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Mechanical modelling of a sheared textile composite unit cell

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Abstract. Composites made using carbon fibre textile reinforcement give an anisotropic material with directional mechanical properties that are dependent on the fabric architecture. The directional properties of a 2D textile are primarily based on weave pattern: The direction of warp and weft yarns, undulation of the tows, and the change in fibre orientation during dry fabric forming process.

During dry fabric forming processes, shear is the dominant deformation mechanism as the 2D fabric conforms to 3D shapes. As the fabric changes its shape to match that of the tool, the fibres rotate away from the orthogonal axes as a function of the shear angle. The modified fibre orientation is carried through the curing process and ends up in the finished composite component. This has an influence on the mechanical properties of a cured composite in localised regions of high deformation. Currently the effect of shear during fabric forming is not usually taken into account when modelling the performance of the finished composite at the macro-scale. Through the development of a novel, robust virtual tool, it is possible to identify the change in mechanical properties for a given shear angle. This will allow the macro FE models to give more accurate results. High deformation regions can be identified from a forming simulation (e.g. a sheet of fabric draped over a tetrahedron tool and causes severe shear near the intrusion) and the change in mechanical properties of these local regions can be adjusted accordingly.

Using the digital element method previously developed in University of Bristol, the dry fabric architecture can be accurately predicted. The current work has created the ability to shear this virtual unit cell to update the unit cell geometry. This deformed woven geometry is then mapped onto a sheared voxel mesh and combined with an epoxy resin matrix to obtain the meso-scale Representative Volume Element (RVE) model. By applying periodic load cases to the model, the stiffness matrix and therefore the mechanical properties of the composite can be determined. This tool is applicable for any 2D woven resin-infused composite.

1. Introduction

The mechanical properties of 2D woven composites is affected by many parameters. Although the effect of individual constituent materials and weave definition is obvious, deformations induced during processing to achieve the final composite are part specific and can also affect final mechanical properties.

In-plane shear has been observed as the primary deformation when forming a textile to a 3D shape [1] [2], this is typically observed at regions of large double curvature. During this process the warp and weft yarns rotate away from their orthogonal axes, changing the anisotropy of the material. This makes the final composite stiffer in the direction where the fibres come together and more compliant at directions away from the fibres.

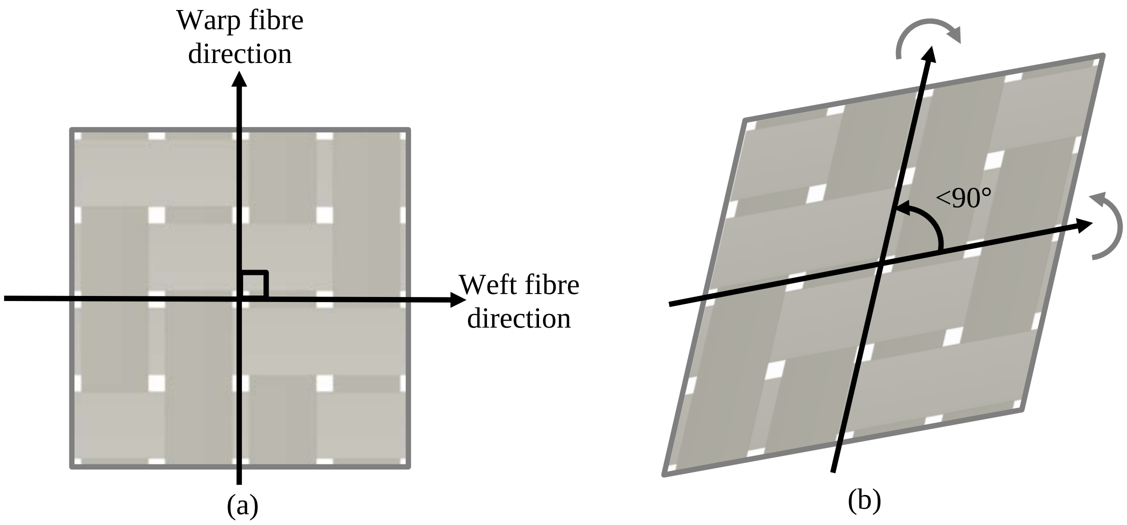

Figure 1. Fibre axis change during shear. (a) Before shear. (b) After shear.

