Modelling of the internal structure and deformability of textile reinforcements: WiseTex software

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ABSTRACT

Textile materials are characterised by the distinct hierarchy of structure, which should be represented by a model of textile geometry and mechanical behaviour. In spite of a profound investigation of textile materials and a number of theoretical models existing in the textile literature for different structures, a model covering all structures typical for composite reinforcements is not available. Hence the challenge addressed in the present work is to take full advantage of the hierarchical principle of textile modelling, creating a truly integrated modelling and design tool for textile composites It allows handling of complex textile structure computations in computer time counted by minutes instead of hours of the same non-linear, non-conservative behaviour of yarns in compression and bending. The architecture of the code implementing the model corresponds to the hierarchical structure of textile materials. The model of the textile geometry serves as a base for meso-mechanical and permeability models for composites, which provide therefore simulation tools for analysis of composites processing and properties. The paper presents an approach to model the behaviour of a representative volume element (RVE) of textile reinforcement in in-plane deformation (bi-axial tension and shear) and in compression. With the internal geometry of the RVE built, the model computes overall parameters of the deformed textile, such as fibre volume fraction, porosity etc. The internal geometry is visualised and such properties as pore structure in typical cross-sections are analysed. The internal geometry description is further fed into flow modelling software, which allow computing local permeability and mechanical properties of the deformed reinforcement.

KEYWORDS: **textile composites, mathematical modelling, textile architecture, deformability, permeability**

1. INTRODUCTION

Textiles and textile composites are hierarchical, structured materials. The quite commonplace statement, however, has important consequences. The complexity of the structure and the presence of a hierarchy of structural and scale levels (10^{-5} m – fibres, 10^{-3} m – yarns, 10^{-1} m – fabrics, 10^{0} m – composite parts) lead to complexity of the predictive models, high level of approximation in them, and to high uncertainty of the predictions, with errors accumulating when the model progresses from one hierarchical level to another. Thus, the strategic questions to be answered are: How to integrate models representing to different levels? What are the scales needed for a particular problem? What are building blocks for each level? The same hierarchy provides a generic, systematic and modular approach for creation of a predictive model: homogenisation on a certain level encapsulates the relevant properties of building blocks for the subsequent level. This strategy is universally recognised. However, for *textile* composites quite important challenges are still there: How to build up a reliable description of the textile architecture? How to implement this architecture in FE models avoiding manual building of volumes? How to describe non-linear, irreversible, friction-controlled mechanical behaviour of textile yarns and fibrous assemblies in general? How to account for damage development in homogenisation procedures? The progress of Composite Materials Group of Department MTM (Metallurgy and materials engineering), K.U.Leuven to implement this approach is depicted in a number of recent publications (Lomov et al. 2000; Lomov et al. 2001; Lomov et al. 2001), where additional references can be found.

Considering homogenisation on a certain hierarchical level, several different classes of problems can be identified:

1. Description of textile architecture. This applies, naturally, to the description of interlacing of yarns, which implies such issues as generic coding of the topology of the structure and application of the principle of minimum energy. This also can apply to the description of fibrous structure of a textile yarn, addressed in literature only marginally. The two mentioned issues will be discussed below.
2. Deformation of a dry textile in composite processing. This involves a description of "strange" behaviour of fibrous assemblies and presents a lot of difficulties in connection with precision of this description. The task is not made easier by the frictional phenomena involved.
3. Flow of resin through a textile structure in RTM process. There are two major difficulties: geometrical complexity and two scales (inter-yarn and intra-yarn) of pores in textiles and uncertainty of conditions on yarn boundaries. The most promising way to deal with them is to use a through-computation method, which eliminates at

least the former difficulty. We shall show the first results of the application of Lattice Boltzmann approach.

4. Homogenisation of mechanical properties of a composite unit cell. Unless damage is developing, this is quite straightforward, providing the geometry of reinforcement is well known and easily imported into an approximate (cell model, inclusion model…) or FE meso-mechanical tool.

The key to the success of the integrated approach is a "happy marriage" between composites mechanics and textile material science, which has its own treasury of theories and predictive models. In fact, the subject of the present paper can be described as "*virtual textile*", which opens a route to "*virtual composite*" – a computer tool for prediction of properties and optimisation of processing of textile composites.

2. TEXTILE ARCHITECTURE

2.1. *Fibres in a yarn or a fibrous layer*

As a rule, models of fibrous structure of textile reinforcements assume an even distribution of fibres over a cross-section of a yarn. This assumption is made in spite of the general knowledge that fibre density can vary locally, as can be seen from the Figure 1 (compare fibrous content in two squares).

