MULTI-SCALE MODELING OF 3D WOVEN STRUCTURES FOR MECHANICAL PERFORMANCE.

B. El Said[1], D. Ivanov[1], A. C. Long[2], S. R. Hallett[1]

[1]*Advanced Composites Centre for Innovation and Science, University of Bristol; Queens Building, University Walk, Bristol, BS8 1TR, United Kingdom*
[2]*Polymer Composites Research Group, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*

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Abstract

3D woven materials are characterized by complex internal fiber architectures leading to complex failure patterns. Due to limitations in available computational power, conventional modelling techniques are limited to either a meso or macro scale which in turns fails to capture the complex phenomena occurring across multiple length scales and effects on a 3D woven mechanical response. To counter these limitations, a multiscale framework for modelling of 3D woven structures is proposed. The modeling process under this framework is divided in two major phases, kinematic and mechanical. The proposed kinematic approach is capable of modelling feature/component scale fabric deformations and defects generated in preforms during weaving and compaction. The mechanical modelling phase extracts the yarn mechanical properties from the kinematic results and runs a multiscale mechanical analysis to find the mechanical response of a finished as woven component.

1. Introduction

The use of conventional composite materials in critical structures subject to impact has been limited by the poor through thickness properties of these materials. 3D woven composites have been shown to have enhanced impact performance and energy absorption characteristics [1, 2] . The manufacturing of 3D woven components involves weaving of yarns, preform compaction, infusion and curing. Research has shown that deformations and defects occurring during weaving and later during compaction can have a significant impact on these materials mechanical performance [3, 4]. Hence, it is necessary to include theses effects in any mechanical model of 3D woven structures. To achieve this goal two major modelling phases are needed. Initially, a set of kinematic models are used to predict the internal fabric architecture of a finished component. Then mechanical models can be used to assess the effects of the fibre architecture on the finished component mechanical performance. The two phases are quite computationally demanding and multi-scale techniques have to be used to achieve a balance between accuracy and practicality.

Preparing an accurate description of the fabric internal fibre architecture can be a complex task. Internal fibre geometries can be extracted from a physical sample using CT scans [5]. However, samples must be prepared before the fibre architecture can be identified which limits the use of such methods as design tools. The topic of two dimensional fabrics draping modelling has been addressed extensively in literature with several effective models presented [6, 7]. However, 3D woven and multi layer 2D woven preform undergo significant out of plane deformations which cannot be predicted by those draping techniques. Several dedicated modelling approaches for these materials have been proposed in literature which can be divided into three main categories, geometric, kinematic and mechanical. Geometric models only take into account the yarn paths and how they interlace inside the unit cell [8, 9]. These techniques do not account for cross section deformations and are generally not capable of predicting waviness and crimp. In kinematic models some form of contact models are used to simulate the yarn interactions with the yarn cross-section deformation taken into account. These models can predict crimp and waviness accurately if calibrated correctly. Mechanical models employ dedicated material models which represent the fibrous nature of the materials [10]. These models predict forces generated inside the fabric and on the tooling surface and are effective tools in the context of composites production engineering. However, they are associated with high computational cost and are limited to small coupon sized simulations. Since, the framework proposed here takes the design perspective of the problem; kinematic models are the optimal approach to predicting the finished structure internal fibre architecture. The prediction of compaction forces and pressures should be the subject of another exercise in a production engineering context.

