Modelling of the flow of generalised Newtonian fluids through deformed textile reinforcements

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ABSTRACT: A method is proposed to compute the macroscopic flow of non-Newtonian fluids through highly deformed woven fabrics. The method is divided in two steps. Firstly, the shear deformation of a textile reinforcement is studied from a mesoscale numerical analysis. The second step consists in simulating the mesoscale flow of the polymer through the as-deformed woven fabrics. Numerical results emphasise the drastic changes of the permeation law when the considered plain weave fabric is sheared. The influence of the flowing fluid rheology is also emphasised in case of generalised Newtonian fluids. A method is proposed to formulate the macroscopic flow law.

KEYWORDS: Deformation of Textile Reinforcement, Flow through fibrous media, Non-Newtonian Fluids

1 INTRODUCTION

It is essential to accurately predict polymer flows in fibre preforms for a number of liquid molding processes among which the Resin Transfer Moulding process (RTM). Nevertheless, the determination with a high precision of the flow description, still remains difficult. Woven fabrics' manufacturers can provide a material property list which sometimes contains the permeability of fabrics, usually measured when fabrics are not deformed:

- During the preforming stage of RTM woven fabrics undergo mechanical loadings which can induce very large deformations of the textiles of which dominant mode is the shear deformation [1]. This affects their permeability and has to be understood and quantified. Indeed, if the relation between textile pre-deformation and permeability is determined and the deformation pattern of the fabrics is known, the related permeability pattern can be drawn for the entire reinforcement in order to better predict the flow within the preform.
- The permeability is a property that is only dedicated to the flow of Newtonian fluids through porous media. However, liquid polymers may exhibit non-Newtonian behaviour (thermoset polymers as they are curing or thermoplastic polymers with long polymer chains), especially at the high shear rates they are subjected when they flow through networks of fibres. Under such circumstances, their flow through textiles reinforcement may severely deviates from that of Newtonian fluids [6, 3, 5].

Within that context, a method is proposed in this work in order to determine the macroscopic flow law for non-Newtonian fluids flowing through highly deformed woven fabrics. The method is divided in two steps. Firstly, the shear deformation of a textile reinforcement until the shear locking is studied from a mesoscale analysis achieved with a Representative Elementary Volume (REV) of the periodic textile. The second step consists in simulating the mesoscale flow through the as-deformed solid REV's in order to study the flow of the polymer through the woven fabrics. Numerical results emphasised the drastic changes of the permeation law when the considered plain weave fabric was sheared, such as its loss of transverse isotropy. The influence of the flowing fluid rheology is also emphasised in case of generalised Newtonian fluids. A method is proposed to formulate the macroscopic flow law, within the framework of the theory of anisotropic tensor functions and using mechanical iso-dissipation curves.

2 PREDEFORMATION OF THE TEXTILE

We have considered here a very simple textile reinforcement. It is a periodic glass plain weave which is balanced since the warp and the weft yarns have identical geometrical and mechanical properties. Its geometry is based on circle arcs and tangent segments. It is simple but ensures consistency of the model, which means that yarns do not penetrate each other [2]. A scheme of the periodic solid REV of such a mesostructure is given in figure 1(a).

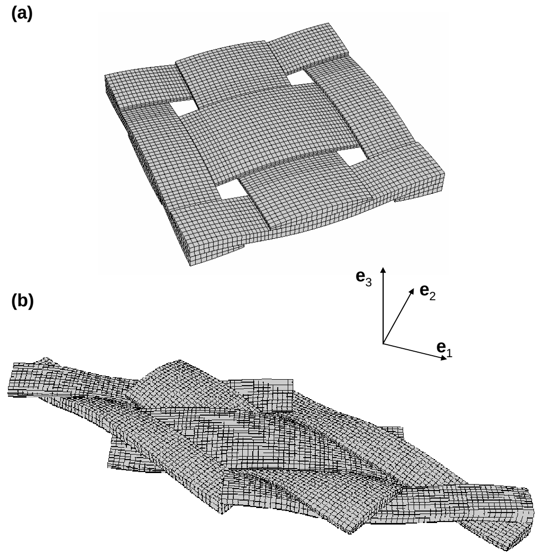

Figure 1: Solid REV of the studied plain weave : geometry and FE mesh before deformation (a) and after a pre-shear angle of $53°$ in the $(\mathbf{e_1}, \mathbf{e_2})$ plane (b).

