MESO SCALE MODELING OF INTERNAL GEOMETRY AND MECHANICAL PROPERTIES OF 3D INTERLOCK FABRICS

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ABSTRACT

The internal geometry of 3D textile reinforcements is an important factor of the composite mechanical performances. The software package WiseTex implements a generalised description of internal structure of textile reinforcements on the unit cell level, integrated with mechanical models of the relaxed and deformed state. It is integrated with micro-mechanical calculations of properties of textile-based composites. This paper describes the use of this software package for modelling geometry and homogenised mechanical properties of 3D interlock reinforced composite. The evolution of mechanical properties of a unit cell of this fabric with weaving parameters is discussed.

KEYWORDS: Interlock, woven fabric, homogenisation, elastic properties, meso-scale

1. 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 to control 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 has been discussed in [3] and demonstrates 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 costful 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.
After a review of the existing analysis methods, this paper focuses on the modelling of ply-to-ply interlock composite using software package WiseTex [7].

2. REVIEW OF MODELING METHODS FOR 3D FABRICS

2.1.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 part 4.

2.2.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 [15-16], 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 [17].

3. 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.
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.

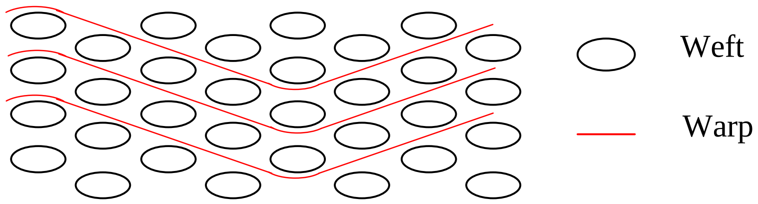


Figure 1: illustration of a warp plan for a ply to ply interlock pattern

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.

4. MESO SCALE MODELING OF THE FABRIC GEOMETRY WITH WISETEX

4.1. WiseTex Software

The geometrical and mechanical model of textiles, implemented in the software package WiseTex, provides a full description of the internal geometry of a fabric: 2D- and 3D-woven, two and three-axial braided, knitted, multi-axial multi-ply stitched (non-crimp fabric). Input data include: (1) Yarn properties: geometry of the cross-section, compression, bending, frictional and tensile behaviour, fibrous content; (2) Yarn interlacing pattern; (3) Yarn spacing within the fabric repeat. Models for compression, bi- and uni-axial tension and shear of the fabric are also based on an energy balance and calculate the internal structure of the deformed fabric, as well as load–deformation relation.
As an example of application of principle of minimum energy, consider the model of internal structure of 2D or 3D woven fabric (Figure 2). A weave pattern (for one- and multi-layered fabrics) is coded with matrix coding [18], Figure 2. It allows separation of the crimped shape of the warp and weft yarns into elementary bent intervals, representing sections of the yarn between interlacing sites.

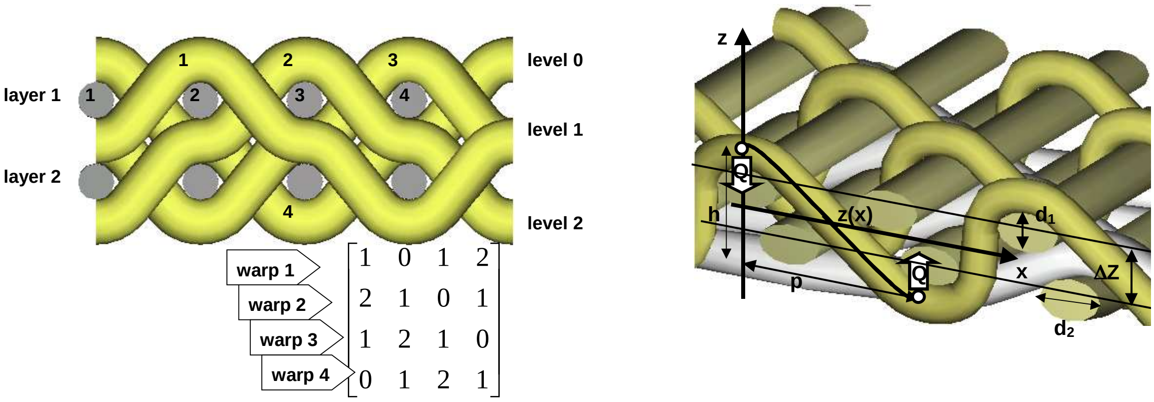


Fig.2 Model of internal structure of woven fabric:
(a) Coding of the weave, (b)Description of the yarn paths

