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A finite element approach of the behaviour of woven materials at microscopic scale

Damien Durville

Abstract A finite element simulation of the mechanical behaviour of woven textile materials at the scale of individual fibers is proposed in this paper. The aim of the simulation is to understand and identify phenomena involved at different scales in such materials. The approach considers small patches of woven textile materials as collections of fibers. Fibers are modelled by 3D beam elements, and contact-friction interactions are considered between them. An original method for the detection of contacts, and the use of efficient algorithms to solve the nonlinearities of the problem, allow to handle patches made of few hundreds of fibers. The computation of the unknown initial configuration of the woven structure is carried out by simulating the weaving process. Various loading cases can then be applied to the studied patches to identify their mechanical characteristics. To approach the mesoscopic behaviour of yarns, 3D strains are calculated at the scale of yarns, as post-processing. These strains display strong inhomogeneities, which raises the question of using continuous models at the scale of yarns.

1 Introduction

The mechanics of woven materials can be addressed at three different scales : the macroscopic scale relevant to pieces of fabric, the mesoscopic scale related to yarns, and the microscopic scale concerning fibers inside yarns. Different approaches are available to handle the problem of the identification and characterization of the complex mechanical behaviour of these materials. Some developments are specially dedicated to the characterization of the geometry of yarns in the woven structure ([6, 5]). Geometries of yarns obtained by these methods can then be meshed and classical finite element codes can be employed to compute the mechanical response of textile

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or textile composite structures. Other approaches concentrate on the finite element simulation at the scale of yarns, representing yarns by means of 3D elements with appropriate constitutive laws [1]. Going down to the scale of fibers requires a description of the geometry of fibers in the initial configuration. Such a geometry is a priori unknown, and therefore needs to be computed, for example by simulating the weaving process. Such an approach has been proposed using a finite element simulation code based on an explicit solver [4]. The method we present here is based on a simulation code specially developed to handle the mechanical behaviour of entangled media [2], and makes use of an implicit solver. This simulation code is able to handle small patches of fabric made of few hundreds of fibers in order to identify their mechanical behaviour [3]. After recalling some basic features of the method, the way the weaving process is simulated to compute the initial configuration of the woven structure is presented, and results for two different weave patterns are given. Classical loading tests are then applied to these patches. The last part is dedicated to the calculation of 3D strains at the scale of yarns by means of meshes generated as post-processing. The results show strong inhomogeneities of strains at the scale of yarns, induced by localized displacements taking place between fibers.

2 Purposes of the simulation at microscopical scale

The needs related to the modelling and simulation of textile materials are diversified. Formability studies require an identification of the global macroscopic behaviour of fabrics, whereas the focus will be put on the local behaviour of individual fibers if damage and fiber breaking phenomena are to be investigated.

The coupling between phenomena at different scales makes the study of such materials complex. The two main mechanisms ruling the behaviour of textile materials, namely the interweaving of yarns constituting the fabric, and the entanglement of fibers within the yarns, occur at different scales but must be considered simultaneously. One possible strategy to solve the problem at the macroscopic scale is to formulate a mesoscopic model for yarns accounting for the behaviour of the bundles of fibers making up the yarns. However, at the scale of yarns, one important issue is to determine whether phenomena between discrete fibers within yarns may be approached by continuous models.

To explore these questions, we propose to address the global problem at the microscopical scale of individual fibers, by considering small patches of fabrics as assemblies of individual fibers, arranged in bundles, and developing between them contact-friction interactions. By this way, models at intermediate scales are no longer required, and the only mechanical characteristics to be known are those of individual fibers. As a downside, the initial geometry of fibers in the woven structure can not be predicted a priori. It is therefore necessary to compute this initial geometry by simulating the weaving process.

