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Implicit kriging model of fibrous reinforcements in composites based on X-ray microtomography

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Résumé — An implicit kriging model is presented to reconstruct the inner and outer geometry of the fibrous reinforcement in composites. The fiber tows are detected automatically in X-ray microtomographic scans using Haar-like features and learning algorithms. A discrete model based on fiber volume fraction is then used to generate 2D and 3D models of fiber tows with a an implicit formulation of parametric kriging for curves and solids. The precision of the final model is controlled by the segmentation error and transform function applied to potential.

Mots clés — woven composites, implicit kriging, X-ray micro-tomography.

1 Introduction

The fibrous reinforcements presently used in composites take complex forms to enable designs with better mechanical properties. To approach the theoretical potential of these materials the parameters of the manufacturing process have to be optimized, especially compaction in the mold and impregnation with the liquid resin of the fibrous reinforcement. These two mechanisms can be analyzed by volume imaging techniques like X-ray micro-tomography, providing insights into the involved phenomena and geometry for numerical simulations [2-6].

There exist several approaches to modeling fiber geometry based on X-ray microtomographic data. One example is a voxel model presented by Straumit et al. [6], which takes into account the fiber orientation and divides the scan into parts corresponding to the fiber tows. The main limitations of this approach are the high computer memory requirement to store the model and lack of mesh suitable for numerical simulations. Another solution has been proposed by Naouar et al. [4], where the outer mesoscale geometry of the fabric is extracted from low-resolution scans. This model follows the realistic geometry of the fibrous reinforcement, but being based on Gaussian blur and threshold operations, it does not take into account the error of the reconstruction.

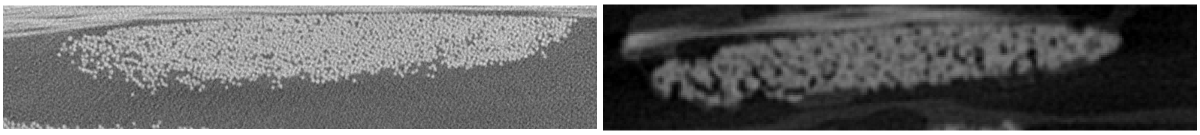
In our previous work, Madra et al. [3], we have presented a method for reconstruction of the mesoscale geometry of a fibrous reinforcement which employed learning algorithms to detect fiber tows and used geometry and segmentation error data to generate a dual kriging model with the level of detail regulated by nugget effect. The resulting model followed the realistic geometry of the material, but it required high-resolution microtomographic scans, increasing the complexity of the treatment and limiting the size of the examined specimen to the Representative Elementary Volume (REV) or smaller.

In the present work, we propose a new approach to generating models of the mesoscale geometry of the fibrous reinforcement based on low-resolution X-ray microtomographic scans. First, the fiber tows are identified automatically with Haar-like image features [8], followed by segmentation with learning algorithms. Secondly, implicit kriging is used to generate 2D and 3D models of the reinforcement, including outer and inner geometry of fiber tows. The level of detail of the model is controlled by mapping an arbitrary function on the value of potential.

2 Fiber tow identification

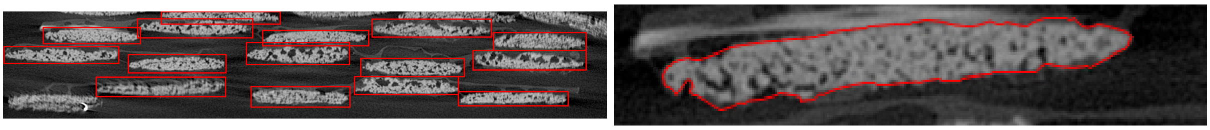
X-ray microtomographic scans represent values of accentuation coefficient for volume elements – voxels in a specimen. Voxel dimensions depend on X-ray scan resolution, with the resolution being inversely proportional to specimen dimensions. In the case of composite materials reinforced with glass or carbon fibers, the scans with voxel dimensions smaller than the fiber diameter enable identification of individual fibers (Fig. 1a). To analyze the REV of complex textile reinforcements, especially with a 3D architecture, the technical parameters of laboratory-scale X-ray microtomographs enforce use of lower resolutions, incapable of capturing distinct fibers (Fig. 1b).

The fiber tows geometry is extracted from low-resolution scans in a two-step process. First, the rectangular areas containing fiber tow cross-sections are identified using Haar Cascades (Fig. 2a) [8]. The Haar-like features used in the classifier have been trained on a database of previous X-ray scans of composites with different types of woven reinforcements. In the second step, a Fast Random Forest learning algorithm [1] detects the contour of the fiber tow cross-section in each rectangle (Fig. 2b). The contour, grayscale values inside it and phase segmentation probability obtained from learning algorithm will now be used to reconstruct the outer and inner geometry of the fiber tows.



(a) Scan resultion 1.7μm (b) Scan resultion 9.3μm

FIGURE 1 – Glass fiber composites at different X-ray scan resolutions.



(a) Fiber tow detection with Haar Cascades (b) Segmentation with Fast Random Forest algorithm

FIGURE 2 – Steps of the fiber tow geometry extraction process.

3 Discrete model

For a material composed of exactly two phases, e.g., fibers and matrix or fibers and air, the image grayscale value within detected contours can be correlated with the fiber volume fraction V_f of the fiber tow. This is usually not true for composites where residual voids distort this correlation. Similarly, a dry fibrous reinforcement requires a coat of adhesive to keep the structure of the weave intact, which introduces an additional phase. The phase segmentation error ρ from the extraction step is used to calculate the corrected V_f of a voxel with coordinates x,y,z

$$V_f(x,y,z) = \rho \cdot u(x,y,z) \tag{1}$$

where $u(x,y,z)$ is a [0,1] normalized 16-bit grayscale value of the voxel, with 0 – porosity, 1 – fibers. A comparison of V_f values before and after correction are shown in Fig. 3.

