PREDICTIVE MODELS FOR TEXTILE COMPOSITES

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Abstract

The article presents a concept of an integrated design tool for textile composites, which combines integration of models and design tools for different hierarchical scales of textile composites with integration along the production chain – from forming and impregnation of a preform to performance of the composite part. The properties of the textile composite are determined by the architecture of the reinforcement and properties of the constituents. The attention is focused on prediction of the mechanical properties of textile composites: stiffness, strength and fatigue resistance.

Introduction

Textile composites are fibre reinforced composite materials, the reinforcement being in the form of a textile fabric (woven, knitted, braided…). In the *production* of composite parts the use of textile reinforcements brings benefits in handability of the fabrics (hence in automation possibilities and in cost) and in easier applicability of closed-mould processes. In *performance*, due to interlacing of yarns in textile, the interlaminar/through-the-thickness/impact properties of composite are improved; matrix cracks, originated inside the yarns, do not propagate through the material, but are stopped when the yarn changes its direction. The latter mechanism leads to higher energy absorption capabilities in crash-resistant applications.

The textile technology allows controlling of the placement of the yarns in the preform, opening ways to development of net-shape and 3D preforms. These benefits originate from the complex, well-organised internal structure of the fabric. The same internal structure, which is created by interlacing, hence waviness, of the yarns, leads to drawbacks in comparison with unidirectional laminates: lower stiffness of the composite due to inclination of fibres to the direction of the loading and somehow earlier damage initiation due to the presence of resin-rich zones created by the internal architecture of the textile.

The complex structure of textile composite comprises several hierarchical levels: macro (composite component or sub-component) – meso (unit cell of the reinforcement structure) – micro (fibre placement inside yarns and fibrous plies). Nano level can be added if a nano-engineered fibre reinforced composite is considered (for example, carbon nano-tubes added to the resin). The most specific to textile composites is meso-level, where the structure-dependent behaviour of the material is most pronounced. This is the most important level for optimisation of the structure and the constituents should be performed. Figure 1 presents a general scheme of integration of models of textile composites. It shows “vertical” integration of the models, which proceed from (1) internal architecture of the reinforcement to (2) mechanical properties, describing deformability and permeability of the reinforcement and local mechanical properties of the composite material, and further (3) to behaviour of the reinforcement during composite production (forming and impregnation) and structural analysis of the ready composite part. Figure 1 also gives an idea of “horizontal” integration of the models along the production chain (forming – impregnation) and further towards in-service behaviour of the part.