As extensively described in [1], this solid REV was subjected to a significant in-plane shear. In order to compute its corresponding deformed shape, finite elements calculations were performed with the commercial FE code Abaqus. Briefly, the following assumptions were stated to run the simulation:

- Very large transformations were taken into account
- Consistent yarn-yarn contacts were assumed to induce Coulombic friction forces (dry friction coefficient $f = 0.2$)
- Yarns were assumed to behave like transversely isotropic hypoelastic continua, which symmetry direction is locally parallel to the direction of fibres within the yarns. Hence, their mechanical behaviour is given by the following constitutive relation:

$$\sigma^{\nabla} = \mathbb{C} : \mathbf{D} \qquad (1)$$

  where $\mathbb{C}$ is the incremental stiffness tensor (requiring 5 constitutive parameters, i.e. longitudinal E_l, ν_l and transverse E_t, ν_t Young moduli and Poisson ratios, and a shear modulus G), $\mathbf{D}$ is the strain rate tensor and σ^{∇} is an objective derivative of the Cauchy stress tensor σ. Such a derivative is computed by following the local rotation of fibres.

- Calculations were achieved by subjecting the whole solid REV to a mean macroscopic displacement gradient corresponding to an in plane shear. Thereby, the periodic fluctuations of the displacement required to accommodate the imposed mechanical loading were computed.

As an example, figure 1(b) give the deformed shape of the solid REV after an imposed shear angle very close to the locking angle [1].

3 FLUID FLOW MESOSCALE SIMULATION

From the as-deformed solid REV's, associated fluid REV's were then built in order to study the flow of the polymer through them. Briefly, solid REV's obtained with the FE code Abaqus are represented by means of meshes for each individual yarn. Those meshes have first to be transformed in solid entities which are then assembled. Once a unique solid entity is obtained, it must be subtracted from a well-chosen volume to give the fluid REV. Keeping same periods as the solid ones would generate difficulties to construct the corresponding fluid REV's. The fluid period has then been adapted, in a appropriate way to easily impose periodic boundary conditions (see figure 2).

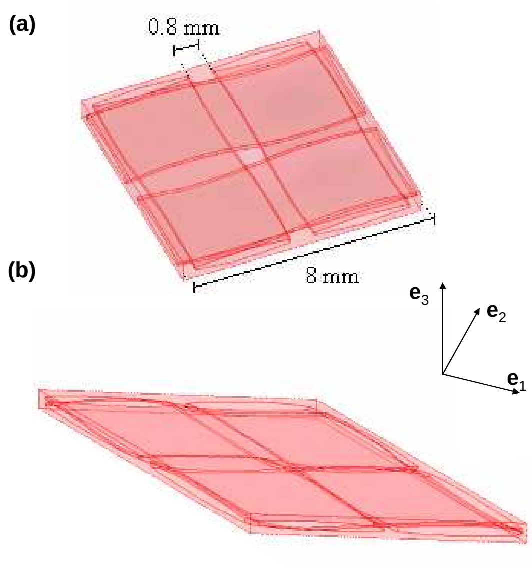

Figure 2: Fluid REV's corresponding to the solid REV's sketched in figure 1.