From a design perspective, when compared to the idealized unit cell geometry, the weaving process introduces a level of defects and deformations which are periodic in nature and related to the fabric unit cell. These are fabric architecture based defects. Preforms can have additional defects as results of sub optimal manufacturing and/or handling but these are not included in this context. Further deformations occur during the compaction phase which unlike the weaving deformation they are a result of the prefom tool interaction, which are dependent on the tool geometry. Current kinematic modelling techniques for 3D woven materials are associated with a high computational expense, which limits its applicability to the fabric unit cell level. These modelling techniques fail to capture the tool geometry effect, which can be of paramount importance for parts with complex geometries, thus a new multi-scale approach is proposed here. At the unit cell scale high fidelity model is used where each yarn is represented by bundles of beam elements in a contact model, is used to predict the as woven fabric architecture. For large scale modelling of preform compaction, a reduced yarn representation using shell elements is adopted where each yarn is represented by a single contact surface. The unit cell as-woven fabric architecture from the digital element is converted to the reduced presentation then tessellated to generate full scale fabric models. These models are trimmed to the desired preform shape and then compacted on the tool of interest.

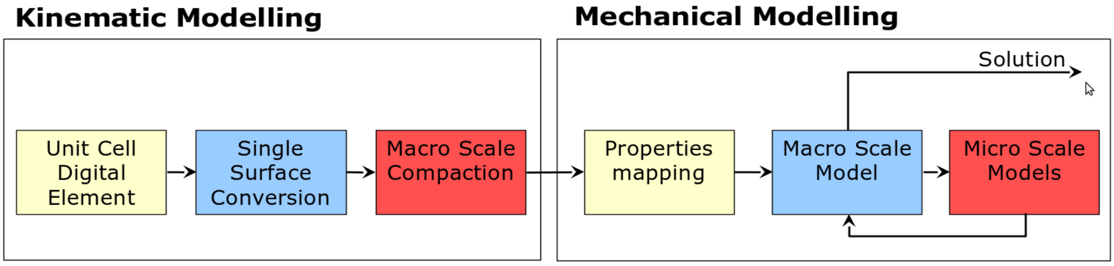

Figure 1. Modelling framework overview

In the second phase a full mechanical model is built based on the fabric architecture resulting from the macro kinematic model. This fabric architecture is no longer periodic since each fabric unit cell has reacted to compaction differently based on the tool geometry at that given location. Building a detailed model of the entire structure is computationally unachievable. Homogenization techniques cannot be used in this case due to the lack of periodicity. Additionally, in most applications, the unit cell size is large compared to the structure size which means there will be significant boundary edge effects. Hence, a multiscale sub-structuring technique is proposed for mechanical modelling of 3D woven components. This technique enables the structure to be divided during analysis and multiple models can be used to investigate each part. 3D woven materials have complex failure patterns and are dominated by features occurring on the micro and meso scales. The meso scale features of woven materials such as crimp and waviness are unique to these types of materials. Hence, this paper will focus on the meso-scale models, since both macro and micro scales mechanical models exhibit commonalities with conventional composites. The overview of the proposed modelling technique is given in Figure 1.

2. Kinematic Modelling

2.1 Meso-scale Modelling

The proposed kinematic modelling process starts with a unit cell model which utilizes the digital element approach from Green et al [11]. In this approach each yarn is represented by a bundle of beam elements. The initial beam geometry shown in Figure 2.a is interlaced to represent the unit cell architecture. A thermal load is applied to the binder yarns, forcing them to contract, hence simulating the fabric compaction during weaving. During the load application phase, the fabric thickness will decrease, thus increasing the volume fraction, until the yarns lock completely and no further thickness reduction can be achieved which will be considered the as-woven status. Periodic constraints are applied to the unit cell edges to ensure that the unit cell geometry remains periodic throughout the simulation and hence representative of the fabric. A rigid tool can be used to compact the unit cell even further to achieve a consolidated state. An example of this approach applied to a layer to layer interlock fabric is given in Figure 2.b and 2.c.

