Voxel Models as Input for Heat Transfer Simulations Based on X-ray Microtomography Images of Random Fiber Reinforced Composites

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Abstract: This paper proposes a method for the creation of a three-dimensional finite element model representing fiber reinforced insulation materials for the simulation software Siemens NX. VoxTex software, a tool for quantification of µCT images of fibrous materials, is used for the transformation of microtomography images of random fiber reinforced composites into finite element models. The paper describes the numerical tools used for the image quantification and the conversion and illustrates them on several thermal simulations of fiber reinforced insulation blankets filled with low thermal conductive fillers. The experimental measurements validate the prediction of the thermal conductivity.

Keywords: analysis, modeling, thermal, voxel.

1 Introduction

Finite element simulations can support the numerical prediction of the thermal performance of random fiber reinforced insulation composites. The conversion of the fibrous inner structure of the composite into a solid finite element model can be based on information provided by quantification of micro-computed tomography (µCT) images of a composite sample [1].

The paper is organized as follows. VoxTex [2] (KU Leuven) can construct voxel models based on a µCT 3D image and combines image segmentation and local orientation analysis through local structure tensor calculations. The voxel models are exported as text files containing e.g. the averaged grey values per voxel and the local orientation tensor. Relevant features of VoxTex are described in section 2. The numerical tool, named PreCon 2.0 (KU Leuven), was developed to convert these voxel models into finite element models for the thermal solver of Siemens NX [3]. PreCon 2.0 can also provide to the user 3D visualization of the voxel models including 3D vectors representing the fiber orientation (section 2). The resulting solid brick element mesh is then used in the prediction of the thermal conductivity of the sample (section 3). The method is tested on a fiber reinforced thermal insulation blanket injected with low thermal conductive powder (figure 1). The calculations are validated by comparison with a thermal conductivity measurement with the hot wire method (section 4). The conclusions were summarized in section 5.
X-ray microtomography is a non-destructive inspection technique allowing obtaining a three-dimensional image of e.g. a composite sample at micron and submicron spatial resolution [4]. A Nanotom S X-ray machine from General Electric with a 180 kV HPNF submicron X-ray tube with a tungsten target at the source was used. A 3D image resolution up to 2304 by 2304 by 2304 pixels can be obtained. Figure 1 shows a 2D image of a fiber reinforced insulation blanket. The resolution in this figure corresponds to a voxel size of 5µm³ (in comparison: the individual fiber diameter is about 20 µm).

To extract redundant information from a 3D image, such as attenuation (grey scale) values per pixel and orientation of fibers based on the individual pixel information, VoxTex software was used. This software supports not only images of Nanotom, SkyScan and Tomohawk CT systems but any stack of images or 3D array of integers [2]. It is used to quantify the fiber structure in the scanned sample and combines different segmentation features. The VoxTex output can be exported to several third party programs such as Abaqus, FlowTex (KU Leuven) and ParaView (Figure 2).

The purpose of this research is to expand these export possibilities by creating a link to the thermal solver module of Siemens. The first step is converting the VoxTex output into the universal file protocol (UNV) developed by SDRC [3]. This UNV file is read by the thermal solver module of Siemens NX12. This latter is used to estimate the thermal conductivity of a fiber reinforced insulation blanket.

2 Transformation of a 3D array into a voxel model for thermal simulations

Typically, a 3D image taken by µCT contains more than 2000³ values. These values are originally the X-ray attenuation of the composite per pixel or in image processing the grey scale value of the image. In further text, this value is called density. By averaging the density values in 3D windows and to use the same window to calculate structure tensors, it is possible to reduce the amount of elements significantly without great loss of information needed in the resulting finite
element model. The density values, which are double scalars in the 3D array, are integrated over a specific volume by the following definition:

\[
\bar{g}(p) = \int_W I(r) dv
\]

where \(W\) is the integration window in the 3D image and \(r(x, y, z)\) is the corresponding location [5]. \(\bar{g}(p)\) represents an average intensity of the image in a specific location defined by \(p\). The window radius and mesh density, which is the distance between the voxels in the resulting voxel model is user-defined. If a region of interest (ROI) of a 3D image of \(29^3\) pixels is considered and a integration window radius of 12 is used combined with a mesh density of one voxel as mesh distance between the resulting voxels, a voxel model of \(3^3\) voxels is created (Figure 3).

