A MESO-FE VOXEL MODEL OF AN INTERLOCK WOVEN COMPOSITE

J. Schneider[1&2], G. Hello[1], Z. Aboura[1], M.L. Benzeggagh[1] and D. Marsal[2]
[1] Université de Technologie de Compiègne, Laboratoire de Mécanique Roberval.
[2] SNECMA Villaroche – 77550 Moissy-Cramayel.
Julien.schneider@utc.fr

SUMMARY

This paper focused on a methodology used to create a meso-scale Finite Element (FE) modelling of textile composites. This model based on a voxel approach can be completely configured. A good agreement has been noticed in terms of elastic and shear moduli for 2D and interlock weave composite. First confrontations with measured strain/displacement fields in the thickness of the interlock have been performed.

Keywords: Interlock, Woven, Mechanical properties, Meso-scale Finite Element modelling, Digital Image Correlation.

INTRODUCTION

Recent improvements of custom looms and manufacturing process enable production of multidimensional composite. Contrary to the 2D woven like taffeta or twill weave, the effect of the weaving in the 3rd direction has to be considered. Moreover, some difficulties persist concerning the out-of-plane behaviour. These points take part in the development of mesoscopic model. It's a powerful tool for homogenization of mechanical properties, visualization of strain/stress fields inside the Unit Cell (UC) and localization of first damage.

Establishment of the geometries and the meshing for complex preforms with interlaced yarns thought the thickness was very difficult. The process of injection requires a compaction and produce confined area and local compression of yarn. Modelling based on contact approaches describe tow geometry [1]. Overlook that type of detail impose a constant section and place the modelling in an unfavourable position for the fibre volume fraction. So, to fit that ratio, some problems concerning interpenetration appear. To realize a full modelling of that kind of material, many developments are provided; a geometric modeller [2] with a compaction yarn's law, a corrective tool for the interpenetration [3] and a solver.

After these works, the homogenization of the macroscopic model compared to the experimental moduli can be a first validation of the model. But with the improvement of new optical measurement technologies like Digital Image Correlation (DIC) [4] or Digital Shearography (DS) [5] and Digital Holography (DH) [6], the measured displacement or strain fields can be used to verify the model in a mesoscopic scale.

MATERIAL PRESENTATION

In this paper, we firstly focus on traditional 2D woven. Macroscopic comparing has been realized with an E-Glass/Vinylester taffeta weave and two kinds of 2/2 twill weave: a classical Glass/Epoxy and a hybrid Glass-PE/Epoxy.

Figure 1: Representation of a taffeta weave (a) and a twill weave (b)

Then, macroscopic and mesoscopic comparisons have been performed on epoxy reinforced by unbalanced layer/layer Carbon interlocks woven.

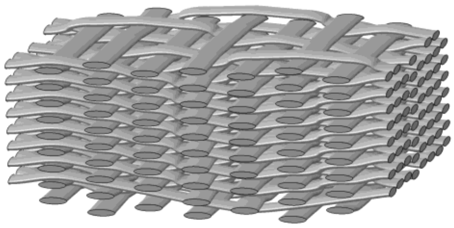

Figure 2: Representation of a complex 3D interlock woven fabric composite

MESO-FE VOXEL MODEL

Voxel approach

The first aim of the Finite Element (FE) model associated to homogenisation technique is to determine 3D elastic moduli. The second is to build an aid tool for the comprehension of the 3D damage mechanics in the interlocks composite. Indeed, concerning this composite a methodology based on different experimental techniques (Acoustic Emission, DIC, Optic observation, X-ray tomography) [7] was developed to understand the damage scenario and the effect of weaving. Nevertheless some interrogations remain and the FE method can bring certain complements of answers.

The use of a traditional technique of meshing is immediately confronted with complexity of weaving and dimensions of the Representative Volume Element (RVE). Indeed, several problems arise:

- The respect of a correct volume fraction involves in certain cases a yarn/yarn interpenetration with need for use of contact elements
- Difficulties to mesh the resin with hexahedral elements
- Degenerated elements in confined zones
- Difficulties to generate hexahedral elements in cut yarns

- Problems of node coincidences
- Need for several tools data processing for the generation of the meshing: tool CAD for the geometry, tool for meshing and then export to a computer code.

