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23rd International Conference on Material Forming (ESAFORM 2020)

## Meso-macro FE Modelling of Composite Forming

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### Abstract

Important information can be obtained by simulating the deformation of composite reinforcements on a mesoscopic scale. The knowledge of the direction and density of the fibres in the deformed reinforcement affects the mechanical properties of the composite and the permeability of the textile reinforcement. The quality of the initial geometry of the finite element model is important for these mesoscopic analyses. The internal reinforcement geometries can be defined by some software. Nevertheless, these are based on certain simplifications that may have drawbacks. In this paper, finite element models are obtained from X-ray tomography. These finite element models are designed for all types of reinforcements and avoid problems of yarn interpenetration. A hyperelastic constitutive equation is used for the behaviour of the yarn made of fibre. The results obtained by the simulation for the compaction of a 3D reinforcement are compared with the experimental results with good consistency.

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*Keywords:* Fabric; Finite Element; Forming; X-ray tomography

### 1. Introduction

The purpose of this paper is to propose simulations of the mesoscopic deformations of composite reinforcements. The simulations are based on finite element models obtained by X-ray microtomography in order to have a geometry of the textile reinforcements as accurate as possible. The quality of a F.E. simulation of the reinforcement forming on the mesoscopic scale strongly depends on the geometry and data associated with the model. Usually, geometries of the model are obtained by textile modelers such as TexGen or WiseTex [1, 2]. But these modelers provide an idealized geometry of the composite reinforcement that does not take into account all the imperfections and specificities of the material. In addition, textile reinforcements are varied and complex for 3D fabrics and not all geometries can be described by these programs. In some cases, when the textile reinforcement is thick and complex, the internal geometry is not completely known. Finally, interpenetrations in certain configurations can occur when using these modelers. In this study, the initial geometry is directly obtained by X-ray microtomography ( $\mu$ CT)[3]. This technique allows precise and non-destructive 3D observations

of the interior of a material, particularly for composites and composite reinforcements [4,5]. It makes it possible to distinguish the yarns and even the fibers inside the yarns and to access the anisotropy directions of the material. An approach is used to build finite element models of 3D composite reinforcements automatically from X-ray microtomography. These models take into account the specificities of the geometry of the analyzed material. They can be obtained for all types of architecture and reinforcement weaving. To distinguish the different yarns a segmentation method is used. It is based on image texture analysis. For 2D weavings, the separation of warp and weft yarns can be achieved by using the structure tensor [4]. This is more difficult for 3D woven fabrics, so an approach based on texture analysis is implemented. Then, a prismatic mesh of the yarns is generated from the segmentation resulting from the microtomography. A hyperelastic behaviour law [6] will be used here to simulate the deformation of the reinforcement. After compaction, the internal geometry of the simulated and experimental deformed 3D reinforcement is compared.

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## 2. Image processing and mesh generation

Finite element models are created from tomography images. Fig.1 shows the X-ray tomography image of an orthogonal 3D reinforcement. These extracted images must undergo a segmentation process in order to differentiate between warp, weft and binder yarns. This phase of the process has a significant impact on the quality of the model. Several segmentation methods exist, one of which is based on the structure tensor [4]. This tensor gives the orientation of the fibres. This method is particularly well suited when the structure of an image is filamentous. This is generally the case for 2D fabric reinforcement images. In some situations, segmentation based on structure tensor cannot be used because the fibres are not clearly visible. But the image has a grainy appearance. A segmentation method called 'image texture analysis' can be obtained from this image texture [7].

Image segmentation by texture analysis is based on the calculation of grayscale co-occurrence matrices [7,8]. This method makes it possible to study the joint behaviour of pairs of pixels spatially separated by a given translation. A GLCM ("Gray Level Cooccurrence Matrix") matrix measures the number of pixel value pairs that appear at a certain distance in the image. It is based on the calculation of the number of times a pixel of color level  $i$  appears at a relative distance  $D$  of a pixel of color level  $j$  and according to a given orientation. Co-occurrence matrices contain a large amount of information but are difficult to use as they stand. As a result, fourteen indices were defined by Haralick [7] to calculate texture characteristics from the co-occurrence matrices. The most commonly used indices are contrast, correlation, energy and homogeneity. Once the co-occurrence matrix is calculated, it is normalized so that the sum of its elements (noted  $p$ ) equals 1 and then the four statistical parameters are extracted (fig. 2).