A current challenge in composite manufacturing is the increase in part complexity as composites are seeing wider use in industries such as automotive and aerospace. Traditionally the effect of fabric shear during manufacture has not been considered in FE simulations due to the difficulty in determining shear angles, shear regions, mechanical property of the sheared region, and how to apply sheared properties in macro scale models.

This paper focuses on a methodology to address the latter two difficulties; to find the mechanical properties of the sheared material and application of these properties into macro-scale simulations. This process is written as a robust automated tool in Python to make it easy to use for FE analysts, with all simulations are performed in Abaqus. The processing effects of resin infusion and curing are not taken into consideration.

2. Extract shear angle

Shear angle can be obtained from either a forming/draping experiment or simulation. Figure 2 shows an example of a drape simulation conducted using Abaqus/explicit and an in-house user material developed at University of Bristol [3]. This is a hypothetical example of a swaged panel to show how the geometry can affect the shear angle over quite significant regions.

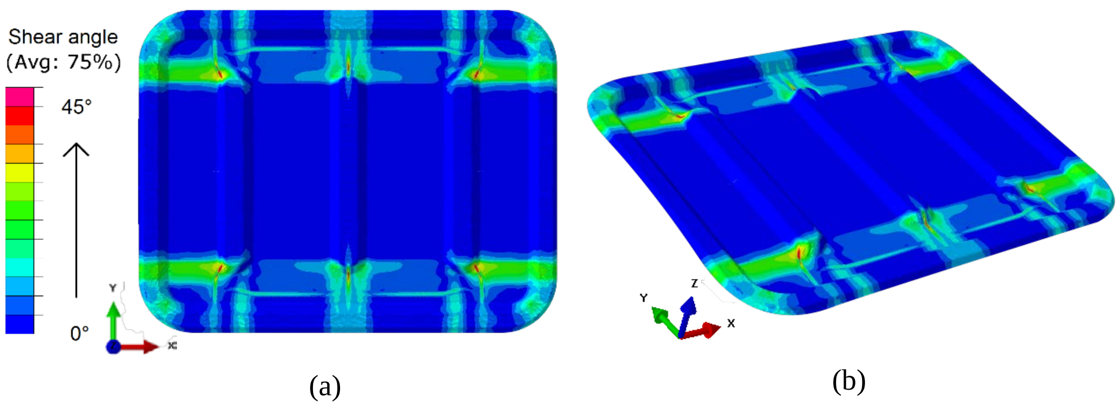

Figure 2. Shear angle distribution after draping simulation of a swaged panel. (a) Top down view. (b) Perspective view.

The shear angles are recorded for each element, and the change in fibre orientations as result of shear is also recorded.

Knowing the maximum shear angle, a set of discrete shear angles are selected in between the maximum and the minimum (0° is the unsheared state) where the mechanical properties are found for these discrete shear angles. A graph can be plotted (as in Figure 3) so the analyst can find the suitable mechanical property for any specified shear angle.

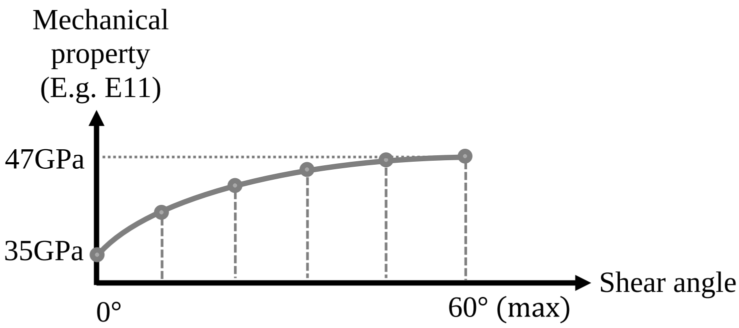

Figure 3. An example graph of material property vs shear angle. Where a total of six shear angles are investigated, with a maximum occurring shear angle of 60 degrees.

