AN OPTICALLY BASED INVERSE PROBLEM TO MEASURE IN-PLANE PERMEABILITY FIELDS

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ABSTRACT: Composite manufacturing relying on Liquid Composite Molding technologies is strongly affected by variability of the fibrous reinforcement. Original optical techniques are detailed and allow field measurements of areal weight (fiber volume fraction) and permeability. The latter requires an additional inverse method to extract data from flow fronts. The current work presents results with a focus on isotropic materials, but the method can be adapted to any anisotropic media. The major advantage of these techniques is fast acquisition of statistical data on reinforcement variability, which can be later utilized in stochastic based process simulations.

KEYWORDS: Reinforcement architecture, permeability measurement, image processing, flow simulation

INTRODUCTION

The manufacturing of composite materials is influenced by variability in the constituent materials. Processing methods involving significant resin flow through the fibre reinforcement, for example the Liquid Composite Molding techniques are strongly affected by variability in the reinforcement structure. Local variations in fibre content and orientation 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 amplified as multiple layer preforms are assembled.

This paper focuses on variability within a single layer of reinforcement, considering physical realisations of the areal weight and permeability fields. A major goal of this research is to develop efficient techniques to experimentally quantify these fields, which are coupled, and require independent measurements. A technique has been developed to experimentally measure the areal weight field within samples of an isotropic chopped strand mat. This procedure utilises optical images of light transmission through the sample of reinforcement, providing a broad measurement area. In parallel, constant flow rate radial injection is carried out within the characterised samples, with detailed flow front information being recorded via image data acquisition. Recorded injection pressure and flow front data are utilised with a finite element / level set based inverse method, which solves for the unknown in-plane permeability field.

EXPERIMENTAL SETUPS

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. By characterising the relationship between intensity of the transmitted light through the reinforcement and the corresponding areal weight, image analysis techniques have been developed that 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, eliminating the effect of non-homogenous back lighting.

Flow front measurements

Injections at constant flow rate are realized using a syringe pump. Red-dyed vegetable oil is used as model fluid. The 20cmx20cm layer of fibrous reinforcement is positioned in the mold cavity. A CCD camera records the flow front progression with time (Fig. 1). The pictures are processed so as to extract flow front location. Then the flow front positions are plotted in radial coordinates to better visualise front distortions and variability (Fig. 2).

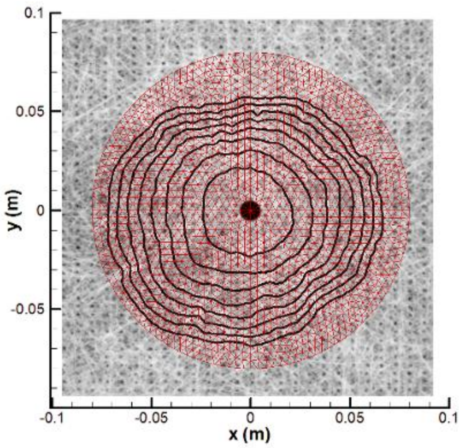


Fig. 1: Superposition of fabric (background), finite element mesh and experimental flow front positions (black solid lines) detected with the CCD camera.

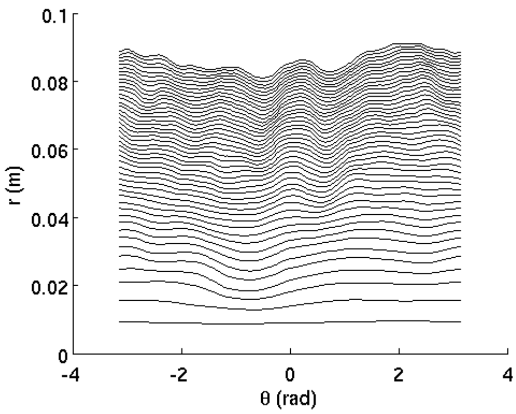


Fig. 2: Experimental flow front positions in radial coordinates.

DATA ANALYSIS

Fiber volume fraction

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

$$V_f = \frac{AW}{t\rho_f} \quad \text{Eq.1}$$

where *AW* is the reinforcement areal weight, *t* is the cavity thickness and ρ_f is the density of the glass fibres. From the corresponding volume fraction maps, it was observed that the data varied by up to +/- 10% as a function of (*x*,*y*) location, having no structured or predictable distribution spatially. These variations in fibre volume fraction are a result of the differences in the local fibre architecture, potentially introduced during reinforcement manufacturing and handling.

