Virtual textile composites software *WiseTex*: Integration with micro-mechanical, permeability and structural analysis

Ignas Verpoest^{*}, Stepan V. Lomov

Department of Metallurgy and Materials Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 44, B-3001 Leuven, Belgium

Received 6 May 2005; accepted 25 May 2005

Available online 26 July 2005

Abstract

The internal geometry of textile reinforcements is an important factor of the reinforcement performance during composite manufacturing and in the service life of the composite material. When a 3D-shaped composite part is concerned, the reinforcement is locally deformed (compressed, stretched and sheared), and any model describing the internal geometry of the reinforcement should account for this deformation. 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 of 2D- and 3D-woven, two- and three-axial braided, weft-knitted and non-crimp warp-knit stitched fabrics and laminates. It is integrated with modelling of resin flow, micro-mechanical calculations of properties of textile based composites and micro-macro analysis of composite parts, finite element models and virtual reality software. The paper describes this family of models, which use a unified description of the geometry of the reinforcement unit cell.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Textile composites; Modelling; Internal structure; Deformability; Permeability; Micro-mechanics; Finite elements

1. Introduction

The internal geometry of a textile reinforcement is an important factor of the reinforcement performance during composite manufacturing and in service life of the composite material. For the former, impregnation of the reinforcement is governed by its porosity (size, distribution and connectivity of pores). For the latter, load transfer from the matrix to the reinforcement is governed by the fibre orientation, which plays a paramount role in the composite stiffness; stress-strain concentration loci, determining the composite strength, are correlated with the resin rich zones and fibre/matrix interfaces, distributed in the composite volume in accordance with the reinforcement geometry. When a 3D

shaped composite part is concerned, the reinforcement is locally deformed (compressed, stretched and sheared), and the geometrical model should account for this deformation.

A generalised description of the internal structure of a textile reinforcement has been developed in K.U.Leuven. It is the final result of a development that started in the mid 1990s, with the work of Vandeurzen et al. [1,2] on woven fabric composites and Gommers et al. [3] on knitted and woven fabric composites. Both authors based the description of the internal geometry of the textile on empirical data on the yarn orientation, obtained by optical or electron-microscopical observations on dry textiles and on cross-sections of textile composites. For woven fabrics, the out-of-plane orientations of the warp and weft yarns at their cross-over points, were taken into account in an approximate way, by representing the curved yarns by a set of straight yarn segments. For knitted fabrics, a similar approach was used, but

^{*} Corresponding author. Tel.: +3216321210; fax: +3216321990.

E-mail addresses: ignass.verpoest@mtm.kuleuven.ac.be (I. Verpoest), stepan.lomov@mtm.kuleuven.be (S.V. Lomov).

also the in-plane curvature of the knitted loops had to be represented.

These geometrical descriptions were then used to calculate the homogenised mechanical properties of the textile based composites. Vandeurzen [1,2] used a multilevel homogenisation method, also called the cell method, which was later on generalised by Prodromou [4]. Gommers [3] used a multi-inclusion Eshelby-type approach, in which each yarn segment is considered to be an inclusion embedded in a medium that has either the matrix properties (Mori–Tanaka method) or the already homogenised composite properties (self-consistent method). Predictions of homogenised stiffness properties were quite accurate for the knits and yarns considered. Some attempts were made to predict damage development, because both methods allow to calculate, be it in an approximate way, the stresses or strains at the lowest level (impregnated yarns and matrix), and hence to predict at which applied stress or strain level the local stresses or strain reach a critical value.

The major drawback of these early models was their dependency on empirically obtained descriptions of the internal geometry of the textile. This means that the textile first has to be produced, and then measured, and that no predictions on the behaviour of yet non-existing textile composites can be made. In this way, the value of these ‘predictive’ models is rather limited. A big step forward could be achieved when collaboration was started with S.V. Lomov, who developed a model for the internal geometry of 2D- and 3D-weaves (the CETKA-model [5–11]), based on a minimum number of topological data (weave style, inter-yarn distance) and yarn mechanical properties. The model is a mechanical model, as it applies a yarn deformation energy minimisation algorithm to predict the internal geometry of any 2D- and 3D-weave. Connecting this approach to the cell- or inclusion models of Gommers and Vandeurzen resulted a more versatile way to calculate the homogenised properties of textile based composites [12–15].