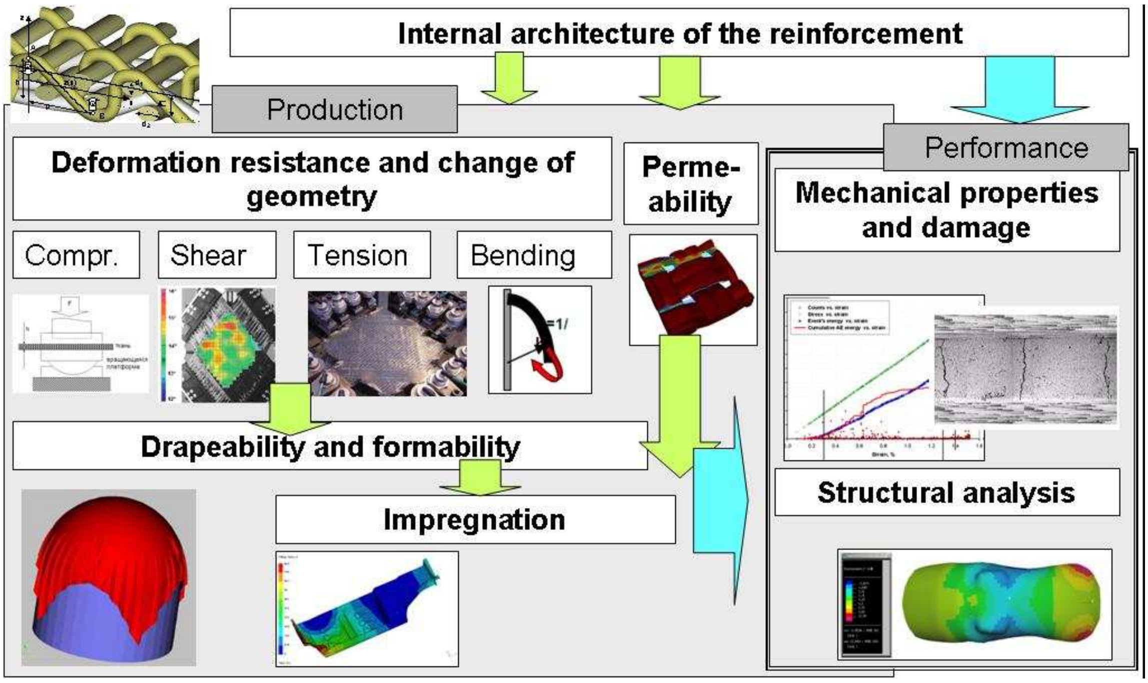


Fig. 1. A scheme of an integrated design tool for textile composites

The various meso-level models shown in Figure 1 are implemented, for example, in *WiseTex* software suite of K.U. Leuven [1-3], presented in Table 1. The geometrical and micro-mechanical part of *WiseTex* software is advanced towards macro-level of structural analysis of composite parts by encapsulation in the Virtual Performance Solution product of ESI Group, namely in SYSPLY structural analysis tool [4].

Table 1 WiseTex software (K.U. Leuven) – virtual textiles and textile composites

Description	*Software*	*Description*	*Software*
Internal geometry and deformability of textile reinforcements	WiseTex, Lam Tex	Micromechanics – stiffness prediction	TexComp
Visualisation – virtual reality*	VRTex	Link to meso-FE modelling	FETex
Permeability	FlowTex		MeshTex**

**in collaboration with T.U. Liberec ** in collaboration with Osaka University*

The article focuses on the “performance” part of the integrated design tool: on prediction of mechanical properties – stiffness, strength, fatigue – of textile composites.

Models of internal architecture of textile laminates and 3D woven textile composites

Geometrical model of a fabric translates the topology of interlacing (woven, braided, knitted…) into actual placement of the yarns in the unit cell space and calculates dimensions and waviness (crimp) of the yarns. Such a model accounts for the interaction between the yarns in the relaxed or loaded state of the fabric, which is defined by the forces due to bending and compression of the yarns and to external loads.

The following input data are given to the geometrical model:

1. Fabric interlacing topology – for example, 2D and 3D weaves are coded by a weave matrix [5]
2. Compression and bending behaviour of warp and weft yarns (there can be any number of different types of yarns in both warp and weft)

3. Spacing of warp and weft yarns (which can be non-uniform)

The algorithm solves equation of equilibrium between yarns under forces created by bending and compression of the yarns, or equations expressing the minimum energy condition, with constraints given by the interlacing. The resulting geometry is presented using a unified data format for different types of the textile (Fig.2).

