MESO-SCALE MODELLING AND HOMOGENIZATION OF INTERLOCK REINFORCED COMPOSITE

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SUMMARY

WiseTex software is developed to model 3D angle interlock fabrics. Based on these geometrical models, homogenized mechanical properties of the final composite are calculated. The models geometry is compared with cut samples by image analysis and calculated mechanical properties are compared with experiments.

Keywords: Interlock, 3D woven fabric, homogenisation, elastic properties, meso-scale

INTRODUCTION

Laminates composite materials are subject to delamination when submitted to inter-ply stresses. Three-dimensional woven fabrics are a relevant solution to improve delamination resistance, fracture toughness and fatigue behaviour of composite materials. Introducing reinforcement in the through-thickness direction allows increasing stiffness and strength in this direction. Furthermore, the weaving process allows controlling path and angle of warp yarns and then gives the possibility to adjust the mechanical properties of the material in the three main directions and shear axis to specifications.

Another benefit of 3D fabrics is their potential for reducing manufacturing costs. First, it gives possibility to produce thick composite parts up to 10 cm. The draping process to reach such a thickness would be a lot more time and work consuming, increasing risks of manufacturing errors. The use of an automated Jacquard loom helps increasing producing rates and enables to make evolve continuously the fabric architecture: a continuous variation of the thickness can be achieved by controlling weft insertion during the weaving process. This gives the opportunity to produce complex shapes and near-net-shape textile performs and then to reduce further cutting or joining operations on the composite part. It has been shown that composites parts can be machined out of thick 3D woven composites pates [1].

Second, some 3D textile performs offers higher permeability, which increases impregnation rates. This allows to reduce time of impregnation process or to use more viscous resins.

A review [2] of the manufacturing processes and the different types of 3D architecture (3D woven, 3D braided, 3D stitched and 3D knitted composites) shows the potential of such materials in aircraft, marine craft, automobiles, civil infrastructure and medical
prosthesis fields. The benefits of the use of a 3D woven reinforcement compared to a laminate solution for lower leg prosthesis have been discussed in [3] and demonstrate in particular the possibility to adjust stiffness by controlling fibre placement in 3D fabrics.

The elastic mechanical properties of these 3D reinforced composite materials are determined by the geometry of the reinforcement. Therefore an accurate definition of the microstructure is needed to predict mechanical properties of a textile composite [4]. But the large number of possible textile structures due to the different weaving parameters (weaving pattern, yarns type, warp/weft spacing, fibre volume fraction, deformation of the fabric…) makes it difficult to consider experimental characterization of fabric microstructure and elastic properties of all range of 3D fabrics composites. Investigating only few parameters can turn expensive and time consuming. Moreover, only few data are available concerning geometrical characterization of geometry [5] and mechanical properties [6] of 3D fabrics composites.

Hence numerical tools are needed for either modelling the internal structure of the fabric at different scales and prediction of mechanical properties of the final composite material.

This paper focuses on the modelling of ply-to-ply interlock composite using software package WiseTex [7-19].

**REVIEW OF MODELING METHODS FOR 3D FABRICS**

**Geometrical Modelling**

Adanur and Liao [8] define a fabric geometrical model using the so-called CAGD (computer aided geometric design) technique. The centre line of the yarns is an arbitrary curve defined by Peirce or Kemp models. Then a generative model is used to generate the yarn cross section, which remains constant, along the centre line of the yarn. Various sectional shapes and complex centre lines can be represented with this generative model.

TexGen software is based on the work of Robitaille et al. [9]. It specifies yarn paths with a series of vectors representing the centrelines of the yarns. The surface of the yarn is then defined by sweeping a simple two-dimensional shape such as an ellipse or lenticular cross-section along the length of the yarn. In this model yarn paths can be created arbitrarily and variable cross-sections can be assigned to the yarn.

WiseTex software package used in this paper is presented in next part.

**Analysis Methods For Mechanical Properties**

The most commonly used method for prediction of elastic mechanical properties is the orientation averaging method [6, 10,11,12] and in particular the first version of it, stiffness averaging method. In this model the textile reinforcement is subdivided into small sub volumes, which are considered as unidirectional composite with some spatial orientation. Then using iso-strain assumptions, the global stiffness is averaged from all local stiffness that are calculated from a micro mechanical model. With this approach, the results highly depend on the number and geometry of the sub volumes.

