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PERMEABILITY OF THE WOVEN FABRICS

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ABSTRACT: The ability to precisely predict the permeability of woven fabrics is compulsory to simulate the RTM processes without having to realize time consuming experiments for each new fabric. Channel network models are generally not working very well with laminates of woven fabrics because of the nesting between the plies that creates a highly complex network. Thus, 3D meshes of woven fabric unit cells are realized *via* a defined number of steps to resolve Stokes and Brinkman equations on a periodical elementary cell using a 3D FE code. Shearing and compression are the most important deformation modes and the determination of their respective influence on the permeability tensors is of prime importance. Therefore, a comparison between WiseTex and Hivet's models of sheared and copressed fabrics is presented. Finally, the representativeness of the elementary volume is discussed in the case of an idealised UD fabric.

KEYWORDS: permeability, woven fabrics, geometrical models, sheared fabric, 3D meshes, finite elements, elementary representative cell

INTRODUCTION

Out of the many processes that can be used to form composite parts, **R**esin **T**ransfer **M**oulding is one that allows producing high mechanical performances, high fibre volume fraction as well as complex shape parts. In the field of **L**iquid **C**omposite **M**oulding, 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 drop and the permeability Tensor, while tracking the free front versus time during the injection process [1]. The key concept here is the permeability [2], which links the microstructure of the reinforcement to the way the polymer resin flows through it. This parameter can be either measured experimentally

[3][4][5], predicted by numerical [6][7] or analytical [8][9][10] models. The first solution is certainly the best in term of quality of the results (when properly done) but suffers from time consuming affliction when the second is generally still not sufficiently accurate to avoid any experimental validation. Additionally, the numerical predictions need an extensive preliminary work on the geometry of the fabric [11] and possibly the construction of a 3D mesh [12] of the unit cell which can also be quite time consuming. The main goal of this study is to detail the specific problems related to the prediction of "wet" or "steady state" permeability of woven/braided fabrics. Indeed, the complex architecture and especially the crimp of the yarns create a particularly complex channel network at the interfaces between plies where nesting occurs. Furthermore, as these classes of fabrics can generally experience high geometrical deformations [13] (shearing especially but also compression), mesoscopic simulations of fabric deformation have to be realised in order to evaluate their respective influences on the permeability. Finally, a limited comparison between Hivet's [14] and WiseTex [15] modellers in the case of sheared, compressed and un-deformed fabric will be presented.

PERMEABILITY MODELS

Since 1856 and Darcy's founding article, a lot work has been done in the field of permeability. In particular, the Kozeny-Carman (K-C) formula gives a general relation for the permeability of porous media as function of the geometry (granular, cylindrical,… media) as well as the porosity. Later on, several researchers have proposed adaptation for the K-C equation to take into account the generally non-isotropic non-homogeneous nature of fibrous reinforcements. Recently, some authors have developed analytical or semi analytical models that allow the prediction of permeability in the case of woven and non-crimp fabrics.

Validity of the Channel Network Model for multi-plies laminates

However, excepted for non-crimp fabrics where the identification of the channel network is somehow "easier" (principally because there is no or little nesting between the plies), the models above-mentioned are generally limited to either mono-ply consideration or simplified geometries (the woven fabric is assumed to behave like a lay-up of several layers of UD for example). The figure bellows illustrates a simplified model of a plain weave fabric with rectangular yarns and its complementary volume which is used to determine the channel network ChN.

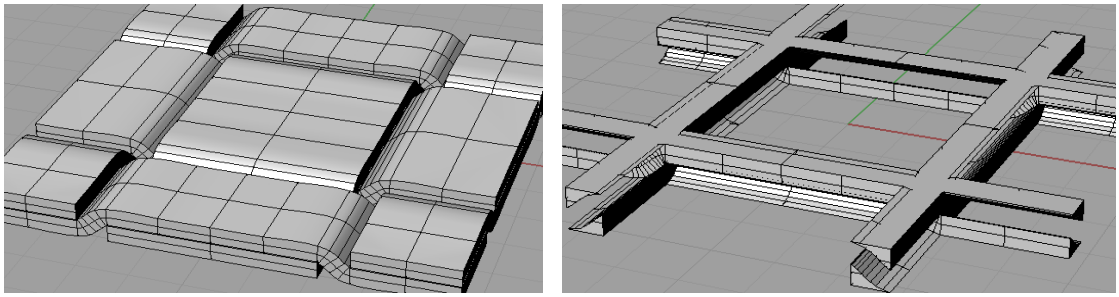

Fig. 1 Rectangular model of a plain weave fabric and its complementary volume

Then, to predict the permeability of this network within the periodic homogenization framework, the well known analogy between electricity and Poiseuil flow at low Reynolds

number in ducts is used together with the Kirchoff law ($\sum_{i=1}^{n} G_i = 0$ with Gi the hydraulic conductance of the ducts intersecting at the considered node) at the intersection nodes. The same procedure can be used in the case of multi-plies, as there is no nesting when using rectangular yarns and high fiber Vf (*cf* Fig. 2 bellows).

