FROM A MICRO-CT IMAGE TO MODELS OF THE INTERNAL GEOMETRY, DEFECTS, MICROMECHANICS AND PERMEABILITY OF TEXTILE COMPOSITES – VOXTEX SOFTWARE

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Abstract

The paper describes the software VoxTex, which realises methods for the analysis of a micro-computed tomography (μCT) image of a textile composite and the transformation of the image into a voxel model in which the fibrous structure of the reinforcement (fibre volume fraction and fibre direction) is identified for each voxel. Based on this model various calculations can be done: geometric characterisation such as the fibre (mis)alignement in the yarns and plies and the void percentage; micro-mechanical calculations of the homogenised stiffness of the composite; creation of a finite element model wich allows meso-level (unit cell level) simulations of the mechanical response of the composite, including damage initiation and development and permeability calculations. This functionality is implemented in VoxTex. The paper gives an overview of VoxTex applications for 2D and 3D woven, non-crimp fabric composites and laminates created with automated tape laying.

1 Introduction

X-ray micro-computed tomography (μCT) is a powerful tool for 3D imaging of the internal structure of materials (Figure 1a). The last decade a rapid growth of μCT applications for textiles and textile composites emerged and this growth is in line with the fast development of the μCT hardware. The X-ray computed tomography apparatus, from desktop to synchrotron-based instruments, allow the registration of 3D images with submicron and micron resolution, with a contrast sufficient to distinguish organic and carbon-based materials (like polymer matrices and carbon fibres) and the image post-processing is very effective in eliminating the imaging artefacts.

Beautiful 3D images, however, are not used in full as the virtual representation of the internal structure of textiles and textile composites, because the voxel structure of the image lacks directionality, which is the paramount local characteristic of fibre reinforced composites and fibrous assemblies. The directionality defines the local axes of the anisotropy, which, in their turn, lead to anisotropic properties of the dry or impregnated fibrous bundle or a ply (like the local permeability and the local stiffness tensor). Another important use of the directionality lies in the fact that it (or rather the local anisotropy) provides an additional image feature for segmentation, together with the grey scale values of the image voxels. The segmentation or thresholding based on the grey scale only is prone to uncertainties, which are made worse by the similarity of the density and chemical composition of carbon or organic or cellulose fibres and organic matrices. The addition of the second feature – the structural anisotropy – allows the use of powerful segmentation methods based on cluster analysis, bringing a decisive improvement of the segmentation precision. Moreover, the identification of the local directionality makes the identification of yarns of different directions (warp vs weft in woven

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fabrics, braiding vs axial yarns in braids etc.) and the analysis of the local fibre misalignement possible.

2 VoxTex software

VoxTex software employs methods of 3D image processing, which use in full the local directionality information, retrieved using the analysis of the local structure tensor [1].

The processing results in a voxel 3D array (the voxel dimentions can be the same as in the initial µCT image or larger), with each voxel carrying information on (1) material type (matrix; yarn/ply, with identification of the yarn/ply in the reinforcement architecture; void) and (2) fibre direction for fibrous yarns/plies. The knowledge of the material phase volume and the known characterisation of the textile structure allows assigning to the voxels (3) the fibre volume fraction. This basic voxel model can be further used for different types of material analysis.

VoxTex functionality includes (Figure 1b):

- Automatic conversion of CT images into voxel models
- Connection to finite element models (Abaqus)
- Connection FlowTex (fluid dynamics) for permeability modelling
- Connections to ParaView and Root Data Analysis Framework for data visualisation
- Orientation analysis, misalignment analysis, image segmentation

The adequacy of voxel models depends on a correct definition of the phases in the model, which is the result of the segmentation procedure. The VoxTex segmentation method is based on the two quantities – average grey value and structural anisotropy – which reflect local physical properties of the material.