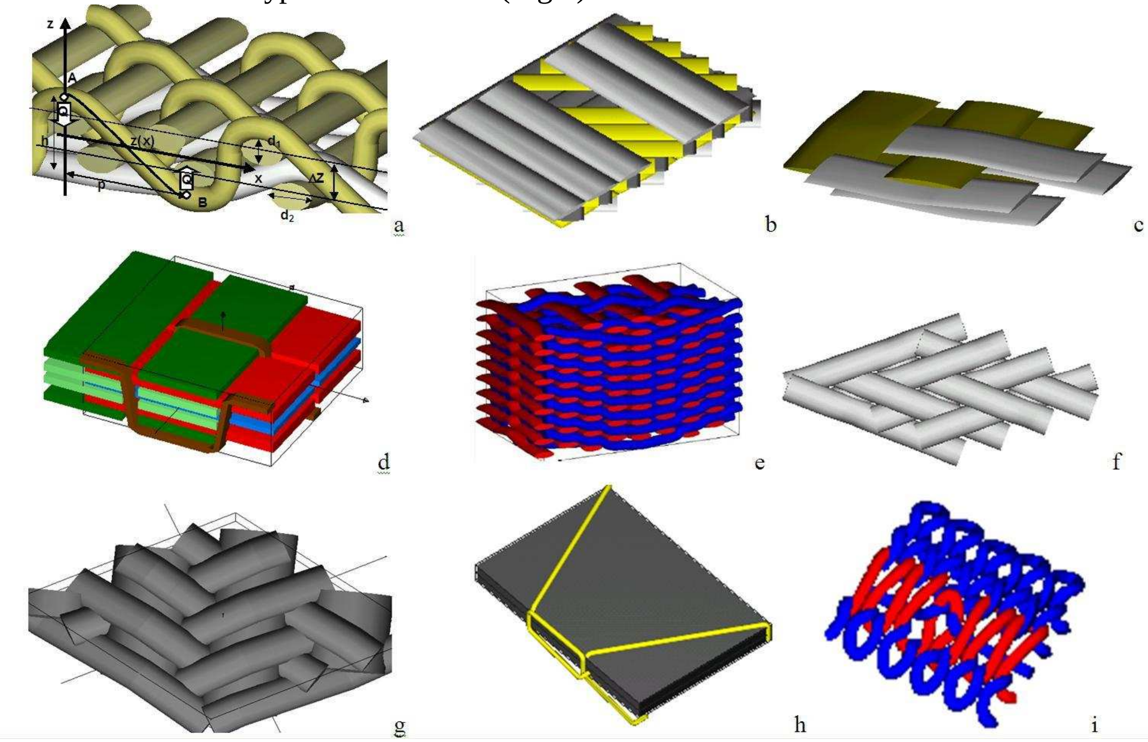


Fig. 2. Geometrical models of textile reinforcements, created by WiseTex software: (a) generic model of a woven fabric with parameters of internal structure, input: p – spacing of yarns; calculated: h – crimp height, z(x) – middle line of the yarn; d_1,d_2 – yarn cross section size; ΔZ – distance between middle planes of the fabric layers for 3D fabrics; Q – forces of interaction of the yarns; specific reinforcement types (from left to right, top to bottom): (b) cross-ply laminate; (c) 2D woven laminate; (d) 3D woven non-crimp fabric; (e) 3D woven angle interlock; (f) 2-axial braid; (g) 3-axial braid; (h) non-crimp fabric; (i) weft knitted fabric

Because the model of internal geometry in relaxed state is built based on description of mechanical interaction between the yarns, the same model can be used to calculate the geometry of the unit cell in deformed fabric – by compression, shear or biaxial tension. The external loading enters into equilibrium equations of the yarns. Alternatively the relaxed geometry can be transformed into geometry under load using finite element modelling of deformation of dry fabric [6].

Fast prediction of elasic properties of textile composites, integrated with structural analysis of composite part

Once a geometrical model of textile composite is ready, the homogenised stiffness can be calculated using the method of inclusions, implemented in the *TexComp* software [1, 2, 7]. 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 applied 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. 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, with use a Mori-Tanaka scheme.

Fast homogenisation with the inclusion model is well-suited to be used in meso-macro calculations, implemented in the latest SYSPLY software of ESI group, which incorporates WiseTex libraries. Simulation of the performance of textile composite parts takes 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. Fig. 3 represents the data flow for such a calculation.

