WISETEX-BASED MODELS OF PERMEABILITY OF TEXTILES

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ABSTRACT: The software package *WiseTex* implements a generalised description of the 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. The paper describes its integration with modelling of resin flow on meso-level.
Calculation of permeability is based on a voxel representation of the unit cell volume. 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 Brinkman 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: (1) lattice Boltzmann, (2) finite difference or (3) finite element algorithms. 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.

KEYWORDS: Textile composites; internal geometry; permeability; modelling; software

INTRODUCTION

Textile composites are structured, hierarchical materials, having three structural levels:

1. The macro(M)-level defines the 3D geometry of the composite part and the distribution of local reinforcement properties.

2. The meso(m)-level defines the internal structure of the reinforcement and variations of the fibre direction and the fibre volume fraction inside the yarns and the fibrous plies. The internal structure is defined by the reinforcement textile architecture and deformations applied to the reinforcement during the part forming.

3. The micro(μ)-level defines the arrangement of the fibres in the RVE of the impregnated yarn or fibrous ply.

The calculation of the permeability of textile composites on the meso-level (a unit cell of the reinforcement) involves a two-way process: (1) homogenisation, which produces average (effective) permeability of the material to be used in the macro-modelling of the composite part, and (2) calculation of the meso-flow field inside the unit cell under given macro conditions. The multi-level description of composites is a well-established approach to the calculation of the permeability [1-3]. The key step in the multi-level calculations is the meso-level.

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 [2, 3, 9, 10]. The geometry provided by *WiseTex* could be transferred into finite element (FE) mesh of the yarns, which could be used for modelling of the flow through the textile. However, building a mesh for complex textile geometry is a problem in itself. The “short-cut” possibility for the representation of the internal geometry of a textile representative volume element (RVE) is mapping the geometric description of the textile meso-structure into a 3D grid of parallelepiped elements (“voxels”). The same mapping could produce a 3D mesh of the pores in the reinforcement, to be used in finite element, finite difference or other methods for calculations of the flow [4-8].

The paper discusses the “road map” for building voxel-based models for permeability of textile composites, starting from a generic model of internal geometry of the textile reinforcement. It can serve as an introduction to three other papers presented by the current authors in this conference (F. Desplentere, B. Laine and B. Verleye), which treat the individual models more in depth.

UNIFIED DESCRIPTION OF THE INTERNAL GEOMETRY OF TEXTILE REINFORCEMENT AND VOXEL REPRESENTATION OF THE UNIT CELL

Building a voxel discretisation of the RVE starts with the definition of the internal geometry of the reinforcement. If the model has to be sufficiently versatile, the unified description of the internal geometry is needed. Such a description has been developed by the present authors [2, 3, 9, 10] and implemented in a software *WiseTex*, which could be considered as a geometrical pre-processor for the calculation of mechanical properties and permeability of textile composites.

The unified format of data, covering a wide range of the reinforcement types (2D and 3D woven, braided, knitted, non-crimp fabrics - NCF) is described in [3] and shown in Figure 1. The yarns in the reinforcement are represented as “tubes”, characterised by a succession of cross-sections (dimension and orientation of which could vary along the yarn path). The fibrous plies (in NCFs) are described as volumes (“slabs”) containing fibres; the dimensions of the volumes and directions of the fibres in them depend on the disturbances (“channels” and “openings”) given to the fibrous plies by the stitches.

Note that the geometry depicted in Figure 1 could be easily transferred to a finite element mesh for the yarn and “slab” volumes, as described in [3] and shown in Figure 2. The mesh, defining the surface of the yarns/“slabs”, defines also the pore volume between the yarns/“slabs”, and could be used for FE or other methods (e.g., FE-SPH).

The voxel representation of the yarns/“slabs” and pore volume is not based on the description of the surfaces, but rather on the continuous definition of pore/fibrous assembly in any point of the RVE of the textile.

For any point P inside the RVE the geometrical model describes the fibrous assembly near this point (Figure 1): physical and mechanical parameters of the fibres near the point (which are not necessarily the same in all points of the fabric), fibre volume fraction Vf and direction $\boldsymbol{f}$ of them. If the point does not lie inside a yarn, then $Vf=0$ and $\boldsymbol{f}$ is not defined. For a point inside a yarn, the fibrous properties are easily calculated, 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.

