MICRO-CT-BASED ANALYSIS OF FIBRE-REINFORCED COMPOSITES: APPLICATIONS

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Abstract

The paper presents an overview of cases in which the analysis of the internal structure and mechanical properties of fibre reinforced composites is performed based on the micro-computed X-ray tomography (micro-CT) reconstruction of the composite reinforcement geometry. In all the cases, the analysis relies on structure tensor-based algorithms for quantification of the micro-CT image, implemented in *VoxTex* software.

Keywords: micro-computed tomography, internal structure, mechanical properties, variability

1. Introduction

The description of a fibre reinforced composite microstructure involves the identification of individual yarns/fibrous plies and the definition of local parameters of the fibrous geometry: local fibre directions, local fibre volume fraction and description of the amount and morphology of voids. The methods and the software, developed at KU Leuven [1] (*VoxTex*), analyse X-ray micro-computed tomography (micro-CT) images, producing a description of the fibrous microstructure as an array of volume elements (voxels), each element carrying information of the fibre directions and fibre volume fraction in it. Apart from that, the amount and morphology of voids in the composite are characterised. The methods are based on a two-parameter analysis of the image: the local grey scale value and the anisotropy, the latter defined via the structure tensor of the grey scale field.

VoxTex has a broad functionality, as depicted in Figure 1. The paper presents a "gallery" of applications of these methods to different problems of the geometrical characterisation and meso-mechanics of fibre reinforced composites.

Apart from the cases shown in this paper, *VoxTex* has been used in different studies of composites presented in ECCM-18 (see papers by K. Ilin et al., O. Shishkina and A. Matveeva et al., H. Tanabi et al. and D. Vasiukov et al.).

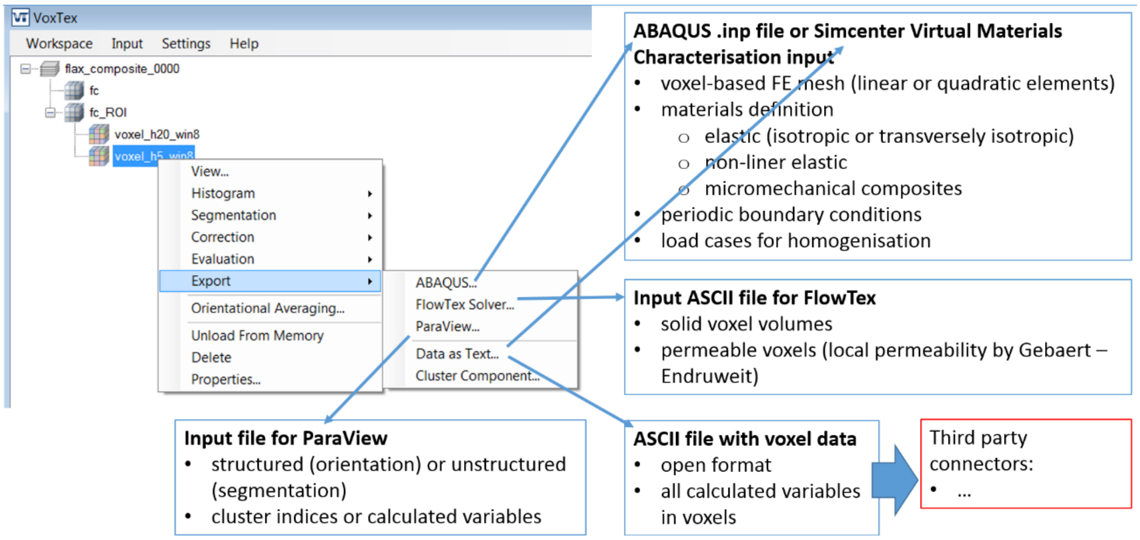


Figure 1 *VoxTex* functionality

2. Regularities and irregularities of the composite internal structure

2.1 Fibre misalignment in composites, created by automated fibre placement of carbon tows and automated tape laying of prepregs

In [2] a methodology is proposed for the analysis of in-plane and out-of-plane fibre misalignment in carbon fibre reinforced laminates, based on micro-CT images, which includes (1) micro-CT image acquisition with the rotation axis parallel with 0° and 90° ply (Figure 2a); (2) transferring micro-CT images into a voxel model using VoxTex, which calculates average greyscale values, an anisotropy index and principal anisotropy orientation for the voxels; (3) selecting a mid-layer volume in each ply to avoid the region with mixed orientation error; (4) analysing the in-plane and out-of-plane orientation distribution of each ply; (5) combining results from the 0° and 90° scans (Figure 2b). VoxTex software is a ready-to-use tool for such measurements.