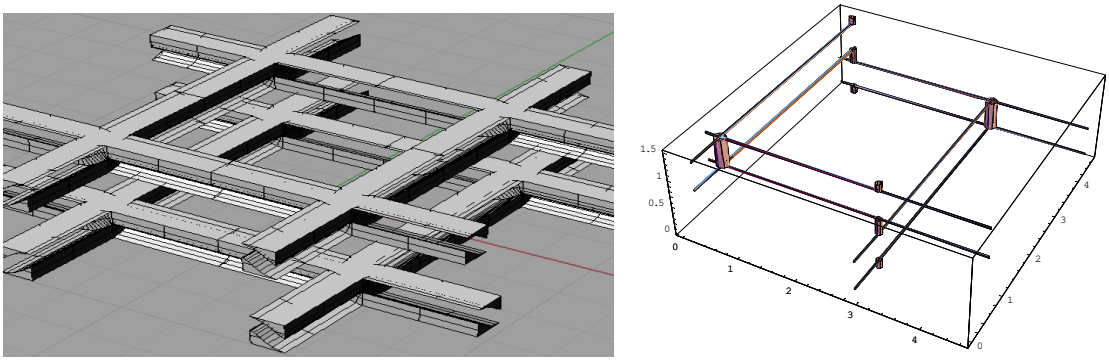

Fig. 2 Rectangular model for two plies and its associated ChN

Moreover, the permeability obtained with the ChN model is almost the same (<4% of difference) as the one obtained *via* 3D FE resolution of stokes equations in the geometry of the figure 2. In fact, the real difficulty comes when one tries to identify the ChN of a multi-plies of woven fabric modeled with non-rectangular yarns. The figures bellows represents the complementary volumes of a twill 2x2 for one and three plies.

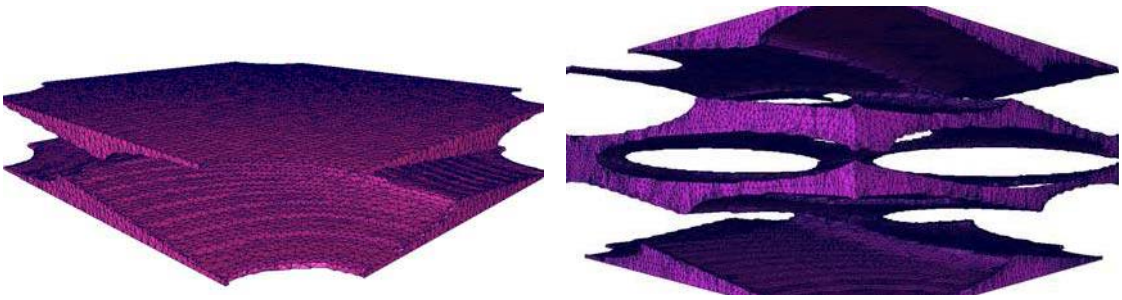

Fig. 3 Complementary volumes of a twill 2x2 (one quarter of the cell is represented)

In the case of a unique ply, the identification of the ChN is again quite straightforward, but the multi-plies case with random nesting (the unit cells of the stacked plies are randomly shifted from one to another) creates a highly complex ChN that can not (or only partially) be analytically defined as function of all the geometrical parameters. Finally, the table 1 bellow represents the permeability of a plain weave fabric as function of the yarns' geometrical section.

Table 1 Influence of the yarn's geometrical section on the permeability

	Number of plies	Lenticular Section	Elliptical Section	Rectangular Section
$K_{xx}(x10^{-11}m^2)$	1	11,84	11,71	1,16
$K_{xx}(x10^{-11}m^2)$	2	16,63	15,93	1,19

With an experimental result close to 10.10^{-11}, we clearly see that the rectangular geometry is too far away from the right result and thus a ChN description which would be based on it can not (at least not always) be used to predict the permeability of woven fabrics. Therefore, and especially when dealing with nested multi-plies, 3D accurate geometries have to be used together with an appropriate solver for Brinkman-Stokes equations.