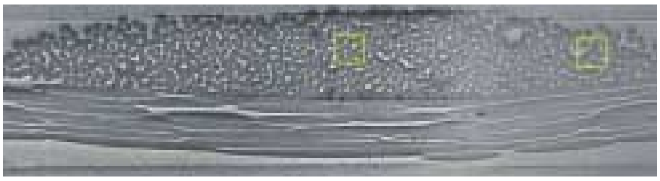


Figure 1. Cross-section of glass reinforcement in epoxy

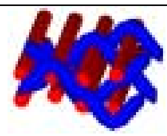
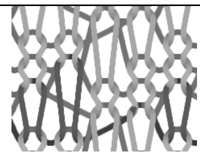
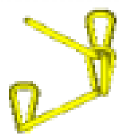
The error, introduced by neglecting this effect, into the homogenised properties (permeability or stiffness) of the unit cell can be estimated as difference between simple average and harmonic average of fibre volume fractions (*Vf*) in different places in the unit cell. For equal regions of high and low *Vf* and a two-fold (say) difference in *Vf* this produces an error of roughly 15%, which is further smoothened by the fact that irregular regions are not that large. However, for such subtle things as damage development, local variations of *Vf* can play more important role.

It would be of help if a method for prediction of variations of *Vf* in a compressed yarn were devised. Grishanov and Lomov (Grishanov et al. 1997) proposed such an algorithm, which requires a knowledge of fibre distribution in a yarn before compression, and then employs an algorithm of conformal mapping to produce fibre distribution in the yarn subject to compression.

2.2. *Yarns in a fabric*

Textile fabrics are highly structured materials, and variation of the structure (topology) of yarn interlacing is an effective way to optimise the performance of the reinforcement. Mathematical models of textiles and textile composites must be able to handle variations of topology, which requires algorithms of coding of the structure and computer tools to interface with these descriptions. Table 1 provides examples of such a coding for 3D woven, warp- and weft-knitted structures. Availability of the coding algorithm and of a user interface for editing of the fabric topology bestows flexibility to the integrated models needed for an intelligent choice of the architecture of the reinforcement.

Table 1. Coding of textile structures

Principle	*Example*	*Picture*
2D and 3D woven		
Matrix where *(i,j)* element gives a layer of intersection of *i*-th warp with *j*-th weft row (Lomov et al. 2000)	1 0 2 1 1 0 2 1 1 0 2 1 1 0 2 1	
Weft-knitted		
A matrix entry represents an individual needle action and is a combination of the position of the needle and the stitch type (Lomov et al. 2001)	+ X X + X X X X X X + X X +	
Warp-knitted		
A sequence of position of guides in relation to needles in the bed (Spencer 1997)	1-0/1- 2/2-1/	

2.2.1. *Internal geometry of a woven fabric*

We shall consider here a woven fabric. The model is extensively described elsewhere (Lomov et al. 2000; Lomov et al. 2001; Lomov et al. 2001), here we give just a brief description. Consider a single repeat of the fabric. Assume further as given: (1) all the necessary yarn properties; (2) the topology of the yarn interlacing pattern within the fabric repeat; (3) the yarn spacing within the repeat (i.e. the mean distance between warp/weft yarns in a woven fabric or the course/wale spacing in weft-knitted fabrics). The problem is to compute the spatial placement of all yarns in the repeat. In more practical terms, this means: determine all the yarn heart-lines within the repeat and define the yarn

cross-sectional shape and its dimensions normal to the yarn heart-line for each point along the yarn heart-lines.
The list of the necessary yarn properties includes yarn geometry in free state and its behaviour in compression, bending and friction. These data are not readily found in a yarn specification, but can be measured on the standard textile laboratory equipment, or predicted if a model of the previous hierarchical level "Fibre → Yarns" is available. Topology of the yarn interlacing inside a multi-layered woven structure is described using a matrix coding algorithms (Table 1). It allows decomposition of yarns in the unit cell into elementary crimp intervals, which leads to a system of algebraic equations representing the minimum energy configuration of the yarns. Solution of the equations gives heights of out-of-plane and in-plane crimp of warp and weft yarns, and the complete yarn geometry is then reconstructed with the help of a spline approximate solution for the mininum energy problem on each crimp interval. This algorithm is implemented in the WiseTex software - Figure 1.

