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Experimental determination of the permeability of textiles: A benchmark exercise

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ABSTRACT

In this international permeability benchmark exercise, in-plane permeability data for two reinforcement fabrics, obtained using a total of 16 different experimental procedures, were compared. Although, for each procedure, the results appear consistent, different procedures result in a scatter of up to one order of magnitude in principal permeability values for each fabric at any given fibre volume fraction. The ratio of the principal permeability values varies by factors of up to 2. While experimental uncertainties and variability of the specimens affect the scatter in results for any single series of experiments, it is suspected that the main source of scatter in results from different procedures is related to human factors. Aiming at standardisation of measurement methods and interchangeability of results, "good practice" guidelines will be formulated in order to eliminate sources of scatter.

1. Introduction

In Liquid Composites Moulding (LCM) processes, a textile reinforcement structure is preformed to the geometrical shape of the component to be produced. The dry preform is inserted into a mould cavity. After closing of the mould, liquid resin is injected. Once the preform is impregnated and the resin is cured, the component is demoulded and can be finished. Its quality is determined by the quality of impregnation of the reinforcement and the degree of cure of the thermoset matrix material. The cure characteristics of the matrix depend on the resin chemistry and will not be discussed here. The impregnation of the textile preform with resin is typically described using the model of a viscous liquid flowing through a (homogeneous) porous medium. Darcy's law [1], which is frequently formulated as

$$\mathbf{v} = -\frac{\mathbf{K}}{\eta}\nabla p, \tag{1}$$

states a dependence of the phase-averaged (resin + fibres) flow velocity, $\mathbf{v}$, on the permeability of the textile material, $\mathbf{K}$, the viscosity of the resin, η, and the gradient of the pore-averaged pressure inside the mould, ∇p. Based on Eq. (1), the process parameters for production of composite components applying LCM-technology (e.g. location of injection gates and vents in the mould) can be optimised to achieve complete impregnation, i.e. high quality, of the finished components, and the cycle time can be predicted.

The permeability of fibrous structures is generally anisotropic and can be described by a second order tensor. For the simplest case of aligned filaments, various models [2–5] describe the axial and transverse permeability as a function of fibre volume fraction, filament radius and geometrical constants. The geometrical constants in the models, and thus the absolute permeability values, can be estimated predictively only for idealised basic cases of uniformly distributed filaments, which allow simplifying approximations to be made for the flow [3,4].

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The permeability of textile fabrics is typically determined by homogenisation of the properties of fibre bundles and inter-bundle gaps, which form a (in some cases geometrically highly complex) dual-scale pore network. Since the orientation of the principal flow directions is determined by the pore configuration (i.e. the fibre orientations), for thin two-dimensional fabrics, the first two principal axes can be assumed to lie in the fabric plane, while the third axis can be assumed to be oriented perpendicular to the fabric plane. However, it can be argued that this is not necessarily the case for fibrous preforms in general [6]. A significant body of work has been published on modelling the permeability of reinforcement fabrics with specific architectures, in particular addressing the problem of dual-scale porosity (a few recent examples are given in [7–9]). A general problem is that the permeability of a bundle of non-uniformly distributed filaments and the geometry of the inter-bundle gaps and their contribution to the fabric permeability are hard to describe accurately. Thus, fabric permeability models describe typically the dependence on the fibre volume fraction, which are of most interest for many practical applications, but cannot predict quantitatively any constants related to the geometry of the complex pore network. These can only be determined directly from permeability measurement (as, e.g., in [9]) or, alternatively, based on advanced numerical methods, e.g. virtual experiments via flow simulations [10], which require detailed input from experimental pore geometry characterisation.