3. Digital element method

The compressed sheared fabric geometry (Figure 4) is generated using an in-house digital element solver from University of Bristol, which is based on the principles of [4] [5] [6] [7].

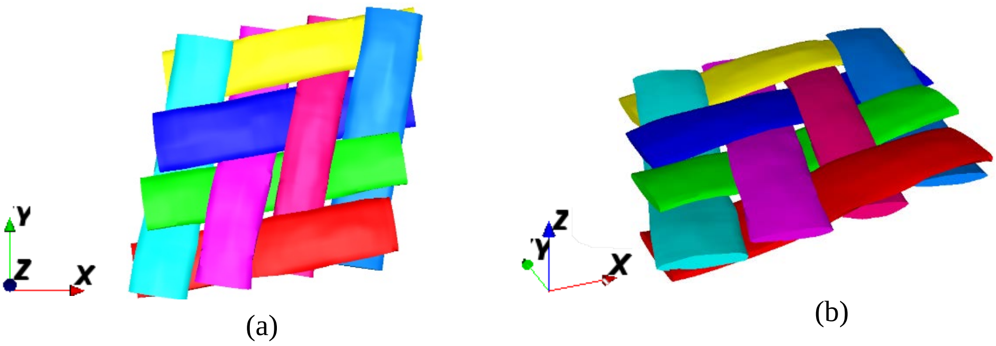

Figure 4. Sheared fabric geometry from in-house digital element solver. Presented via software TexGen. (a) Top down view. (b) Perspective view.

The solver models each tow as a set of 1D chain element, where weaving tension, compaction and shear are taken into consideration through external loads.
The sheared fabric geometry is extracted and then converted to csv files, which specifies the tow path nodes and cross-section profile as shown in Figure 5. This is repeated for the desirable discrete shear angles.

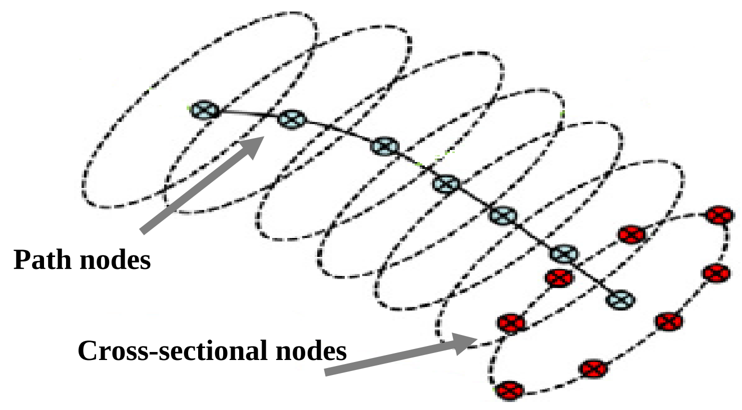

Figure 5. Structure of a tow. Where the path nodes describe undulation and direction of the tow; and the cross-sectional nodes outline the tow profile. A tow section is defined by two adjacent cross-sections [8].

4. Mapping and material cards

Knowing the unit cell dimension and the compacted thickness, a voxel mesh is generated in the unsheared state for the domain of the unit cell. The mesh is then sheared to the corresponding shear angle (Figure 6).

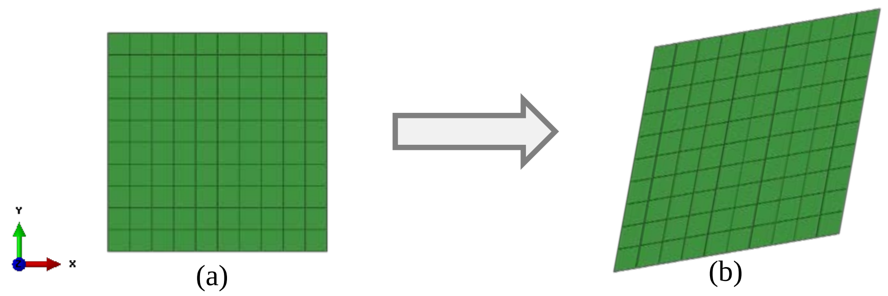

Figure 6. Sheared voxel mesh generation. (a) Unsheared mesh. (b) Sheared mesh.

