DAMAGE EVOLUTION IN CFRP TUBES UNDER TORSION STUDIED BY IN-SITU X-RAY COMPUTED TOMOGRAPHY

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Abstract

Understanding the relationships between braid micro-structure and damage evolution under torsion can help the design of reliable torsion resistant braid structure. Here, we performed in-situ torsion test of 45° braided carbon fibre reinforced plastic (CFRP) tube and employed time-lapse X-ray computed tomography (CT) to monitor the three-dimensional (3D) damage evolution along time. We found that under torsion damage initiates in the form of inter-yarn debonding and intra-yarn matrix cracking, followed by fibre micro-buckling at yarn cross-over points. The interlacing structure of the braided composite helps to avoid large-scale damage propagation by localising damage zones between the yarn cross-over points, which potentially delays detrimental failure.

1. Introduction

Braided composite tubes have been increasingly used in industrial applications to replace metal or polymer tubes because of its high specific strength and design flexibility [1]. Although the relationship between braid geometry and mechanical properties can be summarised based on mechanical testing results [2], establishing the relationship between braid micro-structure and damage evolution to explain the underlying micro-mechanisms remains challenging. This is also partly due to the limitation in characterisation techniques of complex-shaped structures.

X-ray CT has been increasingly employed to study complex-shaped composite structures due to its capability to provide three-dimensional information non-destructively [3]. It has been applied to assess the 3D braid structure and manufacturing defects in tubular braided tube recently [4]. However, correlating the braid structure with damage mechanisms using X-ray CT has not been reported before. Time-lapse X-ray CT imaging, which exhibits 3D information along the timescale can provide unrivalled information about the accumulation of damage in composite materials. This project aims to bridge the gap in knowledge between macro-mechanical behaviour and micro-mechanical mechanisms of braided tubes subjected to torsion by time-lapse X-ray CT. This topic is important because there are a wide range of problems that would benefit from composite tubes to which torsion is a significant failure mode. The better understanding of composite microstructure will help to establish key strategies to improve the properties of composite materials by designing the braid structure.

In this project, 45° braided carbon fibre/epoxy composite tubes were prepared for in-situ torsion test. Time-lapse synchrotron X-ray CT imaging was performed to monitor damage evolution at different stages. The sequence of events leading to failure under increasing rotation angle was tracked in the series of time-lapse 3D images. Further analysis correlating damage evolution with braid microstructure will reveal the key factors affecting torsional performance and aid the future design of torsion-resistant braids, which is the aim of the future work in this project.

2. Materials and Methods

2.1. Materials

T700SC-12K60E (Torayca) carbon fibre yarns were braided onto a 10 mm-diameter steel mandrel (pre-treated with release agent) with a braid angle of 45° in the diamond pattern. IN2/AT30 epoxy was infused into the braid via the vacuum assisted resin infusion method to manufacture the composite tube from the braid. The infused part was cured at 100 °C for 3 hours. The manufactured CFRP tube has an inner diameter of 10 mm and a wall thickness of ~1 mm. The CFRP tube was prepared into test pieces with 15 mm long gauge section between steel end tabs.

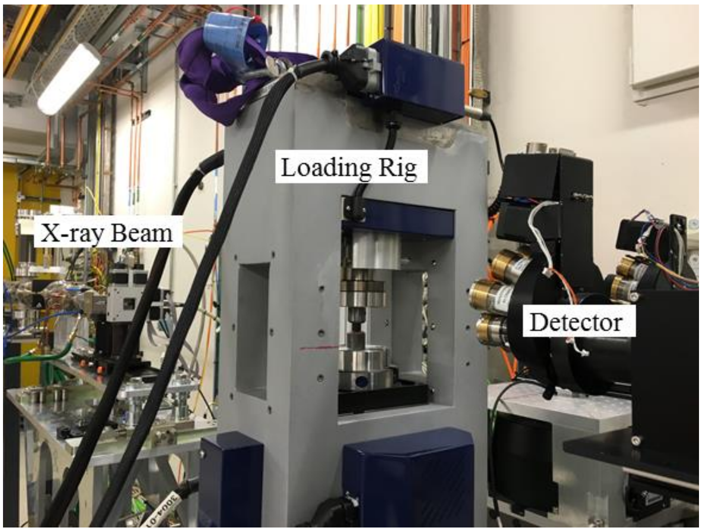

Figure 1. : Photograph of experimental set-up at I13-2 beamline, showing the in-situ torsion loading of composite tube sample performed on the rig positioned in between X-ray beam and detector.