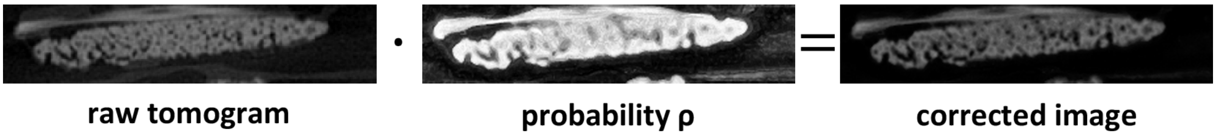


FIGURE 3 – Fiber tow fiber volume fraction V_f before and after correction with segmentation error.

4 Continuous model

The V_f data obtained in the previous section represent the discrete model of the mesoscale geometry of a fiber tow. For a given 2D tomogram at a fixed depth z_k, the contour Γ of a fiber tow can be approximated with a continuous function [7]

$$\hat{\Gamma}(t) = \Sigma_{l=1}^{M} a_l p_l(t) + \Sigma_{j=1}^{N} b_j K(|t - t_j|) \tag{2}$$

where t parameterizes the curve x, y, $0 \leq t \leq 1$; p_l is an arbitrary polynomial with a weight a_l and K a kernel function describing the spatial relation between the approximated point $\hat{\Gamma}$ and the initially sampled points Γ.

This parametric kriging model of the fiber tow contour is a base for the implicit kriging model of the whole cross-section. A potential value is assigned to the points $u(x,y)$ as follows :

$$\begin{aligned} u(x,y) &= 0 && \text{for } u(x,y) \text{ laying on } \Gamma \\ u(x,y) &= -1 && \text{for } u(x,y) \text{ laying outside } \Gamma \\ u(x,y) &= \nu(1 - V_f) && \text{for } u(x,y) \text{ laying inside } \Gamma \end{aligned} \tag{3}$$

where ν is an arbitrary function chosen depending on the final application of the model. Results obtained for different ν are shown in Fig. 4. Constant ν gives only contour for 1 (Fig. 4a) or contour and the solid inner geometry for 0 (Fig. 4b). Linear ν corresponds best to the realistic geometry but may result in a very complex model. A combination of the linear ν with a cutoff value T provides control on the size of holes in the final reconstruction .

The model can be extended into z dimension by applying parametric kriging to solids, resulting in a three-dimensional reconstruction (Fig. 5) where the potentials are assigned to the points of the outer surface, outside and inside it analogically to the 2D case 3.

(a) $\nu(c) = 1$

(b) $\nu(c) = 0$

(c) $\nu(c) = c$

(d) $\nu(c) = \begin{cases} c/T \text{ for } c < T \\ 1 \text{ for } c \geq T \end{cases}$

FIGURE 4 – Implicit kriging model of a fiber tow cross-section for different ν functions.

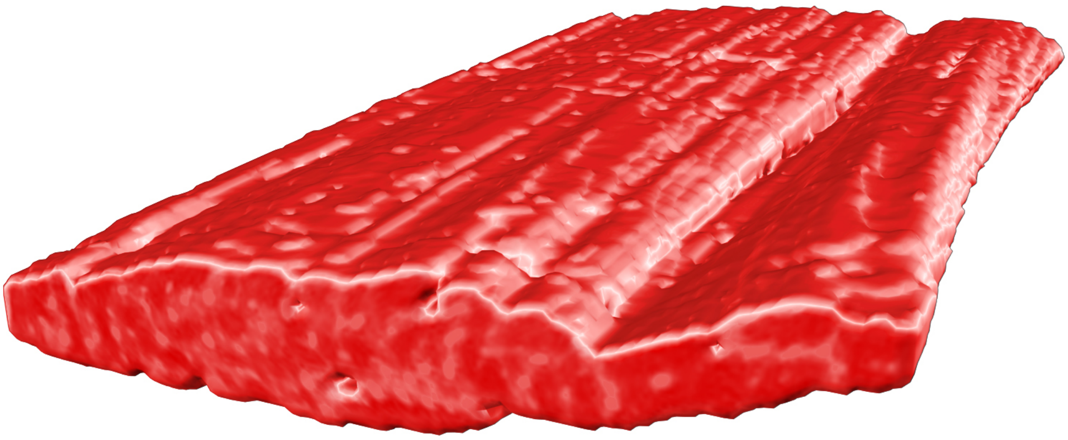


FIGURE 5 – Reconstruction of the 3D geometry of the fiber tow for a linear ν with the cutoff value $T = 0.7$.

5 Conclusions

The presented method of extraction and reconstruction of fiber tow geometry provides volume models with a varying degree of details. By adjusting the value of potential through segmentation error and the mapping function ν, a range of models can be generated that describe fiber tow contours, solid areas and areas with holes for the two-dimensional reconstruction or surfaces, volumes without or with holes in three dimensions. The employed deep learning strategy combining Haar Cascades and learning algorithms with implicit kriging has several advantages for treating low-resolution X-ray microtomographic scans : it is automatic, can handle new materials and reduces the amount of data in the model while retaining key geometric features.

The further work will include adding the nugget effect to control the level of smoothness of the reconstruction as well as a method for creation of surface and volume mesh based on the implicit kriging approximation.

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