Microscopic investigation of tow geometry changes in a woven prepreg material during draping and consolidation

S.H. Chang a, M.P.F. Sutcliffe b,*, S.B. Sharma b

a Department of Mechanical Engineering, Chung-Ang University, 221, Heuksuk-dong, Dongjak-ku, Seoul 156-756, South Korea
b Department of Engineering, Cambridge University, Trumpington Street, Cambridge CB2 1PZ, UK

Received 3 February 2003; received in revised form 5 January 2004; accepted 6 January 2004
Available online 19 March 2004

Abstract

Changes in tow geometry are measured during draping and consolidation of a helmet component with 5-harness satin weave carbon fibre reinforced plastic (CFRP) prepreg. The tow microstructure is found by sectioning specimens cut from the helmet. Various tow geometry parameters are extracted using image analysis. Results are compared with similar measurements on dry fabric specimens sheared using the bias extension and biaxial test methods [Compos. Sci. Technol. 63 (2003) 99], and on unsheared specimens cured under light pressure or in an autoclave. Results suggest that, for this particular material and process route, the significant differences observed in tow geometry over the surface of the helmet are mainly due to differences in contact pressure between the prepreg and the mould, with the effect of shear deformation less significant. Differences between tows running longitudinal and transverse to the axis of the helmet are ascribed to differences in contact conditions between these sets of tows and the mould surface.

Keywords: A. Fabrics/textiles; B. Microstructure; C. Deformation; Tow geometry

1. Introduction

Fibre reinforced composite materials are widely used in many areas of the automotive and aeronautical industries because of their high specific stiffness and 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 resin transfer moulding (RTM) 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. In particular the fabric structure and deformation pattern may significantly affect the properties of the final products. Microscopic investigation of the deformation pattern of the fibre or tow structures is needed to understand the influence of fabric properties such as tow size, weave style, and constituent components on the drapeability of the material.

Long et al. [2], amongst others, identified two mechanisms of fabric deformation during draping of fabric: simple shear and shear-slip at the fibre crossovers. Simple shear consists of a trellising action, whereby the tows in the fabric rotate about the crossover points. This deformation mechanism can accommodate large fibre rotations, typically up to 60°. Fibre ‘lock-up’ occurs at this point as the parallel rotating fibres contact each other. This is followed by either wrinkling or bridging, as the material is no longer able to conform to the surface. Various researchers have considered the details of material deformation during draping. Hofstee et al. [3,4] described the yarn geometry as a function of shear deformation and fabric stretching deformation during the thermoforming of a plain woven composite, while

Various studies have considered tow-level deformation during compaction, whether by autoclaving, vacuum forming or during RTM. For example Simacek and Karbhari [7] discuss tow models for compaction during RTM while Saunders et al. [8] describe compression of fabric assemblies in both the dry and wet states with a range of resins. van West et al. [9] develop a mathematical model for consolidation of commingled fabrics, including models of matrix flow. These studies show how the effects of consolidation pressure, fibre volume fraction, weave style and resin type change the consolidation behaviour at the tow level.

Chang et al. [1] have presented a microscopic investigation of tow geometry changes in a satin weave dry fabric subject to in-plane deformation. Picture frame, bias extension and biaxial tests were used to deform the fabric and the effect of the in-plane forces on the resultant deformation was investigated. They observed significant differences between tests in the way that tows rearranged during deformation and the resulting lock-up behaviour, which was ascribed to differences in the in-plane stresses. In the present work we undertake a similar microscopic study of tow deformation, but for material which has been draped over a helmet component and then vacuum consolidated. The drape behaviour of this same component has been modelled and investigated experimentally [10,11]. It is expected that the different forces occurring during draping will affect the material deformation in a similar way to that observed for the in-plane tests, while the consolidation phase will impose its own deformations on the tow structure. These observed differences in tow behaviour will be valuable in assessing how reliably material properties for drape modelling can be extracted from simple coupon tests.

