MESOSCOPIC FINITE ELEMENT SIMULATION OF THE MECHANICAL BEHAVIOROF WOVEN DRY FABRICS

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Abstract
Numerical simulations are a powerful tool to predict the feasibility of mechanical components. To construct simulations of composite materials with continuous fibre reinforcements, it is necessary to have precise models of the mechanical behaviour and geometrical properties of dry fabrics. The goal of this study is to identify the behaviour law of the homogeneous material equivalent to a fibrous material to feed simulations

1. Introduction

Because of the high strength to weight ratio of composite materials, aircraft manufacturers are increasingly interested in integrating composite parts into their products. To produce these parts, various processes can be used. Some of them, as Resin Transfer Molding (RTM) consist in forming a dry fabric before injecting a resin. This study concerns the first step of the RTM process, i.e. the preforming of a dry fabric and more precisely the interesting challenge of simulating this step in order to build such numerical simulations, it is necessary to have accurate models of the mechanical behaviour and permeability of dry fabrics [1,2]. Two types of methods can be considered to achieve this task: experimental and numerical ones. Although experimental methods are direct and efficient, they exhibit several drawbacks: not only are they often time consuming and expensive to perform, they are limited to existing fabrics and do not allow many steps of optimization. That is why it is judicious to complement them by numerical studies. Nevertheless, modelling the mechanical behaviour of dry fabrics is far from being easy. Indeed, the complexity lies in the multi-scale nature of fibrous reinforcements, which are composed of yarns, themselves composed of thousands of fibres. Three different scales can be distinguished. The first one is the microscopic scale which takes into account the contact between thousands of fibres. In these case calculations are complex and take a huge amount of time. On the opposite, the macroscopic scale, in which the fabric is considered as a continuum with a specific behaviour. In this case, the interlacement between yarns is not explicitly taken into account [3] and does then not permit to model precisely the mechanical behaviour of fabrics. At the mesoscopic scale, in between the previous two scales, yarns are assumed to be homogeneous and the fabric is constituted by the interlacement between these homogeneous yarns. This scale appears consequently to be a good compromise between accuracy and complexity [4-13]. The aim of the present work is therefore to develop a tool to simulate the mechanical behaviour of the unit cell of dry fabrics at the mesoscopic scale. The first part of this research consists of the creation of a as precise as possible unit cell. A fully automated geometrical modeler has been developed, it is based on two crucial properties as regards textile modeling: the consistency that ensures a perfect surface contact between the yarns, that is to say, no spurious voids or interpenetration that would lead to calculation problems and variation of the section shape and dimensions along the yarn trajectory. An iterative strategy based on the contact definition and detection then enables to obtain any kind of fabric from 2d to interlocks. Once the model has been created, it has to be meshed consistently in order to feed the simulations. The mesh is composed of 3D hexahedral elements the latter being the most suitable for the management of the numerous contacts and the bending solicitation, which appears during yarns deformation of woven reinforcements (uncrimp for instance). The employed strategy consists in meshing yarn by yarn thanks to a completely automated meshing tool programmed using python routines. The created meshing tools enables to mesh any kind of fabrics (2D, interlocks, 3D,…). Another benefit of this tool is that it allows also creating all the files required for the simulations (node sets, element sets, contact surfaces...), leading to a considerable time saving. A meshed unit cell example is shown in Figure 1 in the case of G1151® interlock.