For these reasons, FE voxel model was developed through an “easy” automated script. The methodology was programmed through Matlab® for the generation of the input file and the computation was make by Abaqus® FE software. First of all, yarns’ paths coordinates was required.

The Yarn’s paths of the 2D textile were obtained from microscopic observations on the composites. Whereas, in the interlock architecture case, trajectories were collected from Wisetex [2]. The yarn paths are idealized and do not completely reflect the reality of material, in particular after high compaction of these complex weaves. Thereafter, a RVE sized parallelepiped was meshed with 3D regular hexahedral elements (cube) where numbers and coordinates of nodes/elements were controlled. So, an ellipsoid check test follows each path of defined yarn and verify element belonging (warp, weft, resin) according to its coordinates. Then, orientations deducted through the path, are applied to the elements So, for a fine identification of the homogeneous mechanical properties, periodicity conditions [8-9] have been imposed on the boundary. The 6 elementary loadings required have been applied to identify the 3D moduli.

The main advantage of this method lies in its simplicity and the possibility of being fully parameterized. It is then obvious that whatever the complexity of the geometry, the meshing can be carried out in few operations. In the other hand, the Voxel FE method generates imperfect geometries directly dependent on the mesh size. With the actual computation means and their fast-growing, that mesh size can be strongly decreased and fit suitably the geometry. Figure 3 presents an example of taffeta meshed with Voxel technique.

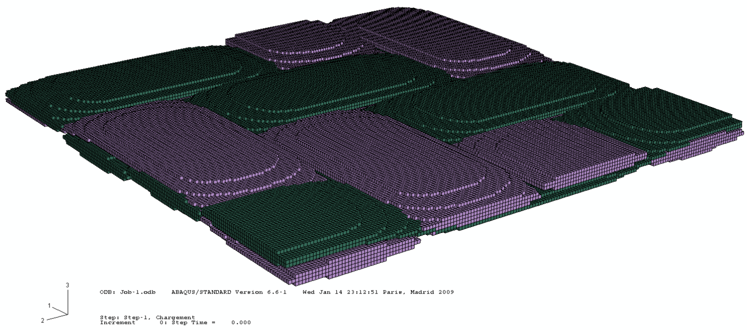

Figure 3 : Example of a twill weave Glass/Vinylester coarse-meshed through the Voxel technique (1 M of DOF)

Results of the 2D woven

Table 1 presents the Degree Of Freedom (DOF) of the Voxel model for the different materials of this study. Two size of element was applied for each model to verify size dependencies. For the size selected, no dependency was observed on the homogenous mechanical properties. Table 1 also presents fibre volumes fractions obtained experimentally and reproduced by Voxel FE. The present model has no difficulty to reproduce the real properties. Note that for all configurations the fibre volume fraction in the yarns is 75%.

Materials	*DOF (in million)*	*Volume fraction experimental*	*Volume fraction Voxel*
Taffeta	0.4 & 3.2	52%	52%
Twill weave	1 & 8	38%	38%
Hybrid Twill weave	1 & 8	Total 52% Glass 32% PE 20%	Total 51% Glass 32% PE 19%
Interlock	0.85 & 6.8	55%	55%

Table 1: Information concerning the different woven studied

Experimental results pertain to the in-plane moduli on these weaving were used for the macroscopic validation [10-11]. With a RVE thickness closed to the tenths of millimetres, only enormous stratification can give a plenty thickness for a specimen. So, the out-of-plane characteristics of the voxel model have been compared to classical FE [12] and Analytical [13] approaches.

The table 2 introduces moduli reached by experiences and simulations for an E-Glass/Vinylester taffeta weave.