2. Specimen preparation

Fig. 1 illustrates the component considered in this paper, which is the back half of a helmet. Fig. 1(a) is a photograph of the final component, while Fig. 1(b) is a reconstruction of the cured component, using the CAMSYS ASAME camera measurement system [11]. The ear parts are seen at the sides, while the top of the component will eventually be at the back of the finished helmet. The component was manufactured from a single layer of prepreg consisting of 5-harness satin weave Tenax HTA carbon fibres in a Hexcel 6376 epoxy resin (Hexcel code 6376-905-36%). The inter-tow spacing is around 1.5 mm and the nominal ply thickness 0.375 mm. The specimen was laid up by hand on the preheated mould (after applying a release coat), vacuum bagged, a vacuum applied (typically 950 m bar) and the component was cured at 185 °C for three hours. The start point for the drape was at the top of the component. The tows were orientated along and transverse to the symmetry axis of the component at this point, as shown in Fig. 1(b). The variation in shear angle over the finished component was measured from a grid pattern marked on the initial prepreg using the CAMSYS ASAME measurements. The grid spacing was uniform (cf. Fig. 1(a)) at a pitch of 10 mm – significantly larger than the tow pitch of 1.5 mm.

Various specimens of dimensions 30×20 mm were cut out from the component along the grid lines originally marked parallel to the tows, ensuring that the specimens could be sectioned along the tows with acceptable alignment accuracy. The specimens were set in polymer resin. To reach the observation surfaces they were then ground and polished using increasingly fine paper and grit, finishing with 1µm diamond paste. For all the specimens three observation layers were prepared, spaced at an interval of 2 mm to obtain profiles for adjacent tows, by grinding down the surface between observations.
Results from the single-ply helmet component are compared with three other types of specimen:

- an undeformed single-ply prepreg specimen which was cured under a very light pressure,
- a flat autoclaved specimen made up of 4 plies of undeformed prepreg (the prepreg used for this and the specimen described in the previous bullet point was identical to that used for the helmet),
- results taken from [1,12] for dry fabric specimens sheared using either bias extension or biaxial tests. This dry fabric had a five harness satin weave using Tenax HTA carbon fibres, as for the prepreg, but with a smaller tow size.

The change in tow geometry during draping will depend on the amount of shear in the material and the forces applied to the tows. To cover a wide range of conditions, specimens were taken from a variety of locations across the helmet, as shown in Fig. 1. At each location sections were taken in both the longitudinal and transverse directions (so that for a longitudinal cut, the path of a longitudinal tow can be observed, whilst transverse tows are seen in cross section). Table 1 shows the measured shear angles of the specimens. The pattern of shear is similar to that seen for a hemispherical component (e.g. [13]). There is only modest shear along thread A1, while the specimen with the maximum shear is at the bottom of thread A3 (with a shear angle of 38°). In some cases the same specimen was used to take longitudinal and transverse sections; in other cases adjacent parts of the helmet were used. Differences in tow geometry where adjacent specimens were used are expected to be slight, as illustrated by the minor differences in shear angle detailed in Table 1.

Fig. 2 shows a sketch of typical forces generated in the material, illustrating membrane forces within the tows, forces applied by hand during draping and the contact forces from the mould. In addition there will be pressure applied during curing, when consolidation of the material will take place. Although the actual forces during draping are not known, it is expected that the nature of the hand-draping process will generate forces acting downwards from the top of the component. All of these forces may influence the way that the tows re-arrange during draping.

Two further considerations relate to the contact with the mould. Near the bottom of the component there is a tendency for the material to lose contact with the mould as it is draped around the radius at the base of the tool (see Fig. 1(a)). Finally it should be noted that the contact conditions differ for the longitudinal and transverse tows. The latter are in contact with the mould for much of their length, while the reverse is true for the longitudinal tows, as illustrated in Fig. 3.

