MODELLING OF 3D WOVEN COMPOSITES WITH REALISTIC UNIT CELL GEOMETRY

S. D. Green1*, M. Y. Matveev2, A. C. Long2, S. R. Hallett1
1 Advanced Composites Centre for Innovation and Science (ACCIS), Department of Aerospace Engineering, University of Bristol, Bristol, UK, 2 Polymer Composites Group, Division of Materials, Mechanics and Structures, University of Nottingham, Nottingham, UK
* Corresponding author (steve.green@bristol.ac.uk)

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1. Introduction

Composite materials have many desirable properties, most notably excellent stiffness and strength combined with low mass. However, the key disadvantages of traditional 2D composites are that they require expensive, labour intensive manufacturing and are prone to delamination due to the lack of through thickness reinforcement. 3D woven composites can address both of these issues due to the addition of yarns, known as binders, which interlace through the fabric thickness. This means that near net shape preforms can be produced directly from the loom to form composites with greatly improved interlaminar properties. However, despite these advantages, 3D woven composites have been largely limited to niche applications. One of the key reasons for this is the lack of predictive numerical tools, which limits their ability to be used at the early stages of design.

Mechanical performance modelling of textile composites typically begins with the definition of textile unit cell geometry using a specialist pre-processor such as TexGen. Such software can produce an idealised representation of a textile sufficient for the modelling of many types of composites with 2D reinforcement. However, some 3D woven textiles present a significant challenge to model due to their inherent complexity. While TexGen is capable of modelling such textiles, the idealised geometries that it produces can neglect realistic features such as yarn waviness and yarn pinching which play a significant role in determining their resulting properties, especially strength [1, 2]. Previous work [3] used a finite element (FE) model, representing each yarn as a bundle of chains of beam elements, in order to predict the deformations of an orthogonal 3D woven fabric. The effects of weaving and compaction were well captured, with results validated against micro computed tomography (CT) scans.

FE models of 2D woven textile composites are traditionally meshed with tetrahedral elements, with the matrix domain assigned as the inverse of the yarn volume within the global unit cell domain (See for example [4]). Nodes of matrix and yarn elements at the interface between the two different material phases must be shared to form a conformal mesh. However, realistic models of complex 3D woven architectures will likely feature degenerated resin regions and small yarn interpenetrations meaning that such meshing practices are not feasible. Other techniques have been proposed to model such textile composites [5, 6]. In this study, a technique based on voxels [7]; meaning a 3D pixel, was used and has been shown to be adequate for mechanical modelling of 2D textile composites [8].

2. Textile Geometry

The accuracy of mechanical modelling of textile composites for strength prediction is dependent on the modelling technique, material models and assumed textile geometry. A previous project considering failure modelling of 3D woven composites concluded that a significant limitation was with regard to the idealised geometries being used. For textiles with complex internal architecture, there was no further merit in pursuing relatively small improvements with the failure model whilst significant discrepancies existed between considered and real geometries. A schematic representation of an orthogonal 3D woven fabric is shown in Fig. 1. The fabric has two sets of binder yarns, each arranged in a 5 harness satin style. One set of these binder yarns float on the upper surface of the fabric while the other float on the bottom surface. The original idealised TexGen unit cell model of this fabric used in the aforementioned study is shown in Fig. 2(a). In this geometrical model, the in-plane warp and weft yarns are completely straight with zero crimp, waviness or cross-sectional variation.
Binder yarns follow a path with straight horizontal or vertical sections, constant cross-section and extend beyond the surface of the fabric, resulting in a resin layer on the surfaces of the composite. None of these features are present in the real moulded composite.

However, there have been recent developments to TexGen aimed specifically at improving the quality of 3D woven textile geometry. A new idealised unit cell model of the same fabric as generated in the latest version of TexGen (3.5.3) is shown in Fig. 2(b). It was however still not possible to generate a model at the level of compaction consistent with the real infused composite (58.5% volume fraction (VF)) without significant yarn interpenetrations. The model therefore has a lower VF of 52.0%, similar to the original idealised model. This new model features binder yarns which are flush with the fabric surface, achieved using binders which are near circular in the vertical sections but flatten considerably on surface while inducing crimp in the surface weft yarns. However, elsewhere the in-plane yarns remain straight with constant cross-section.