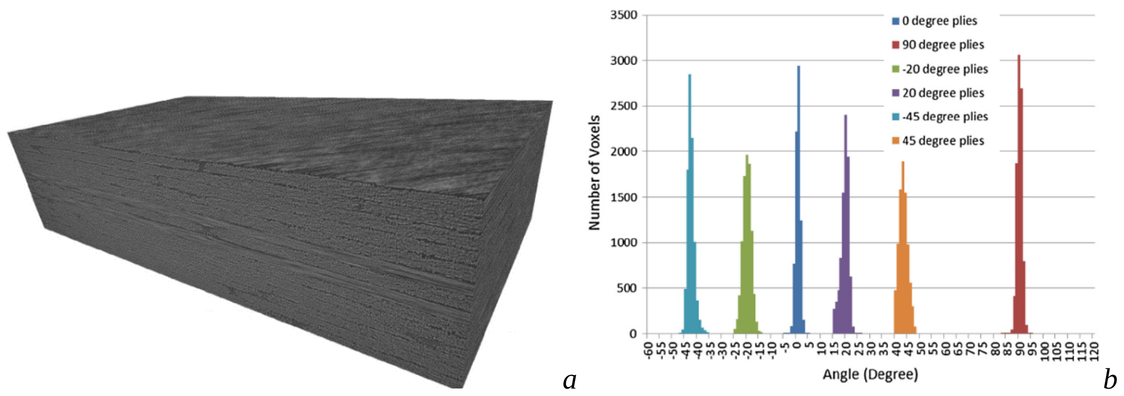
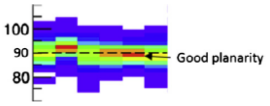
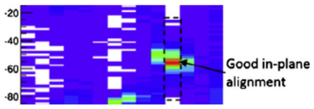
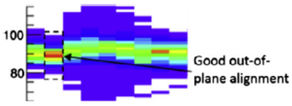
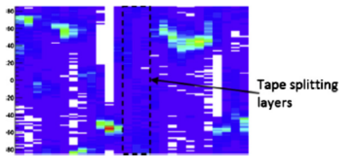
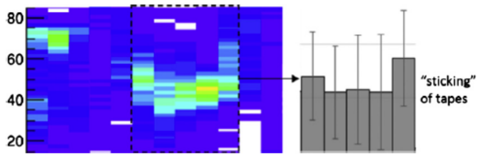
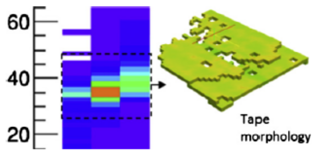


Figure 2 Fibre orientation in composites, produced with automatic tape laying: (a) micro-CT image of the [-45/0/45/-20/0/20/90/0]$_{so}$ laminate; (b) fibre orientation distribution in the plies [2].

Application of the methodology to two laminates manufactured with automated tape laying + autoclave and automated dry fibre placement + VARTM has shown the precision of the placement/laying within (1.2–1.9°) and the out-of-plane misorientation of fibres below 2.4° for both processes. The in-plane inter-ply misalignment of fibres in the prepreg laminate is within 2–4°, which is twice as high as the misalignment in the infusion-produced laminate (1–2°). The observed differences between the two materials have been attributed to the difference in their processing conditions, particularly the cure pressure. The misalignment of the fibres is within 2° degrees for both materials, which reflects the high stability of both manufacturing processes.

