Microscopic investigation of tow geometry of a dry satin weave fabric during deformation

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Abstract

In this paper the changes in tow geometry during deformation of dry woven carbon-fibre satin-weave fabric are measured and correlated with the in-plane forces applied. The evolution of geometric tow parameters such as tow spacing, crimp angle, tow amplitude and wavelength is investigated. To observe the change in the fabric architecture, specimens from bias extension, biaxial and picture frame tests are sectioned and observed under the microscope. It is found that the different loading conditions cause differences in the evolution of tow architecture during deformation, in particular affecting the onset of ‘lock-up’. (At lock-up interactions between tows prevent further significant shear deformation.) In one picture frame test the fabric is deliberately misaligned with respect to the sides of the frame so that, during subsequent deformation, one set of tows is under tension, while the other is compressed. There is a significant difference in behaviour between the two sets of tows. The variation in deformed tow geometry with shear angle is fitted using a simple parametric model.

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1. Introduction

Fibre reinforced composite materials are widely used in many areas of the automotive and aeronautical industries by virtue of their high specific stiffness and specific strength. Because fabric composites are easy to handle and have the flexibility to deform over mould surfaces, they are especially suitable for making parts with a complex geometry using the thermoforming or RTM (Resin Transfer Moulding) processes. For successful forming of complex structures, for example those containing surfaces with double curvature, it is important to understand the draping behaviour of the material, because the fabric structure and deformation pattern may significantly affect the properties of the final products. Microscopic investigation of the deformation patterns of fibre or tow structures is needed to understand the influence of fabric properties such as tow size, weave style, and constituent materials on the drapeability of the material. Typically these can lead to greater understanding of tow slippage and fibre lock-up phenomena. Fibre lock-up refers to the condition where interaction between tows after a given shear deformation prevents significant further shear of the material. Several researchers have modelled the deformation of the woven fabric geometry. Hofstee and van Keulen [1] suggested closed form relations that describe the 3-D geometry of a draped balanced plain weave and also presented a fibre bundle architecture which estimates the local deformation of tows. Vandeurzen et al. [2] proposed a 3-D geometric description for a 2-D woven architecture, which serves as the basis for stiffness and strength modelling of fabric composites. Hofstee et al. [3] tried to describe the yarn geometry as a function of shear deformation and fabric stretching deformation during the thermoforming of a plain woven composite. In their paper, the wavelength and amplitude of yarns were measured and compared with an analytical solution. The yarn crimp phenomenon was considered, as were shear deformation and yarn stretching. McBride et al. [4] defined the unit cell with 4 sinusoidal functions, which were composed of yarn width, yarn spacing and fabric thickness terms to represent fabric structure. These results are applicable to a sheared plain weave.
for which geometric parameters are given as a function of shear angle.

In this paper, the change of tow geometry in a satin weave fabric during deformation is investigated by observations of specimens that experience different loading conditions during biaxial, bias extension and picture frame tests. Because the fabric is subjected to different levels of in-plane membrane loading in these tests, we expect to see significant differences in internal forces developed between tows during fabric shear. These supposed forces are illustrated schematically in Fig. 1, showing lateral compression forces developed between adjacent tows and normal compression forces between the upper and lower sets of tows. The differences in these internal forces may in turn affect the way in which the tows can reorganise themselves in the different tests, and hence in the overall fabric response. Any such differences will have important implications for applying such coupon tests to real structures, where similar in-plane forces will develop in the fabric during draping. Observations of the change in tow geometric parameters during these tests are quantified. Although researchers have investigated tow deformation [3], they have not correlated the geometric changes with differences in membrane forces.

2. Experimental work

Three types of tests are described in this paper; bias extension, biaxial and picture frame tests. Carbon fibre dry fabric (Tenax HTA 6k, five harness satin weave) is
used for all the experimental tests. Its properties are listed in Table 1. Details of the test methods are given below. In all the tests the shear angle $\theta$ of the fabric was determined by observation of lines marked on the fabric.