The main motivator for the development of beam element fabric deformation models was to produce accurate geometry for unit cell analysis of textile composites. In order to generate mechanical performance models from the output of these deformation models, the yarns required conversion from a bundle of beams to solid entities. A python script was written to extract yarn paths, as well as cross-sections using an algorithm which traced around the outline of the beams, to produce a realistic TexGen model of the 3D woven fabric unit cell. Whilst the deformation models can produce geometry at levels of compaction as high as the real fabric, for comparative purposes, this realistic TexGen model is also shown at 52.0% VF in Fig. 2(c), and is visually considerably different to the idealised models. It features significant out-of-plane waviness of warp yarns, in-plane waviness of weft yarns and variation of cross-sections in all yarns. The output of the deformation model was validated against CT scans of the real fabric in [3], with a CT image of a unit cell presented in Fig. 2(d). It can clearly be seen that the realistic model much more accurately represents the architecture of the real fabric than the idealised models.

3. Methodology
In this study, tensile loading in warp and weft directions will be considered for the following four scenarios:
A. New idealised model (52.0% VF)
B. Realistic model (52.0% VF)
C. Realistic model (58.5% VF)
D. Experimental data (58.5% VF)

The results of A and B will be used to assess the effect of geometry assumptions on mechanical performance prediction. Further insight can be gained regarding the effect of compaction from B and C, while the accuracy of each model compared to experiment will also be assessed.

3.1. Modelling Procedure
Voxel meshes can be automatically generated in TexGen with each voxel being designated part of the matrix or yarn domain depending on the location of its centroid. Using this technique, it is trivial to generate periodic meshes of complex geometries. It also avoids the need to specify fictitious resin gaps between yarns often resorted to in conventional modelling of textile composites to produce adequate quality elements (see for example [9]). Periodic boundary conditions for the unit cell with stagger in tessellation shown in Fig. 1(a) were applied as in [10].

3.2. Material Properties
In each of the models the yarn area and hence VF varied in different segments of the yarns. This variation was from 47-78% VF in the idealised model, with most of this variation occurring in the binders. In the realistic models, VF ranged from 36-87%, with continuous variation in all yarns and high VFs where yarns come into contact with each other at cross-over points during weaving and compaction. Whilst the VF remains below the maximum hexagonal array fibre packing limit of ~91%, since this cannot be violated in such multi filament based deformation models, the high VFs suggested in certain localised regions is exaggerated. In practice it is difficult to exceed VFs greater than 75% (see for example [11, 12]) as unlike the model, fibres in a real yarn are not perfectly aligned and have some level of entanglement.

Yarns were treated as transversely isotropic, with properties applied to each element depending on the local VF in order to avoid stiffness discontinuities in
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the yarn. Constituent and yarn properties as applied to the models are shown in Table 1. Fibre and matrix properties were taken from manufacturer’s data where available, as well as the literature. Yarn elastic constants were calculated from constituents using a micromechanical FE model with a hexagonal fibre packing. Strength properties were calculated using a new analytical model proposed by Ivanov, based on a generalisation of the Chamis concept [13]. The four-element system approximates quarter of the unit cell in the square fibre grid. Three sets of conditions are utilised: continuity of traction on the inter-block boundaries, symmetry and equilibrium. These equations along with the Hooke’s law are sufficient to identify the stresses in the blocks. Failure is assumed to be governed by the critical hydrostatic tension (crucial for failure of brittle epoxies [14, 15]) or the critical Mises stress (responsible for ductile failure in shear or tension) whichever is reached faster:

$$max\left(\frac{P_{mx}}{P_{cr}}, \frac{q_{mx}}{q_{cr}}\right) \geq 1$$  \hspace{1cm} (1)

where the indexes ‘mx’ stands for the maximum value in matrix elements, and ‘cr’ stands for the critical value. The conservative estimate of the latter can be extracted from a uniaxial tensile test on pure epoxy. At failure $p = S/3$ and $q = S$ (S is the uniaxial strength of matrix), which leads to:

$$max(\sigma_{11} + \sigma_{22} + \sigma_{33})_{mx}, q_{mx} \geq S$$  \hspace{1cm} (2)

The prediction of the transverse strength follows the anticipated trend; strength drops when fibre VF is increased from 0 to 40% and remains nearly constant as it further increases.

### 3.3. Material Models

The behaviour of yarns and matrix were assumed to be linear prior to damage onset. After damage initiation a continuum damage mechanics (CDM) model [16] was applied both to yarns and matrix. It proposes that damage in material can be considered as a reduction of stiffness properties over a region of material, a finite element in this case.

