PERMEABILITY OF WOVEN FABRICS: ANALYTICAL AND NUMERICAL PREDICTIONS

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ABSTRACT: The trend in the industry nowadays is to produce larger and larger as well as more and more geometrically complex composite parts. Introduction of the resin in the fibrous reinforcement by LCM (Liquid Composite Moulding) techniques is increasingly used. The simulation of this injection step is of prime importance in order to ensure the quality of the so-produced part. To do so, it is necessary to take into account the influence of local deformations (shear, compression and nesting) of the fibrous reinforcement on its permeability in the simulation. This work presents a numerical tool which has been developed in order to predict the influence of each individual deformation on reinforcement permeability. Our tool uses 3D unit cell description which is eventually deformed and meshed. Stokes and Brinkman equations are then solved on this mesh together with adequate boundary conditions in order to determine the permeability by classical homogenization techniques. An analytical model based on weaving parameters is proposed and shows very good correlation with 3D model. This model takes into account shearing, nesting and compression effects to a certain extend. Influence of shear, compression and nesting has been assessed for two woven fabrics as well as the influence of the geometrical model used. These models allow to reduce the quantity of experiments needed to fully characterize a fibrous reinforcement.

KEYWORDS: Permeability, Prediction, Textile, Finite Element, Analytical model, Experimental.

INTRODUCTION

Out of the many processes that can be used to form composite parts, Liquid Composite Moulding (LCM) family allows producing high mechanical performances, high fibre volume fraction as well as complex shape parts. In the field of LCM processes, the Darcy law is extensively used to describe the resin flux at the macroscopic scale through the preform by relating the local mean velocity to the pressure gradient, the permeation liquid's viscosity and the permeability Tensor:

$$\left\langle \vec{v} \right\rangle = -\frac{K}{\mu}\nabla P \tag{1}$$

The permeability tensor, which is the key parameter in the macroscopic scale LCM simulation, has to be known as function of the reinforcement's local deformation (mainly shearing and compression). In order to identify this parameter, two principal approaches are available: experimental tests and numerical or analytical predictive models. These models are in fact generally not totally (or at all) quantitatively predictive, but rather able to predict trends and evolutions as function of the reinforcement deformations, for instance.

Therefore, the experimental approach is always needed to a certain extend and the main objective of the analytical of numerical models is to reduce the quantity of (time -and money- consuming) experiments needed to fully characterize a given fibrous reinforcement in terms of permeability. Many different experimental setups exist and the results obtained using these devices in the same "conditions" (same reinforcement, number of plies, volume fraction …) may vary of more than one order of magnitude (See paper 87 for further details concerning a Benchmark exercise on permeability).

The permeability as defined by H. Darcy, is the so called "saturated permeability", which is an intrinsic parameter of a porous medium (when measured accordingly to classical hypothesis). The abusively called "dry or unsaturated or transient permeability" is not an intrinsic parameter of the porous medium. Nevertheless, this "unsaturated permeability" is the correct input parameter for macroscopic LCM simulation.

In this work, we propose an analytical model able to account for various fibrous reinforcement deformations (shearing, compression, number of plies and nesting) and compare it to an in house 3D finite element (FE) code which allows to predict (Darcy) permeability trends/evolution as function of these deformations. We also compare the influence of the geometrical model used for the reinforcement unit cell's representation.

PERMEABILITY MODELS

Geometrical models of the unit cell

As the permeability is an intrinsic parameter of porous medium, it is clear that the unit cell geometry will be of first importance. One of the interests of dry fibrous reinforcements used together with an infusion/injection process is its ability to undergo important in-plane (but also out-of-plane like compression) deformation and in particular shearing. This particularity makes it possible to preform them on highly non developable geometries [1]. A direct consequence (and origin) of this macroscopic ability is the important level of deformation (again especially shearing but also compression) of the fibrous architecture at the unit cell level. The influence of such deformations on the unit cell's permeability have to be assed as well as the potential influence of the geometrical model used to represent the reinforcement architecture.

