HYBRID THERMOPLASTIC YARN TO 3D COMPLEX SHAPED THERMOPLASTIC COMPOSITE STRUCTURE: SIMULATION OF BRAIDING AND SUBSEQUENT CONSOLIDATION

Y. Duplessis Kergomard[a*], M. Perrin[b], A. Trameçon[c] , P. De Luca[a]

[a] *ESI GROUP, 25 avenue Marcel Issartier, BP 20005, 33702 Mérignac, France*
[b] *ESI GROUP, Le Recamier, 70 rue Robert, 69458 Lyon Cedex 06, France*
[c] *ESI GROUP, 99 rue des solets, Zone Silic 112, 94513 Rungis Cedex, France*
**ydk@esi-group.com*

Keywords: Simulation, braiding, consolidation, manufacturing.

Abstract

This presentation will introduce the simulation of commingled thermoplastic manufacturing, which is split into two phases: the textile manufacturing process and then thermo-compression This work is performed in the frame of an European project MAPICC 3D. The simulation tools able to simulate this process chain have been developed. The objective of the thermoplastic consolidation simulations is to assess the occurrence of intra and inter yarn porosities.

1. **Introduction**

Driven by the future environmental standards, transport industries look for CO2 impact reduction of theirs vehicles. A way to reach this goal is to decrease the weight of the structural parts, by replacing some metallic ones by lighter thermoplastic composite parts. However, for the moment, the development of these composite parts is slowed down by a lack of applicable manufacturing processes. New processes have to be developed, faster and less expensive than the actual ones. It is especially true in the automotive domain.

In this framework, the European project MAPICC 3D presents two main goals. The first one aims to develop integrated and automated process chain able to produce 3D complex shaped thermoplastic composite structure from hybrid thermoplastic yarns. The second goal consists in the development of modeling tools able to support these new technologies. Indeed, the virtual prototyping concept is a powerful tool for composite process improvement, by modeling the whole process chain from the input material characteristics to the final part manufacturing and performance tests. In other words, the full End to End Virtual Prototyping solution for this process is being developed in MAPICC 3D. This paper describes the current works done for the manufacturing simulation in the MAPICC 3D project as of today, the braiding process for the preform manufacturing, followed by the consolidation simulation.

Some authors have modeled processes at microscopic scale, with application to woven structures and braids ([1, 2, 3]), as to knitted fabrics [4]. This approach is characterized by the fact that it only requires the identification of very few materials and process parameters to describe the complex behavior of the yarns in the structure (compaction, fibers rearrangement, inter-fibers friction…).

Though, micro-models are often limited by the small size of the representative cells. At mesoscopic scale, the yarn is considered continuous. Micro-effects are taken into account with a representative yarn behavior. To describe braiding process, the modeling of each yarn must be simple enough to make the simulation possible. Interactions between yarns are precisely taken into account by considering the contact and the friction caused by relative motions between yarns ([5, 6]).

In this paper, the braiding process is simulated at the mesoscopic level. Yarns will be modeled using bar elements. In a previous paper [8], first steps of a multi-scale approach have been presented. Some representative cells (RC) of the structures have been extracted from the macro model and have been used to build local models with realistic position and orientation of the yarns. These local models aim to describe realistic 3D shapes of the yarns.

In this paper, a multi-scale approach is considered. After parametric study of the process using the developed simulation algorithm, the whole process will be simulated at the mesoscopic scale [1]. Yarns will be modeled with bar elements. Some representative cells (RC) of the structures will be extracted from the macro model and will be used to build local models [2] with realistic position and orientation of the yarns. Boundary conditions applied to the end yarns of the RC are also extracted from the mesoscopic model. With these local models, the realistic 3D shape of the yarns is finally obtained.

From these simulations, representative cells (RC) of the structure will be extracted to characterize the produced structures in term of braiding angle and local fiber volume fraction.