The shape of the yarn on an elementary interval is described using a parameterised function *z(x; h/p)*, where *z* and *x* are coordinates of the yarn middle line, *h* is the crimp height and *p* is the distance between the interval ends (spacing of the yarns).
The shape *z(x; h/p)* for a given relative crimp height *h/p* is computed using the principle of minimum of bending energy of the yarn on the interval and has a form

$$z(x) = h[1/2 - 3(x/p)^2 + 4(x/p)^3 + A(h/p)(x/p)^2((x/p)-1)^2((x/p)-1/2)]$$

where the first term is a spline function, corresponding to the solution of the linearised minimum energy problem, and the second term represents a correction for a non-linear formulation. The function *A(h/p)* is calculated from the solution of the minimum energy problem and is tabulated.
With this function known, the *characteristic function F* of the crimp interval is computed, representing the bending energy of the yarn:

$$w = \frac{1}{2}\int_0^p B(\kappa)\frac{(z'')^2}{\left(1+(z')^2\right)^{5/2}}dx = \frac{B(\bar{\kappa})}{p}F(h/p)$$

where $B(\kappa)$ is the (measured experimentally) bending rigidity of the yarn, which depends (non-linearly) on the local curvature $\kappa(x)$, or, after the integration, on an average curvature over the interval. Function *F(h/p)* is tabulated. With the function *F* known, the transversal forces acting on the interval ends can be estimated as

$$Q = \frac{2w}{h} = \frac{2B(\bar{\kappa})}{p}F(h/p)$$

Warp and weft yarns in the relaxed fabric are compressed by the transversal forces *Q* according to experimental diagrams, measured on "virgin" yarns

$$d_1 = d_{10}\eta_1(Q), d_2 = d_{20}\eta_2(Q)$$

where subscript "0" refer to the uncompressed state of the yarn, d_1 and d_2 are dimensions of the yarn cross-section (Fig 2b). These dimensions and crimp heights of the yarns are interconnected:

$$h^{Wa} = \Delta Z + (d^{Wa} + d^{We}) - \left(h_1^{Wa} + h_2^{We}\right)/2$$

where superscripts refer to the warp and weft yarns, subscripts "1" and "2" refer to two weft yarns in different layers, ΔZ is the distance between fabric layers (Figure 2b).

With crimp heights of weft yarns given, these equations provide a closed system of non-linear equations for calculation of the transversal forces Q and yarn dimensions d_1 and d_2.The weft crimp heights are found using the principle of minimum bending energy of the yarns inside the unit cell

$$W_{\Sigma} = \sum_{i=1}^{N_{Wa}} \sum_{k=1}^{K_i^{Wa}} w_{ik}^{Wa} + \sum_{j=1}^{N_{We}} \sum_{k=1}^{K_j^{We}} w_{jk}^{We} \rightarrow \min$$

where subscripts *i,j* refer to different warp and weft yarns, *k* – to the elementary crimp interval of the warp/weft yarn. The minimum problem is solved for the weft crimp heights, all other parameters defined inside the minimisation algorithm via solution of the system for the given current crimp heights.

4.2.Developments for Interlock Fabrics Modelling

The aim of these developments is the modelling of the specific weft disposition with shifted layers (fig.1).

The chosen solution was to enable the user to remove weft yarns in the weft network in the interface in order to model this weft configuration. (figure 5).

First, 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.

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.5a). In the second one contact with weft is added in every weft row (fig.5b). 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.

