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IN-PLANE ANISOTROPIC PERMEABILITY CHARACTERIZATION OF DEFORMED WOVEN FABRICS BY UNIDIRECTIONAL INJECTION

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SUMMARY: Because of the increasing use of polymer composites in a wide variety of industrial applications, the manufacturing of complex composite parts has become an important research topic. When a part is manufactured by liquid composite moulding (LCM), the reinforcement undergoes a certain amount of deformation after closure and sealing of the mould. In the case of bidirectional woven fabrics, this deformation may significantly affect the resin flow and mould filling because of changes in the values of permeability. Among other considerations that govern the accuracy of numerical simulations of mould filling, it is important to predict the changes of permeability as a function of the local shearing angle of the preform. The resin flow through a fibrous reinforcement is governed by Darcy's law, which states that the fluid flow rate is proportional to the pressure gradient. The shape of the flow front in a point-wise injection through an anisotropic preform is an ellipse. This article describes a new methodology based on the ellipse equation to derive the in-plane permeability tensor from unidirectional injection experiments in deformed woven fabrics. It also presents a mathematical model that predicts the principal permeabilities and their orientation for sheared fabrics from the permeability characterization of unsheared fabrics. Unidirectional flow experiments were conducted for a non-stitched, balanced, woven fabric for different shearing angles and fiber volume fractions. Experimental results are presented for deformed and undeformed fabrics obtained by unidirectional flow measurements as well as a comparison of the proposed characterization methodology with radial flow experiments. As result of this study, a new computer interface was developed allowing real-time acquisition data and processing for both unidirectional and transverse permeability measurements.

KEYWORDS: Liquid Composite Moulding (LCM), permeability measurements, sheared fabrics

INTRODUCTION

Over the recent years, industrial applications of polymer composites have gained ground for technological, economical and environmental reasons. *Liquid Composite Molding* (LCM) processes such as *Resin Transfer Molding* (RTM) and *Structural Reaction Injection Molding* (SRIM) have become increasingly popular. These techniques based on resin injection through fibrous reinforcements allow a significant reduction of the cost of composite manufacturing compared with traditional autoclave processing or hand lay-up. RTM is a well-known closed-mold injection process widely used to manufacture polymer composites for low to medium volume production. In a typical RTM process, the reinforcement is placed into the cavity of a mold. Once the mold is closed, a thermoset resin system is injected under constant pressure or flow rate. During the closing and sealing of the mold, the reinforcement undergoes a certain amount of deformation. Although a small degree of *"inter-yarn slip"* as third mode of deformation has been reported by Potter (1) and Wang, et al. (2), most studies have shown that in-plane shear is the main mode of deformation in the draping of fabrics over a complex mold geometry (1, 3-4). A reorientation of fiber tows takes place, which affects the in-plane permeability of the reinforcement. The deformations of the fabric structure alter the resin flow and the filling of the mold cavity. Hence, the measurement and prediction of the in-plane permeability of deformed fabrics are important tasks for structural design and LCM process simulation (5-7).

Permeability is a critical parameter that was investigated by several researchers in the last years. Basically, two methods have been extensively used in the literature to measure permeability. The first one is based on unidirectional injections, and the second one on bi-directional flow measurements from a pointwise injection gate. Bi-directional measurements for radial injections have been described and implemented by several researchers (8-14). Although this approach looks attractive for fabrics because the two directional permeabilities, K_1 and K_2, and the principal flow direction are obtained in just one experiment, some difficulties have been reported (15-16). In this work, unidirectional flow experiments have been conducted because measurements based on central injections were not found sufficiently reliable.

This article begins by describing a new approach based on unidirectional injections, which is based on the shape of the observed injection ellipse. Results of permeability measurements of the unsheared fabric are first presented. Then, the special experimental set-up devised to induce uniform shear on fabric samples is described. A series of unidirectional permeability measurements are then conducted and permeability variations are reported as a function of shear angle for three different fiber volume fractions. Finally, a new predictive model of sheared permeability is proposed.

METHODOLOGY

Bear [17] has shown that the square root of the effective permeability along one direction of a porous medium, K_{eff}, follows an ellipse as displayed in Fig. 1, where the semi-major and minor axes represent the square roots of the principal permeabilities K_1 and K_2. Hence, if the effective permeability is measured in three different preform directions by unidirectional flow experiments, it is possible to reconstruct the permeability ellipse, the principal axes of which fully defining the in-plane permeability tensor of the fibrous reinforcement.