After the preform manufacturing has been simulated, the consolidation stage is considered. Controlling the defects and porosities coming of the consolidation process is essential. The consolidation process established for MAPICC 3D is divided into two distinct stages. A prior heating phase is performed in order to engage the melting phase of polypropylene filaments. It also aims to bring thermal homogeneity inside the fabric for multiple layers textile. The second stage of this consolidation process is a compression phase in order to enforce the resin diffusion and to eventually obtain the ultimate composite thickness.

In this paper, the braiding modeling is first describes, followed by the consolidation one.

2. Mesoscopic model of the braiding process

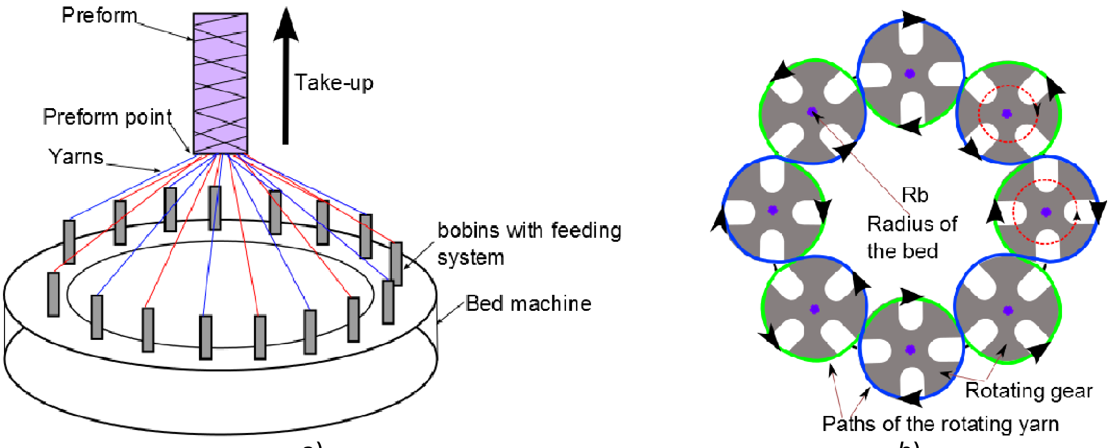
At this scale, the whole braiding process is simulated. The objectives of this simulation are to get the realistic position and the realistic yarns orientation around the mandrel at the end of the process. The simulations at this scale will be named further “meso-simulations”.

Fiber yarns are separated into 3 groups of yarns: unidirectional yarns, clockwise rotating yarns and anticlockwise rotating yarns. One extremity of the yarn is fixed to the mandrel and the other side is connected to a spring element which is used to simulate the continuous supply of fiber, as in [8]. The kinematics of the bobbins is imposed at the end of these spring elements.

The mandrel moves transversely at a given speed while the yarns rotate around the mandrel. The extremity of the yarns attached to the mandrel move in the same way in the z direction. A ring is added to change the direction of yarns and ensure the numerical stability during the braiding simulation.

The yarns are considered homogeneous. The bending stiffness of a dry yarn is very low and can be neglected in a first approximation. Thus 1D bar element has been used. The material behavior is elastic (material 201 for beam/bar element in VPS), which can be a correct approximation for fragile fibers like the carbon or the glass ones.

