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Evolution of Kink Bands in a Notched Unidirectional Carbon Fibre-Epoxy Composite Under Four-point Bending

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Abstract
Kink-band nucleation and propagation has been monitored over time in three dimensions (3D) by time-lapse X-ray computed tomography (CT) in the compressive zone of a blunt notched unidirectional (UD) T800 carbon fibre/epoxy composite under in situ four-point bending (FPB). The kink bands that develop from micro-buckling are classified into two types namely type 1 and type 2 by analogy with Euler buckling. Type 1 (shear) kink bands accommodate a lateral displacement of the fibres either side of the kink band; whereas type 2 kinks comprise conjugate pairs forming chevrons (accompanied by a tilt if the bands are wedge-shaped). In the central plane of the sample the kink bands lie in the plane of bending whereas near the side surfaces the lack of lateral constraint means that type 2 kink band pairs protrude out of the surface (normal to the bending plane) from the notch corners down the sides of the sample. Moreover, a comparison of loaded and unloaded X-ray CT scans shows that geometries measured post-mortem on cross-sections may not be wholly representative, with the angle of the broken fibre segments within the kink bands reduced by 10-20° and the curvature of buckled fibres almost halved. The novelty of this work relates to the observation of the nucleation and propagation of fibre kink bands in three dimensions and the definition and quantification of kink band variables that could lead to more accurate modelling and simulation of compressive behaviour.
Keywords: A. Carbon fibres, B. Fracture, C. Buckling, C. Damage mechanisms, D. Non-destructive testing

1. Introduction

Carbon fibre reinforced plastics (CFRPs) exhibit excellent specific tensile strength and stiffness; however, their compressive strength is often 30-40% lower. This, combined with the fact that failure by fibre instability followed by kink-band formation can occur suddenly, presents a problem in structural design [1]. A number of studies have focused on the damage mechanisms leading to compressive failure, and the interaction between these damage modes [2–5], including fibre kink bands, matrix shear cracks, and longitudinal splitting along the interface or in the matrix. The occurrence of kink bands has been found to be the key mechanism resulting in premature and catastrophic failure under compressive loading [6]. Thus, a better understanding of the kink-band formation mechanisms is essential in order to improve the compressive performance of CFRP.

Since early studies were limited to post-mortem observation by serial sectioning combined with optical or scanning electron microscopy (SEM), our understanding of the evolution of kink bands has largely been based on the post-failure damage patterns [7]. With the help of in situ loading rigs in electron and optical microscopes, the development of kink bands has also been observed on the sample surface of composites loaded under compression [3–5,8]. Vogler and Kyriakydes [3] and Pimenta et al.[4] observed kink-band propagation along the kink-band boundary direction and the formation of multiple kink bands on the ground and polished surface of UD CFRP samples. Hapke et al. [5] evidenced the sudden nature of kink-band formation with their observation that in two sequential SEM images of the sample surface, the kink band had formed and propagated over 100 µm in 0.2 s. In these studies, the observation of kink-band development is in two dimensions from the sample surface.

However, because of the reduced constraint, it is not clear whether kink-band formation at a free surface is representative of what happens within the bulk material. Therefore, there is a
need to explore the morphology and development of kink bands in three dimensions (3D). X-ray computed tomography (CT) enables the non-destructive characterisation of the 3D micro-structures of materials and components [9]. It has proven to be effective in assessing internal defects and damage in CFRP [10]. We have previously reported the post-mortem 3D morphology of kink-band induced failure under uniaxial compression for unidirectional (UD) T700 carbon fibre/epoxy composite [11]. The geometrical correlation between damage modes, including fibre micro-buckling, longitudinal splitting and matrix micro-cracking, has been postulated within the damage zone of multiple kink bands [11]. However, it is difficult to infer the temporal evolution of such multiple kink bands on the basis of post-mortem observations. Moreover, monitoring the nucleation and propagation of kink bands during loading by axial compression is challenging because of sudden fibre fracture without prior warning. According to our recent high frame rate (10,000 Hz) synchrotron X-ray imaging experiments [12], the kink band formed in less than 1.2 ms, making real-time capture of the kink-band formation under axial compression by X-ray CT infeasible at present.