2.2 Regularities and irregularities of the internal structure of the composites, reinforced with randomly oriented chopped carbon strands

Table 1 Features of the internal geometry of chopped carbon fibre tapes reinforced thermoplastic, revealed via micro-CT image analysis [3]

Features	Required data	Example characterization	
Planarity of layers	Unfolded histograms of θ_{XY}	The layer have good planarity if the θ_{XY} of corresponding VOI is close to 90°	
In-plane fiber deviations in the tapes	Unfolded histograms of φ_{XY}	The fibers in tape have good in-plane alignment if the φ_{XY} of corresponding VOI is concentrated to certain angle	
Out-of-plane fiber deviations in the tapes	Unfolded histograms of θ_{XY}	The fibers in tape have good out-of-plane alignment if the θ_{XY} of corresponding VOI is concentrated to certain angle close to 90°	
"splitting" of the tapes	Unfolded histograms of φ_{XY}	Tape splitting was occurred if the φ_{XY} of corresponding VOI is widespread and does not have significant concentration	
"sticking" of the tapes	Unfolded and quantified histograms of φ_{XY}	Tapes in several layers are considered was stuck if the corresponding adjacent VOI exhibit cluster of φ_{XY} distribution and the SD show similar value	
Tape morphology after molding	Unfolded histograms of φ_{XY} and 3D model	The integral, fractional and split tapes' morphology can be determined and built by combining the corresponding φ_{XY} concentrations in the VOI with thresholded subsets of 3D model	

The VoxTex tools have been applied in [3] to determine the internal geometry of chopped carbon fibre reinforced thermoplastic tapes with complex multi-scale structure. Features of fibre orientation distribution of in-plane and out-of-plane fibre directions were interpreted to reveal the structural features of the placement and fibre misalignment of the tapes (Table 1). The combination of fibre orientation histograms with visualized 3D models gives a highly intuitive method for the understanding of the fibrous structure of the material.

2.3 Fibre alignment, structure of fibre bundles and void content in pultruded glass reinforcement profiles

The internal geometry and presence of manufacturing induced defects in a glass/polyester pultruded composite profile were investigated using micro-CT images analysed with VoxTex in [4].

Resin rich areas are observed in between the glass rovings at which the unidirectional fibres are misaligned with respect to the desired pulling direction. The results show that the misalignment for the in-plane fibre orientation is more severe (30-40°) than for the out-plane fibre orientation (10-20°). Two different types of porosities are identified: the first one is discontinuous and located inside the resin rich areas; the second one is more severe, continuous and located between the glass rovings (Figure 3). The fibre misalignments and voids cause a 15-20% reduction in the longitudinal stiffness of the part in comparison with the expectations for ideal microstructure.