Five modes of failure were considered for the yarns: longitudinal tension/compression, transverse shear and transverse tension/compression. The damage state of the material was defined by set of three parameters $D_i$ defined by equations (3) – (5) with respect to chosen failure modes. Damage initiation was assumed when one of the parameters $D_i$ exceeded value of 1.0.

$$D_1 = \max\left(\frac{\sigma_{11}}{F_{11}^c}, \frac{-\sigma_{11}}{F_{11}^c}\right)$$  \hspace{1cm} (3)

$$D_2 = \sqrt{\sigma_{12}^2 + \sigma_{13}^2}$$  \hspace{1cm} (4)

$$D_3 = \max\left(\frac{\sigma_{22}}{F_{22}^c}, \frac{-\min(\sigma_{22}, \sigma_{33})}{F_{22}^c}\right)$$  \hspace{1cm} (5)

where $\sigma_{ij}$ – components of stress tensor, $\sigma_2$ and $\sigma_3$ are principal stress in the plane orthogonal to the fibre direction, $F_{ij}^m$ are strengths of yarn, where indexes $i,j = 1,2$ corresponds to directions and index $m = t,c$ stands for tensile and compression strength.

Following the CDM approach, damage propagation was modelled by reduction of stiffness properties of an element. Young’s and shear moduli of the damaged yarn were described as follows:

$$E_1 = \begin{cases} E_1^0, & D_1 \leq 1 \\ 0.001E_1^0, & D_1 > 1 \end{cases}$$  \hspace{1cm} (6)

$$E_2 = E_3 = E_2^0 \max\left(0.001, \min(P(D_2), P(D_3))\right)$$  \hspace{1cm} (7)

$$G_{12} = G_{13} = G_{12}^0 \max\left(0.001, \min(P(D_2), P(D_3))\right)$$  \hspace{1cm} (8)

where $P(D_i)$ is a penalty function defined as:

$$P = \left(1 - \frac{1}{\exp(-c_1D_i + c_2)}\right)$$  \hspace{1cm} (9)

It can be seen that damage in the longitudinal direction causes abrupt degradation of longitudinal properties. Ratio $c_2/c_1$ of parameters in the penalty function determines how fast damage will propagate through an element and defines final failure of element (Fig. 3). This parameter is mesh and material dependent with coarse meshes requiring a higher parameter. Ratio $c_2/c_1$ was empirically chosen to be equal to 4.0. Poisson ratios remained intact.

Damage initiation in the matrix was defined by a pressure dependent modified von Mises criterion [17]. The matrix behaviour after damage was defined by reduction of Young’s modulus using the
penalty function described above.

4. Results and discussion

Voxel meshes used for the idealised and realistic models are shown in Fig. 4. It was relatively simple to represent the straight yarns of the idealised model with voxels, but the complex geometry of the realistic models proved more challenging with angled or curved yarns having stepped or jagged surfaces. The quality of the voxel representation of geometry improves with refinement however, the large unit cell size of this fabric placed a practical limit of the level of refinement possible.

Young’s moduli and ultimate strength values are presented for each of the models compared to experiment in Table 2. Stress-strain curves for each data set are shown for the warp and weft directions in Fig. 5 and Fig. 6 respectively. Experimental curves shown are for a representative test [18] and model results using the low compaction geometry have been normalised by VF. The result of the idealised model was an overestimation of stiffness in both directions by around 15%. The low compaction realistic model predicted moduli very close to experiment with the high compaction model having slightly reduced values. The same trend is replicated with strength prediction for each model. Experimental curves appear bi-linear with a kink at around 0.6% strain. It is believed that this stiffness reduction is due to transverse yarn and resin cracks which were observed in an orthogonal 3D composite of similar weave style but fewer layers prior in interrupted tests (Fig. 7). The damage model used for the analysis is based on a simplified mechanical approach and thus cannot capture transverse failure with great accuracy. However, it correctly predicts strain of the onset of yarn transverse damage accumulation in the stress-strain curve and shows the main trend of stiffness reduction, (in the realistic models). The final failure depends mainly on correct prediction of longitudinal stresses although artificial stress concentrations due to the voxel discretisation of geometry may reduce the final strength.