Figure 2. Models of woven fabrics built with WiseTex

Once the geometrical model of a fabric is built, the model of fibre distribution inside yarns can be used to produce a complete description of the unit cell fibrous structure. In the simplest case such a model assumes even distribution of fibres, taking into account yarn compression inside the fabric. Alternatively, more complex models of fibre distribution can be employed. The result can be expressed in two ways: Yarn Path Mode and Fibre Distribution Mode. The former uses a description of spatial placement of yarns in the unit cell. The latter mode generates fibre volume fraction *Vf* and the direction of fibres for any point inside the unit cell. The value of *Vf* can be zero if the point does not lie inside a yarn. These two types of output data constitute the input for the models of permeability and meso-mechanical models of composites, which are described below.

2.2.2. *Internal geometry of 2D braids*

The study of the geometry of flat braids started with the early work of Brunnschweiler (Brunnschweiler 1953; Brunnschweiler 1954). He described braided patterns in connection with their production techniques and introduced a description of crimp geometry in braids based on Peirce's theory for woven fabrics (Peirce 1937). The same Peirce-based theory is used in the recent work of Zhang et al. (Zhang et al. 1997). Pastore et al. (Pastore et al. 1995) (Bogdanovich et al. 1992; Bogdanovich 1993) used a Bezier interpolating technique to produce 3D models of two- and three-axial braids, which serve as a starting point for deformability calculations and for evaluating the micro-mechanical properties of composites reinforced by braids. A vector model of the braided geometry was used by Robitaille et al (Robitaille et al. 1999). A number of works were also dedicated to evaluation of composite properties using various simplified descriptions of the geometry of the braided reinforcement (Hasselbrack et al. 1992; Naik et al. 1994; Li et al. 2000). All the work cited above are purely geometrical models, which do not consider mechanics of the yarns interactions in the braid. The above-mentioned theories do not also include some minor effects, which, however, can play a role in geometrical characterisation, such as side crimp in twill-like braided patterns and yarn twists induced by the skewness of the structure. These phenomena are included in the model proposed in the present paper (see also (Lomov et al. in print)).
The balance of crimp in a flat braid (crimp heights h_1 and h_2, Figure 3a) is computed using the formulae for woven fabrics with the length of elementary crimp intervals computed along (non-orthogonal) yarns. This assumption follows a generally accepted description of braided structures as analogues to woven structures.

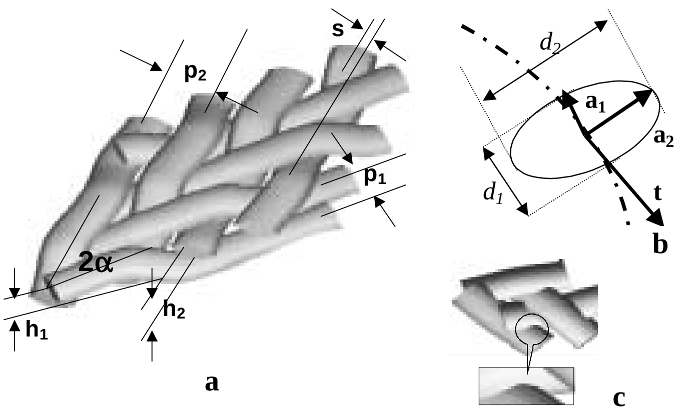


Figure 3 Yarns in flat braid: (a) Spacing *p*, crimp heights *h* and side crimp *s* of the yarns and a braiding angle α; (b) Vectors characterising the cross-section; (c) Intermixing volumes of yarns (no rotation of cross-sections).

The path of the yarn middle lines between intersections is described with the model used in (Lomov et al. 2001) for woven fabrics: a minimum energy solution, taking account of contact regions of yarns. The difference is in the treatment of positioning of the yarn cross-sections along the path. Consider a cross-section of a yarn in a braid with braiding angle $\alpha \neq 45°$ (Figure 3). Let $\boldsymbol{a_1}$ and $\boldsymbol{a_2}$ be unit vectors of its shorter and longer axis, ***t*** – a tangent vector of the yarn middle line and d_1 and d_2 – the dimensions of the shorter and longer axis (Figure 3b). Assume d_1 and d_2 to be constant along the yarn contact region. If, as in a woven fabric ($\alpha = 45°$), $\boldsymbol{a_1}$ lies in the plane formed by ***t*** and *z*-axis, then the assumption of constant cross-section leads to penetration of the intersecting yarn volumes (Figure 3c). This effect is clearly seen also in illustrations in (Bogdanovich et al. 1992; Bogdanovich 1993; Pastore et al. 1995). To provide a realistic description one must introduce some deformation of the cross-section. In the present model we do this by imposing rotation (twist) on the yarns (which can be described by simple geometrical considerations) rather than by distorting the shape of the cross-section.

