Interpretation of Permeability in a Unidirectional Non-Crimp Stitched Preform by Geometrical Description of the Porosity

L. Bizet [1], J. Bréard [1], G. Bouquet [1], J.P. Jernot [2], and M. Gomina [2]

[1] *Laboratoire de Mécanique, Physique et Géosciences,*
Université du Havre, BP540, 76058 Le Havre Cedex, France.
laurent.bizet@univ-lehavre.fr, joel.breard@univ-lehavre.fr, guy.bouquet@univ-lehavre.fr,
[2] *ESCTM du CRISMAT, ENSICAEN,*
6, Boulevard du Maréchal Juin, 14050 Caen Cedex, France.
jernot@ismra.fr, gomina@ismra.fr

SUMMARY: For a unidirectional non-crimp stitched glass fabric (also called quasi-UD), we present experimental results of permeability (saturated and unsaturated values) and a description of the pore structure using stereology. It is shown that for real fibrous media, the permeability can be related to the experimentally measured porosity by the well-known Kozeny-Carman equation in terms of the mean free path through the porous phase within and around the fiber bundles.

KEYWORDS: unidirectional composites, non-crimp stitched fibrous preform, permeability, stereology.

INTRODUCTION

In the modeling of resin transfer molding process, an abundant literature exists which assimilates the structure of fibrous preforms with an ideal geometrical arrangement [1,2]. Thus numerical studies are facilitated and qualitative indications are obtained on the influence of the fibrous architecture on the macroscopic resin flow. But this kind of approach does not rely on the microstructural parameters which really characterize the porosity.

The objective of this study is to demonstrate that flow properties within a real fibrous media can be assessed by mean of microstructural parameters of the porous phase directly attainable from stereology. The porosity of a unidirectional composite material is first investigated using image analysis. The permeability for the resin flow parallel to the fibers is then expressed as a function of porosity and in terms of the characteristics of the porous phase. Finally, a comparison between the experimentally measured permeability on real fibrous composites and the prediction from the microstructural characteristics of the porous phase is presented.

MICROSTRUCTURE ASSESSMENT

Influence of the Stitching

Even for the simple fabric used in this work (UD glass fiber-reinforced polyester), primary investigations had shown a complex relationship between the geometrical parameters and the volume fraction of fibers [3]. As can be seen on Figs. 1 and 2, a two-scale microstructure is observed : the microscale, inside the yarns and the macroscale, between the yarns. That defines a microporosity and a macroporosity respectively denoted further as μ and M. Moreover, the dispersion of the fibers is not the same near and far away from the stitching yarns. Consequently, in order to describe the microstructure, a simple geometric model using a regular array of fibers and/or yarns is unrealistic : a more general microstructural description must be used.

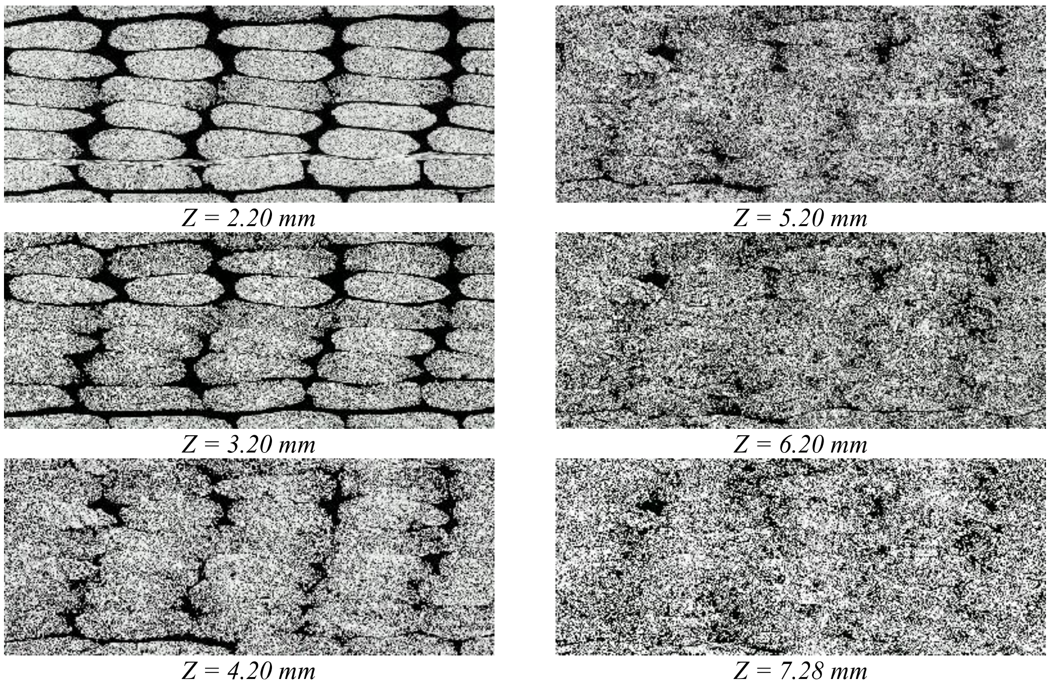
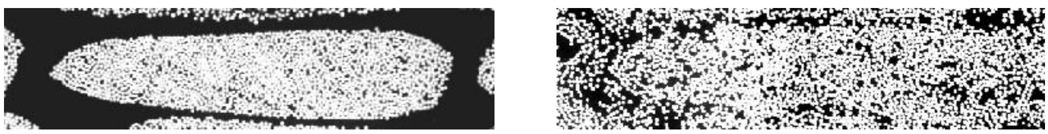


Fig. 1 : Serial sections through a RTM sample along the direction of fibers (the volume fraction of glass fibers is 0.55 and the thickness of one layer is approximately 0.45 mm)



(a) *(b)*

Fig. 2 : Two sections through the same yarn : (a) near the stitching, (b) far away from the stitching.

