FINITE ELEMENT MODELING OF MECHANICAL BEHAVIOR OF 3D COMPOSITE MATERIALS

Z. Aboura, G. Hello, H. Kebir, M.A. Tiar, M.L Benzeggagh

Université de Technologie de Compiègne, Laboratoire Roberval, UMR CNRS 7337
Centre de recherché de Royallieu BP 20529 60205 Compiègne Cedex

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Abstract

This study concerns the finite element modeling of mechanical behavior of 3D composites. It offers two Strategies at two scales. The originality of the first approach lies in its ability to model any representative elementary volume simply and robustly. *It is based on voxelization techniques. The second approach, more pragmatic, discusses the modeling of stitched composites at structure level. The validation of the approach is through a dialogue test calculation.*

1 Introduction

The advent of the new generation of 3D composites expands the scope of these materials. Indeed, throughout reinforcement in the third direction, it addressed two main drawbacks whose suffering composites: off-plan weakness properties and delamination resistance.

Modern weaving techniques offer a multitude of architectures 3D with some great structural complexity. The designer is faced with an important choice. However, it does not have tools and robust indicators that highlight suitability the choice of building architecture and the requirements of the specifications.

It is then clear that the development of this new generation of composite materials will be, if there are parallel development of predictive tools for the mechanical behaviour.

The complex architectures of these materials, associated with representative elementary volume (REV) well above those of the composite 2D (on the order of tens of mm) raise the legitimate question: should be regarded as materials or structures? It is obvious that the morphology of the geometrical REV determines the mechanical response of the material.

This question has not yet decided, but it is clear that at this stage of knowledge and means of numerical calculations we have (despite a significant increase in computing capabilities and storage at reasonable cost), it n 'is not reasonable to expect to mesh the detailed architectural enhancements on a structure in the classical sense of the word. The passage of scale with the assumptions of homogenization remains for the moment unavoidable.

One of the difficulties in applying these techniques of homogenization is in our ability to represent more accurately these 3D architectures digitally. Indeed, these materials are generally infused by liquid way, and are therefore highly compacted in the molds. This generates a final shape far from the ideal form. It is then necessary to develop means, robust, able to model numerically the REV so truthful.

Through this article, we propose two strategies for modeling 3D reinforced composites. The first is located across the REV. Its goal is a generalist approach, based on voxelization, capable of generating any type of 3D architecture, whatever its complexity. The second approach, at the structure level, is particularly interested to stitched composites. Its goal is a pragmatic approach to take into account the strengthening in the third direction in a structural analysis by finite elements.

2 Simulation of mechanical behavior of FE-voxel models

2.1. Introduction

Access to reliable quantitative information on the mechanical behavior of woven composite materials is now possible by digital simulation [1]. The lowering of the costs of calculating associated with developments of digital solutions and suitable software [2], [3] promote cross, often fruitful investigations between experimental and numerical approaches.

One of the difficulties raised by the use of numerical methods (primarily GEF) the management of the discretization. Traditional techniques are sometimes inadequate to the considered geometries (degeneration of elements, interpenetration between strands, difficulty of imposition of conditions limits of frequency for homogenization, difficult relationship with data tomographique…). A voxel discretization technique may be relevant. The intuitive idea of wanting to represent the geometry of the field of study by regular hexahedron mesh has been used for applications in Biomechanics by Hollister et al. [4]. Applications to the study of weaving were conducted by Crookston et al. [5] Potter et al. [6]. We propose a method for generation of FE-voxel models that is both flexible (simplicity of the definition of the user templates), robust (high level of automation) and General (management of CMO, CMC, PMMC composites and polycrystalline aggregates).

2.2 Cellular automata method

The decomposition of the field of study (for example a worm) into a set of regular hexahedron mesh allows to escape the problem of a volume mesh generation with the surfaces of discontinuity between phases. The good representation of the material will therefore be to assign to each voxel (or to its points of Gauss) Act of behavior which corresponds to its actual spatial position.

A direct approach would be to search for each of voxels, the geometric entity (strand, salary) to which it belongs. In practice this approach can be expensive in time and difficult to implement for complex architectures (woven composites…). The proposed alternative is to use cellular automata [7] who will undertake to achieve the affection of voxels properties. Hexahedron mesh network connectivity allows drastically faster by spreading "waves of contamination" [8].