Flow front / Permeability

As shown in the previous section, the fiber volume fraction of a fibrous reinforcement is not constant and depends on the (*x*,*y*) location. As a consequence of this variability, the permeability of fabrics is also a function of space. In this section, an original method is proposed to identify the permeability field of fabrics using an inverse method. The method combines the finite element and the level set methods.

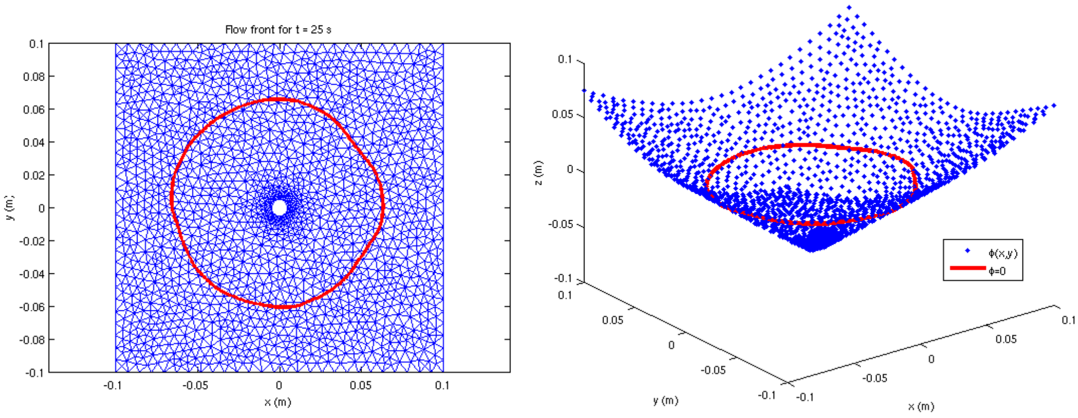
The level set method is used in a variety of applications (chemical or fluid simulations [1]). The goal of this method is to track a moving boundary within a simulated two-phase flow without re-meshing. The flow front is defined as:

$$\Gamma(t) = \left\{ x \in R^2 : \psi(x,t) = 0 \right\} \qquad \text{Eq.2}$$

with

$$\psi(t) = \pm \min_{x_\Gamma \in \Gamma(t)} \left\| x - x_\Gamma \right\| \qquad \text{Eq.3}$$

where $\psi(t)$ is the level set function. The level set function is the signed distance function: this is the distance between a point and the front. In the case of porous medium flow simulations (described by Darcy's law [2]), the two moving phases are the injected resin and the air expulsed ahead of the front. The level set function is negative within the resin domain, equal to zero at the flow front location and positive outside the resin domain (i.e. in the air domain) (Fig. 3).



(a) (b)

Fig.3: (a) flow front position at t = 25 s, (b) associated level set function.

The evolution of the flow front position is then described by the evolution equation of the function $\psi(t)$, which is given in [3].

$$\frac{\partial \psi(x,t)}{\partial t} + v(x,t)\nabla \psi(x,t) = 0 \qquad \text{Eq.4}$$

where $v(x,t)$ is the fluid velocity field (computed in all domains: air and resin) and $\psi(x,t)$ is given. The velocity field is computed by solving the following equations:

$$\begin{cases} \nabla \cdot (\psi\, v(x,t)) = 0 \\ v(x,t) = \dfrac{u(x,t)}{\phi(x)} \\ u(x,t) = -\dfrac{K(x)}{\mu} \nabla p(x,t) \end{cases} \qquad \text{Eq.5}$$