To make sure that the fabric geometry is correctly mapped into the voxel mesh, the weave architecture is first tessellated to avoid any discontinuities in the tow profile. The mesh is then projected onto the tessellated fabric geometry and the centroid of each mesh element are queried whether it is inside or outside a tow (Figure 7).

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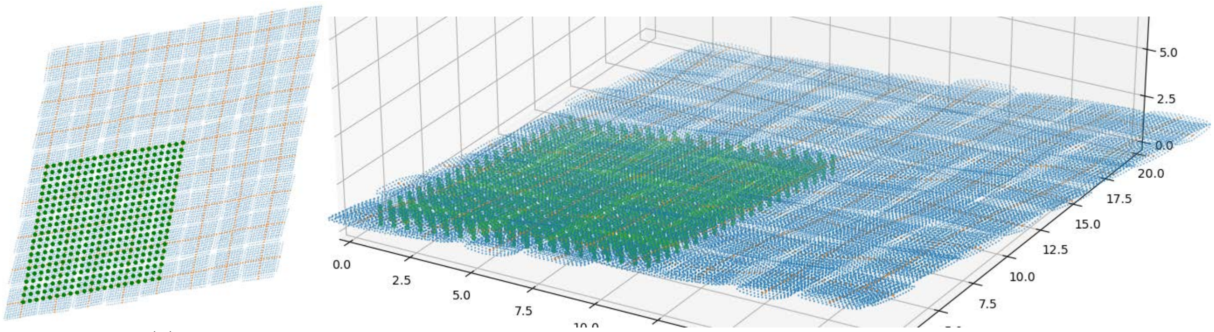


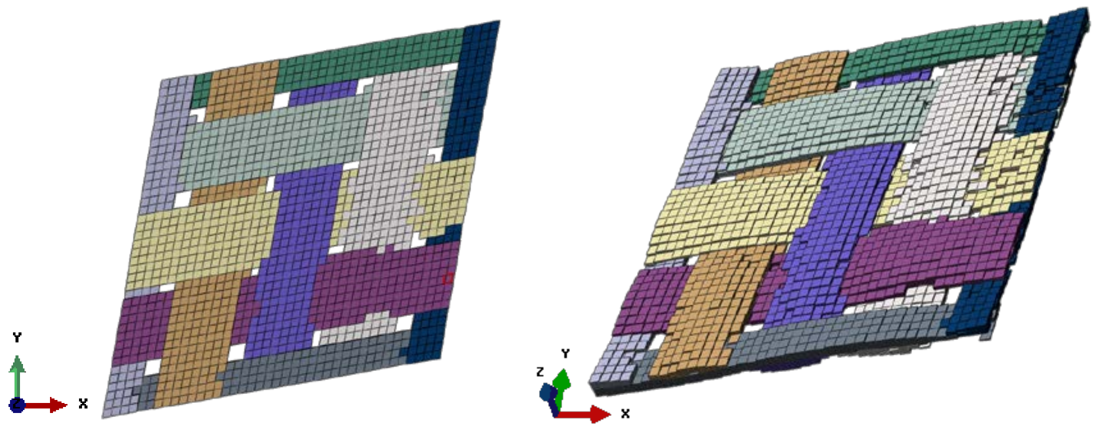
(a) (b)

Figure 7. Projecting the tessellated weave geometry onto the sheared voxel mesh, to cut out the mechanical model. Where the path nodes, the cross-section nodes and voxel mesh nodes are shown. (a) Top down view. (b) Perspective view.

These mesh elements are grouped according to which tow and which tow section they belong to. Figure 8 shows an example of the tow meshes of a sheared unit cell voxel model. The elements that do not belong to any tow sections represent the matrix.

