Following the effect of braid architecture on performance and damage of carbon fibre/epoxy composite tubes during torsional straining
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Abstract

The torsional performance of bi-axially braided carbon fibre reinforced polymer (CFRP) tubes as a function of braid architecture is investigated. It is found that for a given braid pattern, the 45° braided CFRP tubes have higher shear moduli and lower shear strength than the 35° braids. In general, 2/2 (regular) braided CFRP tubes exhibit both higher shear strength and higher shear modulus than 1/1 (diamond) braids. However, beyond the peak load, the shear strength of 2/2 braided CFRPs exhibits sudden, steep drops, resulting in a lower remnant shear strength than 1/1 structures after the shear strain exceeds 4.5%. Moreover, the damage evolution is monitored in-situ by synchrotron X-ray computed tomography during torsional straining. It showed that for a 2/2 structure, inter-tow debonded regions are vertically interconnected...
allowing rapid crack propagation and strength drops, whereas for the 1/1 braid they are
distributed in a chequer board causing more gradual loss of strength. The fibre/matrix
interfacial strength and tow cross-over density play key roles in the torsional failure of
1/1 and 2/2 braided CFRP tubes, as the former controls damage initiation and the
latter controls damage propagation.

1. Introduction

In the drive to reduce carbon emission and improve energy efficiency in industries such
as aerospace and automotive, employing light-weight materials is an attractive approach
[1]. Carbon fibre reinforced polymers (CFRPs) exhibit higher strength-to-weight and
stiffness-to-weight ratios than metals and alloys, as well as offering other advantages
including high corrosion resistance attractive to the oil and gas industry for example
[2]. Thus, CFRP structures are increasingly being considered as candidates to replace
metal components. For example, in the Airbus A350 XWB and Boeing 787 aircraft
more than 50% (by weight) of the components are made of CFRPs [3]. Moreover, the
application of CFRPs has expanded their consideration from secondary structures to
load-bearing structures. Composite structures also offer a wide range of geometries and
architectures, from laminated panels to complex three-dimensional (3D) woven/braided
architectures. Among these, tubular structures are widely used in industrial applications,
such as the drive shafts in hybrid/electric automobiles, drive shafts for aircraft control
surfaces, the body frame of drones, the casing of aero-engines and pipelines in the oil
and gas industry. For the safe and reliable application of tubular CFRPs, there is a need
to further our understanding of the dependence of the mechanical performance on the
fibre architecture for this materials class.

Braided and filament wound architectures are well suited to tubular structures. Filament
wound structures are much more susceptible to large-scale delamination than braided
ones [4]. Two-dimensional (2D) bi-axial braiding is a highly automated technique and is
thus commonly used [5]. It involves interlacing fibre tows oriented at a braiding angle
of $\pm \theta$ with respect to the long axis of the tube continuously in a helix. A number of
studies have reported the failure mechanisms of braided composite laminates under
tension [6,7], compression [8], shear and impact [9,10]. Perhaps surprisingly, there have
been limited studies on the mechanical performance of braided composite of tube
structures, especially under torsion, which is a common loading scenario in industrial
applications [11]. Melenka and Carey [12] studied the tensile and torsional performance
of both 1/1 and 2/2 braided Kevlar fibre/epoxy composite tubes with braid angles of
35°, 45° and 55°. They found that tensile strength and Young’s modulus decrease with
increasing braid angle for both 1/1 and 2/2 braid patterns; however, there is no distinct
trend for the torsional/shear properties across different braid architectures. Potluri et al.
[13] found that the shear modulus and shear strength of the braided composites decrease
with increasing braid angle in 1/1 braided glass fibre/epoxy composite tubes with braid
angles of 31°, 45° and 60°, which was attributed to the difference in fibre volume
fraction ($V_f$) and the sensitivity to tube diameter variation in the used testing
configuration. Harte and Fleck [14] reported that the shear strength of braided
composites increase with increasing braid angle in 2/2 braided glass fibre/epoxy
composite tubes with braid angles of 23°, 40° and 55°, in contrast to that in 1/1 braids.