### 2.1. Bias extension tests

Fig. 2a shows a schematic of the bias extension test, showing how the specimen is gripped at two ends and elongated along the bias direction. The shape and dimension of the specimen followed the ASTM standard D1774-93 for bias extension tests [5], which specifies $200 \times 75$ mm$^2$ with $[\pm 45^\circ]$ bias angle. Tests were performed using a relative velocity of the two ends of the specimen $v_x$ equal to 60 mm/min.

### 2.2. Biaxial tests

In the biaxial test, illustrated in Fig. 2b, fabric is pulled simultaneously in two perpendicular directions, both orientated in this case along the bias directions of the fabric. Because there is no standard for biaxial tests, a symmetrical cruciform specimen with the same length as the bias extension specimens was used. The left and right arms of the specimen are moved apart by a velocity $v_x$, while the top and bottom are separated by a velocity $v_y$ (see Fig. 2b). Different velocities are applied in the two directions to induce different stresses in these directions. A relative velocity of $v_x = 60$ mm/min is used for the major direction. The speed ratio $v_y/v_x$ of the minor to major axis velocities is set to be $0.25$. In other words the minor axis velocity $v_y$ is one fourth that of the major axis, and acts in the opposite direction, with the crossheads approaching each other. In these tests the large forces developed in the

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**Table 1**

Properties of Tenax HTA 6k, five harness satin weave

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tr>
<td>Areal weight (g/m$^2$)</td>
<td>370</td>
</tr>
<tr>
<td>Tow width (mm)</td>
<td>2.03</td>
</tr>
<tr>
<td>Centre-line tow spacing (mm)</td>
<td>2.17</td>
</tr>
<tr>
<td>Binder</td>
<td>2.5% per each side (5% total)</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Test arrangement; (a) bias extension test; (b) biaxial test; (c) sectioning details.
fabric limited the degree of shear attainable by the test rig to 60°.

2.3. Picture frame tests

The picture frame test is illustrated in Fig. 3. The specimen size is 200×200 mm². Slippage between the specimen and the grips was avoided by using four bars which clamped the specimen. The specimens were aligned carefully within the bars of the picture frame. After clamping the specimen, the rig was installed on an Instron 5584 tensile tester. An extensional speed \( v_y = 60 \text{ mm/min} \) was again used. The effect of specimen misalignment was investigated by preparing specimens with a misalignment angle of 2.5°. In addition one specimen, which was intended to be properly aligned, was found to deform asymmetrically during the subsequent loading, in a similar though less severe manner than the deliberately misaligned specimen. From this observation it was inferred that a smaller degree of misalignment, perhaps of the order of 1°, was present in this specimen. In order to examine the variation of tow deformation of the tows as the fabric was sheared, various specimens were prepared for microscopic observation as listed in Table 2.

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3. Microscopic observations

3.1. Preparation of specimens

Specimens were prepared from the various tests for microscopic observation as follows. After completing each test, polymer resin was pasted on the surface of the deformed specimens to fix the sheared geometry. The resin was then cured for 12 h at room temperature and

<table>
<thead>
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<th>Shear angle (°)</th>
<th>Method</th>
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<tr>
<td></td>
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</tr>
<tr>
<td>Without shear</td>
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</tr>
<tr>
<td>15</td>
<td>∅</td>
</tr>
<tr>
<td>30</td>
<td>∅</td>
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<td>∅</td>
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<td>70</td>
<td>∅</td>
</tr>
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```

Fig. 3. Testing rig and specimen for picture frame tests.
specimens of size 30×20 mm$^2$ were cut along the tow direction, as shown in Fig. 2(c). The cut specimens were placed in a mould and polymer resin was poured in and cured for 12 h at room temperature, then for 5 h at 80°C. To reach the observation surfaces the specimens were then ground and polished using increasingly fine paper and grit, finishing with 1 μm diamond paste. For all the specimens, three observation layers were prepared, spaced at an interval of 2 mm, by grinding down the surface between observations as shown in Fig. 2.