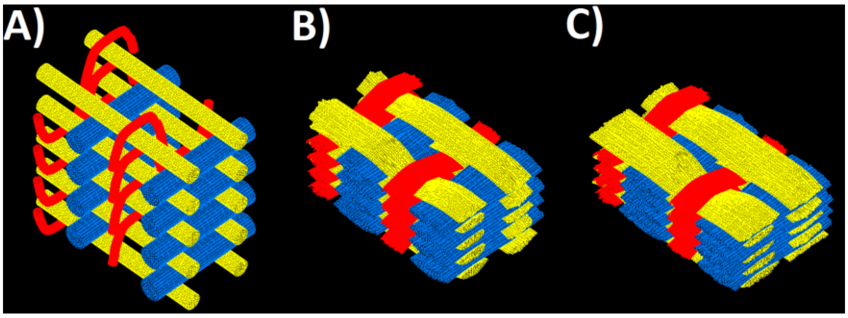

Figure 2. a) Initial fabric geometry b) As-woven unit cell geometry c) compacted unit cell geometry

2.2 Macro-scale Modelling

The digital element method can provide high fidelity, accurate unit cell geometries. However the numerous contacts occurring between the bundles of beams representing each yarn are computationally expensive. This high computational cost limits the applicability of these models to the unit cell scale. For the macro scale, an approach proposed by El Said et al [12] is adopted. In this approach the yarn surfaces are created by processing the yarn geometry generated from a digital element model and a cross-section shape is fitted around each beam bundle. This conversion process creates a hollow yarn surface, which is represented by shell elements during contact modelling. To avoid excessive unrealistic yarn deformation, a viscoelastic core is introduced for each yarn. This core simulates the fibrous nature of the material without having to represent the fibres individually and increase the computational load. Figure 3 shows the results of a unit cell compaction under periodic constraints for both the single surface and digital element models as compared with CT scan experimental results as shown for a layer to layer interlock fabric.

The single surface geometries generated in this manner can be tessellated to from 3D woven fabric preform models of any size and/or shape. These preform models can be combined in contact models with tool geometries to simulate compaction with either rigid or flexible tooling. A simulation for the compaction of a 360X300mm 5 harness satin weave preform with orthogonal binders on a hemispherical tool was carried out (Figure 4.). The results show that the multi-scale modelling approach is capable of capturing the deformation on the fabric and yarn levels in addition to capturing the through thickness deformation.

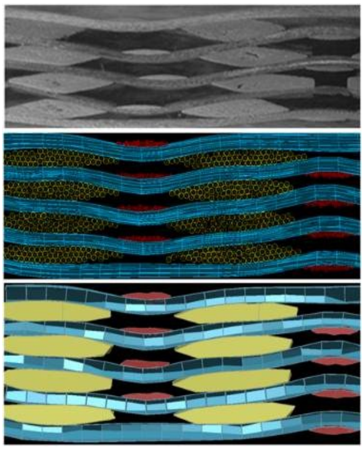

Figure 3. Comparison between the compacted unit cell geometries. From the top: CT scan results, digital element model and single surface model.

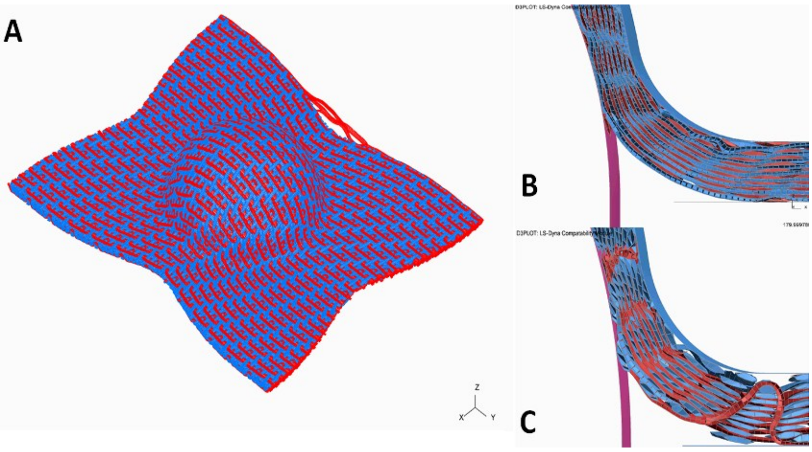

Figure 4. Macro-scale kinematic model: A) Through thickness section at dome base in weft direction B) Results of macro-scale modelling of dome compaction C) Through thickness section at dome base in warp direction