Since the year 1999, this approach has been systematically followed, extending the types of textiles to 2D- and 3D-woven [14–17], two- and three-axial braided [18], weft-knitted [19] and non-crimp warp-knit stitched

[20] fabrics and laminates [21]. The mechanical models not only generate the internal geometry of relaxed textiles, but also of textiles deformed in tension, compression and shear. The models are implemented in the software package *WiseTex*.

A further step was the full integration of the geometrical models with other predictive models relevant for composites processing and performance prediction. Permeability tensors can be predicted by modelling of resin flow through the reinforcement [22,23]; the homogenised mechanical properties and the local stresses and strains can be generated by micro-mechanical calculations of properties of the composite [14,15], and can then be further linked to a micro–macro analysis of the composite parts [24,25], finite element models [26–30] and virtual reality software [31] (Table 1 and Fig. 12). All these models use a unified description of the geometry of the reinforcement unit cell.

As is evidenced by Table 1, the *WiseTex* family of software is now the product of an intensive and widespread collaboration between different universities and research centres worldwide: University of Osaka, Japan (Prof. Zako, H. Nakai, S. Hirose), Politecnico de Milano, Italy (Prof. Poggi, Prof. Carvelli), Technical University of Liberec, Czech Republic (T. Mikolanda), University of Zaragoza, Spain (E. Bernal), ONERA, France (F. Boust, B. Laine) and ESI, France (P. de Luca, L. Dufort). Further contributions to the model and software development, reported in this paper, were made by a group of researchers in our own department (J-F. Delerue, S. Kondratiev, G. Huysmans, F. Tumer, B. van den Broucke) and in the Department of Computer Science of our university (Prof. D. Roose, T. Peeters, B. Verleye).

The present paper summarises these developments, with an aim to facilitate its future use of the unified textile models by other researchers.

2. Unified description of geometry of unit cell and its translation to FE models

The geometrical and mechanical model of textiles, implemented in the software package *WiseTex*, provides

Table 1
WiseTex family of software

	Purpose	Developed by
<i>WiseTex</i>	Internal geometry of textiles in relaxed state; compression, tension and shear of the textile	Lomov, Verpoest, K.U.Leuven
<i>LamTex</i>	Internal geometry of textile laminates	Lomov, Peeters, K.U.Leuven
<i>FETex</i>	Convertor of <i>WiseTex</i> data into FE description	Lomov, Kondratiev, Bernal, K.U.Leuven; Poggi, Carvelli, Politecnico di Milano
<i>MeshTex</i>	Convertor of <i>WiseTex</i> data into FE description (SACOM)	Zako, Nakai, Hirose, Osaka University
<i>TexComp</i>	Stiffness properties of a textile composite, inclusion model	Huysmans, Prodromou, Lomov, Verpoest, K.U.Leuven
<i>FlowTex</i>	Permeability of textile, lattice Boltzmann/finite difference	Belov, Peeters, Roose, Verleye K.U.Leuven
<i>Celper</i>	Permeability of textile, finite elements, voxel discretisation	Laine, Boust, ONERA
<i>VRTex</i>	Virtual reality of textiles on meso-level	Mikolanda, T.U.Liberec

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 (Fig. 1). A weave pattern (for one- and multi-layered fabrics) is coded with matrix coding [7,16], Fig. 1(a). 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. 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,

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

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

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

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

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

where subscript “0” refer to the uncompressed state of the yarn, d_1 and d_2 are dimensions of the yarn cross-section (Fig. 1(b)). These dimensions and crimp heights of the yarns are interconnected

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

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 (Fig. 1(b)). 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

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

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. It takes about 10 s on a 1 MHz PC to compute parameters for

Fig. 1. Model of internal structure of woven fabric: (a) coding of the weave; (b) description of the yarn paths.