Since an infinite number of ellipses centered at (0, 0) pass through two arbitrary points, measurements of effective permeability in at least three directions are required to define the ellipse. In this investigation it is proposed to measure the effective permeability in the 0º, 90º and 45º directions. Therefore, the task consists of finding the ellipse centered at (0,0) that passes through the three following points ($\sqrt{K_{eff}^{0^\circ}}$, 0), (0, $\sqrt{K_{eff}^{90^\circ}}$) and ($\sqrt{K_{eff}^{45^\circ}} * \cos 45^\circ, \sqrt{K_{eff}^{45^\circ}} * \sin 45^\circ$). In the implementation of this approach, the orientation of principal directions is assumed to be independent of the fiber volume fraction. The angle β between the larger axis of the ellipse and one tow direction, namely the warp in this paper, depends only on the shear deformation.

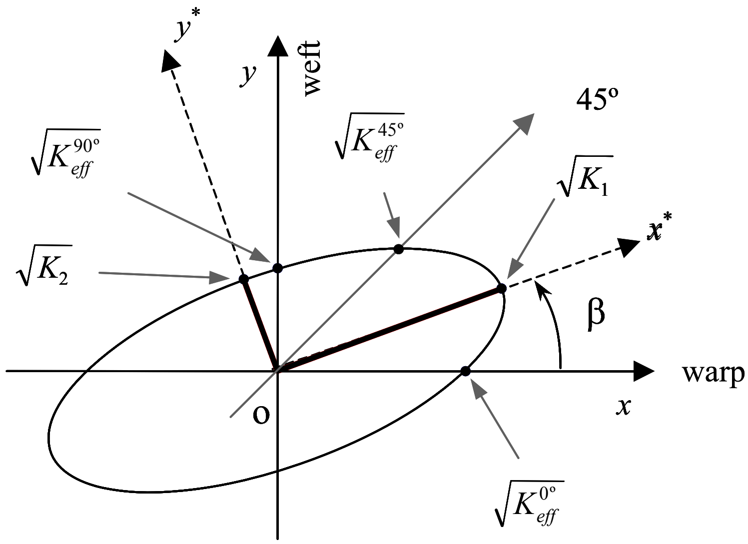


Fig. 1 Elliptic pattern of the effective permeability (17).

The general equation of an ellipse centered at the origin with its major axis oriented along the x*-axis is given by:

$$\frac{(x^*)^2}{r_1^2} + \frac{(y^*)^2}{r_2^2} = 1 \tag{1}$$

where r_1 and r_2 denote respectively the half length of the major and minor axes. When the ellipse is not aligned with the x*-axis (as illustrated in Fig. 1), a rotation of the coordinate system must be performed around the z-axis:

$$\begin{pmatrix} x^* \\ y^* \\ z^* \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{2}$$

where β is the rotation angle between the two reference systems 0xy and $0x^*y^*$. Hence, a modified ellipse equation is obtained by replacing equation 2 in equation 1. This equation is then written in terms of permeability for the three measured directions. Thus, a system of 3 equations with 3 unknowns is obtained, and the final system to solve is:

$$\begin{bmatrix} K_{eff}^{0°}\cos^2\beta & K_{eff}^{0°}\sin^2\beta & 0 \\ \frac{1}{\sqrt{2}}K_{eff}^{45°} & \frac{1}{\sqrt{2}}K_{eff}^{45°} & \frac{\sqrt{2}}{2}K_{eff}^{45°}\sin 2\beta \\ K_{eff}^{90°}\sin^2\beta & K_{eff}^{90°}\cos^2\beta & 0 \end{bmatrix} \begin{bmatrix} 1/K_1 \\ 1/K_2 \\ 1/K_1 - 1/K_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (3)$$

Note that the angle β is also unknown in the above system, which remains however a system of three equations with three unknowns K_1, K_2 and β. By imposing an initial value of β, the system is solved iteratively until the condition $C=B-A$ is verified, with A= $1/K_1$, B=$1/K_2$ and C = $1/K_1 - 1/K_2$.

