MESOSCOPIC SIMULATION OF WOVEN FABRIC FORMING: FROM A CONSISTENT GEOMETRY TO FINITE ELEMENT MODELLING

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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 develop a simulation tool of 2D and interlock unit cell of dry fabrics and to simulate mechanical behaviour of these unit cells under simple stress. In order to feed simulations, 3D geometrical model of the unit cell have to be defined and meshed.

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. Processes such 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 the dry fabric. In order to build numerical simulations, it is necessary to have precise models of the mechanical behaviour and permeability of dry fabrics**[1][3]**. To define the mechanical behaviour of fabrics, two types of methods can be considered: experimental and numerical. Although experimental methods are direct and efficient, they present several drawbacks: not only are they often time consuming and expensive to perform, they are limited to existing fabrics and do not allow optimization. That is why it is judicious to complement them by numerical studies. The complexity of the study 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 [4,5]. In these case calculations are complex and take a huge amount of time. On the opposite, the macroscopic scale, which considers the fabric as a continuum with a specific behaviour. In this case, the interlacement between yarns is not taken into account **[6]**. This scale is not sufficient to define precisely the mechanical behaviour of fabrics. The mesoscopic scale, in between the previous two scales, where yarns are assumed to be homogeneous and the fabric is constituted by the interlacement between yarns. This scale represents a good compromise between accuracy and complexity **[7-13,16-19]**.
The aim of this study is therefore to develop a tool to simulate the mechanical behaviour of the unit cell of dry fabrics at the mesoscopic scale. The first step of this research is the

creation of a unit cell as precise as possible. Once these models have been done, they have to be meshed consistently in order to feed simulations.

2 CAD modeling of unit cells

2.1 Fabric structure

For 2D fabrics, three types of structure can be distinguished: plain, twill and satin weaves. As the unit cell geometry of these fabrics is a priori known, 2D models can be easily obtained. More complex fabrics such as interlock, however, have an infinite number of architectures, each depending on the mechanical properties and formability intended. The user must be able to model each of these structures easily and, if necessary, create new structures. The modelling process of these fabrics is therefore more complex and time consuming.

2.2 Contact between yarns

The main difficulty is locating contacts between yarns. In 2D fabrics, the localisation and number of contacts are easily determined because these fabrics have weaving contacts only **[14][15]**, i.e. contacts caused by yarn interlacement.

Contact characterization is much more complex for interlock fabrics because there are a large number of contacts, which change with the yarn arrangements. Three types of contact can exist (**Figure 1**).

- Weaving contacts caused by yarn interlacement.
- Lateral contacts between yarns of the same network. The weaving process assumes that yarns of the same network are strictly parallel and interspaced. While this property is verified for fabrics with low yarn density, many fabrics, especially interlocks, are becoming increasingly dense, so that the interval between two yarns can be less than the initial yarn width. As a result, some lateral contacts between yarns of the same network can occur.
- Non designed contacts occur when yarn density is high and the fabric structure complex. In this case, the interval between yarns is small and a supposedly straight yarn between two weaving contacts may intersect a transverse yarn.

Thus it is difficult to predict a priori all the contacts for complex fabrics such as interlocks.

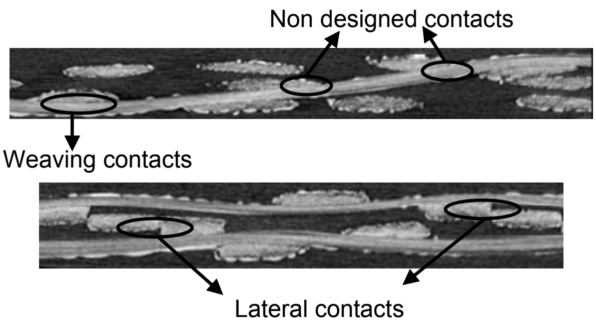


Figure 1. Cross-section of G1151® and associated contacts

2.3 Modelisation of yarn geometry

Each yarn is built as a pipe composed of various sections and a trajectory. The trajectory is defined by the succession of parabolas and straight segments. The parabolas represent the contact zone between two yarns and the straight segments correspond to areas between two contact zones. Along each pipe, transverse contacts vary, leading to variations in the yarn's local shape. Yarns are variable section pipes.

As for the 2D model **[17]**, and in agreement with tomography studies, the section shape of the yarn comprises two parabolas connected with two segments called flat flanges. This geometry

is simple and can acceptably model all section shapes from lenticular to pseudo elliptic, depending on the size of the flat flanges.
Tangency and consistency equations ensure that both surfaces at the contact zone are identical. The contact surfaces of each yarn are defined with the same parabola for both parabolas in contact. Between two contacts, as no load is applied except residual stress, yarns are assumed to be straight. The transverse section at the contact zone is built with the same parabola.