3 Main features of the simulation code

3.1 A kinematically enriched beam model for fibers

The beam elements used to take into account fibers in the simulation are based on an enriched kinematical model that describes kinematics of each cross-section by the means of three vector fields : one for the translation of the centroid, and two to represent planar and linear deformations of the cross-section. This model, characterized by nine degrees of freedom, allows to calculate full 3D strain tensors, accounting for deformations of cross-sections.

3.2 Modelling of contact between fibers

An original method [2, 3] has been developed to detect quickly and accurately the numerous contacts taking place within a collection of fibers submitted to large deformations. This method is based on the determination of contact elements made of pairs of material particles that are predicted to enter into contact. The determination of these elements relies on the construction of intermediate geometries in any region where two parts of beam are sufficiently close to each other. These geometries are defined as the average of the two close parts of line. Normal directions to these geometries are used as contact search directions to define material particles of contact elements. By this way, the process of determination of contact elements is symmetrical with respect to the two considered beams –which is not the case when the normal direction to only one structure is chosen as contact search direction.

3.3 Rigid bodies for the driving of boundary conditions

To simulate the various conditions corresponding to the initial weaving process or the different loading tests, a versatile driving of boundary conditions is required. For this purpose, rigid bodies are attached to each end of yarn, and to each side of the patch. These rigid bodies can be driven either by displacements or by forces, applied to their degrees of freedom in both translation and rotation.

4 Computation of the initial configuration : simulation of the weaving process

4.1 Modelling of the weaving process

The simulation of the weaving process is necessary to determine the unknown initial configuration of the woven structure. The weave pattern specifies which yarn must be above or below the other at each crossing. The basic idea to simulate the weaving process is to make these conditions progressively fulfilled.

To do so, we start from a flat configuration where all yarns are straight and penetrate each other at crossings. Then, for a few steps, for any penetration detected between two fibers belonging to crossing yarns, we take as the normal direction of contact a vertical direction oriented according to the local crossing order prescribed by the weave pattern. This process is applied until yarns are completely separated at crossings. Then, in a second stage, classical contact directions, depending only on the local geometry of fibers, are considered, while forces and displacements applied on the sides of the patch are progressively relaxed. At the end of this process, an equilibrium configuration of the woven structure after weaving is obtained.

4.2 Application to the studied patches

Two patches of fabric, made with the same yarns, but according to two different weave patterns –a plain weave and a twill weave–, have been considered for the results presented here. The main features characterizing these patches are given in Table 1. Each patch is made of 408 fibers, and about 80.000 contact elements are considered in the simulation.

Nb. of fibers weft yarns	44
Nb. of fibers warp yarns	24
Nb. of weft yarns	6
Nb. of warp yarns	6
Total nb. of fibers	408
Nb. of nodes	35.000
Nb. of dofs	300.000
Nb. of contact elements	≈ 80.000

Table 1 Characteristics of the studied patches

Computed configurations for the two weavings are shown on Fig. 4.2. Cuts of the two computed initial configurations and details of these cuts (Fig. 2) show the rearrangement of fibers and typical shapes of cross-sections obtained by the simulation. Whereas for plain weaves shapes of yarn cross-sections are predominantly

lenticular, for twill weave cross-sections are more complex and vary along the yarn (Fig. 3).