2.2. In-situ Torsion Test

The in-situ torsion test was performed on a Deben-Manchester Open Frame Rig. Figure 1 shows the experimental set-up of the sample mounted on the rig at synchrotron beamline. One major advantage of the Deben-Manchester open frame rig is that only the sample grips rotate during the scan so that the supporting pillars never rotate into the beam and an uninterrupted view of the sample is obtained for all the projections. The sample was loaded under torsion by rotating the top grip relative to the bottom grip. The relative position between the top and bottom grips was maintained during each X-ray CT scan. It should be noted that the torsion test assesses the shear performance of the material. Although extensometer could not be used on the sample due to the short gauge section, the shear stress and shear strain can be estimated based on the rotation angle, the torque and the dimensions of the composite tube, according to the following equations,

$$\bar{\tau} = \frac{3\mathrm{T}}{2\pi(r_{OD}^3 - r_{ID}^3)} \tag{1}$$

$$\bar{\gamma} = \frac{\bar{r} \times \varphi_{rad}}{L} \tag{2}$$

where $\bar{\tau}$ is the mean shear stress, T the applied torque, r_{OD} the outter raidus of the tube, r_{ID} the inner radius of the tube, $\bar{\gamma}$ the mean shear strain, $\bar{r}$ the mean radius of the tube, φ_{rad} the radian rotation angle, and L the length between grips.

2.3. Time-lapse X-ray Computed Tomography

The time-lapse X-ray imaging was conducted at the Diamond-Manchester Imaging Beamline I13-2. A parallel polychromatic pink beam (20-24 keV) was used for imaging. An off-centre imaging strategy [5] was applied to enable doubled field-of-view at the designated pixel size (2.3 µm) in order to ensure the full composite tube can be imaged. In each CT scan, 9000 projections were taken at exposure time of 0.1 s over 360° rotation in fly-scan mode. Loading was interrupted for CT imaging at different torsional angles to obtain a time series of 3D images depicting the damage evolution. Tomographic projections were reconstructed into 2D slices using N. T. Vo python codes [7]. The pre-processing pipeline used the following techniques: 1) distortion correction [8]; 2) converting 0-360° sinograms to 0-180° sinograms; 3) zinger removal; 4) blob removal; 5) ring removal. Then the GRIDEC algorithm was used for reconstruction [9].

3. Results and Discussion

3.1. Overall Mechanical Performance

The mean shear stress and shear strain of the CFRP tube at the interrupted steps are estimated based on Equation 1 and 2 are plotted in Figure 2. The maximum shear stress of 90 MPa was attained at shear strain of 0.08, which corresponds to the applied torque of 22.5 Nm at rotation angle of 13°. The shear strength of in-situ tested composite tube is consistent with our results from tests on Instron loading frames, which to some extent manifests that the damage observed in-situ here is representative of the performance of this material.

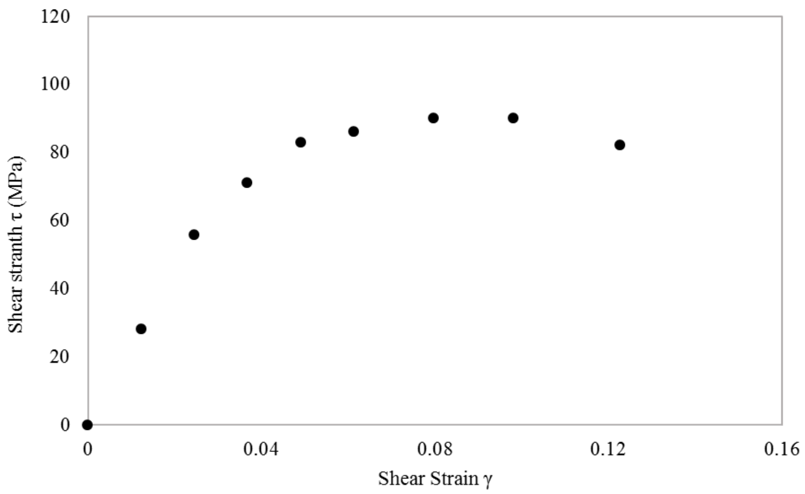

Figure 2. Shear stress-strain plot of the composite tube tested under interrupted in-situ torsion.