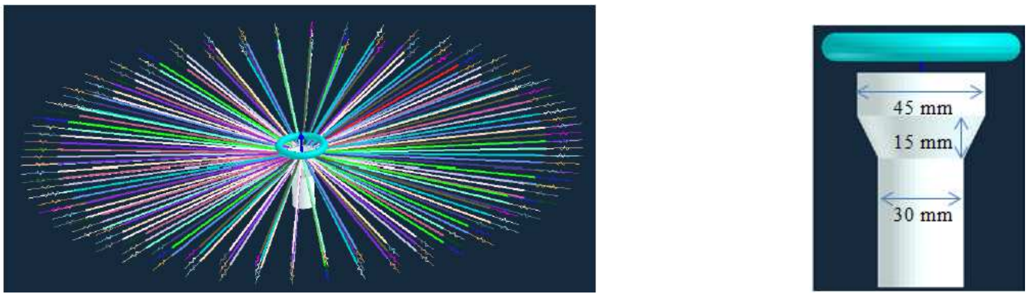
The tools of the process like the mandrel and the braider ring are considered as rigid bodies. They are modeled with shell elements and the “null material for shell” 100. The meshes of the tools will be used to simulate the contacts between the yarns and these ones during the process. The contact definitions are in most importance in these kinds of simulations as they describe the interaction between the yarns, as between the yarns and the tools. The contact used in VPS is the type 43, “Edge-to-Edge Symmetric Contact”. The main input parameters specified in this simulation for the contact 43 are the contact thickness Hcont and the constant friction coefficient. Hcont defines the volume around the element in which contact is active if another element penetrates it. Along the yarns, a perpendicular section of this volume simulates the occupied space of a section of the yarn. With the bar element, the shape of this section is circular. However, it is well known that realistic shape of the yarn at the end of the process is closer to a flat ellipse. Considering that the results of the meso-simulation will be used in the next step to build the micro-simulation, the smaller diameter of the ellipse has been chosen as the value of Hcont. In that way, more realistic mean distance between yarns in the thickness direction of the preform must be obtained. For the friction behavior, without data on it, a simple Coulomb behavior has been chosen in a first approach, with a constant friction coefficient. There are three types of interaction during the simulation: interaction between yarns, between yarn and guiding ring and between yarn and mandrel. It assumes that the friction laws are all the same for all interaction types, only the value of the friction coefficient is changed.



a) b)

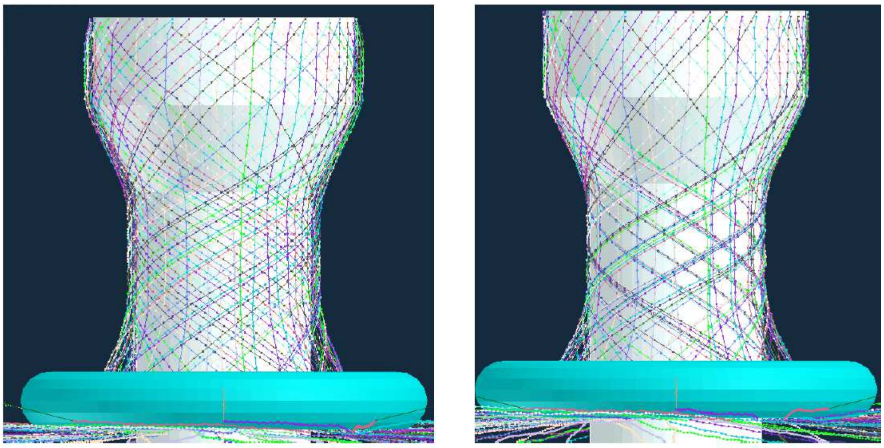
Figure 1: a) sketch of a conventional circular braider; b) Sinusoidal path of the bobbins holding the yarns

A model with 144 yarns have been created and simulate, as shown in Figure 1**Erreur ! Source du renvoi introuvable.**a. This is common number of yarns in braiding process. The modeled mandrel is shown in Figure 1b. Two simulations have been made, the first one without friction and the second one, with an arbitrary friction coefficient of 0.15. The results are shown in Figure 2. The results emphasize the need of taking into account of the friction effect, regarding the difference of yarn distribution.



a) b)

Figure 2: a) Initial state for a radial braiding simulation with 144 yarns; b) Side view of the mandrel and the ring used for the simulation



With friction

Without friction

Figure 3: Simulation results at the meso-scale

3. Thermoplastics consolidation simulation

3.1. Presentation of the software simulation

To obtain the porosity out of the simulation, the main physical mechanisms involved in this manufacturing process must be considered and modeled: change of phase of the thermoplastics through heating, thermal conduction, non-Newtonian behavior flow, deformations of glass fibers through compression and resin diffusion, and interfaces between resin and air/void.