ACCURATE 3D MODELS FOR PERMEABILITY PREDICTION

Using WiseTex modeler and Hivet's 3D model, accurate geometries can be constructed for permeability prediction. Once the geometrical parameters have been identified on the actual fabric, 3D models of the looming unit cell can be produced and eventually stacked to form the representative elementary volume (REV).

The Meshing

A meshing of the Stokes and eventually the Brinkman regions is realized using different commercial and dedicated software. Excepted for non-deformed Hivet's 3D models where meshing can be carried out directly from the 3D geometry, all the others geometries have to pass through a number of steps to finally obtain the 3D mesh. Firstly, the REVs are discretized into voxels (from hundred of thousands to about ten millions), then, this new geometry is filtered in order to remove some of the artifacts resulting from discretization and geometrical misfits (interpenetration as well as spurious voids between yarns). Afterward, the voxels' faces are divided into triangles and the surfaces dividing the different regions (Stokes; Brinkman and Exterior) are identified in terms of triangles. At this point, these surfaces define a set of closed volumes. After that, the number triangles forming the surfaces are lowered so that the final volumes do not represent millions of tetrahedrons and finally, a tetrahedral mesh is seeded from the existing triangular surface mesh. The above-described method can be applied to almost any kind of porous media. The figures bellows illustrate the 3D meshes that can be obtained *via* this technique as well as some results of 3D FE calculation.

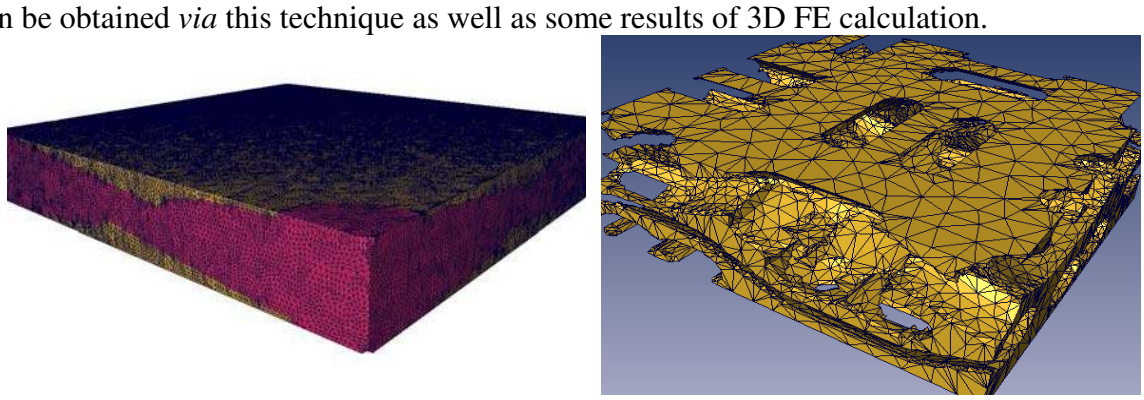

Fig. 4 Stokes and Brinkman mesh of a plain weave fabric (left) and complementary volume of two plies of a woven fabric.

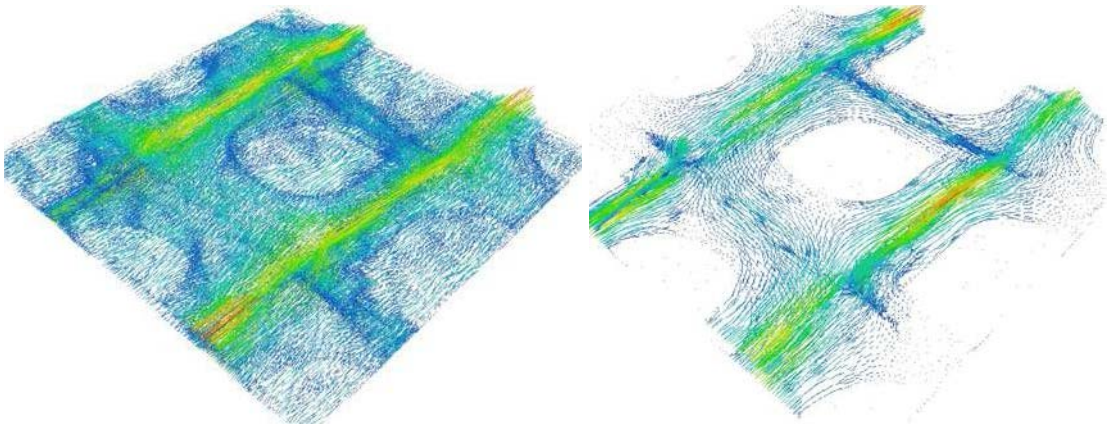

Fig. 5 Speed field from FE calculation with (left) and without Brinkman medium
Experimental result: 2.5 E-11 Left: Right:

Deformed geometries

In order to simulate accurately the injection of a complex shape part, one has to take into account the influence of both shearing and compression on the permeability of the REV. The WiseTex modeler allows us to obtain quite easily sheared and compressed 3D models (if it is fed with right mechanical properties). However, this is done the shearing is done in a mainly "geometrical way". On the other hand, the Hivet's model can be sheared and compressed using a mechanical FE code, which probably gives "more realistic" results but is also a "time consuming" process. The figure 6 shows an example of the influence of shearing on both in-plane principal direction of the permeability tensor.

