PREDICTING MECHANICAL BEHAVIOUR AND DAMAGE KINETICS OF A 3D INTERLOCK COMPOSITE MATERIAL BY USING A MULTISCALE APPROACH

Mamadou Abdoul Mbacké[1*], Jacques Renard[1], Alain Thionnet[1,2], Sébastien Joannès[1]

[1]*MINES ParisTech, Centre des Matériaux CNRS UMR 7633, BP 87, 91003 Evry cedex, France,*
e-mail : mamadou-abdoul.mbacke@mines-paristech.fr, jacques.renard@mines-paristech.fr, alain.thionnet@mines-paristech.fr, sebastien.joannes@mines-paristech.fr
[2]*Université de Bourgogne, Mirande, BP 47870, 21078 Dijon, France,*
e-mail : Alain.thionnet@u-bourgogne.fr

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Abstract

The present work aims to investigate the mechanical behaviour and the damage kinetics of a 3D interlock woven fabric composite, especially used for natural gas tanks dedicated to the transportation industry. On the one hand, we aim at predicting the macroscopic coefficients of the stiffness matrix by homogenization multiscale approach. For this, we identified a basic unit cell which represents well the composite microstructure. On the other hand, damage mechanisms are analyzed: optical microscopy examinations on damaged specimens revealed several types of defects. We used the same multi-scale approach to assess the impact of these defects on the decrease of stiffness.

1 Introduction

This study is devoted to the mechanical constitutive modelling and the damage of a 3D interlock woven fabric composite. The composite material is made of fiberglass and epoxy resin. The fiber volume fraction is estimated at 46%. The big advantage of these composite structures is to offer a better resistance to impact and reduce significantly the delamination phenomenons which remain a major problem in laminated structures. Indeed, textile composites exhibit anisotropic behavior. Modelling their behavior requires a multi-scale approach.

The purpose is twofold:

- predicting the coefficients of the stiffness matrix in terms of braiding parameters, nature of the components and volume fraction;
- having access to local variables in order to better understand damage mechanisms.

The use of this approach requires at first the modelling of a representative volume element (RVE) of the material. Because of the complexity of the microstructure, it becomes difficult to model the architecture of the RVE. To circumvent this difficulty, several authors have created a number of models of prediction according to their needs but they are either specific to a type of weaving and therefore unsuitable for other or too simplistic to be applied to our material 3D interlock. We note several analytical methods: BV Sankar and RV Marrey [1] proposed the "Selective Averaging Method" applied on textile composites. This is an analytical method which predicts thermo elastic constants of textile composite consisting in

dividing the cell into several slices and to subdivide these slices into several microelements. The constants of elasticity are obtained by averaging the coefficients of elements. Ping Tan, Liyong Tong and Grant P. Steven [2] used an approach based on the modelling of stratified blocks to develop two analytical models, namely the "model ZXY" and the "model ZYX".
These models are used to determine the mechanical properties and thermal expansion coefficients of 3D woven composites. It turns out that these methods do not fully meet the requirements. If certain methods allow more or less exact prediction of the effective properties at the macroscopic level, they do not give access to the local phenomena which occur within the studied composite. The most promising solution is the use of numerical methods based on the finite element analysis (FEA). They are general methods that offer great flexibility and allow the development of a specific model for a given application: modelling, optimization of process development and processing. First, the finite element method solves the problem geometry modelling of the microstructure of some textile composites. Thus, different authors have developed efficient numerical tools to generate quite complex designs. Indeed, Lomov et al. have produced WISETEX software [3], G. Couillegnat developed GENTEX [4], Martin Sherburn created TEXGEN [5]. However, these tools do not generate all possible configurations of fabrics: this is the case of 3D interlock woven fabric composite with orientations of + / -45 °. For a meaningful analysis of this material, we identified a basic unit cell which represents well its architecture. This choice allows us to overcome the difficulty of modelling mentioned above. In this study, WISETEX software is coupled with ABAQUS software to model this basic unit cell.

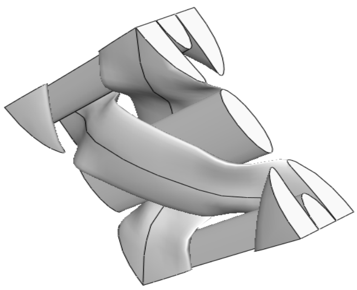

Figure 1. Basic unit cell

On the one hand, this cell is used to predict the effective properties of the material. On the other hand, the cell is used to study the influence of different types of damage mechanisms on the mechanical properties of this composite.

