AUTOMATIC TRANSFORMATION OF 3D MICRO-CT IMAGES INTO FINITE ELEMENT MODELS WITH ANISOTROPIC LOCAL PROPERTIES

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Abstract

Finite element models derived from micro-CT images can be used for modelling of the actual material geometry and prediction of mechanical properties. The primary direction of anisotropy in a composite material is determined by the orientation of fibres, which can be calculated by means of the structure tensor. This paper presents results on direct conversion of a 3D micro-CT image into the finite element model with anisotropic local mechanical properties of the reinforcement.

1. Introduction

X-ray computed tomography (micro-CT) is a non-destructive testing technique that allows obtaining a three-dimensional image of an object. Grey value in such an image reflects X-ray attenuation coefficient, which in turn depends on molecular weight and density inside the object. This information can be used for prediction of mechanical properties of an object by conversion of the micro-CT image into voxel-based finite element model. In biomechanics, this approach finds application for the evaluation of strength of bones and bone implants, when grey value in the micro-CT image is converted into Young's modulus using a non-linear transformation function. Resulting finite element models feature regular mesh and isotropic material properties of the elements [1,2].

Composite materials and textile composites in particular exhibit intrinsically anisotropic properties due to the oriented fibrous structure of the reinforcement. A yarn inside the composite can be locally regarded as a unidirectional material, which has transversally isotropic mechanical properties. The orientation of the local properties tensor is determined by the orientation of the fibres. Finite element modelling of the textile composites therefore requires the solution of two problems: separation of the pure matrix volume from the impregnated reinforcement in order to assign material properties to the finite elements; and finding the fibres orientations in order to define local coordinate systems for the material properties in the impregnated reinforcement volumes.

It was shown in [3] that the problem of finding fibre orientations can be solved with the structure tensor, calculated from the micro-CT image. This paper presents the results of conversion of the micro-CT images into the finite element models with anisotropic properties of the reinforcement, and the results of computations of these models. The orientation of local coordinate systems of the elements is calculated with the structure tensor. The separation of the material’s components is achieved by clustering on the basis of the variables derived from the image.

2. Implementation

The detailed description of the structure tensor method of determining fibres orientations can be found in [3]. The method provides an orthogonal basis of vectors, which is used to define the orientation of the local coordinate system of a finite element. The separation of materials (matrix – impregnated reinforcement) is accomplished using K-means clustering of the image voxels based on two parameters: the degree of anisotropy, which is also defined on the basis of the structure tensor, and the average grey value. After all the voxels are marked as “matrix” or “reinforcement”, and orientation is assigned to the reinforcement voxels, the voxels are transformed into finite elements one by one.

Nodes of the model form rectilinear grid and are equidistant from each other so that the elements have cubic shape. Element of type C3D8 is used, which is a linear 8-node brick element. Six node sets are defined corresponding to the facets of the model in order to define boundary conditions. Local orientations are defined as a per-element table.

The processing of a micro-CT image, which is stored as a three-dimensional array of 8 bit grey values, is implemented in VoxTex software (written in C#). The software produces the following set of variables at each calculation point (voxel): components of the orientation vector, degree of anisotropy and average grey value. This output is the voxel model, which is a three-dimensional array of vectors, and is stored in a binary file format. After segmentation, an additional integer variable representing material index is added to this array. Each voxel of the voxel model is converted into a finite element, and the Abaqus output file is created.