### 3. Extraction of tow geometry parameters

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. These images were then used to extract key tow geometry parameters, as illustrated in Fig. 4(a), following the method described in [1]. Sets of points \((x_i, y_i)\) were picked using image processing software to define the outline of the tow cross section and an ellipse was fitted to the data to locate the centre point \((x_c, y_c)\) of each tow, as illustrated in Fig. 4(b). An equivalent tow width \((w)\) and tow thickness \((t)\) are used to characterise the tow cross section, defined by the following formulae expressing twice the

### Table 1
Shear angle measured in the various specimens

<table>
<thead>
<tr>
<th>Specimen location</th>
<th>Top</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting direction</td>
<td>L</td>
<td>T</td>
<td>L</td>
</tr>
<tr>
<td>Thread A1</td>
<td>5°</td>
<td>4°</td>
<td>6°</td>
</tr>
<tr>
<td>Thread A2</td>
<td>5°</td>
<td>5°</td>
<td>8°</td>
</tr>
<tr>
<td>Thread A3</td>
<td>7°</td>
<td>7°</td>
<td>10°</td>
</tr>
</tbody>
</table>

‘L’ and ‘T’ denote longitudinal and transverse sections.
average distance of the tow from the centre of the fitted ellipse [14]:

\[ w = \frac{2}{A} \sum_{i} |x_i - x_c| \cdot \Delta A, \quad t = \frac{2}{A} \sum_{i} |y_i - y_c| \cdot \Delta A. \]  

(1)

The area \( \Delta A \) is an element of area associated with each data point [14] while \( A \) is the total area enclosed by the curve. Tow spacings \( \Delta X \) and \( \Delta Y \) in the \( x \) and \( y \) directions are 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 (\( \lambda \)) of the longitudinal tow profile was measured from the left side of tow number one, to the same position of the next equivalent tow, as shown in Fig. 4(a). The centre line of the tows seen in longitudinal section was identified by visual inspection and used to quantify the peak-to-peak crimp amplitude (\( A \)), as shown in Fig. 4(a). The maximum crimp angle (\( \xi \)) in the longitudinal tow was estimated by constructing a tangent to the tow between the 4th and the 5th transverse tows at the point visually identified as having the maximum slope. The measurements of tow thickness and spacing taken from transverse cross sections are averaged over 15 tows (five tows per section, three sections per sample), while for the longitudinal section measurements of crimp amplitude and angle, values are averaged over the three sections per sample.

4. Results

4.1. Microstructural observations

Longitudinal sections from threads A1 and A3 are shown in Fig. 5. In all cases the mould contact is at the upper side of the micrograph and the longitudinal tow runs horizontally. For thread A1 (Fig. 5(a)-(c)) the amount of shear in the specimen is small and there is little contact between tows. The poor contact between the material and the mould is evident at the bottom of the thread (Fig. 5(c)). Thread A3 (Fig. 5(d)-(f)), by contrast, runs into a region at the bottom of the mould with much higher shear. The corresponding cross section, Fig. 5(f), shows that there is significant contact and overlap between the transverse tows seen in cross section.

Details of typical cross-sections of transverse and longitudinal tows, taken from the bottom part of thread A2, are shown in Fig. 6(a) and (b), respectively. The transverse tows (Fig. 6(a)), which are in contact with the mould for much of their length (cf. Fig. 3), have lost much of their original shape. Moreover these tows appear thicker, with more gaps between the fibres, than the corresponding longitudinal tows seen in cross section in Fig. 6(a), where the tows have packed together to obscure the original tow structure.

4.2. Evolution of tow geometry parameters

The microstructural observations presented above give some indication of the effect of shear and specimen location on tow deformation. In this section we quantify the changes in tow geometry, using the methodology of Section 3, and compare the findings with results for unsheared prepreg and sheared dry fabric.

Fig. 7 shows the variation of normalised out-of-plane tow spacing \( \Delta Y/\Delta Y_0 \) with shear angle for the various specimens. Figs. 8 and 9 show corresponding graphs for the normalised tow thickness \( t/t_0 \) and tow crimp amplitude \( A/A_0 \). All results are normalised by the value for the unsheared prepreg cured with very light pressure. As all three tow geometry parameters measure out-of-plane displacements, it is not surprising that the autoclaved specimen has considerably smaller values of these parameters than the lightly-loaded cured prepreg. Similarly values for tow gap, thickness and crimp amplitude at the left-most points on each of the lines for the helmet results, corresponding to specimens at the top of the helmet component, are significantly smaller than for the undeformed prepreg. This compaction is caused by
the contact pressure between the material and mould, either during draping or vacuum curing. The good contact seen between the mould surface and material at the top of the component, Fig. 5(a) and (d), confirms this picture.