PERMEABILITY CHARACTERIZATION OF UNDEFORMED FABRIC: EXPERIMENTAL RESULTS

In this investigation, flow experiments were conducted with a 0/90º bi-directional non-stitched reinforcement, an equilibrated carbon fiber fabric from Excel Fabrics. This equilibrated preform was first characterized without shear by performing unidirectional flow measurements for three fiber volume fractions, i.e., 34.2%, 45.7% and 57.1%. The fluid used was a 100 cp silicon oil, which behaves as a Newtonian fluid. All flow measurements were conducted at constant pressure injection.

The effective permeabilities measured in the three selected directions 0º, 45º and 90^o are plotted in Fig. 2. Reported values represent an average of at least two experiments conducted for each direction and fiber volume fraction. The principal in-plane permeabilities and their orientation are then estimated by the iterative ellipse method (eq. 3). These experimental values, namely $K_{eff}^{0°}$, $K_{eff}^{45°}$ and $K_{eff}^{90°}$, can be fitted by Kozeny-Carman equation if a modification is introduced. In fact, the Kozeny constant coefficient does not remain constant as the fiber volume fraction varies. This constant is derived from experimental data for each fiber volume fraction and direction of measurement. These values may be then fitted by a polynomial trend. Thus, The Kozeny equation may be written as follows:

$$K_{eff}^{i} = (C_1^i V_f^2 + C_2^i V_f + C_3^i) * \frac{(1-V_f)^3}{V_f^2}, \qquad \text{for } i = 0^o, 45^o \text{ and } 90^o \quad (4)$$

where C_1^i, C_2^i and C_3^i are the polynomial coefficients in each direction. As observed in Fig. 2, a good agreement is showed between experimental values and Eqn. 4.

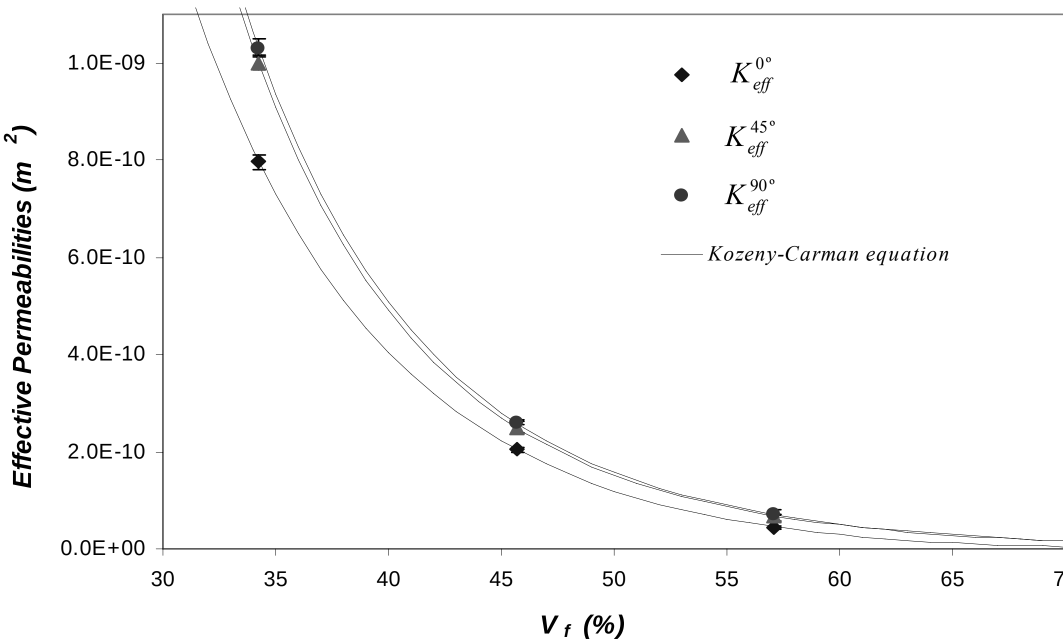


Fig. 2 Effective permeability characterization as a function of fiber volume fraction.