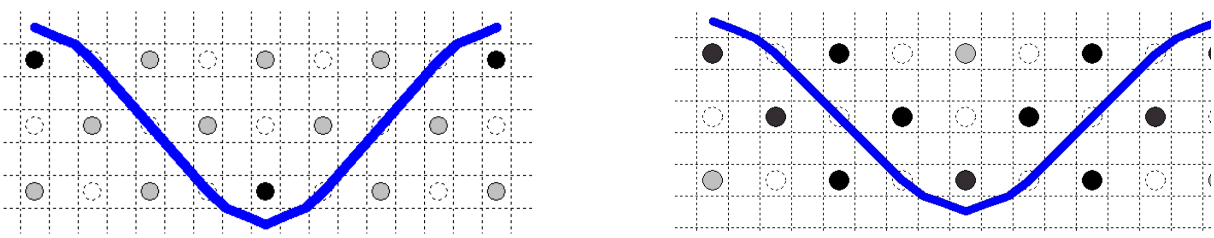


Fig. 5 : Definition of interlacing sites

a) first model *b) second model*

4.3.Results and discussion

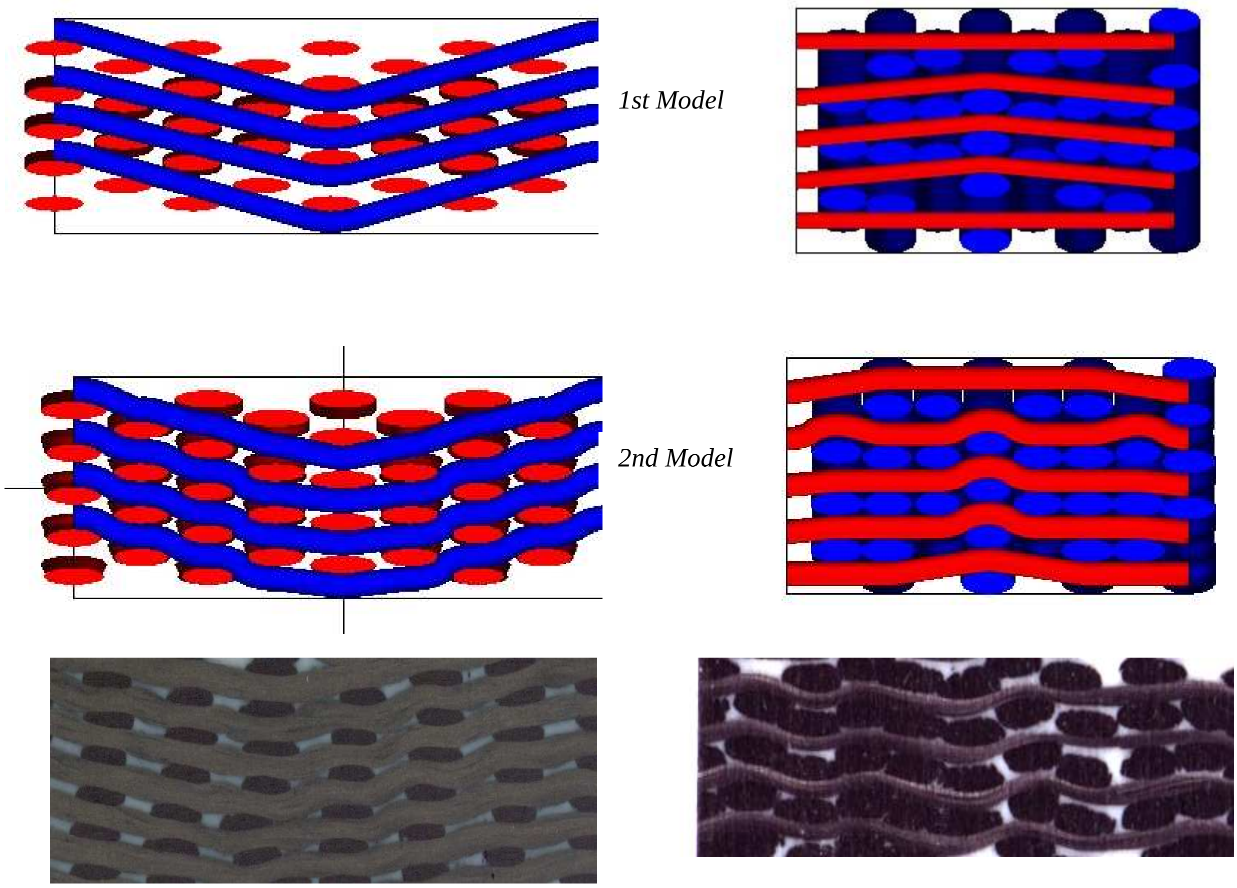
Figure 6 compares geometry calculated by WiseTex for both models described above with samples. Compression is applied on the WiseTex Model to reach the fibre volume fraction of 58 % measured on the samples.
Results of measurements made on the samples can be seen in table 1.