Mean Free Path through the Porous Phase versus Porosity

For a two-phase material, a general stereological relationship exists between the mean free paths through each of the two phases [4]. It can be written as $\overline{L(F)} + \overline{L(P)} = 1/N_L$ where $\overline{L(F)}$ and $\overline{L(P)}$ are respectively the mean free paths through the fibers and through the pores and N_L is the number of intersections, per unit length, between the fiber/pore interface and a random line of analysis. Moreover, as the composite is unidirectional, the microstructure observed on a plane cut perpendicular to the yarns can be analyzed as if it was defined in 2D space : for a random dispersion of non-overlapping discs of radius r, it can be demonstrated, from geometrical probabilities, that $N_L = 2r\, N_A$, where N_A is the number of discs per unit area. It follows that $\overline{L(F)} = (\pi/2)\,r$ and the mean free path through the porous phase is expressed as a function of the areal fraction of porosity, $A_A(P)$, by

$$\overline{L(P)} = \frac{\pi\, r}{2} \frac{A_A(P)}{1 - A_A(P)} \tag{1}$$

This equation is valid, whatever the dispersion of the discs, under the hypothesis that they possess the same size. It can be extended to non-overlapping ellipses with the same orientation if r is replaced by the semiaxis, a, of the ellipse (the choice of the semiaxis depends on the direction of analysis). The application of formula (1) to the microstructure of our UD composite allows to define mean free paths through the microporosity and through the macroporosity (the yarns are then modelized as ellipses). The theoretical results are compared, in Figs. 3 and 4, with the experimental ones measured by image analysis.

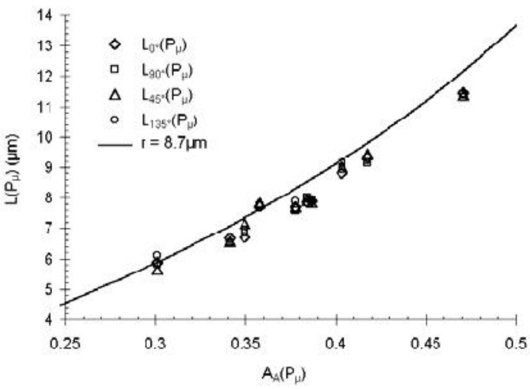


Fig. 3 : Mean free path through the microporosity (same radius r for all fibers).

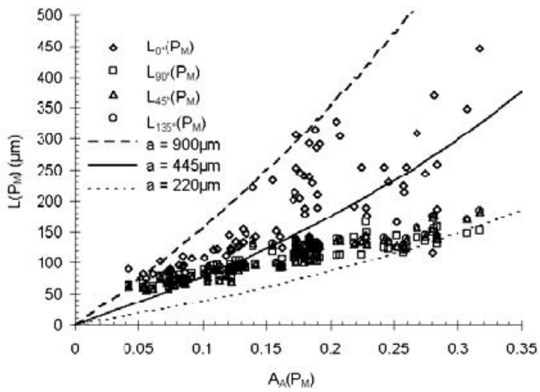


Fig. 4 : Mean free path through the macroporosity (around the yarns)

PERMEABILITY ASSESSMENT

Permeability versus Mean Free Path through the Porous Phase

For a 3D porous material, the permeability, K, can be expressed as a function of the porosity, $V_V(P)$, by the classical Kozeny-Carman equation [5] : $K = c_0 \left[V_V(P)\right]^3 / \left[S_V\right]^2$ in which c_0 is a constant and S_V the specific surface of the solid/pore interface (per unit volume of material). But there is a stereological relationship [4] between the mean free path through the porous phase, the porosity content and the specific interface area : $\overline{L(P)} = 4\ V_V(P)/S_V$. The Kozeny-Carman equation can then be written :

$$K = \frac{c_0}{16}\ \overline{L(P)}^2\ V_V(P) \qquad (2)$$

In this equation, the permeability is simply expressed as the product of the volume fraction of the material accessible to the flow by the square of a characteristic length.

Permeability versus porosity

For the UD composite under consideration, on a plane cut perpendicular to the yarns the areal fraction of porosity, $A_A(P)$, is nothing else but its volume fraction, $V_V(P)$. Combining equations (1) and (2), the permeability can then be expressed by

$$K = \frac{c_0 \pi^2}{64}\ r^2\ \frac{A_A(P)^3}{\left[1 - A_A(P)\right]^2} \qquad (3)$$

This equation can be found in the literature [5] but it is classically obtained via the introduction of an hydraulic radius. Only stereological relationships have been used here and applied to the particular case of the UD composite.