With regards to braided CFRP tubes, the torsional/shear properties of CFRP tubes of
different braid architectures haven’t yet been reported in literature. Apart from the lack of macro-mechanical studies, little is known about the damage
mechanisms that give rise to the difference in torsional properties across composite
tubes having different braid structures. Lomov et al. [15] summarised a variety of non-
destructive techniques to study damage evolution in textile composites, including digital
image correlation [6,16], acoustic emission [17], X-ray radiography [18] and X-ray
computed tomography (CT). Although acoustic emission could identify the damage
modes including matrix cracking, debonding between fibre tow and matrix, and fibre
fracture, in the torsional failure of 3D braided CFRP tubes, the 3D distribution of the
various damage modes cannot be mapped. X-ray computed tomography (CT) is a
promising technique to assess microstructure and damage in braided tubes owing to its
3D non-destructive nature. Time-lapse X-ray CT under in-situ loading has been used
increasingly to obtain insights into the damage mechanisms in unidirectional [19,20]
and woven [21] CFRPs as reviewed by Garcea et al. [22] and Wang et al. [23]. With
regards to braided composites, Melenka et al. [24] reported the first use of X-ray CT to assess the 3D braid structure and defects in 2D 1/1 braided Kevlar fibre/epoxy composite tubes, where the actual interlacing paths of individual braid Kevlar fibre tows were extracted in 3D. Zhou et al. [9] used post-mortem X-ray CT to assess the impact damage in 3D braided CFRP tubes of different braid angles, in which they found that impact damage is more severe with decreasing braid angle because of their looser structure. Due to the intrinsic complexity associated with the in-situ mechanical testing of tubular shaped structures, time-lapse X-ray imaging of the damage evolution in braided composite tubes under load has not been realised until recently. We recently reported the first real time 3D imaging of damage development under torsion [25]. The damage in 2D 1/1-45° braided CFRP tube was mapped in 3D during torsional straining and the damage sequence was observed to initiate through radial intra-tow cracking and circumferential inter-tow debonding, followed by fibre micro-buckling and ultimately kink-band formation [25]. This paper aims to compare and contrast the damage behaviour for braided CFRP tubes having different braid interlacement topologies in order to extend our understanding of the effect of braid architecture on the mechanical performance of braided CFRPs under torsion. The torsional/shear properties of 1/1 and 2/2 braided CFRPs tubes having braiding angles of 35° and 45° are compared and time-lapse synchrotron X-ray CT used to provide insights into the key damage mechanisms involved in failure. The findings reported here provide important information for the design of braided composite tubes bearing torsional loads.

2. Materials and methods

2.1. CFRP tube manufacture

Toray T700-12K carbon fibre and IN2/AT30 epoxy resin were used to manufacture all the braided composite tubes in this study. The single layer 2D braided sleeves were fabricated into two patterns – diamond (1/1) and regular (2/2) onto a 10 mm-diameter steel mandrel (pre-treated with release agent to aid demoulding) using a maypole braiding machine (Cobra Braiding Machinery Ltd) as shown in Fig. 1a. Braids with two
braiding angles (35° and 45°) were prepared for each braid pattern, thus providing four braid structures (1/1-35°, 1/1-45°, 2/2-35° and 2/2-45°). The braided sleeves (on the mandrels) were then infused with IN2/AT30 epoxy resin using the vacuum assisted resin infusion (VARI) method, followed by consolidation at 100 °C for 3 hours. The manufactured tubes have a 10 mm inner diameter and were cut into 55 mm lengths (15 mm gauge length). The final 20 mm at the ends of each specimen was glued into end-tabbing fixtures, comprising an insert and an outer shell (adapted from ASTM standard D5448/D5448M [26]), by epoxy adhesive (3M™ Scotch-Weld™ EC-9323 B/A).

Fig. 1. (a) Photograph showing the braiding process. (b) Schematic of the composite manufactured by the VARI system, with 1/1-45° and 2/2-45° braid patterns extracted from the X-ray CT images inset.

In order to reduce defects (such as wrinkles, voids and uneven wall thickness) induced by the resin infusion process, the moulds for the VARI system were modified as shown in Fig. 1b. An extra outer-shell mould was added outside the braid (following [13] and [25]). The resulting tubes had a smooth surface finish and a wall thickness of ~1.3 mm, which contains about 0.3-0.4 mm thick resin-rich area (considering both inner and outer surfaces). The fibre volume fractions of the braided tubes were calculated based on segmented CT images (see section 2.4), excluding the resin-rich skins caused by the mould.

