THE HYBRID APPROACH OF A 3D TEXTILE COMPOSITE FINITE ELEMENT MODELLING TECHNIQUE AT MESO-SCALE LEVEL

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1 Abstract

The specific contribution of this paper is to present a detailed FE modelling approach to simulate 3D composites behaviour from stiffness through to failure using commercially available software and existing computational capabilities. In this approach the composite constituents including the fibre, interface and resin regions are modelled with Tetrahedral, Pyramid and Hexahedral finite elements respectively.

As manufacturing technology becomes more sophisticated, it will drive the need for the capability to predict the mechanical performance of materials with different 3D reinforcement architectures. Challenges for the application of finite element method include significant meshing extremes, excessive numbers of elements, and the limitations of element types for particular analysis applications. One such important analysis case is to model fibre and resin interplay in material at the brink of failure. Hexahedral finite elements are the preferred element type for assigning material orientation, for contact and, impact analyses, and reducing the element count, but the complexity of the 3D composite resin region presents extraordinary meshing difficulties.

2 Introduction

The performance of a composite material depends not only on the type of fibre and matrix, but also the nature of the fibre matrix interface [1, 2] and the fibre architecture. Composites with a 3D reinforcement architecture are known to provide delamination resistance, and it is desirable to predict and understand the characteristics of such material better. A particular interest is the potential for improved ballistic damage resistance and impact damage tolerance [3, 4, 5] in 3D woven composites, compared with conventional laminates, and through-thickness reinforcement alternatives such as tufting, stitching and z-pinning. The processes of weaving and consolidation introduce irregularities such as tow waviness, and tow cross-sectional shape and spacing variations.

This distortion is primarily a function of the tension applied to the binder during the weaving process as the warp tows are pulled towards the centre of the fabric. This in turn forces the weft tows to deviate around the warp binder intersection points [6]. In addition to this, the weft tows are not generally held in tension during weaving, conforming to the trajectory of the warp tows and experiencing a comparatively greater degree of distortion [7]. The distortion induced on a Satin type weave as a result of the initial weaving process by the Jacquard controlled loom in the University of Ulster Engineering Composites Research Centre (ECRE) is illustrated in Figure 1a. Note how this structure differs to an idealisation of the intended design illustrated in Figure 1b.

In some applications, such distortions are seen as introducing undesirable reductions in stiffness, but until the consequences of manufacturing parameters can be modeled geometrically and understood in terms of the mechanical performance, architecture optimization cannot be undertaken.

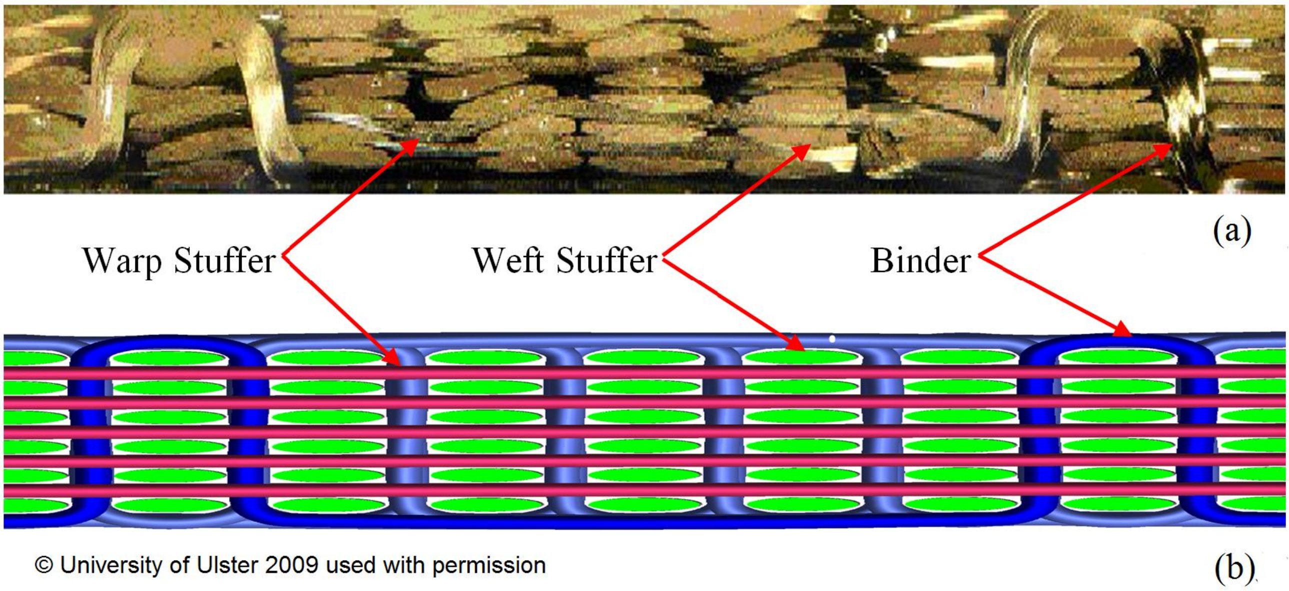

Figure 1 (a) A Satin Type structure sectioned on the warp axis[8] **(b)** A modelled Satin Type structure