2.3 Reconstruction of railways by radial basis functions

The purpose of the method is able to represent any type of composite reinforced (long fibre, short fibers, inclusions…), the architecture of the composite management should be as General as possible. The solution adopted is thus that the user defines the properties of the architecture by nodal information. In practice, the paths of strands are defined by series of points which are for example specified the local mechanical properties, the geometry of the section and its orientation. This discrete information being generally less dense than the voxel grid resolution, it is therefore appropriate to make continuous to correctly complete the process of allocation of properties. This reconstruction is made using radial basis functions [9]. It is to exploit information discreet f (si) = fi, i = 1.. N order to obtain a function continues$\tilde{f}(s)$. In practice, once the choice of radial function is ($\phi(r) = r^2 \log(r)$ – thin plate spline, $\phi(r) = r^3$...), the approximation is fully set after a linear system due to the satisfaction of the conditions of nodal interpolation has been resolved. The quality of reconstruction is in most cases higher than other methods of interpolation [10].

2.4. Example of Application

The cellular automata algorithms are adapted so to consider limiting the extension of the frontiers propagation phenomenon. Contrary to the case of polycrystalline aggregates where the waves can grow freely, "contagion" of voxels here is limited by the boundaries of strands. In practice, for a given strand, "waves" are emitted from the points defining its centerline then propagate to reach other waves or voxels supporting the border of the strand. Management and possible interpenetration is natively managed by the competition between the waves emitted by points belonging to different strands.

Figure 1 presents an example of meshing of 5-satin obtained from the fabric.skeleton definition.

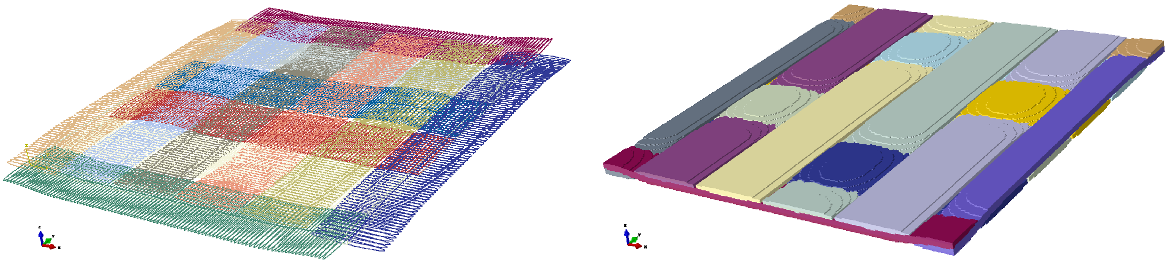

Figure 1 : Example for a satin 5fabric: skeleton definition (a) and associated Voxel model (b) [11].

The validation of the approach was made on 2D and 3D Woven composites materials. First, we compare the fiber volumes fractions obtained experimentally and reproduced by Voxel FE for different type of architecture. We can see that the present model does not have any difficulty to reproduce the good values.

Materials	***Volume fraction experimental***	***Volume fraction Voxel***
Taffeta	52%	52%
Twill weave	38%	38%
Hybrid Twill weave	Total 51% Glass 32% PE 19%	Total 52% Glass 32% PE 19%
3D composite	55%	55%

Table 1: comparison of fiber volume fraction obtained from FE Voxel and experiments

The validation of the approach is made through a comparison between the elastic properties obtained by different methods [experience, analytical method and finite classical element method MesoTex] and voxel approach (Table 2 and 3). It shows that the Voxel method properly predicts the mechanical behavior at the REV level.

Hybrid Twill Weave	$E_1=E_2$	E_3	G_{12}	$G_{13}=G_{23}$
Experience	18 ±0.4	/	3.5 ±0.1	/
MesoTex [12]	19,9	12,8	3,9	4,3
Chouchaoui [13]	16,6	8,4	3,3	2,5
Voxel	17,8	11,6	3,6	2,5

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able 2: Elastic properties (Gpa) obtained by Voxel approach versus different methods.

3D composite	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}
Experience/Voxel	1,03	0,87	0,97	1,01	1,07	0,81

Table 3: Elastic properties (Gpa) obtained by Voxel approach versus experiment on 3D composite material [14].

The validation of the approach on mesoscopic scale was done by comparing the local strain field obtained by Voxel method and experimentally by Digital image correlation (DIC). Figures 2a and 2b compare the longitudinal and shear strain obtained from Voxel FE and DIC. 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). 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. 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 wicks in the Voxel model. This problem will be certainly increased by the yarns' discretization. Works in progress address the problem of smoothing to erase this local effect.