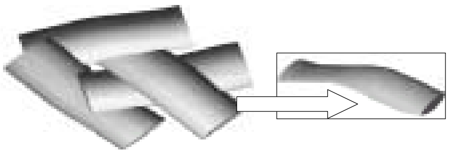


Figure 4. Twist of the yarns caused by skewness

As a result of the twist the penetration of the yarns in the model decreases considerably (the volume of the intermingled region for the flat braid model in Figure 4 is about 6% of the intermingled volume of the model in Figure 3). It is not completely eliminated, as the cross-sections are supposed to keep their shape along the yarn. The remaining penetration represents an error of the current model, which is caused by neglecting a change of the cross-section shape.

In braids with inlays, axial yarns are inlaid between the braided yarns in the machine direction. Study of the geometry of tri-axial braids in (Naik et al. 1994) reveals almost no crimp for axial yarns. This is logical for balanced braids. If a braid is unbalanced (which is rarely the case in practice), then the crimp of inlays, fixed between the two systems of braiding yarns, and therefore prevented from significant bending, must be quite low. Based on these considerations and experimental evidence, we assume that inlays are perfectly straight. More rigorous treatment of the crimp of inlays may be a subject of future development of the model. Figure 5 shows an example of simulation of a tri-axial braided structure.

Figure 5. Braid with inlays: Example of the simulation

Comparison of theoretical predictions and experiment was made on composite samples, and therefore the glass braids were in a slightly compressed state. This route (and not investigating the dry fabrics) was chosen because of the paramount importance of reinforcement geometry in the composite material for evaluation of its properties. A flat braided fabric with 2/2-intersection repeat was fabricated by using a flat braiding machine with 25 spindles, using glass yarns of 575 tex.

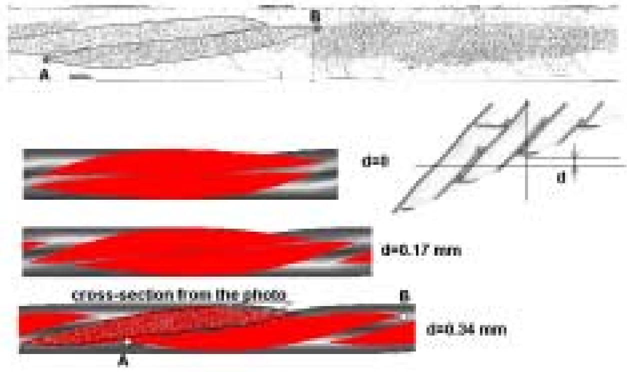


Figure 6. Cross-section of sample along the centre line and comparison with the computed images. Contours of yarns are added on the photo manually for clarity

A verification of the model is provided by a comparison between the predicted and the actual shapes of yarns in the fabric. Figure 6 shows that this is not a simple task. The computed cross-section along the centre line of the braid does not resemble the photo. However, if the cross-section is slightly moved away from the centre, we achieve the perfect correspondance with the experiment (compare the photo with the third cross-section, which corresponds to the actual position of the cut): the shapes of the yarns are the same, and inclination of the line AB is 6.2° for the photo and 5.7° for the computed cross-section and a real shape of the yarn corresponds quite well to the computed one.

2.2.3. Internal geometry of multiaxial multiply stitched fabrics

The following assumptions are used as the basis of the geometrical model of multi-axial multi-ply warp-knit stitched fabrics (MMF - Figure 7c).

Stitching loops:

1. Spacing of the stitching loops is regular. This is a common assumption for a well-controlled warp-knitting process. The spacing of the loops is characterised by its values *A* – perpendicular to the machine direction, along the needle bed –and *B* – in the machine direction. Deviations from the regular spacing are discussed below.
2. Transitions of the stitching yarn from one face of the fabric to another are straight and perpendicular to the fabric plane. This is a simplifying assumption. Because of the complex relative movement of a needle and the fabric, the stitching yarn can be and is inclined by a certain angle, as revealed by experimental data below. This

inclination should not play an important role in the behaviour of the preform, as long as the stitching is used for the preform consolidation only, and not as a reinforcing. The inclination of the loops is difficult to model without building a complete description of the knitting process, which would be an unnecessary complication.

3. Loops on the back face of the fabric are oriented in the machine direction. In a "normal" warp-knitted structure the loops have different orientations in the fabric plane depending on the pattern. This is not the case for a warp-knit stitching, because positions of feet and heads of the loops are fixed by the stitching yarn piercing the fibrous ply. However, this is a simplifying assumption, as the loops deviate from the machine direction.
4. Stitching yarn in the regions of contact of the loops is ultimately compressed from all sides and has a circular cross-section. This is a simplifying assumption, supported by experimental evidence for knitted fabrics (Grosberg 1960; Grosberg 1964) and by our experimental observations.
5. Stitching yarn in the leg of the loop and in the transition regions on the face of the fabric is ultimately compressed in the vertical direction, flattened in the in-plane direction. This is supported by our experimental observations.