3.2. Data acquisition and extraction of parameters from the microscopic observation

A digital camera attached to a low-power microscope was used to record images of the tow architecture for each of the cross-sections studied. In this section we describe how these images are used to extract quantitative information about the tow geometry. For those tows seen in transverse section, the co-ordinates of a number of points (typically 60 points per tow) around the perimeter of each tow were obtained from each image using Matlab digitising routines (picking points using a mouse-controlled cursor). This provides a set of data points defining the closed curve outlining the tow:

$$P_i = \left\{ \left[ x_i, y_i \right] \right\}_{i=1}^n$$

The tow cross-section is then approximated by an ellipse, whose centre is located at the co-ordinates ($x_c$, $y_c$). A first estimate of $x_c$ and $y_c$ is determined by locating the area-centroid of the closed curve based on Green’s theorem in a plane [6]:

$$x_c = \frac{\sum_{i=1}^{n} (x_{i+1} + x_i) a_i}{\sum_{i=1}^{n} a_i}, \quad y_c = \frac{\sum_{i=1}^{n} (y_{i+1} + y_i) a_i}{\sum_{i=1}^{n} a_i}$$

where $a_i$ is given by $(x_{i+1}, y_{i+1} - x_{i+1}, y_i)$. This is used as a starting point to find a best-fit ellipse to the data, adjusting the centre point, the lengths of the major and minor axes and the orientation of the ellipse using a standard least-squares minimisation routine, coded in Matlab programming language.

The shape of the tows become more irregular as shear angle increases, perhaps because of the internal tow forces generated during shear [c.f. Figs. 1 and 6(d)]. Hence the dimensions of the fitted ellipse are no longer reliable measures of the tow geometry. Therefore, an equivalent tow width $\bar{w}$ and tow thickness $\bar{t}$ are proposed to characterise the tow cross section, using the following formulae [6], expressing twice the average distance of the tow from the centre of the ellipse

$$\bar{w} = \frac{2}{A} \sum_{i=1}^{n} \left| x_i - x_c \right| \Delta A, \quad \bar{t} = \frac{2}{A} \sum_{i=1}^{n} \left| y_i - y_c \right| \Delta A$$

The area $\Delta A$ is an element of area associated with each data point [6] while $A$ is the total area enclosed by the curve.

Having established the shape and position of each transverse tow, it is straightforward to define tow geometric parameters additional to the tow width and thickness described above. These are illustrated schematically in Fig. 4. Tow spacings $\Delta X$ and $\Delta Y$ in the $x$ and $y$ directions are simply the mean values of the corresponding $x$ and $y$ separations between the centre points of adjacent tows, taking the absolute value of separation in each case. The wavelength of the longitudinal tow shape was measured from the left side of the first tow to the same position of the next equivalent tow, as shown in Fig. 4. The centre line of the longitudinal tow was identified by eye and used to quantify the peak-to-peak amplitude of the longitudinal tows, as shown in Fig. 4. For the tow cross section parameters, values are averaged over 15 tows (five tows per section, three sections per sample), while for the longitudinal tow measurements of amplitude, values are averaged over the three sections per sample.

![Fig. 4. Definition of tow geometry parameters.](image-url)
4. Results

4.1. Force data

The measured force-displacement curves during testing of the specimens examined in this paper were used by Sharma et al. [7] to infer in-plane stresses resolved in the tows directions. For the picture frame test the shear line force $N_s$ is related to the force $F$ applied at the ends of the frame via equilibrium as

$$N_s = \frac{F}{2L\cos\left(\frac{\pi}{4} - \frac{\theta}{2}\right)}$$  \hspace{1cm} (4)

where $L$ is the side length of the picture frame and $\theta$ is the shear angle. It is not possible to deduce the forces acting along the tow directions for the picture frame tests from the applied loads; indeed this is a significant drawback of this test method. For the biaxial test, applied line loads $N_x = F_x/L$ and $N_y = F_y/L$ (where $L$ is the length of fabric over which the force acts) are resolved via Mohr’s circle to a shear line load $N_s$ acting parallel to the tow direction

$$N_s = (N_x - N_y)\sin\phi\cos\phi$$  \hspace{1cm} (5)

where $\phi$ is the angle that the tows make with the x axis, and to direct line load components $N_L$ and $N_T$ acting along and normal to the tow direction

$$N_L = N_x\cos^2\phi + N_y\sin^2\phi \quad \text{and} \quad N_T = N_x\sin^2\phi + N_y\cos^2\phi$$  \hspace{1cm} (6)