TAFFETA WEAVE	$E_1 = E_2$	E_3	G_{12}	$G_{13} = G_{23}$
Experience	24.8 ± 1.1	/	6.5 ± 0.8	/
MesoTex [13]	25.3	13.5	5.2	5.2
Chouchaoui [12]	23.5	8.3	4.4	4.5
Voxel	24.5	12.2	5.7	3.3

Table 2: Experience and simulation results for the taffeta weave

Comparatively to the experimental results, the voxel model provides good agreement for the elastic moduli. The worst agreement relates to the in plane shearing module G_{12}. The variation reaches the 12%. However, taking into account the dispersion of the experimental results, this difference remains acceptable.
With regard to the comparison with the analytical model Mesotex and traditional calculation FE, the Voxel model is closer to the analytical model for tensile behavior, whereas it strongly deviates for the out-of-plane shearing properties (G_{13} and G_{23}). But without experimental data, no conclusion can be pronounced.

The tables 3 and 4 present experimental and modelling results of respectively a Glass/Epoxy twill weave and an hybrid Glass-PE/Epoxy twill weave (Fig. 4).

CLASSIC TWILL WEAVE	$E_1 = E_2$	E_3	G_{12}	$G_{13} = G_{23}$
Experience	19.2 ± 0.2	/	3.6 ± 0.1	/
MesoTex [15]	19.5	10.9	3.9	3.8
Chouchaoui [14]	18	8	3.3	2.2
Voxel	19.1	9.6	3.6	2.1

Table 3: Experience and simulation results for the classic twill weave

HYBRID TWILL WEAVE	$E_1 = E_2$	E_3	G_{12}	$G_{13} = G_{23}$
Experience	18 ± 0.4	/	3.5 ± 0.1	/
MesoTex [15]	19.9	12.8	3.9	4.3
Chouchaoui [14]	16.6	8.4	3.3	2.5
Voxel	17.8	11.6	3.6	2.5

Table 4: Experience and simulation results for the hybrid twill weave

Contrary to the taffeta case, the voxel model provides good agreement for the in-plane elastic and shear moduli (based on experimental). Concerning the out-of-plane characterization, shear modulus on the two FE approaches provide the same result, but a gap exists for the rigidity through the thickness. Besides, let us note that modulus in the third direction is enclosed by the Chouchaoui's model and MesoTex predictions for all the weaving considered.

According to these results, the voxel FEM is a good method for prediction of the homogenized mechanical properties.

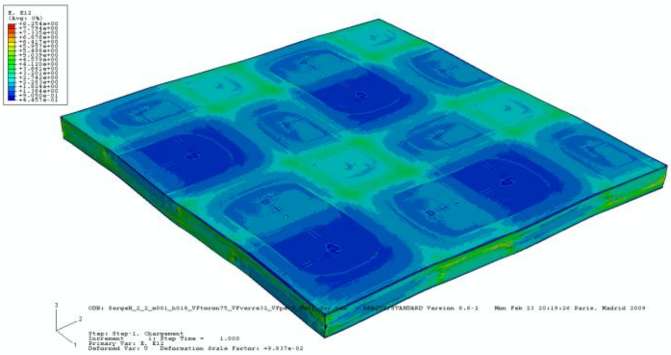

Figure 4: Hybrid twill weave on a shear loading in the plane

Results of the interlocks woven

Macroscopic scale Validation

Contrary to the 2D woven cases, the 3D elastic and shear moduli of these composite have been experimentally provided. The trough-the-thickness elasticity has been deducted by 2 kinds of specimens [14-15] and the out-of-plane shear extracted by torsion on bar and bending on short specimens [16]. Due to the experimental difficulties to set up a robust method for the out-of-plane characterization, the FE model can be included in our self improving approach surrounded by DIC, EA and observations [7]. The macroscopic validation realized on the 2D weave increase the confidence for this new case.

The table 5 supplies ratios of the moduli reached by experiences and simulation for an unbalanced Carbon/Epoxy interlock woven.

INTERLOCK	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}
Experience/Voxel	1.03	0.81	0.97	1.01	1.07	0.87

Table 5

A good agreement could be noticed for the moduli except in the weft direction. This difference comes from the idealization of the yarns' paths evoked previously. Thus the microscopic observations indicate that the weft yarns undulate slightly. This phenomenon is due to the passage of the warp yarn.