In light of these mechanisms, it has been chosen to simulate the consolidation process with the VPS/FPM solution which can model the fluid (thermoplastics) and the deformations of the yarn at the same time as well as prescribed process conditions. VPS (Virtual Performance Solution) is used also for part performance evaluation taking into account the process. FPM is a mesh free advanced CFD module, mainly designed to overcome several drawbacks of classical CFD methods (Finite Element Method (FEM), Finite Volume Method (FVM)). The main drawback of these classical methods (FEM, FVM) is the relatively expensive geometrical mesh grid required to carry out all numerical computations. The computational cost to establish and maintain these grids becomes more dominant as the considered geometry becomes complex or moves in time. For several applications, the effort for grid maintenance is beyond acceptance, the computations take too long or fail completely. Thus, FPM opens up new fields of application in computational fluid mechanics, or makes the handling of several problems much easier.

Virtual Performance Solution (VPS), developed by ESI Group, includes (among other capabilities) a structural finite element software for non-linear, high velocity, dynamic simulations (PAM-CRASH), as well as a coupled, mesh free CFD module, FPM (Finite Point Method) [9, 10].

FPM is a Lagrangian particle method, based on Navier-Stokes equations where the fluid domain is represented by a set of particles carrying all fluid information such as pressure and velocity. Spatial derivatives are approximated at each particle location by the moving least squares method, from its neighbour’s particles.

FPM mesh free method solves the general Navier Stokes equation (1) as written below in a Lagrange form here for laminar flows:

$$\begin{aligned} &\tfrac{d}{dt}\rho = 0 \quad \Rightarrow \quad \nabla\mathbf{v} = 0 \\ &\tfrac{d}{dt}\mathbf{v} = -\frac{1}{\rho}\nabla p + \frac{\eta}{\rho}\cdot\Delta\mathbf{v} + \mathbf{g} \\ &\tfrac{d}{dt}T = \frac{1}{\rho\cdot c}\cdot\nabla(k\cdot\nabla T) \end{aligned} \tag{1}$$

FPM does not require the support of a mesh and therefore values are known at discrete ‘interpolation’ points which do not have a fixed connection like finite elements between them.

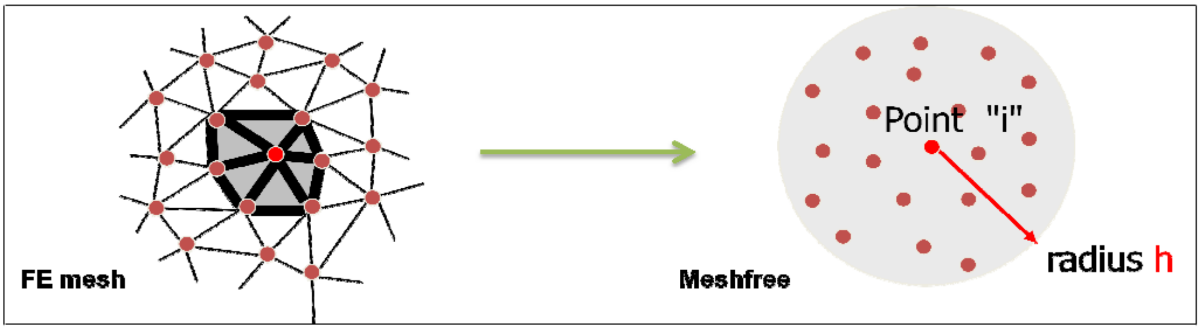


Figure 4: Definition of the smoothing length h

The list of neighbor points is determined for each point at each time step in order to construct afterwards a proper interpolation function using a 2nd order Moving Least Square (MLS) method. As FPM is a mesh free method, the interpolation points move with the fluid velocity, enabling an accurate description of the free surface of the water without simplification.

The fluid pressure is applied over the wetted external surfaces of the structures. Then the structure deforms and moves according to the applied fluid and all other loadings (gravity, contacts, compression load …). The deformation of the structure is provided back as the geometrical boundary conditions for the fluid to define the fluid boundary conditions for the next time step.