Fig. 5. Variation of resolved line load with shear angle for biaxial, bias extension and picture frame tests; (a) shear line load; (b) Longitudinal and transverse line loads.
These same expression are valid for the bias extension tests, with $N_y = 0$. The variation in these resolved line loads with shear angle is shown in Fig. 5. For the bias extension test, the shear line load rise significantly at a shear angle of about $55–60^\circ$, while in the case of the biaxial test, there is a significant increase occurring between 30 and 35°, see Fig. 5a. Corresponding forces resolved along and normal to the fibre directions are shown in Fig. 5b. The biaxial test specimen suffers significantly larger line loads acting along and transverse to the tow directions than the bias extension test. These can be expected to lead to significant differences in tow deformation.

4.2. Microscopic observations

The observations were used to investigate two kinds of geometry change: deformation within a tow (e.g. tow thickness, amplitude and wavelength) and relative deformation between tows (e.g. tow spacing in the out-of-plane direction).

Fig. 6 shows the observed tow structures after selected amounts of shear during a bias extension test. As the shear angle increases, the $x$-directional tow spacing $\Delta X$ falls and the gap between transverse and longitudinal tows increases. At a low shear angle, Fig. 6(b), some sliding of tows over each other has occurred, but contact between the tows is not severe. At a high shear angle, Fig. 6(c) and (d), the contact between tows is more severe; the contact forces generated lead to a significant change in the tow shape. By this point, the cross-sectional shape of almost all the tows has been modified, and some break-up of the tow structure is observed, Fig. 6(d). The exception to this is the fifth tow (i.e. the tow underneath the longitudinal tows, see Fig. 4), which is unaffected by the other transverse tows.

For the biaxial tests, the general deformation pattern is similar to that for bias extension results presented above, although the onset of severe contact between tows is observed at smaller shear angles. An increase of tow thickness is observed clearly in both tests.

4.3. Quantitative measures of the variation in tow geometry during shear

In this section microscopic observations of the type described in the previous section are quantified to illustrate the evolution in tow structure during shear. A comparison is made between the three test methods to see how the in-plane forces developed affect the change.

Fig. 6. Micrographs of the evolution of tow structure with shear angle for a bias extension test specimen: (a) initial geometry before shear; (b) 30° sheared specimen; (c) 60° sheared specimen; (d) 70° sheared specimen.
in tow structure. Fig. 7 shows the variation of out-of-plane tow spacing $\Delta Y$ with shear angle for the various tests, normalised by the initial tow spacing $\Delta Y_0$. Figs. 8 and 9 show corresponding graphs for the normalised tow thickness and longitudinal tow amplitude. As shear proceeds the area covered by the fabric falls, so that all these through-thickness geometric parameters tend to increase. For small shear angles (up to about 15°), Figs. 7–9 show a relatively small change in the tow geometry. The fabric forces are relatively low in this phase of shear, which we denote the ‘placing phase’. In the next stage (the ‘sliding phase’), there are more significant changes in tow geometry, corresponding to the shear angles for which sliding and overlapping is observed between the tows, see Fig. 6(c). Finally in the ‘locking region’ saturation behaviour is observed as lock-up of the tows occurs. This saturation behaviour is particularly evident in the measurements of tow spacing, Fig. 7, while less evident for the tow thickness results. Even when the tows are no longer free to slide relative to each other at lock-up, nevertheless the increasing forces within the fabric can result in further changes in tow shape. For example break-up of the tow cross section seen in Fig. 6(d), perhaps due to increasing lateral compression forces between tows, will tend to increase the tow thickness.