2 Methods

2.1 Homogenization: geometrical modelling

This study of homogenization is initiated to predict the elastic moduli of the textile composite material. The principle consists in determining the macroscopic properties of the material from the properties of its constituents. For this, a first process determines the properties of the yarns (mesoscopic scale) from the properties of fibers and matrix (microscopic scale). Finally, the second process determines the properties of the homogenized material (macroscopic scale) from the properties of yarns (mesoscopic scale). This latter step is presented in this work.
The study involved:

i) The choice of a representative cell of the material microstructure.
ii) The modelling and the periodic mesh of the unit cell with WISETEX and ABAQUS:

WISETEX generates the contours of the geometry while FETEX[3] translates the model (geometry and/or mesh) in an executable file on ANSYS [3]. However, the mesh by FETEX is sometimes rather heavy in terms of degrees of freedom and presents little flexibility for the modification. To circumvent these limitations, we have built a basic structure of type "braided with inlays" on which is cut our elementary cell. This cell is then transferred on ABAQUS. Subsequently, we picked the geometric points of the elliptical sections at the extremities and the points of the trajectories. A new geometry is designed from these points. Afterward, the unit cell is extracted from this new geometry and the matrix is added. Finally, the procedure closes this step meshing.

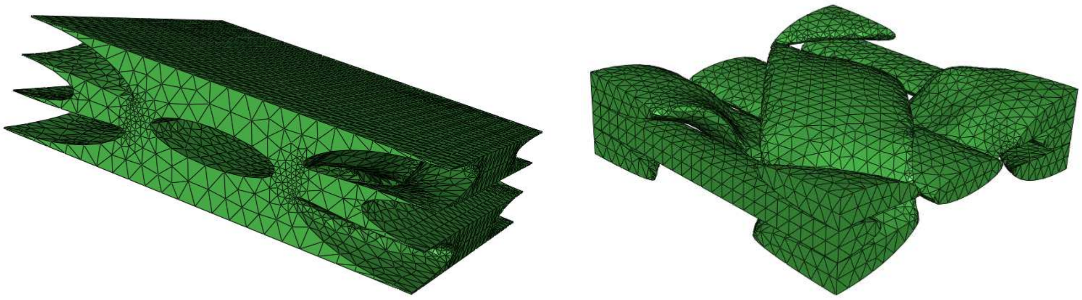

Figure 2. Periodic mesh of the unit cell

iii) The determination of mechanical properties of the yarns which are considered as isotropic transverse material.

iv) The creation of boundary conditions using a fortran program. This program creates automatically a group of nodes by linking the nodes of a face to the nodes of the opposite face. This means that the mesh of opposite faces must be identical. On output, this program provides a file containing the periodic boundary conditions (mpc = multi-point constraint) and commands for setting up the calculation. In his thesis, Benoit PIEZEL [6] used the same process. The boundary conditions are defined as follows:

$$u(x) = v(x) + \varepsilon_{ij}^{\mu+1}.x \tag{1}$$

where u(x)= microscopic displacement, x = local coordinate
v(x)= periodic displacement, v is equal values on opposite sides of the cell periodic
$\varepsilon_{ij}^{\mu+1}$= strain tensor defined at the macroscopic scale

v) And finally, Calculations and post-processing are performed by using in house FE Zset software [7]. A consideration of the material anisotropy in the yarns requires the use of local coordinates defined using Euler angles. Another fortran program creates these coordinates, using the nodes of the middle line of every yarns. Finally, it is necessary to update these local coordinates after every step of the calculation to determine the new Euler angles. And then another program is compiled after every calculation step to reposition the new local coordinates.