2.2. Torsion testing
Torsion tests (zero axial load) on the braided CFRP tubes were carried out on an Instron 8802 machine to investigate the torsional behaviour and also to validate the in-situ tests.
Three specimens were tested for each of the four braid architectures. During each test, 100 bar gripping pressure was applied to hold the samples and loading was performed at 2°/min. High-resolution videos of the samples throughout the loading process were recorded using LaVision Imager E-lite (105 mm lens), to track the damage on the sample surface at a frame rate of 5 Hz.

The composite mean shear stress, $\bar{\tau}$, was inferred from the torque, $T$, according to Equations 1 and 2, which are obtained by assuming that the sum moment caused by the mean shear stress equals the torque applied on the specimen. The mean shear strain, $\bar{\gamma}$, was inferred from the torsion angle ($\varphi_{\text{rad}}$) according to Equation 3. Considering the difficulties in installing strain gauges on small-diameter tubes with a short gauge length ($L$), $\varphi_{\text{rad}}$ has been computed from the crosshead rotation angle after applying appropriate compliance correction (crosshead compliance has been estimated using a steel bar of known properties). In the following equations, $r$ is the radius of the annular element on the cross-section of the specimen, $dA$ is the area of the annular element, $dr$ and $d\theta$ are the thickness and angle of the annular element, respectively, $r_{OD}$, $r_{ID}$ and $\bar{r}$ are the outer, inner and mean radius of the tube, respectively.

$$T = \int_{A} \int r \bar{\tau} dA = \int_{0}^{\bar{r}} \int_{r_{ID}}^{r_{OD}} \bar{\tau} r^2 dr d\theta$$  \hspace{1cm} (1)

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

$$\bar{\gamma} = \frac{\bar{r} \times \varphi_{\text{rad}}}{L}$$  \hspace{1cm} (3)

### 2.3. In-situ torsion test

The in-situ torsion tests were performed on the Deben-Manchester Open Frame Rig (Mark II) which exploits a pair of independently controllable rotating grips. It was mounted on the I13-2 Diamond-Manchester beamline, Diamond Light Source, UK. The in-situ test specimens have the same gauge length as those for Instron 8802 tests, but metal tabs were specially designed with two parallel side surfaces for gripping to apply the torque (see Fig. 2). The torsional load was applied by rotating the top grip relative to the bottom one while maintaining zero axial load.
The progressive evolution of damage was monitored in real-time by interrupting the test at different stages for synchrotron X-ray CT imaging. A parallel polychromatic ‘pink’ (20-24 keV) beam was used for CT imaging with the radiographs recorded on a PCO.4000 camera providing a cropped field of view (FoV) of 10.8 mm × 7.2 mm at a voxel size of (3.6 μm). In each CT scan, the two opposing grips were rotated in synchrony such that 4500 radiographs/projections were acquired at an exposure time of 0.12 s over 360° rotation using an off-centred imaging approach [27]. The acquisition time for each tomogram was about 30 minutes. To facilitate the CT scan, the control of the rig was switched from load control (for torsional straining) to position control (for imaging with minimal sample movement). The load was stabilised for 20 minutes at each load step prior to starting the CT scan.

2.4. X-ray CT image processing
The acquired projections were reconstructed into 32-bit float CT data using in-house python codes. The pre-processing pipeline incorporated the following elements: 1) Flat-field correction; 2) distortion correction [28]; 3) converting 0-360° sinograms to 0-180°
sinograms [29]; 4) zinger removal; 5) blob removal [30]; 6) ring removal [30]. Then the GRIDEC algorithm was used for reconstruction [31,32]. 3D image analysis was performed in Avizo 2019.1 software. The CT images were firstly transformed into 8-bit (from 32-bit), in order to reduce the data size thus accelerate the following image analysis processes. The non-local means filter was applied to remove noise. With the help of the image segmentation toolbox in Avizo, the bias fibre tows and the damage types can be segmented semi-automatically based on their different greyscale levels. Thus, the topology of the braided structure can be extracted and visualised in 3D as shown in Fig. 3. Moreover, the volumes of the braid tows (including intra-tow resin) and the composite were obtained from the CT images based on the segmentation results to facilitate the measurement of $V_f$, which was calculated by the volume of fibres divided by the volume of the composite. The volume of fibres equals the volume of tows multiplied by the intra-tow fibre volume fraction. The intra-tow fibre volume fraction was calculated by the area of carbon fibres (obtained from known parameters – the fibre diameter and the number of fibres in each tow) divided by the area of the tows (obtained from CT image sections) [33].

