EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE DEFORMATION OF A WOVEN COMPOSITE REINFORCEMENT CONSEQUENCES ON THE PERMEABILITY

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ABSTRACT: The permeability of a composite reinforcement depends on the geometry of the fiber network. This is often complex because of the weaving but also because of the deformation due to the preforming stage. The objective of the present work is to propose a numerical analysis of the deformation of the unit woven cell of the fibrous reinforcement (mesoscopic scale) and of the resin flow within this deformed unit cell (permeability determination). A specific constitutive behavior of the yarn material is used to numerically simulate the preforming stage. A set of simulations of large deformations of textile composite reinforcements at mesoscopic scale will be presented.
The CelPer2 software uses deformed 3D REV description. The yarns and their complement are meshed and the Stokes and Brinkman equations are solved in order to determine the permeability.

KEYWORDS: Finite element, Permeability, Mesoscopic scale, woven preform, hypoelastic behavior, large strain.

INTRODUCTION

In order to increase the use of composite materials in the industry, modeling of the processing phases is a key point. Most of the high performance composite parts use woven reinforcements and are realized using Liquid Composite Moulding processes (LMC). During such processes, a first stage (the preforming stage) consists in shaping a dry reinforcement. A second phase consists in injecting a thermoset matrix and finally, the third and last stage is the curing of the preform in order to obtain the final part.
Generally, the first and second stages of the LCM processes are not modeled using the same numerical tools as they deal with different physical phenomena: if the second stage is mostly concerned with the flow of the liquid phase (i.e. the matrix), the first one is mainly linked to the deformation of the solid phase (i.e. the fibrous skeleton).

Experimental evidences have proved that the permeability of textile reinforcements is influenced by their actual shape [1]. In order to provide a predicting tool for injection simulation, it is consequently necessary to evaluate the permeability tensor for all the possible geometrical configurations of the solid skeleton.
Textile reinforcements are made up of interlaced yarns, each of them constituted of thousands of fibers. Consequently, textile reinforcements can be observed at various scales: the macroscopic one, i.e. the scale of the entire structural part; the mesoscopic one (the scale of the yarn); and a microscopic scale (i.e. the scale of the individual fiber). The mechanical behavior of a woven reinforcement is of course highly influenced by that multi-scale structure. In particular, the macroscopic behavior is due to the possible sliding between yarns; and the yarn behavior in linked to the possible relative motions between neighboring fibers.
In the same manner the global permeability response of textile reinforcements is linked to the local geometries of the weaving and of the yarns, which means that the flow simulation must also be seen as a multi-scale problem.
One way to deal with those two multi-scale problems is to realize successively numerical simulations at various scales (from the smallest to the biggest one).
Up to now, the microscopic approach is not massively used because of its high computational cost. It is not the case for the mesoscopic approach; it is widely used for both mechanical and flow simulations. Those simulations provide mechanical characteristics available for the macroscopic simulations.
The aim of the present communication is to show the ability of such approach to give efficient information for forming simulations in terms of permeability tensor.
In order to evaluate that tensor of a given reinforcement in a given geometrical configuration, a Representative Elementary Volume (REV) is studied in the undeformed and various deformed configurations. The CelPer2 software is then used. Yarns and their complementary volumes are meshed and Stokes and Brinkman equations are solved in order to determine the permeability tensor.
The deformed yarn geometries are obtained from a finite element simulation using ABAQUS/Explicit® software. The numerical analyses are validated by X-ray tomography experiments. The present paper gives the most important topics for the simulations to be relevant: yarn constitutive behavior; REV boundary conditions; permeability evaluations.

MECHANICAL SIMULATIONS

Experimental observations

X-ray tomography observations have shown that the yarn behavior can be considered as transversely isotropic, with the orthotropic direction corresponding to the longitudinal one. Based on this assumption, the constitutive relation used in this paper is decomposed into two parts. First, the longitudinal direction is considered; and then, the isotropic transverse behavior is split into a “spherical” and a “deviatoric” part. The “spherical” part is linked to the transverse section surface changes and the “deviator” one is related to the transverse section shape changes.

Mechanical behavior

The constitutive model used here, is based on the work of Badel et al. [2,3] and used a hypo-elastic formulation.

$$\underline{\underline{\boldsymbol{\sigma}}}^{\nabla} = \underline{\underline{\underline{\underline{\mathbf{C}}}}} : \underline{\underline{\mathbf{D}}} \tag{1}$$

where $\underline{\underline{\boldsymbol{\sigma}}}^{\nabla}$, $\underline{\underline{\mathbf{D}}}$ and $\underline{\underline{\underline{\underline{\mathbf{C}}}}}$ are respectively the Cauchy stress objective rate tensor, the strain rate tensor and the constitutive tensor. This equation is integrated over a time increment $\Delta t = t^{n+1} - t^{n}$ using the formula of Hughes and Winget [4] widely used in finite element codes at finite strains.

The large longitudinal stiffness of the fibers requires to strictly monitoring their direction to avoid the accumulation of significant spurious stresses at each time step. Therefore the rotating basis, denoted as $\{\underline{\mathbf{f}}_i\}$ in the present case of fibrous material, must be attached to $\underline{\mathbf{f}}_1$ the fiber direction, which means using a rotational objective derivative based on the fiber rotation [5].

Longitudinal behavior

The importance of a correct follow up of the fiber direction has been already pointed out by the authors in [2,3]. The procedure described in [5] is used in this work.

The material parameters of the yarn constitutive tensor are determined from different experimental tests. The longitudinal Young modulus E_1 is known from a tension test on a single yarn. In order to ensure a very law bending stiffness for the yarn material, the longitudinal shear moduli G_{12} and G_{13} are chosen significantly lower than the longitudinal Young's modulus [6] and assumed to have equal values: $G_{12} = G_{13} = G_1$.