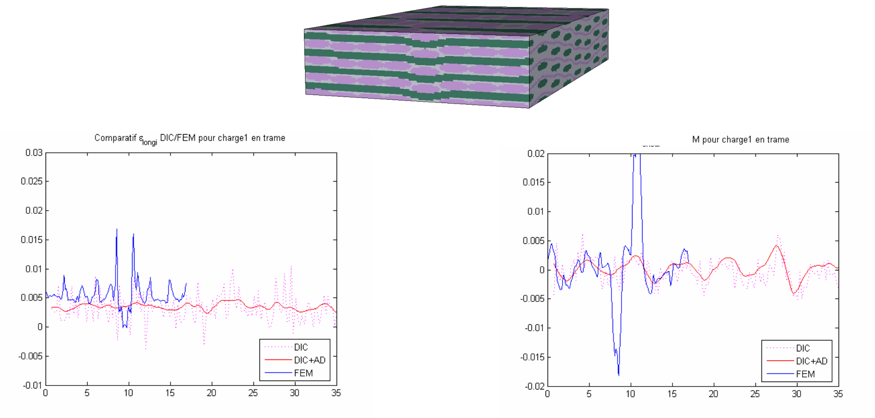

Figure 2: Comparison of measured and computed longitudinal strain (a) and shear strain (b) on 3D composite material.

3 FE Simulation of mechanical behavior of stitched composites at macroscopic level

The simulation of stitched composite behavior is approached by KSP code (Kernel of the Simulation Platform). KSP is software of numerical computation developed in Roberval laboratory at the University of Technology of Compiegne (UTC) by H. KEBIR.

KSP involves two methods of calculation: Finite element method (FEM) and Boundary element method (BEM). It offers the ability to model the 2D and 3D problems of elasticity, elastoplasticity, fracture mechanics and design the structures subjected to fatigue. This platform was extended to the simulation of stitched composite material. Indeed a tool in KSP was developed to introduce Stitches in a given geometry and then create an INP file contain all the characteristics of the studied. The nodal coincidence, between the native mesh and the stitch elements is automatically managed by the software. The stitches are either simulated by beam or truss elements depending of the loading case. Figure 3 shows an example of meshing of stitched sandwich. We can see that the mesh of the sandwich foam is perfectly coinciding with the stitches' mesh. The designer no longer has to worry about this problem.

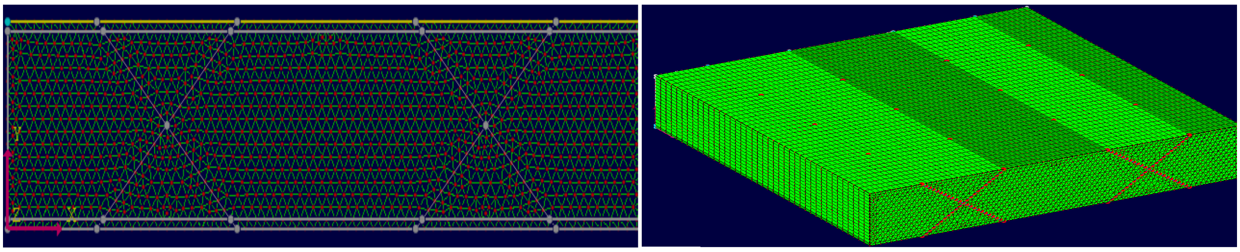

Figure 3: Meshing of stitched sandwich with KSP

3.1. Example of Application

The validation of the approach was made by simulating the out off plane behavior of stitched sandwich. Experimental results were given by Lascoup and al [ref]. Flatwise compression test and out off plane shear test were thus simulated by this approach. The elastic proprieties were determined for different stitch angles and steps (Figures 4 & 5).