Given the technical limitations in characterising such rapid failure, an alternative strategy has been to slow down the failure process. Vogler and Kyriakides [3] employed biaxial loading (combined shear and axial compression loading) to stabilise the kink-band propagation process in UD CFRP for in situ observation of the sample surface. Alternatively, Pimenta et al. [4] used samples with the fibres oriented off-axis to induce shear under compressive loading. It has also been reported that the development of kink bands can be slowed by the presence of 90° laminae [13], by introducing a notch, or by testing in bending [14,15] to achieve a gradient in the stress field. In the last case, the kink band initiates in the location with the highest compressive stress and propagates into the less compressively stressed regions giving rise to a more stable failure process; it should also be noted that initial fibre misalignment contributes to the initiation of fibre instability.
In this paper, a blunt notched UD CFRP specimen is loaded progressively under four-point bending (FPB) *in situ* for time-lapse X-ray CT imaging so as to identify the nucleation and propagation sequence and mechanisms by which the kink bands occur.

### 2. Materials and Methods

#### 2.1 Composite sample preparation

The carbon fibre/epoxy $[0]_{32}$ laminate was manufactured from 32 plies of UD T800H/MTM28-1 pre-preg supplied by Umeco Structural Materials Ltd. The tensile properties of the carbon fibre and a similar composite system obtained from material datasheets are shown in Table 1. The ply thickness was 0.125 mm and fibre volume fraction was approximately 51%, measured by the matrix digestion method described in ASTM D3171 [16]. Specimens with nominal dimensions of 25 mm in length, 2 mm in width and 4 mm in depth were cut from the laminate using a diamond saw. Fig. 1 shows the schematic of the specimen geometry, with the nominal 0° fibre direction lying along the X axis and the lay-up sequence along the Z axis. To stabilise the development of kink bands and constrain the damage site within the limited field of view (FoV) of X-ray CT, each sample was pre-notched (notch width ~0.8 mm and depth ~2 mm) mid-length using two cutting wheels (each 0.35 mm thick) stacked together to make a wider notch on a precision cutting machine.

| Mechanical Property | T800H Carbon Fibre [17] | T700/MTM28 Composite (normalised to 60% fibre volume fraction) [18] |
|---------------------|-------------------------|---------------------------------------------------------------|
| Tensile Strength (MPa) | 5490                     | 1726                                                        |
| Tensile Modulus (GPa) | 294                      | 121                                                         |
Fig. 1: (a) Schematic of the four-point bending (FPB) specimen geometry and loading configuration. (b) Load versus displacement plot for the in situ FPB test.

2.2 In situ four-point bend test

The FPB test was performed in a Deben CT5000 Tension/Compression loading rig (see Fig. 2(a)). The inner ($l_1$) and outer ($l_2$) loading spans were 7.5 mm and 20 mm, respectively, Fig. 1(a), with the load applied at 0.1 mm/min under displacement control via 5 mm-diameter glassy carbon loading rollers. The load versus displacement curve for the specimen during the in situ FPB test is shown in Fig. 1(b) with the load interrupted (fixed displacement) to acquire each X-ray CT scan (numbered 0-4) during which time the load decreased by ~13%. The maximum flexural stress of an unnotched specimen is given by

$$\sigma = \frac{3}{2} \frac{P (l_2 - l_1)}{bd^2}$$

where $P$ is the applied load, $b$ the specimen width and $d$ the specimen depth (thickness).

Under the FPB loading condition in Fig. 1(a), the nominal compressive stress along the X direction at the notch top surface is estimated using Equation (1) with $d=2$ mm, which is the net section of the specimen.
Fig. 2: Photographs of experimental set-up for (a) in-situ and (b) post-mortem X-ray CT imaging. The insets in (a) show the sample on loading rollers inside the rig and the damage observed in a radiograph after load step 3.