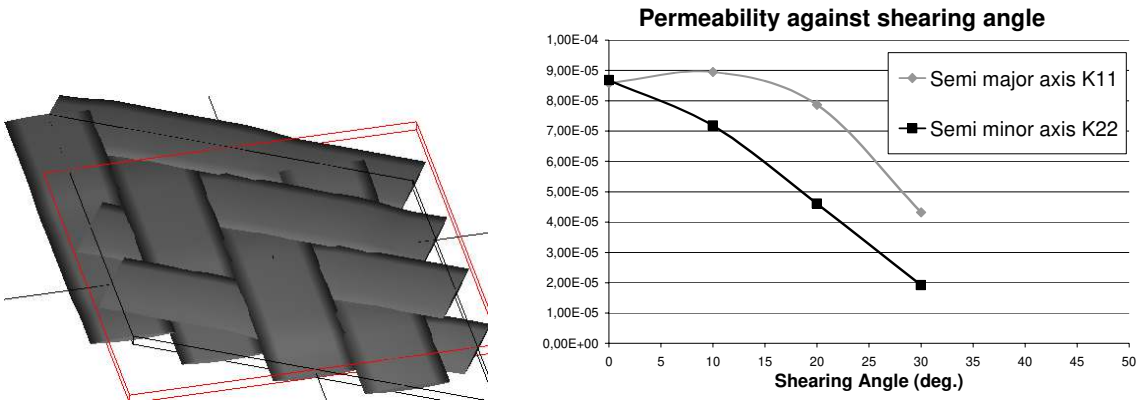

Fig. 6 Sheared geometry of a twill 2x2 and evolution of the permeability tensor

Comparison between the two models for both compression and shearing will be presented at the conference. The case of compression is of prime importance today with the increasing use of infusion in the industrial world. In general, the FE codes simulating the infusion process need both the thickness of the fabric versus pressure and the permeability of the fabric versus thickness. As this process mainly consists in a "through the thickness" impregnation of the fabric (from the upper conducting medium where the resin preferentially flows towards the fabric underneath because of the pressure gradient), the most relevant stationary/wet permeability value is the K_{zz}. The figure 7 represents a permeability prediction for ten plies of a balanced carbon twill 2x2. The blue surfaces are iso-speed and they clearly shows us two things: first of all, as we said in the first section, the channel network is highly complex and

would have been difficult to guess or determine analytically; and the second point is that our representative volume is maybe too small to be really representative of the percolation path(s) trough the thickness. Finally, the figure 8 illustrates the problematic of fabric compression using an FE code.

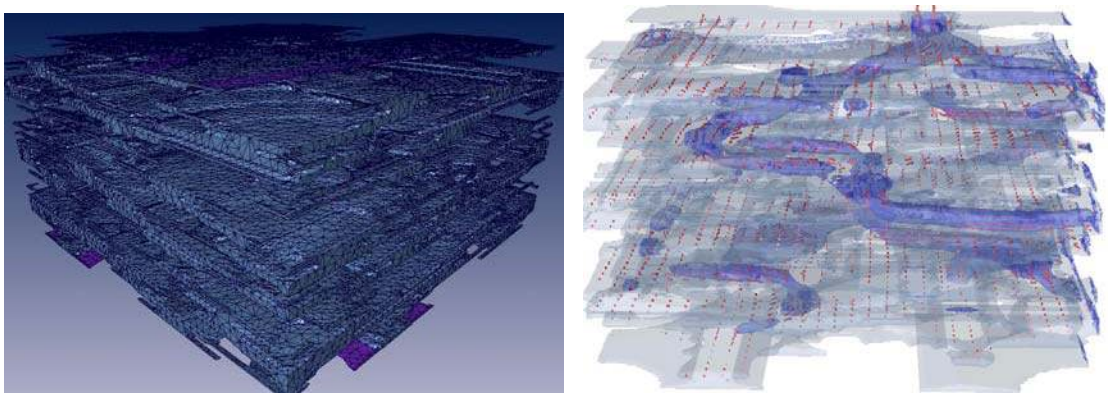

Fig. 7 Mesh and iso-speed surfaces for 10 plies of carbon fabric with a transversal pressure gradient