Fig. 3. (a) 3D rendering of the X-ray CT scan showing the alternately biased fibre tows in the 2/2-45° braided tube illustrating the image unwrapping process. (b) A schematic of the X-ray CT section along A-A in (a) illustrating the calculation of the crimp angle.
The level of crimp is a crucial factor for textile composites as it directly influences the mechanical behaviour of the composite [34]. The crimp angle ($\Phi_c$) was measured by unwrapping CT slices from the tubular shape to form a virtual flat panel using the Polar Transformer plugin in Fiji ImageJ [24,35]. The unwrapped flat panel has a height equal to the imaged tube height, a thickness equal to the wall thickness and a width equal to the mean circumference of the tube. In addition, the damage area fraction in the tubular specimen was calculated based on the unwrapped data, as will be discussed in Section 5.

3. Microstructure and mechanical performance of braided CFRP tubes

3.1. Microstructure of the braided tubes

The 3D microstructure of the braided CFRP tubes can be assessed by X-ray CT. Other than qualitative visualisation of the braid architecture and manufacturing defects, quantitative measurement of the braid parameters such as crimp and fibre volume fraction are also of importance in comparing the behaviours. The crimp angle has been calculated based on unwrapped images as shown in Fig. 3c. Unsurprisingly, the crimp angles for the 1/1 braids are higher than those for the 2/2 braids (see Table 1) because that the tow interlacing interval for the 1/1 structures is shorter than for the 2/2 structures, which results in larger waviness at tow cross-overs. For a specific braid pattern, the crimp angle for 45° structures are relatively higher than that for the 35° structures. Table 1 also shows the fibre volume fractions of the composites having the different braid structures measured following the approach reported in [25].

Table 1. Microstructural parameters of the braided composite tubes measured by X-ray CT.

| Braiding pattern | Braiding angle (°) | Crimp angle (°) | Fibre volume fraction (%) |
|------------------|--------------------|-----------------|---------------------------|
| 1/1 diamond      | 35                 | 16.5±2.3        | 41.1                      |
| 2/2 regular      | 35                 | 11.7±1.0        | 44.5                      |
|                  | 45                 | 13.2±0.8        | 45.7                      |
3.2. Torsional performance of braided CFRP tubes

The shear stress-strain behaviours of the test-pieces were calculated from the applied torque and twisting angle according to Equations (1) and (2). Typical curves for the four braid structures are plotted in Fig. 4a. It is noteworthy that for 1/1 braided tubes the stress-strain curve is rather stable after the peak stress (indicating stable damage accumulation); whereas the shear stress response for the 2/2 braided tubes typically exhibits several steep drops upon exceeding the ultimate shear strength (peak load), suggestive of bursts of rapid damage accumulation. This also results in a lower remnant shear strength for the 2/2 braided structures than 1/1 at large shear strains (>4.5%). Moreover, the torsional performance is observed to be broadly repeatable from sample to sample. Fig. 4b shows the shear stress-strain curves for all three 2/2-45° specimens tested on the Instron 8802 alongside the 2/2-45° specimen tested in-situ. It is also reassuring that the in-situ tested specimen behaves similarly to the off-line tested specimens, which means that the damage evolution observed in-situ by X-ray CT is likely to be representative of the general behaviour of this braid structure. Note that the large stress drops at steps S3-36 for the in-situ specimen were caused by both the inherent damage-driven mechanical response of the material and the stress relaxation under fixed displacement during image acquisition.

The shear moduli and shear strengths of various braiding architectures are summarised in Fig. 5, including measured and normalised (to a $V_f$ of 45%) values for comparison across different structures. Overall, the 2/2 braided CFRP tubes exhibit higher shear strength (maximum shear stress) and higher shear modulus than 1/1 braids. For a given braiding angle, the 2/2 structures exhibit ~15-20% higher shear moduli and ~25-30% higher shear strength than the corresponding 1/1 structures. For a given braid pattern, the 45° braided CFRPs have higher shear moduli and lower shear strength than the 35° braids. Overall, the 2/2-45° braided CFRP exhibits the highest shear modulus and the 2/2-35° braided CFRP the highest shear strength among the four braid architectures studied. Comparing the trends in shear strengths and crimp angles of these braid structures, it is noteworthy that the composite shear strength decreases as the crimp angle increases.
Fig. 4. (a) Typical shear stress-strain curves of the 1/1 (in black) and 2/2 (in blue) braided CFRP tubes with different braiding angles tested on an Instron 8802. (b) Shear stress-strain curves for the 2/2-45° braided tubes tested on an Instron 8802 (1-3) and recorded by the in-situ load rig during the CT scanning where the load drops and the red circles indicate the CT scan periods recorded at constant displacement.

