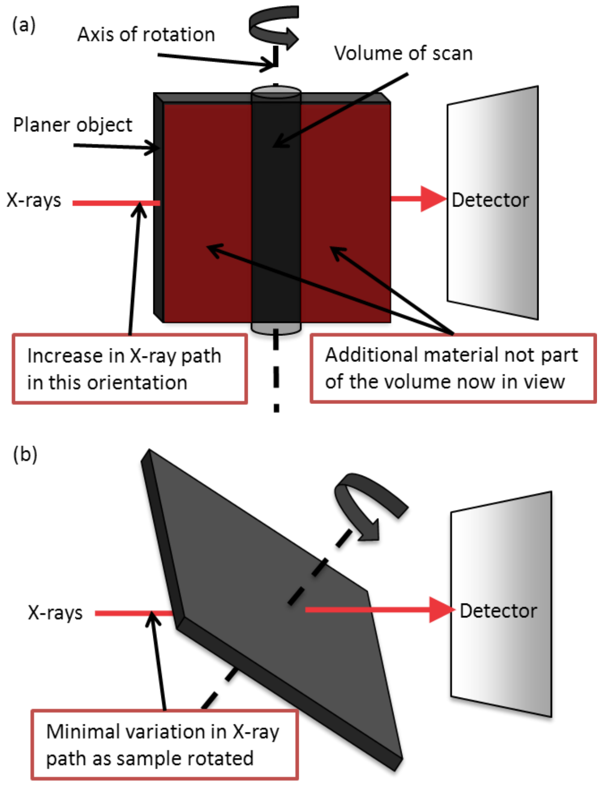

Fig.1. Schematic of (a) CT and (b) CL methods, highlighting the limitations of scanning planer objects with CT.

2 Materials and Methods

2.1 Materials

In keeping with previous SRCL studies on similar materials [8], 1mm thick laminates were used. Overall impact sample dimensions consisted of eight ply CFRP specimens measuring 80x80x1mm with a $[+45, 0, -45, 90]_S$ layup. Two systems were manufactured of toughened and non-toughened materials, with particles introduced into the matrix of the toughened system.

2.2 Drop tower impact testing procedures

Specimens were loosely clamped onto a base plate over a circular window of 60mm diameter. The upper clamp consisted of a plate with a window of the same dimensions to offer support around the edge of the specimen as achieved in [3]. The impactor consisted of a 4.9kg striker with a hemispherical 16mm diameter tup.

The drop tower procedure aimed to achieve a damage radius approximately 5mm as measured by C-scan, this was to enable a larger proportion of damage to be scanned using the X-ray techniques. This required toughened and non-toughened specimens to be impacted at separate energies to achieve similar damage areas for like for like comparisons.

2.3 3D X-ray tomography

Micro-CT scans were undertaken at the μ-VIS CT facility at the University of Southampton, UK [1]. SRCT and SRCL scans were carried out using beamline ID19 at the European Synchrotron Radiation Facility (ESRF), France.

2.3.1 Micro-CT

To maximize the potential of SRCT and SRCL, micro-CT scans of the impacted specimens were undertaken first. The overall aim was to locate the impact location and identify the edge of the damage area.

To achieve a spatial resolution of 4.3μm, ROIs from the specimens were cut as shown in Fig. 2(a) and stacked in pairs to form ‘matchstick’ samples with a cross section of approximately 2.0x4.5mm. It should be noted that with every cut, 0.3mm of material is lost due to the thickness of the blade. Epoxy markers were placed along the length of the ‘matchstick’ to allow regions to be identified in the scans.

2.3.2 SRCT

SRCT was performed at the European Synchrotron Radiation Facility, France (ESRF). Samples were scanned with a spatial resolution of 1.4μm at the two ROIs identified by the micro-CT method.

2.3.3 SRCL

A second set of impacted specimens was used to carry out SRCL scans. Impacted samples were kept intact and scanned at locations shown in Fig. 2(b) using a spatial resolution of 0.7μm. These locations make up a quadrant of the damage area to focus a limited number of scans within this region.