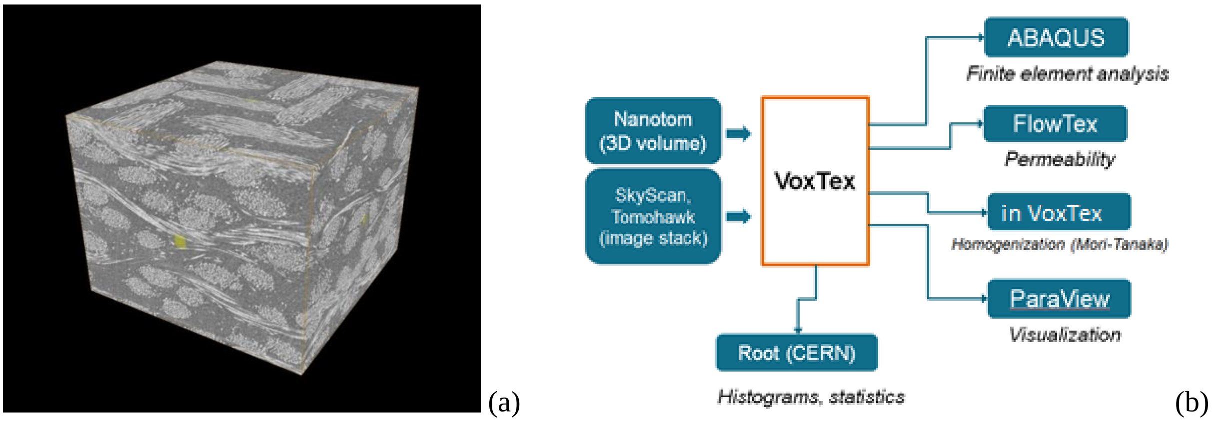
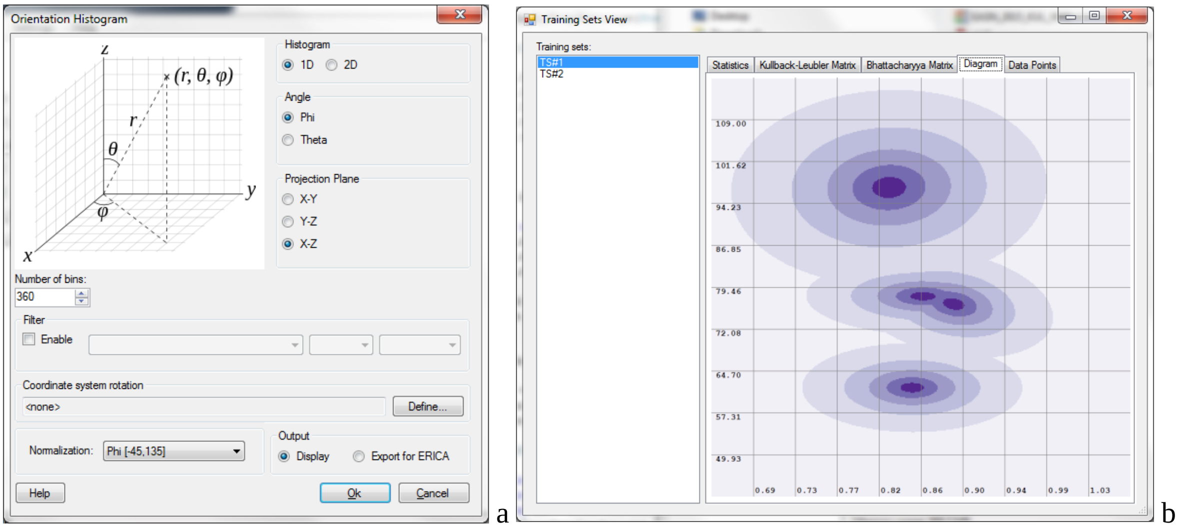


Figure 1 A typical µCT image of textile composite (a) and a dataflow in VoxTex (b)



Histogram: ● 1D ○ 2D
Angle: ● Phi ○ Theta
Projection Plane: ○ X-Y ○ Y-Z ● X-Z
Number of bins: 360
Filter: ☐ Enable
Coordinate system rotation: <none>
Normalization: Phi [-45,135]
Output: ● Display ○ Export for ERICA

Training sets:
TS#1
TS#2

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Figure 2 Orientation analysis and segmentation of image in VoxTex: (a) GUI for orientation analysis; (b) identification of voxel sets for warp, weft, matrix and voids

The average grey value reflects the X-ray attenuation in the material, which is proportional to its density and atomic weight (averaged). The structural anisotropy reflects the local structural properties of the material and allows making a distinction between matrix, which is structurally isotropic, and reinforcement, which is structurally anisotropic due to the presence of fibers with a particular primary orientation. The construction of a Gaussian mixture model on the basis of the selected subset of data is known as supervised classification. For micro-CT images of composite materials, the application of statistical methods is necessitated by the noise, always present in the CT image, and by the variability of the material's microstructure, which make all the derived quantities inherently non-deterministic.

3 Internal geometry and characterisation of defects

The image segmentation gives direct values of the material porosity and the position of the voids. The segmented voxel model is visualised via *ParaView*. The information of the direction of the fibres is processed to yield histograms of the fibre misalignment angles and the deviations of the yarns from the nominal directions. The VoxTex functionality includes tools which allow such an analysis.

Figure 3 illustrates such an analysis for a $(-45/0/45/-20/0/20/90/0)_{so}$ carbon/epoxy laminate, created with a Dry Tape Laying process. It allows identifying the precision of the tow placement, which is within 1° and the in-plane and out-of-plane misorientation of fibres, which is (2…4)° and (1…2)° respectively.