To distinguish warp and weft yarns, a segmentation using the most relevant parameter is performed in the case of an orthogonal 3D woven fabric. The chosen quantity must allow to keep as much information as possible inside a yarn section and remove the pixels outside it. In this case, the homogeneity parameter is best suited to extract the yarn sections. The contrast and energy parameters can separate the yarns but contain less information within the sections compared to the homogeneity parameter.

In addition, the application of a straightening filter to the parameter facilitates thresholding. By applying a 3D Gaussian filter or a 3D median filter, it is possible to homogenize the image information: the yarn sections appear more complete. In general, the inside of these yarn sections is not full. Therefore, mathematical morphological operations are necessary in order to have a good segmentation of the volume.

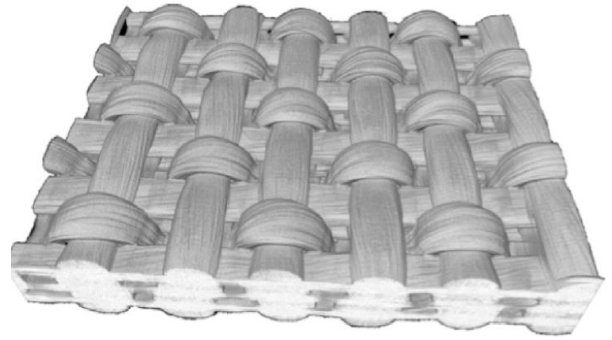
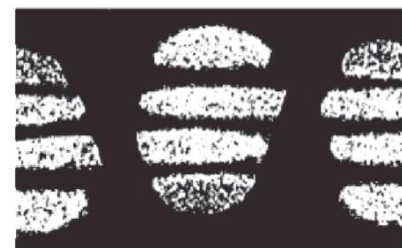


Fig. 1. X-ray Tomography of a 3D orthogonal non-crimp fabric.



(a) Threshold



(c) Hole filling



(b) Closing



(d) Convex hull

Fig. 2. Statistical parameters of a 3D reinforcement.

In mesoscopic modelling of a composite textile, the yarn is considered as a continuous material. The yarn meshes can be made of hexahedral or tetrahedral elements. However, none of these elements are completely satisfactory. The hexahedral elements are the most efficient numerically and are well suited to describe the yarn in the fiber direction [6,9,10]. However, it is difficult to mesh the cross section of the drill bit properly. Most composite yarns have a lenticular shape and, therefore, it is very difficult to mesh at its ends. On the other hand, tetrahedral elements can mesh any volume and perfectly describe the cross sections of the yarns. However, a mesh based on tetrahedrons requires a large number of elements to be accurate enough. In this work, a prismatic mesh is proposed for a VER of the orthogonal 3D woven fabric (Fig. 3). The yarn cross sections are meshed by the triangles of the prism and the prism quadrangles are in the direction of the fibers.