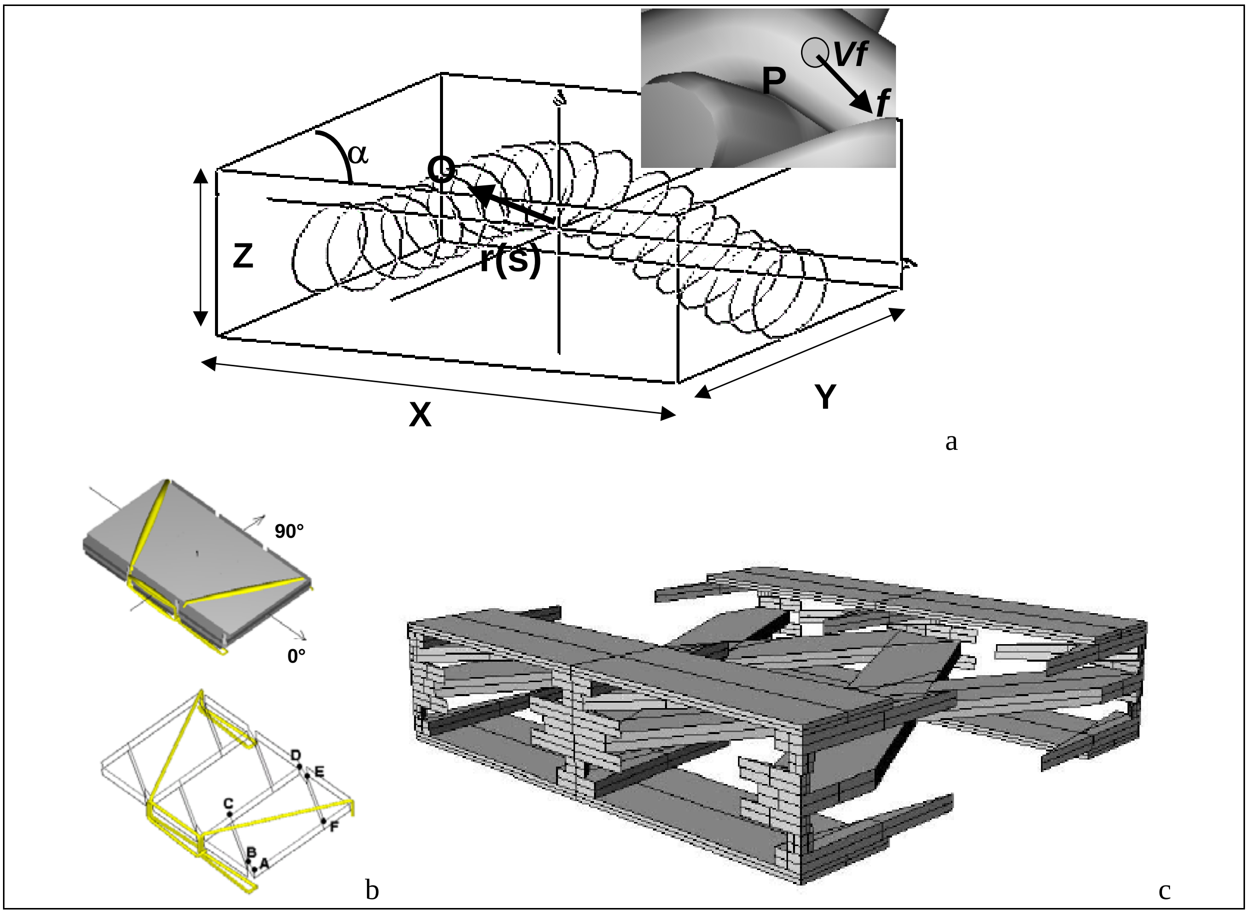

Figure 1 (a) Set of cross-sections defining a yarn in a unit cell, properties of fibres near point P; (b) Quadriaxial NCF, orientation of the fibres in the plies 0°/-45°/90°/45°:) Full geometrical model with stitching. Note a “channel” in the first 0° ply and slab representation of a ply with -45° "cracks". ABCDEF – vertices of the upper polygon of one of the slabs; (c) Example of the pore structure of biaxial NCF

The information of the local fibrous content is output in so-called Fibre Distribution (FD) mode. The fabric repeat is mapped into an orthorombic, regular grid of cells (= voxels), where each cell has homogenised properties according to the amount and respective orientations of the yarn sections it contains. The following data are stored in the FD Mode: (1) RVE (unit cell) size; (2) Data for all fibre types in the reinforcement: fibre diameter, density, mechanical properties; (3) For each cell/voxel: fibre type reference; average fibre orientation; average fibre volume fraction. The number of cells is chosen by the user.