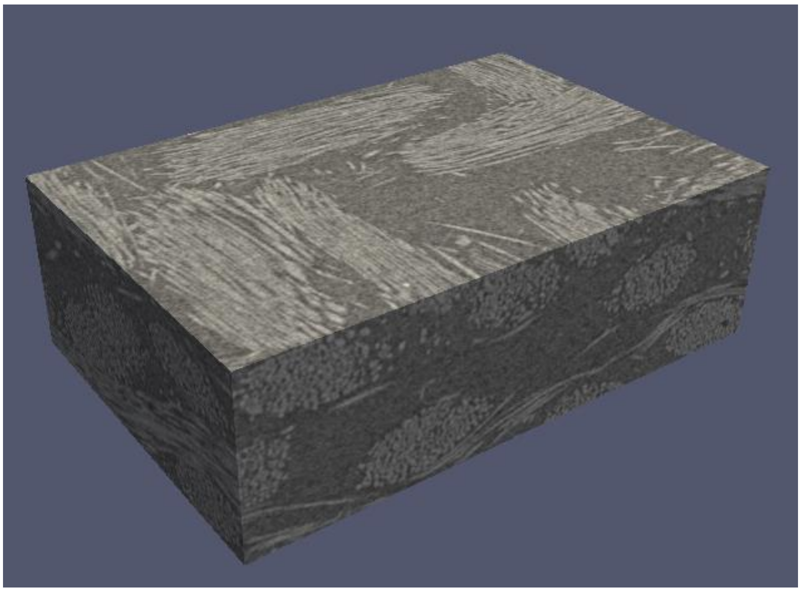


Figure 1. The region of interest from the micro-CT image of flax/epoxy composite.

3. Experimental

A sample of a flax fibre reinforced composite with the size of the cross-section 9.5x2.0 mm was used in the study. The composite was made by combining a thermoset epoxy matrix with a Twill 2x2 textile. For the cross-linking, the matrix *Epikote 828LVEL* ($\eta \approx$ 10-12 Pa.s) was mixed with the *Dytek DCH-99* hardener at a 15.2 phr ratio. The 2 mm thick laminate is composed of six layers fabric which gives fibre volume fraction of 40%. Each ply have a thickness of 0.14 mm, 9º twist angle and 1% crimp in both warp and weft direction.

The sample was scanned with the Nanotom X-ray computed tomography system. Parameters of the acquisition are given in Table 1.

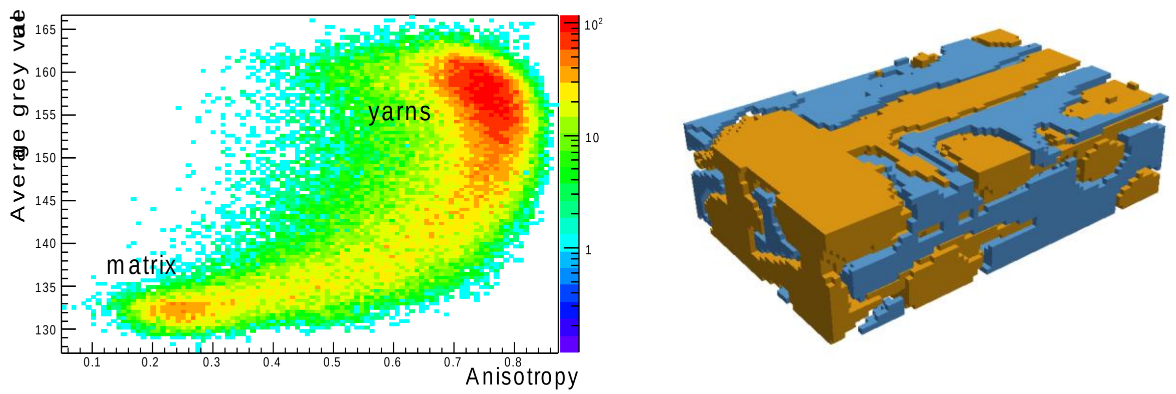
Parameter	**Value**
Resolution	5.5 µm
Voltage	50 kV
Current	420 µA
Averaging	5
Rotation step	0.1 (3500 projections)

Table 1. Parameters of the tomographical acquisition.