Figs. 7 and 8 show that the out-of-plane tow spacing $\Delta Y$ and tow thickness $t$ increase sharply with increasing shear angle for the helmet specimens. This tendency is expected given the fall in area covered by the fabric with increasing shear angle, but the rise is too great to be explained wholly by this effect (compare the gentle rise for dry fabric with the steep rise for thread A1). Data points towards the right-hand end of the thread curves corresponds to locations at the bottom of the component where the material is losing contact with the mould, so that there are much reduced normal pressures compacting the tows. Hence conditions are much closer to those of the bias extension or biaxial tests. This suggests that much of the increase in tow spacing and thickness with shear angle seen for the helmet component is associated with the drop in contact pressure rather than the increase in shear. The micrographs of Fig. 6 show that the transverse tows, which are in greater contact with the mould, are not able to reorganise themselves as neatly as the longitudinal tows. This explains the greater tow spacing and thickness seen for these transverse tows.

Fig. 10 presents results for the maximum crimp angle, which is particularly relevant to the prediction of in-plane compressive strength of the composite [15]. The small crimp amplitude and large crimp angle of the autoclaved specimen illustrate the importance of normal pressure in determining these geometric parameters. Fig. 9 shows that the crimp amplitude of the helmet specimens tends to increase slightly with shear stress, but still lies well below the dry fabric curves. A comparison of the micrographs, Fig. 5(c) and (f), with equivalent pictures for dry fabrics [1] suggests that even modest mould contact pressures can flatten out long-range undulations in the material and so reduce the tow crimp amplitude below those seen for the coupon tests. Both the crimp amplitude and angle are significantly greater for the longitudinal tows as compared with the transverse tows. Again it appears that the different contact conditions for the two sets of tows (cf. Fig. 3) affect the tow deformation behaviour. The fall in maximum crimp

![Fig. 5. Micrographs of longitudinal sections (so that the transverse tows are seen in cross section). The mould surface is at the top of each cross section: (a) thread A1 – top; (b) thread A1 – middle; (c) thread – A1-bottom; (d) thread A3 – top; (e) thread A3 – middle; (f) thread A3 – bottom.](image_url)
angle with increasing shear angle for the longitudinal
tows is somewhat unexpected, as the crimp amplitude
would be expected to increase as the material thickens
during shearing. However the micrographs suggest that
the loss of mould contact allows a more gradual crimp
profile to develop at the bottom of the component (see
Fig. 5(c) and (f)).

5. Conclusions

The tow architecture of a draped and vacuum con-
solidated helmet component is investigated by micro-
scopic examination of sectioned specimens taken from
various locations on the helmet, including regions at the
edge of the mould where the contact pressure between
the material and the mould is relatively small. Various
geometric parameters, including tow thickness, tow
spacing, crimp amplitude and crimp angle are deter-
mined from the measurements. Results for the helmet specimens are compared with those from unsheared specimens cured either with light pressure or in an autoclave, and with specimens sheared during coupon tests with no normal pressure. Results suggest that, although shear in the fabric has some effect on the change in tow architecture, the most important influence is the contact pressure between the material and the mould for this material and process route. Changes in the consolidation pressure, fibre volume fraction, weave style and resin type can be expected to alter the relative importance of these tow deformation mechanisms. Differences in the helmet specimens between the tows running longitudinally and transversely to the helmet axis are ascribed to the different contact conditions between the tows and the mould.

Acknowledgements

This work was supported by the postdoctoral fellowship programme from Korea Science & Engineering Foundation (KOSEF). The authors would like to acknowledge the support of the EPSRC and research collaborators at the University of Nottingham, and industrial partners BAESYSTEMS, QinetiQ, ESI Software, Ford Motor Company, MSC.Software Ltd., Vantage Polymers, St. Gobain Vetrotex, BP Amoco and Hexcel Composites. The authors are especially grateful to QinetiQ for the loan of the helmet mould used in the tests.

References