2.3 Time-lapse X-ray computed tomography

The Deben rig was accommodated within a Zeiss Xradia Versa 520 scanner and radiographs were acquired continuously during loading. The loading was interrupted when new damage appeared in the X-ray radiographs (see inset in Fig. 2(a)). A CT scan was then acquired once the load had stabilised (after ~0.5 hour) to avoid motion blur. The displacement was maintained during each scan, but some degree of load relaxation was observed during each dwell, Fig. 1(b). Five scans (labelled 0-4) of the notched region were taken at compressive stresses of around 0, 860, 910, 1040, 1120 MPa (a nominal value estimated by Equation (1) with $d=2$mm). A post-mortem scan was acquired on a Zeiss Xradia Versa 400 scanner after unloading. For in situ imaging, the sample was oriented horizontally in the loading rig. In this case, the X-ray path is much longer for projections (radiographs) through the length of the specimen than those through the width. This variation in X-ray attenuation can cause reconstruction artefacts which degrade the image quality. In the post-mortem scan, the length
of the sample was mounted vertically to improve X-ray CT image quality, Fig. 2(b). The X-ray CT imaging set-up parameters are summarised in Table 2. The X-ray CT scans were reconstructed in the TXM Reconstructor software and then imported into the Avizo 8.0 software (FEI Visualisation Sciences Group) for image analysis.

Table 2: Scanning parameters employed for the *in situ* and *post-mortem* X-ray CT.

| Experiment                  | *In situ*                   | *Post-mortem*               |
|-----------------------------|-----------------------------|-----------------------------|
| X-ray CT Instrument        | Zeiss Xradia Versa 520      | Zeiss Xradia Versa 400      |
| Accelerating Voltage (kV)  | 80                          | 40                          |
| Power (W)                   | 7                           | 10                          |
| Source to Sample Distance (mm) | 65                          | 40                          |
| Detector to Sample Distance (mm) | 180                         | 20                          |
| Optical Magnification       | 4x                          | 4x                          |
| Binning                     | 2                           | 1                           |
| Exposure time (s)           | 22                          | 10                          |
| Number of Projections       | 1001                        | 1501                        |
| Voxel size (µm)             | 1.8                         | 2.2                         |
| FoV Width (mm)              | 1.8                         | 4.4                         |

3. Results

3.1 Nucleation and propagation of kink-bands in the mid-plane section

As anticipated the failure process took place in a more stable progressive manner for the FPB tests compared with previous axial compression tests [12]. The mid-plane virtual XZ cross-sections are shown in Fig. 3 for loading steps 0–4. At step 0, no voids have been observed in the sample at the resolution with the applied X-ray CT settings.

Two types of fibre instability (fibre micro-buckling) are evident. As depicted in Fig. 4, type 1 (shear) fibre micro-buckling is associated with a lateral displacement either side of the kink band, while no lateral displacement is evident for type 2 (chevron (V-shaped)) fibre micro-buckling.

From images of the mid-plane section the following sequence of events can be discerned:
Load step 1 at 860 MPa (see Fig. 3(b)): Fibre fracture due to type 2 fibre micro-buckling is evident close to the left notch corner (LNC) giving rise to a kink band – feature A, where fibres bend and break into the free surface.

Load step 2 at 910 MPa (see Fig. 3(c)): The kink band has propagated from near the LNC into the inner part of the sample, indicated by the arrow in Fig. 3(b). The onset of type 1 fibre micro-buckling (feature B) is now also evident just below the right notch corner (RNC).

Load step 3 at 1040 MPa (see Fig. 3(d)): The propagation of fibre failure from the LNC appears to have been arrested; meanwhile a kink band (feature C) has developed from type 1 fibre micro-buckling below the RNC, accompanied by a split (feature D) stopping the further growth of the kink band; bent but unbroken fibres are evident above feature C.