[1] μ-VIS: Multidisciplinary, Multiscale, Microtomographic Volume Imaging, *www.soton.ac.uk/muvis*

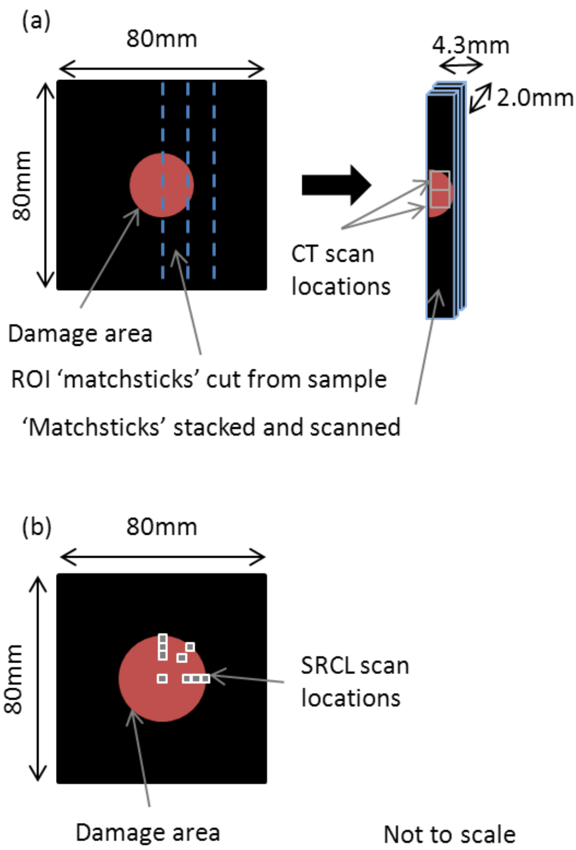

Fig.2. Schematic of specimen setup for (a) CT and (b) SRCL scans.

2.4 Software

Reconstructed volumes were analysed using VG Studio Max. SRCT volumes were concatenated from multiple scans to form a larger volume. Different crack modes from SRCT and SRCL were identified and segmented by hand using the region growing tool to form a 3D representation of damage. Additionally, 2D cross-sectional slices of the damage were assessed.

3 Results and discussion

3.1 Mechanical impact

Due to the use of thin specimens, low impact energies were used. To achieve the desired damage area, the toughened and non-toughened specimens were impacted at 1.3J and 0.6J respectively.

3.1 3D damage characteristics

Cracks were segmented from SRCT volumes to reveal the 3D damage morphologies as can be seen in Fig. 3(a) and 3(b) where the arrows indicate the impact location. This segmentation reveals that the 3D damage patterns are common to both systems studied. This consisted of a region of damage that extends outwards from the impact zone and increases towards the back face plies.

Apart from tensile cracks that are present within the bottom ply, little damage exists directly beneath the impacted region; however, towards the edge of this region, a perimeter of matrix cracks is formed, with the cracks running parallel to the direction of the fibres in their respective plies. Additionally, the presence of delaminations forms within the boundaries of these matrix cracks where the crack interacts with different ply interfaces.

3.2 Micromechanical crack behaviour

Comparisons between the image quality of SRCT, Fig. 4, and SRCL, Fig. 5, for studying the micromechanical crack behaviour highlights that both methods are feasible in acquiring detailed 2D slices. Although the SRCL image shows slightly more artefacts, the level of detail in both Figures allows individual fibres to be distinguished from the matrix and cracks with an opening displacement from 0.5μm. Whilst both methods yield scans of similar image quality, the prominent advantage of SRCL is that intact impacted samples are scanned without the need for physically cutting ROIs; this removes any risk of introducing new damage that could influence the results. This demonstrates that a truly non-destructive inspection technique is possible at this resolution and 3D detail.

A cross section of impact damage taken from SRCT shown in Fig. 4 displays the conical ‘pine tree’ pattern of damage consistent with previous studies [6] forming to the side of the impact location as indicated by the arrow. Three principal modes of damage are observed consisting of (a) interlaminar matrix shear cracks, (b) interlaminar tensile cracks on the back face due to bending, and (c) intralaminar

