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Quantification of the internal structure and automatic generation of voxel models of textile composites from X-ray computed tomography data

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ABSTRACT

X-ray computed tomography provides an opportunity for a detailed examination of the inner structure of fibre reinforced composites. Three-dimensional images, obtained with micro-CT, can be used for a realistic modelling of composite materials. All modelling objectives imply the knowledge of the orientations of the fibres inside the composite, which determine the local (anisotropic) properties. This paper investigates application of the structure tensor, a concept from the image processing field, to the determination of the orientations of fibres and to segment the image into the material's components, for the purpose of an automatic generation of a voxel-based description of the representative volume element. The segmentation of the images of CFRP materials into its components is performed by thresholding, or by clustering in a two-dimensional parameter space of the degree of anisotropy and average grey value or one of the components of the orientation vector. Clustering allows not only separating the matrix from the yarns, but also distinguishing the yarns of different primary orientations.

1. Introduction

X-ray computed tomography (micro-CT) enables a highly detailed examination of the inner structure of fibre reinforced composites. Modern micro-CT equipment allows resolutions high enough not only to reconstruct the yarn architecture in a textile composite, but even to distinguish individual fibres in the yarns [1–3]. The next challenge is to utilize this tremendous amount of information to predict the properties of the material.

The most accurate method in modelling the mechanical behaviour of textile composites on the meso-level (unit cell) is finite element (FE) modelling [4]. The first step of any meso-FE model is the creation of a volumetric model of the yarn geometry. Transversally isotropic properties of yarns, derived from the local fibre volume fraction are then assigned to the yarn homogenized material [5], requiring the knowledge of the local fibre orientations. The local fibre orientations are also needed for damage modelling [6–9], be it for the orientation of a damage tensor, for the positioning of a crack plane, or for the application of fibre breakage statistics.

The accurate description of the textile composite at the meso-level therefore requires segmentation of the material into its components and knowledge of the orientations of the fibres at the points inside the (anisotropic) composite.

The problem of segmentation is a problem of an appropriate description of the geometry of the reinforcement. There are two approaches to this: the extraction of the yarns' surface and a voxel-based description. According to the first approach, a smooth boundary surface between yarn and matrix is defined, the whole volume is meshed taking into account the surfaces of the yarns, and the material properties (yarns or matrix) are assigned to the elements of the mesh. The resulting mesh is irregular, as yarns may have a complex shape and often touch each other. Moreover, the segmentation of a noisy grey-scale image may lead to rough irregular surfaces. An easier way to describe the yarns is a voxel-based approach, for this a region of the material is meshed with a regular rectangular mesh of voxels, and the material properties are then assigned to each voxel. There are several studies in orthopaedics biomechanics that involve the conversion of micro-CT images into finite element models [10–14], using both approaches described above. In these studies, a finite element mesh is produced with an element size varying from 20 μm to 5 mm and make use of the isotropic mechanical properties of the material. The value of the Young's modulus is assigned either constant throughout the specimen or using non-linear transformation from the grey value in the micro-CT image [12]. A composite materials related

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study [15] presents the model of the unit cell of a fabric and a procedure for the finite element model generation on the basis of yarns trajectories and the cross-section shapes derived from optical images.

Characterisation of the structure of some composite materials from the micro-CT has been done in various ways. In [16,17] the shape of yarns in a dry fabric was analysed under different loading cases in order to validate the deformation modes of the fibre bundle under the loading. The prediction of the permeability, the mechanical behaviour and some meso-scale damage simulations were conducted in [17]. The damage evolution in a unidirectional natural fibre reinforced composite was studied in [18]. Micro-CT was also used to extract the fibre orientations and length distributions [19,20], and for the analysis of the local fibre volume fraction in unidirectional reinforced composites. A statistical analysis of the tow geometry in [21,22] was done to characterise the stochastic deviations of the tows from the ideal shape and to build a model that would allow generating virtual samples with the same statistical properties as the real ones.

Determination of the orientations of the fibres is vital for modelling textile composites. One of the oldest approaches to this problem is the optical analysis method, where the elliptical footprints of fibres are examined in the microscopic image of the sample's polished cross-section [23]. More recent methods deal with optical images as well as three-dimensional micro-CT images, and may or may not require segmentation of the image into fibres and matrix domains. Many of the methods measure the variability of the microstructure reflected in the image, in different directions. The process of measurement may involve counting the number of intersections with a fibre–matrix boundary, as in the Mean Intercept Length (MIL) technique [24]; or a step by step rotation of a region of the image and the application of an anisotropic filter to find more probable direction [25]; or the transformation of the image into the frequency domain with two-dimensional Fourier transform [26].