Load step 4 at 1120 MPa (see Fig. 3(e)): Multiple kink bands (feature E) have formed from the primary kink band (the first kink band in a series of multiple kink bands) and the compressive misfit near the notch has been alleviated by forcing upwards a wedge thus opening the split into an elongated rectangular shape. The split appears to impede the propagation of Set 2 kink bands. At the other end of the split, further fibre micro-buckling and another set of shear type kink bands form (Set 3) (feature F).
Fig. 3: (a-e) X-ray CT virtual cross-sections of the mid-width (XZ-3 as marked in Fig. 5(c)) plane in the specimen at steps 0-4, showing damage evolution under four point bending. (f) Schematic illustrating the in-plane damage evolution and kink-band parameters ($\omega$, $\phi$ and $\beta$) that will be detailed in Section 4.1.
The damage sequence reported here is in line with our offline FPB tests on a range of UD CRFP systems [19] in that due to the stress concentration at the notch tip, kink bands tend to initiate near the notch top surface at a set distance from one or other notch corner as a result of type 2 fibre micro-buckling (Feature A), followed by the development of a second set of kink bands localised close to the other notch corner due to type 1 fibre micro-buckling (feature C). Splits tend to occur accompanying the formation of kink bands. It is evident that the fibre kink bands act together to move a ‘wedge’ of material upwards thereby relieving some of the axial compressive misfit. The above damage sequence was observed in all of the three samples that were imaged with X-ray CT following the approach reported here. It is worth noting that as reported by Davidson and Waas [20], the peak compressive stress for kinking instability is dictated not only by the matrix yield strength but also by other composite properties affecting the onset of fibre rotation in a yielded matrix such as the initial fibre misalignment angle.

Fig. 4: Schematic diagram showing the two fibre micro-buckling types here referred to as: (a) type 1 (shear), and (b) type 2 (chevron (V-shaped)).
Fig. 5: (a) Post-mortem X-ray CT 3D volume rendering showing the out-of-plane micro-buckling at the side surfaces. (b) Schematic of the out-of-plane damage zones near the sides. (c)-(f) virtual X-ray CT XY sections showing the in-plane and out-of-plane buckling and kink bands at different depths from the notch top surface. The locations of the XY sections shown in (c)-(f) are illustrated in (a). The FoV of the in situ scans is represented in (d) as a white circle, and the corresponding section acquired in situ at step 4 shown as an inset.
3.2 In-plane (in the plane of bending) and out-of-plane kink bands

In axial compression studies, features lying in the plane of lamina are often termed as ‘in-plane’. In the present FPB testing, the XZ plane in which the bending moment was applied, Fig. 1(a), is referred to as ‘in-plane’. It is evident from Fig. 3 that for the mid-plane section damage occurs by the formation of in-plane kink bands (i.e. kink bands within the XZ plane).

The regions close to the sides of the specimen were not in the FoV of the *in situ* scans. However, due to the larger FoV (lower resolution) employed in the post mortem scan they can be seen in Fig. 5 where it is evident that out-of-plane kink bands occur in the region of reduced lateral constraint locally around the band, top notch surface and near the specimen sides (edges). Indeed at the junction of the top and side surfaces (inset in Fig. 5(a)) the kink damage has both in-plane and out-of-plane components.

It is noteworthy in Fig. 5 that near the top surface of the notch (slice XY-1) the in-plane (in the interior) and out-of-plane (near the sides) kink bands occur at approximately the same distance in X from the corner of the notch, but while the out-of-plane damage runs vertically down the side of the sample (constant X position), the in-plane damage in the interior moves inwards towards the centre of the notch with depth forming a wedge (See Fig. 3(e)). This gives rise to an increasing step between the two kink types with increasing depth when viewed in the XY plane (Fig. 5(c)-(e)). In XY-3 these can be seen to be joined by a longitudinal split through a shearing mechanism. The downward propagation front of the out-of-plane buckling wave is evident in XY-4 further below the notch, where there is evidence of splitting and an outwards type 2 micro-buckling (see Fig. 5(f)).