With permeability measurement being of major importance for characterisation of textile impregnation, not only in the field of composites processing, standards have been established for measurement of the through-thickness permeability of clothing and technical textiles (ASTM D737: air flow; ISO 15496: water vapour flow) and compressed geotextiles (ASTM D5493: water flow). To characterise resin flow in reinforcement textiles, a wide variety of experimental methods for permeability measurement has been developed [11]. Most address measurement of the in-plane permeability, which is of high relevance to LCM, since composites are most frequently processed in thin shell-like structures. However, there is a complete lack of standardisation for measurement of the in-plane permeability of fabrics, and it is well known that permeability data obtained using different methods are not necessarily consistent. In 1995, Parnas et al. [12] proposed use of a reference fabric for standardisation of permeability measurement methods, but to date no standards or guidelines have been put in place. Lundström et al. [13] report on a small-scale benchmark exercise, in which issues of repeatability and reproducibility of permeability measurement were addressed. For a reference material, the scatter of results obtained by different laboratories was in the same order of magnitude as the experimental uncertainty. However, there were only three participants, who all used the same set-up and were trained before carrying out the experiments. Thus, the observed scatter was attributed to differences in specimen preparation.

The international permeability benchmark exercise documented here was initiated by ONERA (Office National d'Études et de Recherches Aérospatiales, France) and Katholieke Universiteit Leuven. As a first step towards standardisation of permeability measurement, the aim was to get an overview of the methods in practical use and the range of results obtained implementing these methods. Twenty institutions and industrial end users from 12 countries replied to a first invitation to participate. For the two reinforcement textiles discussed in this report (Table 1), a 2×2 twill weave carbon fibre fabric (G0986) and a 2×2 twill weave E-glass fibre fabric (01113), both provided by HEXCEL, 11 participants (Table 2) submitted measured in-plane permeability data (for either one or both materials). Participants were instructed to measure the permeability at a target fibre volume fraction of 50% or as close as possible to this value, and were then left to implement their own procedures and protocols. Feedback on procedures and results was provided to all participants in round table discussions at the Flow Processes in Composite Materials conferences in Montréal (FPCM 9, 2008) and Ascona (FPCM 10, 2010).

2. Permeability measurement

2.1. General considerations

A variety of experimental methods for determination of the fabric permeability has been developed. They can be distinguished based on three main criteria:

- flow geometry (linear/radial),
- injection boundary condition (constant pressure/constant flow rate),
- saturation state of the fabric specimen (saturated/unsaturated).

While a more complete review of methods for permeability measurement is given in a recent paper by Sharma and Siginer [11], the basic principles of frequently implemented methods will be discussed in the following.

For unsaturated linear flow at constant injection pressure, the permeability is determined from injection experiments in a rectangular flow channel with a linear injection gate, which needs to be realised such that the fluid penetrates all layers of the specimen equally. The flow front is assumed to be straight and oriented perpendicular to the flow channel axis. Time integration of Darcy's law gives the permeability along the flow direction,

$$K = -\frac{x_{ff}^2 \Phi \eta}{2\Delta p t_{ff}}. \tag{2}$$

Here x_{ff} is the flow front position at an injection time t_{ff}, Δp is the pressure difference between injection pressure and ambient pressure (i.e. gauge pressure), η is the viscosity of the injected fluid, and Φ is the porosity of the fabric specimen. Issues of fibre wetting and its influence on Δp and the determination of K will be discussed below. Inclusion of the factor Φ results from the difference between the flow front velocity in unsaturated flow (corresponding to the average flow velocity of the fluid molecules along the applied pressure gradient) and the velocity defined in Darcy's law. The porosity of a specimen is related to the fibre volume fraction V_f via

$$\Phi = 1 - V_f. \tag{3}$$

In practice, V_f can be determined from

$$V_f = \frac{nS_0}{\rho_f h}, \tag{4}$$

where n is the number of fabric layers in the specimen, S_0 is the superficial density of the fabric, ρ_f is the density of the fibre material, and h is the cavity height. The flow front position as a function of injection time, $x_{ff}(t_{ff})$, is most frequently determined by visual monitoring through the transparent top of the flow channel [14,15]. Alternative approaches for flow front tracking are use of fibre optic sensors [16], thermistors [17], pressure transducers [18] or ultrasound and electrical resistance measurements [19]. Concurrent data reduction schemes for the acquired $x_{ff}(t_{ff})$ raw data are discussed by Ferland et al. [20].

For saturated linear flow, Darcy's law can directly be solved for the permeability

$$K = -\frac{Q\eta L}{A\Delta p}, \tag{5}$$

where Q is the flow rate, A is the flow channel cross-sectional area, and L is the specimen length. In the case of constant injection