3 Composite Modelling Background

Existing modelling approaches exploit the periodicity of the woven fabric architecture, identifying the unit cell or RVE, and generating a mathematical representation of average constitutive constants based on assumptions of the geometry and deformation. It is relatively straightforward to determine the mechanical properties of the individual fibre and resin constituents but an understanding of the interaction between the individual constituents and modelling of the stress or strain field is required to determine the mechanical properties of the material as a composite.

A large number of authors have used finite element modelling approaches to simulate the fibre and matrix phases of the composite material, and to make predictions of composite material properties. Paumelle [9] was among the first to present a 2D plain weave FEA model combining hexahedral and prism elements. Whitcomb et al. [10] used hexahedral and prism element models of plain weave composites to study the effects of fibre bundle undulation, and found that the in-plane moduli decreased almost linearly with increasing tow waviness. Other more detailed approaches include the works of Tang et al. [11], Sun et al. [12] and Lomov et al. [13]. In an attempt to limit the computational expense Woo and Whitcomb [14] proposed a global-local method combined with special macro elements. Other modelling methods, such as the Voxel [15] and Domain Superposition Technique (DST) [16] were devised to simplify the complexities surrounding the finite element and 3D composite geometry modelling procedure.

This paper considers the three sub-processes of FE modelling; pre-processing, solving, and post-processing, hence addressing the particular challenges raised by geometry creation, mesh generation and material definition with orientation.

4. Pre-processing

Pre-processing usually involves generating a mesh that conforms to a well defined geometry, 3D composite fibre architecture geometry can be defined according to tow shape, spacing, and trajectory. Difficulties specific to geometry modelling software arise in performing elementary modelling operations such as sweeping or surface extrusion, resulting in broken, holed or even dual geometry. Good quality geometry is required to achieve a well structured mesh Codes such as 3Tex© [17], WiseTex© [18] and TexGen [19] have been developed to automate the creation of 3D textile fabric geometries, avoiding the manual building of volumes, however, a bridge between geometry creation and finite element packages is still needed.

Current automatic mesh generation techniques suitable for complex material volumes are limited to tetrahedral elements. While ease of meshing makes this a popular choice of element, it is not always ideal for modelling anisotropic materials.

In this paper a combination of tetrahedral and hexahedral elements is employed, utilising pyramid elements at the interface (Figure 2).

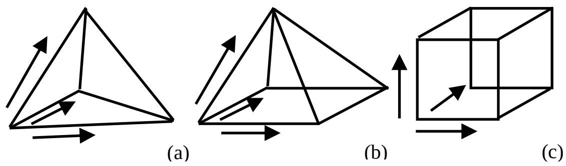

Figure 2 (a) Tetrahedral Element **(b)** Pyramid Element **(c)** Hexahedral Element

5. Tow Modelling Assumptions

1. The tow is considered to consist of 100% fibre, and therefore of smaller cross section than would be measured.
2. The intra-tow resin is assumed to have the same properties as the bulk resin material.
3. Tow shape. It was deemed preferable to maintain a finite resin thickness between tows, therefore a racetrack tow shape was selected, which was assumed constant.
4. Tow Undulation was limited to two axes i.e. in the case of a 3D composite, the warp and weft stuffers were assumed to remain on the x and y planes respectively and the warp binder tow assumed to undulated through x and z planes only.
5. The tows were assumed to be regularly spaced and aligned with no voids in the form of random air pockets present.

6. Modelling and Meshing Approach

Ansys AI*Environment was chosen to construct the geometry, and the top down blocking approach adopted to partition the tow and resin geometry. The user generates a topology that is independent of the underlying CAD. This permits a greater tolerance for imperfect CAD and the potential ability to re-use existing topologies for design changes or sensitivity studies such as tow waviness or cross-sectional shape variation analysis.