4. Discussion

According to the observations two types of fibre kink bands have been identified, namely: type 1 (shear) kink bands (e.g. feature E in Fig. 3) which originate from type 1 fibre micro-buckling (see Fig. 4(a)); and type 2 (chevron (V-shaped)) kink bands (e.g. feature A in Fig. 3)
that arise from type 2 fibre micro-buckling (see Fig. 4(b)). The two classes of kink bands are shown schematically in Fig. 6. Given that in this FPB test geometry in-plane kink bands predominate in the bulk, our discussion on kink-band morphology and development below is focused on the in-plane kink band observations, although initial damage can also arise from out-of-plane fibre micro-buckling as observed in Fig. 5(f).

Fig. 6: Schematic diagrams showing the proposed mechanisms of a) type 1 (shear) and b) type 2 (chevron (V-shaped)) kink-band formation.

4.1. Geometrical characteristics of the kink bands

The geometrical characteristics of the in-plane kink bands were measured in 20 virtual XZ cross-sections along the Y axis, in terms of the kink-band width ($\omega$), the fibre rotation angle within the kink band ($\phi$) with reference to the X direction and the kink-band boundary angle ($\beta$) with reference to the Z direction (see Fig. 3(f)). The measured kink-band parameters both when under load and after unloading are summarised in Table 3. The kink band width, $\omega$, for
type 2 kink bands ranges more widely than for type 1. It is also worth noting that the $\beta$ angle for type 2 is smaller than that for type 1. It can be inferred that this variation is caused by a difference in the nucleating mechanisms, which are discussed in Section 4.2.

Table 3: Kink-band parameters for type 1 and type 2 in-plane kink bands measured from X-ray CT virtual XZ slices at step 4 under load (in situ) and after unloading (post-mortem).

| Geometry Parameters | Type 1 | Loaded | Unloaded | Type 2 | Loaded | Unloaded |
|---------------------|--------|--------|----------|--------|--------|----------|
| $\omega$ ($\mu$m)   | 15-30  | 15-30  | 15-125   | 15-125 |
| $\phi$ (°)          | 45-60  | 20-50  | 30-50    | 20-40  |
| $\beta$ (°)         | 20-35  | 20-35  | 0-25     | 0-25   |

Fig. 7: Virtual X-ray CT slices of the XZ-2 section (see Fig. 5(c)) acquired at a) load step 3, b) load step 4 and c) after unloading, showing that the geometry of the type 1 primary kink band (feature C, Fig. 3(d)) barely changes with increasing loading despite an increase in the number of bands. The fibre rotation angle reduced upon unloading, while the boundary angle was maintained.

Given that the diameter, $d_f$, of the T800 carbon fibre is around 5 $\mu$m, it is noted that $\omega$ is in the range 3-25 $d_f$. This is consistent with our previous observation for axial compressive failure [11], and further validates the dependence between kink-band width and fibre diameter [21].
The three individual narrow kink bands (see Fig. 7(b)), each of which is between 15 to 25 µm (~3-5$d_f$) wide, making up a multiple kink band exhibit shorter broken fibre segments than those in previous observations in literature which range from 5 to 20$d_f$ [22–24]. This may be caused by the difference in the material system, the loading conditions and the local stress distribution, or by the fact that our analysis of the kink bands made in 3D, providing more detailed information than a selected 2D section.

4.2. Mechanisms of kink-band development

As discussed in Section 3.1, type 2 kink bands (Set 1) form first from type 2 fibre micro-buckling at the LNC, followed by type 1 kink bands (Set 2) at the RNC and then both type 1 and type 2 kink bands (Set 3) developed below Set 1 (see Fig. 4(e)). Longitudinal splitting was also observed that can arrest growth of or trigger fibre micro-buckling, absorbing energy in the process and delaying ultimate failure. The importance of splitting as a relief mechanism in the post-peak regime has been reported by Prabhakar and Waas [25]. The mechanisms are discussed in the order of their occurrence in the following sections.