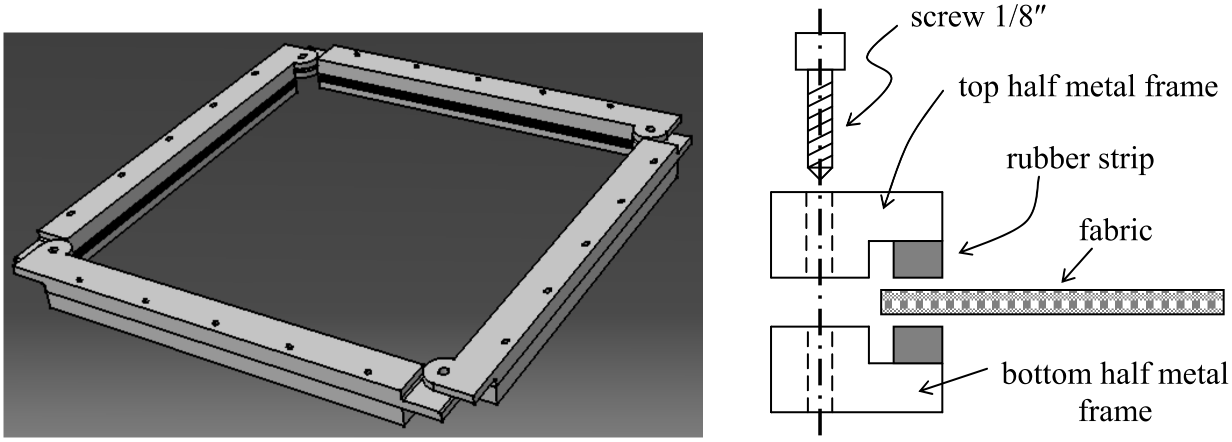
EXPERIMENTAL SET-UP TO INDUCE FABRIC SHEARING

To characterize the in-plane permeability of a woven fabric after shearing of the fibrous reinforcement, an experimental set-up was built to induce uniform shearing deformation to the fabric. Following the approach first proposed by Ueda (18), a shear fixture was constructed from aluminum bars. The 0.50 m x 0.50 m articulated aluminum frame is shown in Fig. 3.

As early mentioned, in order to characterize the in-plane permeability of the unsheared fabric, three fiber volume contents were considered. In the case of sheared fabrics, the same three *Vf* were used as initial parameter. For each *Vf*, the fabric was sheared at different shearing angles and permeability was computed by the iterative ellipse method.

The fabric is firstly cut in a 0.50 m x 0.50 m square section and placed on the lower frame and clamped. Then, the fabric is sheared by deforming the frame sides at a desired angle. Once the fabric is sheared, a support tool is used to cut the samples in 0.40 m x 0.10 m rectangular sections. The angle between the warp and weft directions after shearing was manually measured in at least 10 points of the sample surface.

Although satisfactory results were obtained with this method, some limitations were observed. Firstly, the useful area that allows proper cutting of the sheared sample decreases in size as the deformation angle increases. In fact, the fiber tows tend to remain perpendicular to each sides of the frame because they are clamped, although they are at the same time required to shear. Therefore, the change in tow direction close to the fixture edges promotes the appearance of inflexion points on the yarn, which results in out-of-plane bending in proximity of the frame. This effect begins to be noticed for shearing angles larger than 20º. Another limitation of this set-up is connected with wrinkling. As mentioned by Rudd and Long (19), the formability of many fabric reinforcements is limited by the fiber architecture, which induces wrinkling after a certain amount of shear deformation. As a matter of fact, a reduction of the distance between adjacent tows takes place during deformation, which results in overlapping of the fiber tows for large shearing angles. For the structure of the fabric tested (the equilibrated carbon fiber), wrinkling phenomenon was observed for a shearing angle of 40º. Hence, the maximum shear of the experimental set-up was limited to 35º to prevent wrinkling.



(a) (b)

Fig. 3 Experimental set-up used to induce shearing deformation to fabrics: (a) assembled fixture; (b) clamping system.