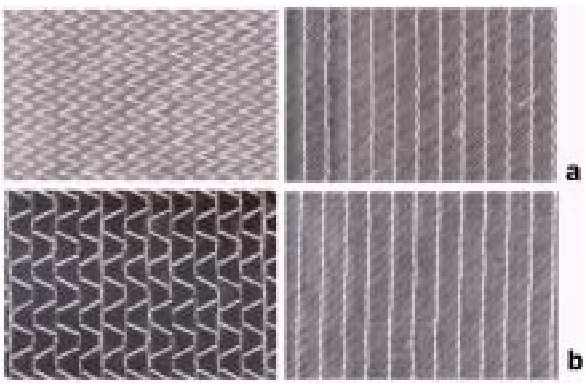


Figure 7. Multi-axial multi-ply fabrics: (a) bixial and (b) quadriaxial

Fibrous plies:

1. A ply has uniform thickness
2. In the absence of stitching, fibres in a ply are straight, parallel and uniformly distributed in the ply.

Interaction of stitching and plies

1. Stitching causes deviations of fibres in a ply from their uniform directions. These deviations produce fibre-free zones near stitching locations. The fibre-free zones can stay located (and called "cracks" below), or can form continuous channels in the ply. These statements describe an actual behaviour, observed in the preforms.
2. Local volume fraction of the fibres in a ply is increased as a result of the stitching, but is evenly distributed in the ply. Increase of the volume fraction is a natural effect of pushing aside the fibres by the stitching. The uniformity is a simplification in the absence of positive data on local changes of the volume fraction of fibres.

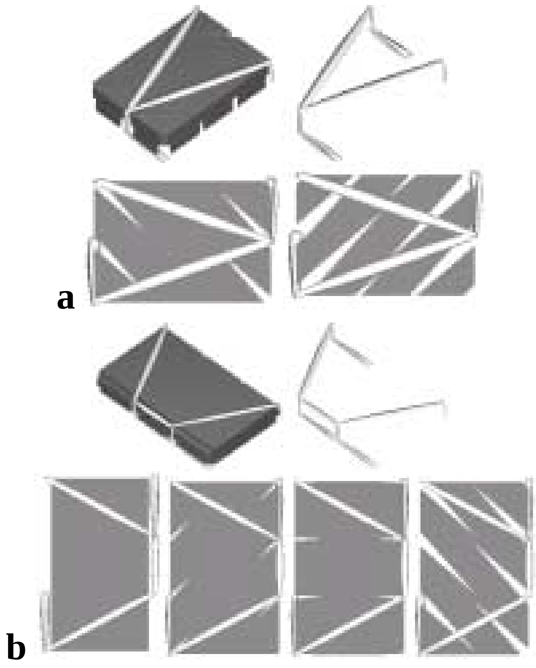


Figure 8. 3D images of the biaxial (a) and quadriaxial (b) fabrics B. From left to right: unit cell; stitching yarn; structure of the fibrous plies.

The mathematical model described above is implemented as a module of the textile simulating software WiseTex. Figure 8 shows 3D images of the fabrics, created with WiseTex. Comparison with real fabric structure (Figure 7, Figure 9) shows that the model captures the important features of the real fabric structure.

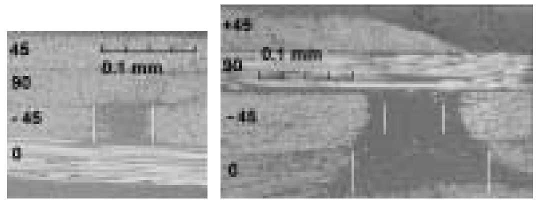


Figure 9. Channels/cracks width in cross-sections of the composite plate made of the quadriaxial fabric. Thick white lines show computed width of the cracks. Left: Section in the machine direction, crack in the -45° inner ply; Right: Section in the cross-direction, channel in the 0° face ply and a crack in the -45° inner ply

