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An optically-based inverse method to measure in-plane permeability fields of fibrous reinforcements

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ABSTRACT

Structural composite manufacturing relying on Liquid Composite Molding technologies is strongly affected by local variability of the fibrous reinforcement. Optical techniques using light transmission are used and allow field measurements of areal weight (and fibre volume fraction) of glass fibre reinforcement. The coupling of obtained areal weight mappings along with injection flow fronts is used to extract in-plane permeability fields. The current work presents results with a focus on glass random mats, but the method can be adapted to any glass fibrous medium. A study of convergence and error due to discretization is performed. Also the influence of the stacking of fibrous layers on the preform variability is analyzed. The major advantage of the proposed technique is a relatively fast acquisition of statistical data on reinforcement variability, which can be later utilized in stochastic based process simulations.

1. Introduction

The manufacturing of fibre-reinforced structural composites is influenced by the variability of the constituent materials (i.e. fibrous media and organic matrix). Processing methods involving significant resin flow through the fibre reinforcement, for example the Liquid Composite Moulding techniques, are strongly affected by variability in the reinforcement structure. For a given fibrous reinforcement, local variations in fibre content and orientation exist [6] and will lead to variation in permeability and through-thickness compaction response. Significant in-plane variability has been shown to exist within a single reinforcement layer, and the influence of this variability can possibly be modified as multiple-layer preforms are assembled [1–5,8,10,13]. A new field of research has emerged with respect to modeling the variability of composite manufacturing, especially during the injection stage [11,15,17,21]. Stochastic simulation can help quantifying the robustness of a process, which is of major importance for high series production such as in the automotive industry.

In a deterministic numerical formulation, the resin injection stage is modeled coupling Darcy's law with the conservation of mass. The inputs for such models are the resin viscosity, the fibrous medium permeability tensor, the domain geometry and initial and boundary conditions. The input being unique will lead to a unique (deterministic) solution. However, when stochastic manufacturing simulations are performed, the inputs must represent some extent of variability in the process and/or materials. For instance in the case of Resin Transfer Molding (RTM) one can agree that the mold geometry is not too variable whereas the permeability can be highly dispersed from preform to preform and even within the preform itself. Therefore when stochastic simulation is of concern, the input cannot be a unique value, but has to be a field (in space and/or in time). The new challenge is to propose techniques that can provide the field of the variable parameters required in the stochastic simulations. For example, a previous study coupling optical techniques with numerical flow simulation have been proposed [9].

This paper focuses on measuring the in-plane permeability field of single- or multi-layers of fibrous reinforcement. The technique has been developed around the measurement of the areal weight field of each layers coupled to central injection of the samples. It is an alternative to the statistical technique based on image analysis of dry fabrics and permeability models proposed in [22]. Recorded injection pressure and flow front data are utilized with a finite element/level set based inverse method, which solves for the unknown in-plane permeability field.

It is worth mentioning that both porosity and permeability are parameters that depend on the volume where averaging is performed. The results in [22] have shown that, for the material of interest in this study, a 95% confidence on porosity and permeability values is attained for respectively 10 and 350 mm square-sample size. Here because of the discretization, which will be modified

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along the study, the porosity and permeability fields presented are apparent values. For the sake of simplicity, the adjective apparent will not be used in the following when referring to either porosity or permeability.

First, the setups for areal weight field measurement and central injection flow fronts are briefly described. Then, the methodology based on an inverse method is detailed. Finally results of permeability fields are given. The sensitivity of the results with respect to the number of stacked layers and numerical discretization is discussed.

2. Experimental setups for field-measurements

2.1. Materials

The fibrous material is an E-glass chopped strand mat (CSM) whose reference is M705450 (Owens Corning). It has an average areal weight of 457 (+/-24) g/m^2 measured on 37 samples. The fibrous material has been statistically studied for average and local porosity and permeability fields in a former study [22]. The mineral oil used in the central injection has a viscosity of 0.21 Pa s at room temperature. Because of possible temperature variation from one test to another, the temperature was recorded for each injection, then the viscosity was interpolated from a viscosity measurement database. Also one injection lasted around 1 min, therefore the risk of significant temperature change during the injection is negligible.

Since CSM are made of thin tows, the local unsaturation induced by the dual-scale porosity is very limited; there is no need to develop a multi-scale FE model to solve for fluid flow to get the intrinsic (also referred as effective or saturated) permeability [16]. Then the permeability field identified through the proposed technique is assumed to be a mapping of Darcian permeabilities. For woven or fibrous materials that would consist of large tows (therefore presenting a double scale porosity), another model including that feature should be used.