PERMEABILITY CHARACTERIZATION OF SHEARED FABRIC: EXPERIMENTAL RESULTS

If shear deformation is considered as the principal mode of fabric distortion, the degree of deformation can be determined through the shearing angle. This angle is defined here as the angle between the deformed weft yarn and its original direction. The more this angle increases, the larger is the deformation. As discussed by Heardman, et al. (3), fiber volume fraction is altered after shear as a result of fiber tows rearrangement. It may then be stated that the sheared permeability, i.e., the permeability of a sheared fabric, is related to both, the sheared fiber volume fraction and the reorientation of fiber tows. Fig. 4 display the effective permeability as a function of the fiber volume fraction for the 0º direction. As observed, sheared permeability is not only affected by the changes of fiber volume fraction after shearing, but also by the deformation of the fabric geometry.

MODELING OF IN-PLANE PERMEABILITIES OF SHEARED FABRICS

There is enough evidence showing that the in-plane permeability is not only affected by changes of the fiber volume fraction after shearing, but also by the change of the in-plane and out-of-plane fiber orientations. As presented in Fig. 5 for the planar woven carbon fabric tested, these two factors seem to affect fabric permeability. So, sheared permeability may be modeled from the unsheared permeability with two corrective factors. The first one denoted $F_{Vf}(\alpha)$ represents the changes in the fiber volume content after a shear of α degrees. The second one, $F_{geo}(\alpha)$, models the effect of fiber reorientation. Thus, the sheared permeability in the two principal directions (i.e., 1 and 2) can be expressed as follows:

$$K_{1,2}(\alpha) = K_{1,2}^{Vf}(\alpha)\ F_{geo}(\alpha) = K_{1,2}(\alpha = 0^o)\ F_{Vf}(\alpha)\ F_{geo}(\alpha) \tag{5}$$

where $K_{1,2}(\alpha=0^o)$ represents the permeabilities in the principal directions for the unsheared fabric.

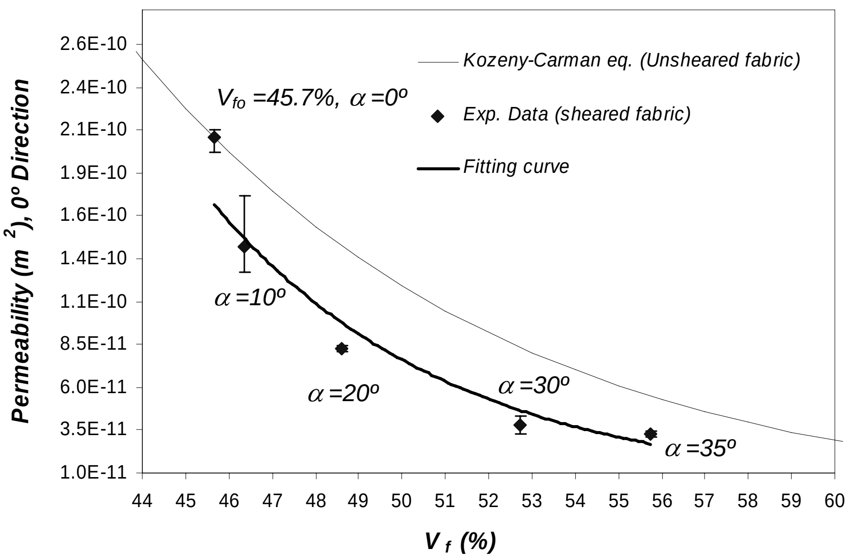


Fig. 4 Effective permeability for unsheared and sheared woven carbon fabric in the 0º direction.

The correction factor which takes into account the changes of the fiber volume fraction can be modeled by Kozeny-Carman relation. The fiber volume fraction after shearing can be deduced from the geometrical analysis of the unit cell and is related to the cosine of the deformation angle. Thus, Kozeny-Carman equation is written in terms of the sheared fiber volume fraction as follows:

$$F_{Vf}(\alpha) = \frac{1}{cos\alpha}\left(\frac{cos\alpha - Vf_o}{1 - Vf_o}\right)^3 \tag{6}$$