	Sample	*1st model*	*2nd model*
Warp Crimp	1.44 %	1 %	1.5 %
Weft Crimp	1.49 %	0.2 %	1.5 %
Average interlock angle	9.2 °	9 °	8 °
Thickness	1	1.11	1.15

Table 1 : Comparison of measurements

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



Warp Direction *Weft Direction*

Fig. 6 : Geometry of WiseTex Models and cut samples

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. 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 a geometry with almost no crimp in the weft direction whereas undulations are present in the second model.

We also observe higher values (around 10%) of thickness for both models compared to samples. This can be explained either by an insufficient packing of the fabric structure or by an inaccurate compressive behaviour of the yarn. The one used for this carbon yarns has been deduced from measurements of the thickness of the cross section of yarns on cut samples. A more accurate characterization by performing compressive test has to be investigates to control evolution of yarns thickness with compression.

5. MODELING OF ELASTIC MECHANICAL PROPERTIES

5.1.TexComp Software

To apply the method of inclusions, implemented in the TexComp software [19–20], 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, crosssectional 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 $\mathbf{C}^C$ of the composite is hence obtained as: $\mathbf{C}^C = \left[c_m \mathbf{C}^m + \left\langle c_s \mathbf{C}^s \mathbf{A}^s \right\rangle \right] \left[c_m \mathbf{I} + \left\langle c_s \mathbf{A}^s \right\rangle \right]^{-1}$

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.

5.2.Parametrical study

First a new interface has been created linking WiseTex geometry calculation with TexComp homogenisation method. This make easier and quicker producing a lot of geometrical models with associated mechanical properties, with the aim of building databases of materials. 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 homogenisation method to calculate mechanical properties of the composite.
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. This means that thickness of WiseTex models and samples decreases with pick spacing.
You can see in figure 7 the evolution of the models geometry with pick spacing.

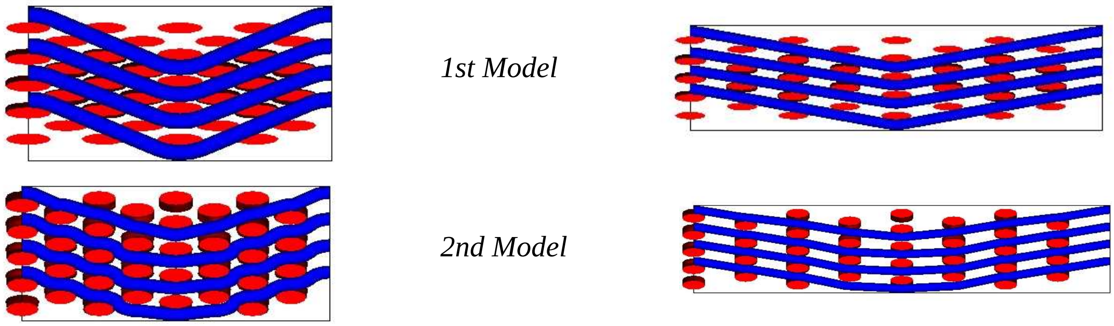


Fig 7 : Evolution of microstructure with pick spacing

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.
The effect of these changes in the geometry on the elastic mechanical properties is discussed in the next part.