Therefrom, the mescocale slow flow of a generalised Newtonian fluid through the as-deformed solid REV's was extensively analysed by using an upscaling technique which is described in [4]. For a sake of simplicity, we have considered here a power-law fluid, which viscosity μ is simply expressed as:

$$\mu = \mu_0 \dot{\gamma}^{n-1} \tag{2}$$

$\dot{\gamma}$ being the generalised shear strain rate, μ_0 the consistency and n the strain rate sensistivity. Hence, by assuming sticking boundary conditions at the fluid solid interfaces, the following fluid flow problem deduced from the upscaling process was solved within the fluid REV's:

$$\nabla \cdot \bar{\mathbf{v}} = 0, \tag{3}$$

$$2\mu_0 \nabla \cdot \left(\dot{\bar{\gamma}}^{n-1} \, \bar{\mathbf{D}} \right) = \nabla \varepsilon p + \nabla \bar{p}, \tag{4}$$

where the so-called first order pressure gradient $\nabla \bar{p}$ is constant and given in the entire fluid REV's, and where the first order velocity field $\bar{\mathbf{v}}$ as well as the fluctuation pressure εp are the periodic unknowns. This boundary value problem was solved with a mixt pressure-velocity formulation implemented in the finite element commercial code Comsol.

4 STUDY OF THE MACROSCOPIC FLOW LAW

It can be proved from the upscaling process [4], that the macroscopic description corresponding to the above mesoscale fluid flow problem is expressed by the following macroscopic mass and momentum balance equations:

$$\nabla \cdot \langle \bar{\mathbf{v}} \rangle = 0, \tag{5}$$

$$\nabla \bar{p} = \mathbf{f}(\langle \bar{\mathbf{v}} \rangle, \mu_0, n, mesostructure), \tag{6}$$

where the macroscopic velocity field $\langle \bar{\mathbf{v}} \rangle$ is the volume average of the mesoscopic velocity field $\bar{\mathbf{v}}$, and where $\mathbf{f}$ is a volumetric viscous drag force. Moreover, $\mathbf{f}$ can be expressed as the gradient of a viscous dissipation potential $\langle \Phi \rangle$ with respect to the macroscopic velocity field $\langle \bar{\mathbf{v}} \rangle$ [4]:

$$\mathbf{f} = -\frac{\partial \langle \Phi \rangle}{\partial \langle \bar{\mathbf{v}} \rangle} = -\frac{\mu_0}{l_c} \left(\frac{v_{eq}}{\phi l_c} \right)^n \frac{\partial v_{eq}}{\partial \langle \bar{\mathbf{v}} \rangle}, \tag{7}$$

where l_c is the characteristic length of sheared fluid at the mesoscale, ϕ can be defined as the "active" volume fraction of pores effectively contributing to the flow: they can be obtained by simulating and analysing the flow in the $\mathbf{e_1}$ direction. The positive scalar v_{eq} also appearing in the last equation is an equivalent macroscopic velocity: any iso-equivalent velocity surface (iso-v_{eq}) plotted in the velocity space corresponds to an iso-dissipation surface and to an iso-potential surface (iso-$\langle \Phi \rangle$). Fitting with a suitable phenomenological form numerical iso-v_{eq} surfaces deduced from mesoscale simulations allows to obtain the whole macroscopic flow law. Indeed, in accordance with (7), the volumetric viscous drag force $\mathbf{f}$ is normal to the iso-v_{eq} surfaces.

5 APPLICATION TO THE PLAIN WEAVE

For the considered mesostrucutres, which exhibit orthotropic macroscopic flow law, the following continuous form of v_{eq} is proposed [4], here expressed in the principal reference frame $(\mathbf{e_1}, \mathbf{e_2}, \mathbf{e_3})$:

$$v_{eq}^m = v_{eqa}^m + v_{eqb}^m, \tag{8}$$

where

$$\left\{ \begin{array}{lcl} v_{eqa}^{m_a} & = & |v_1|^{m_a} + (|v_2|/A)^{m_a} \\ v_{eqb} & = & |v_3|/B \\ m & = & \left(m_b|v_1|^2 + m_c|v_2|^2\right) / \left(|v_1|^2 + |v_2|^2\right) \end{array} \right. \tag{9}$$

This form involves five additional constitutive parameters. A and B can be directly deduced from the mesoscale simulation of the flow along the $\mathbf{e_2}$ and

$\mathbf{e_3}$ directions, respectively. The curvature parameters m_a, m_b and m_c are chosen to fit the above continuous iso-v_{eq} surface to numerical ones. The proposed expression of v_{eq} was compared to numerical iso-dissipation surfaces obtained from numerical simulation achieved on the REVs shown in figure 2, for a Newtonian ($n = 1$) and a power-law fluid ($n = 0.3$). Results which are given in figure 3, conjure up the following comments:

• The proposed form of v_{eq} (continuous surfaces given by (7)) allows a nice fit of numerical iso-dissipation surfaces (stars) plotted in the velocity space.

