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Micro-computed tomography determination of glass fibre reinforced polymer meso-structure

J.S.U. Schell [a,*], M. Renggli [a], G.H. van Lenthe [b], R. Müller [b], P. Ermanni [a]

[a] *Centre of Structure Technologies, ETH Zurich, Leonhardstrasse 27, CH-8092 Zurich, Switzerland*
[b] *Institute for Biomedical Engineering, University and ETH Zurich, Moussonstrasse 18, CH-8044 Zurich, Switzerland*

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Abstract

The local laminate quality of parts manufactured with liquid composite moulding (LCM) cannot be predicted in a reliable manner without knowledge of flow phenomena on a meso-scale. To better predict local laminate quality, the long-term goal is to simulate meso flow around fibre bundles. Such simulations allow to determine how fibre bundles are impregnated and how voids develop. The aim of the present paper is to evaluate micro-computed tomography (μCT) as a tool to determine the geometry of fibre bundles and voids in glass fibre reinforced polymers (GFRP). The resolution of the used μCT enabled visualization of each fibre bundle separately and of inter bundle voids. Using post-processing techniques, the data of the μCT can be converted to finite element models. These models can be taken as input for future Computational Fluid Dynamics (CFD) simulations.

Keywords: E. Resin transfer moulding (RTM); B. Microstructure; D. Non-destructive testing; Micro-computed Tomography

1. Introduction

The nowadays used LCM-simulation predicts the macroscopic flow and mould filling in a reliable manner. Nevertheless prediction of the laminate quality is still not possible. Laminate quality is related to content, size, and distribution of voids in a laminate. The reasons for voids creation are well known: air entrapment is caused by the dual scale structure of the textile influencing the flow behaviour on meso-scale. It consists of fibre bundles which are composed of thousands of fibres. The fibre free regions between the bundles are in the order of 0.2 mm. The interstitial spaces between the single fibres are in the order of micrometers. Different flow velocities due to capillary effects or due to varying permeabilities in the fibre bed [1] result in an uneven flow front. Jinliana [2] describes the voids creation in two unit cells which differ in the nesting mode. In these models, resin flows slower in the warp yarn than in the weft yarn, due to the slower transverse flow in the warp yarn. These different flow velocities cause air entrapment. In [3] the impregnation of dual-scale porous media is described with inter- and intra-bundle flow. The resulting impregnation of the dual-scale flow is experimentally investigated by Pillai [4]. Bréard [5] introduces the hydrodynamic dispersion and the relative permeability in the simulation of void formation. Other reasons for voids are gas in the matrix or fabrication mistakes. The latter are not investigated in this project. Voids strongly influence the matrix dominated mechanical properties such as the interlaminar shear strength and the flexural strength [6–8], and the moisture absorption of a composite part [8]. In this context the long-term aim of this research project is to provide the necessary knowledge of the flow behaviour at micro- and meso-level to better describe and predict the development of voids during LCM-injection processes. In other studies the meso-structure of reinforcements has been investigated and modelled as input for simulation on meso-scale. The results of the simulations were used to predict

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[*] Corresponding author. Tel.: +41 44 632 7367; fax: +41 44 633 1125.
E-mail address: jschell@ethz.ch (J.S.U. Schell).
URL: www.structures.ethz.ch (J.S.U. Schell).

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the permeability of the reinforcements [9–11]. The influence of the image processing on the resulting permeability was studied in [9].

This contribution deals with the experimental investigations carried on so far to support modelling activities. Preliminary investigations have shown that μCT technologies are capable to visualize each fibre bundle separately and density variation within a fibre bundle, thus providing the necessary input to create an accurate FE-model of the textile structure. In a further study, the FE-model will be used as geometrical input to simulate the meso flow. The results of the simulation will be used to predict the voids creation. Hence, the focus of this study is the investigation of the meso-structure of a fabric and the voids analysis of an impregnated fabric. The results of this study will be used as base for the FE-model which has to take into account all particularities influencing the voids creation. Not a single unit cell or simplified model with elliptical tows, like in other studies [2,12,13], representing the average reinforcement structure is taken. In [13] a hierarchical construction from the fibres to yarn and to fabric and then to a unit cell is described. The structure finally has a periodicity. In [14] the permeabilities of FE-models representing different nested fabrics are calculated. The fabrics are modelled using WiseTex. Hoes shows in [15] that nesting is a major source of variations in experimental determined permeabilities. Due to its influence on the permeability, nesting on meso-scale is assumed to influence the meso flow and is taken into account in the study.