providing that the fibrous structure of the yarns in the virgin state and its dependency of local compression, bending and twisting of the yarn are given. Consider a point P. Searching the cross-sections of the yarns, the cross-sections S_i and S_{i+1} , containing between their planes the point P, are found (binary search in the unit cell volume is employed to speed up the calculations), and then by interpolation, the cross-section S , which plane contains the point P, is built. Using the dimensions of the cross-section S , for a given shape of it, point P is identified as lying inside or outside the yarn. In the former case, with the position of the point P inside the yarn known, using the model of the yarn microstructure, the parameters of fibrous assembly in the vicinity of the point P are calculated.

2.1.2. Translation to finite element model: Woven reinforcements

The geometry of the yarn volumes can be easily transferred to a finite element description. A section of a yarn between neighbouring cross-sections is subdivided into four volumes (or kept intact if $d_2/d_1 > 5$). An assembly of these volumes constitutes a solid model of the fabric. For all the yarns a transversal isotropic material model is used, the properties of the impregnated yarns calculated using local fibre volume fraction and fibre orientation in the yarns (assumed constant within one segment between two neighboring cross-sections).

The yarn volumes are effectively meshed, using a “sweep” meshing operation: a mesh built on the first cross-section of the yarn is being “swept” through the yarn, creating a quite regular mesh. Building a mesh inside the matrix is a more challenging proposition. The meshes in the yarns can penetrate one another

due to approximations in the geometrical model (Fig. 3). To eliminate the penetration, yarn elements are first separated, with a resistant media placed between them, and then compressed together, so that the edges get to the initial position. The resulting mesh has no penetrations [29,30].

2.2. Fibrous plies

2.2.1. Description of the plies geometry in the textile modelling software

The description of the geometry of multi-axial multiply stitched preforms (also called “non-crimp fabrics”, NCF) includes the geometry of the stitching yarns and geometry of the fibrous plies [7].

The stitching, even thin, interacts with the fibrous plies, which are unidirectional arrays of fibres with approximately constant thickness. The stitching causes deviations of the fibres in a ply from their uniform directions. These deviations produce fibre-free zones near stitching locations, which are regularly spaced over the ply. The fibre-free zones can be local (and called “openings” below), or can form continuous channels in the ply (Fig. 4). The local fibre volume fraction in a ply is increased and voids are created as a result of the stitching.

The width and length of the “cracks” and “channels” should be measured or calculated with empirical formulae based on dimensions of the stitching yarn [20,32]. When sheared, the fibre density in the plies increases, and the width of the “cracks” and “channels” decreases. After shear angle of 30°, the width reaches its minimum. This change of the width in shear is described by empirical formulae [32,33]. The complex geometry of a fibrous ply with “openings” and “channels” is represented in

Fig. 4. Quadriaxial NCF, orientation of the fibres in the plies 0°/-45°/90°/45°. (a) Full geometrical model with stitching. Note a “channel” in the first 0° ply; (b) “cracks” in the -45° ply; (c) Channels/cracks width in cross-sections of the composite plate, thick white lines show width of the cracks as computed by the model, section in the cross-direction, channel in the 0° face ply and a crack in the -45° inner ply; (d) Slab representation of a ply with -45° “cracks”. ABCDEF – vertices of the upper polygon of one of the slabs.

the *WiseTex* model as a set of “slabs”. A slab is a volume formed by two parallel polygons. Vertices of all the slabs are stored in the counter-clockwise order (Fig. 4(d)).

2.2.2. Translation to finite element model: non-crimp fabrics

The translation to a FE model is done in the following steps [28]: an automatic procedure is used to generate a continuous model satisfying the compatibility conditions. Then, the resulting meshes on the boundary surfaces are built as to have matching node patterns in order for periodic boundary conditions to be applied in the analysis.