In this work, we chose to use the WiseTex [2] "modeling suite" as well as Hivet/Badel's model [3][4] (Fig. 1). It can be seen that if the unit cells *seems* to be equivalent when not deformed (Fig. 1), they are visibly quite different when sheared, because of the difference of approaches used to deform them between WiseTex (mainly geometrical deformation) and Hivet/Badel's (mechanical calculation using Abaqus) models. The influence of these differences on the unit cell's permeability is presented in the next paragraphs.

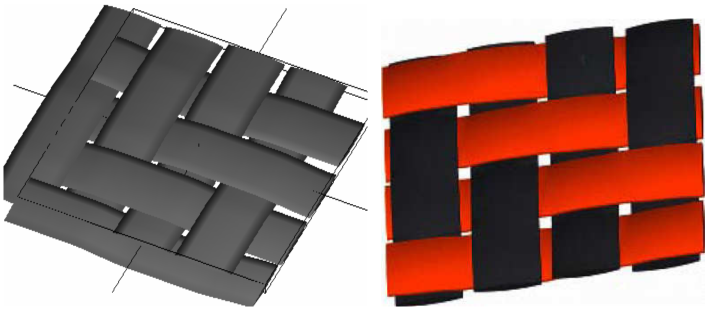

Fig. 1 WiseTex (left) and Hivet/Badel's (right) geometrical modeling of a twill 2x2

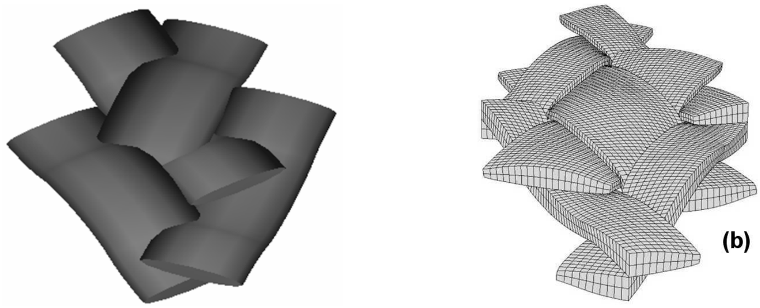

Fig. 2 WiseTex (left) and Hivet/Badel's (right) representation of a sheared plain weave

Permeability models

The prediction of porous medium's permeability has received quite a lot of interest from many research communities (geology, textile, composite …) in the past and is still an active field of research. Indeed, as previously mentioned, this parameter is of importance when one wants to simulate LCM processes and the difficulties related to its experimental determination are a strong support to the scientific community to develop codes and models able to alleviate this time and money consuming activity.

3D permeability model

The prediction of reinforcement's permeability is generally based on the resolution of Stokes and Brinkman equations in the period homogenization framework. Many different numerical methods can be used to solve these equations such as finite elements [5], finite differences [6], lattice Boltzmann … Onera has developed in the past a 3D FE code able to tackle this problem together with the meshing issues generally reported [7].

Analytical permeability model

In this work, we propose an analytical model for permeability prediction of woven fabric [7]. It is built up on the distinction between macro (Stokes) and micro (Brinkman) porosities and based on geometrical parameters. The Stokes regions are represented as constant section channels with a section geometry depending on the type of reinforcement, the volume and permeability of the Brinkman region (the tows) are also taken into account as well as other parameters like the nesting between the plies … It is a predictive model able to predict trends/evolution after fitting of only one parameter (not a multi-parametric fit on experimental or numerical results).

Results

Permeability predictions have been performed on twill and plain weave fabrics with both WiseTex and Hivet/Badel's models and for the following parameters: compression, shearing, nesting and number of plies. The Figure 3 bellow, illustrate the results obtained with the 3D FE (dots) and analytical (lines) models on a twill 2x2 fabric as function of the number and nesting between plies for a given and constant volume fraction of fiber (55%). The red and blue lines define a "region of permeability" for this fabric. This figure shows that the nesting greatly influences the permeability of woven fabrics. The configurations illustrated by the red line, which is the one obtained for "minimum nesting" -that is to say with the plies stacked on each other without any "in-plane" shift of the unit cell- are clearly statistically not the most probable ones as the nesting (energetically) eases the compression of stacked plies. Nevertheless, the analytical model is able to represent both the influence of nesting and number of plies after fitting on the permeability value obtained with the 3D FE in the case of one ply.