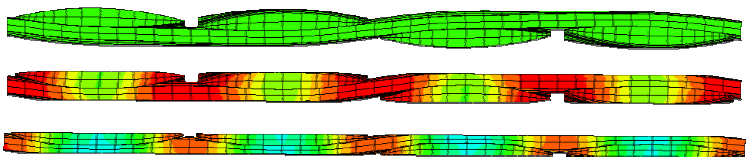

Fig. 8 E_{33} deformation during compression of a carbon twill 2x2 from relaxed state (up) to 46% (middle) and finally 94% of compression (bottom)

(RE)DEFINITION OF THE REV?

In order to predict the permeability of woven fabrics in the framework of periodical homogenisation, a REV has to be defined. The looming unit cell is generally used because of its geometrical periodical boundaries and convenient size. Nevertheless, the statistical geometrical variations that occur at the studied scale are only taken into account through the mean value of each geometrical parameter determined on the real fabric prior to geometrical modeling. In other words, we build up a “mean” unit cell with dimensions the mean dimensions observed on the actual reinforcement. The problem is that we have a non-linear equation for the permeability of a duct of radius R, and the hypothesis of the “mean cell” implies that the mean permeability (or the macroscopic permeability) of a fabric equals the permeability of the cell of mean dimensions, which is true is the permeability of a duct were linear with its radius. Therefore, how false is this hypothesis? Certainly not too false, because the cell of mean dimensions minimizes the permeability and an array of cells of distributed permeabilities (the reality) is not likely to maximize the overall permeability. The figure bellows illustrates the influence of the “erroneous” hypothesis in the simplest (and certainly not more realistic) case of one ply of an UD fabric with identical, impermeable, parallel square yarns and all the classical boundary conditions and simplification of Navier-Stokes equations.

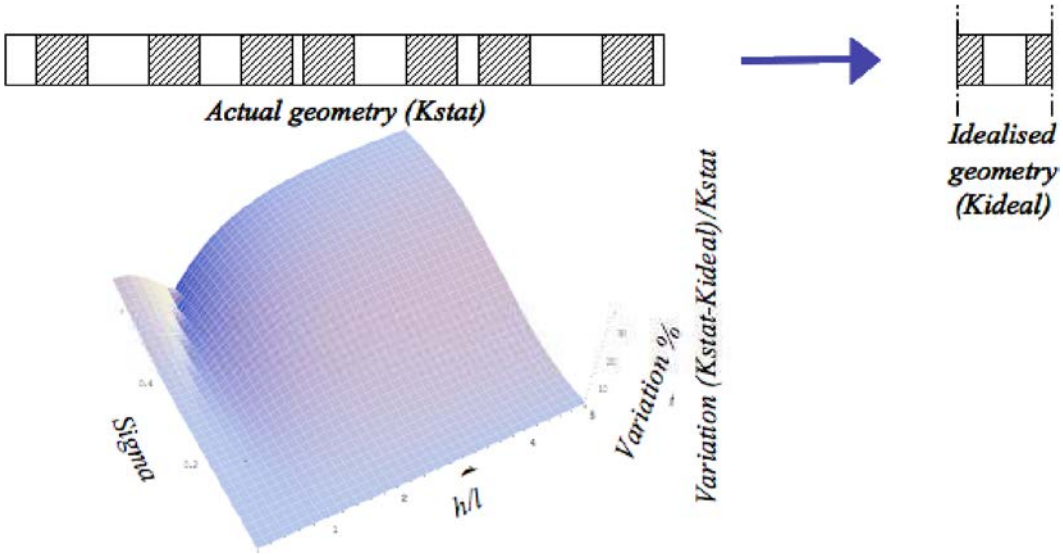

Fig. 9 Geometry of the model medium and influence of the statistical dispersion of the geometrical parameters on the permeability of the UD fabric

CONCLUSION

The particularities of woven fabrics in terms of permeability modelling have been exposed. Two three dimensional modellers exhibiting different advantages have been used to study the permeability of the woven fabrics along with a Finite Elements code to resolve the Stokes-Brinkman equations at the mesoscopic scale. The importance of the parameters describing the unit cell together with the influence of shearing and compression on its permeability have been studied. The influence of the shearing angle as well as compaction on the permeability principal values has also been studied and the importance of an accurate geometrical description discussed. Full set of results will be presented at the conference. Finally, the validity of the REV has been discussed and would need further developments.

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