Because of weaving tension, compression and undulation, each section of the tow will have a different orientation and tow cross-section, therefore the intra-yarn volume fraction also varies along the tows. The orientation of each element that belongs to a given section is assigned via the path node coordinates of the corresponding section.

To write material cards for elements belonging to each tow sections, the volume fraction is found and new elastic, orthotropic material cards are written for each corresponding section. The matrix is assigned as an elastic, isotropic material.



(a) (b)

Figure 8. Mechanical model of a sheared unit cell composite. Only showing elements that belong to the tows, for a 2x2 twill weave. (a) Top down view. (b) Perspective view.

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5. Primary axis

Once the unit cell model is built, loads will be applied so the strains and stresses can be extracted, and a stiffness matrix can be assembled. This can be done in any position, for example in Figure 9a where one fibre axis is aligned to the global axis.

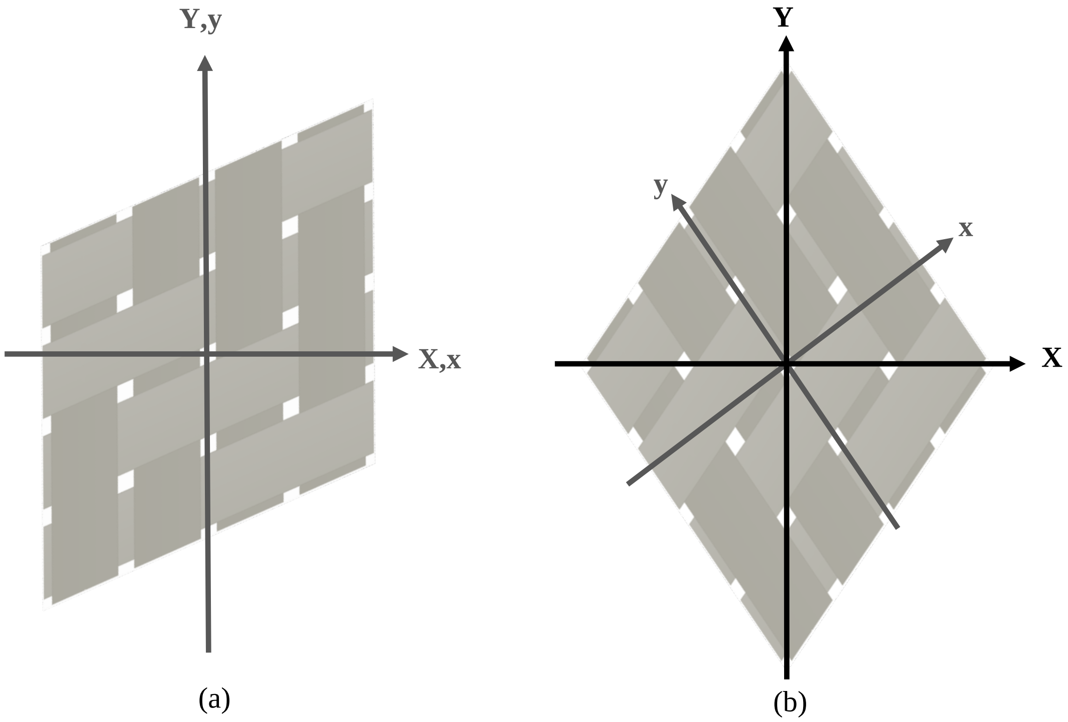

Figure 9. (a) An example unit cell axial orientation while extracting the stiffness matrix. (b) Rotate stiffness to match the global axis (from x, y to X, Y), to be used in macro simulations.

As the macro-scale shell and membrane model does not take through-thickness values, the stiffness matrix can be reduced to 2-dimensional plane stiffness matrix as shown in equation (1).