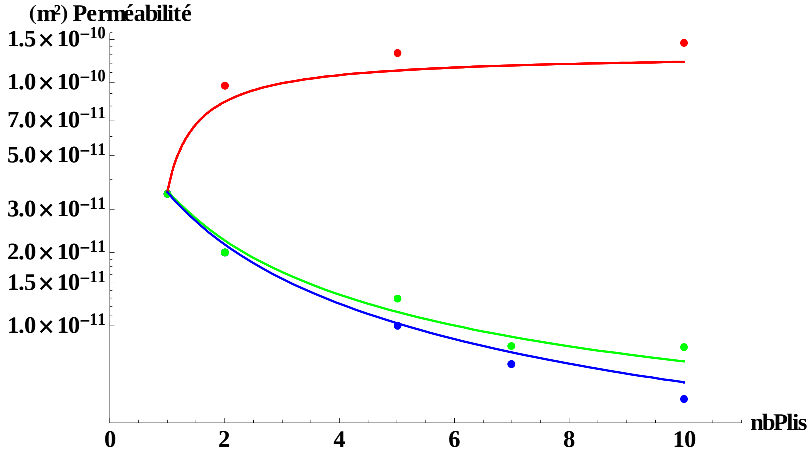

Fig. 3 Permeability prediction (line for analytical and dots for 3D FE model) as function of number of plies with -maximum- (red) and without (blue) nesting

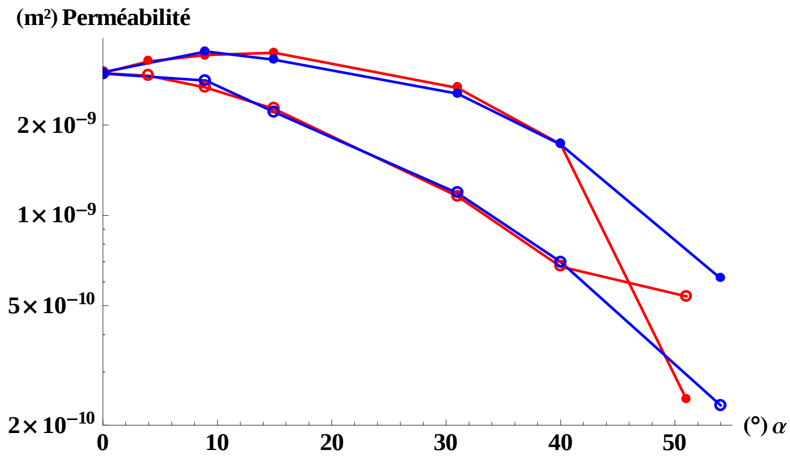

Fig. 4 Permeability prediction (3D FE model) as function of shearing angle for WiseTex (red) and Hivet/Badel's unit cell models (plain weave fabric)

The Figure 4 illustrates the influence of the model on the permeability prediction. Again, it points out the fact that a simplified model can be used when dealing with limited deformation, but should be avoided for higher deformation states. In this case (shearing), the "limit angle" is important (~40°) because of the quite "loose" geometry used (the gaps between tows were important in the non deformed state, and the nesting between plies has not been considered here), but for other reinforcements, it could be considerably lower. As a general statement, it can be said that the "limit angle" can be, somehow related to the mechanical "locking angle".

CONCLUSION

We presented a limited comparison (full to be presented during FPCM10) between permeability results obtained with a 3D FE code and an analytical model. Good correlation is found in most of the cases. We also investigated the influence of the geometrical model used and have shown that it was worth using a more complex but realistic geometry of the unit cell in the case of high deformations.

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