Fig. 5. Plots of (a) measured and (b) normalised ($V_f = 45\%$) shear moduli (blue) and shear strengths (amber) of CFRP tubes with different braid architectures, the error bars represent the variation across three tests.

4. Damage mechanisms in braided CFRP tubes

The damage evolution in the 1/1-45° braided CFRP tube has been reported previously [25]. In that case we found that torsional damage tends to initiate from axial
compression/transverse tension induced radial intra-tow cracking, followed by circumferential inter-tow debonding between oppositely biased tows (where the compressive tows are on the outside and the tensile ones the inside) followed by fibre micro-buckling in the axially compressed tows. In this section, the distribution and evolution of torsional damage in the 2/2-45° braided CFRP tube is explored from the time-lapse X-ray CT images. Under the applied torque (shear stress), the +45° tows are approximately in a state of axial tension and transverse compression, whereas the -45° tows are under axial compression and transverse tension. For clarity in the following discussions, the +45° tows which are loaded in axial tension are termed AT tows (color-coded yellow in Fig. 3), and the -45° tows which are being axially compressed are termed AC tows (color-coded green in Fig. 3).

4.1. Damage initiation and propagation

The mechanism by which damage first initiates in 2/2 regular braided CFRP tube is different from that in the 1/1-45° braided architecture [25]. The first cracks to appear at a torsional strain of around 1.2% are the result of a new damage mode - radial inter-tow debonding (see Fig. 6a (bottom)), which occurs between the paired AC tows (see Fig. 6b). This mode is not available for the 1/1 braids; by contrast the first damage to appear in the 1/1-45° braid is circumferential inter-tow debonding between ±45° tows (see the schematic in Fig. 6a (top)) and intra-tow cracking. Although adjacent AC tows tend to buckle under the shear-induced axial compression, the locations of the two buckles are shifted by the width of an AT tow, thereby generating a shear stress between the two adjacent AC tows and resulting in the radial inter-tow debonding between them. This damage mode is also clearly visible on the surface of the specimen as shown in Fig. 6c.
Fig. 6. (a) Schematic illustration of circumferential (top) and radial (bottom) inter-tow debonding damage modes. (b) X-ray CT 3D volume rendering of AC (green) and AT (yellow) tows highlighting the inter-tow debonding damage mode between adjacent AC tows which is the first damage mode to initiate for the 2/2 braid and (c) post-mortem photograph of the 2/2-45° braided CFRP specimen tested in-situ.

The sequence of damage development in the 2/2-45° structure can be established from the time-lapse sequence of the virtual 2D X-ray CT section oriented parallel to the tow (fibre) directions (see Fig. 7) and compared with that for the 1/1-45° case reported previously [25]. As discussed above, damage initiates through radial inter-tow debonding between adjacent AC tows in locations where they lie on the outside of the tube at a shear strain of 1.2% (see Feature A in Fig. 7). It is worth noting that subsequently this radial inter-tow debonding is also observed towards the interior of the tube (i.e. between two AC tows lying inside the AT tow) after a shear strain of 2.0% (see Feature B). The fact that damage tends to initiate from the outer surface of the tube, rather than the inner surface, can be attributed to the stress gradient along the tube radius observed in non-thin-walled tubes [36]. In the meantime, circumferential inter-tow debonding (Feature C) induced by the shear stress (similar to that observed in the 1/1-45° structure [25]) has occurred along the interface between the oppositely biased tows by 2.0% strain, where AC tows lie outside AT tows. We can see that it tends to
extend as far as the width of the AC tows on this section. By 2.9% strain (S4), intra-tow cracks (Feature D and F) start to appear and develop in AC tows. It is also worth noting that debonding between AC tows and the matrix (Feature E) is observed at the interior of the CFRP tube at this stage, accompanied by wavy deformation of the tube inner surface.

Fig. 7. Time lapse sequence of a virtual X-ray CT slice cut parallel to an AT tow of the 2/2-45° braided CFRP tube with increasing shear strain from 0 to 5.4%, showing the evolution of damage (yellow (AT tow) and green (AC tow) tinting added to black and white sections for clarity).