2.2 Damage investigation: identification of damage mechanisms

Finally, we launched an experimental and numerical study of damage mechanisms in order to better take them into account in the future design of tanks. On the resulting curves of tensile tests, there are a linear part and a nonlinear part. The nonlinear part is the consequence of the progressive degradation of the material microstructure during the uniaxial loading. Microscopic observations of damaged specimens allowed identification of several degradation modes: debonding fiber/matrix, debonding axial yarns/off-axial yarns and cracking yarns. Initially, an in-situ optical analysis during testing coupled with microscopic observations allowed to detect and follow damage phenomena. This approach aimed at a better understanding of these mechanisms to establish a chronology of their appearance before complete rupture of the tested specimen. First, the damage mechanisms observed are a debonding fiber/matrix within the yarns off-axis (Fig.3). These microcracks appear beyond 40% of failure stress. They coalesce inside the yarns during the mechanical solicitation to finally create transverse cracks (Fig.4). The transverse cracks become denser when the load reaches 50% of the failure stress. Thus they propagate until axial yarns where a decohesion between the axial yarns and the off-axial yarns begins (Fig.5). The different types of above mentioned defects propagate throughout the specimen to beyond 60% of the failure stress where we begin to observe longitudinal cracks in the yarns oriented in the loading axis. The longitudinal cracks are accompanied by progressive failure of fibers leading to the final rupture of the specimen.

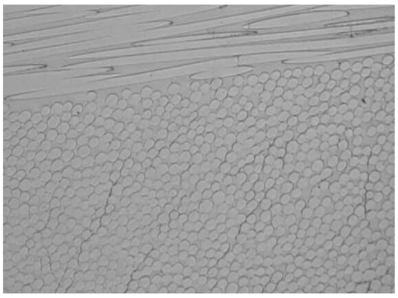

Figure 3. Debonding fiber/matrix

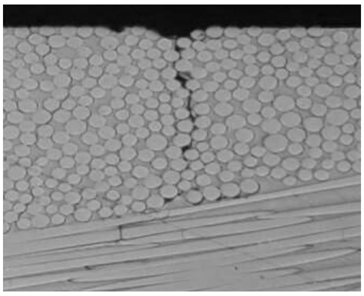

Figure 4. Transverse cracks

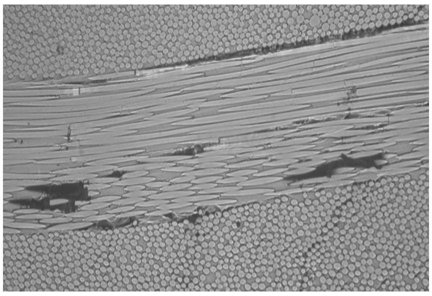

Figure 5. Decohesion between the axial yarns and off-axial yarns

In a second step, we used the same multi-scale approach to assess the impact of these defects on the stiffness decrease.

3 Results and discussions

3.1 Modelling the mechanical behavior

The objective of this study is the identification of the macroscopic stiffness matrix. It defines the linear relationship between stress and strain using the generalized Hooke's law [8]:

$$\{\sigma\}=[C_{ij}]\{\varepsilon\} \quad (i,j=1,2,3) \qquad (2)$$

$\{\sigma\}$ is the macroscopic stress vector, $\{\varepsilon\}$ is macroscopic strain vector, $[C_{ij}]$ is macroscopic stiffness matrix.

$$C=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

Thus, obtaining the coefficients C_{11}, C_{22}, C_{33}, C_{12}, C_{13} and C_{23} requires solving six problems by imposing respectively the average deformations E_{11}, E_{22}, E_{33}, E_{12}, E_{13} and E_{23}.

The results of numerical simulation of a homogenized sample are compared to experimental tests.

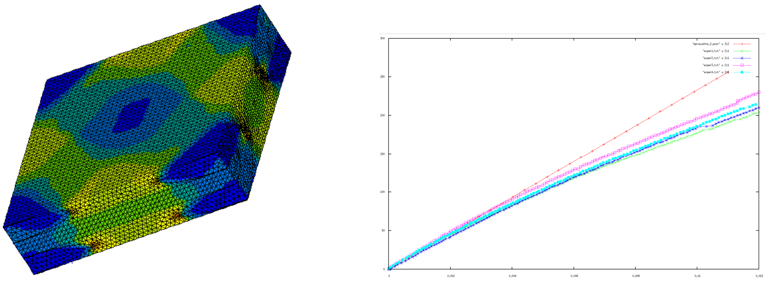

Figure 6. Calculation results of homogenization

There is a good correlation results in elastic region. The curves deviate beyond the elastic limit where the material starts to be damaged.

The model predicts fairly well the Young's moduli E_{11}, E_{22} and E_{33} and the Poisson's ratios ν_{12}, ν_{13} and ν_{23}. Moreover, there was a slight under-estimation of G_{12} shear modulus.