Surfaces generated at the geometry decomposition stage are meshed using quadrilateral elements, and the resulting mesh is projected (swept) through the thickness direction, thus obtaining regular hexahedral elements (Fig. 5(a)). Meshes obtained in this way are, in general, unconnected finite element domains whose nodes do not coincide along their common boundaries. In order to preserve nodal connectivity across the interface, a transition region is built by using an intermediate space to glue the partitioned domains using tetrahedral elements (Fig. 5(b)). This technique provides a useful method to satisfy the continuity and the compatibility conditions on non-conforming interfaces between consecutive plies without increasing significantly the computational cost. Finally, matching node patterns are defined on the model boundaries by translating node positions along the fabric periodicity vectors. The FE model

obtained in this way is suitable for applying periodic boundary conditions.

3. Permeability

Calculation of permeability is based on a voxel representation of the unit cell volume (Fig. 6(a)). A voxel is either empty (pore) or filled with fibres. The flow of the fluid in the pores is governed by Navier–Stokes equations (NS-voxels), inside the permeable tows – by Brinkmann equation (B-voxels). In the latter case, local permeability (micro-level) is calculated with the formulae of Gebart and Berdichevsky for a unidirectional array of fibres. These equations are solved by numerical schemes based on lattice Boltzmann (*FlowTex* [22]), finite difference (*FlowTex*, currently being developed using the solver based on the algorithms of Griebel et al. [34]) or finite element algorithms (*CELPER* [23]). The homogenised permeability of a unit cell is then determined using an average flux of the fluid through the unit cell under periodic boundary conditions for the given pressure difference on the unit cell facets.

Fig. 6(b) illustrates the calculation of flow through a fabric made of monofilament fibres. The precise definition of the geometry, available for this type of fabric, results in a very good prediction of the permeability: measured [35] $270 \pm 20 \mu\text{m}^2$, calculated $330 \mu\text{m}^2$ by the lattice Boltzmann method and $270 \mu\text{m}^2$ by the finite difference method by *FlowTex*. When reinforcement with permeable tows is considered, the correct calculation

Fig. 5. Automatic meshing process for NCF. (a) Hexahedral finite elements created by sweeping operation; (b) tetrahedral mesh built in the transition region; (c) composite surface at the interface between plies; (d) 2D mesh at the interface.

Fig. 6. Calculation of permeability: (a) unit cell and voxel model; (b) two layers of monofilament fabric: *WiseTex/LamTex* model and flow velocity field (FlowTex); (c) carbon woven reinforcement: fabric, cross-section of the laminate ($V_f = 55\%$), CELPER calculations with different compression of the fabric.

of the preform compression is of major importance. Fig. 6(c) illustrates how *CELP*ER calculations come close to the measurements, when the correct parameters of the reinforcement are chosen.

4. Mechanical properties and damage behaviour

4.1. Method of inclusions

To apply the method of inclusions, implemented in the *TexComp* software [12–15], 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 $\mathbf{C}^C$ of the composite is hence obtained as: $\mathbf{C}^C = [c_m \mathbf{C}^m + \langle c_s \mathbf{C}^s \mathbf{A}^s \rangle] [c_m \mathbf{I} + \langle c_s \mathbf{A}^s \rangle]^{-1}$, where the subscripts m and s denote the matrix and a yarn segment

respectively, c_i is the volume fraction of phase 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. Fig. 7 illustrates the homogenisation results for a unit cell of a twill fabric glass composite for different shear angles. Such calculations are used (see below) for multi-level μ –m–M modelling of composite parts.

Fig. 7. Elastic properties of a sheared unit cell of a twill glass fabric as functions of shear angle.

4.2. FE modelling of elastic and damage behaviour

The meshing procedure for woven fabrics is implemented in the software *MeshTex*, which is integrated with *WiseTex*, forming a geometrical and meshing preprocessor for a finite element solver *SACOM* [29,30,36]. The data flow and FE modelling of 3D-woven glass/epoxy composites are illustrated in Fig. 8. The ‘convertor’ within *MeshTex* converts the *WiseTex* output into a FE-model, also taking into account the boundary conditions and loads imposed by the problem to be solved. The *SACOM*-software then calculates local stresses and strains, and by averaging them, issues also the initial stiffness tensor (before damage occurs).