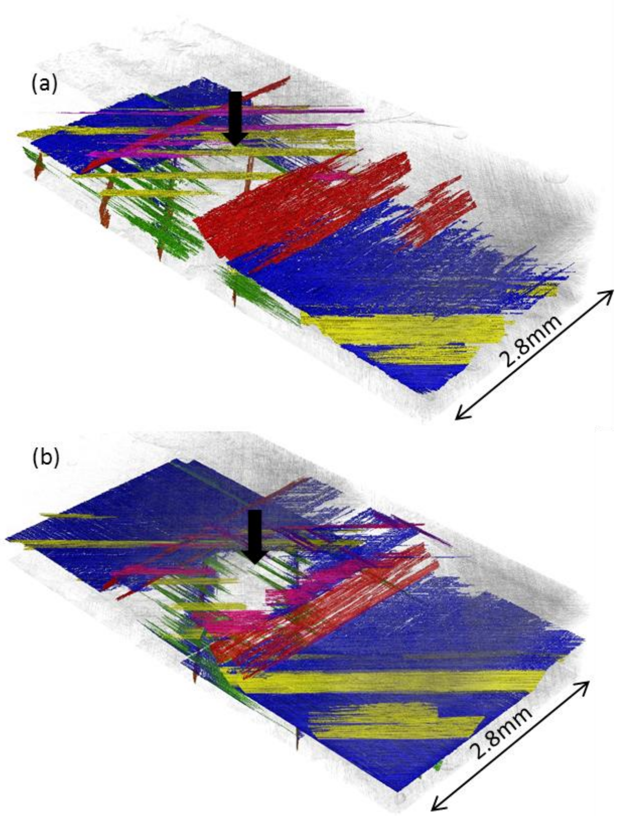

Fig.3. SRCT 3D segmented damage of (a) toughened and (b) non-toughened, impacted specimens.

delamination within the resin rich regions between plies of different orientations.

Towards the mid-point of the damage area, cross-sectional slices of damage taken from SRCL scans are shown in Fig. 5 highlighting key differences between toughened Fig. 5(a) and non-toughened Fig. 5(b) systems. A thicker resin rich region is shown in the toughened system and exhibits significant discontinuities in the delamination crack path consistent with the toughening particles blunting and diverting the crack leading to bridging in the crack wake. Common to both systems, the overall shape of these delaminations suggests that crack propagation is dominated by mode II shear stresses [12]. This suggests crack formation is likely to be caused by the bending stiffness mismatch between the two plies of different orientations as suggested by [13, 14].

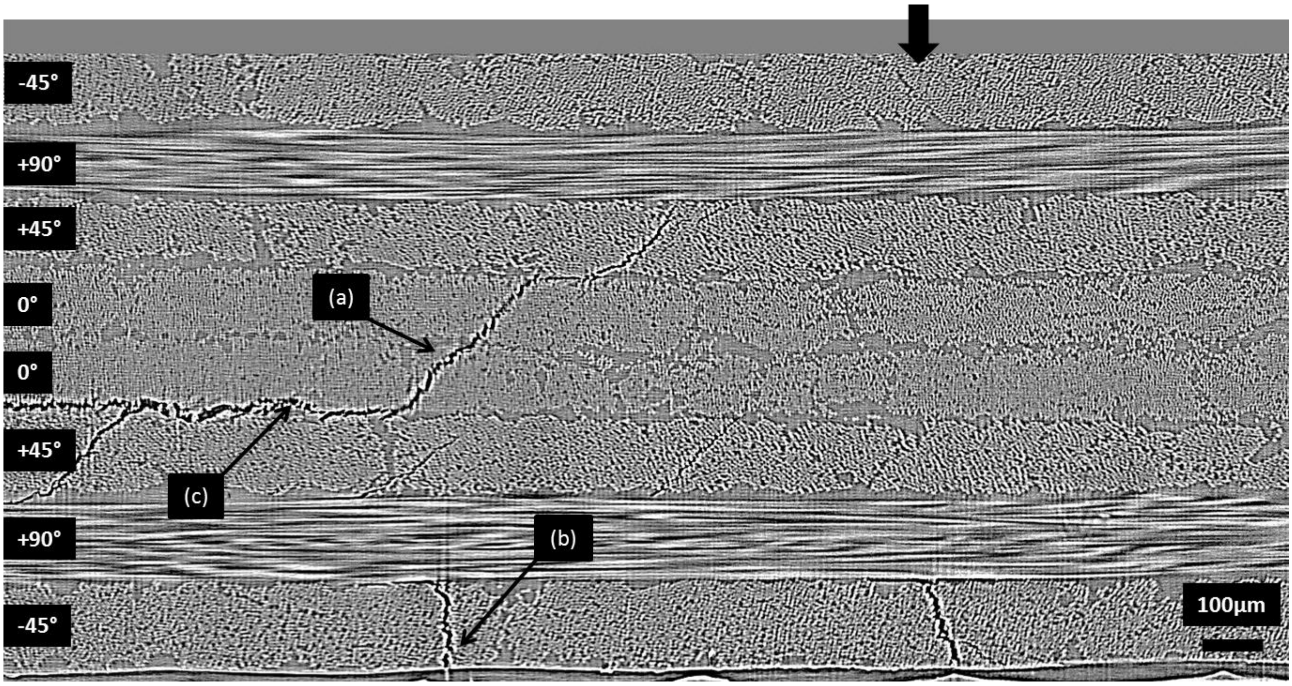

Fig.4. SRCT slice of the impacted toughened CFRP sample. (a) Matrix shear crack, (b) matrix tensile crack (c) delamination.