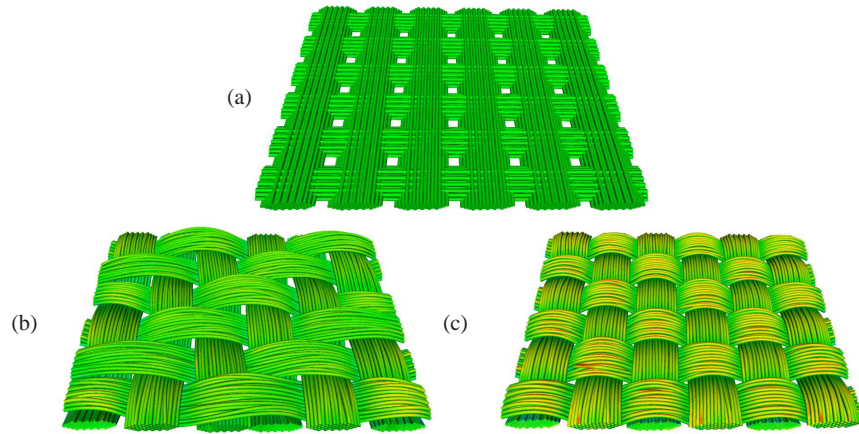


Fig. 1 Simulation of the weaving process : configuration before weaving (a), computed configuration for plain weave (b) and twill weave (c)

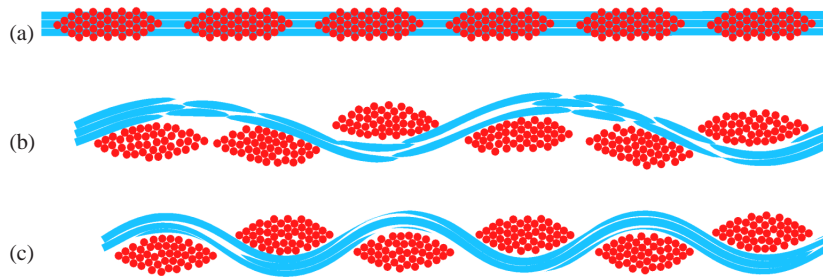


Fig. 2 Cuts of configuration before weaving (a), and of computed configuration for a plain weave (b) and a twill weave (c) patches



Fig. 3 Variation of cross-section shapes along a warp yarn for twill weave

4.3 Application of loading tests

Once the initial configuration has been computed, various loading cases can be simulated by applying appropriate loadings (displacements or forces) to rigid bodies attached to each side of the patches. Biaxial tension loadings are applied up to a 2% extension in the warp direction, with a ratio α , taken successively equal to 0 and 1, for the extension in the weft direction. Typical J-shape force/displacement curves are obtained (Fig. 4). Nonlinear effects at the start of the curves are related to the compaction of cross-sections as the tensile force increases.

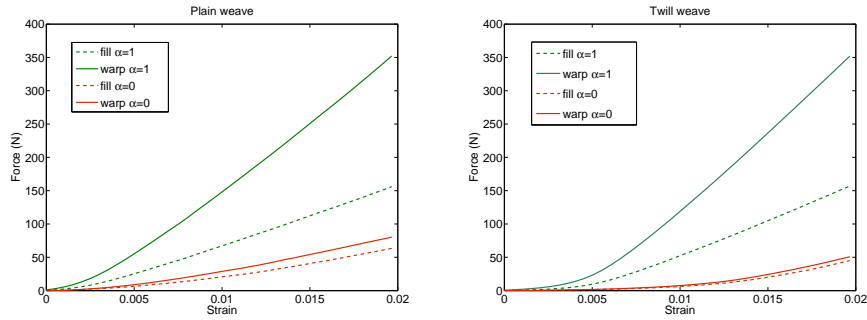


Fig. 4 Force/strain curves for biaxial tension tests for plain weave and twill weave

5 Strain measures at the scale of yarns

The formulation of mesoscopic models to represent the behaviour of yarns requires to define measures for both strains and stresses at the scale of yarn. The definition of a stress measure is difficult because stresses within yarns are of two different kinds : continuous stresses inside yarns, and discrete contact-friction interactions between fibers.

As a first step, the definition of a strain measure at the scale of yarn is easier. To approximate such a quantity, we propose to consider each yarn as a continuum, and to compute, as post-processing, Green-Lagrange strain tensors using a 3D finite element mesh based on the nodes defined on fibers (Fig.5). Once the mesh connectivity has been defined for the initial configuration, nodal displacements and strain tensors can be easily derived. It is also possible to consider strains generated by displacements only between two given loading increments.