Comparison of the two 52% VF models clearly demonstrates the effect of textile geometry on the resulting mechanical properties. Non-conservative results were produced by the idealised model because of the geometrical assumptions outlined in section 2, most notably the lack of yarn waviness. Assessment of the two realistic models shows a reduction in properties with compaction, with the highly compacted model featuring greater waviness. In these cases, the relative reduction in tensile strength was typically over double the relative reduction in stiffness. This effect will be even more severe for compressive strength since the presence of waviness causes kink-band formation in yarns [1, 2]. The differences between idealised and realistic geometries will therefore be even more striking when subject to compressive loading. Interestingly, the compacted realistic model has a higher weft modulus than warp, contrary to the low compaction realistic model as well as experiment. The reason for this is the relative levels of yarn waviness in each model. Average waviness for the low compaction model was 3.1° and 3.9° in warp and weft respectively while for the compacted model, 4.8° and 4.1°. This was determined by splitting the yarn path into segments and calculating the angle of each segment from the nominal path. Weft yarn waviness in the model does not vary much with compaction as it is dominated by crimp at the surface due to contact with binders, and in-plane waviness which develops during weaving and light compaction. However, the warp yarns feature mostly out-of-plane waviness which increases significantly with compaction causing overall waviness to become greater than in the weft yarns at high compaction.

One would expect the fully compacted realistic model to produce closest match with experiment, however material properties were slightly underestimated. Examination of CT scan data showed that this was despite the model having marginally underestimated crimp levels. One source of error is the applied boundary conditions. The models behaves as infinite material due to enforcement of periodicity, however, due to the physically large unit cell size, coupons for testing were only around 1 unit cell width for weft loading and 2.5 for warp loading. However, relaxing the boundary conditions on the model would cause a further reduction in predicted stiffness. Whilst every care was taken in determining material properties, this discrepancy could be explained by the input properties to the model being less stiff than with the real material.

5. Conclusions

In this work various geometrical models of a complex orthogonal 3D woven composite have been assessed using voxel meshing and a continuum damage model for elastic and failure analysis.
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Geometrical assumptions used in an idealised model have been shown to have significant implications for stiffness and especially strength predictions, with a realistic model at same level of compaction producing reduced, and more accurate values. A high compaction realistic model produced a further reduction in properties due to the increase in crimp levels. Realistic models showed good agreement with experiment using the voxel approximation and a simple damage model.

Acknowledgments

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References

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Fig. 1. Schematic representation of orthogonal 3D woven fabric showing (a) unit cell with tessellation and (b) fabric cross-section.

Fig. 2. Various TexGen unit cell models of 3D woven fabric compared to CT scan, at 52% VF.
Table 1. Table of material properties for constituents and yarn (at nominal 70% VF)

<table>
<thead>
<tr>
<th></th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$v_{12} = v_{13}$</th>
<th>$v_{23}$</th>
<th>$G_{12} = G_{13}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$S_{11}$ (MPa)</th>
<th>$S_{22}$ (MPa)</th>
<th>$S_{12}$ (MPa)</th>
<th>$S_{23}$ (MPa)</th>
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</thead>
<tbody>
<tr>
<td>Fibre</td>
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<td>13</td>
<td>0.20</td>
<td>0.25</td>
<td>13</td>
<td>6</td>
<td>4620* / 3825**</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Matrix</td>
<td>3.1</td>
<td>3.1</td>
<td>0.35</td>
<td>0.35</td>
<td>1.2</td>
<td>1.2</td>
<td>77.6</td>
<td>77.6</td>
<td>61.5</td>
<td>61.5</td>
</tr>
<tr>
<td>Yarn (70% VF)</td>
<td>167</td>
<td>8.1</td>
<td>0.21</td>
<td>0.30</td>
<td>4.5</td>
<td>3.0</td>
<td>3234* / 2678**</td>
<td>36.4</td>
<td>53.8</td>
<td>61.5</td>
</tr>
</tbody>
</table>

*Warp / weft yarns
** Binder yarns

Fig. 3. Stiffness reduction penalty function.

Fig. 4. Voxel meshes for; (a) idealised model, (b) realistic model.
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Table 2. Comparison of moduli and strength predicted by the models with experiment.

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Ideal (52.0% VF)</th>
<th>Realistic (58.5% VF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E (GPa)</td>
<td>σ_y (MPa)</td>
<td>E (GPa)</td>
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<tr>
<td>Warp</td>
<td>63.94</td>
<td>701</td>
<td>72.79</td>
</tr>
<tr>
<td>Weft</td>
<td>60.84</td>
<td>625</td>
<td>71.01</td>
</tr>
</tbody>
</table>

Fig. 5. Graph showing stress strain curves of each model alongside experiment for tensile warp loading.
Fig. 6. Graph showing stress strain curves of each model alongside experiment for tensile weft loading.

Fig. 7. Micrograph of a thinner orthogonal 3D woven fabric of similar weave style showing transverse cracks in yarns and resin at 90% failure load in interrupted test [18].