This attenuation averaging was carried out on a µCT scan of a real insulation blanket specimen consisting of three materials (E glass fiber, low conductive particles and air). The ROI consisted of 171 images (dz) of each 378x434 pixels in size (dx, dy respectively). The ROI was cut from the full 3D image (1677 images of each 2284x2284 pixels in size). After using the described integration method (window radius 8, mesh density 2), a voxel model was created with about 10 times less elements. At this point, it is the purpose to convert this voxel model into a thermal simulation model which represents the real composite structure and material volume fractions. The fabrication process of the blanket significantly affects the volume fraction of both the glass fiber and low conductive filler fraction. The process comprises the injection of a low conductive particles suspension into an empty stitched fiber mat by an industrial process. A supercritical drying step after the injection ensure that only the particles remain between the glass fibers. Based on density measurements of the blanket material, segmentation and estimation of the volume fraction of each of the three materials was carried out on the voxel model by the PreCon 2.0 tool. The volume fractions were summarized in table 1. The voxel model is presented in figure 4.

One density image of the mentioned ROI is depicted in figure 5. By use of structure tensor calculations, an illustration of the fiber orientations is possible (figures 6 and 7).
Figure 5. A density image showing a fiber bundle (white) and matrix (grey and black). In the middle of the image, a Z stitch bundle is visible (located in the orange rectangle).

Figure 6. Voxel model shown by the PreCon 2.0 tool with inside the voxels the orientation tensors in green.

Figure 7. Illustration of the voxel structure tensors after filtering the most perpendicular fibers located in the orange rectangle from figure 5.

3 Voxel model as FEM mesh in steady state thermal simulations

The voxel model from section 2 has been converted into the UNV file format [3]. The thermal solver calculates the thermal flow after applying thermal constraints: \( \Delta T_{\text{top, bottom}} = 1 \text{K} \) and \( Q_{\text{vertical side}} = 0 \). The designated material properties are summarized in table 1.

| Material                        | Volume fraction (v%) | Thermal conductivity (Wm\(^{-1}\)K\(^{-1}\)) | Intrinsic mass density (kgm\(^{-3}\)) | Color (in figure 4) |
|---------------------------------|----------------------|---------------------------------------------|----------------------------------------|---------------------|
| Air (at rest, not moving)       | 5.00                 | 0.025                                       | 1.2 [7]                                | black               |
| Low thermal conductive particles| 90.67                | 0.018                                       | 80                                     | grey                |
| E glass fiber                   | 4.33                 | 1.35 [6]                                    | 2540 [6]                               | white               |

The calculated thermal flow and flux in steady state resulted in \( Q = 10.06 \mu\text{W} \) and \( Q = 271.5 \mu\text{W/mm}^2 \) respectively. With a temperature difference of 1K, the thermal conductivity can be calculated as:

\[
\lambda = \frac{Q \cdot e}{A} \tag{2}
\]

where \( Q \) is the calculated thermal flow (\( \mu\text{W} \)), \( e \) the thickness (\( \mu\text{m} \)) and \( A \) is the area which the thermal flow goes through [3]. In that case, the simulated thermal conductivity \( \lambda \) becomes 0.0206 Wm\(^{-1}\)K\(^{-1}\).
4 Comparison with an experimental measurement