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_6\end{Bmatrix} = \begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_6\end{Bmatrix} \tag{1}$$

Once the reduced stiffness matrix is established, its components need to be rotated to find the effective mechanical properties in the global axis, as shown in Figure 9b. This can be achieved using a transformation matrix in (2) corresponding to the rotation direction between x and X.

$$[T] = \begin{bmatrix}cos^2\theta & sin^2\theta & 2sin\theta cos\theta\\ sin^2\theta & cos^2\theta & -2sin\theta cos\theta\\ -sin\theta cos\theta & sin\theta cos\theta & cos^2\theta - sin^2\theta\end{bmatrix} \tag{2}$$

As mentioned in section 2, the draping simulation is able to capture the rotation of the weft and warp tows. Therefore, the element orientations for each element belonging to the sheared region can be found, as shown by the white arrows in Figure 10a.

By orientating the material axis to align with the global X, Y axis as shown in Figure 9b, these axes are no longer dependent on shear angle. This allows the analyst to apply material orientation on a macro scale model where the global axis of the unit cell becomes local axis for each element, to assign mesh element orientation inside the macro scale simulation as shown in Figure 10b.

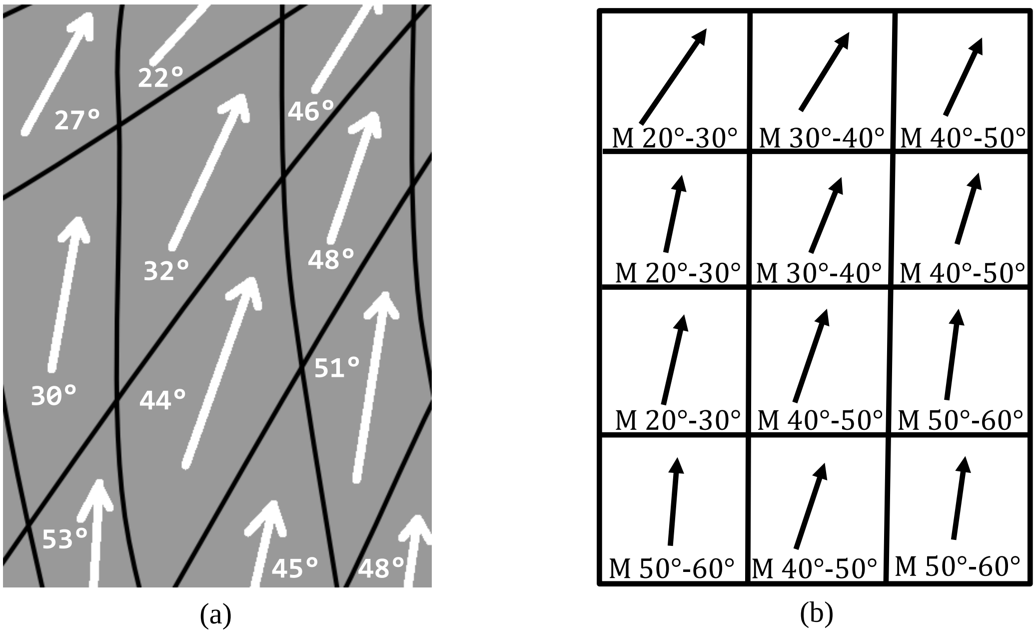

Figure 10. Example of how sheared properties are applied to macro scale model. (a) The unit cells from sheared region, where the orientation (thick white arrows) matches to the global axis of the unit cell, and shear angles are known from draping simulation. (b) Elements that corresponds to the sheared region. Where each element is assigned a local orientation that corresponds to the unit cell's global axis. Moreover, a set of material cards can be written for a set of shear angle ranges that are assigned to these 2D elements.

6. Conclusion

Shear deformations are inevitable as composite parts are becoming more complex. A numerical framework has been established here to account for the effect of composite fabric reinforcement shear due to forming processes on mechanical properties. A methodology to predict the mechanical properties of a sheared unit cell has first been proposed. A system for applying the sheared unit cell properties to a macro-scale simulation is then also defined.

The development of this tool is an essential part of determining the material properties as result of manufacturing deformations, and thus improving the accuracy of the structural scale simulations for mechanical performance.

Acknowledgements
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