RESULTS AND DISCUSSION

Equation (3) can be applied to any homogeneous medium i.e. with a uniform distribution of the porous phase. But this is not the case for the UD composite under consideration (cf. Fig. 1) hence the global porosity cannot be used to compute the permeability. Consequently, the contributions of the microporosity, $A_A(P_\mu)$, and the macroporosity, $A_A(P_M)$, must be calculated separately. They are related to the global porosity, $A_A(P)$, by

$$A_A(P) = A_A(P_M) + \left[1 - A_A(P_M)\right] A_A(P_\mu) \qquad (4)$$

and thus the macroporosity P_M can be derived from the measures of the total porosity, P, and the microporosity P_μ. The evolutions of $A_A(P_\mu)$ and $A_A(P_M)$ are reported in Figs. 5 and 6 for measurements performed near and far away from the stitching yarn. One can observe that, when the total porosity increases (i.e. the fiber volume fraction decreases) the mean microporosity remains roughly the same while the mean macroporosity increases.

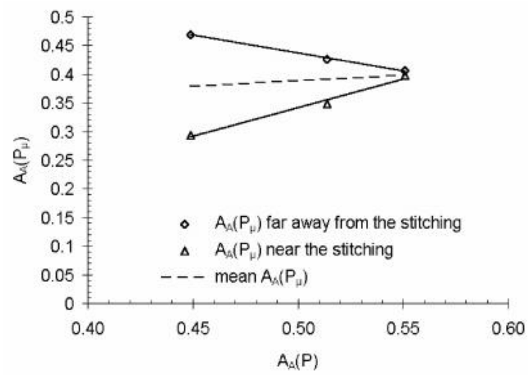


Fig. 5 : P_μ versus global porosity.

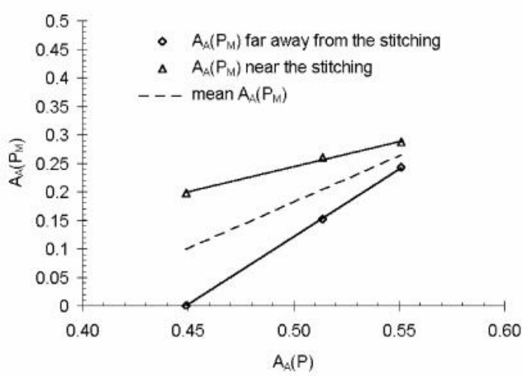


Fig. 6 : P_M versus global porosity.

The permeability K_μ corresponding to P_μ is calculated using the areal fraction $A_A(P_\mu)$ and the fiber radius r : $K_\mu = \left(c_0\pi^2/64\right)\ r^2\ A_A\left(P_\mu\right)^3/\left[1 - A_A\left(P_\mu\right)\right]^2$. The permeability K_M corresponding to P_M is calculated using the areal fraction $A_A(P_M)$ and the semiaxis, a, of the ellipse-shape yarn : $K_M = \left(c_0\pi^2/64\right)\ a^2\ A_A\left(P_M\right)^3/\left[1 - A_A\left(P_M\right)\right]^2$. For a direction of macroscopic flow parallel to the fiber bundles, the global permeability of the composite may be expressed as the sum of the micro and the macro permeabilities weighed by their respective areal fractions :

$$K = A_A\left(P_\mu\right)K_\mu + A_A\left(P_M\right)K_M \tag{5}$$

The theoretical values calculated from equation (5) are reported in Fig. 7 and compared with the experimental measurements. The best fit to the experimental results is obtained with $A_A(P_M)$ and $A_A(P_\mu)$ determined near the stitching yarns, for r=8.7 µm and a=445 µm. This last value corresponds to the radius of a disc with an area equivalent to the one of the yarns.

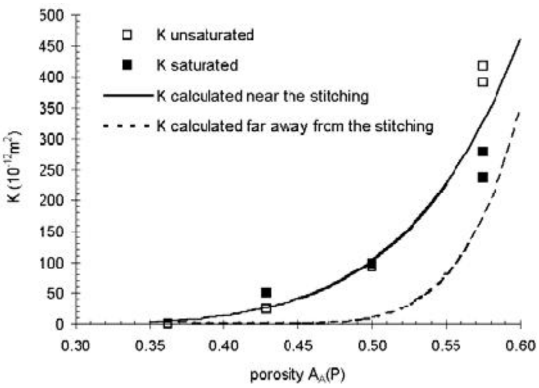


Fig. 7 : Experimental and calculated results of permeability.

CONCLUSIONS

The permeability of a stacking of unidirectional glass-fiber fabrics was assessed using microstructural parameters of the porous phase determined by stereology, and compared with experimental measurements. The free mean path through the porous phase and fractions of micro and macroporosity are shown to be the relevant microstructural parameters needed for an intrinsic determination of the permeability. Such an approach, which might be applied to any fibrous media, may provide useful information for the numerical simulations of the permeability and for the analysis of the unsaturated-saturated transition.

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