4. Results

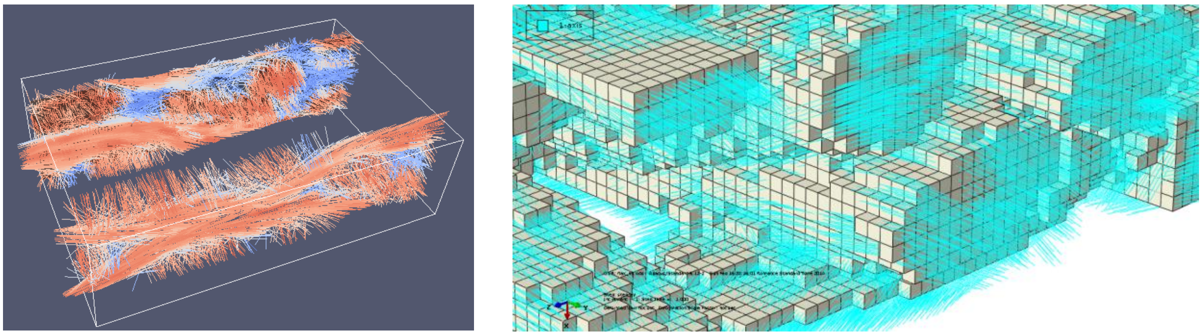
A region of interest (Fig.1), chosen arbitrarily, was extracted from the micro-CT image and processed with the VoxTex software. The histogram of the degree of anisotropy and average grey value calculated from the image (Fig.2a) indicates presence of two clusters corresponding to the matrix and yarns. On the basis of this, the image was segmented using k-means clustering algorithm with the number of clusters 2. The result of this operation is shown in Fig.2b.

A finite element model of the size 21x47x74 and with the total number of elements 73038 was generated from the region of interest (Fig.3). X-axis of the model corresponds to the out-of-plane direction; Y and Z axes are oriented approximately along the direction of warp and weft yarns.



a *b*

Figure 2. Histogram of the degree of anisotropy and average grey value for the region of interest (left) and the result of segmentation (right).



a *b*

Figure 3. Orientation vectors visualized with ParaView (a) and a fragment of finite element model with primary axis of anisotropy shown (b).

Mechanical properties of the matrix and flax fibre that were used in simulation are given in Table 2. Properties of the yarns were calculated from the constituents using Chamis micromechanical model ([4]) with the fibre volume fraction 0.4. Three boundary value problems were solved, with the Dirichlet boundary conditions set to produce 1% elongation along the X, Y and Z axis correspondingly.

	Matrix	**Flax fibre**	**Flax/epoxy yarn (calculated)**
Longitudinal modulus, GPa	3.5	60	26.1
Transversal modulus, GPa	3.5	10	5.9

Table 2. Mechanical properties of the materials.

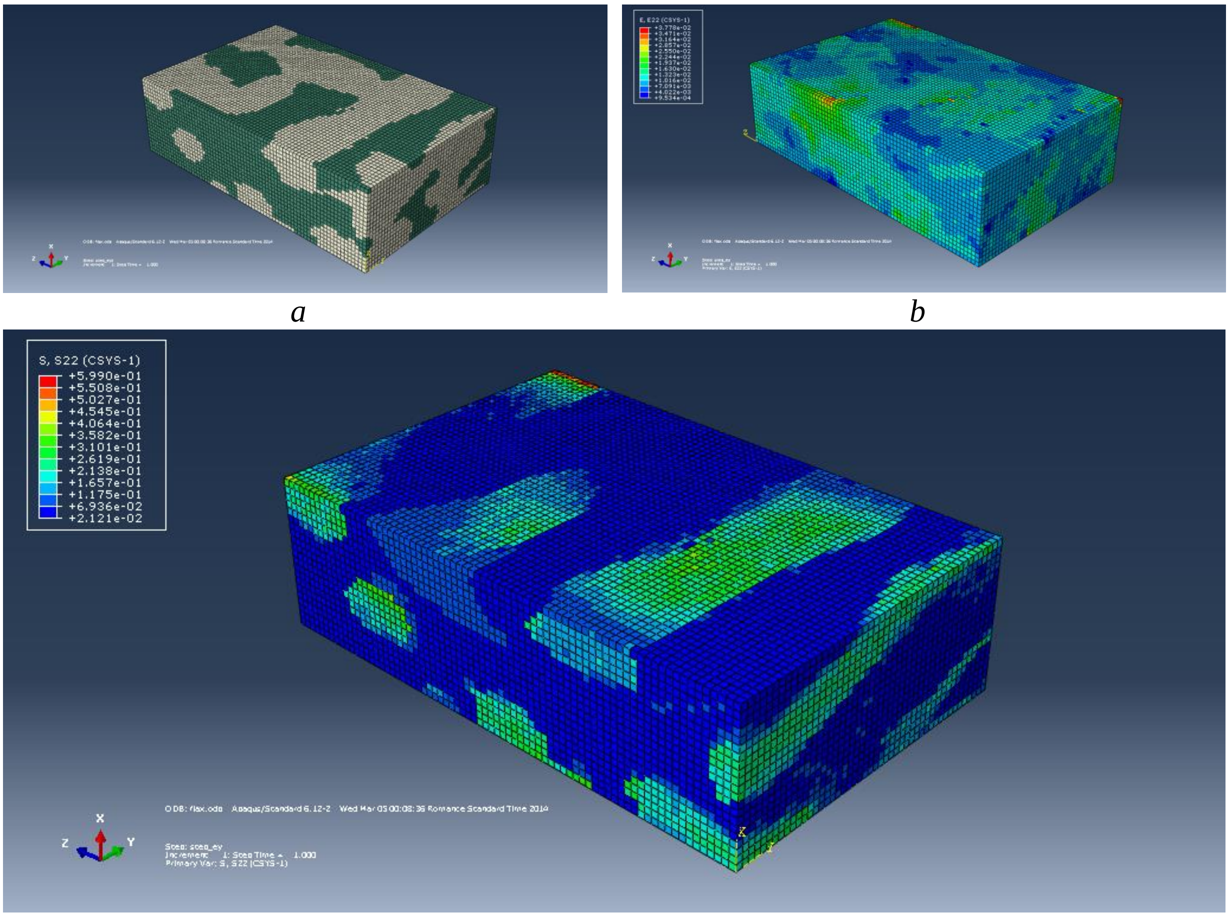
As the material properties defined in GPa, the resulting stresses are of the same units. The strain and stress fields are presented in Fig. 4. The distribution of stresses in the components of the model is given in Table 3, where each stress component is related to corresponding boundary value problem, e.g. σ_{11} is the stress component from the boundary value problem with 1% elongation along X axis. The yarns in the material, which have higher stiffness, exhibit elevated level of stresses compared to the matrix.