This coupled solution will therefore accurately predict fluid-structure interactions, taking into all the physical mechanisms acting in the consolidation process.

3.2. Pre-heating process

Micro modelling for pre-heating process will describe with accuracy the real geometry of the yarns. Air entrapment between filaments inside the yarn will be modeled at this scale. Besides, both material (i.e. glass fiber and polypropylene) are defined with their own mechanical and thermal properties. However, microscopic simulation requires an important number of elements to model filaments, and will therefore be time-expensive.

The simulations will therefore include a reduced number of filaments per yarn, called macro-filaments. The following woven cell in Figure 5 has been considered for these micro-scale simulations, using 26 macro filaments per yarn, with a 60% fiber volume ratio.

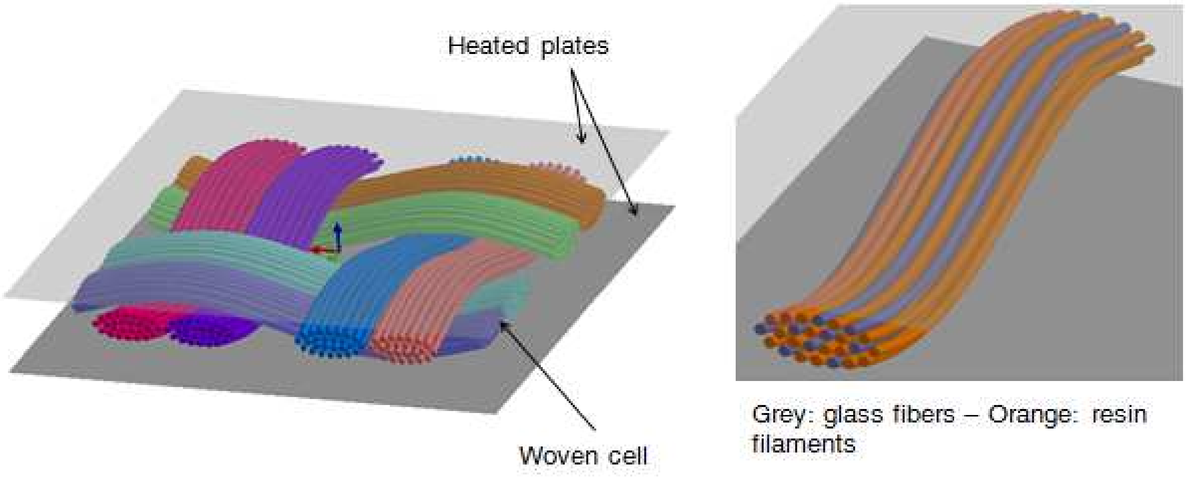


Figure 5: Textile cell used for consolidation process

The modelling of the seven-minute-heating-phase has been done within VPS taking into account the geometry of the yarns, the contacts between the consolidation mold and the yarns, the contacts between the yarn and the materials properties of the yarns, both mechanical and thermal.

Yarns are modeled with macro filaments discretized with solid element carrying material properties either of glass fiber or of polypropylene. Symmetric node-to-segment contacts (contact 33) are defined between filaments. Non symmetric node-to-segment contacts (contact 34) are defined between the filaments and the plates. Plates are modeled with shell elements and null material (non-deformable geometry). Each end of filaments is considered with a specific infinite boundary condition to take into account the continuity of temperature diffusion within the rest of the fabric.

Several gauge points have been positioned on one yarn in order to monitor the temperature evolution, as shown in the following Figure 6:

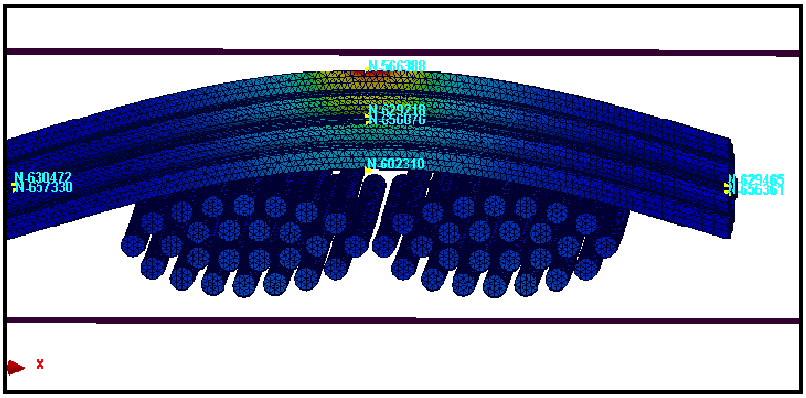


Figure 6: Location of temperature gauges

The Figure 7 here below shows the temperature evolution for each gauge point. Pink to red curves represent the temperature evolution for glass fiber material. Blue to purple curves describes the temperature evolution for polypropylene material.

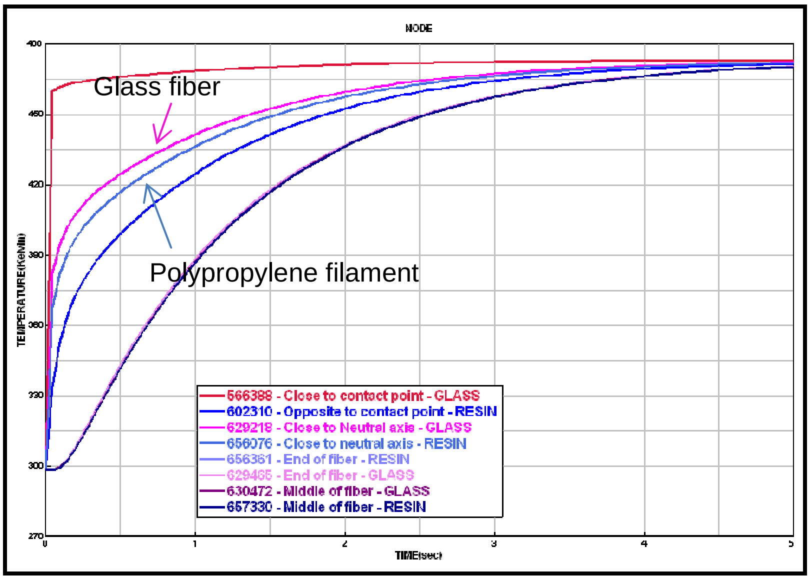


Figure 7: Temperature evolution inside the textile cell

Polypropylene filaments require more heating time to reach the final temperature than glass fibers. The two highlighted curves in the graph show for a similar distance from the heating source the difference in the heating rate.
Yet, thermal homogeneity is reached within several seconds of pre-heating.
The following graph in Figure 8 shows the comparison in the temperature evolution between a one-layer fabric and a two-layer fabric.

