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Influence of shear on the permeability tensor and compaction behaviour of a non-crimp fabric

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ABSTRACT

This work presents the results of a study on the permeability and compaction behaviour of textiles under shear deformation. In this study a 0°/90° non-crimp carbon fibre fabric with an areal weight of 200 g/m^2 is used. The influence of shear is observed under two conditions: constant cavity height and constant fibre volume fraction (V_f). Permeability measurements were conducted as one-dimensional as well as two-dimensional flow experiments, totalling 119 experiments. Additional compaction tests of the sheared textiles (13 experiments) lead to a more thorough understanding of the mechanisms at work.

It is shown that for constant cavity heights the behaviour of the textile greatly changes between a shear angle of 15° and 20°. Up to an angle of 15° the permeability shows a linear increase for the principal axis and a linear decrease for the secondary axis. At shear angles above 20° the behaviour for both is non-linear. Furthermore this change of behaviour can also be observed in the rotation of the flow ellipse and the compaction measurements. Both show a double-linear development with a change of behaviour in the region of 15–20°.

1. Introduction

Resin transfer moulding (RTM) processes gain more and more importance for many applications for example in the automotive and aeronautic industry. In RTM dry fibrous reinforcement is placed into a mould consisting of two rigid mould halves. The reinforcement is either placed as cut from the roll or after being preformed to the geometrical shape of the final part. The mould cavity is then filled with a polymeric resin. Once the resin is cured, the finished component can be demoulded. To be able to estimate filling times, position inlets and vents, determine injection pressure and estimate clamping force, a simulation of the injection process should be conducted. Key parameters for this simulation are the permeability of the preform and the development of the resin's viscosity. The permeability defines how easily a fluid can flow through a porous medium and is a property of such medium. Henry Darcy first described this property in 1856 for the groundwater flow of the city of Dijon [1]. A commonly used variation of his original equation is:

$$v = -\left(\frac{k}{\mu \cdot \delta}\right) \cdot \nabla p \qquad (1)$$

where v, μ, ∇p, δ, and k are respectively the flow front velocity, its dynamic viscosity, the pressure gradient across the preform and the preform's porosity and permeability. By rearranging, this equation can be used to determine the permeability of fabrics in a certain stacking sequence.

However, during the draping process of the fabric – either in a special preforming tool, or in the mould – shear forces deform the fabric. This deformation leads to a change in textile properties, influencing compaction behaviour, permeability and mechanical properties. Characterising the influence of shear on permeability therefore plays a key role in conducting proper simulations of the flow front progression in RTM processes.

Several authors have performed such investigations for woven textiles [2–6]. Out of these Endruweit and Ermanni [3] and Verleye et al. [4] also include NCFs in their consideration. However, unfortunately, neither of the works provides experimental data on sheared NCFs to compare their analytical approach [3] or simulation [4] with. Smith et al. [7] published another important work on the topic as early as 1997, providing both, experimental data and a simple model for the prediction of the permeability of sheared preforms. Hammami et al. [8] conducted further experimental work on the shear of a NCF already the year before, in 1996. However, generally little experimental data is available, making further investigation of the effect of shear deformation

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on the permeability of NCFs necessary. Furthermore the observations made in [7,8] do not match those made in the present study.

Shearing a textile decreases its overall area while leaving the amount of fibres constant (see Fig. 1). The mechanism behind it is purely geometric: as the length of the edges of textile remains constant, shear will reduce the overall area according basic trigonometric functions. This results in an increase of the areal weight (Aw) of textiles:

$$Aw(\varphi) = \frac{Aw_{init}}{\cos(\varphi)} \tag{2}$$

When leaving the cavity height of the tool constant, this increase of areal weight results in an increase of the fibre volume fraction (V_f) as a function of the shear angle φ:

$$V_f(\varphi) = \frac{V_{f,init}}{\cos(\varphi)}, \quad \text{for} \quad h = \text{const}. \tag{3}$$

Another approach to the increase of areal weight is locally adapting the tool's cavity height in a way that V_f remains constant. To achieve this, the cavity height of the tool has to be adjusted according to the following formula:

$$h(\varphi) = \frac{h_{init}}{\cos(\varphi)} \quad \text{for} \quad V_f = \text{const}. \tag{4}$$