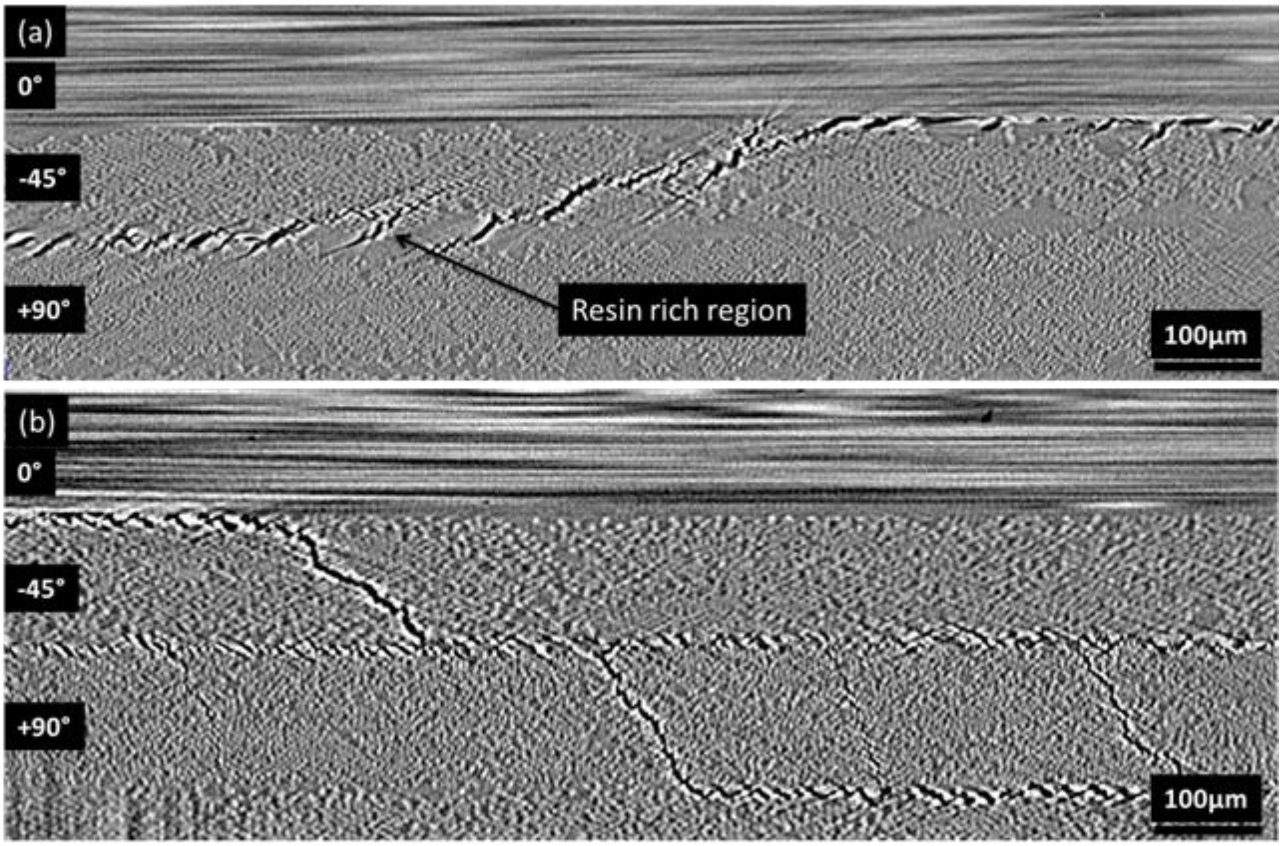

Fig.5. SRCL cross-sectional slice highlighting the differences between the delamination in the resin rich regions of (a) toughened and (b) non-toughened impacted specimens.

4 Conclusions

Micro-CT, SRCT and SRCL have been demonstrated to be valuable tools for performing 3D assessments of impact damage in composite laminates. SRCL in particular has exhibited that a truly non-destructive inspection technique is possible at this level and detail whereas micro-CT and SRCT require ROIs to be cut to achieve the highest resolutions. SRCL therefore is preferable in cases in which samples are required afterwards for further experiments such as compression after impact, and also enables the performance of in-situ work whilst the sample is scanned, such as time-series loading experiments.

Analysis of scans shows similarities and differences between the toughened and non-toughened specimens. At the macro level, the overall segmented 3D damage patterns show very similar results; it is only when the cracks are studied at the micro level that differences between the two systems become apparent. High resolution scans highlight key differences between the microcracking behaviour of toughened and non-toughened systems; toughened materials show distinct discontinuous delamination paths along the resin rich inter-ply regions leading to bridging of the plies.

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