5.3.Results and discussion

5.3.1 Warp direction

The evolution of modulus in the warp direction is shown in figure 8.
We notice first a strong increase for both models. This can be explained by both the increase of warp ratio in the unit cell and by the decreasing interlock angle. The orientation of warp yarns become closer to the x axis, increasing mechanical properties in this direction.
We see that the second model tend to join the first model for higher pick spacing. This was explained in 5.2 with the geometry of the models that become closer, with nearly same

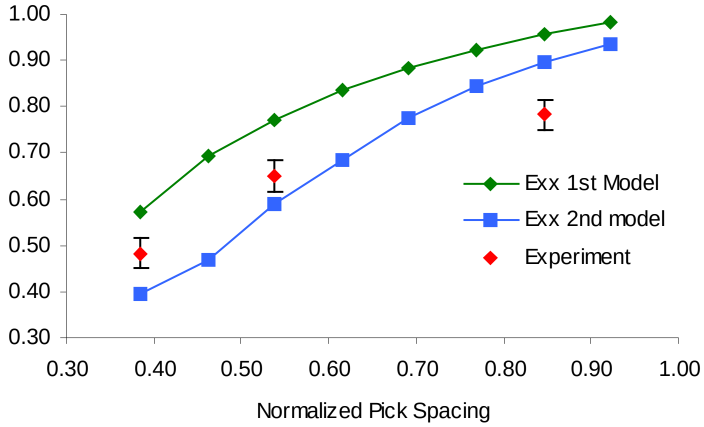


Fig 8 : Evolution of Modulus in Warp direction values of crimp in warp direction, for higher pick spacing. For the first model we measure a nearly constant error in the prediction of the modulus with an average overestimation of 20 % of the warp direction modulus. The simple modelling of yarn path with this model explains this overestimation. This geometry doesn't take into account the undulations of the warp path in the weft network but only the average yarn direction. Fig 8 shows that introduction of these undulations with the second model produces a drop of the modulus for low pick spacing. As these undulations vary with pick spacing, the error on the predicted is non-constant with a maximum of 18 % for the first experimental point.

5.3.2 Weft direction

Figure 9 shows the evolution of modulus in weft direction.

For both models we notice a drop of the modulus with the increasing of the pick spacing. Only the drop of the weft ratio in the unit cell is responsible of it. Indeed, an increase of the pick spacing has no effect on crimp or orientation of the weft yarns.

The first model present a geometry that has almost no crimp in weft direction, weft yarns are almost straight and horizontal. This explains the strong overestimation.

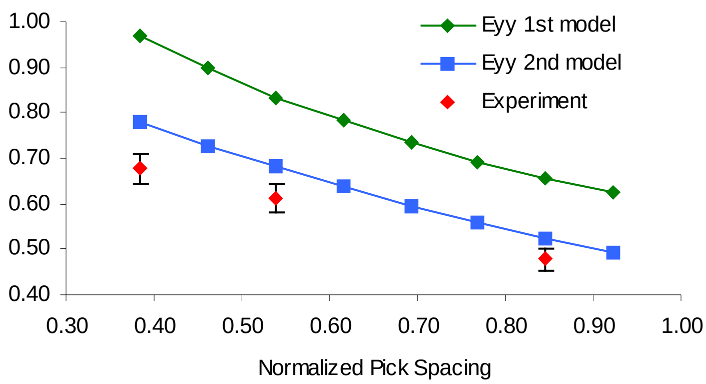


Fig9 : Evolution of Modulus in Warp direction

The second model which has a much more realistic weft path modelling, shows good results with an average overestimation of 11% of the modulus. The fact that we overestimate the modulus can be explained with analysis of the geometry in the weft direction. Figure 6 shows that the second WiseTex model models the local undulations that are observed on the sample, but weft yarn remains straight and horizontal between two undulations whereas on the sample, small angle of the weft path can be measured between undulations.