Figs. 7 to 9 show that the changes in all the out-of-plane tow deformation parameters are smaller for the biaxial tests than the bias extension tests. This is presumably because of the larger in-plane forces developed during biaxial testing, which tend to suppress out-of-plane deformation. Moreover the lock-up point, as inferred from the tow spacing curves, Fig. 7, occurs earlier for the biaxial test (at a shear angle of about 45°) than for the bias extension test (at around 60°). This observation correlates well with the observed rise in resolved shear force, Fig. 5, which again occurs at a smaller shear angle for the biaxial than for the bias extension test. These findings emphasise how in-plane forces can have a significant influence on the way that the tows reorganise themselves during shear, and hence on the force response and lock-up behaviour.

Measurements for the picture frame test with an aligned specimen\(^1\) are included on Figs. 7 to 9. The results for out-of-plane tow spacing lie between the bias extension and biaxial test data, while the amplitude and tow thickness results lie below the curves for the other two tests. Because the magnitudes of the membrane forces developed in the picture frame test are not known, it is difficult to interpret these results. Nevertheless there will almost certainly be differences in the in-plane forces, leading to the significant differences observed between this test and the others. A geometric argument gives a possible explanation for the observation that the amplitude does not change significantly with shear for the picture frame test, in contrast to the other tests. The distance across the picture frame and hence the wavelength must remain fixed during deformation. Since the tow is effectively inextensible, any increase in crimp amplitude is severely limited, as this will tend to increase the path length of the tow.

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\(^1\) Picture frame results, shown in Fig. 9 for the misaligned test, are described in the following section.
5. Misaligned picture frame tests

This section describes picture frame tests in which the nominal tow directions of the material were misaligned relative to the picture frame, exploring experimentally a problem addressed theoretically by Harrison et al. [8]. As deformation proceeds, one diagonal of the picture frame shortens while the other lengthens. In a similar manner, the distance across the picture frame increases for one set of tows while it decreases for the other set in the presence of misalignment. The picture is slightly confused by any increase in the tow path length associated with increased crimp amplitude during shearing. Nevertheless the lengthening tows will develop high tensile stresses while the shortening tows have lower tensile stresses, or may even be under compression. For simplicity we refer to these two sets of tows as tensile and compressive.

Differences of amplitude between tensile and compressive tows were investigated using microscopic observation. One specimen was deliberately misaligned by an angle of 2.5°. Another picture frame specimen, which was nominally aligned, produced excessive force during the test. Microscopic observations revealed a similar architecture to the deliberately misaligned specimen, from which it was inferred that the excessive force was due to misalignment, estimated as of the order of 1° by comparison with the misaligned tests.

Fig. 10 shows the microstructure of compressive and tensile tows after shear deformations of 30 and 56° for the accidentally and deliberately misaligned fabrics, along with a corresponding observation for the aligned picture frame test. Note that the relevant tow (compressive or tensile) runs horizontally in each of the photographs. While the aligned picture frame test [Fig. 10(e)] shows a similar deformation pattern to the bias extension and biaxial tests, there is a clear difference for the misaligned tests. Where there are tensile forces along the tows [Fig. 10(b) and (d)], the longitudinal tow remains nearly straight. On the other hand, the compressive tows [Fig. 10(a) and (c)] show a large waviness amplitude. These differences in amplitude for the 2.5° misaligned test are quantitatively compared with the other test results in Fig. 9. The large differences observed for this misaligned test supports the supposition that the tensile tow forces developed during the biaxial and bias extension tests are the cause of the differences seen in those tests. The results also highlight the importance of alignment in the picture frame test, with accidentally misalignment leading to a significant difference in behaviour.

6. Parametric geometric model

To characterise the observed variations of longitudinal tow geometry with shear angle, the wavy geometry of each longitudinal tow was fitted using two circular arcs (‘major’ and ‘minor’ circles), following the methods described by Newton et al. [9] for satin weaves and Hofstee [3] for plain weave fabrics. In the latter case the method was used to estimate the maximum crimp angle, a method adopted in this paper. Appropriate
circles are fitted as follows. A major circle arc for each longitudinal tow is drawn from the right side of one of the ‘fifth tows’ to the left side of the next fifth tow. The corresponding minor circle arc goes from the left side of the fifth tow to the right side of the fifth tow, as shown in Fig. 11. The circle is defined by the co-ordinates of the centre of the tow at these end points and at the point midway between these ends. The centre of the tow is established from the photographs by hand. From these radii of curvature ($R_1$, $R_2$) corresponding arc angles ($\Phi_1$, $\Phi_2$) and amplitudes of longitudinal tows ($A_1$, $A_2$) were estimated as illustrated in Fig. 11.