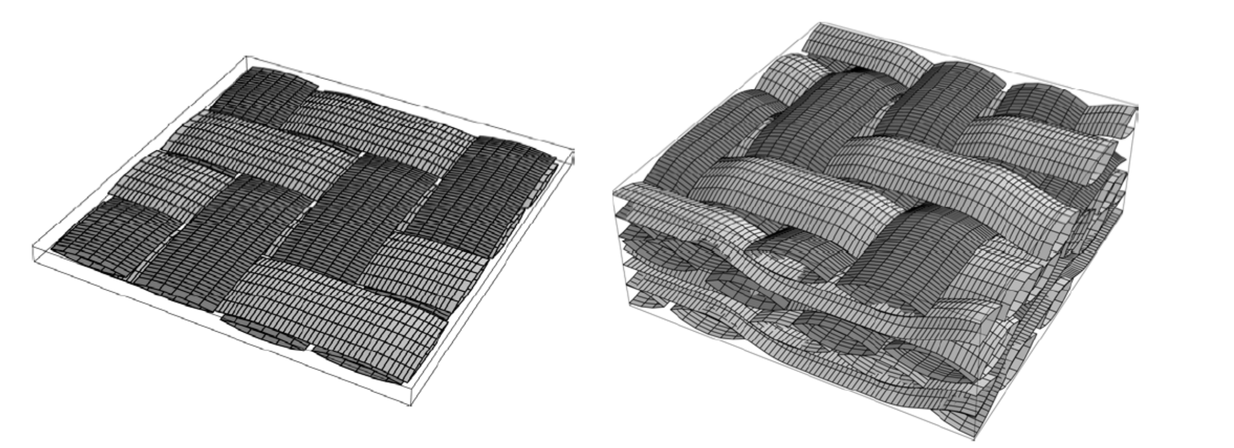

Figure 2 FE mesh for surfaces of yarns of one layer of woven fabric and a laminate

Averaging over a sub-cell is done as follows. The geometrical model gives an answer to the question “does a given point *P* in the RVE volume lie inside a yarn?” If answer is *yes*, then the fibre volume fraction (from the fibre count inside the yarn and the cross-section compressed dimensions) and the fibre orientation (from the yarn heart-line direction and the yarn twist) can be computed for the point *P*. Integrating over a sub-cell volume, the average parameters are computed for each of the fibre types present in the particular sub-cell

$$V_f = \frac{1}{V}\int_V v_f\, dv\,,\ \mathbf{A}_f = \frac{1}{V}\int_V \mathbf{a}_f\, dv\,,$$

where V is a subcell volume, v_f is the fibre volume fraction (of the fibres of the given type) near a given point P – centre of differential volume dv, $\boldsymbol{a_f}$ is fibre orientation vector at P, V_f is an average fibre volume fraction, $\boldsymbol{A_f}$ is an average fibre orientation (this vector is normalised after integration). The integrals are computed with a numerical formula:

$$\int_V f dv \approx \sum_{i=1}^{n} a_i\, f(P_i)$$

where n, coefficients a_i and reference points P_i inside a unit cell are pre-defined for a given polynomial order of accuracy (1,3,5 or 7, chosen by the user) [11].

PERMEABILITY OF THE REINFORCEMENT

The calculation of the permeability is based on a voxel representation of the unit cell volume (Figure 3a). A voxel is either empty (pore) or filled with fibres. The flow of the fluid in the pores is governed by the Navier-Stokes equations (NS-voxels), inside the permeable tows – by the Brinkman equation (B-voxels). In the latter case local permeability (micro-level) is calculated with the formulae of Berdichevsky [12] and Gebart [13] for longitudinal (“l”) and transversal (“t”) permeability of the unidirectional array of fibres:

$$K_l = \frac{d^2}{32V_f}\left(\ln\frac{1}{V_f^2} - \left(3 - V_f\right)\left(1 - V_f\right)\right) \qquad K_t = \frac{4d^2}{9\pi\sqrt{2}}\left(\sqrt{\frac{\pi}{4V_f}} - 1\right)^{5/2}$$

where K is the permeability, V_f is local fibre volume fraction, d is the fibre diameter.