Fig. 9 compares results of the FE modelling of elastic deformation of woven carbon/epoxy composite with full field optical measurements [37]. To enable a clear comparison between the calculated and the measured strain fields, the strains along a line in the x - and another line in the y -direction are shown. It can be observed that there is a good match between both; moreover, a strong variation of the strains depending on the location relative to the warp and weft yarns indicates that reliable local strain analyses are essential to predict damage development in textile based composites.

The FEA of progressive damage of the stitched NCF composite was performed by Carvelli et al., assuming the Tsai–Hill failure criteria for the anisotropic homogenized layers. The Tsai–Hill strength parameters of the homogenized layers are derived from a micro model, assuming a transversally isotropic carbon fibres and an isotropic matrix. A simple degradation procedure, proposed by Zako [38–40], is applied to evaluate the damage in the layers up to complete failure. When the stress state in an element satisfies the assumed failure criterion, certain (depending of the failure mode) stiffness matrix elements are dropped down.

As shown in Fig. 10, the FE-analysis accounts for the presence of resin-rich zones (channels), created by the stitching. It gives good estimation of the initial damage strain (red arrows, at about 0.3% strain in both graphs), which was also measured [41,42] using AE registration and X-ray observations of damage.

5. Micro–meso–macro structural analysis

Fast homogenisation with the inclusion model is well-suited to be used in micro–macro calculations. Simulation of the performance of textile composite parts takes

Fig. 8. *WiseTex–MeshTex–SACOM* data flow and example of FEA of 3D-woven composite.

Fig. 9. Full field strain registration [37] on the surface of carbon–epoxy (one fabric layer) and FEA: longitudinal and transversal strain along the yarn centre line (points – experiment, lines – FEA).

Fig. 10. FEA of damage in NCF carbon/epoxy composites: FE model, X-ray registration of damage, at a strain of 0.8%; calculated and measured stress-strain diagrams with (“con”) and without (“senza”) resin-rich zone (“canali”) produced by the stitching; AE registration of damage. Arrows show initial damage strain (0.3%) in calculation and experiment.

into account variability of local properties of the composite, as a 3D-shaped textile preform undergoes shear deformations in the processing. The intensity of shear varies from point to point, changing the local properties of the composite part.

As reported in detail in [24,25], four different parts (Fig. 11(a)) were modelled with commercial CAD software packages providing a geometrical description, which was transferred to a FE mesh that is needed for

further simulations (graphs below show results for woven glass/epoxy hemisphere with diameter of 400 mm).

Although a kinematical draping algorithm (*QuikForm*) is used and hence the material properties are not taken into account during the draping simulation, the prediction of the textile deformation is relatively accurate (Fig. 11(b)). The local stiffness of the parts was calculated as follows. The *QuikForm* output file contains shear angles of the reinforcement in all the

Fig. 11. Micro-macro analysis: (a) composite parts: NCF carbon/epoxy and woven glass/epoxy hemispheres, Twintex glass/PP hemisphere, Twintex motorbike mudguard; (b) draping: simulation and measurements, glass/epoxy hemisphere.; (c) experimental and calculated load-deflection curves (left) and local strains (right, 1-mm displacement of the compression head). Glass/epoxy hemisphere, (1) strain in horizontal direction; (2) strain in vertical direction. (A) low shear positions; (B) high shear positions.

Fig. 12. VRTex: data transfer scheme (a) and travel in textile virtual world (b).

elements of the mesh (the difference between shear of the different layers of the preform was neglected). For each element *WiseTex* calculated the internal geometry of the sheared reinforcement. The result was processed by *TexComp* to produce the full stiffness matrix of the impregnated reinforcement in the element. This calculation accounts for the differences of the properties in elements induced by local shear: (1) fibre volume fraction; (2) in-plane orientations of the yarns and fibres inside them; (3) out-of-plane orientations of the yarns in the sheared woven structure.