• The isodissipation surface exhibits transverse isotropy for the non deformed REV and when the fluid is Newtonian (see figure 3(a)). Such a symmetry is broken for the same REV and for a power-law fluid (see figure 3(b)): the macroscopic flow law then exhibits orthotropy [3].

• Shearing the plain weave (i) increase the anisotropy and (ii) induce a more difficult flow. Indeed, compared to the non deformed isodissipation surface plotted in figure 3(b), the isodissipation surface obtained for the same fluid but with the sheared REV is (i) flattened in the $\mathbf{e_3}$ direction and (ii) smaller (figure 3(c)).

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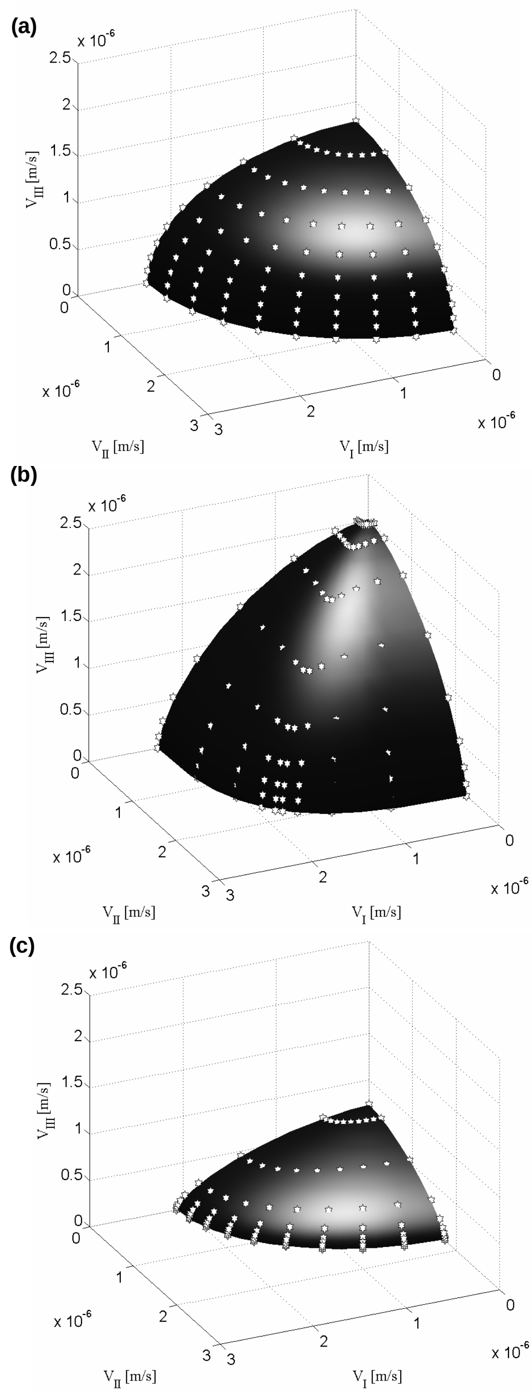

Figure 3: Numerical (stars) and fitted (continuous surfaces) isodissipation surfaces (100 W m^{-3}) plotted in the velocity space and obtained (a) for the non deformed plain weave (figure 1(a)) and for a Newtonian fluid ($\mu_0 = 1$ Pa s, $n = 1$), (b) for the non deformed plain weave and for a power-law shear thinning fluid ($\mu_0 = 1$ Pa s^n,$n = 0.3$) (c) for the sheared plain weave (figure 1(a)) for a power-law shear thinning fluid ($\mu_0 = 1$ Pa s^n,$n = 0.3$).