Based on the observations above, we can conclude that damage occurs predominantly along interfaces (between adjacent AC tows and between outer AC tows and inner AT tows) and within the AC tows. Fig. 8 shows a time series for a virtual section parallel to an AC (green) tow with increasing strain. It can be seen that the length of the circumferential inter-tow debonding along the AC tow is shorter than that along the AT tow (see Feature C in Fig. 7 and Fig. 8). Here, the debond extends to about two-thirds the width of two AT tows, as the AC tow is constrained in the through-the-thickness direction by the AT tows at the tow cross-over points. Moreover, the inner and outer surfaces of the tube both take up an increasingly wavy conformation with increasing shear strain due to tendency for the AC tows to protrude radially and the AT tows to
intrude. As the shear strain reaches 5.4%, the axial compression along the AC tow, together with the shear stress concentration at the tow cross-over points, promotes fibre micro-buckling and fibre kinking, see Fig. 8. Moreover, as shown in Fig. 7 and Fig. 8, it is evident that under increasing shear strain, the AT tows become straighter (lower crimp) under shear induced axial tension, while the AC tows become wavier (higher crimp) under shear induced axial compression.

Fig. 8. A time-lapse sequence for an X-ray CT virtual slice cut parallel to an AC tow of the 2/2-45° braided CFRP tube with increasing shear strain from 0 to 5.4%, showing the evolution of damage (yellow (AT tow) and green (AC tow) tinting added to black and white sections for clarity).

As illustrated in Fig. 9a, the 2/2 pattern gives rise to waviness (crimp) in the fibre tows with a half-wavelength of about two times the tow-width. Given that fibre misalignment and waviness can significantly degrade the compressive strength of unidirectional CFRP [37], the intrinsic waviness in the braid structure makes the braided CFRP susceptible to shear (torque) induced axial compressive stress along the AC tows. Various conformations of fibre micro-buckling and fibre kinking have been observed in the 2/2-45° specimen (see Fig. 9b-d). Fibre micro-buckling and fibre kinking tend to occur
within the AC tow segments lying outside the AT tows (Fig. 9b-c), accompanied by circumferential inter-tow debonding, similar to that developed from a notched region under four-point bending reported in Wang et al [38], due to the lower through-the-thickness constraint near surface. Two typical positions for fibre kink bands to develop have been observed, either close to one tow cross-over point (see Fig. 9b) or in the middle between the two cross-over points (see Fig. 9c), depending on the local stress distribution. In addition, fibre micro-buckling/kinking can also be found in the AC tow segments lying inside the two AT tows (see Fig. 9d), which initiated from the point between the two AT tows and developed towards the inner surface of the tube. The matrix deformations on the inner and outer surfaces of the tube are indicative of large shear stresses in this local band. The three typical cases presented in Fig. 9b-d resemble the type 1 (shear) fibre micro-buckling defined by Wang et al. [38], where lateral displacement either side of the kink band is pronounced.

Fig. 9. (a) Schematic of a typical section along the AC tow (the blue shading indicates where AC tow lies outside AT tows, while the pink shading indicates where the AC tow lies inside the AT tows). (b-d) Regions of interest taken from X-ray CT sections (parallel to AC (green) tows) for the 2/2-45° braided tube under 6% shear strain and the corresponding schematics illustrating different types of fibre micro-buckling and fibre kink-band formation (red lines) caused by the shear-induced axial compression.
4.2. Overall damage distribution

Apart from the detailed examination of various damage modes within a region-of-interest as discussed above, the overall damage distribution in the 2/2-45° structure under torsion can also be assessed by 3D volume rendering of the X-ray CT images. Fig. 10 shows the 3D rendered volume of the 2/2-45° CFRP tube under increasing shear strain, where the damaged regions appear lighter than the undamaged ones. It is evident that the damage is localised into vertically interconnected bands (columns) parallel to the tube axis. This damage has occurred in regions where the AC tows lie outside the AT tows (i.e. the green columns in the colourized rendering in Fig. 10). In these locations the AC tows have buckled outwards under the shear (torque) induced axial compression and the interface between the outer AC tow and the inner AT tow have debonded.

Overall, the damage in the 2/2-45° structure has propagated by almost simultaneous circumferential debonding for all the (green) patches down a vertical column, and then sequentially (green) column by (green) column thereby causing the sequential load drops with increasing shear strain, as highlighted by the dashed boxes in the loading sequence shown in Fig. 10.