Voids and resin pockets are clearly seen in the µCT image (Figure 3a) and their volume can be easily calculated; therefore VoxTex is a useful instrument for the characterisation of defects in fibre reinforced composites.

The analysis of the fibre misorientation is applied in [2] to evaluate the changes of the fibrous structure of a woven reinforcement after shearing during forming.

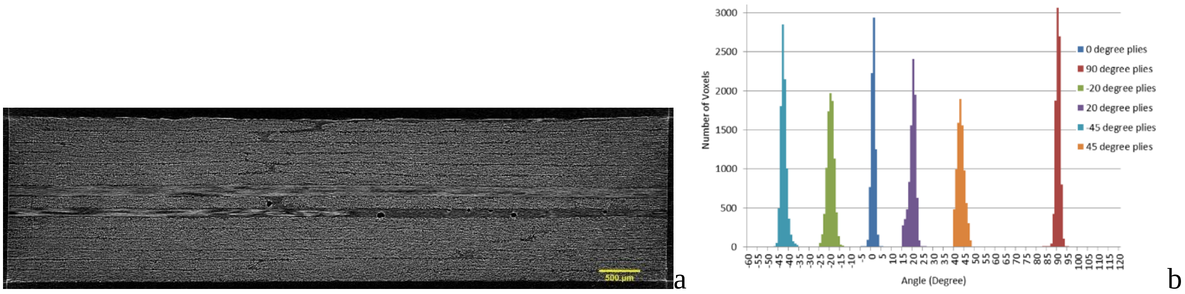

Figure 3 Analysis of fibre misalignement in plies of $(-45/0/45/-20/0/20/90/0)_{so}$ laminate, created with Dry Tape Laying process: (a) µCT image; (b) histogram of fibre misalignment in different plies

4 Permeability

After segmentation into voxels representing the inter-yarn space (matrix and voids) and yarn volumes, the voxel model is ready to be transferred to a CFD software to calculate the homogenised permeability solving Navier-Stokes or Stokes equations. Intra-yarn/ply permeability can be taken into account by assigning a local permeability to voxels, belonging to yarn/plies volumes, using the homogenisation formulae and the information on the fibre volume fraction and the fibre direction in the voxel. The Brinkmann equation is solved in this case. VoxTex is integrated with FlowTex solver (KU Leuven) [3, 4] for such calculations.

The possibility of a correct (within the experimental scatter) calculation of a textile reinforcement permeability based on X-ray micro-computed tomography registration of the textile internal architecture (Figure 4) is demonstrated in [5] for an example of a non-crimp carbon fabric laminate (540 g/m2, +45/-45, tricot stitch).

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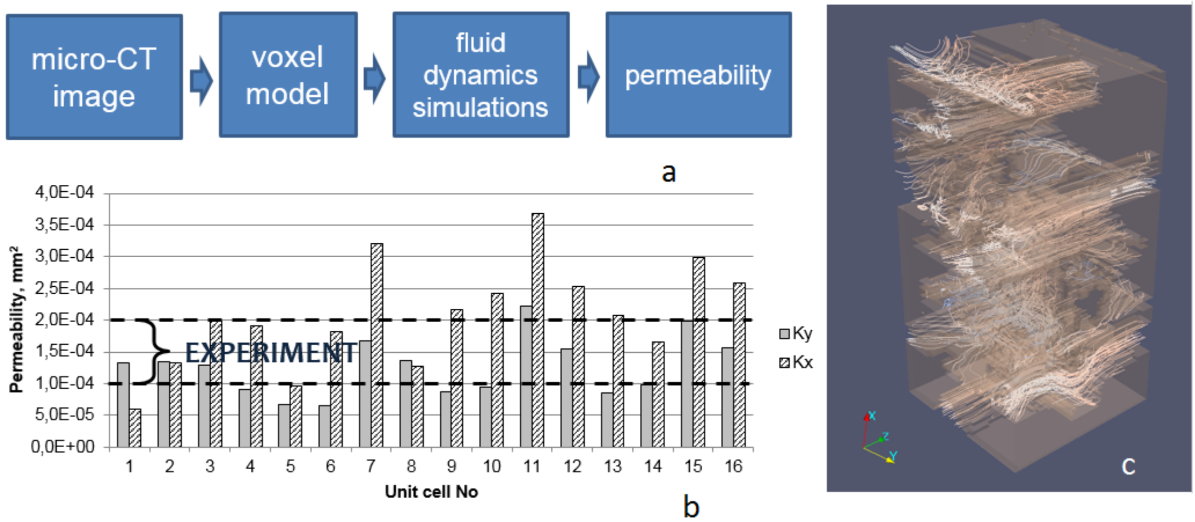

Figure 4 VoxTex calculations of permeability: (a) data flow; (b) comparison of calculated and experimental permeability of a NCF laminate; (c) liquid flow lines in a unit cell voxel model, calculated with FlowTex

5 Micromechanics and finite element models

Considering a representative volume of the composite and assigning the mechanical properties to voxels, according to the voxel fibre volume fraction and fibre direction or to properties of the matrix, a homogenisation routine (iso-strain, Mori-Tanaka…) can be employed to calculate homogenised stiffness of the composite. These capabilities are integrated in VoxTex.