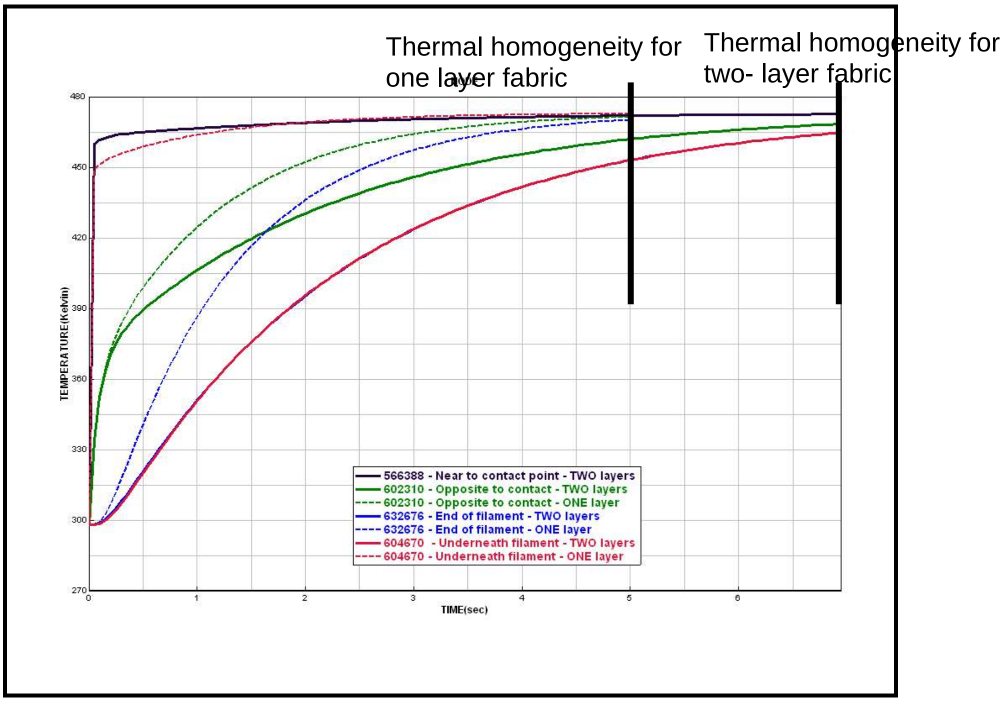


Figure 8: Comparison of temperature evolution for one and two-layer fabric

This two-layer simulation shows that increasing the number of layer increases the required heating time to reach thermal homogeneity. Several-layer fabrics modelling may be studied with this methodology to determine the optimal heating time to prescribe.

4. Perspective and conclusions

The current work made in MAPICC 3D for the full End to End Virtual Prototyping solution has been presented. With the simulations made at the mesoscopic scale, the position and the orientation of the yarns are obtained and process key parameter as the fiber ratio has be assessed. First runs of this model have been performed and realistic position and shape of the yarns are obtained.

A micro-modelling simulation has been proposed to study thermal behavior of the fabric through pre-heating process. This data will be used for the second stage of the consolidation process, i.e. the compression phase.

In future simulations, consolidation process will be modeled to obtain the porosity map of the preformed composite part through the compression phase using the simulation software VPS/FPM. The representative cell (RC) obtained from the micro-model of the braiding process will be used. At the end, the geometry of the final RC (as other parameters calculated during the simulation process) will be used in the assessment process of the mechanical properties of the structure.

References

[1] G. Zhou, X. Sun et Y. Wang, «Multi-chain digital element analysis in textile mechanics,» *Composites Science and Technology,* vol. 64, pp. 239-244, 2004.

[2] D. Durville, «A finite element approach of the behaviour of woven materials at microscopic scale,» chez *11th Euromech-Mecamat Conference*, Torino, Italy, 2008.

[3] Y. Miao, E. Zhou et Y. Wang, «Mechanics of textile composites: Micro-geometry,» *Composites Science and Technology,* vol. 68, pp. 1671-1678, 2008.

[4] M. Duhovic et D. Bhattacharya, «Simulating the deformation mechanisms of knitted fabric composites,» *Composites: Part A,* vol. 37, pp. 1897-1915, 2006.

[5] A. K. Pickett, J. Sirtoutas et A. Erber, «Braiding simulation and prediction of mechanical properties,» *Appl. Compos. Mater.,* vol. 16, pp. 345-364, 2009.

[6] B. Hadège, *Simulation du comportement mécanique des milieux fibreux en grandes déformations: application aux renforts tricotés,* Ecole National des Arts et Métiers, 2004.

[7] M. Duhovic, «Deformation characteristics of knitted fabric composites,» Thesis (PhD--Mechanical Engineering)--University of Auckland, 2004.

[8] Y. D. Kergomard, M. Perrin, M. Deléglise et B. Li, «Numerical simulation of braided structures using PAM-FORM,» chez *TEXCOMP-11,* Leuven, Sept. 2013.

[9] J. Kuhnert et S. Tiwari, «Finite Pointset Method based on the projection method for simulations of the incompressible Navier-Stokes equations,» chez *Berichte des Fraunhofer ITWN*, 2001.

[10] ESI GROUP, FPM Incompressible: User's manual and basic validation test manual, 2006.