Fig. 10. Semi translucent X-ray CT 3D volume renderings showing the propagation of damage in 2/2-45° braided tube with increasing shear strain, where the lighter regions indicate the presence of damage.
5. Effect of braid pattern on torsional damage evolution

Comparing the damage evolution of 1/1-45° CFRP reported by Chai et al [25] with that of the 2/2-45° CFRP reported here, we can explore the effect of braid pattern, diamond (1/1) or regular (2/2), on the damage mechanisms under torsion. Fig. 11 shows typical shear stress-strain curves alongside photographs of the specimen surfaces for the 2/2-45° specimen (a1-a4) and the 1/1-45° specimen (b1-b4) at the corresponding stages of the torsional straining. From these photographs we can see that damage propagates quite differently for the two structures. As discussed above for the 2/2 structure from the 3D CT renderings in Fig. 10, the vertical bands of damage (highlighted by ellipses in Fig. 11) are evident on the specimen surface. For the 1/1-45° braided structure, intra-tow cracking damage (marked by the small ellipses) is evident on the specimen surface. These damage features are localised and are evenly distributed almost uniformly across the tube. By correlating the video sequence with the stress-strain response it is evident that each steep drop in the shear strength of the 2/2-45° specimen corresponds to the occurrence of a new ‘damaged column’ caused by the deformation of AC tows together with the circumferential ‘popping’ of interface between the outer AC tows and the inner AT tows. In the 2/2 structure, failure (buckling and debonding) of a single tow leads to a dynamic transfer of load to the adjacent tow: this stimulates failure of the adjacent tow, whereas for the 1/1 structure this local load-transfer effect is not evident. For the 1/1-45° specimen, damage initiates in the form of radial intra-tow cracks in the AC tows along with circumferential inter-tow debonding between the bias tows in regions where the AC tows are outermost (the green patches (see Fig. 1b)). whereas in the 2/2-45° specimen, damage initiates from radial inter-tow debonding followed by circumferential inter-tow debonding. The radial intra-tow cracks in AC tows observed in 1/1-45° specimen are similar to the longitudinal splitting in unidirectional CFRP developed under axial compression, which is likely to occur along the fibre/matrix interface. Thus, in both braid patterns interfacial performance is critical during the early stages of torsional damage. As damage propagates, circumferential inter-tow debonding becomes the dominant mechanism of strain relief in both structures.
Fig. 11. Stress-strain curves for 2/2-45 and 1/1-45 braided tubes alongside stills taken from live video imaging (see supplementary info) showing surface damage accumulation in the 2/2-45° (at stages a1-a4) and 1/1-45° (at stages b1-b4) samples with increasing shear strain.

In order to understand the difference in the propagation of circumferential inter-tow debonding between the 1/1 and 2/2 braids, the inter-tow debonding damage was extracted from the X-ray CT images of the 1/1-45° and 2/2-45° specimens at $\bar{\gamma} = 2.0\%$ (just after the peak in shear stress). The unwrapped segmented circumferential inter-tow debonding damage is projected throughout the wall thickness onto one image (see Fig. 12). The area fraction of the debonding damage was calculated at $\bar{\gamma} = 2.0\%$ from Fig. 12. The debonded area fraction in the 2/2-45° specimen (18%) is larger than that of the 1/1-45° specimen (15%). More importantly, each debonded ‘patch’ is much larger than that for the 1/1-45° specimen. This is because the tow interlacing distance is doubled in the 2/2-45° structure, which gives rise to a larger individual interfacial area between bias
tows. The denser array of tow cross-over points in the 1/1-45° braid structure helps to constrain the extent of circumferential inter-tow debonding. Further, the fact that the regions where the AC tows are outermost are connected as vertical bands in the 2/2 case, but distributed into a checker board pattern for the 1/1 braid means that the strain relief and hence strength drop caused by the buckling of AC tows and the propagation of the circumferential cracks means that the degradation in strength for the 2/2 stress strain curve is less gradual than for the 1/1 braid once the peak strength has been exceeded.

Fig. 12. Unwrapped and projected circumferential inter-tow debonding damage (blue) obtained from segmented X-ray CT images, showing the distribution of this damage mode between biased tows for 1/1-45° (top) and 2/2-45° (bottom) braided CFRP tubes at a shear strain of ~2.0%, overlaid on top of the braid pattern of AC (green) and AT (yellow) tows.