5.3.3 Thickness direction

The results of homogenisation shows that modulus in the thickness direction remains constant when pick spacing is increased. However, modulus in Z direction should decrease because of the decrease of interlock angle caused by the rise of the pick spacing, which means less fibres in the thickness direction. Indeed, compression was used to maintain constant fibre volume fraction of the unit cells, compression that has increased intra yarns fibre volume fraction and transversal properties of yarns. This means that the decrease of Ezz that should be observed is balanced by this increase of transversal properties of yarns, introduced by compression of the fabric.

5.3.4 Shear modulus Gxz

Shear modulus is influenced by orientation of fibres in xz plan, which means interlock angle. That what is shown in figure 10 with first model where warp yarns are straight in the interlock direction. The increase of pick spacing, which causes diminution

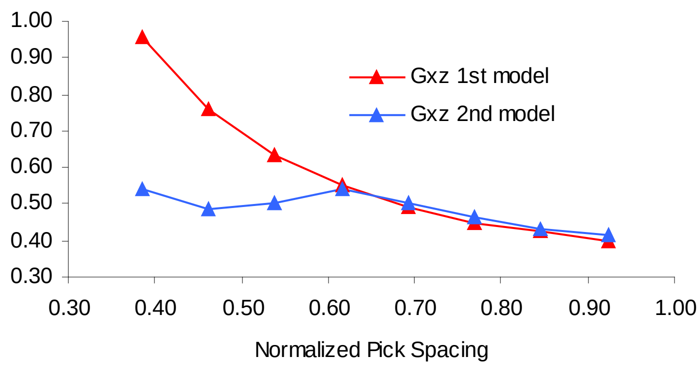


Fig 10: evolution of Gxz shear modulus

of interlock angle, has for effect an important drop of Gxz modulus.
The introduction of crimp in the interlock angle direction with the second model causes a strong diminution of Gxz for lower pick spacing. Then the diminution of Gxz that should occur is balanced by the progressive elimination of local undulations in the interlock direction while increasing pick spacing.
No experimental characterization of this behaviour has been achieved for validation, but this result shows the importance of yarn crimp in the three main directions.

5.3.4 Fibre volume fraction dependence

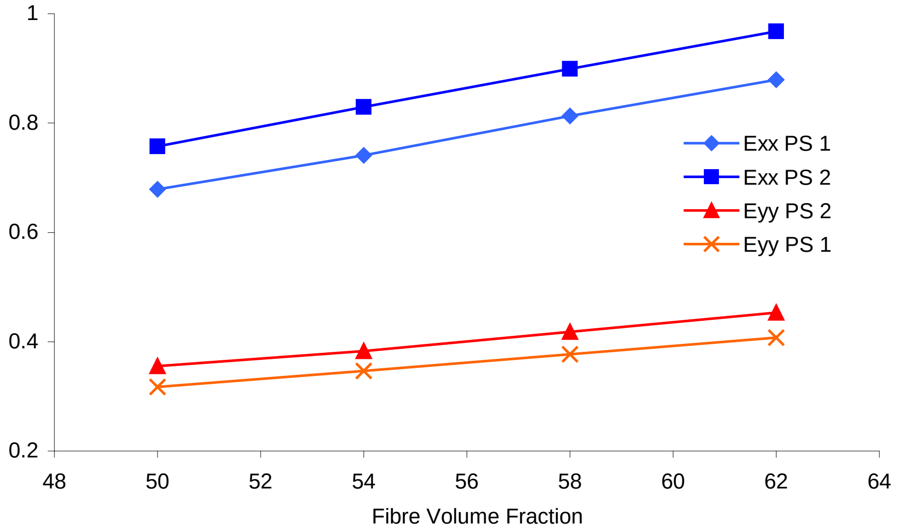


Fig 11: Evolution of Exx and Eyy with Vf for different pick spacing (PS)

Figure 11 shows a linear dependence of the modulus with fibre volume fraction and this for two different pick spacing.
Al these mechanical results demonstrate one of the interest of 3D woven fabrics which is the possibility to adjust to requirements and cover a wild range of mechanical properties by modifying weaving or manufacturing parameters such as spacing between yarns or fibre volume fraction of the composite. Databases of materials now have to be built, in order to help design or selection of these 3D textile reinforced composites.

6. CONCLUSION

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 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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