This paper investigates the application of a so-called *structure tensor* for the determination of the orientations of the fibres in textile composites based on micro-CT images. The concept of the structure tensor is known from the field of image processing, where it is used for the detection of edges in images [27,28], image segmentation [29], to visualize and quantify tissue microstructure [30], to quantify structural anisotropy in tissue [31] and for analysis of textures in images [32]. Here the structure tensor is also used for the segmentation of the micro-CT image into matrix, yarns and voids (pores) for the purpose of automatic generation of a voxel-based description or voxel model of a composite material. The micro-CT image is considered as a three-dimensional array of grey values and all computations are performed on such arrays. Each voxel of the resulting model conveys information about the material type and orientation (for anisotropic materials). The voxel models can be converted into finite element models for mechanical calculations; or into voxel models specific for permeability analysis, where the local anisotropic permeability tensor, derived from theoretical models for unidirectional material, is rotated according to the orientation of fibres.

This paper is organized as follows. Section 2 discusses the methods and algorithms of the orientation analysis and segmentation, which are needed in the steps to create a voxel model. Section 3 describes the material samples used in the study and the micro-CT acquisition procedure. Section 4 presents the results of the methods applied to the micro-CT images. Analysis of the factors influencing the accuracy is done using the micro-CT images of a steel/epoxy composite with different voxel sizes and is presented in paragraph 4.1. The rest of Section 4 is devoted to the orientation analysis and segmentation of a micro-CT image of a 3D reinforced carbon/epoxy composite sample.

2. Methods and algorithms

The term "voxel model" in this paper will be used to designate a high-level description of the material's microstructure. This usage of this term should not be confused with the micro-CT image used as a starting point for the model derivation, even if the image can also be described as array of "voxels", containing grey-scale values only. The "voxel models" derived from the image can be different from it in two aspects: first, the dimensions of voxels in the model can differ from the elements of the image, and second, voxels of the model contain physical rather than grey-scale information. The original micro-CT image, which can be stored as an image stack or a single file containing grey values, is converted into a single three-dimensional array of grey values with 256 levels (8 bit) of gradation. Further on, if not specified otherwise, the expression "micro-CT image" means this three-dimensional array of grey values. The term "voxel", which has two meanings in the context of this paper: as a pixel of three-dimensional image and as an element of voxel model, will be used mainly in its second meaning, except when it is used to define physical size of the voxels in the micro-CT image. According to the given definition of the voxel model, a voxel is a subdomain of the material's domain, with centroid coordinates, dimensions and associated vector of variables. Derivation of the voxel model from a three-dimensional micro-CT image involves partitioning of the image domain into subdomains, centred at the nodes of a regular lattice; calculation of the principal direction, the degree of anisotropy and the average grey value at each subdomain; and segmentation of the image domain into material components using the derived variables. Result of the segmentation is an additional integer value assigned to each voxel, which indicates its material type.

Density of the voxels in the voxel model can be chosen on the basis of a trade-off between the level of details required for final application (visualization, permeability, mechanical calculations), and computation time, which depends on the total number of voxels.

2.1. Principal direction and degree of anisotropy

The principal direction and the degree of microstructural anisotropy are calculated from the image $I(x_1,x_2,x_3)$, represented as a three-dimensional function of grey value, using structure tensor, which is defined as follows:

$$S(\boldsymbol{p}) = \int_{W(\boldsymbol{p})} S'(\boldsymbol{r})dr$$

$$S'(x_1,x_2,x_3) = \begin{bmatrix} \left(\frac{\partial I}{\partial x_1}\right)^2 & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_2} & \frac{\partial I}{\partial x_1}\frac{\partial I}{\partial x_3} \\ & \left(\frac{\partial I}{\partial x_2}\right)^2 & \frac{\partial I}{\partial x_2}\frac{\partial I}{\partial x_3} \\ sym & & \left(\frac{\partial I}{\partial x_3}\right)^2 \end{bmatrix}$$

where $\boldsymbol{p}$, $\boldsymbol{r}$ – three-dimensional vectors and $W(\boldsymbol{p})$ is the window of integration, $W(\boldsymbol{p}) : \forall\{x_1,x_2,x_3\}(|x_1 - p_1| \leqslant w_r, |x_2 - p_2| \leqslant w_r, |x_3 - p_3| \leqslant w_r)$. The vector $\boldsymbol{p}$ defines a current position of the integration

Table 1
Parameters of the micro-CT acquisition of the samples.

	Carbon/epoxy	Steel/epoxy
Voxel size, μm^3	2.34	2.5, 4.2, 4.4, 6.4, 8.3, 13.6
Voltage, kV	70	85
Current, μA	220	413
Number of projections	5000	633
Averaging	1	32