3. DEFORMABILITY OF TEXTILE FABRICS

Consider a unit cell of textile reinforcement. Internal geometry of the unit cell can be described using the WiseTex family of textile geometrical models.
When the positions of all the yarns of the unit cell are thus known, as well as parameters of a fibre assembly inside a yarn (spatial distribution of fibre volume fraction and direction of fibres, which are readily provided by WiseTex). It is a question of using one or another homogenisation techniques to obtain mechanical parameters of the unit cell (see below).
The same routine can be applied to a unit cell deformed when the preform is shaped in the RTM-like process. The internal geometry of the yarns in the unit cell would then depend on local compression pressure and strain tensor. Homogenised properties, which depend on the unit cell position in the mould, would constitute input for software packages analysing behaviour of the preform as a whole. The input data include distribution of permeability tensor for Darcy equation solvers analysing mould filling, and distribution of stiffness matrix (or more complex non-linear mechanical properties) for FE structural analysis of the composite part.
Based on these considerations, the problem addressed in this section is as follows:
Consider a unit cell of a woven (2D or 3D) fabric under given compaction pressure or under given in-plane deformation (bi-axial tension or/and shear). Based on the internal geometry of the fabric in relaxed state, compute the internal geometry after the deformation (paths of the yarns and their cross-sections along the paths). For compression, compute also the fabric deformation under given pressure; for in-plane deformation – loads caused it.

3.1. Compression

Research on compressibility of woven fabrics in composite technological processes is mostly empirical. A theoretical model, developed by the authors and published elsewhere , uses the WiseTex model as the starting point and accounts for two physical phenomena associated with the fabric compression: change of the yarns crimp and compression of the individual yarns. The result is pressure-thickness curve for the fabric, from which fibre volume fraction for the given preform compaction is easily deduced. When applied to 3D fabrics, the model also computes change of the yarn paths (Figure 10).
Internal structure of laminated preforms after compression is affected also by relative shift and nesting of the layers in lay-up. This factor, changing the fibre volume fraction by percents in comparison which non-shifted configuration (see (Lomov et al. 2000)), drastically changes the preform permeability. The change can be simulated using the model for input of the preform configuration for a Lattice Boltzmann model of the resin flow through the preform (taking into account two scales of the pores: inter-yarn and inter-fibre within the yarns). Figure 11 shows a result of such a calculation for glass reinforcement. It can be seen that irregularities in the placement of layers in a laminate can drastically affect the permeability, which explains wide distribution of experimentally measured permeability values (Hoes et al. 2001).

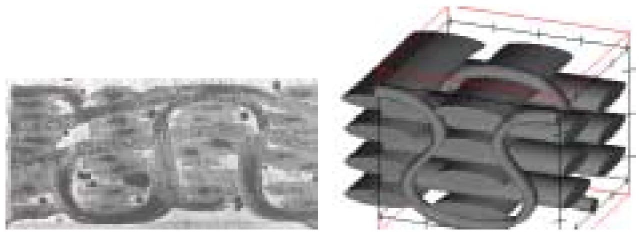


Figure 10. Typical deformed Z-yarns (cross-section and computed) in 3D fabrics

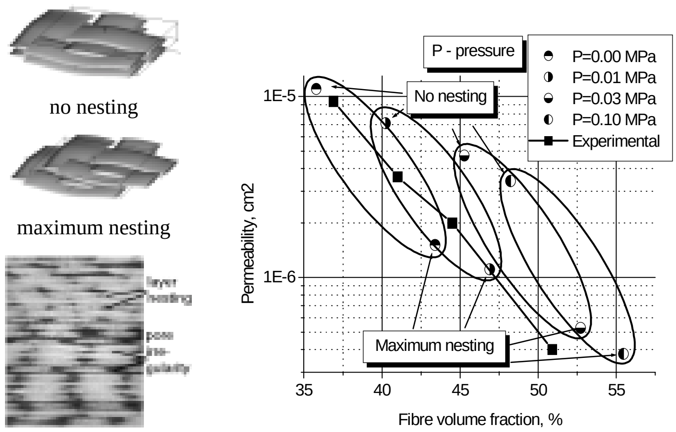


Figure 11. Influence of the compaction pressure and layers nesting on permeability of glass fabric laminate preforms

3.2. Bi-axial tension

Consider a woven fabric under bi-axial tension characterised by deformations in warp (*x*-axis) and weft (*y*-axis) directions $e_x = Y'/Y-1$, $e_y = X'/X-1$, where X and Y are sizes of the fabric repeat, dashed values correspond to the state after the deformation. Inside the *WiseTex* model, the internal structure of the fabric is described based on weft crimp heights h_j^{We} and weft and warp cross-section dimensions at the intersections d_{ij}^{Wa} and d_{ji}^{We} (subscripts designate different yarns in the fabric repeat). These values change after the deformation. Tension of the yarns induces transversal forces, which compress the yarns, changing *d*'s. The same transversal forces change the equilibrium conditions between warp and weft, which leads to a redistribution of crimp and change of crimp heights. When the mentioned values in the deformed configuration are computed, the internal geometry of the deformed fabric is built using the *WiseTex* algorithms as explained in the section 2.2.1. Change of length of the yarns determines their average (in the repeat) deformations, which, through the tension-deformation diagrams of the yarns allow computing tensions of the yarns. When summed up, with yarns inclinations due to the crimp accounted for, the yarn tensions are transformed into loads, caused the fabric deformations. This computational scheme has been proposed for plain weaves in 70s (e.g.,) and also recently implemented via FEA (Boisse et al. 2001); the present implementation of it puts it into the scope of WiseTex modelling, covering the wide range of woven structures.