The parts were tested in compression at the constant displacement rate of 1 mm/min. Care was taken to ensure that the boundary conditions correspond to rigid clamping of the part edges: they were glued to the base with epoxy glue. Local strains on the surface of the parts were registered using strain gages. A FE-analysis (*SYSPLY*) was performed using stiffness of the elements calculated with: (1) *WiseTex/TexComp*; (2) simple model based on Classical Laminate Theory and in-plane changes of the fibre orientations.

Comparison (Fig. 11(c)) between the global part behaviour (force–displacement for the whole part) during loading and the FE simulation shows a reasonable prediction of the part stiffness in the elastic region. For local strains, the ‘micro–macro modelling’ technique based on the homogenisation of a real reinforcement textile structure approaches the tested values better than a simplified model, especially in areas where textile structures are highly deformed during production (large shearing angle of the fabric), as it could be expected.

6. Textile virtual reality

One of important applications of models of internal geometry is visualisation of the textile architecture. The ultimate result of visualisation of a model is the

creation of a virtual reality (VR) world. Up to now, complicated textile VR is being created mostly on macro-level, displaying drape of a cloth and serving needs of garment designers and producers of animations, supported by the appeal for the wide public. Micro-level (internal structure) textile VR (below we will also use a shortened term ‘micro-VR’) attracts lesser attention. However, such an application is of great interest for textile education and for the popularisation of textile industry and science (e.g., interactive exhibits for industrial and science museums). It can be also used for research purposes in the same way as stereo-chemistry takes advantage of 3D-models of large molecules.

The *VRTex* software is a tool (developed by Mikolanda [31,43]), which transforms a *WiseTex* data file to the virtual reality data files according to VRML standard, which can be used for any VRML browser, providing 3D visualisation, navigation and interaction facilities. VRML commands, defining the VR-world, are generated by *VRTex* for all the yarns and the fibrous plies in the fabric unit cell. These definitions are translated in three directions as requested by the user; VRML instruments allow doing this almost without penalty in the file size, but the user interaction time increases linearly with the enlargement of the virtual world. Fig. 12 shows the usage of *VRTex*, illustrating ‘travelling’ in the virtual world.

7. Conclusion

The *WiseTex* family of models and software provides an integrated description of the internal geometry and properties of textile fabrics and composites on unit cell level and is used for multilevel μ –m–M analysis. The general format of description of the internal geometry of textile reinforcements is open to be used in further developments.

Acknowledgements

The work reported here was supported by EC (TE-CABS, ITOOL and Marie Curie projects), Government of Flanders (STWW and GBOU projects) and Research Council of K.U.Leuven (GOA and OT projects). The contributions of all the members of the international team, mentioned earlier, are greatly acknowledged as well.