	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
Experimental results	20.0	15.8	10.0	11.5	3.9	2.9	0.38	0.35	0.40
Numerical results	20.12	16.3	13.1	8.12	6.0	5.5	0.33	0.35	0.30

Table 1. Comparison of experimental and numerical results

3.2 Damage investigation: decrease of the stiffness

This study will allow to identify a anisotropic damage model. Defects are introduced during the meshing using a program that allows duplication of nodes at the interface to create a decohesion or to create a crack inside yarns. This method based on the duplication of nodes at the interface is used by G. COUEGNAT [4] by developing GENCRACK. Moreover, other authors address the damage phenomena in post-processing. Several parameters were studied in this paper: i) the influence of crack lengths and ii) the influence of the type of crack.

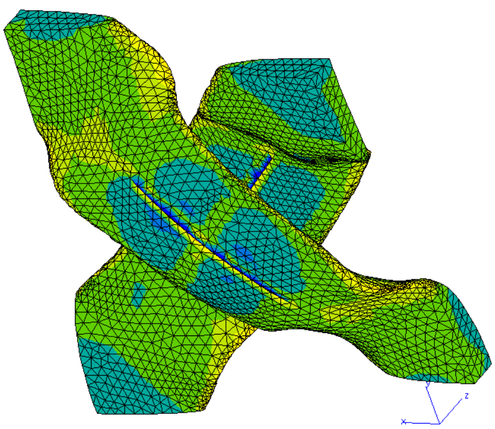

Figure 7. Introduction of a crack on off-axial yarns

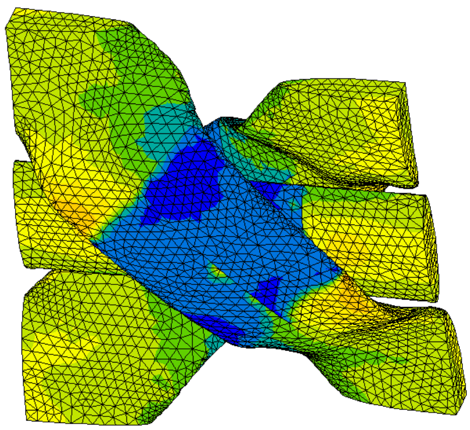

Figure 8. Introduction of a crack and decohesion on off-axial yarns coupled with decohesion on axial yarns

Figure 7 shows two yarns oriented at 45° cracked according to the median plane. Figure 8 exhibits a decohesion around the axial yarn coupled to cracking of yarns oriented at 45°. The transverse cracks have limited influence on the elastic modulus. Moreover, we note that debonding yarns/matrix leads to a larger decrease of elastic moduli. The curves below shows decrease of stiffness coefficients according to levels of loading.