3 Mechanical Modelling

Macro scale mechanical models of composites material have always relied on some form of homogenization technique. These techniques calculate equivalent material properties from a detailed smaller scale model. These equivalent material properties are used to build a larger scale model where the meso and micro scale details are not included. While these techniques work for most 2D woven problems, they have drawbacks that make them unfeasible for 3D woven materials modelling. As has been shown in the kinematic modelling section, the unit cell architecture changes before and after compaction, hence the fabric is no longer periodic and the homogenised material properties calculated using a flat unit cell can no longer represent the final structure. Additionally, the representative unit cell size in 3D woven materials is large compared to the average aerospace component size. This large size will create edge effects which invalidates homogenization assumptions. Any macro scale mechanical model also needs to capture the material nonlinearity since the failure mechanisms in 3D woven materials are complex and will require some form of progressive damage models. On the other hand, yarn defects developing on the meso scale such as waviness and crimp usually dominate the yarn failure. As a result, these effects have to be included in the macro scale models. Even with the recent progress in computational power, building such an extensive model will be practically unfeasible. A multi-scale technique is needed to achieve both solution accuracy and speed. A schematic of this modelling framework is presented in Figure 5.

The proposed technique relies on calculating the meso-scale material properties from a set of micro mechanical models representative of the problem. A high fidelity meso scale model is built based on the detailed kinematic geometry including defects and deformation generated during weaving and compaction. This full meso scale model will be divided into substructures, which do not necessarily relate to unit cells but rather to substructures of manageable model sizes. A sub model is built for each substructure where the sub stiffness matrix is passed to a macro scale model where the load and boundary condition are applied.

3.1 Mechanical Properties of Realistic Woven Materials

Developing the modelling framework described in the previous section requires developing three modelling levels micro, meso and macro. The main focus of this current work is the meso-scale models, which connect directly to the kinematic modelling phase. Mechanical properties for this level are combined from both micro-scale material models and the fibre architectures. For each yarn, the intra-yarn volume fraction can be found directly from the kinematic model. This information can be fed into a micro-scale mechanical model where the equivalent yarn properties can be calculated. Figure 6 shows the variation of intra-yarn volume fraction for the binder yarn in an orthogonal fabric. The intra-yarn volume fraction can be seen to vary as the yarn interacts with stacks of weft yarns which indicate that the material properties will vary along the yarn length. The other key information is the material axes definition which can be extracted from the yarn path at each as specific location. The material axes can be defined as the tangent to the yarn centreline at any location along the yarn path as seen in Figure 7.