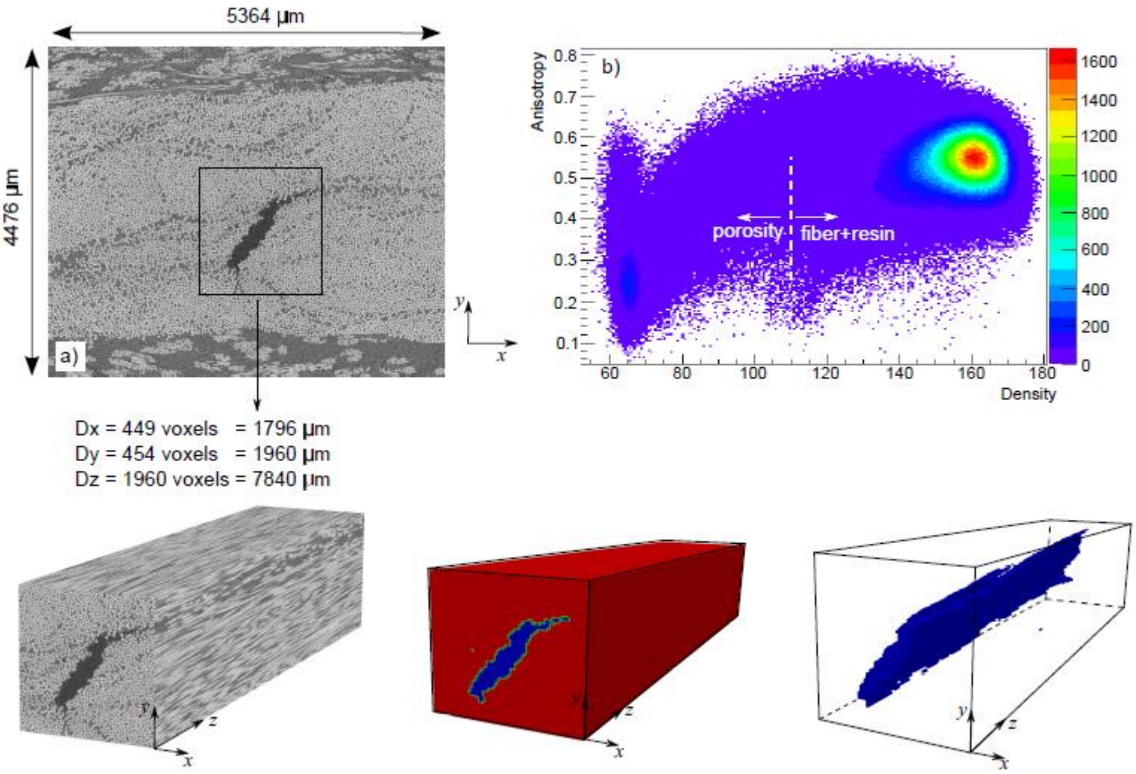


Figure 3. Longitudinal crack in a pultruded glass/epoxy profile: micro-CT cross section, anisotropy – density histogram of the image and segmentation of the crack volume [4]

3. Mechanical properties of composites

3.1 Use of the micro-CT fibre orientation information for analysis of the impregnated fibre bundle test

The paper [5] proposes a method to calculate the modulus in tension of quasi-UD impregnated fibre bundles accounting the bundle deviations from uni-directionality, caused by yarn twist and fibre misalignment. In quasi-UD materials, fibres may be misaligned, which makes the inverted rule of mixtures not applicable for the calculation of the fibre modulus. The modulus of flax fibre is identified through a fitting procedure on finite element models of quasi-UD samples, which explicitly takes into account misalignment of fibres: the modulus of the fibres in the model is chosen so that the calculations produce correct value of the bundle modulus. The spatial distribution of fibre orientations in the material is measured based on X-ray computed tomography images (Figure 4a). For each sample a voxel finite element model (Figure 4b) is constructed, using local fibre orientations to assign local material properties.

This calculation accounts explicitly for the misalignment and twist of the yarns in the material. The method is verified with experimental data on a UD material, manufactured from the same fibres. The uncertainty in the fibre modulus, calculated from the quasi-UD data and finite element models, comes from the uncertainty in the experimental value of the quasi-UD material, and from the individual structural differences in the samples that are modelled. Estimation of the total contribution of these factors to the uncertainty in the fibre modulus value is done using Monte-Carlo simulation.

The value of the flax fibre modulus, obtained with the proposed method, is 63.0±1.46 GPa, which is in good agreement with the value from the UD material tests (62.4±2.87 GPa).

The same approach can be used for the investigation of premature damage in UD composites due to local inhomogeneity of unidirectional fibres misalignment and voids (see the paper of K. Ilin et al in the present Proceedings).

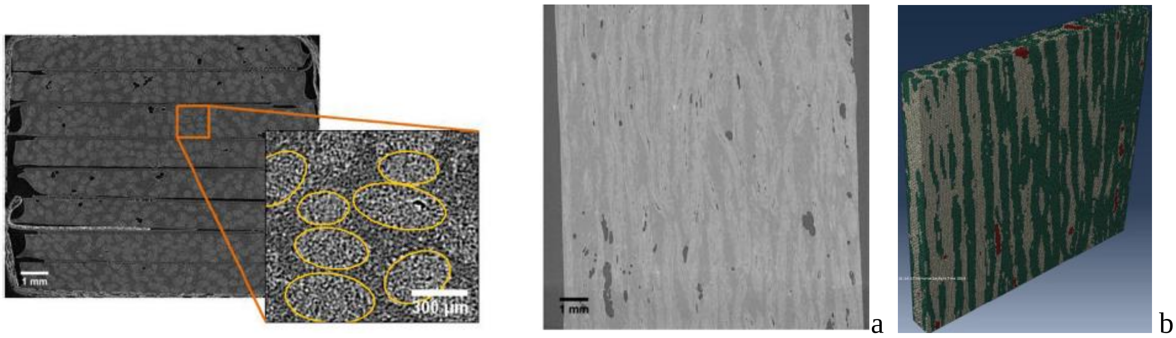


Figure 4 UD fibre bundle sample, flax/epoxy: (a) micro-CT image, section across and along the fibre direction; (b) FE model [5]