Results are presented in Fig. 12 for the variation with shear angle of the radius of curvature for bias extension and biaxial specimens. The radii have been normalised by the radius of curvature before shear. Fig. 12 shows that the radii of curvature fall significantly with increasing shear angle. The relatively slight initial change in the major axis radius of curvature is associated with the placing phase of deformation. With increasing shear the radii of curvature fall until lock-up is reached. The corresponding variations in major and minor circle arc angles with shear are shown in Fig. 13, showing a similar trend to that found for the radii of curvature.

The bold lines added to Figs. 12 and 13 are ‘master curves’, fitted to the data for the major and the minor circles using the least square method. The following sinusoidal functions were used:

$$\hat{R}_i(\theta) = \hat{b}_i \left( \frac{R_{\max} + R_{\min}}{2} + \frac{R_{\max} - R_{\min}}{2} \cos \frac{\theta}{\hat{\theta}} \pi \right), \quad i = 1, 2$$

$$\hat{R}_i(\theta) = \hat{b}_i \left( \frac{\Phi_{\max} + \Phi_{\min}}{2} + \frac{\Phi_{\max} - \Phi_{\min}}{2} \cos \frac{\theta}{\hat{\theta}} \pi \right), \quad i = 1, 2$$

(7)
Fig. 11. Circular arc model of deformed tow shape.

Fig. 12. Variation of normalised radius of curvature with shear angle.
where the subscript $i$ in the formulae represents the major (1) and the minor (2) circles, respectively and $\theta_f$ is the final measured angle of each test method ($60^\circ$ for the biaxial test and $62^\circ$ for the bias extension test). The parameters $\epsilon_i$ and $\eta_i$ are shifting factors for each fitting scheme and $R_{\text{max}}$, $R_{\text{min}}$, $\Phi_{\text{max}}$ and $\Phi_{\text{min}}$ represent the maximum and the minimum radii of curvatures and the maximum and the minimum arc angles, respectively. The coefficients and the shifting factors of all the fitted functions are listed in Table 3.

The magnitude of the crimp angle will be important in predicting the compressive strength of the laminate. Fig. 14 compares the measured maximum crimp angle with an estimate taken as half the arc angle from the fitted data, Eq. (7). The crimp angle estimate based on the fitted arcs is good. Similarly good agreement was found between the measured amplitude of the tow and that calculated from the fitted arcs. Hence the simple parametric fitting model presented above realistically captures the geometric changes in the tow architecture during shear.

### Table 3

<table>
<thead>
<tr>
<th>Coefficients/ Shifting factors</th>
<th>Major (1)</th>
<th>Minor (2)</th>
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<tr>
<td>$\epsilon_i$</td>
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<tr>
<td>$\Phi_{\text{min}}$ [°]</td>
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Fig. 13. Variation of arc angle with shear angle.

### 7. Conclusion

This paper presented a micromechanical examination of material which has been sheared in three different tests (bias extension, biaxial and picture frame tests). The measured changes in geometry were interpreted in terms of the deformation mechanisms in the material, including material ‘lock-up’ at high shear. Various geometric parameters such as tow spacing, amplitude of longitudinal tow, and tow thickness were measured from microscopic observations. Details of the deformation depended on the test method, which it was suggested was due to the different applied forces within the material with each test. From the measured change in
tow geometry with shear angle, three different regimes were identified: the placing, sliding and lock-up regimes. The onset of lock-up took place at a shear angle around 60° for the bias extension test and 45° for the biaxial test. Picture frame tests were performed on material which was deliberately misaligned relative to the frame. A clear difference in tow geometry was observed between tensile and compressive tows. This demonstrated the importance of in-plane tow forces on deformation of the material during shear. To characterise the change in the geometry of longitudinal tows with shear, their shape was fitted using circular arcs.

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