In order to overcome this problem without modification of the geometry of the interlock, the local orientations of the element properties were introduced in agreement with the microscopic observations. Figure 5 indicates the orientation of elements properties after correction.

INTERLOCK	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}
Experience/Voxel	/	0.95	/	/	/	/

Table 6

Table 6 shows that this correction improves the correlation tests/model in the weft direction. These results increase the confidence in both experiences and Voxel model.

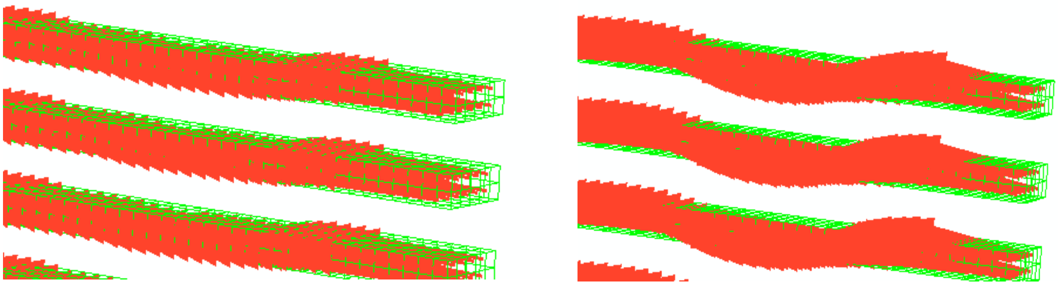

Figure 5: Original orientations due to the geometry (a) and implemented orientations (b) in a weft yarns column

The first aim of modelling relating to the prediction of 3D elastic was approved on the condition that a right description of the weaving has been introduced.

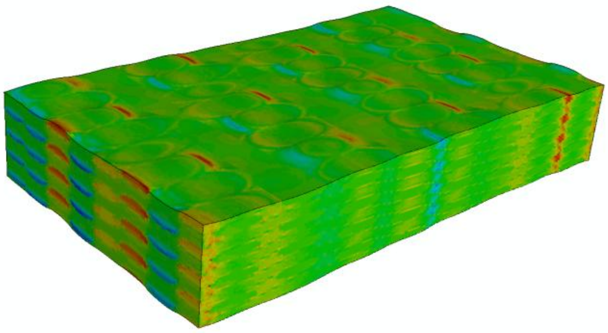

Figure 6: Unbalanced layer/layer interlock out-of-plane shear on a tensile loading.

Mesoscopic scale Validation

According to many studies [17-19], draw a parallel between full-field and FEM strain can be used as a mesoscopic validation. Usually, these comparisons were carrying out through face's cross-section of the Unit Cell.

In our modelling, because of the thickness of the weaving, we choose to compare full-field and FEM strain on the side edge.

Due to a simulation based on the elastic material response, full-field strain have to be measured in a low level case ($\varepsilon_{11} < 0.5\%$) to avoid any damages. Thus, the rough measurements are still quite noisy and a filtering through Diffuse Approximation [20] was carried out to regularize the pattern. Figure 6a and 6b compare the unfiltered and filtered responses of full-field measurements (dashed pink curves and red curves)