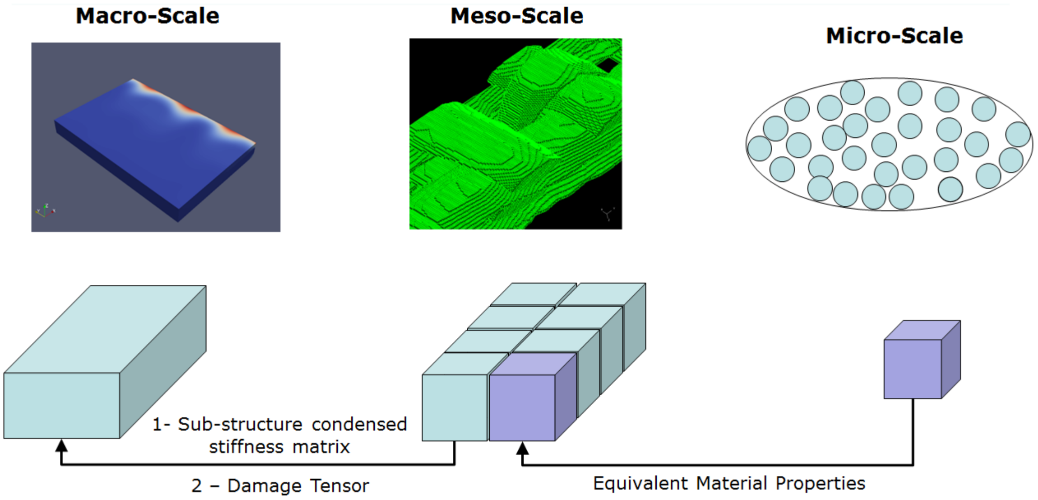

Figure 5. Overview of the proposed multiscale modeling technique

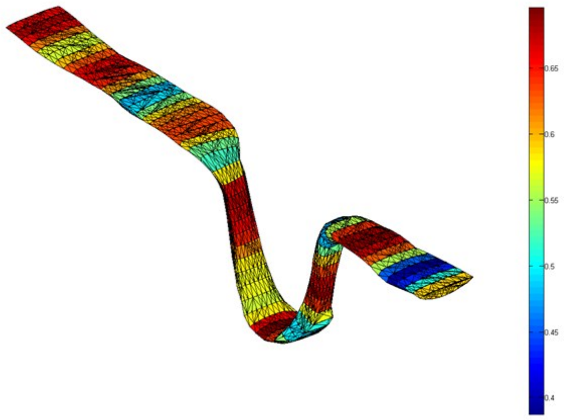

Figure 6. Intra-yarn volume fraction of a binder in an orthogonal fabric.

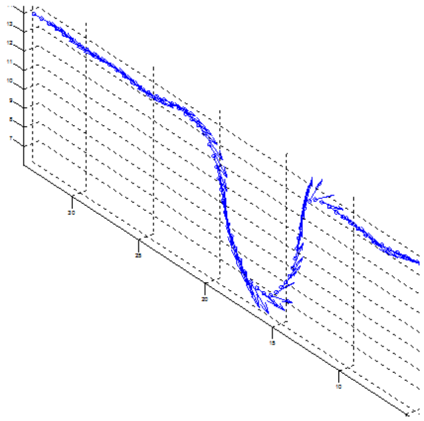

Figure 7. Material axis as calculated for a binder yarn from orthogonal fabric.

Meshing realistic 3D woven composites geometries for mechanical modelling using brick elements can be a complex task since it involves combining yarn meshes with a matrix mesh. Due to fabric architecture complexity, traditional meshing techniques can generate significantly distorted elements. To overcome these challenges several meshing techniques have been proposed in literature such as domain superposition techniques [13] and Voxel meshing [14]. Voxel meshes cannot trace the geometries exactly and will introduce modelling inaccuracies. Consequently, a finer mesh with a higher computational load is required to achieve a reasonable degree of accuracy. On the other hand, these meshes are versatile and can represent arbitrary geometries of any degree of complexity. As a result, Voxel meshing is the method of choice for the verification exercises in this paper. However, the proposed modelling framework is not limited to these meshes only, but is also applicable to any suitable meshing technique. By processing the compacted fabric geometry, the yarn axis direction, the intra-yarn volume fraction and the associated material properties can be mapped directly to the mechanical modelling mesh. A dedicated solver was built to carry out the mapping, build an FEA model then solve the system. A computational graphics library CGAL [15] is used to build triangulations for each yarn surface. Each finite element integration point is associated with a specific yarn surface using its triangulation. The integration points then takes the material properties associated with the specific yarn location. Assigning material properties directly to integration points allows for the use of transition elements between yarn material and resin material which in turn can reduce the stress concentrations associated with the use of Voxel meshes.