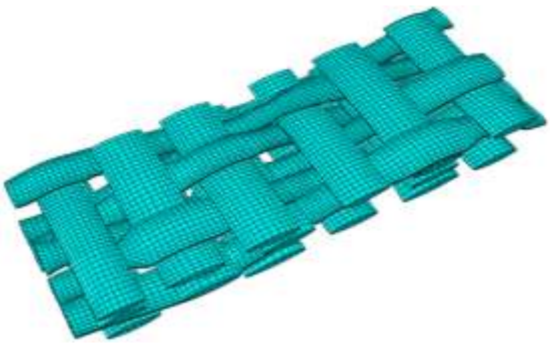


Figure 1. Meshed unit cell of G1151® interlock

Finally, in order to obtain an accurate meso simulation, a constitutive law of the homogeneous material equivalent to a fibrous material is needed. That point is developed here after. The different steps are developed taking the example of a glass quasi-UD whose architecture is similar to a plain weave with double weft yarns the size of which being very different from warp one (Figure 2) (average width: 3.07mm for warp and 0.44mm for weft). Moreover, this fabric exhibits a high pattern variability between several unit cells.

Figure 2. Glass quasi-UD

2. Behavior law

Studying unit-cells behavior consists in analyzing yarns behavior and interactions between them. The single yarn behavior inherits of the behavior of fibers and of their interactions. Experimental tests have been performed: on yarns of the considered material have been performed in order to determine material parameters to be incorporated into the behavior law and on the fabric so as to compare the simulated behavior with the real one.

2.1. Behavior model of homogeneous equivalent material

The constitutive law used implemented in the mesoscopic simulation of dry fabrics forming should take into account both geometrical non linearities, caused by yarns large displacements and large strains, and material non linearities linked to the yarn constitution (thousands of fibers). Indeed, fibrous materials particularity yarns behavior, which is the association of single fibers behavior and of the assembly of fibers as yarn. Moreover, fibers constituting these yarns exhibit a diameter in the range of a few microns. As a consequence, they exhibit almost exclusively longitudinal stiffness and can slide one according the other. Yarns are therefore highly anisotropic with a longitudinal stiffness significantly superior to the others; this requires to follow strictly this direction not to accumulate errors (stress actualization for example).In other words, the material directions have to be strictly identified and followed during large strains undergone by the fabric (shear for example). This has been achieved here using a specific objective derivative, which can be called a "material" derivative developed in the LaMCoS within the works of Hagege and Badel [4,14] adapted to medias with one anisotropy direction. In addition, tomography observations show a transverse isotropy of the fibers distribution. The hypothesis of transverse mechanical isotropy can consequently be adopted [4]. Endly, the low yarns bending stiffness is taken into account through the introduction of a low shear modulus compared to the longitudinal one [15]. An approach that fits to all the criterion has already been proposed by Pr. Boisse's team [4,14], based on a hypoelastic non linear behavior law and the use of the previously presented objective derivative. The transverse isotropic behavior tensor in material directions base was defined as follows:

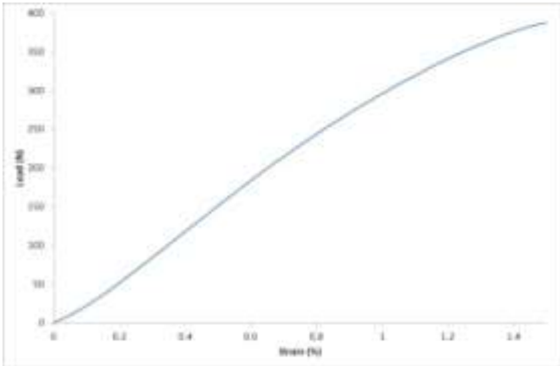
$$d\sigma_{ij} = C_{ijkl} d\varepsilon_{kl} \qquad [C] = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & 0 & 0 & 0 \\ & C_{2222} & C_{2233} & 0 & 0 & 0 \\ & & C_{3333} & 0 & 0 & 0 \\ & & & C_{1212} & 0 & 0 \\ & Symmetry & & & C_{2323} & 0 \\ & & & & & C_{1313} \end{bmatrix} \qquad (1)$$

Up to now, the behavior tensor components were obtained by inverse identification on experimental tests on the reinforcement, which is time consuming and a significant drawback: for parametric studies and to deal with non-existing fabrics. So, the first goal of this study consists in avoiding any inverse identification of fabric tests and in modifying the behavior law in order to improve its physics accounting recent works concerning transverse behavior law in fibrous materials. This will then enable to go increasingly towards predictive analyses. In order to achieve this task, new formulations have been proposed for the yarn mechanical behavior and experimental tests have been performed in the PRISME Laboratory. to identify all the material coefficients (1). They are presented in the next sections.