	Matrix		Yarns	
	μ	σ	μ	σ
σ_{11}, MPa	53.0	4.3	62.6	4.8
σ_{22}, MPa	53.0	7.6	125.1	7.3
σ_{33}, MPa	52.2	9.6	142.7	8.0

Table 3. Mean (μ) and standard deviation (σ) of stresses in the components of the finite element model.

5. Discussion

The purpose of this paper is to assess qualitative correctness of the algorithms, used to transform a micro-CT image into a finite element model. This transformation involves two tasks: computation of the local orientations and segmentation of the image. The assessment is attained by comparison of original micro-CT image with the result of segmentation and with the distribution of stresses in the finite element model. As the yarns have significantly higher longitudinal stiffness, the level of stresses inside them is expected to be higher than in the matrix, provided that the local orientations are set correctly.



a *b*

c

Figure 4. The finite element model (a), ε_y strain field (b) and σ_y stress field (c) under 1% deformation along Y axis.

Computation of the effective properties requires solution of the six boundary value problems with representative volume element (RVE). The boundaries of RVE should be defined to coincide with the boundaries of the periodic cell of the material. This can be attained only approximately, as the boundaries are set manually. Real material always has deviations of the geometry of reinforcement from the ideal shape, and nesting of the layers. All this makes it difficult to cut a region of interest from the micro-CT image that would be periodic. Periodic boundary conditions are therefore inapplicable. Available options are Dirichlet or Neimann boundary conditions.

In order to increase accuracy of the estimation of effective properties, the RVE can be selected to contain more than one cell of periodicity, but natural number of them. It can reduce the effect of uncertainty of the boundaries definition. However, larger RVE makes calculated effective properties non-local and diminishes influence of defects and imperfections. This can be undesirable if the final goal is to estimate local mechanical properties, taking the defects into account.

6. Conclusions

The method to generate locally anisotropic finite element models from micro-CT images was tested with an image of flax/epoxy composite. Distribution of stresses in the produced finite element model showed correlation with the original image and the distribution of material properties in the model. Local orientations are non-random and correspond to the geometry of the material. This indicates that the conversion micro-CT image into the finite element model is qualitatively correct.

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