The thermal conductivity was measured with the hot wire method in order to make a comparison with the simulation result. This is a transient measuring technique to log the temperature rise in a test material at a well-defined distance [3]. The thermal conductivity $\lambda$ can be calculated by:

$$\lambda = \left( \frac{q}{4\pi} \right) \cdot \left( \frac{dT}{d(ln(t))} \right)^{-1}$$  (3)

where $dT/d(ln(t))$ is a constant derived from the measurements and $q$ the heat flux per length [8]. The measurement yielded the value $\lambda = 0.025$ Wm$^{-1}$K$^{-1}$. Compared to the measurement, the voxel model overestimates the thermal insulation ability with approximately 20%. A few possible arguments for this deviation can be listed. Firstly, thresholding, was done based upon volume fractions of the full blanket properties and process parameters (e.g. loading of the glass fiber mat and low conductive fillers). A small difference in loading or volume fraction in an ROI will significantly influence the segmentation of the voxel model into the three material types. Secondly, the material properties used in this model are obtained separately from process parameters and literature and are not exact values. Consequently, the simulation result depends on these property ranges. Thirdly, the density of the individual materials should be high enough to distinguish them in the segmentation step. Since the used low conductive particles belong to the same silica group as glass fibers, the density and hence the contrast and segmentation is influenced. Fourthly, during the process, low conductive particles fell out of the composite, which has its influence on the total thermal conductivity. These handling effects will be investigated in detail to estimate the error.

Finally, the described voxel model is based upon an ROI of the 3D image which may not represent the full blanket performance. Therefore, the full 3D image (2248x2248x1677 pixels) was exported into a new voxel model (with a window size of six pixels and a mesh density of 13 pixels with a minimum of overlap between the windows), which resulted in a voxel model of about four million elements. The simulation result was $\lambda = 0.0202$ Wm$^{-1}$K$^{-1}$ which corresponds with the ROI simulation. However, as stated in previous arguments, not only the ROI size, but also the segmentation step and the individual material properties play a major role in this type of simulations. A design of experiments (DOE) will be carried out to evaluate each individual variation on the result.

5 Conclusions

A method was proposed to convert a 3D image obtained by a µCT scan of an insulation composite or any other 3D array into a finite element model. The voxel model of the composite was then used to predict the total thermal conductivity of that composite. The estimated conductivity was compared with an experimental measurement. Some arguments were listed in the previous section and will be investigated in future research. However, one can conclude that the proposed method efficiently reduces the amount of elements without great loss of information needed in the resulting finite element model while fiber orientations are calculated simultaneously.

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References

[1] Van De Walle W and Janssen H 2017 Validation of a 3D Pore Scale Prediction Model for the Thermal Conductivity of Porous Building Materials 11th Nordic Symposium on Building Physics (Trondheim).

[2] Straumit I, Vladimirovitch Lomov S and Wevers M 2017 Quantification of Micro-CT Images of Textile Reinforcements AIP Conf. Proc. vol 1896.

[3] Koen Latrié S, De Pooter S, Seveno D and Desplentere F 2018 Numerical Mesh Generation Tool for Thermal Conductivity Simulations of Nanoparticle Filled Inorganic Plates Polym Eng Sci. (Preprint doi/10.1002/pen.24783)

[4] Landis E and Keane T 2010 X-ray Microtomography. Materials Characterization. 61 1305–16.

[5] Aravand A, Shishkina O, Straumit I, Liotta H, Wicks S, Wardle L and Gorbatikh L 2016 Internal Geometry of Woven Composite Laminates with “fuzzy” Carbon Nanotube Grafted Fibers. Comp Part A: Appl Sci and Man. 88 295–304

[6] Bansal N. and Doremus R 1986. Handbook of glass properties. (Orlando: Academic Press)

[7] Malcolm McPherson J 1993 Subsurface Ventilation and Environmental Engineering. (Dordrecht: Springer Netherlands Imprint Springer)

[8] Carslaw H and Jaeger J 1959 Conduction of Heat in Solids (Oxford: University Press)