3.2. Damage Micro-mechanisms Under Torsion

Damage evolution was monitored in 2D cross-sectional X-ray CT images from the same location in the braided composite tube. Figure 3 shows the zoomed-in partial X-ray CT cross-sections at 4°, 8°, 13° and 16° respectively. We found that damage initiates in the form of inter-yarn debonding and intra-yarn matrix cracking along with the undulation of yarns. Inter-yarn debonding tends to be arrested at the yarn cross-over points. Under further rotation, fibre micro-buckling due to the compressive stress along the yarns occurs at the yarn cross-over points.

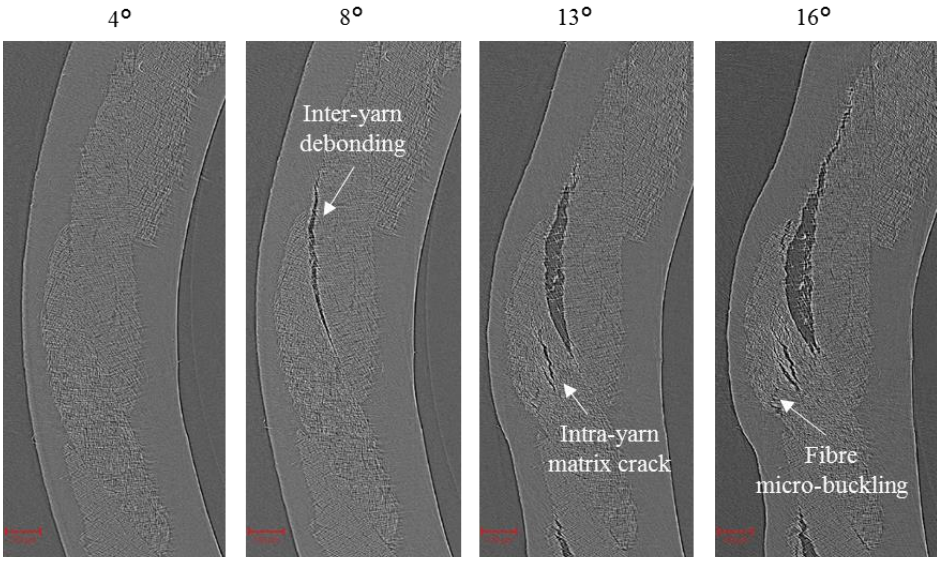

Figure 3. 2D X-ray CT cross-sectional images of the braided CFRP tube at different rotation angles, showing inter-yarn and intra-yarn cracks and localised fibre micro-buckling.

The overall damage distribution can be assessed by segmenting and visualising the damage in 3D and also the correlation between damage and the braid structure can be postulated. Figure 4 shows the extracted inter-yarn debonding and intra-yarn matrix cracks at 10°. In general, the torsional damage is regularly distributed across the braided CRRP tube, while the individual damage zones are localised between the yarn cross-over points. This observation indicates that the interlacing structure of braids contributes to preventing large-scale damage propagation and therefore potentially delays the detrimental failure.

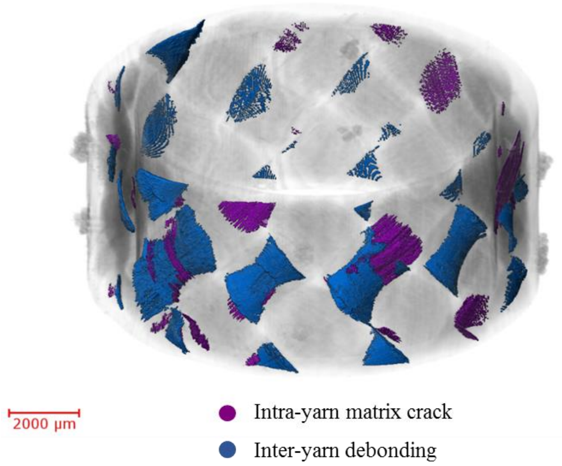

Figure 4. X-ray CT 3D volume rendering of extracted damage at 10°, showing the distribution of inter-yarn debonding and intra-yarn matrix cracks in the braided CFRP tube.

4. Conclusions

The work reported here is the first torsion test of 45° braided CFRP tube performed in-situ accompanied with time-lapse X-ray imaging. The shear strength of the braided CFRP tube is 90 MPa. The progressive damage evolution under torsion initiates in the form of inter-yarn debonding and intra-yarn matrix cracking, followed by fibre micro-buckling at yarn cross-over points. The interlacing structure of braided composite helps to avoid large-scale damage propagation and potentially delays detrimental failure, as damage zones are localised between the yarn cross-over points.

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