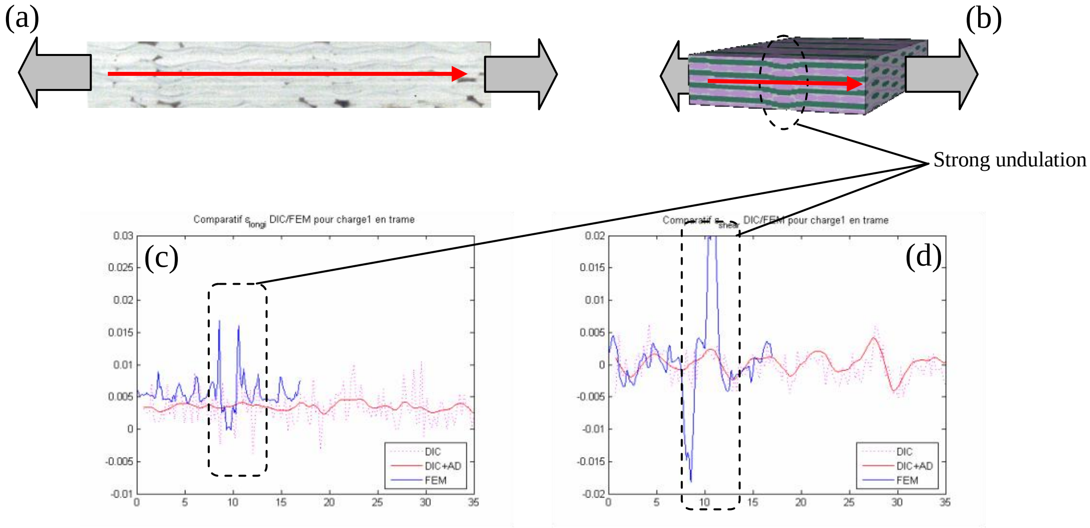

Fig. 7 Comparison of measured and computed longitudinal strain (c) and shear strain(d) along lines defined in the real woven (a) and the modelling (b)

Before comparing the results between finite elements calculation and experimental strain fields' measurements, it is interesting to compare the real microstructure of material and the model idealization. Figures 7a and 7b show the area where the comparison will be done. We can observe that Voxel model has a local strong undulation which is absent in reality. Note that the Voxel's seize elements are close to the pixel size of digital image correlation (DIC).

Figure 7c and 7d compare the longitudinal and shear strain obtained from Voxel FE and DIC. The order of magnitude of the values is very close. We can observe that both experimental and model results reveal the yarn columns behaviour and then reflect the passage between the yarns and the resin. This phenomenon is traduced by a quasi-sinusoid evolution of the strains.

The correlation would be almost perfect if it is not the existence of a peak of strain obtained numerically. This anomaly coincides with the strong local undulation of the tows in the Voxel model. This problem will be certainly increased by the yarns' discretization.

Obviously, as the macroscopic validation case, implementation of real paths is required to accurate the simulation of the mesoscopic behaviour of the woven. On the warp/weft plane, gaps between the two techniques are probably less than in the thickness plane. Contrary to the face of the specimen, side of woven composite, in addition to the free edges effects, contain multiple and strong material boundaries.

CONCLUSION

The voxel FEM presented in this paper was validated in a macroscopic scale for simple geometries like taffeta and twill-weave. For these kinds of weaving, description of yarn's paths is unambiguous, thus homogeneous mechanical properties was deducted accurately. Without, experimental full-field measurements on these materials, mesoscopic validation were not carried out.

Concerning the interlock case, a 3D macroscopic validation was fulfilled. A first dependency with the weaving was highlighted. Obviously, the real and the simulated weave differ. Simplifications made on the simulated weaving have involved a partial straight weft yarn. So, gaps were shown only for moduli linked with the weft direction. Implementation in the model of orientations extracted from the observations enables to suppress gaps between experimental and computed homogeneous mechanical properties.

The fact of having simulated infinite thickness throught periodic conditions prevents a mesoscopic validation on the weft/warp plane. Thus, comparison between measured and computed strain has to be performed along the weft or warp direction in the thickness. In addition to the free edges effects, discontinuities due to multiple and strong material boundaries were obvious in this configuration.

Nevertheless, the mesoscopic comparisons of the longitudinal and shear strain were similar. Quasi-constancy of the longitudinal strain and oscillations of the shear strain describe the yarn columns behaviour in the two approaches. These good agreements represent a first validation of the model in a mesoscopic scale.

According to the complexities and weaving's dependencies for a comparison in the thickness of the woven, an approach based on a translated "virtual gauge" will be considered.

To improve the validation on these thick fabrics, further works will focus on the extraction of paths coordinates through X-Ray tomography. Then, an accurate weaving with surface fabrics will open the way for a complete mesoscopic validation.

To conclude, the first aim of this voxel model concerning a reinforcement of the homogeneous mechanical properties (especially the out-off-plane properties) is fulfilled. The second purpose about the study of strain/stress concentration to localize the site of first damage is partly performed but need to be confirmed by a better confrontation between DIC and FEM.

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