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Experimental determination of the permeability of engineering textiles: Benchmark II

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ABSTRACT

In this second international permeability benchmark, the in-plane permeability values of a carbon fabric were studied by twelve research groups worldwide. One participant also investigated the deformation of the tested carbon fabric. The aim of this work was to obtain comparable results in order to make a step toward standardization of permeability measurements. Unidirectional injections were thus conducted to determine the unsaturated in-plane permeability tensor of the fabric. Procedures used by participants were specified in the guidelines defined for this benchmark. Participants were asked to use the same values for parameters such as fiber volume fraction, injection pressure and fluid viscosity to minimize sources of scatter. The comparison of the results from each participant was encouraging. The scatter between data obtained while respecting the guidelines was below 25%. However, a higher dispersion was observed when some parameters differed from the recommendations of this exercise.

1. Introduction

Liquid Composite Molding (LCM) processes are increasingly used in the automotive and aeronautic industries. Five common steps in LCM are necessary to manufacture a composite part. Firstly, the fibrous reinforcement is preformed to the desired geometrical shape. Then, it is placed in the mold cavity. A flexible or rigid top is used to close the mold in order to inject the polymeric resin in the next step. Once the mold is completely filled, the injection is discontinued allowing the resin to cure after which the composite is demolded.

The filling of complex-shaped molds is a critical step. Indeed, dry zones (region not covered by resin) may appear if specifications like positions of injection and vent gates, injection pressure and clamping force are not well defined. Mold filling simulation

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softwares such as PAM-RTM [1], LIMS [2] and Polyworx [3] allow one to predict the resin flow and filling time, the flow front shapes, the pressure and velocity fields of the complete manufacturing process. A complete characterization of the material properties is necessary to run such simulations.

The permeability of fibrous reinforcement is one of the key parameters governing the mold filling. It corresponds to the ease of a fluid to flow through a porous medium. This property was first identified by Darcy [4] in 1856 in the form of hydraulic conductivity. Based on the observation of water flowing through a vertical column of sand, an empirical formula now known as Darcy's law was derived:

$$v = -\left(\frac{K}{\mu}\right) \cdot \nabla P \tag{1}$$

where v, μ, ∇P and K are respectively the volume averaged Darcy velocity, the dynamic fluid viscosity, the pressure gradient across the porous medium and the permeability. In porous media such as fibrous reinforcements, the permeability is anisotropic. Thus the second order tensor describing this property can be written as:

$$K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \tag{2}$$

This tensor can be diagonalized to obtain the three principal permeability values of a fibrous reinforcement. It is typically assumed that the first two principal permeability K_1 and K_2 lie in the plane of the fiber bed while the third one K_3 is oriented through it thickness. The in-plane flowing pattern is thus an ellipse oriented at an angle β which can be defined as the angle between the warp direction and the principal flow direction as shown in Fig. 1 (extracted from [5]). In-plane principal permeability values are of particular interest because in several composite manufacturing processes are performed injecting resin in the plane of the fibrous reinforcement.

A wide variety of methods and approaches have been developed to determine the in-plane permeability of a fibrous reinforcement. Firstly, it is possible to apply models to estimate the permeability. Kozeny and Carman [6] and Gebart [7] have developed equations taking into account geometrical parameters and the solid volume fraction to calculate the permeability of a single scale porous medium. This kind of model is still used to approximate the permeability of a fiber tow. However, they are not well adapted to determine the permeability of dual scale porous media such as fabric. Thus, more complex analytical models, such as for example Lundström [8] or Papathanasiou [9], have been created considering the fibrous reinforcement as a medium composed of fiber tows. Thus, the flow was divided in two components: the mainly capillary flow in the tows and the viscous flow between the tows. Numerical simulations have also been developed to calculate the permeability of a fibrous reinforcement. Various techniques have been explored: lattice Boltzmann method [10], finite differences calculation [11,12] and the finite element method [13–16]. However, to validate all these models, experimental permeability data are necessary.

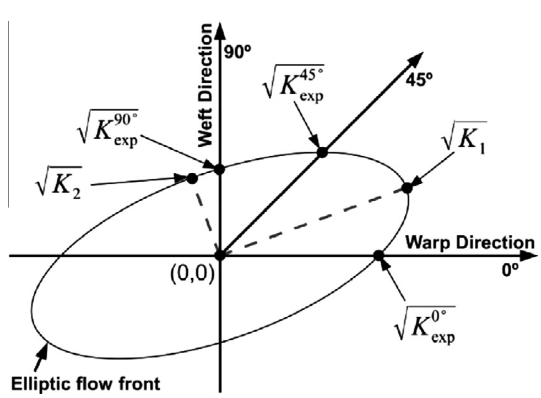

Fig. 1. Elliptic pattern of a fluid flowing through a fibrous reinforcement [5].

As summarized in [17], numerous experimental techniques have been developed and described in the scientific literature. Two of them are commonly used to determine K_1 and K_2: unidirectional [5,18] and radial techniques [19,20]. Both methods show advantages and drawbacks. The former method has a higher repeatability thanks to an easier tracking of the straight unidirectional flow front. Moreover, the experiment is less complicated to set up since the flow front is straight. This method can be used to determine both unsaturated permeability by following the flow front and saturated permeability after the flow has filled the entire preform. However, the radial method permits the determination of the unsaturated permeability ellipse with only one experiment. In addition, the possible race-tracking observed in a unidirectional measurement [21] is avoided here.

The lack of standardization of permeability measurements impedes researchers from comparing permeability obtained from different experimental setups. Parnas et al. [22] and Lundström et al. [23] have respectively initiated the creation of a permeability database and organized a small-scale benchmark. Their efforts were important, but the involvement of a larger part of the research community is necessary to take a step towards standardization. A first international permeability benchmark exercise [24], initiated by ONERA (Office National d'Étude et de Recherche Aérospatiales, France) and KU Leuven, was conducted for this purpose. The aim was to get an overview of the methods, practical uses and range of results obtained by different participants worldwide. The permeability data of twelve institutions from six countries were compiled and compared for two different fabrics. The main finding of this study was a significant scatter of more than one order of magnitude between all participants for both reinforcements tested. The explanation then was that human factors such as skilled and experienced personnel, preparation of specimens or evaluation of raw data were principally responsible for this scatter. In that work, it was suggested that another benchmark based on a common procedure and more controlled experimental conditions needed to be conducted in order to confirm the causes of the scatter and allow a better comparison of experimental results.

For this purpose, a guideline document [25] was written in a collaborative effort among the participants of this first exercise. In these guidelines, test conditions for unidirectional unsaturated permeability measurements are defined. Based on them and the common desire of researchers to standardize the determination of permeability, it was agreed to conduct a second benchmark with the support of Hexcel Fabrics. A total of twelve participants (see details in Table 1) were invited to carry out the in-plane unsaturated permeability measurements of a carbon fabric using their respective setups and following the guidelines of this benchmark. As the unidirectional method was chosen, three directions of measurement were necessary to obtain the in-plane ellipse of permeability [5]. Thus, nine institutions were able to carry out these measurements and obtain the permeability ellipse. This paper presents the procedure used, the experimental conditions adhered to and the results obtained by each participant. The permeability values were analyzed and compared in order to determine the scatter of values occurring with the stated guidelines. Finally, a short comparison with the first benchmark was performed and concluding remarks are presented regarding permeability measurements.