2.2. Tension behavior

In some cases, yarn tension behavior exhibits a non-linearity at the beginning of the test. This non-linearity is due to the layout of the thousands of fibers, whose crimp, average course, or entanglement, differ within a single yarn. As a consequence, all fibers are not stretched simultaneously at the beginning of tension tests. However, for roving technical fabrics classically used and concerned in this study, users look for the as high as possible yarn stiffness for a constant fibers density. Manufacturers therefore look for and then succeed in obtaining yarns constituted by quasi parallel fibers, with a global stiffness close to the amount of fibers stiffness. Thus yarns tension behavior is quasi linear [1] and will then be rightfully considered so in that study.

a) Tension test machine



b) Tension test results

Figure 3. Tension test

The tension tests have been done in the PRISME Laboratory according to the protocol defined by J.E. ROCHER [16], leading to reliable results for tension tests on fabric or single yarn. Samples composed by a single yarn are scored to allow optical measurements using a marker tracking system and glued between aluminum plates for their fixation into the jaws of the tension machine (Figure 3.a)). The results of these tests, presented in Figure 3.b), exhibit that yarn stiffness is linear and eligible strains before fibers failure are small and less than a percent (IFT). The, tension results for a single yarn are expressed by tension load (F) as a linear function of longitudinal strain $\left(\frac{dl}{l_0}\right)$, as:

$$F = K\left(\frac{dl}{l_0}\right) \tag{2}$$

With l_0 the initial length of the yarn and K the yarn stiffness, supposed to be constant during the test and corresponding to the slope of the yarn tension curve. This yarn tension stiffness is only a function of the number of fibers and the transverse strains. As a consequence, it is possible to assume that the longitudinal strain increment $d\varepsilon_{11}$ is independent of the other strains (transverse and shear strains). Furthermore, during a tension test, stresses can be considered as homogeneous in the equivalent material; it is so possible to write:

$$d\sigma_{11} = \frac{K}{S_m} d\varepsilon_{11} \tag{3}$$

The stiffness K that as to be integrated into simulations is then obtained directly from the experimental on the yarn tension curve and the surface S_m is updated at each increment. Moreover, if the fibers network can be related to a parallel fibers network, longitudinal strains do not cause either transverse strains during a tension test on single yarns. A slight narrowing of initial width of the section can be observed (optical measurements) at the beginning of the tests, but this narrowing is rather related to the bulking of external fibers when the yarn is not stressed and not to a real modification of the section. Transverse strains measurements appears, as a conclusion, to be very law and can then be neglected. Poisson coefficient ν_{12} and ν_{13} are consequently null and, the related tensor components defined in (1) are:

$$C_{1122} = C_{1133} = 0 \tag{4}$$

Finally, three components of the researched tensor have been identified thanks to tension tests. Four other components are identified thanks to compression tests.

2.3. Comression behavior

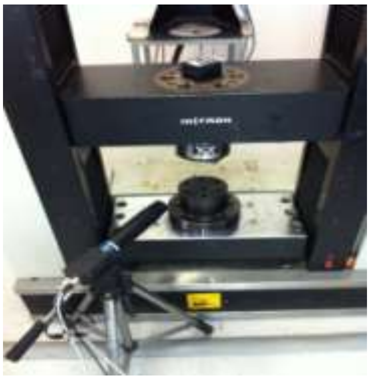
Yarn compression is one of the most important strain modes as it intervenes in most fabrics solicitations (biaxial tension, shear, compression…). Furthermore, the characterization of the yarn compression behavior is, of course, significant as it directly influences fibers density and thus, for example, local permeability, which is essential to model the injection phase [17]. Yarn compaction behavior is characterized by a modification of the area in a transverse plane, i.e. a plane which is perpendicular to fibers direction; this modification is linked to a reorganization of the fibers and thus to a decrease of the fibers interspaces. As a consequence, it is a non linear behavior linked to the material discontinuity and directly in relation to the fiber density. It is therefore better to express the compression behavior in function of the fibers density. Indeed, whatever the yarn considered, any decreasing of voids between fibers, i.e. any increasing of fibers density generates an increase of compression stiffness. Thereby compression stiffness for yarns constituted by aligned fibers is in literature classically expressed in function of fibers density [18-21]. Recent works gives the following relations between the uniaxial compression pressure P and the fibers density:

$$P = K_c(V_f^{\gamma} - V_{f0}^{\gamma})\ [20,21] \tag{5}$$

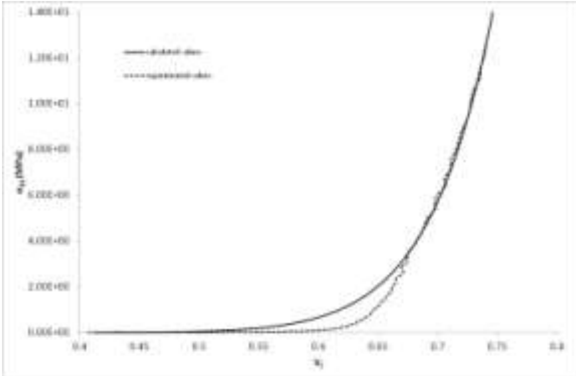
With V_{f0} the initial fibers density of yarn, K_c and γ 2 coefficients identified from experimental curves. The main objective of the next section therefore consists in identifying the parameters of the behavior law previously expressed in function of fibers density. As the yarn section when extracted out of the coil is rectangular [22], the hypothesis of uniform pressure distribution during the compaction test is done.

2.4. Compression tests protocol

The protocol has been developed at the PRISME Laboratory and uses a tension machine (Figure 4.a)), on which circular plates are adapted on the upper and lower jaws to realize compression tests. The upper plate is made out of PMMA, allowing to visualizing the sample from above thanks to a CCD camera. As a consequence the spreading of the yarn under compression can be measured through the PMMA, using image analysis. The lower plate is connected to a ball joint that ensures the parallelism of both plates. A second camera, placed close to the side of the sample allows measuring the yarn crushing.



a) Compression test machine



b) Compression test results

Figure 4. Compression test

The compression tests (Figure 4.b)) on yarns and fabrics confirm the results from literature, i.e. curves exhibit two linear parts related by a non linear zone. Furthermore, the curve shape appears in very good agreement with the one given by equation (5) and K_c and γ coefficients can be identified as:

$$\gamma = 14$$
$$K_c = 850$$

These values are, in addition consistent with those found in the literature for glass fiber yarns ($K_c = 700, \gamma = 15.5$ [20]). Despite the interesting potentiality of the protocol used, the transverse strains identification during the compression test on a yarn is not easy because they are very low, but above all subjects to high amount of discrepancy because the fibrous network cohesion especially near the yarn edge is not always good. Thus, the curve obtained (Figure 4.b)) lead at the moment to preliminary results that should be refined improving protocols and post-treatments.

