MULTILEVEL MODELLING OF MECHANICAL PROPERTIES OF TEXTILE COMPOSITES: ITOOL PROJECT

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SUMMARY

The paper presents an overview of the multi-level modelling of textile composites in the ITOOL project, focusing on the models of textile reinforcements, which serve as a basis for micromechanical models of textile composites on the unit cell level. The modelling is performed using finite element analysis (FEA) or approximate methods (method of inclusions), which provide local stiffness and damage information to FEA of a composite part on the macro-level.

1 INTRODUCTION

The ITOOL (“Integrated Design Tool”) project aims at capturing the simulation based capability and understanding of textile manufactured composite structures. This is the prerequisite for future application of this cost efficient technology in various target markets. One of the basic work packages is the multilevel modelling of textile composites, aiming at developing the following models:

- Geometrical models of textile reinforcements, which serve as a basis for
- Micromechanical models of textile composites on the unit cell level, using finite element analysis (FEA) and approximate methods (method of inclusions), which provide local stiffness and damage information to FEA of a composite part.

Models are developed on two structural levels:

- micro (scale of 10 to 100 µm): individual fibres inside yarns/fibrous plies
- meso (scale 0.1 to 100 mm): unit cell of textile composites –

To be integrated with structural analysis on the macro scale (0.1 to 10 m) in a composite part.
The models contribute to the achievement of the core objective of the integrated design tool. They provide crucial information of variability of mechanical properties of the composite material over a part, accounting for anisotropy of these properties and damage initiation/propagation.

Modelling on the Micro – Meso level can be described as assembling the representative volume element of textile composites (or unit cell), using geometrical models on Micro level (fibre distribution in yarns and fibrous plies) and on the Meso level (yarn/plies architecture of the reinforcement). This assembling results in a full description of the reinforcement as a structured fibrous assembly. When ready, this description is used as input data for homogenisation of the mechanical properties of the composite on the Meso (unit cell) level; these properties can then be integrated into structural analysis on the Macro level.

2 MICRO-LEVEL: UNEVEN FIBRE DISTRIBUTION IN YARNS AND FIBROUS PLIES

Micro-level investigations address fine structure of fibre distribution in yarns in woven or braided composites or near structural stitching sites. Four representative types of stitching are studied: ordinary CNC-sewing, tufting, two-needle, and curved needle techniques using multifilament yarns: aramide and glass [1]. The following major conclusions have been drawn from the experimental study:

1) The structural stitching causes a considerable distortion of fibres even in dry performs: a significant decrease (up to 25%) of the fibrous content is measured near the stitching sites; in contrast with the initial assumption that it should increase (Fig.1).

2) Multifilament yarns have a non-uniform fibre distribution over the cross-section. The fibre content usually decreases towards the edge of a yarn, with the statistically significant difference of 10…15%.

![Figure 1. Fibre distribution in NCF near a structural stitching](image)

The uneven distribution of the fibres has been formalized in mathematical models, which are implemented in WiseTex textile modelling software and used for specification of the material properties in the meso-FE modelling.

3 GEOMETRICAL MODELS AT MESO-LEVEL

3.1 3D braids

The main objective of the development of models of 3D braids in ITOOL is to simulate their internal architecture. The description should be compatible with the unified data structure for representation internal geometry of the reinforcement, as used in WiseTex models [2]. This opens a way to direct calculation of stiffness of 3D-braid reinforced composite, permeability of the reinforcement and other modules of the integrated design tool. The developments capitalise on the results of previous EC-funded research, using the CabRun software as process model, which determines the movement of bobbins on the braider.
The simulation is based on the interlacing pattern of the braid, which is determined by the braiding machine initial configuration and operation program. The code summarizes the movement of horngears and bobbins in the braiding plate, yielding different types of interlacing. This depends on which rotary gripping forks (which allow the interchange of bobbins between adjacent horngears) are free or blocked at each braiding step of the process (Fig.2). Yarn paths are built then, using B-splines (NURBS), which provide a good choice for representing complex yarn paths because the path and the cross-section of the yarn may be locally adjusted through small variations on the points or weights. The B-splines also preserve continuity on direction, derivative and curvature of the path at bobbin interchanging.

3.2 Structural stitching

Structural stitching (as opposed to “non-structural” stitching, which keeps plies of non-crimp fabric preform together but does not contribute to the mechanical properties of the material) is a powerful method for creating 3D preforms and for local reinforcement of textile preforms. Geometrical models of the structural stitching (Fig.3) are a necessary step in integrated models of composite production characteristics and mechanical properties. The models, developed in the ITOOL, focus on two aspects: (1) distortions (“openings”) in the fibrous plies created by the stitching and (2) shape of the stitching loop. With these data available, the geometry of the stitched textile laminate is described using the unified format [2], and other modules of the integrated tool are applied.

![Figure 2. Representation of the bobbin positions in the 3D-braid model](image1)

![Figure 3. Geometrical models of the stitching loop shapes](image2)

Shape of the distortions in the plies of non-crimp fabrics structurally stitched with different types of yarns and using different stitching techniques were studied and parameters necessary for modelling of the distortions (width and length of the “openings” normalised by the stitching yarn compressed diameter) were determined.

4 DAMAGE AT MESO-LEVEL

Models for damage at the meso- and micro-level are tested against experimental observations of damage in composite reinforced with different textiles, including 3-axial braid, uniaxial braid, NCFs [3, 4].