To analyse the voids occurrence in composite parts, voids of an impregnated fabric are visualized.

This paper is structured in four major parts: Section 2 presents an overview over the experimental set-up. μCT images are presented and discussed in Section 3. Section 4 shows the possibility to visualize voids using μCT. Potential of this method is finally discussed in Section 5. Section 6 presents the continuation.

2. Materials and methods

2.1. MicroCT

Micro-computed tomography has been originally used for biomedical purposes [16]. It is a non-destructive method to get geometrical information about the internal microstructure of an object. The field was pioneered by Feldkamp et al. [17]. In the past, destructive methods like serial sectioning has been used to determine the fabric structure. μCT is an alternate approach to image and quantify GFRP in 3D. It is also used for the 3D-characterisation of paper, board and felt and polymeric fabrics used in paper manufacturing [18–20]. In these studies the porosity, specific surface area, pore size distribution and tortuosity of paper or its reinforcing materials were investigated. Other researchers like Lomov [21], Delerue [22], Cornelis [23] and Vodolan [24] have also used the μCT for invesigations of composites. Cornelis investigated carbon fibres reinforced polymers and metals. He determined the fibre arrangement and the fibre and matrix distribution. Lomov used the μCT to get the dimensions of the rovings and the spaces between them to genetrate geometrical models of the 3D textiles using WiseTex software. These models serve as input for simulation of permeability and meso-mechanical properties determination. Delerue acquires the pore network geometry of a reinforcement to model its permeability. Vodolan developed some methods to get automatically information of the yarn centre structure, textile layer position or yarn shape estimation from μCT images.

Another nondestructive method used to image micro- and meso-structure of GFRP is the optical coherence tomography (OCT) [9,25]. One of the disadvantages of OCT is the refractive index mismatch between the resin and glass fibres. As a result the boundaries between the two phases are blurred. X-ray–CT images more clearly the structure of the reinforcement.

An X-ray source illuminates the object. The transmitted X-rays are recorded on a detector that measures the different intensities of the attenuated X-rays. The intensities vary due to the different X-ray absorption. High-density materials absorb more X-rays than low-density materials. These intensities give information of the irradiated material density. The advantage of the CT is the possibility to X-ray the sample in all directions for every slice. Therefore, either the object or the X-ray source can be rotated at least over 180°. In certain distances several slices are scanned from the interested parts of the object. [26] A data retransformation enables a correct 3D-reconstruction of the object. A comparison of different μCT methods may be found in Bonse et al. [27].

To ensure a high resolution, the object should not be big. A large object reduces the resolution, what can be easily seen from Eq. (1):

$$R = \frac{N}{D}. \tag{1}$$

R is the resolution, D the diameter of the object, and N the number of pixels: 2048, 1024, or 512.

Samples were measured with a μCT-40 (Scanco Medical, Bassersdorf, Switzerland). This is a fan-beam-CT. Its X-ray tube has an energy of 20–70 keV. The highest achievable resolution is 6 μm. The spatial resolution of the system was defined by the 10% contrast-level of the modulation transfer function.

2.2. Samples

The micro-structure of the fabric was investigated using rectangular samples with a size of 7 × 50 × 4 mm. The size of the samples is limited by the device. Samples were cut from GFRP-plates produced by using a RTM-process. Fig. 1 shows a plate with marked areas from where the samples were taken: area 1 is near the inlet, area 2 near the vent. Injection pressure was set to 1 bar, the pressure at the vent is ambient pressure. The resin, Biresin L84