Transverse behavior

As shown [7], during the reinforcement deformation, the fiber bundle exhibits both surface and shape changes. Those observations, lead to use the same kind of decompositions of the strain tensor as used for metal plasticity: the planar strain field is split in a "spherical" part, representative to the surface change of the yarn section, and a "deviatoric" part, characterizing the shape change of the fiber bundle. Such decomposition leads to:

$$\left[\tilde{\varepsilon}_T\right]_{fi} = \begin{bmatrix} \varepsilon_s & 0 \\ 0 & \varepsilon_s \end{bmatrix} + \begin{bmatrix} \varepsilon_d & \varepsilon_{23} \\ \varepsilon_{23} & -\varepsilon_d \end{bmatrix} \tag{2}$$

with $\varepsilon_s = \dfrac{\varepsilon_{22} + \varepsilon_{33}}{2}$ and $\varepsilon_d = \dfrac{\varepsilon_{22} - \varepsilon_{33}}{2}$

That decomposition is assumed to be also valid for the strain increment and for the stress increment tensors. That leads to the constitutive Eqn 3.

$$\begin{aligned} \Delta\sigma_s &= A\,\Delta\varepsilon_s \\ \Delta\sigma_d &= B\,\Delta\varepsilon_d \\ \Delta\sigma_{23} &= B\,\Delta\varepsilon_{23} \end{aligned} \tag{3}$$

in which A and B are material parameters depending on both longitudinal tensile strain ε_{11} and spherical strain ε_S and identified by an inverse method.

$\Delta\sigma_s$, $\Delta\sigma_d$, $\Delta\varepsilon_s$ and $\Delta\varepsilon_d$ are respectively spherical and deviatoric stress and strain increments.

A reasonable experimental fit is found with parameters A and B given by the expressions of Eqn 4.

$$A = A_0 \ e^{-p\varepsilon_s} \ e^{n\varepsilon_{11}}$$
$$B = B_0 \ e^{-p\varepsilon_s} \quad (4)$$

Numerical simulations and X-ray validation

3D finite element simulations have been carried out on a RUC of a 2x2 carbon twill. The geometrical model is named consistent as it avoids any interpenetration or spurious voids between yarns [8]. It used 8-nodes reduced integration elements within the dynamic explicit code ABAQUS/Explicit®.
Qualitative comparisons have been made with X-ray observations I the case of in-plane shear. The transverse section changes show reasonable agreement with numerical ones.

FLOW SIMULATIONS

Geometrical modelling

In order to evaluate the permeability of the deformed reinforcement, it is necessary to extract the channel network in which the polymer resin can flow. The solid skeleton obtained with the previous simulations is then used as an input to mesh the complementary volume of the representative unit cell. Such operation is not easy to achieve because the volume to be meshed is geometrically complex with dimensions possibly small.

Flow simulations

The 3D finite element code CELPER2 [9] developed at ONERA is then used to solve the fluid mechanics equations (Stokes equations for incompressible fluid). The code is also able to resolve the Brinkman equation within the yarns, which becomes important when the permeability of the whole fabric approaches the permeability of the tows.

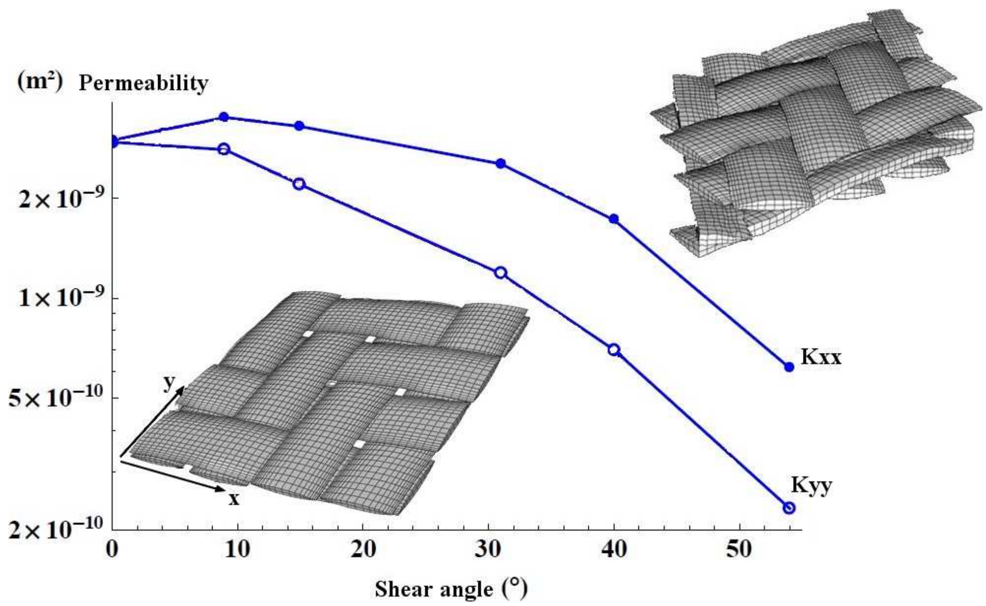

Fig. 1 Undeformed and deformed 2x2 carbon twill and influence of shear angle on permeabilities on x and y directions [10]

This is not the case in general and in particular with the kind of fabrics we are working with. The results are promising as they show results in good agreement with experimental evidences.

CONCLUSIONS

The influence of the actual strain of textile reinforcements on their permeability tensors shows that a numerical evaluation of it is of great interest. The results of this paper show that such numerical evaluation is possible. It opens the way to full LCM process simulations from the mechanical simulation of the preforming stage to the flow simulation of the resin injection.

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