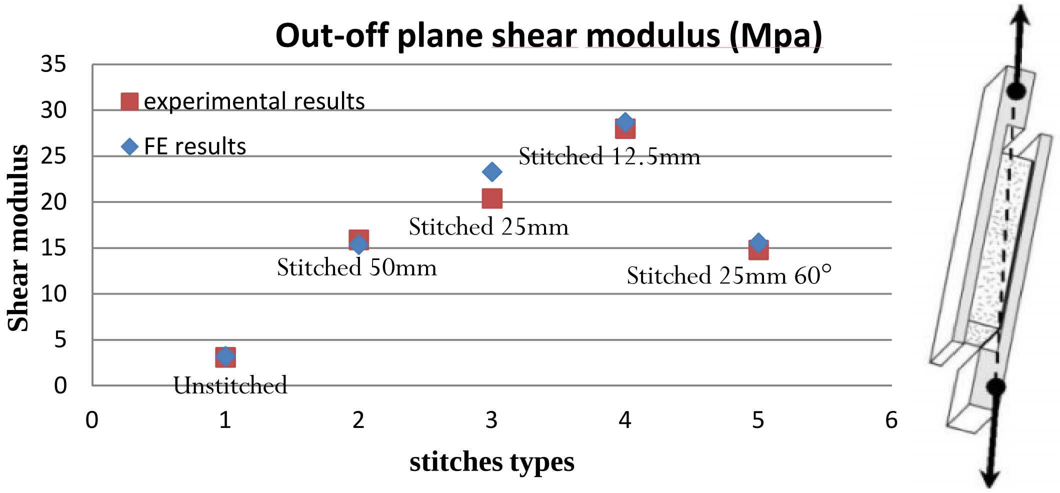

Figure 4: Comparison of Gxz (MPa) obtained by FE and experiment

The results obtained are in perfect agreement with experiment. It thus appears that in a global elastic calculation, the proposed method is entirely satisfactory even for relatively complex tests. Moreover it allows, easily, to take account the specificities of the stitches.

Beyond the overall elastic properties, this approach has the advantage of having access to the states of stresses and strains within the stitches. Figure 6 shows an example of 4-points bending simulation of stitched sandwich. It brings up the stress state at the stitches. It appears that the most constraints areas are those near the external support. Qualitatively, we find that this result is consistent with the work of Lascoup et al [15]. Indeed, the author shows experimentally that the rupture is localized in the area subject to shear stress.

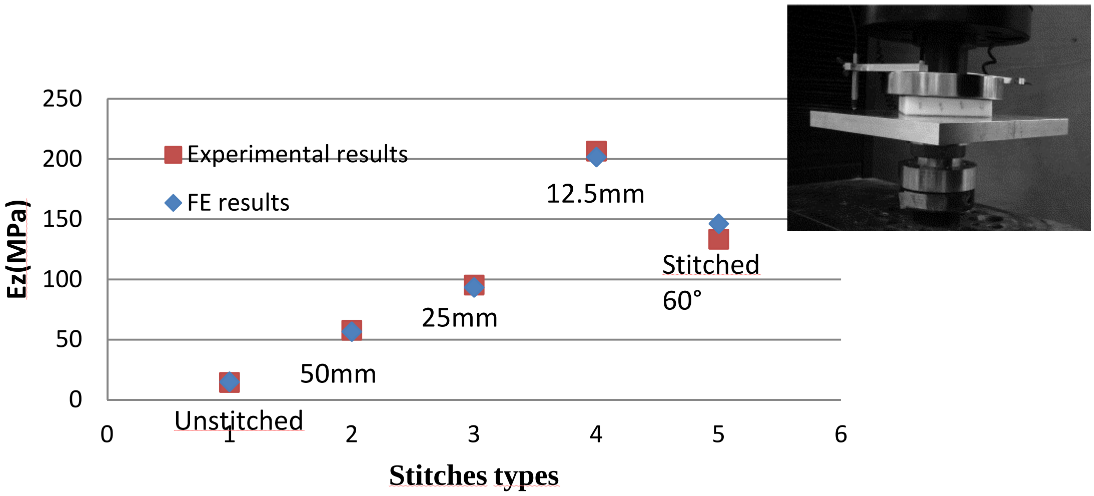

Figure 5: Comparison of Ez (MPa) obtained by FE and experiment

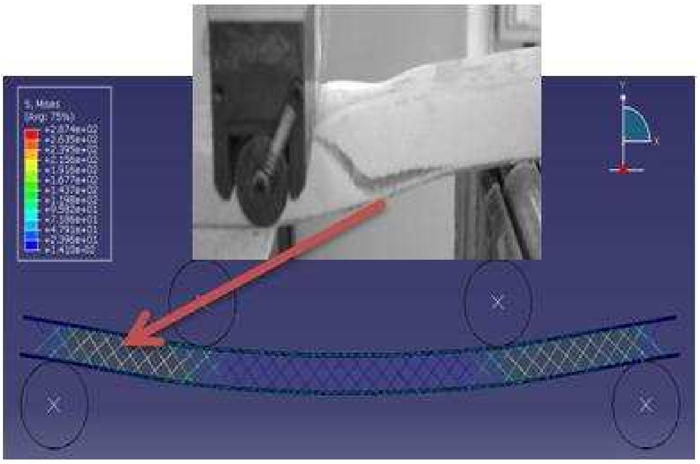

Figure 6 : 4 points bending simulation. Stress sate on the stitches. Comparison with experiment

These encouraging results lead us to verify quantitatively the local response. Interlaminar shear strength (ILSS) tests have been thus performed on stitched composite glass / epoxy with a step of 5 mm.