3.2 Micro-CT-based finite element homogenization of sheared organo sheets

In *(*O. Shishkina, A.Matveeva et al, *in the ECCM-18 proceedings)* the authors assessed the effect of shear on the local stiffness properties of thermoplastic-based sheared organo sheets (glass-PA6) with a woven architecture both experimentally and virtually. 3D micro-CT images of the samples were segmented into voxel models based on the anisotropy and orientation vectors in VoxTex software [1]. Next, finite element (FE) models were automatically created in the Simcenter 3D FE environment to seamlessly perform micro-CT-based FE-homogenization on the unit cells (Figure 5).

The error between the average experimental values and predicted Young's moduli lies in the range of 2-15% in the warp direction and in the range of 5-32% in the direction of shear. The differences are assumed to be due to the variability in the material and in the sample preparation and testing.

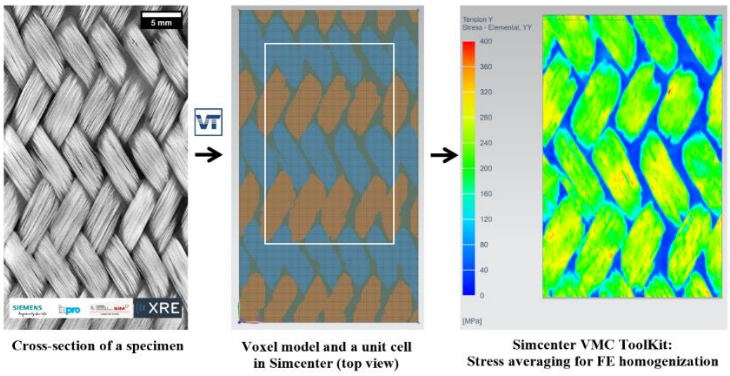


Figure 5 Micro-CT-based FE homogenization for stiffness in the Simcenter 3D FE environment including VMC ToolKit and VoxTex software (KU Leuven, MTM).

3.3 Damage initiation and development in 3D woven carbon reinforced composites

In [6], the models of a 3D orthogonal glass/epoxy woven composite based on reconstructed X-ray CT images (referred to as 'real' models), are compared with the conventional parametric modelling scheme. The micro-CT reconstruction allows a high-fidelity reconstruction of the composite mesostructure, including the waviness of the yarns, the variation of yarns' thickness, the complex shapes of the yarn cross sections and the unevenness of yarn surfaces (Figure 6a,b).

The performance of the real and the idealized (TexGen) models is examined via the homogenization of in-plane properties and via the simulation of the damage and failure process (Figure 6c). The accuracy in prediction of both effective elastic and damage properties using real models is higher in comparison with idealized ones. The predicted non-linear stress-strain diagrams adequately represent the measured ones.

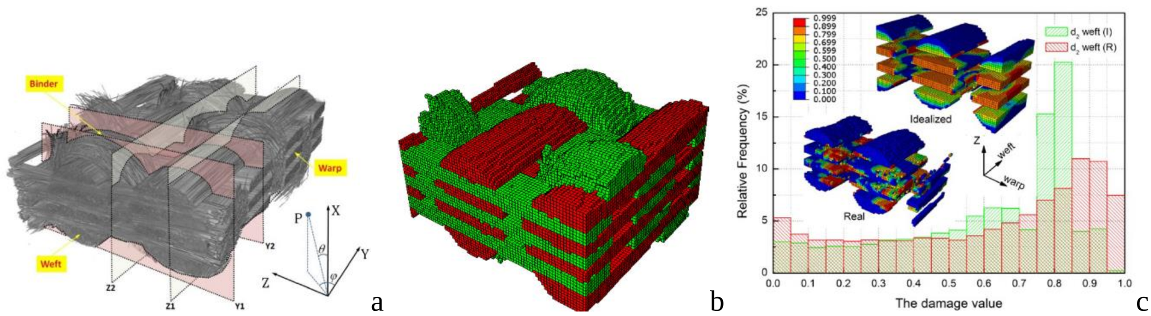


Figure 6 Damage modelling of 3D woven glass/epoxy composite (matrix is hidden in the images): (a) micro-CT image; (b) voxel model of the yarns; (c) damage distribution in weft yarns in the micro-CT based (Real, R) and TexGen (Ideal, I) model just before the failure [6]