4.1 “Road map” for meso-FE modelling

Consider a typical problem of meso-FE modelling of the unit cell of a textile composite under loading conditions representing its actual loading in a composite part. The following tasks can be performed (Fig 4):
- For the given load (which may include also thermal and cure stresses) calculate the stress-strain fields inside the unit cell;
- Assess stress-strain concentrations and identify damage sites;
- When damage occurs, recalculate the local mechanical properties of the impregnated yarns and matrix and recalculate the homogenised properties of the damaged composite. These calculations proceed for loading along a certain monotonically increasing loading path to calculate the non-linear behaviour of the damaged composite.
- Calculate the homogenised properties of the composite material (undamaged or damaged);

The textile modeller WiseTex is integrated with FE packages in two ways. First, a WiseTex model is transformed into a set of ANSYS commands, which, after being read and executed by ANSYS, creates solid CAD-description of textile. Subsequent stages (meshing) have limitations due to interpenetration of the yarn volumes. However, simple cases, like not very tight plain, twill or satin weaves, are handled effectively, and the model in ANSYS is built fully automatically, including assignment of the orthotropic elastic properties to the yarns and applying the periodic boundary conditions.

Second, WiseTex is integrated with SACOM FE solver via the MeshTex software with. In the current version MeshTex implements algorithms of correcting yarn interpenetration for woven fabrics (2D and 3D), assigns orthotropic elastic properties to the yarns, applies periodic boundary conditions, performs elastic calculations and accounts for the damage initiation and development.

Figure 4. “Road maps” for meso-FE: (a) linear; (b) with damage

4.2 Damage modelling in 3-axial braid

After building a meso-FE model for a textile composite (Fig.5), the damage initiation modelling becomes possible. Several decisions must be made for meso-FE modelling of damage: (1) choice of the damage initiation criteria, (2) formulae for decrease of the stiffness of the damaged elements and (3) algorithm for the damage propagation. Damage initiation criteria, applied on the micro-level, treats yarns and fibrous plies locally as unidirectional composites. Hence, the whole selection of criteria, analysed and benchmarked during World Wide Failure Exercise (WWFE) can be used. Existing formulae for the decrease of stiffness after damage and damage propagation have several weak points, the most important being the arbitrary choice of constants for deterioration of properties and possible mesh dependency of the damage propagation process.
For the calculations of the 3-axial braided composite the Hoffmann and Puck criteria were used. In the absence of reliable data on the dependency of the strength properties on the local fibre volume fraction in the impregnated yarns, the strength parameters were assumed to be the same everywhere in the yarn and correspond to experimental data on UD plies for the fibre volume fraction range 40…60%.

Acoustic emission, full-field strain measurements and X-ray investigation indicate the damage onset at the applied strain of 0.3%. The maximum value of the calculated transversal damage index $H_T = 0.94$, hence the applied strain of 0.3% is close to the theoretical damage initiation strain. The damage is caused by the transversal tensile stresses, and starts in the braiding yarn, lying at 45° to the loading direction. This corresponds to the X-ray observation of the damage.

### 4.3 3D damage criterion

The failure behaviour of three dimensionally reinforced textiles is more complex compared with the failure of unidirectional reinforced prepgs, for which the failure criteria of Hashin, Puck and Cuntze et al. were originally developed. Therefore Juhasz [5] enhanced the simple parabolic failure criterion of Cuntze et al. and considered a slightly three-dimensional reinforced material. Thereby it was supposed that the fibre volume fraction of the out-of-plane reinforcement fibres, which is a stitched or tufted yarn, is significantly lower than the in-plane fibre reinforcement. Therefore a single ply of a three dimensionally reinforced lamina can generally be characterised by an orthotropic material behaviour.

The simple parabolic criterion of Cuntze et al. was modified in accordance with the orthotropic material behaviour of three-dimensional reinforced textiles by definition of new strength parameters and a certain procedure for the determination of the material parameters. The basic strength parameters are defined by tests in the primary material directions. Therefore compression as well as tension test results are required for all three dimensional material directions. The calculation of the strength parameters of the criterion as well as the numerical parameters are based on a variation of the off-axis angle (Fig.6).

### 4.4 Implementation of Ladevéze model for textile composites

The model of Ladevéze was applied to textile composites, both on micro-level, as a local damage criterion, and on meso-level – characterisation of UD-braid reinforced material. The model describes unidirectional fibre reinforced composites using
continuum damage mechanics formalism. The elementary material behaviour law is modified by introducing scalar damage variables. The model distinguishes between fibre damage, transverse damage and shear damage.

A set of FORTRAN subroutines for MSC.Marc are developed to implement the Ladevèze damage model and to allow calculations with periodic boundary conditions.

4.5 FE modelling of damage propagation

When it comes to the damage propagation, the calculations show an unexpected behaviour. The damage propagates along the yarn (Fig 7), in the direction of the fibres, as one expects and as it is observed in experiments. However, it also propagates across the yarn, suggesting a multitude of micro-cracks, which is not observed in experiment (there are one-two well-separated cracks over the whole yarn width). This seems to be a common drawback for meso-FE modelling of damage, which uses local damage criteria and properties degradation scheme. The reason of this behaviour is believed to be the fact that the real propagation of a thin crack is substituted in the damage mechanics approach by analysis of a stress field around a damaged volume element. This gives wrong position of the maxima of the damage criterion for the case of shear loading. This will be a subject of further investigations.

5 CONCLUSIONS

The multi-level geometrical and damage models of textile composites developed in the ITOOL project form a solid basis for integrated design tool for textile composite parts.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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