2. Material and processes

2.1. Material used

The material used in this study is HexForce NLT00 HR1270 0200 UGZ0F from Hexcel. It has an areal weight (Aw_{fibres}) of 200 g/m^2, and is a balanced, non-crimp carbon fibre textile with a 0°/90° orientation, which is made from Zoltek Panex 35 50 K fibres. The stitching yarn was assumed to be 6 g/m^2 and have a density (ρ_{yarn}) of 1200 kg/m^3. The stitching type is tricot with a gauge of approx. 5 mm. For the experiments five layers of textile (n) were stacked in an asymmetrical fashion by putting them on top of each other in the same orientation. For these five sheets an initial cavity height (h) of 1.25 mm was chosen and a density of the fibres assumed to be 1800 kg/m^3. By putting the assumed values into Eq. (5) – which is based on basic physical principles – a V_f of 46.4% is calculated, taking the stitching yarn into account, or 44.4%, in terms of carbon fibre. For the evaluation of permeability experiments the overall V_f of 46.4% is to be used.

$$V_f = \left(\frac{Aw_{fibres}}{\rho_{fibres}} + \frac{Aw_{yarn}}{\rho_{yarn}}\right) \cdot \frac{n}{h} \tag{5}$$

2.2. Apparatus for the measurement of permeability

The permeability was measured using an apparatus devised by the authors, which allows for optical tracking of the flow front. The textile is placed between a glass plate and a steel plate. To avoid deflection of the cavity, the steel plate and the glass plate are both supported by a block of cross beams with a height of 15 cm each. A plate made of PMMA is inserted between the glass plate and the supporting block to prevent the glass from frequently breaking due to inserted stresses. The blocks are bolted together to achieve the desired compaction of the textile. The height of the cavity is determined by a set of spacers, which are inserted around the textile. A schematic illustration of this setup is shown in Fig. 2. The height of the cavity is furthermore measured ex-post using waxen pellets that are placed along the sides of the textile and compacted along with it. This allows for determining the actual height and for noticing possible deflections of the cavity.

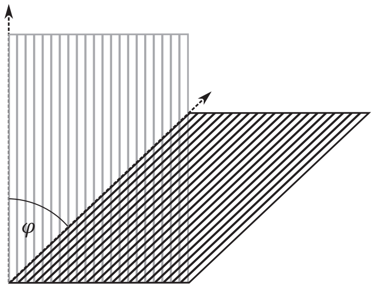

Fig. 1. Schematic illustration of area decrease due to shear.

The injection fluid is a vegetable oil of a known, temperature-dependent viscosity of about 100 mPa·s at room temperature and the injection pressure is adjusted using a pressure control valve. To determine the correct viscosity of the fluid, the temperature prevailing during the experiment is measured.

Due to the special nature of sheared textiles it was necessary to measure the permeability of the textile in 2D experiments [9]. This means that the flow front spreads in an elliptical shape from a central injection point (Fig. 3). In contrast to this, the experiments for the permeability's dependency on V_f are conducted as linear flow (1D) experiments. In this experimental setup the principal directions of the permeability tensor are measured independently. Runners are avoided by use of a solidifying liquid, which is distributed along the sides of the textile after its compaction in the cavity.

A camera captures the advance of the flow front using continuous shooting mode. The obtained images are then evaluated using an in-house semi-automated Matlab software and the permeability is calculated by the application of Darcy's law (see Section 1). For the 2D experiments the Matlab software uses a least square fit to fit the flow ellipse of each captured image. For this the centre of the ellipse is held constant at the injection point and the semi axis and rotational angle of the ellipse are fitted. The permeability is then calculated for each image according to the following equations [11]:

$$k_a = \frac{a_f}{b_f} \cdot \left(\left(a_f \cdot \sqrt{\frac{b_f}{a_f}} \right)^2 \cdot 2 \cdot \ln\left(\frac{a_f \cdot \sqrt{\frac{b_f}{a_f}}}{r_{in}} - 1 \right) + r_{in}^2 \right) \cdot \frac{\mu \cdot \delta}{4t_f \cdot \Delta p} \tag{6}$$

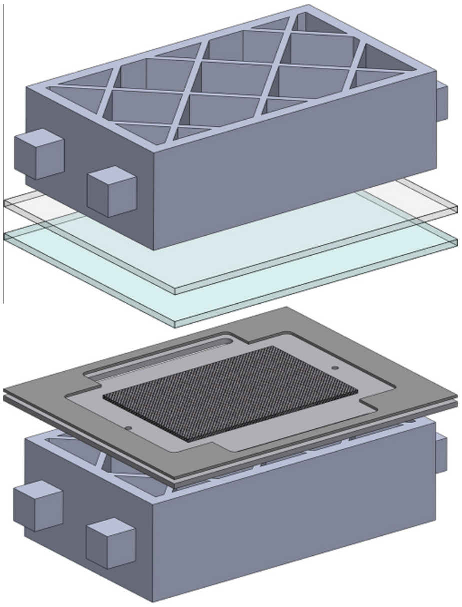

Fig. 2. Schematic illustration of the used apparatus.

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