References

- [1] Vandeuren P. Structure-performance modelling of two-dimensional woven fabric composites. Leuven: Department of MTM, Katholieke Universiteit Leuven; 1998.
- [2] Vandeuren P, Ivens J, Verpoest I. Micro-stress analysis of woven fabric composites by multilevel decomposition. *J Compos Mater* 1998;32(7):623–51.
- [3] Gommers B, Verpoest I, Van Houtte P. The Mori–Tanaka method applied to textile composite materials. *Acta Mater* 1998;46(6):2223–35.
- [4] Prodromou A. Mechanical modelling of textile composites utilising a cell method. Leuven: Department of MTM, Katholieke Universiteit Leuven; 2004. p. 149.
- [5] Lomov SV, Truettzev NN. A software package for the prediction of woven fabrics geometrical and mechanical properties. *Fibres Text East Eur* 1995;3(2):49–52.
- [6] Shtut II, Bezin PB, Lomov SV. Optimizing the fibrous content and properties of blended SVM-cotton yarns. *Chimicheskie Volokna* 1995(4):31–3.
- [7] Lomov SV, Gusakov AV. Modellierung von drei-dimensionalen gewebe Strukturen. *Tech Text* 1995;38:20–1.
- [8] Lomov SV, Primachenko BM, Truettzev NN. Two-component multilayered woven fabrics: weaves, properties and computer simulation. *Int J Cloth Sci Technol* 1997;9:98–112.
- [9] Gusakov AV, Lomov SV. Parametric studies of the internal structure of 3D-woven fabrics. *Fibres Text East Eur* 1998;6(2):60–3.
- [10] Lomov SV, Gusakov AV. Computation of the porosity of one and multi-layered woven synthetic fabrics. *Chimicheskie Volokna* 1998:52–5.
- [11] Lomov SV, Gusakov AV. Mathematical modelling of 3D and conventional woven fabrics. *Int J Cloth Sci Technol* 1998;10(6):90–1.
- [12] Huysmans G, Verpoest I, Van Houtte P. A poly-inclusion approach for the elastic modelling of knitted fabric composites. *Acta Mater* 1998;46(9):3003–13.
- [13] Huysmans G, Verpoest I, Van Houtte P. A damage model for knitted fabric composites. *Compos Part A* 2001;32(10):1465–75.
- [14] Lomov SV, Huysmans G, Luo Y, Parnas R, Prodromou A, Verpoest I, et al. Textile composites models: integrating strategies. *Compos Part A* 2001;32(10):1379–94.
- [15] Lomov SV, Gusakov AV, Huysmans G, Prodromou A, Verpoest I. Textile geometry preprocessor for meso-mechanical models of woven composites. *Compos Sci Technol* 2000;60:2083–95.
- [16] Lomov SV, Huysmans G, Verpoest I. Hierarchy of textile structures and architecture of fabric geometric models. *Text Res J* 2001;71(6):534–43.
- [17] Lomov SV, Truong Chi T, Verpoest I, Peeters T, Roose V, Boisse P. Mathematical modelling of internal geometry and deformability of woven preforms. *Int J Form Process* 2003; 6(3–4):413–42.
- [18] Lomov SV, Nakai A, Parnas RS, Bandyopadhyay Ghosh S, Verpoest I. Experimental and theoretical characterisation of the geometry of flat two- and three-axial braids. *Text Res J* 2002;72(8):706–12.
- [19] Moesen M, Lomov SV, Verpoest I. Modelling of the geometry of weft-knit fabrics. In: *TechTextil symposium, Frankfurt; 2003* [CD edition].
- [20] Lomov SV, Belov EB, Bischoff T, Ghosh SB, Truong Chi T, Verpoest I. Carbon composites based on multiaxial multiply stitched preforms. Part 1: Geometry of the preform. *Compos Part A* 2002;33(9):1171–83.
- [21] Lomov SV, Verpoest I, Peeters T, Roose D, Zako M. Nesting in textile laminates: geometrical modelling of the laminate. *Compos Sci Technol* 2002;63(7):993–1007.
- [22] Belov EB, Lomov SV, Verpoest I, Peeters T, Roose D, Parnas RS. Modelling of permeability of textile reinforcements: lattice Boltzmann method. *Compos Sci Technol* 2004;64:1069–80.
- [23] Laine B, Hivet G, Boisse P, Boust F, Lomov SV. Permeability of the woven fabrics: a parametric study. In: *Proceedings ESA-FORM-8 conference; 2005*. p. 995–8.
- [24] Van den Broucke B, Tumer F, Lomov SV, Verpoest I, De Luka P, Dufort L. Micro–macro structural analysis of textile composite parts: case study. In: *Proceedings of the 25th international SAMPE Europe conference, Paris; March 30th–April 1st 2004*. p. 194–99.
- [25] Lomov SV, Van den Broucke B, Tumer F, Verpoest I, De Luka P, Dufort L. Micro–macro structural analysis of textile composite parts. In: *Proceedings of ECCM-11, Rodos; 2004* [CD edition].
- [26] Carvelli V, Truong Chi T, Larosa M, Lomov SV, Poggi C, Ranz Angulo D, et al. Experimental and numerical determination of the mechanical properties of multi-axial multi-ply composites. In: *Proceedings of ECCM-11, Rodos; 2004* [CD edition].
- [27] Lomov SV, Verpoest I, Kondratiev SV, Borovkov AI. An integrated model strategy for processing and properties of textile composites: new results. In: McCarthy RFJ, editor. *Proceedings of the 22nd international SAMPE Europe conference. Paris: SAMPE; 2001*. p. 379–89.
- [28] Lomov SV, Bernal E, Ivanov DS, Kondratiev SV, Verpoest I. Homogenisation of a sheared unit cell of textile composites: FEA and approximate inclusion model. *Revue européenne des éléments finis* [in print].
- [29] Lomov SV, Ding X, Hirosawa S, Kondratiev SV, Molimard J, Nakai H, et al. FE simulations of textile composites on unit cell level: validation with full-field strain measurements. In: *Proceedings of the 26th SAMPE-Europe conference, Paris; 5th–7th April 2005* [CD edition].
- [30] Kurashiki T, Zako M, Hirosawa S, Lomov SV, Verpoest I. Estimation of a mechanical characterization for woven fabric composites by FEM based on damage mechanics. In: *Proceedings of ECCM-11, Rodos; 2004* [CD edition].
- [31] Lomov SV, Mikolanda T. Textile virtual reality. In: *Proceedings of TechTextil symposium, Frankfurt am Main; 2005* [CD edition].
- [32] Loendersloot R, Lomov SV, Akkerman R, Verpoest I. Carbon composites based on multiaxial multiply stitched preforms. Part 5: Geometry of sheared biaxial fabrics. *Compos Part A* [in print].
- [33] Loendersloot R, Lomov SV, Akkerman R, Verpoest I. Architecture and permeability of sheared carbon fibre non-crimp fabrics. In: Drechsler K, editor. *Proceedings of the 24th international SAMPE Europe conference, Paris; 2003*. p. 141–8.
- [34] Griebel M, Dornseifer T, Neunhoeffer T. Numerical simulation in fluid dynamics, a practical introduction. Philadelphia: SIAM; 1998.
- [35] Hoes K, Sol H, Dinescu D, Lomov SV, Parnas R. Study of nesting induced scatter of permeability values in layered reinforcement fabrics. *Compos Part A* 2004;35(12):1407–18.
- [36] Kurashiki T, Hirosawa S, Zako M, Lomov SV, Verpoest I. On a numerical simulation of the mechanical behaviour for laminated