2.4 Automation
The automation is based on an iterative process that takes into account all the parameters that are easily identified by the manufacturer or thanks to tomography. They are recorded on a data sheet that can be easily read by a VBA program.
The geometry is then constructed in a CAD Software: CATIA V5®. Each yarn is built separately. A procedure to search for interferences has also been drawn up: each time a yarn is added, Boolean operations are performed to locate contacts. Once contacts are located, it is possible either to modify locally the section shape or to integrate these new contacts to the data sheet in order to obtain a consistent geometry of all reinforcements (2D and interlocks). **Figure 2** shows an example of consistent geometry of G1151.

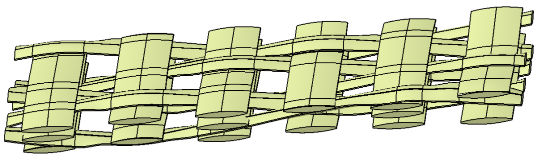
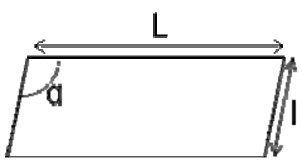


Figure 2. Unit cell of G1151®

3 Mesh

3.1 Global strategy
Once the unit cell has been defined, the goal is to mesh the geometry and to compute it. Both meshing and computation are done with Abaqus®. The mesh is constructed with hexahedral elements; the aim of this step is to create a mesh that depends on yarn geometry and in particular on the section shape, and to automate it. The main objective of this step is to optimize calculation time by minimizing the number of elements. Moreover, yarn geometry can lead to distorted elements and the strategy should work whatever the shapes and parameters of the yarns. That is why it is based on the respect of validity criteria. In the case of 3D elements, Abaqus defines two validity criteria (**Figure 3**):

- The shear angle: all the angles of the element have to be between 10° and 160°
- The aspect ratio: the ratio between the biggest and the smallest edges have to be less than 10



$10° < \alpha < 160°$

$\frac{L}{l} < 10$

Figure 3. Validity criteria

Looking at yarn sections (**Figure 4**), most restrictive elements are the first element and the central one: they are the most sheared and rectangular. If these elements validate the criteria, the others will be valid too. That is why the calculations will be done on both these elements to validate mesh.

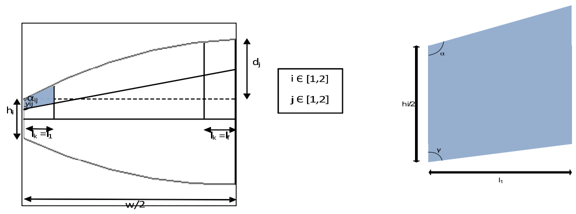


Figure 4. Elements choice

3.2 Criteria calculation

From geometry provided by CAD model, the angles can be deduced. Two strategies can then be envisaged: if the section shape is not too curved, the mesh is direct, in the case of a too curved section shape, the mesh will be impossible due to a shear angle higher than 160°. The section can be cut (**Figure 5**) to respect criteria.

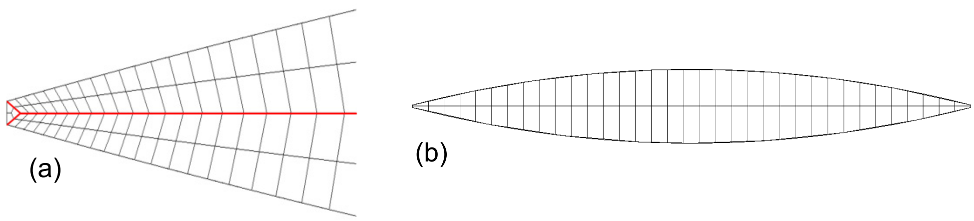


Figure 5. Section shapes. a) Too curved and cut b) Not too curved

The next objective is to determine minimum and maximum element edge length, function of the flat flange and the number of elements through the thickness. The aspect ratio is calculated to determine l_1, l_2 and H (**Figure 6** and equations **(1)**)

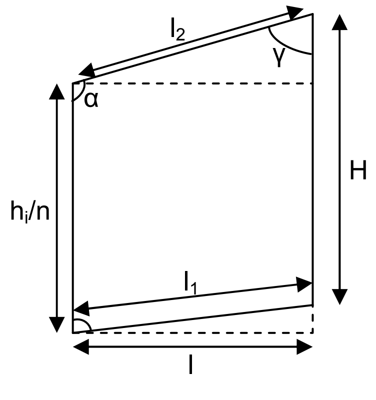


Figure 6. Quadratic Element in Abaqus

$$\begin{cases} \boldsymbol{l_1 = \frac{l}{\sin\alpha}} \\ \boldsymbol{l_2 = \frac{l}{\sin\gamma}} \\ \boldsymbol{H = \frac{h_i}{n} - l(\cot\alpha + \cot\gamma)} \end{cases} \qquad \mathbf{(1)}$$

3.3 Automation

In order to minimise the number of elements while respecting the validity criteria, the strategy of meshing is defined like in **Figure 7**, i.e. by defining a mesh seed by bias on curved edges of sections. The largest element will be situated in the middle of the section. Through the thickness, the seed is defined by number and along the length, the seed is define by size. All the parameters are provided by the user in a data sheet. A first verification is done to validate the elements. In the case of valid elements, a python program enables to mesh each yarn in Abaqus from mesh data and model data. This method enables consistent mesh of dry fabrics.