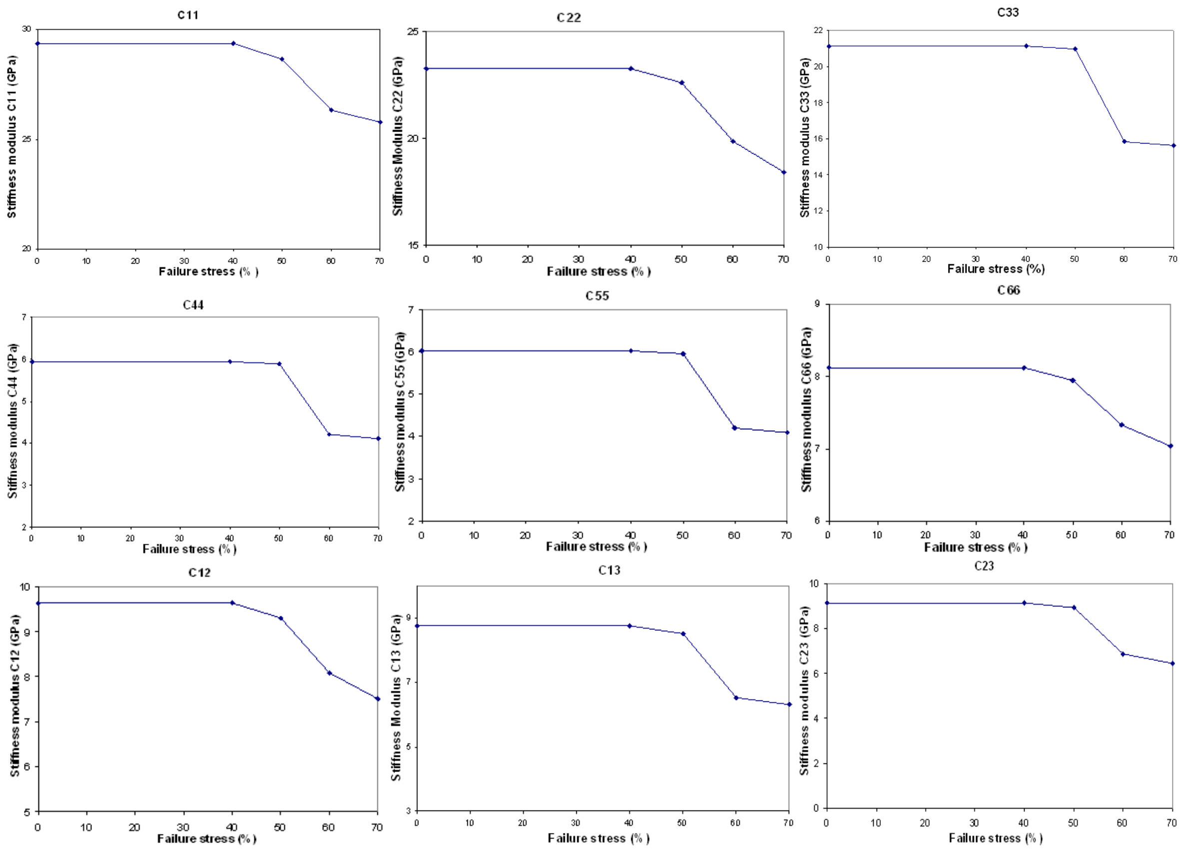

Figure 9. Evolution of stiffness coefficients according to mechanical loading in a tensile test

In perspective, this step is a prelude to the identification of a damage model to take into account mechanisms in design of tanks. We take inspiration from the works of Alain THIONNET [9] who proposes a hyperelastic behavior law for a microcracked composite, respecting all the conditions associated with the damage activation/deactivation, stress/strain relation continuity, induced anisotropy and the Clausius–Duhem inequality [9]. This model will be written in a way that takes into account:
- (c1): any discontinuity in the stress/strain relation;
- (c2): anisotropy induced by damage;
- (c3): decreases of the appropriate modulus;
- (c4): damage activation/deactivation.

The Principles of Physics and Mechanics also have to be satisfied.
Hence, the modelling should be:
- (c5): S-invariant (where S denotes the material symmetry group);
- (c6): objective;
- (c7): in agreement with the Second Principle of Thermodynamics.

4. Conclusion:

The present work allowed to investigate the mechanical behaviour and the damage kinetics of a 3D interlock woven fabric composite using a multiscale approach.
Despite the complexity of the microstructure, a unit cell predicts quite well the coefficients of the stiffness matrix. Similarly, the cell medium was used to evaluate the influence of damage mechanisms on the mechanical behavior of the material. This study will allow to identify a anisotropic damage model already chosen.

References

[1] Sankar B.V. and Marrey R.V., Analytical method for micromechanics of textile composites, *Composites Science and Technology,* **57**, 703-713 (1997)

[2] P. Tan, L. Tong and G. P. Steven, Micromechanics models for mechanical and thermomechanical properties of 3D through-the-thickness angle interlock woven composites, *Composites: Part A*, **30,** 637–648 (1999)

[3] S.V. Lomov, E. Bernal, V. KOISSIN, T. PEETERS, User's guide for the WiseTex software – Integrated Textile Preprocessor - *Leuven: Department of MTM, Katholieke Universiteit Leuven*; 2006

[4] G. COUEGNAT, Approche multiéchelle du comportement mécanique de matériaux composites à renfort tissé, *Thèse Université Bordeaux1* (2008)

[5] M. Sherburn, Geometric and mechanical modelling of textiles, *Thesis submitted to The University of Nottingham* (2007)

[6] B. PIEZEL, Mechanical response and multiscale analysis of a woven fabric composite, *Thèse Mines Paristech* (2010)

[7] J. Besson and R. Foerch. Large scale object oriented Finite element code design, *Computer Methods in Applied Mechanics and Engineering*, **142**, 165–187 (1997)

[8] M. Ansar, W. Xinwei, Z. Chouwei, Modeling strategie of 3D woven composites: A preview, *Composite Structures*, **93**, 1947-1963 (2011)

[9] A. Thionnet, From Fracture to Damage Mechanics: A behavior law for microcracked composites using the concept of Crack Opening Mode, *Composite Structures,* **92**, 780-794 (2010)