The key problem in the bi-axial modelling is computation of crimp heights and transversal forces in the deformed structure. Assuming that the spacing of the yarns in the fabric is changed proportionally to the change of the repeat size, we compute the *x* and *y* positions of intersections of warp and weft in the deformed structure. The configuration of the yarns in the crimp intervals between the intersections is determined by these positions and (unknown) crimp heights. Consider some values of the crimp heights. Then the WiseTex geometrical model determines positions of the ends of crimp intervals (warp/weft intersections) and bent shape of the yarns in the intervals. The transversal forces are computed then using the following formula:

$$Q = Q_{bend} + 2T\cos\theta \qquad (1)$$

where Q_{bend} is the transversal force due to the yarn bending (it is computed using the crimp heights and bending rigidity of the yarns in the crimp interval under consideration, see), T is the yarn tension, θ is the angle of inclination of the yarn on the crimp interval. Note that T depend on yarn length after the deformation, which in its turn depend on crimp heights and yarn dimensions. The transversal forces compress the yarns according to an experimental law of the compression: $d=d(Q)$. When the yarn dimensions are computed and "frosen", then crimp heights are determined using the minimum energy condition:

$$W = W_{bend} + W_{tens} \to \min \qquad (2)$$

where W_{bend} and W_{tens} are the bending and tension energy of the yarns. The former is computed summing up bending energies of the yarns in crimp intervals between yarn intersections, as explained in (Lomov et al. 2000; Lomov et al. 2001; Lomov et al. 2001), the latter is the sum of tension energies of all the yarns, which are computed using their (linear or non-linear) tension diagrams and yarn deformations.

The computations described above determine one step in the iteration process: started from current values of the crimp heights we compute yarn lengths, yarn tensions, transversal forces, yarn compressed dimensions and then new values of the crimp heights. These iterations are the same as are employed in the model for the relaxed state [2-4] with the addition of the terms responsible for the yarn tensions in Equations (1) and (2).

Table 2. Tension along warp of a model fabric: uncompressible circular yarns

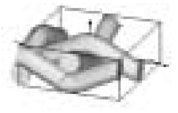
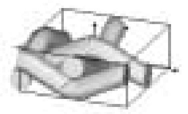
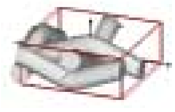
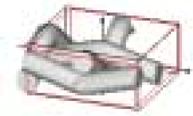
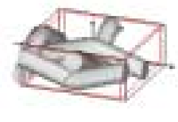
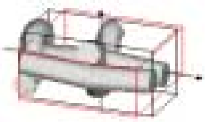
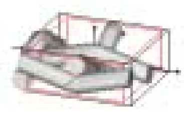
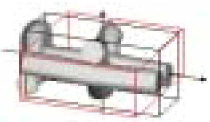
Fixed weft	e_x,%	Free weft
	0	
	5	
	10	
	15	

Table 3. Tension along warp of a typical glass reinforcement (compressible yarns)

e_x, %		0	0.2	0.5	1	2
free weft	load, N/yarn	0	6.17	18.9	98.2	270
	warp strain,%	0	<0.1	0.1	0.6	1.6
	warp tension, N/yarn	0	6.18	19.0	98.2	270
	thickness, mm	.460	.355	.435	.490	.500
fixed weft: e_y=0	load, N/yarn	0	6.25	47.8	132	302
	warp strain,%	0	<0.1	0.3	0.8	1.8
	warp tension, N/yarn	0	6.26	48.0	132	303
	thickness, mm	.460	.358	.353	.354	.356

If one side of the fabric is kept free (uni-axial tension, say, along the warp), then the described algorithm has another, the outmost iteration loop, searching for $X'<X$ (negative e_y) which would lead to zero loads along weft (*y)* direction. This allows computing Poisson coefficient for the fabric.