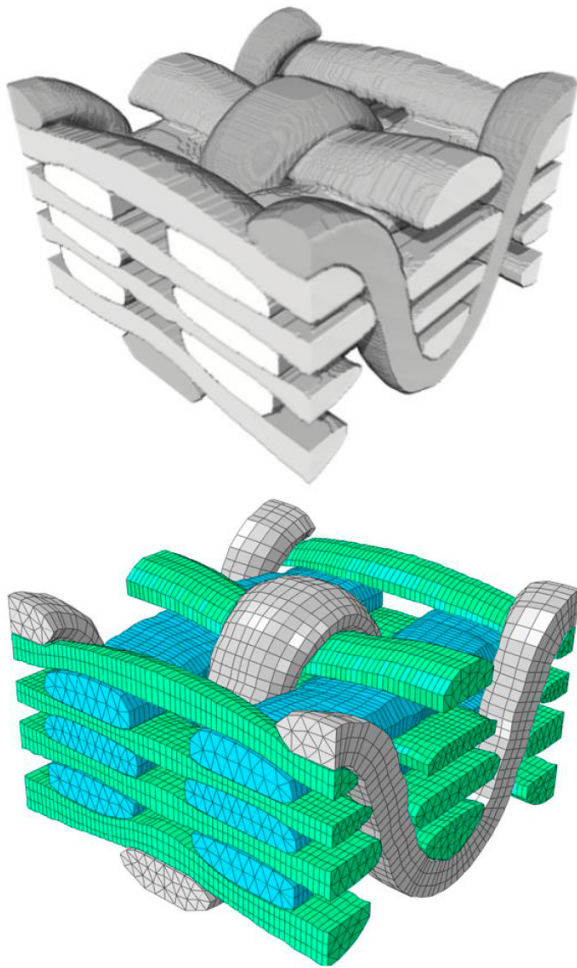


Fig. 3. 3D orthogonal non-crimp woven Fabric. Segmented RVE and prismatic mesh

### 3. Mechanical behavior of the yarn

At the mesoscopic scale as well as at the macroscopic scale [11-14], the mechanical behaviour of composite

reinforcements is specific considering its composition made of continuous fibres. Different types of approaches have been proposed [15]. The mechanical behaviour of the yarn is modeled in the present paper by a hyperelastic behavior law [6]. The deformation energy is a function of the right Cauchy-Green tensor  $\underline{\underline{C}}$ :

$$w = w(\underline{\underline{C}}) \quad \text{with} \quad \underline{\underline{C}} = \underline{\underline{F}}^T \cdot \underline{\underline{F}} \quad (1)$$

The yarn is assumed to be transversely isotropic. A direction  $\underline{\underline{M}}$  (norm=1) characterizes a transversely isotropic material in the initial configuration. The structure tensor  $\underline{\underline{M}} = \underline{\underline{M}} \otimes \underline{\underline{M}}$  is defined from this direction. In this case the deformation potential is written:

$$w = w(I_1, I_2, I_3, I_4, I_5) \quad (2)$$

where the invariants of  $\underline{\underline{C}}$  are:

$$I_1 = \text{Tr}(\underline{\underline{C}}) \quad I_2 = \frac{1}{2} \left( \text{Tr}(\underline{\underline{C}})^2 - \text{Tr}(\underline{\underline{C}}^2) \right) \quad I_3 = \text{Det}(\underline{\underline{C}}) \\ I_4 = \underline{\underline{C}} : \underline{\underline{M}} \quad I_5 = \underline{\underline{C}}^2 : \underline{\underline{M}} \quad (3)$$

The second Piola-Kirchhoff stress tensor is then written:

$$\underline{\underline{S}} = 2 \frac{\partial w}{\partial \underline{\underline{C}}} = \\ 2 \left( \frac{\partial w}{\partial I_1} \frac{\partial I_1}{\partial \underline{\underline{C}}} + \frac{\partial w}{\partial I_2} \frac{\partial I_2}{\partial \underline{\underline{C}}} + \frac{\partial w}{\partial I_3} \frac{\partial I_3}{\partial \underline{\underline{C}}} + \frac{\partial w}{\partial I_4} \frac{\partial I_4}{\partial \underline{\underline{C}}} + \frac{\partial w}{\partial I_5} \frac{\partial I_5}{\partial \underline{\underline{C}}} \right) \quad (4)$$

A hyperelastic law for reinforcement yarns has been formulated using invariants that carry physical meaning [6]. The advantage of this type of formulation lies in the fact that deformation modes appear which will be directly measured in the characterization tests. Four modes of yarn deformation can then be identified: elongation, compaction, distortion (shear in the transverse section) and longitudinal yarn. The latter mode mainly controls the bending stiffness of the yarn. For each deformation mode, an invariant can be defined:

$$I_{\text{elong}} = \frac{1}{2} \ln(I_4), \quad I_{\text{comp}} = \frac{1}{4} \ln\left(\frac{I_3}{I_4}\right) \\ I_{\text{dist}} = \frac{1}{2} \ln\left(\frac{I_1 I_4 - I_5}{2\sqrt{I_3 I_4}} + \sqrt{\left(\frac{I_1 I_4 - I_5}{2\sqrt{I_3 I_4}}\right)^2 - 1}\right), \quad (5) \\ I_{\text{sh}} = \sqrt{\frac{I_5}{I_4} - 1}$$

The form of the potentials  $w_{\text{elong}}, w_{\text{comp}}, w_{\text{dist}}, w_{\text{sh}}$  (elongation, compaction [16], distortion, shear [17]) is chosen from the results of the corresponding tests. In the present work, they depend on 8 parameters. Four correspond to longitudinal elongation, two to compaction, one for distortion and one for

shear. These parameters are specified in table 1 for the different deformation modes and their identified values are given in table 2 in the case of a glass yarn.