4.2.1 Development of type 2 kink bands

Fig. 3(b) shows that by load step 1 a type 2 kink band has already formed from the LNC. Although the precursor to fibre fracture before step 1 was not captured here, observations of a similar T700 carbon fibre/epoxy composite loaded under FPB [19] have captured the initiation process, which is similar to the manner in which the out-of-plane type 2 damage is observed to propagate down the sides of the sample in Fig. 5(c-f). This sequence is illustrated in Fig. 6(b). Fibres first fracture due to type 2 micro-buckling at the maximum bending point when the critical minimum bend radius is approached. This is followed by a plane of fibre fractures on one or both sides of the symmetry plane to form one or a pair of conjugate kink bands. The term conjugate kink bands has been used to describe oppositely inclined kink bands [26,27]. The incipient fracture line lies down the centre (perpendicular to the
compression axis, while the second fracture line tends to lie at an angle of approximately half of $\phi$ with respect to the incipient boundary (this explains the smaller average $\beta$ angle of type 2 kink bands) thereby forming a double wedge-shaped kink band similar to that previously observed by Liu et al. [28] in a plastic hinge failure of a [0/90]$_{4s}$ PE fibre laminate cantilever. The formation of type 2 kink bands introduces an axial shortening but as illustrated in Fig. 6 this wedge angle also confers a tilt. A net bending deformation exists so that there is no volumetric change. As the two fibre fracture planes are not parallel, the kink-band width defined by the length of broken fibres changes gradually along the band boundary, resulting in a broader range of width. Hahn et al. [29] reported type 2 fibre micro-buckling induced kink bands in the post-mortem observation of axial compression failure of T300/epoxy composite, but this feature is more common to flexural tests [30,31]. This can be attributed to the facts that greater lateral constraint is present in region of loading rollers under FPB loading and also type 2 fibre micro-buckling induced wedge-shaped kink bands can accommodate the tilt resulting from the applied bending moment, Fig. 6(b).

4.2.2 Development of type 1 kink bands
The development of type 1 kink bands can be inferred by studying the formation of kinking (Set 2 in Fig. 3) at the RNC in the time-lapse sequence. It is evident that the primary kink band nucleates from type 1 fibre micro-buckling (with lateral displacement) which is evidenced that after load step 2 (Feature B) showing a band of fibres misoriented by less than 5º to the original fibre direction (see Fig. 3(c)). Upon further loading (step 3) some fibres have formed a partial type 1 kink band while other fibres are buckled with no fracture and could fully or partially recover once the load is removed.

With increased loading the misfit is accommodated by propagation of the primary kink band and its broadening into multiple kink bands (see Fig. 7). The 3D visualisation of the kinking sequence with increasing load in Fig. 8 shows that the primary kink band propagates through
the width (Y) of the specimen. Here, the propagation in this dimension is termed as the transverse propagation in order to distinguish it from the lateral propagation (along the kink-band boundary direction in the XZ plane) and axial propagation (the broadening along the fibre direction) discussed in 2D studies [3,22–24,32–34]. Fig. 8(c) shows that the kink band propagates transversely for around 1000 µm before deviating slightly (by ~10°). It is evident that the kink-band geometry barely changes once it has formed, as has been reported by Vogler and Kyriakides in AS4 carbon fibre/PEEK system [3]. It is noteworthy that the in-plane kink band in the interior interact with the out-of-plane kink bands near the surface (see Fig. 5) which may pin the transverse edges of the primary kink band.

Fig. 8: X-ray CT 3D volume rendering of the segmented a) primary kink band at step 3, b) primary kink band at step 4, c) angled view showing the transverse propagation of the primary kink band, and (d-f) fully developed kink bands, coloured according to Fig. 7(b), beneath the RNC at step 4 showing the spatial arrangement of multiple kink bands.