The meshing approach adopted was to combine element types, where the element type for each domain was selected based on its ability to facilitate the proposed material property vs. the geometrical meshing challenge it presented. Thus the tows were meshed with hexahedral elements, preferred for assigning material orthotropy, and the isotropic resin region with tetrahedral elements. For each tow component of the composite, an AI*Environment “block” of material was created and sectioned relating to the structure of the geometry. The relative blocks were associated to the geometry, thus creating a ‘block representation’ of the composite architecture illustrated in Figure 3. In another FE pre-processor package, these might be referred to as “partitions of the geometry”. Irrespective of the terminology, the blocks or partitions enable controlled hexahedral meshing. In the case of the binder component, the blocking was cut, reflected and constrained by association, allowing it to follow the 90 degree bends and thus undulate through the unit cell.

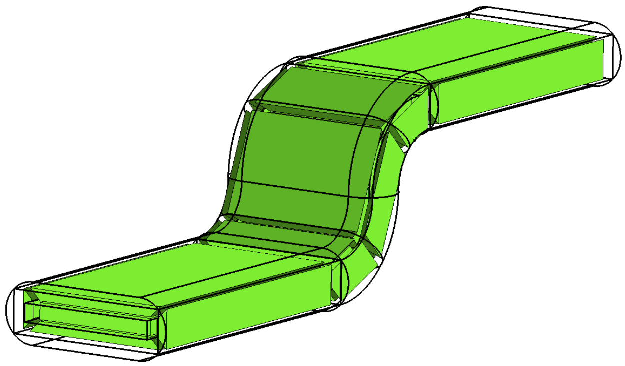

Figure 3 Binder repeat blocking

Two tow repeats were used to construct the binders of the unit cell, one to build the upward section, (up) and one to build the downward section (down). The warp and weft binder tows were constructed in a similar manner using symmetry to offset them much faster than achieved with the binder repeats.

Simply filling the resin region with unstructured tetrahedral elements around the hexahedral meshed tows would result in a totally unmatched interface between the two types of elements. A generalised constraint might have been introduced between the element types but this would have resulted in a mismatch of stresses at the interface, thus reducing accuracy; and this would be exacerbated by element volume aspect ratio differences. Since high fidelity modelling of the tow/resin interface is essential for accurate prediction of stresses and deformations, it was undesirable to use a tied interface. A matched mesh interface was achieved through the use of the pyramid element type at the resin side of the interface. This is illustrated in Figure 4.

The Delaunay automatic mesh generator was used to construct the resin tetrahedral mesh. The model size, made it impractical to model the full unit cell, but one twentieth sub-unit cell was meshed with 643,000 elements (Figure 5).

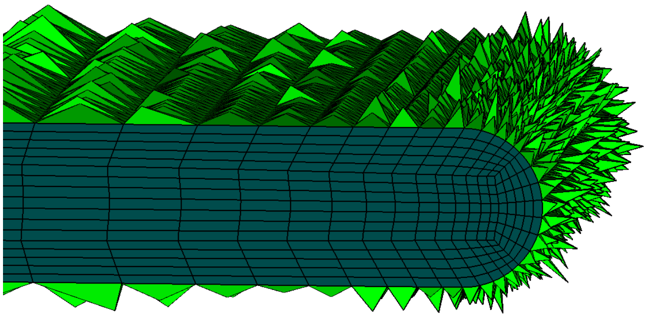

Figure 4 (a) Hexahedral Element Tow Representation and Interfacial Pyramid Elements

The hexahedral mesh of the composite tows permits the tow material property orientation to be assigned with relative ease. This was performed in SC03 [20], which allows material transverse isotropy direction to be assigned to long strings of elements and defined by their boundaries.