The second factor is deducted from the analysis of a deformed unit cell. Fig. 6 shows a unit cell deformed α degrees where their sides retain a geometric relationship as equal to the permeability anisotropy ratio. In other words, the length denoted as a in Fig. 6 is equal to the unit, since K_1/K_1, while the length represented as b becomes K_2/K_1. Vectors R_1 and R_2 represent the major and minor semi-axes of the elliptic flow front respectively. By analyzing the variations of vectors R_1 and R_2, a trigonometric relation can be obtained as given below:

$$F_{geo}(\alpha)=\frac{1-\Delta r_2}{1+\Delta r_1}=\frac{1-\dfrac{b}{\cos(90-\beta_o)}+\dfrac{b\sin(90-\alpha)}{\sin\beta_o}}{1+\dfrac{a\cos\alpha}{\sin(\beta_o-\alpha)}-\dfrac{a}{\cos(90-\beta_o)}}\propto \textit{variation of the unit cell area} \qquad (7)$$

where r_1 and r_2 represent the magnitude of the vectors R_1 and R_2, a and b denote the lengths of the unit cell sides, and β_o is the orientation angle of the major axis of the elliptic flow front with respect to the warp direction for the non-deformed fabric.

It was observed experimentally that the major direction, i.e., the principal direction 1, is affected by the geometric factor $F_{geo}(\alpha)$ while the minor direction, i.e., the principal direction 2, is affected by the square of the $F_{geo}(\alpha)$. In other words, the permeability in the major principal direction is proportionately affected by the geometric deformation of the unit cell, while the permeability in the minor direction is modified by the square of the unit cell deformation. As showed by Bear (17), the square root of effective permeability follows the geometric coordinates of an ellipse. Then, the geometric correction factor $F_{geo}(\alpha)$ should be square related to permeability. Thus, the principal permeabilites can be estimated as:

$$K_1(\alpha)=\frac{K_1(\alpha=0^o)}{\cos\alpha}\left(\frac{\cos\alpha-Vf_o}{1-Vf_o}\right)^3\left(\frac{1-\Delta r_2}{1+\Delta r_1}\right)^2$$

$$K_2(\alpha)=\frac{K_2(\alpha=0^o)}{\cos\alpha}\left(\frac{\cos\alpha-Vf_o}{1-Vf_o}\right)^3\left(\frac{1-\Delta r_2}{1+\Delta r_1}\right)^4 \qquad (8)$$

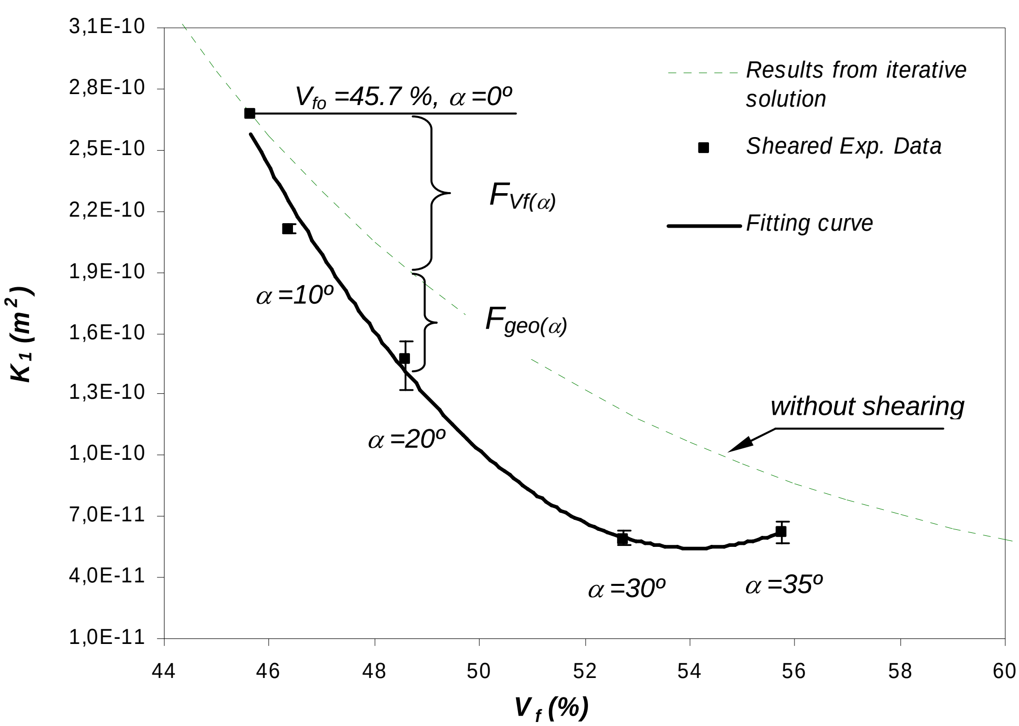


Fig. 5 Major permeability of sheared woven carbon fabric for an initial fiber volume fraction, *Vfo* = 45,7%. Permeability is affected by at least two factors, a geometry change (F_{geo}) and a fiber volume fraction change (F_{Vf}).