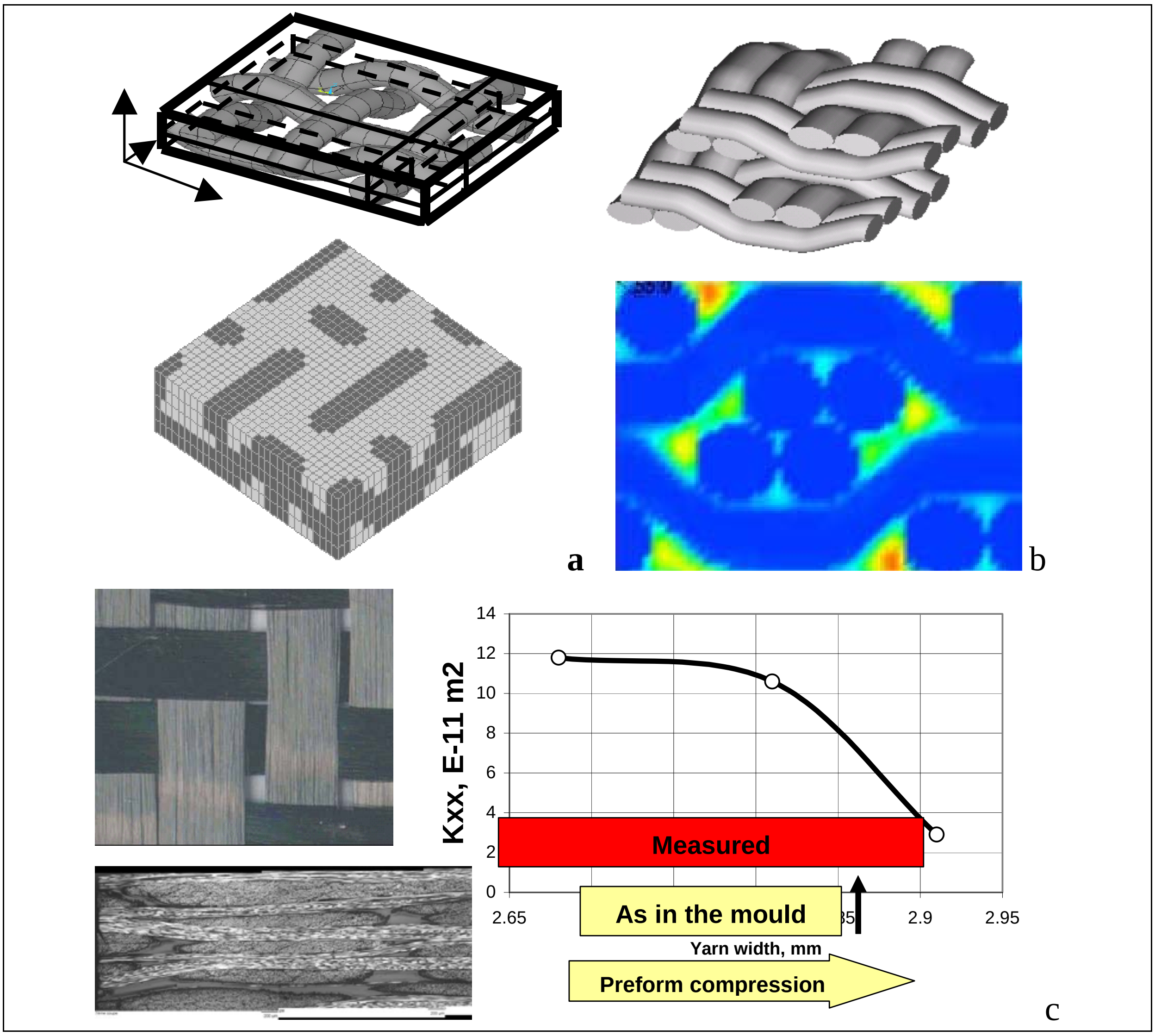

Figure 3 Calculation of permeability: (a) unit cell and voxel model; (b) Two layers of monofilament fabric: *WiseTex/LamTex* model and flow velocity field (finite difference method); (c) Carbon woven reinforcement: fabric, cross-section of the laminate (Vf=55%), finite element calculations with different compression of the fabric

The Navier-Stokes/Brinkman equations are solved by numerical schemes based on lattice Boltzmann [4], finite difference (based on a Navier-Stokes solver NaSt3DGP developed by the research group of Prof. M. Griebel in the institute of Numerical Simulation at the University of Bonn [14,16,17,18]) or finite element algorithms [5]. 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.

Figure 3b illustrates the calculation of the 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 [15] 270±20 μm^2, calculated 330 μm^2 by the lattice Boltzmann method and 270 μm^2 by the finite difference Navier-Stokes method. When a reinforcement with permeable tows is considered, the correct calculation of the preform compression is of major importance. Figure 3c illustrates how finite element calculations come close to the measurements, when the correct parameters of the reinforcement are chosen.

CONCLUSION

The textile internal geometry models of *WiseTex* provide a generic data format for the description of the distribution of the properties (micro-homogenised permeability of fibre bundles) in a RVE of a textile composite, discretised using voxel partitioning. The voxel models are effectively used for calculation of the permeability of the RVE (using finite difference, finite element or lattice Boltzmann methods for flow simulation). The versatility of the geometrical modelling makes the approach applicable to virtually any textile reinforcement structure using the same modelling and software implementation framework.

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