As seen in Fig. 7 multiple kink bands form and these are shown in 3D in Fig. 8(d–f). Apart from the primary kink band (cyan), the width and length of narrow kink bands (pink and green) are almost identical (see Fig. 8(d–e)). The wider kink bands (orange and blue)
propagated further transversely in the Y direction than the two narrow kink bands (pink and green) (see Fig. 8(f)), but only the primary kink band (cyan) extends across the whole of the interior width.

The fibre orientation and reorientations that occur during the formation of the multiple kink bands can be discerned in the time sequence in Fig. 7. In Region 1, the fibre segments comprising the secondary bands are closely aligned with the orientation of the fibres in the primary kink band which do not significantly reorient as additional bands nucleate. In Region 2, the fibre segments in the secondary kink bands are less misoriented than those in the primary kink band. This suggests that the secondary kink bands form at a lower \( \phi \) angle and then fibre segments within secondary bands rotate to align with the primary band fibre segments in accordance with the ‘bend-break-rotate’ mechanism proposed by Vogler and Kyriakides [24].

Critically, the formation of multiple kink bands below RNC allows a larger lateral (vertical, along Z) displacement causing the split to open. This is complemented by the formation of an inwardly inclined type 1 kink band (Set 3 in Fig. 3(e)) at step 4. Taken together they cause a wedge of undamaged material to pop up vertically accommodating the compressive strain. This morphology is analogous to the box encountered seen in geology [26]. This long range complementary behaviour is in contrast to type 2 fibre kink bands which bring about no long range lateral displacement of undamaged material beyond the displacement of kinked region itself. The longitudinal splitting plays an important role in the development of kink bands here. It arrests kink propagation (Set 2) at RNC while triggering fibre micro-buckling below LNC (Set 3).

4.3. Effect of unloading on kinking

We have already seen that the kink damage modes are quite different on the surfaces of the sample from in the interior suggesting that 2D surface \textit{in situ} observation can be very
misleading. Given the reliance in the literature on post-mortem sectioning it is important to assess the degree to which the post-mortem features are representative of those present during loading. As both elastic and plastic deformation occur during kink-band formation, one might expect that the damage morphology will change when load is removed. In order to quantify the changes that take place before and after load removal we have compared the two sets of CT scans. The results are summarised in Table 3; in terms of the kink-band geometry parameters, comparison shows that the $\omega$ and $\beta$ values are not much affected by unloading, while the fibre rotation angle within the kink band $\phi$ tends to be reduced by 10-20°, as can be seen in Fig. 7 and Fig. 9. This is accompanied by a narrowing of the split adjacent to the kink bands.

Unloading also allows some recovery of fibre rotation in curved, but unbroken, fibres. Under load, fibre micro-buckling has been captured in the XZ-4 section close to the specimen side surface at step 4 (see Fig. 9(a)). The geometry of the buckled fibres was measured in Fiji ImageJ according to the schematic Fig. 9(c). The peak amplitude ($\sim$10 $\mu$m) and wavelength ($\sim$130 $\mu$m) of the two peaks were identical and the buckled fibres were 10-15° to the X axis.