The voxel model with assigned material properties per voxel is ready to be transferred to FE software. VoxTex produces an ABAQUS input file for the voxel model, or invokes own FE solver. Using a continuum damage model for a unidirectional fibre reinforced material, the calculation can include the damage initiation and growth and simulate a reduction of the load-carrying ability of the textile composite with damage progression.

Figure 5 and 6a illustrate the finite element models of a unit cell of a 3D woven glass/epoxy composite and results of the calculation of homogenised moduli of this material. Figure 6b shows response of a carbon-epoxy composite with the same weave structure under tension loading in shear direction (difficult case for damage models).

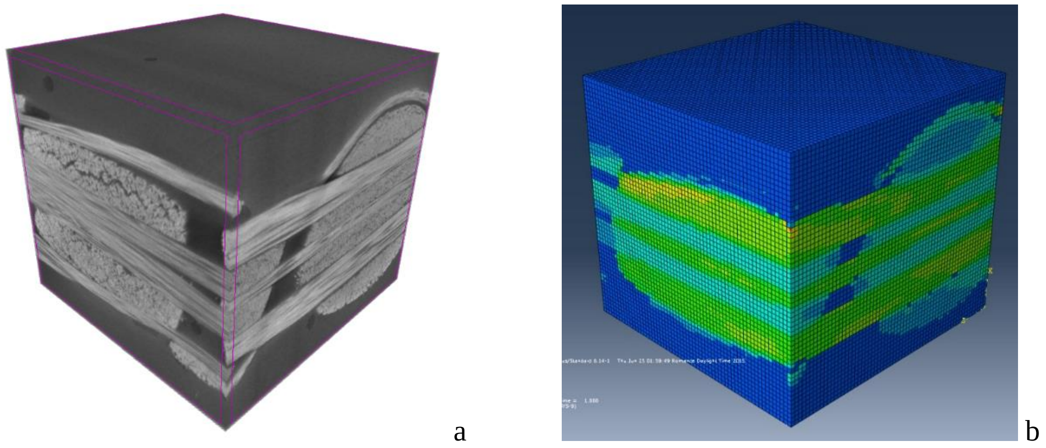

Figure 5 Transformation of a µCT image of a 3D glass/epoxy woven composite (a) into finite element model (b)

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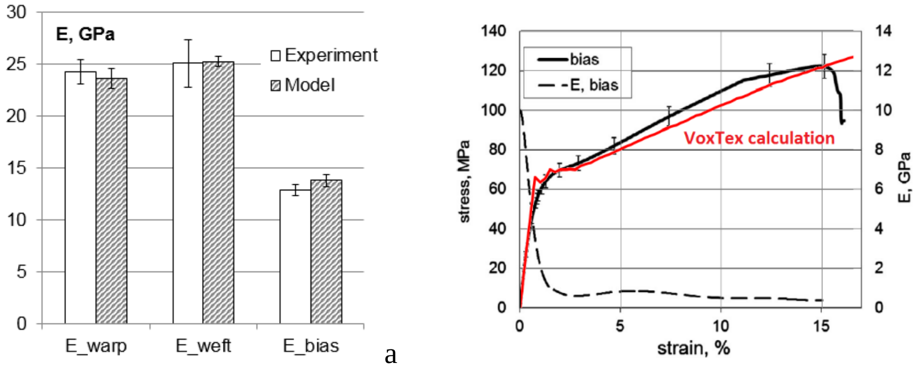

a b

Figure 6 Comparison of the µCT-based VoxTex calculations of the mechanical properties of a 3D woven composite: (a) homogenised properties of a glass/epoxy composite (experimental data: [6]); (b) tensile stress-strain diagram for loading of carbon/epoxy composite in bias direction (experimental data:[7])

6 Conclusion

VoxTex is a powerful and validated tool for µCT based investigations of the fibrous structure of textile composites and the mechanical behaviour of the composite. Compared to the existing approaches for the modelling of composite reinforcements on the basis of experimental data, VoxTex does not require any significant manual effort for the data extraction to create a geometrical model and to proceed with the analysis of the internal structure, permeability or mechanical simulations.

Acknowledgments

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