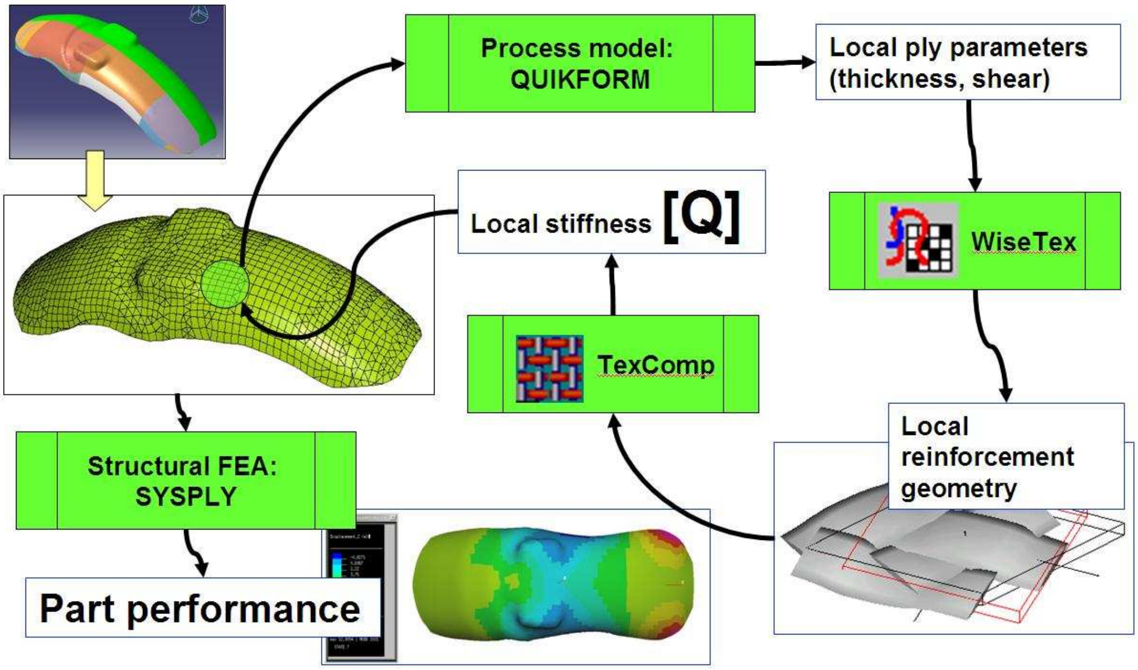


Fig. 3. Micro-meso-macro modelling loop

meso-FE modelling of quasi-static and fatigue damage initiation and progression in textile composites

Meso-scale finite element modelling of textiles and textile composites (scale of the unit cell of the textile structure) is a powerful tool for homogenisation of mechanical properties, study of stress-strain fields inside the unit cell, determination of damage initiation conditions and sites and simulation of damage development and associated deterioration of the homogenised mechanical properties of the composite [8, 9], and of fatigue resistance of the composite [10]. An integrated FE-modeller includes the following modules:

– *Geometric modeller*, which defines the volumes of yarns and fibrous plies in the unit cell of textile composite, local fibre parameters on the micro-scale and provides interface with FE package to export these data;

– *Geometry corrector*, which adapts the geometrical model for requirements of the meshing engine and the particular necessities of boundary conditions formulation process;

– *Meshing engine;*

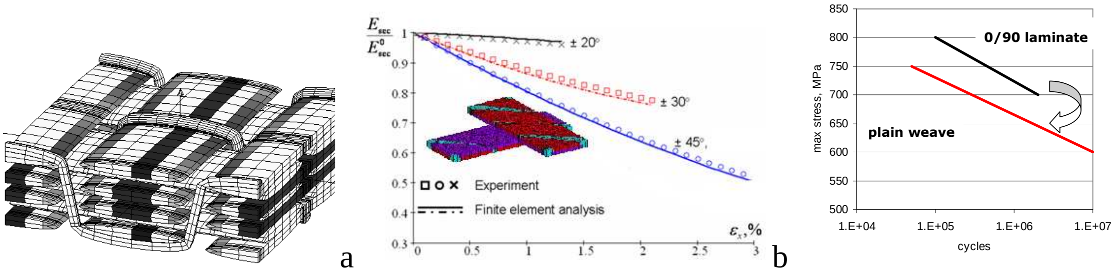
– *Material property processor*, which assigns material properties to volumes/elements, using local fibre assembly parameters on micro-scale, and applying a certain model of homogenisation on micro-level;

– *Boundary conditions routines*;

– *FE solver and post-proccessor*;

– *Homogenisation engine*, which automatically applies the necessary loading and boundary condition, processes the results and outputs homogenised meso-stiffness matrix of the textile composite;
– *Damage detection processor*, employing one of (user-chosen) damage initiation criteria;
– *Damage development processor*, responsible for monitoring the damage tensor, change of the homogenised (on micro-level) properties and decisions on the damage propagation modelling.

Fig.4 presents examples of meso-FE modelling of textile composites.



a b c

Fig. 4. meso-FE modeling of textile composites: (a) prediction of transversal damage in glass/epoxy 3D woven composite; (b) predicted and measured stiffness evolution of NCF carbon/epoxy composites for different orientation of the plies; (c) comparison of the predicted S-N fatigue curves for plain woven carbon/epoxy composite [10]

Conclusion

Modelling of textile composites is a mature research topic, which has reached a level of development of software tools, useful for optimization of material structure and for structural analysis and design of textile composite parts.

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