Table 1. Parameters to be identified

Deformation mode	Extension
Parameters	$S_0, I_{elong}^0, K_{elong}^0, K_{elong}$
Experimental test	Tensile test on a yarn

Table 1 (continued). Parameters to be identified

Deformation mode	compaction	distortion	shear
Parameters	$K_{comp}, p$	$K_{dist}$	$K_{cis}$
Experimental test	Biaxial tensile test Inverse approach		Longitudinal shear test

Table 2. Identified parameters

$S_0$	$I_{elong}^0$	$K_{elong}^0$	$K_{elong}$
0.489	0.00386	11000	37486
(mm <sup>2</sup> )	(N)	(N)	(N)

Table 2 (continued). Identified parameters

$K_{comp}$	$p$	$K_{dist}$	$K_{cis}$
17800	7.72	0.0608	3
(MPa)		(MPa)	(MPa)

#### 4. Mesoscopic analysis of the compaction of a 3D orthogonal reinforcement.

A simulation at mesoscopic scale of the compaction of an orthogonal 3D reinforcement is performed. The material parameters are given in Table 2. The sections  $S_0$  of the yarns are determined by X-ray microtomography. A finite element model composed of 40,000 linear prismatic elements is built. This mesh is without interpenetrations [19]. Periodicity conditions are prescribed on the boundaries of the model. The contact and sliding friction between the yarns is taken into account with an isotropic Coulomb coefficient equal to 0.3.

Figure 4 shows the geometries obtained by microtomography and simulation of an orthogonal 3D woven fabric subjected to transverse compaction. The deformations obtained for each yarn are in good qualitative agreement. The compression behaviour in the yarn direction of the woven reinforcements is difficult to characterize. Individually, a yarn will tend to buckle in compression. However, by the weaving process, they are bound in the reinforcement. Their movements are constrained by the positions of their neighbours. Modelling of the longitudinal compression of the fibre yarns during forming is carried out in [18].

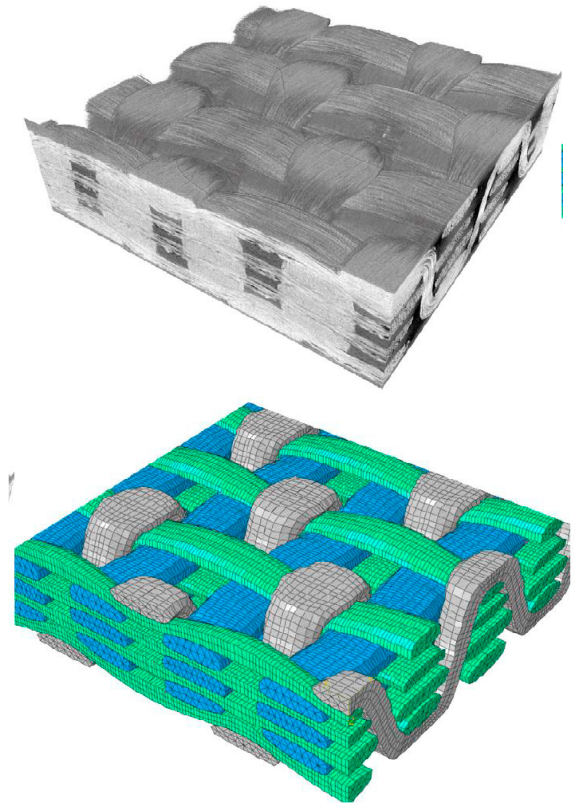


Fig. 4 X-ray tomograph and meso F.E. analysis of the compaction of a 3D orthogonal reinforcement.

Figure 6 shows a comparison between tomography section images and simulated section images of the orthogonal 3D reinforcement in its initial state and compacted to 22%.