To predict principal flow directions, an empirical formula can be deduced from the experimental data. Although there is no theoretical derivation, the principal flow orientation β can be estimated as:

$$\beta(\alpha) = \beta_o^{\cos^2\left(\frac{2}{3}\alpha\right)} \tag{9}$$

MODELING RESULTS

The approach presented above requires information on undeformed material permeability. Based on changes of the fiber volume fraction and reorientation of the fiber tows, the model is expected to predict the in-plane principal permeabilities up to the geometric locking angle because no wrinkling phenomenon is taken into account. For the fabric material tested, predicted values of $K_1(\alpha)$ and $K_2(\alpha)$ are shown in Fig. 6. In general, a good agreement between predicted values and experimental results is observed for all fiber volume fractions considered. Both principal permeabilities present a steady decrease behavior, which is more pronounced for the minor principal permeability K_2. Finally, Fig. 7 plot the principal flow orientation as estimated by equation (9).

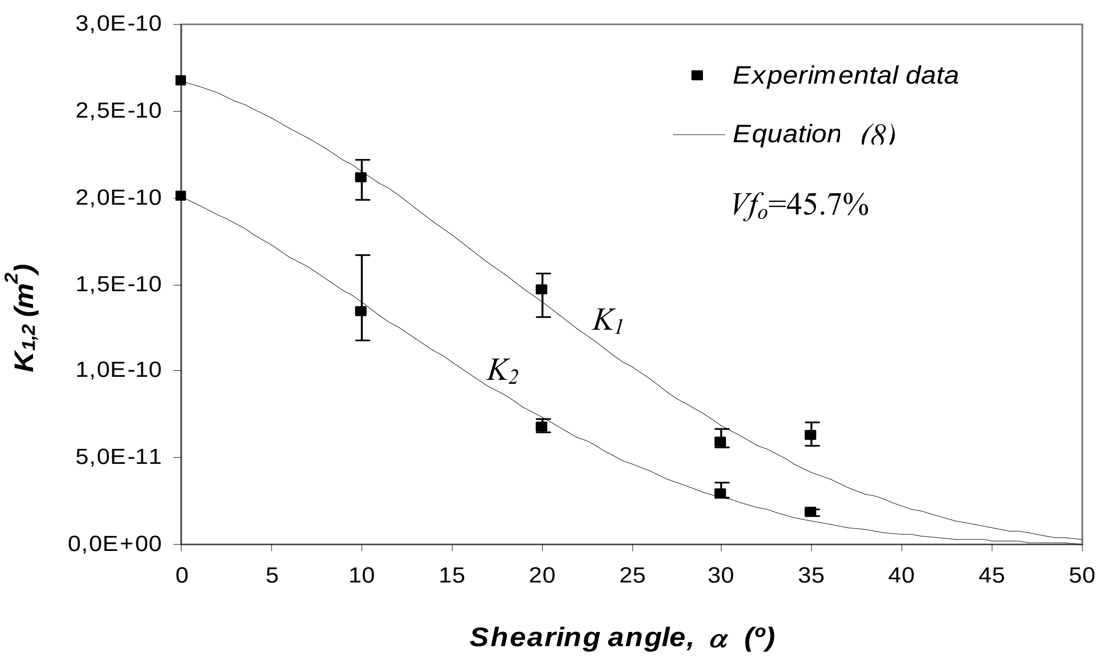


Fig. 6 Predicted principal permeabilities as function of shearing angle for *Vfo* = 45.7%.