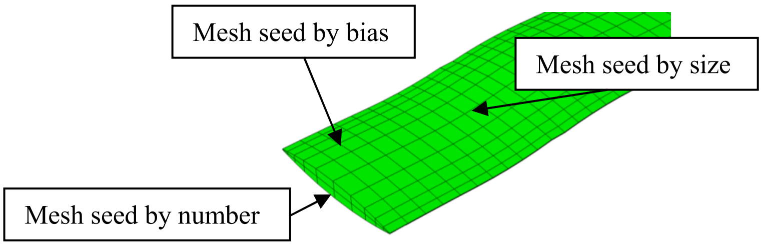


Figure 7. Mesh parameters

4 Computation

The computation is done on three cases: biaxial tension, shear and compression. This step requires several data. To realise realistic simulations, a representative behaviour law is necessary. The second need is the material parameters and finally adequate boundary conditions representative of the solicitation and the periodicity of the structure.

4.1 Behaviour law

The behavior model has to respect the geometrical non linearities caused by large displacements and large strains of the yarns and material non linearities. That is why a hypoelastic behavior law is chosen, that can answer both these conditions.

This study concerns an assembly of yarns, composed of fibers; so it is necessary to define a homogenous equivalent material representative of these yarns. The behavior of yarns is difficult to define as it inherits from fibers behavior and from the characteristics of the fibers assembly in a yarn. The specificities of the homogenous equivalent material are triple: concerning longitudinal behavior of the yarn, the yarn rigidity is mostly superior to all the others. As a consequence, this behavior drives strain modes and it is very important to follow perfectly this direction. Concerning transverse behavior, observations by tomography show an isotropic repartition of fibers. The assumption of transverse isotropy is then done and the transverse behavior is defined as the combination of a surface modification and a shape modification. The third specificity to respect is a low bending rigidity which will be assure by integrating a low shear modulus. These specificities enable to define the behavior tensor **(2)** **[7]**.

$$[C_{f_i}] = \begin{vmatrix} E^* & 0 & 0 & 0 & 0 & 0 \\ 0 & \left(\frac{A+B}{2}\right) & \left(\frac{A-B}{2}\right) & 0 & 0 & 0 \\ 0 & \left(\frac{A+B}{2}\right) & \left(\frac{A+B}{2}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & B & 0 \\ 0 & 0 & 0 & 0 & 0 & G \end{vmatrix} \quad \text{with} \quad \begin{cases} A = A_0 e^{-p\varepsilon_s} e^{-n\varepsilon_{11}} \\ B = B_0 e^{-p\varepsilon_s} \end{cases} \tag{2}$$

4.2 Follow material directions

The major difficulty caused by the definition of a continuous material equivalent to a fibrous material is the follow of the strong direction of anisotropy that can produce errors, for example concerning stress actualization. It is therefore imperative to define an objective derivative based on the rotation of fiber direction. For a classical continuous material, Green Naghdi derivative is used, but this derivative is based on the average rotation of the solid and is not adapted to follow perfectly material direction. This derivative cannot be used here **[8]**. In the case of a material strongly oriented, the rotation chosen is that of fibers direction.

Concretely, in Abaqus, after import and mesh of a yarn, all elements are reoriented automatically to follow fibers direction. This is done thanks to the same python program that creates the mesh.

4.3 Material parameters

Six parameters have to be identified to define behaviour tensor: Young's Modulus, transverse shear modulus, and four elastic coefficients. This is done by analysing experimental tests done on the concerned fabrics. These tests are tension test on a yarn, biaxial test on the reinforcement and compression test. Moreover, friction tests are realised to define friction coefficient between yarns and between the reinforcement and a metallic tool.

5 Conclusion and results

A 3D geometrical model of weaving fabrics such as interlock has been defined thanks to an iterative strategy. The model respects two properties: consistency, which ensures that the model contains no interpenetrations or voids at the contact zone, and variation in the section shape along the trajectory. Thanks to this model, any kind of weaving fabric can be modelled and then meshed in Abaqus. This mesh is done automatically and respecting validity criteria. These models of reinforcement can also be integrated to calculation codes based on ahypoelastic behaviour of yarn and results can be obtained for simple solicitations. **Figure 8**shows a result of a tension test made on a plain wave fabric of glass fibres.

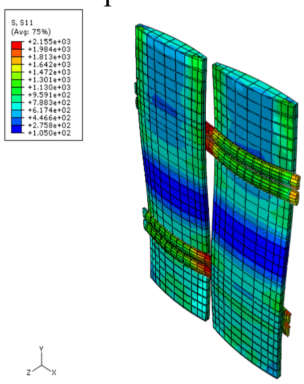


Figure 8. Tension test simulation

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