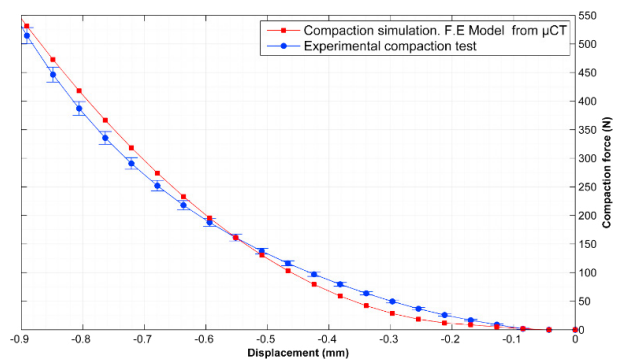


Fig. 5 - Comparison between experimental and simulated transverse load

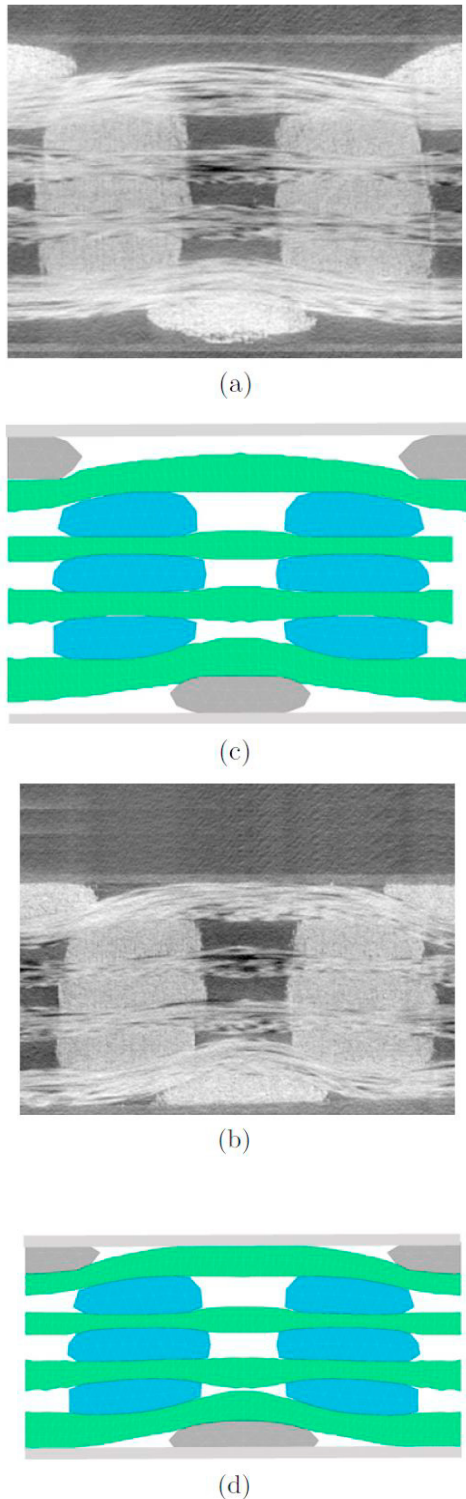


Fig. 6. Cross-section image: X-ray tomography and meso F.E. analysis in the undeformed state (a,c) and compacted state (b, d)

Figure 5 compares the experimental transverse force with the simulated transverse force versus the displacement in the thickness direction. The simulated curve has a good correspondence with the experimental curve. The small difference between the curves can be explained by the difficulty of experimentally determining the origin of the displacements for the reinforcement compaction. It is difficult to know the exact location of the contact between the yarns and the plate of the compaction machine.

## 5. Conclusion

X-ray microtomography is well suited to the development of realistic mesoscopic E.F models of 3D composite reinforcements. The complexity of their geometry can be taken into account by microtomography. A segmentation method based on image texture was explored to separate warp, weft and orthogonal yarns. This segmentation method is appropriate when tomographic images show a granular aspect, whereas the method of segmentation by structure tensor is well adapted to the case of filamentous aspect of the yarns. The yarns are meshed by prismatic elements. This shape is well suited for fibre yarns.

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