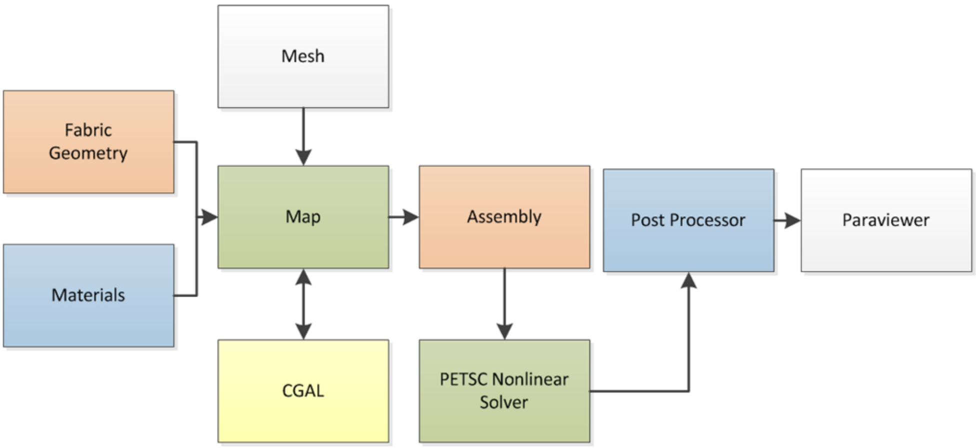

Figure 8. Dedicated meso-scale solver structure

3.2 Meso - Scale Mechanical Modelling

After the mapping stage is complete, the finite element model integration and system assembly is carried out. The final model is later submitted to the FEA solver which employs the PETSC [16] nonlinear equations solver. The results can then be post processed for stresses and strains. This level of analysis can predict the mechanical performance of a single substructure. Additionally, a condensed stiffness matrix can be passed to a macro scale model were only the substructure's external degrees of freedom are included.

To evaluate the model accuracy, a model was prepared to compare the mechanical performance of an iso-phase multilayer 2D woven preform presented by Ito et al [17]. The unit cell geometry was built using TexGen then tessellated to form a full width sample 19 mm and 8 layers. Figure 9 shows the unit cell geometry and the tessellated fabric. An FEA model 1 unit cell in the length direction with periodic boundary conditions applied lengthwise was constructed. A fixed displacement was applied to the sample. Figure 10 shows FEA model results. The experimental results as given by Ito et al [17] as $E_{11} = 43(2.91)$ GPa. The model has predicted to be $E_{11} = 42.95$ GPa showing good agreement with the experimental results. Figure 11 shows a slice across the sample at the mid length location showing the axial stress variation through the thickness displayed in material coordinates. This slice goes through 3 unit cells in the width direction and eight in the thickness, thus totalling 24 unit cells. The stresses are clearly higher on the surface unit cells than those inside the sample Ivanov et al [18, 19] and Owens et al have reported similar effects. This observation seems true for all the sample surfaces in both the width and the thickness directions. Since the behaviour of composite materials is normally non linear and depends on the stress state. This result further reinforces the assumption that homogenization techniques are not sufficient to model the failure of 3D and multi-layer 2D woven even with flat samples.

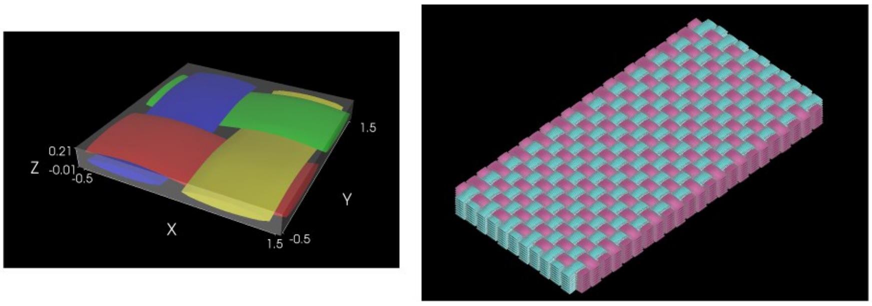

Figure 9. Kinematic models: a) Unit cell geometry b) Tessellated fabric geometry.