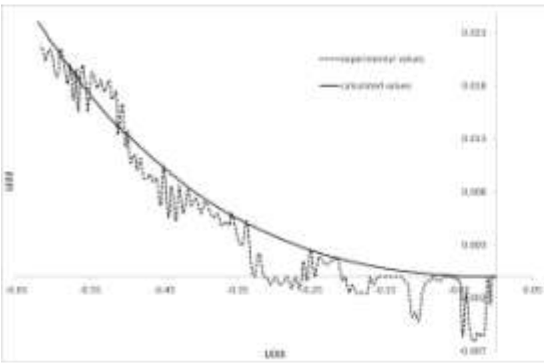


Figure 5. Compression test results: strain ratio

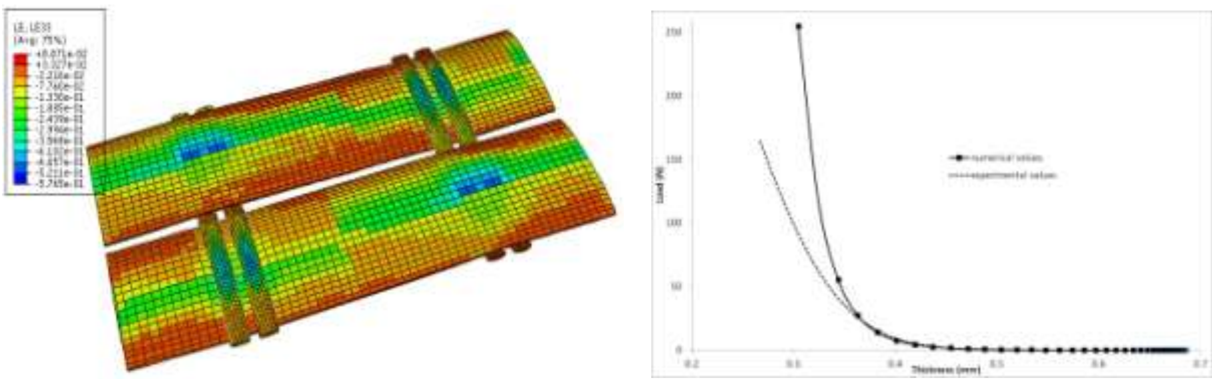
However, the curve presented in Figure 5 gives a first approximation of strains ratio $R_{23} = \frac{LE_{22}}{LE_{33}}$. It can be noted that this ratio increase during compression test. R_{23} is therefore not constant. Moreover at a law fibers volume fraction, the strains ratio is almost null. If the results are as already explained scattered, it is possible, as a first step, to interpolate them with a power law (Figure 5). Derivate the obtained curve then enables to obtain the looked for strains rate ratio r_{23} (hypo elastic approach). Furthermore, it seems physically consistent to consider that strains rate ratio reaches Poisson's ratio of the fibers constitutive material when the fibers density tends toward 1. The following two conditions can therefore be written for the strains rate ratio:

- If $V_f = V_{f0}$, then $r_{23} = 0$;
- If $V_f = 1$, then $r_{23} = \nu_{23mat}$ with ν_{23mat} Poisson's ratio of fibers constitutive material.

$$r_{23} = -\nu_{23mat} V_f^{n-1} \quad (6)$$

3. Computation examples and conclusion

A constitutive model has been identified for roving yarns within a hypoelastic approach proposed by P. Badel [4,5]. Modifications have been proposed, based on recent experimental laws of the literature. The method is based on the characterization of the constitutive tensor components from yarns tests and/or on an analytical identification (bibliography, fibers properties and yarn structure), representing a first step to predictive analyses. This method allows the obtaining of good estimations of fabrics behavior and numerical results, which are consistent with experimental ones (Figure 6.b)) and, above all, to overcome inverse identification. Results shown on Figure 6 are compression tests on warp yarns. Since the weft yarns are more complex to extract from the fabric and to test due to their size and the glue remaining on them, their mechanical behavior has been extrapolated from the warp ones thanks to a Weibull law [16]. Of course, these results could be refined by performing tests on weft yarns or by taking into account fabric variability. But, they however show that a good estimation of the yarns parameters enables to obtain a good estimation of fabric behavior.



a) Deformed geometry of the unit-cell of the glass plain weave fabric

b) Experimental/numerical comparison of a compression test on the unit-cell of the glass plain weave fabric

Figure 6. Numerical results of the compression test on the unit-cell of the glass plain weave fabric and comparison with the experimental ones

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