The described algorithm is implemented in WiseTex, and would be thoroughly validated against experimental data in future work. Table 2 and Table 3 present qualitative results, which provide an insight into phenomena associated with the tension of woven fabrics. In the Table 2 the boxes show the repeat size before and after the deformation. For the results of Table 3 note that the compressibility of yarns and redistribution of crimp lead to low initial stiffness, which rapidly approach the stiffness of the yarns themselves. The compressibility of yarns also leads to decrease of the fabric thickness in the case of fixed weft; for the free weft case the behaviour is reverse due to the redistribution of crimp.

3.3. Shear

When a woven fabric is sheared, the orthogonal directions of warp and weft become skewed. Such a configuration is similar to a braided structure. A model for internal geometry of braids is proposed in [5] and is used to construct the sheared woven fabric internal geometry. The problem then is in computation of the loads associated with a given shear deformation. In formulating the model we again follow the lines sketched by S.Kawabata in 70s [10], which are also followed by more recent publications (e.g.[12]).

When a fabric is sheared, the deformation is resisted by friction between yarns, bending and compression of the yarns. Friction forces are estimated in the model using normal forces of the yarn interaction, computed with (1), tension being a pretension normally employed in the shear test. The transversal forces are increased by the internal pressure, developed inside yarns due to their lateral compression in the sheared structure (Long 2000). This is taken into account using the experimental compression diagrams of the yarns. Resistance due to bending is estimated using the difference in bending energies in deformed and undeformed configurations, the latter computed with algorithms for non-orthogonal structures as described above (2.2.2).

Figure 12 depicts the results of computation of shear resistance for fabrics studied in (Long 2000). The data from this paper is used as the input; the typical compression diagrams of glass rovings reported in (Lomov et al. 2000) were used as an approximation. This explains the difference between experimental and computed values, which are, however in qualitative agreement.

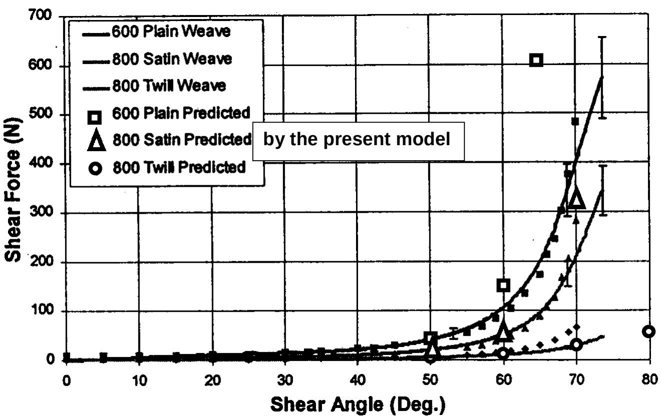


Figure 12. Measured (Long 2000) shear resistance of glass woven fabrics and results of calculations with the present model

4. CONCLUSION

The modelling strategy proposed in the present work, provides a link between meso-mechanical and permeability models of composites and currently developed geometry models of textile reinforcement. It provides an opportunity to use manufacturer's fabric and yarns data, obtained on the standard equipment for textile testing, as a starting point for modelling of composite material. This gives more solid foundation for a *priori* predictions of mechanical properties of composites, allowing accounting for geometry peculiarities (complex crimp and porosity pattern) and yarn mechanical behaviour (compression) non-accessible in simple models. Different textile structures are easily modelled with a user-friendly software application WiseTex. It allows easy manipulating of fabric and yarn data and visualisation tools. The model of the textile geometry and mechanics serves as a base for meso-mechanical and permeability models for composites, which provide therefore simulation tools for analysis of composites processing and properties. The critical hierarchical concept applies to many different types of textile reinforcement structures, resulting in integrated design software for textile composite modelling.

A generic approach for modelling woven fabric deformability in compression, bi-axial tension and shear is presented. The models are implemented in WiseTex software and allow computing the loads led to given deformations of the fabric unit cell as well as the internal geometry of the fabric after the deformation. The deformed configuration can be fed into a Lattice Boltzmann flow modelling code to produce permeability tensor, and into micro-mechanical models to predict mechanical behaviour of the composite unit cell. These data can be used in simulations of the fabric drapability, mould filling in RTM process and structural analysis of composite parts.

5. ACKNOWLEDGEMENTS

This work was done in the framework of the projects "Development of unified models for the mechanical behaviour of textile composites" (GOA/98/05), funded by the Flemish Government through the Research Council of K.U.Leuven, "Advanced numerical techniques in R&D on processing and properties of textiles and textile composites " (IWT-000148), funded by the Flemish Government, and "Technologies for Carbon Fibre Reinforced Modular Automotive Body Structures" (TECABS, Brite-Euram), funded by the European Commission.

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