- woven fabric composites under tensile loading. In: Proceedings of the 7th international conference on textile composites (TexComp-7), Yonezawa; 2004. p. 1–4 [Textile 13].
- [37] Lee JR, Molimard J, Vautrin A, Surrel Y. Digital phase-shifting grating shearography for experimental analysis of fabric composites under tension. *Compos Part A* 2004;35:849–59.
- [38] Kurashiki T, Zako M, Verpoest I. Damage development of woven fabric composites considering an effect of mismatch of lay-up. In: Degrieck J, editor. *Composites for the future, proceedings of the 10th European conference on composite materials (ECCM-10)*, Brugge; 2002 [CD edition].
- [39] Uetsuji Y, Zako M, Nishiyabu K. Numerical analysis and in situ SEM observation of damage development for woven fabric composite materials. *J Soc Mater Sci Jpn* 2002;51(10): 1147–53.
- [40] Zako M, Uetsuji Y, Kurashiki T. Finite element analysis of damaged woven fabric composite materials. *Compos Sci Technol* 2003;63:507–16.
- [41] Truong Chi T, Vettori M, Lomov SV, Verpoest I. Carbon composites based on multi-axial multiply stitched preforms. Part 4: Mechanical properties of composites and damage observation. *Compos Part A* [in print].
- [42] Vettori M, Truong Chi T, Lomov SV, Verpoest I. Progressive damage characterization of stitched, biaxial, multi-ply carbon fabrics composites. In: *Proceedings of ECCM-11, Rodos; 2004* [CD edition].
- [43] Mikolanda T, Lomov SV, Kosek M, Verpoest I. Simple use of virtual reality for effective visualization of textile material structures. In: *CODATA Prague workshop on information visualization, presentation, and design, Prague; 2004* [CD edition].