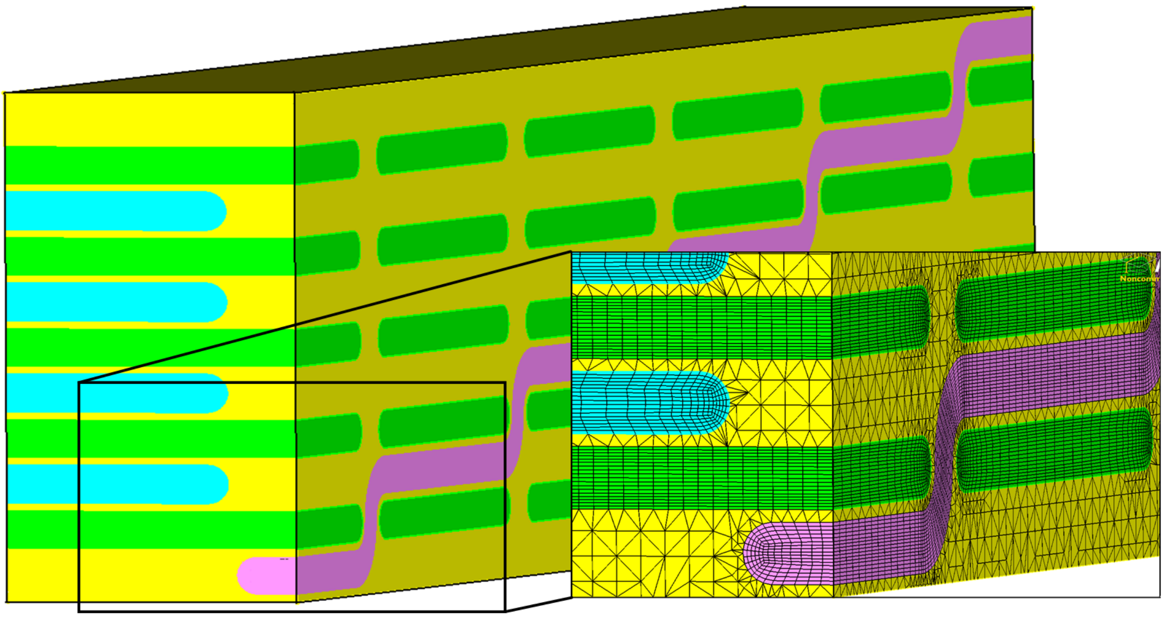

Figure 5 A Hybrid Meshed 3D AI composite 1/20 sub-unit cell section

7. Post-processing

The resulting stresses and subsequent modulus was calculated using the results file reaction force. The numerically most stable method of data extraction was found to measure the force required to keep the model in equilibrium.

8. Results

Element types for each domain have been selected based on their ability to facilitate the proposed material property. The approach can be generalised to provide a hexahedral element mesh extending part-way into the resin interface region, as would be required for modelling resin failure progression (Figure 6).

Mesh size and computational expense was the primary concern of this approach. As stated, this was highly dependant on the size of mesh required to sufficiently replicate the tow whilst still permitting sufficient transition through to the resin elements and onto the subsequent neighbouring tows. It was possible to generate a lower fidelity reduced element count 1,757,000 hybrid element representation of the unit cell using the AI*Environment tool.

As the hybrid approach is based on off-the-shelf commercial codes, a certain amount of manual manipulation has been necessary, however with appropriate development, the approach could be automated. With the block meshing technique a composite designer could create a library of blocking files for model automation. Essentially a conceptual training guide could be generated to aid learning on each 3D weave style, typically the angle interlock and layer to layer type configuration.

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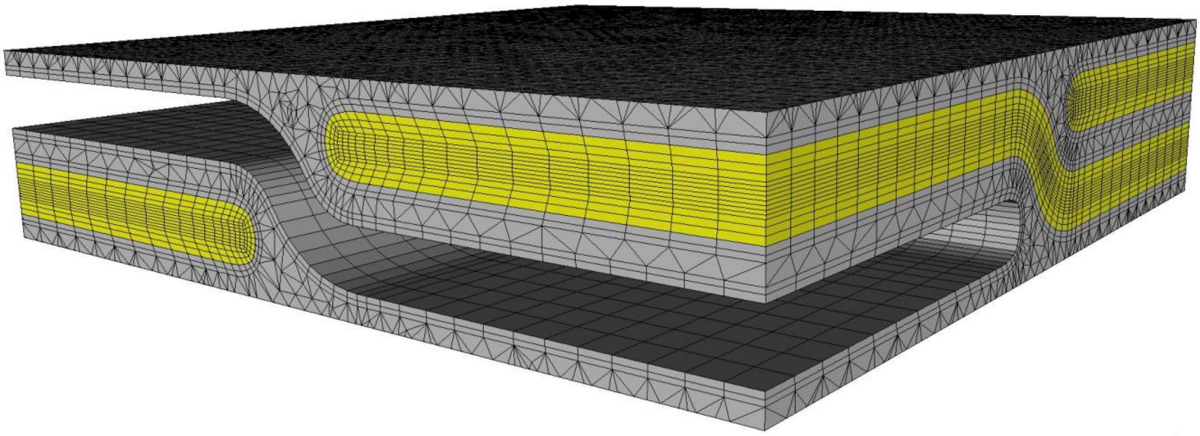

Figure 6 Hexahedral, Tetrahedral and Pyramid Element Resin

9. Conclusion

A fibre reinforced polymer meso-level modelling approach with an optimised finite element formulation has been presented. A considerable mesh count reduction in the presented approach can be obtained by reducing the element count towards the tow centre. This approach lends itself to represent complex tow-matrix interface behaviour which may help the understanding of failure /debonding initiation in composite analysis.

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