In the modified matrix method [13], each direction of reinforcement is treated separately and averaged with the matrix to create a new modified matrix for others
orientation reinforcements. It has been shown that this model can only be applied to 3D orthogonal composites, which reduces its interest.

The binary model proposes an original approach. Yarns are represented by two-noded line elements that contain axial properties of the yarns, and transverse stiffness, shear stiffness, and Poisson's effects of the composite are represented by solid "effective medium" elements. Some parameters of this model need to be calibrated with some experimental results. But it enables to reduce computational issues for complex 3D fabrics compared to a finite element approach. In [14], Cox discusses calibration of the model for an Interlock 3D fabric and compares results with orientation averaging method. It shows good predictions of macroscopic elastic constants.

Bogdanovich introduced the concept of 3-D Mosaic model, which represents composite structure at any hierarchical level as a Mosaic assemblage of an arbitrary number of distinct homogeneous anisotropic meso-volumes in the three coordinate directions. The properties of each specific meso-volume can be predicted using more detailed model at the next lower level of structural hierarchy by using the different methods described above. The efficiency of this model for prediction of elastic properties of 3D fabrics is demonstrated in [15].

**MATERIAL PROPERTIES**

Many variations exist in the basic geometry of 3D angle interlock preforms, depending on the number of layers interlaced by warp yarns. In general, 3D angle interlock woven composites can be classified into two types, referred to as through-the-thickness angle interlock woven composites and ply-to-ply angle interlock woven composites. This paper study focuses on ply-to-ply interlock woven composites.

![Figure 1: illustration of a warp plan for a ply to ply interlock pattern](image)

The composite material used in this study is made of carbon fibre interlock reinforcement. The specificity of the chosen textile structure is the weft configuration with shifted layers (cf. figure1). This weave pattern is defined on several warp and weft plans by shifting position of warp interlacing yarns. The fabric is then injected with epoxy resin by RTM process to produce panels. Compression is applied on the fabric during the process to reach the desired fibre volume fraction.

The parameters explored in this study are the fibre volume fraction and the spacing of weft rows. As the warp plans spacing is fixed by the dimensions of the reed during the weaving process, this parameter won't be investigated. For confidential reasons only normalized values of mechanical properties and dimensions of the samples will be displayed.
GEOMETRICAL MODELLING

In this part we present the different concepts and algorithms used in WiseTex for modelling fabrics. In part 5 will be presented the different modifications that have been performed to handle the modelling of interlock 3D Fabrics.

Coding of the weave topology

In Wisetex, a weave is defined by a set of data as follows:
- Number of warp zones in a repeat $NW_a$
- Numbers of warps in zones $NW_{Z[a..NW_a-1]}$
A Warp zone is a set of warp yarns layered one over another. A warp yarn is then identified by a pair $(i_{Wa}, i_{WaZ})$ where $i_{Wa}$ is a number of the warp zone ($i_{Wa}=1...NW_a$), and $i_{WaZ}$ is the number of the warp in the warp zone ($i_{WaZ}=1...NW_{Z[i_{Wa}]}$).
- Number of weft rows $NW_e$
- Number of weft layers $L$.
A weft yarn is then identified by a pair $(l, i_{We})$, where $l$ is a number of the layer, $i_{We}$ is a number of the row.

The topological coding of the weave is then based on the warp yarns paths. The $i$-th warp path is coded by a sequence of intersection levels $w_{ij}$ – denoting either the index number of the weft layer situated above the warp yarn in its intersection with the $j_k$-th weft row, or 0, if the warp yarn lies on the face of the fabric.

$$W[i_{Wa}][i_{WaZ}][j] = \begin{cases} 
  l & \text{where } l \text{ is the number of the weft layer lying above warp } (i_{Wa}, i_{WaZ}) \text{ in its intersection with the weft row } j \\
  0 & \text{if warp } (i_{Wa}, i_{WaZ}) \text{ lies on the top surface of the fabric in its intersection with the weft row } j
\end{cases}$$

Figure 2 shows an example of coding for a multilayered fabric:

![Figure 2: Matrix coding of a multilayered weave](image)

This coding system needed developments to be able to model the specific weft disposition with shifted layers (fig.12).
Then the matrix coding has been modified to represent weaves which do not have necessarily the same number/placement of the weft yarns in the weft rows/layer (it’s the case for our interlock weave). The simple solution to represent such weaves is to skip weft yarns in certain positions. This is done by introducing Boolean values $WE_{lj}$.
\[ l = 1 \ldots L, j = N_{We} \], where \( N_{We} \) is the number of weft rows, which are true if the weft yarn is present in the position and false if not. When processing the weave topology, the weft yarns with \( WE_{lj} = \text{false} \) are considered as not present.