The two zones of buckled fibres in Fig. 9(a) correspond to the Set 2 and Set 3 kink bands in the interior of the specimen in Fig. 3(e). This could indicate the propagation of the kink bands along the Y direction. Moreover, fibre micro-buckling of an entire waveform was captured in a localised region (XZ-1) close to the other side surface of the specimen (see Fig. 9(b)). The amplitude of the wave was $\sim$5 $\mu$m and the wavelength was $\sim$145 $\mu$m. This wavy pattern resulted from the complex local stress field in between a kink band (Feature H) and fibre shear breaks (Feature I) as shown in Fig. 9(b). Gutkin et al. [35] reported that this mode of shear-driven fibre fracture preceded the formation of kink bands. After unloading, the buckled fibres became significantly straightened as expected in the yellow boxes in Fig. 9(a-b). The curvature of the buckled fibres was found to halve when load was removed (see Fig.
Apart from recovering some of the deformation, unloading can also give rise to the development of new damage. For example, new splitting was opened at the tip of the narrow kink band (Feature G in Fig. 9(a)), which was located below the original fibre micro-buckling region. Moreover, kink-band boundary cracks tend to broaden upon unloading. Consequently, one should only regard the unloaded state as broadly indicative of the conditions under which the damage occurred.
Fig. 9: Virtual X-ray CT slice images showing two near surface sections a) XZ-4 and b) a XZ-1 section at maximum load (right) and after unloading (left); (c) Schematic diagram illustrating the measurement of fibre geometry.

Not only can deformation within the kinking plane (2D) be affected by unloading, the recovery of fibre rotation out of the kinking plane (3D) can also be brought about as highlighted with the white box in Fig. 9(a). Detailed examination of the fibres in this region at step 4 revealed that the fibres were not lying in any of the three orthogonal planes. However, after unloading the fibres appeared to lie almost within the XZ plane. In previous studies, most of the kink bands were found to be lying either in-plane or out-of-plane, which rationalised the 2D characterisation of kink bands. However, the present work suggests that fibre micro-buckling and the formation of kink bands are 3D in nature, thus it is important to study the mechanism of fibre micro-buckling followed by kink-band formation during loading rather than after unloading in order to avoid errors in kink band geometric parameters.

5. Conclusions

Four-point bending of notched samples gives rise to the stable and progressive development of kink bands in contrast to those that form under axial compression loading [12]. By undertaking such tests in situ we have been able to observe the nucleation and propagation of kink bands within the composite in 4D (3D+time) by time-lapse X-ray CT for the first time. As expected, in the interior the kink bands lie in the plane of the bending moment; however, near the side surfaces the kink bands are quite different and protrude out of the sides due to the lower sideways constraint. This means that surface observations are unrepresentative of bulk behaviour. Two fibre micro-buckling types have been observed through our loading sequences and we classify these as type 1 and type 2. Type 1 kink bands form as a result of type 1 fibre micro-buckling where the fibres are laterally displaced either side of the kink band. It is the most common mode for uniaxial compression of unidirectional composites.
Type 2 kink bands comprise conjugate (oppositely inclined) pairs, creating a V-shaped, chevron pattern of broken fibres. If the kink band boundaries are inclined (as in our case) this mode is also accompanied by a tilt.

In our case, type 2 kink bands tend to initiate first near a notch corner where high localised stresses develop and the surface ply is not constrained by a neighbouring layer; while in the long range greater lateral constraint is in place under the loading rollers. This is then followed by a type 1 kink zone near the opposing corner developing a damage zone between the notch corners. Upon further deformation the misfit is accommodated by multiple type 1 kink bands which form approximately parallel to the primary band through a ‘bend-break-rotate’ [24] process such that the kink angle is the same and their lateral displacements add. In contrast, the wedge shape of the type 2 fibre micro-buckling accommodates long range tilting. As damage propagates, a wedge of material tends to be vertically displaced to reduce the axial elastic strain near the notch in which longitudinal splitting plays an important role.

Upon unloading the fibre rotation angle within the kink bands can be reduced by as much as 10-20°, while the kink-band width and boundary angle are unaffected. Elastic fibre micro-buckling can recover on unloading. Longitudinal splits or cracks can either be narrowed or broadened upon unloading depending on the local stress distribution under load and in some regions extra damage can form. All these factors point to the need to observe kink-band damage under load where possible. While the precise sequence and interplay between type 1 and type 2 fibre kinking is specific to the notched FPB geometry, our other studies suggest that the morphologies, the nucleation and propagation effects are characteristic of many composite material systems [19].

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