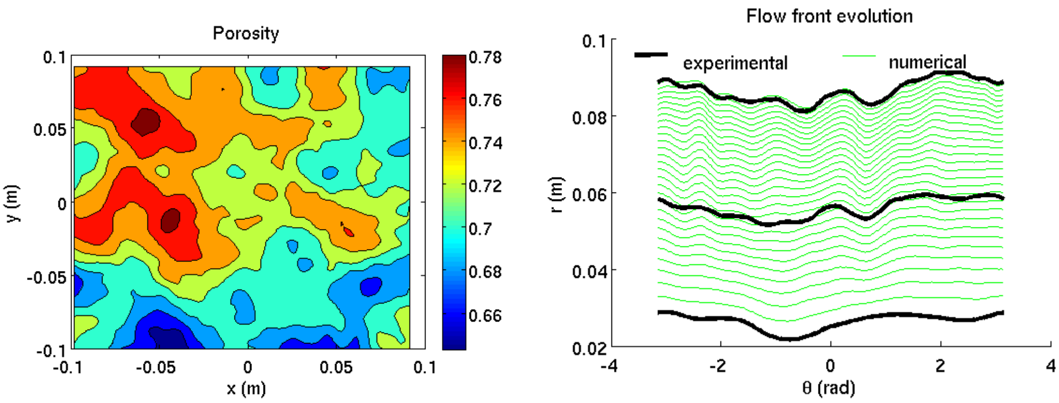
where $p(x,t)$ is the pressure field, $u(x,t)$ is the Darcy's velocity field, $K(x)$ is the permeability field, μ is the viscosity (0.1 Pa.s when x is in the resin domain and 10^{-6} Pa.s when x is in the air domain) and $\phi(x)$ is the porosity field. In order to identify the permeability field $K(x)$, the latter is discretized in a fixed number of points (regular mesh) and then interpolated at each integration points of the finite element mesh. In this problem, the fmincon Matlab function is used in order to solve the inverse problem and identify the permeability field. The inverse problem is equivalent to the minimization of the following objective function:

$$E_r(t_f) = \sqrt{\frac{\int_0^{2\pi} \left(r_{num}(t_f,\theta) - r_{\exp}(t_f,\theta)\right)^2 d\theta}{\int_0^{2\pi} \left(r_{\exp}(t_f,\theta)\right)^2 d\theta}} \qquad \text{Eq.6}$$

where $r_{num}(t_f,\theta)$ is the radius of the simulated flow front at time t_f and $r_{\exp}(t_f,\theta)$ is the radius of the experimental flow front at time t_f.

RESULTS

The permeability field is calculated from the porosity field (Fig.4(a)) and the flow fronts (Fig.2), both obtained experimentally. As shown on Fig.4(b), only three experimental flow fronts (out of the 50 given by the experimental injection) are used to identify the permeability field. The first half of the permeability field is identified using the first and the second flow fronts, while the second half using the second and the third flow fronts.



(a) (b)

Fig.4: (a) porosity field (input data), (b) flow front evolution.

The permeability identification using an inverse method is realized on a 12x12 discretization grid. In the example shown here, the value of the objective function $E_r(t_f)$ is below 0.2%. The permeability field obtained is shown in Fig.5. Since experimental data are obtained from a constant injection flow rate, the area between two successive flow fronts curves is constant in the (r^2, θ) representation. In Fig.5, with such representation, a higher distance between two flow fronts (white lines) can be directly related to a higher flow front velocity. The permeability field shows a very good agreement with the local variations of flow front velocities and comforts both accuracy and potential of the methodology presented here.

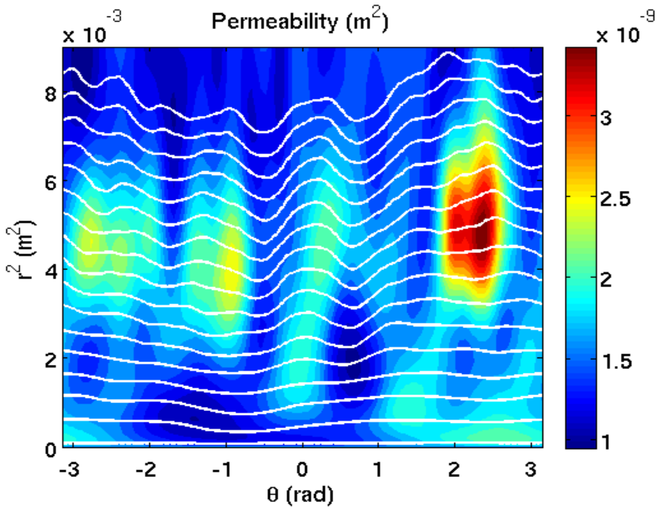


Fig.5: Permeability field and experimental flow front evolution.

CONCLUSION

An inverse identification method of in-plane permeability field based on optical measurement of fiber volume fraction field and 2D flow front measurements has been detailed. The results shown in this article are related to an isotropic fibrous material. The extension of this work to an anisotropic media is straightforward. The major advantage of these techniques is fast acquisition of statistical data on reinforcement variability, which can be later utilized in stochastic based process simulations.

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