4. Permeability of textile reinforcement

The paper [7] demonstrates 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. A supervised image segmentation procedure was used to achieve the necessary precision of reconstruction of the geometry and to study variability of the geometry and local permeability.

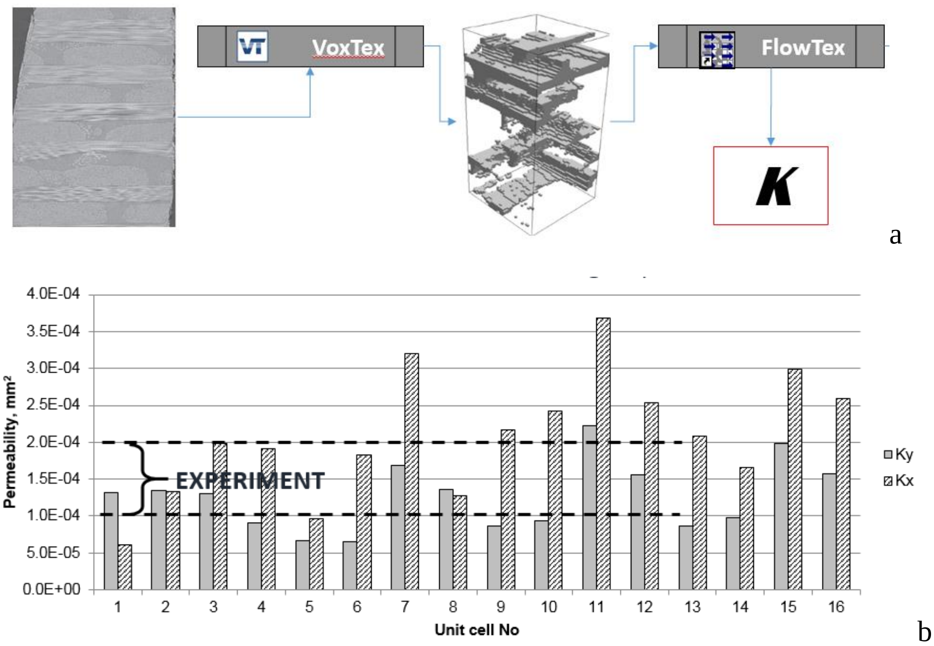


Figure 7 Micro-CT based calculation of permeability: (a) data flow; (b) comparison between the calculated and experimental results.

The homogenized permeability of a non-crimp textile reinforcement is computed using computational fluid dynamics software FlowTex with voxel geometrical models (Figure 6a). The models are constructed from X-ray computed tomography images using a statistical image segmentation method based on a Gaussian mixture model. The computed permeability shows a significant variability across different unit cells, in the range of $(0.5…3.5)\cdot10^{-4}$ mm^2 (Figure 7b), which is strongly correlated with the solid volume fraction in the unit cell. The good agreement of the modelling results with the experimental data (Figure 7b) indicates that the segmentation procedure provides the phase domain boundaries that are close to the true ones.

In [8] the voxel porosity descriptions, created by VoxTex, are used to perform diffusive transport and tortuosity factor calculations, which can serve as a proxy for permeability in composite materials.

5. Conclusion

Micro-computed X-Ray tomography is a state-of-the-art tool. An efficient way to address scientific and industrial needs for detailed investigation of internal structure of fibre reinforced composites is implemented in *VoxTex* software. It provides a ready-to-use user-friendly solutions to micro-CT imaging data processing and allows a seamless data transfer to mechanical modelling software in order to calculate homogenised stiffness, damage development, strength and permeability, leading finally to quantification of the manufacturing effects on fibre reinforced composites performance.

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