Then, a modification of the matrix coding is needed to take into account the eventual "missing" wefts. To describe cases where a warp yarn goes through a space where a weft yarn have been removed, negative values for the matrix coding have been introduced. Consider a missing weft on the first weft layer number \( L \): if a warp goes though this empty space, the corresponding value of the matrix coding will be equal to \(-L\). In this case the matrix coding value does not correspond directly to the supporting weft layer but indicates the position of the warp yarn in the weft network. These negative values are easily handled in the existing code by using absolute values.

Figure 3: Complex placement of weft yarns in the layers

On the weave example on Figure 3, in each weft layer one weft yarn on two has been removed to obtain this shifted weft layers configuration.

But with this configuration, a new definition of interlacing sites, where mechanical contact is assumed between warp and weft yarns, has to be implemented in order to calculate bending energy of the warp yarns and crimp heights of weft yarns.

Two models have been implemented. In the first one only two interlacing sites are defined where warp yarn changes of direction (fig.4a). In the second one contact with weft is added in every weft row (fig.4b). For each bent interval between two consecutive weft rows, a specific algorithm determines the pair of weft yarns between which the bending energy will be calculated.

Figure 4: Definition of interlacing sites (in black) for 1st (left) and 2nd (right) model

**Compression behaviour of carbon yarns**

Mechanical properties of composite materials highly depend on geometry of the textile reinforcement, which include direction of the yarns but also their dimension and intra fiber volume fraction. One of the most critical input in WiseTex is the compression
behavior of yarns, in order to compute accurately yarns dimension depending on contact forces between yarns and pressure applied on the fabric. The Kawabata equipment is dedicated to the characterization of fabrics and yarns: a set of different machines measure tensile, compression, bending and shear behaviour of textiles. But this equipment is not usable for composite reinforcement weaved with heavy yarns. These type of yarns are too stiff and the limit of these machines are reached quickly.

A special device for measuring the transverse mechanical behavior of polymer monofilaments [16] has been developed in LMPT. This set-up was used to characterize the compression behavior of carbon yarns we use. Both thickness and width of the yarn are measured during compression and enables to have the evolution of yarn dimension depending on the force applied.

![Graph showing the evolution of thickness and width of yarn during compression](image)

**Figure 5: evolution of thickness and width of yarn during compression**

**Geometrical model: results and discussion**

Figure 6 compares geometry calculated by WiseTex for both models described above with samples. Compression is applied on the WiseTex Model to reach the fibre volume fraction of 58 % measured on the samples. Results of measurements made on the samples can be seen in table 1.

<table>
<thead>
<tr>
<th></th>
<th>Sample</th>
<th>1st model</th>
<th>2nd model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp Crimp</td>
<td>1.44 %</td>
<td>1 %</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Weft Crimp</td>
<td>1.49 %</td>
<td>0.2 %</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Average interlock angle</td>
<td>9.2 °</td>
<td>9 °</td>
<td>8.5 °</td>
</tr>
<tr>
<td>Thickness</td>
<td>1</td>
<td>1.11</td>
<td>1.15</td>
</tr>
</tbody>
</table>

As expected the second model gives a much more realistic geometry compared to the sample. On the First model, in warp direction, we can observe interpenetration of warp and weft yarns in the bent interval.

In WiseTex calculation, the different weft layers are shifted one by one in the thickness direction until a warp yarn is found between the considered layer and the one above. This enables to get a compact fabric structure. On the first model, as no contact is assumed between warp and weft in the bent interval, the packing process will create interpenetration in this region, as we can see on the model. On the contrary, the second model produces a much more accurate warp path in the weft network with a good modelling of the local undulations. In Weft direction the second model is also a lot
better. The lack of mechanical contact between yarns in the first model gives geometry with almost no crimp in the weft direction whereas undulations are present in the second model.