The plotting of horizontal strains due to the initial forming (Fig. 6) shows strong inhomogeneities. Zones looking like diagonal shear bands can be observed on the cuts of strains in both horizontal and vertical directions (Fig. 7 and 8).

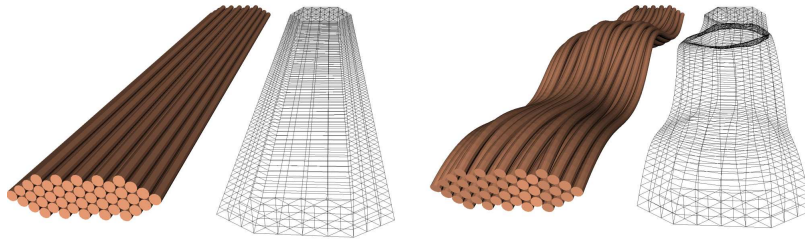


Fig. 5 Fibers of a yarn, and corresponding 3D meshes in two different configurations

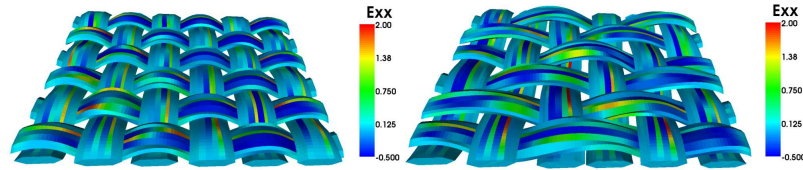


Fig. 6 Horizontal strains in yarns generated by the simulation of the weaving process

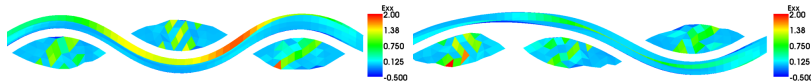


Fig. 7 Cuts of horizontal strains in yarns generated by the simulation of the weaving process

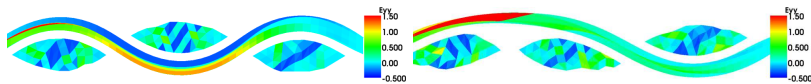


Fig. 8 Cuts of vertical strains in yarns generated by the simulation of the weaving process

Similar inhomogeneities can be observed for strains induced by the equibiaxial tension (Fig. 9). In this case, the axial strain is twice higher on the sides of the yarn than in the center. The appearance of shear bands shows a rearrangement of fibers in the center of the yarn. This rearrangement reduces the height of the cross-section, allowing fibers to undergo lower extensions.

Inhomogeneities revealed by this post-processing are of first importance since they raise the question of using continuous models to describe the behaviour of yarns.

6 Conclusion

Models and algorithms developed for the simulation of the mechanical behaviour of entangled media can be applied for the modelling of woven structures. Patches of fabric made of few hundreds of fibers can be considered by the model. The simula-

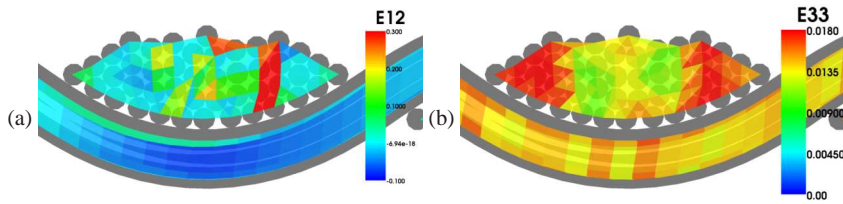


Fig. 9 Shear strains (a) and axial strains (b) in yarns generated by equibiaxial tension

tion of the weaving process provide accurate geometrical descriptions of both yarns trajectories and varying shapes of yarns cross-sections. The mechanical response of the fabric can then be characterized by simulating typical loading tests. The computation of 3D strains at the scale of yarns reveals strong inhomogeneities and raises the question of the validity of considering yarns as continuaums.

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