Figure 7 shows the shear deformation field obtained by DIC and finite elements simulation. The effects of stitching induce local stiffening. If we compare experimental results to the numerical one, we note that FE proposes a similar shape comparatively to experiment. Figure 7 quantifies also the results by showing the shear strain measured on middle of the sample. We note that the gap between simulation and experiment does not exceed 30%. This result is interpreted by the fact that the twisting of stitches is not considered in the simulation. A correction of local properties will reduces this difference.

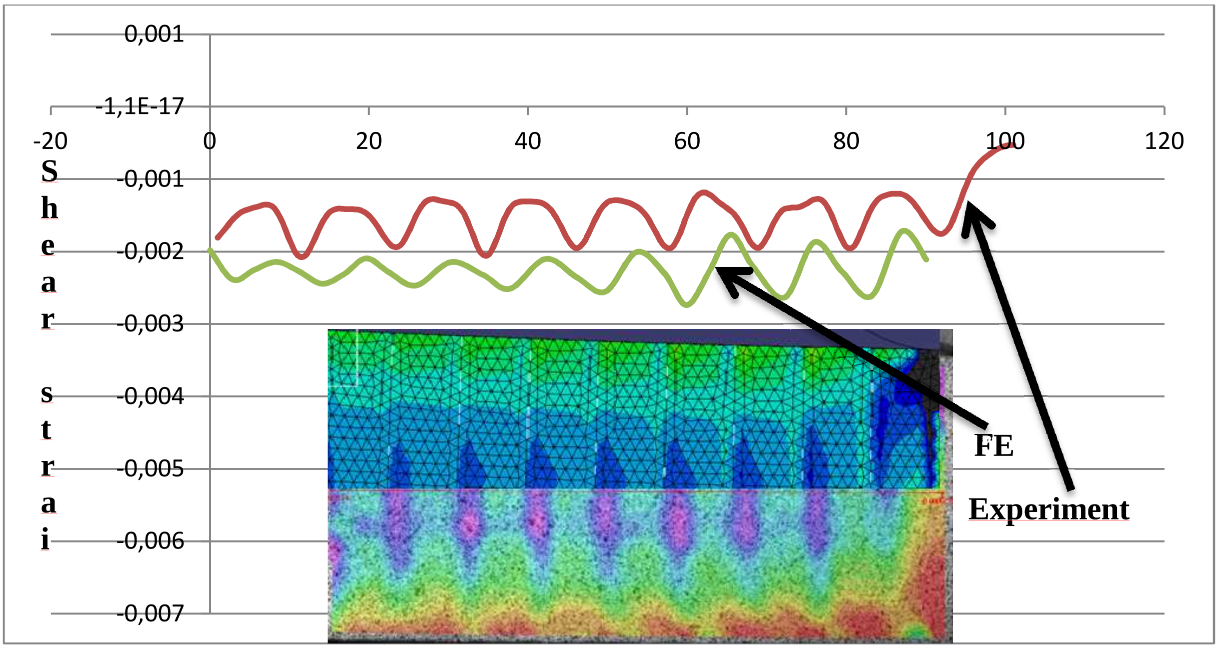

Figure 7 : Shear strain field obtained experimentally and by FE analysis

4 Conclusions

This study proposed two strategies for finite elements modeling of the elastic behavior of 3D composite materials. The first one takes place at the mesoscopic scale. From an original approach of voxelization, the proposed approach can accurately describe any architecture and whatever its complexity. The elastic behavior at local and REV scale was validated. Future studies are directed towards the nonlinearity material and damage prediction.

The second approach concerns the stitched composite materials. The modeling was carried at the structure level. A pragmatic methodology was tested to simulate the presence of stitches in the structure. The overall elastic behavior has been validated on relatively complex tests. Thus, the state of stress and strain is now available in the seams. Analyses of local strain fields are encouraging and allow in the future to propose local criteria to simulate the failure of these materials.

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