2.2. Areal weight measurements

An apparatus consisting of a light-box and digital SLR camera is used to capture high-resolution images of the reinforcement layers [6]. By characterizing the relationship between intensity of the transmitted light through the reinforcement and the corresponding areal weight, image analysis techniques have been developed and are capable of translating the surface images into maps detailing areal weight spatially. Optical distortions such as vignetting and barrelling have been compensated for within these analyses. Also the effect of non-homogenous back lighting has been eliminated. Readers can refer to the work carried out by Gan et al. for the details of the technique [6].

2.3. Injection and flow front measurements

Central injections at constant pressure (0.1 MPa, 1 bar) are realized within a cavity consisting of a bottom glass platen and top cylindrical aluminum platen. The mineral oil is used as a model Newtonian fluid. The 25 cm $\times$ 25cm fibrous reinforcement preform is positioned in the mold cavity. The plies have been punched with a 15 mm-diameter hole to create a circular injection inlet at the centre of the sample. In order to avoid risks of variability of the holes' diameters and ensure a clean cut, the latter are very efficiently and reproductively punched with a hydraulic press.

The injection setup is mounted in an Instron universal testing machine (Fig. 1). The cavity thickness is set from the total areal weight of the single or stacked plies to achieve a target fibre volume fraction V_f of 38%. A CCD camera records the flow front progression with time through the transparent glass platen (Fig. 2). The digital images are processed so as to extract flow front profiles (Fig. 3 (bottom). The flow front profiles can also be plotted in radial coordinates (r, θ (where $x = r\cos\theta$ and $y = r\sin\theta$) to better visualize front distortions and variability with respect to space and time (Fig. 3 (top left)) [14]. As expected at constant injection pressure, the flow front slows down with respect to time (the fronts are not equidistant for a given time step). In order to even better visualize the extent of distortion without being penalized by that effect, the fronts can also be plotted in a (r^2, θ space that forces the injection fronts to be more equidistant (Fig. 3 (top right)). In other words, in the (r^2, θ space, a slowdown or rise of the flow front speed due to local permeability change can be more easily observed independently from the inevitable slowdown induced by the central injection at constant inlet pressure.

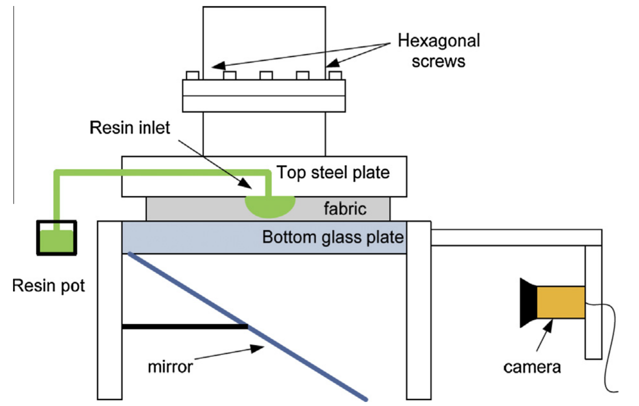

Fig. 1. Experimental injection setup [20]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Data processing methodology

3.1. Fibre volume fraction

With a cavity thickness t in which the reinforcement is applied, areal weight fields obtained from the image analysis mentioned earlier are converted to fibre volume fraction fields using:

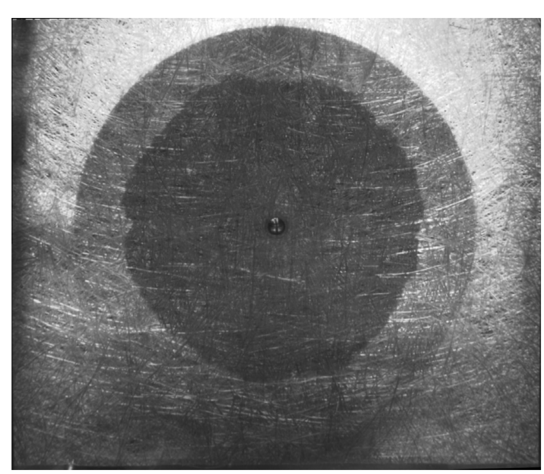

Fig. 2. Raw image taken through the bottom glass platen during the central injection of a chopped strand mat (CSM) material after 54 s of injection. The fibrous CSM appears in light gray, the circle (in intermediate gray) is the top platen and the darkest area is the impregnated material.