**Figure 6**: Comparison between WiseTex models and a material sample

**HOMOGENISED PROPERTIES: RESULTS AND DISCUSSION**

To apply the method of inclusions, implemented in the TexComp software [17–19], the yarns in the unit cell are subdivided into a number of smaller segments, where each yarn segment is geometrically characterised by its total volume fraction, spatial orientation, cross-sectional aspect ratio and local curvature (all these parameters are readily provided by the geometrical model). Next, Eshelby's equivalent inclusion principle is adopted to transform each heterogeneous yarn segment into homogeneity with a fictitious transformation strain distribution. The solution makes use of a short fibre equivalent, which physically reflects the drop in the axial load carrying capability of a curved yarn with respect to an initially straight yarn. Every yarn segment is hence linked to an equivalent short fibre, possessing an identical cross-sectional shape, volume fraction and orientation as the original segment it is derived from. The length of the equivalent fibre on the other hand is related to the curvature of the original yarn. For textiles with smoothly varying curvature radii, a proportional relationship between the short fibre length and the local yarn curvature radius is the most straightforward choice and sufficiently accurate for the present purpose. The interaction problem between the different reinforcing yarns is solved in the traditional way, by averaging out the image stress sampling over the different phases. If a Mori–Tanaka scheme is used, the stiffness tensor $C^c$ of the composite is hence obtained as: $$C^c = \left[ c_m C^m + \langle c_s C^s \rangle \right] \left[ c_m I + \langle c_s A_s \rangle \right]^{-1}$$ where the subscripts $m$ and $s$ denote the matrix and a yarn segment respectively, $c_i$ is the volume fraction of phase $i$ ($i = m,s$), and the angle brackets denote a configurational
average. As follows from this brief description, the homogenisation procedure does not depend on the configuration of the unit cell.

A single interface has been created to link WiseTex geometry calculation with TexComp homogenization method. In this interface the user provides the weaving pattern with WiseTex geometrical interface or with matrix coding, the type of yarns with associated mechanical properties, and can specify ranges for parameters such as warp spacing, weft spacing, braiding angle in case of braided fabrics, fibre volume fraction and deformation of the fabric (longitudinal or shear). The software will then automatically calculate the geometry of all possible configurations and launch homogenization method to calculate mechanical properties of the composite and build databases of mechanical properties.

On the materials we studied the parameters were pick spacing (which is the interval between two consecutive weft rows) and fibre volume fraction of the samples. WiseTex models of this interlock fabric have been created with evolution of the pick spacing. In order to compare mechanical properties of these different configurations, fibre volume fraction has to remain constant. Compression was then applied to maintain the fibre volume fraction at the level of 58 %, which is the one, measured on the samples used for tensile tests.

![Figure 7: Evolution of microstructure with pick spacing](image)

This means that thickness of WiseTex models and samples decreases with pick spacing. The average interlock angle decreases, and the warp/weft ratio in the unit cell increases in warp direction, decreases in weft direction. We can also notice that the geometry of the two models become close for high pick spacing. The undulations in the warp path imposed by the tightened weft network for low pick spacing are attenuated when the fabric become looser.

**Results and Discussion**

Mechanical tests have been performed by the team of UTC (Université de Technologie de Compiègne, France) to identify the mechanical properties of the composite:

- Tensile tests in warp (1), weft (2) and thickness (3) directions
- Bias Tests to identify G12
- Strain mapping on 3 points bending test to identify G13 and G23

Results of homogenization with geometrical model n°2 are shown on figure 8.
First we see that Mori Tanaka Method is much more accurate than Iso-Strain calculation.
The most important error is in warp direction (till 15%). Indeed, orientation of yarns is very complex in this direction, particularly for small pick spacing. Then it becomes more difficult to have an accurate prediction of yarn orientations without taking into account effects that occur in really compact fabrics. (deformation of yarns with shapes different from ellipses, shifting of weft columns...).
Modifications have been made in WiseTex Software in order to model complex three dimensional woven fabrics. Measurements on cut samples show accurate modelling of the internal geometry calculated. The geometrical models obtained are used as inputs for micro mechanical calculations. The results of homogenization are good. The homogenised mechanical properties obtained show the importance of fibre orientation modelling in the accuracy of the results. The mechanical results presented in this paper show the wide range of mechanical properties that can be obtained by modifying weaving and processing parameters.

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References