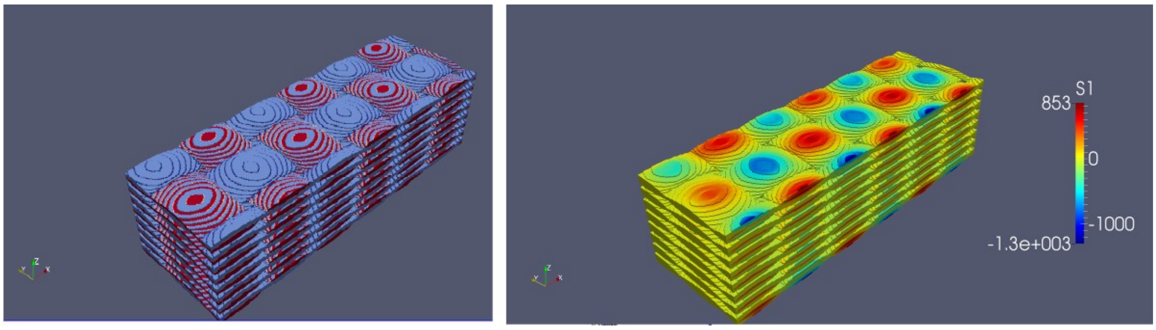

Figure 10. Mechanical models a) Material properties mapping b) Fiber direction stresses results under 0.5 mm axial displacement (only yarn type materials are shown)

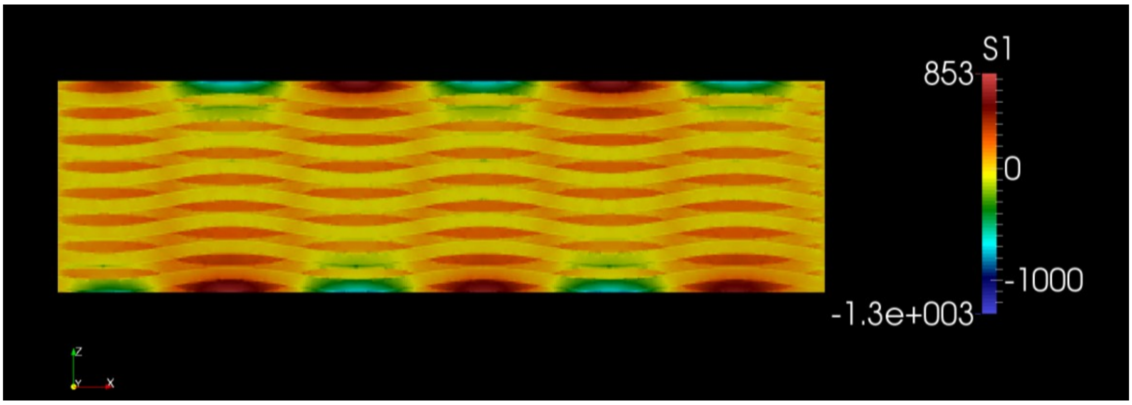

Figure 11. A slice through the sample showing the through thickness axial stress variation, stresses are displayed in material coordinates for yarn elements and global coordinates for matrix elements.

4. Conclusion and Future Work

An integrated framework for modelling of 3D woven materials is proposed. The modelling framework is divided into two phases, a kinematic phase and a mechanical phase. During the kinematic phase, the framework is capable of capturing the effects of defects and deformations on the 3D woven preforms internal architectures. In the mechanical phase accurate multiscale models can be built using the detailed fabric architecture from the kinematic models. Comparison to experimental results has shown good agreement between simulations and experimental work. The results have shown that conventional homogenization techniques are not suitable for 3D woven material and multi-scale approaches should be adopted.

The next stage of this work includes identifying and integrating macro and micro scale models with the current meso scale modelling capabilities. Nonlinear material models and progressive damage capabilities will be introduced in order to allow for accurate strength prediction.

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