During the latter stages of torsional failure, fibre micro-buckling and kink-band formation (along with fibre fracture) in the AC tows are the key damage modes in both 1/1-45° and 2/2-45° structures. In the 1/1-45° structure, fibre micro-buckling and kink bands tend to develop close to tow cross-over points [25], while in the 2/2-45° structure, the mid-point between two tow cross-overs is also susceptible to fibre kinking (see Fig. 9c). This might be due to the fact that the tow interlacing distance is almost doubled in the 2/2 structure compared with the 1/1 structure, which imposes less through-the-
thickness constraint thereby promoting fibre micro-buckling/kinking. For the 1/1 braid, kink bands were only observed where the AC tow segments lie at the outer surface of the tube, whereas for the 2/2 braid, fibre kink bands were also observed where the AC tow segments lie at the inner diameter of the tube (see Fig. 9d). It is also noteworthy that under the excessive buckling of the AC tows in the 1/1-45° structure intra-tow cracking occurred rapidly in AT tows, while in the 2/2-45° structure the AT tows were barely damaged even at \( \bar{\gamma} = 6\% \).

6. Conclusions

In this study, we have investigated the torsional behaviour of T700 carbon fibre/epoxy resin braided composite tubes with various braid architectures. The key findings can be summarised as follows,

- In general, 2/2 braided CFRPs exhibit both higher shear strength and higher shear modulus than 1/1 braided CFRPs. This is related to the lower crimp (crimp angle) associated with the 2/2 braids. However, the shear strength for the 2/2 braided CFRP drops significantly beyond the peak stress showing significant and sudden load drops. By contrast the 1/1 braids show very modest falls in strength after the peak stress and the degradation in strength is gradual, thus exhibiting a degree of ‘ductility’ under torsion. As a consequence, the 1/1 has a higher remnant strength at torsional strains in excess of 4.5 %.

- While 45° is the optimum angle for a filament-wound tube under torsion, for braided tubes, the braid angle has a complex relation with the shear modulus and strength. For a given braid pattern, the 45° braided CFRPs have higher shear moduli and a lower shear strength than the 35° braids. It appears that the torsional strength of a braided tube is highly sensitive to the crimp angle, which could be attributed to the susceptibility of crimped tows to axial compression.

- Through time-lapse synchrotron X-ray CT monitoring of the stress-strain behaviour the damage sequences have been captured. For the 2/2-45° braided CFRP tube, damage initiates from radial inter-tow debonds between adjacent AC (i.e. under shear (torque) induced axial compression) tows, followed by circumferential inter-tow debonding between \( \pm 45° \) biased tows in locations...
where the AC tows are outermost. At higher strains intra-tow cracking, fibre micro-buckling and kink-band formation (fibre fracture) are also observed in AC tows. The significant drops in shear strength recorded for the 2/2 braids have been shown to be related to the occurrence of the buckling of AC tows together with the propagation of circumferential debonding of the AC tows from the AT tows down vertical zones. The chequer board nature of the tows for the 1/1 structures prevents the formation of such interconnected damage zones.

- The fibre/matrix interfacial strength is important, as it controls damage initiation under torsion. Tow cross-over density is a key factor in controlling damage propagation under torsion. Tow cross-overs can arrest circumferential inter-tow debonding, thus gives rise to smaller debonding area in the 1/1 structure than 2/2 structure. However, the crimp caused by the tow cross-overs contributes to the occurrence of fibre micro-buckling. It is found that the fewer tow cross-overs in 2/2 structure gives rise to larger tow interlacing distance which imposes less through-the-thickness constraint that could promote fibre micro-buckling.

The above key findings provide key insights into the design of braid architecture for torsionally loaded components. For applications requiring high shear strength and/or high shear modulus, 2/2 braided CFRP tubes are advantageous over 1/1 braided CFRP tubes. However, for applications that require higher structural integrity once damage has started to develop, 1/1 braided CFRP tubes could be a better option since 2/2 structures suffer from significant drops in shear strength once damage starts to propagate.

In the current study the lack of radial constraint of the AC tows is critical in terms of damage propagation in the form of debonding and fibre micro-buckling. This suggests that the additional through-the-thickness constraint offered by through-the-thickness binders, hoop-winding or multiple layers may improve torsional strength. Future research could focus on developing novel braided structures with low crimp angle (for strength) but increased number of cross-over points (for damage tolerance).

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