CONCLUSIONS

When a fabric is draped on a complex shape, it undergoes shear deformations that affect the local permeability and hence the flow behavior. Therefore it is important to characterize the permeability of sheared fabrics. A method based on unidirectional injections was developed in this article to measure the components of the in-plane permeability tensor. The iterative ellipse method developed in this paper allows determining the elliptic permeability tensor even if the measured directions do not remain at 45º between them. The method was found to be sensitive to differences in the measured effective permeabilities. Therefore, reliable permeability data must be employed in order to give acceptable results. A special tool has been developed to induce uniform shear deformations to fabric samples. Unidirectional and radial experiments were conducted on unsheared and sheared woven carbon fabrics. Principal permeabilities and their orientation as a function of fiber volume fraction and shearing angle were characterized. Kozeny-Carman equation seems to describe correctly the unsheared experimental data within the fiber volume fraction range tested. It was found that the variation of Kozeny constant as a function of the fiber volume fraction has a considerable influence on Kozeny-Carman predictions.

This investigation shows that permeability is not only affected by the reduction of the sheared fiber volume fraction, but also by changes in the geometry of the fabric structure. In-plane major permeability behavior is influenced by an effective permeability direction when they tend to align in the 45º direction. The behavior of the in-plane principal permeabilities is found to be dependent on the initial orientation of the elliptic flow front. In general, for unsheared and sheared fabrics, the principal flow orientation remains practically constant for a given shearing angle. This enables to consider the flow as independent of the fiber volume fraction for a given shearing angle (in a ±2º range).

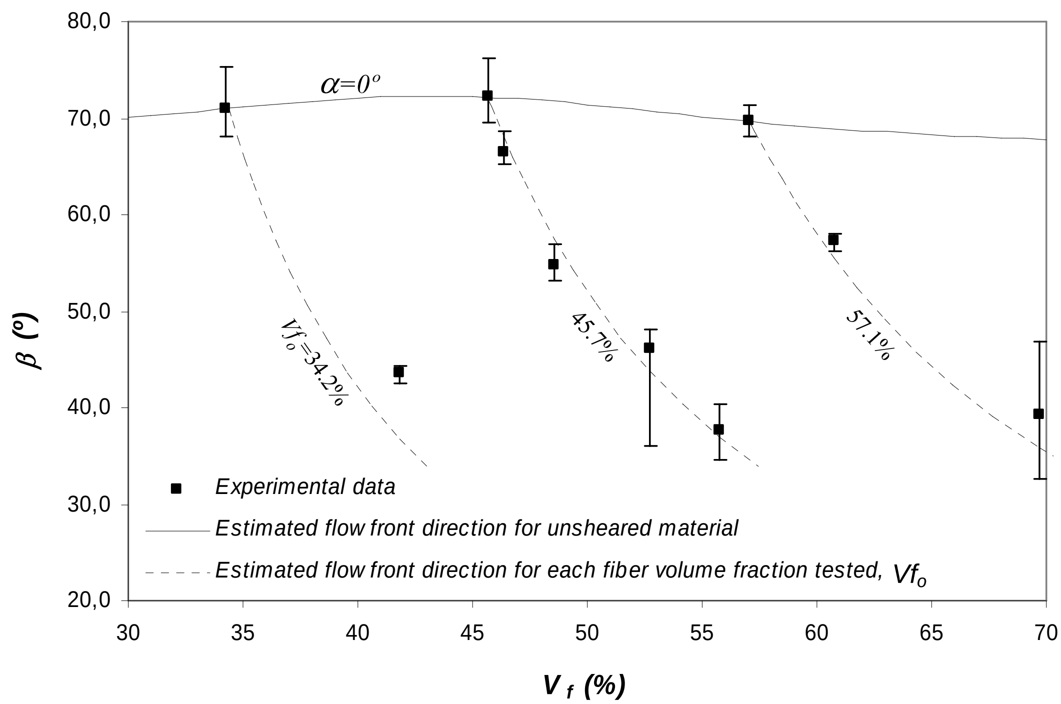


Fig. 7 Estimated flow front direction using equation (9).

A permeability prediction model was developed to estimate the in-plane principal permeabilities and their orientation as a function of the deformation degree. The model requires knowing the in-plane principal permeability of the undeformed fabric. It is based on two principal factors that were found to govern the permeability of woven fabrics after draping: the change of fiber volume fraction and the reorientation of the fibers. For the fabric tested, it was observed that the change of local fiber volume fraction seems to play here the major role. This could be explained by small channels between adjacent fibers that exist in the tested carbon fabric. In general, a very good agreement between predicted values and experimental results was observed within the range of shear angles tested.

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