3D SIMULATION OF COMPOSITE STRANDS COMPRESSION MOLDING BY USING THE PROPER GENERALIZED DECOMPOSITION

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Abstract
Nowadays, composite forming processes are constantly improved. Recently, composite forming through compression molding of inserts or strands appeared, offering faster manufacturing possibilities of complex parts [1]. However, such processes are not mastered yet and their simulation is compulsory to be able to optimize the process parameters. In this work, we aim at modelling and simulating this process by using the Proper Generalized Decomposition (PGD). We starts by simulating the 3D flow of a stratified plate with unidirectional fiber reinforcement modeled as a transversally isotropic fluid – TIF –. Afterwards, composite strands are modeled as uniaxial discontinuous tapes immersed in a large viscous suspending fluid, and the simulation is carried out. Simulation reveals strands interaction in the contact zone. Moreover, the simulation shows a translation combined with a rotation of the strands induced by the effective squeeze flow.

1. Introduction

Composite materials are recently preferred on metals thanks to their excellent mechanical properties at low weight. Therefore, the composite forming processes are being constantly improved by creating a better fiber suspension models. Different papers describe quite well the short and long fiber suspension reinforcements involved in composite manufacturing, we may cite among many others [2, 3]. However, recently appeared a new composite manufacturing process that relies on the use of fiber inserts or strands as reinforcement of the part [1]. Such reinforcements are large enough so they can't be treated neither as small fiber suspensions, nor as continuous fiber reinforcements.

From an applicative point of view, short fiber suspensions are used to manufacture reinforced thermoplastics using extrusion or injection. However, pre-preg thermo-compresion uses continuous fibers to elaborate parts.

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The design flexibility of composite materials can be achieved by using simultaneously continuous and discontinuous fiber suspensions. The main difference is that continuous fiber reinforcements are hold by means of blank holders during forming, however discontinuous fibers are fiber patches that are free to move inside the mold. Therefore during compression molding of such parts, the patches are free to translate, rotate and deform under the effect of the flow inside the thermoplastic fluid matrix. On the other hand, 2D simulations are not enough to characterize the exact behavior of the strands. In fact, when laminates are squeezed, depending on the plies orientation and lubrication conditions, the flow exhibits a rich evolution along the thickness direction and therefore a detailed 3D description of the flow is required [4, 5].

To the knowledge of the authors, there are very few studies focusing on the flow of strands or fiber patches in composite parts. Moreover, there is no commercial software able to predict the final orientation of such inserts nor their final shape. Therefore, and because of the complexity of the problem and the physics involved, simulation is needed to understand the forming process.

Unidirectional prepregs can be modeled as transversally isotropic fluids [6]. In this work, we model the behavior of the melted prepregs by using the Ericksen fluid flow formulation. Afterwards, we use the suggested model to simulate the behavior or unidirectional prepregs inserts in a squeeze flow.

To simulate the 3D flow, we use an in-plane-out-of-plane separated representation by using the Proper Generalized Decomposition (PGD) [7]. In this work, using the PGD, we reduce the 3D complexity of the simulation to few 2Dx1D simulations [8–10]. Such approach can dramatically reduce the computation time of the solution. The interested reader can refer to [11–14] and references therein.

2. Modeling of the problem

2.1. The in-plane-out-of-plane separation

Using the PGD, we transform the 3D simulation into a sequence of $2D \times 1D$ simulations. Therefore we start by assuming that the velocity $\mathbf{v}(x, y, z)$ at each point can be written as :

$$\mathbf{v}(x,y,z) = \begin{pmatrix} u(x,y,z) \\ v(x,y,z) \\ w(x,y,z) \end{pmatrix} \approx \begin{pmatrix} \sum_{i=1}^{N} F_1^i(x,y) \cdot Z_1^i(z) \\ \sum_{i=1}^{N} F_2^i(x,y) \cdot Z_2^i(z) \\ \sum_{i=1}^{N} F_3^i(x,y) \cdot Z_3^i(z) \end{pmatrix} \tag{1}$$

where u, v and w are the 3 components of the velocity field. Therefore the velocity gradient $\nabla\mathbf{v}(x, y, z)$ can also be written in a separated form:

$$\nabla\mathbf{v} = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{pmatrix} \approx \sum_{i=1}^{N} \begin{pmatrix} \frac{\partial P_i^1}{\partial x} & \frac{\partial P_i^1}{\partial y} & P_i^1 \\ \frac{\partial P_i^2}{\partial x} & \frac{\partial P_i^2}{\partial y} & P_i^2 \\ \frac{\partial P_i^3}{\partial x} & \frac{\partial P_i^3}{\partial y} & P_i^3 \end{pmatrix} \circ \begin{pmatrix} T_i^1 & T_i^1 & \frac{\partial T_i^1}{\partial z} \\ T_i^2 & T_i^2 & \frac{\partial T_i^2}{\partial z} \\ T_i^3 & T_i^3 & \frac{\partial T_i^3}{\partial z} \end{pmatrix} =$$

$$\sum_{i=1}^{N} \mathbb{P}_i(\mathbf{x}) \circ \mathbb{T}_i(z). \tag{2}$$

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where $\circ$ denotes the Hadamard's product. The 3D solution can be obtained by replacing the above expressions into the Ericksen flow model depicted in section 2.2 and then solve it using the PGD.

2.2. The Ericksen flow model in a single ply

The simplest form of the Ericksen constitutive equation can be written as [15]:

$$\sigma = -P\mathbf{I} + T\mathbf{a} + 2\eta_T \mathbf{D} + 2\left(\eta_L - \eta_T\right)\left(\mathbf{D}\cdot\mathbf{a} + \mathbf{a}\cdot\mathbf{D}\right) \tag{3}$$

where η_L and η_T being the longitudinal and transversal viscosity of the fluid inside the fiber bed, P the pressure, $\mathbf{I}$ the identity matrix, T the tension in the fibers. On the other hand, $\mathbf{a}$ can be defined by using the orientation vector of the fibers $\mathbf{p}^T = (p_x, p_y, 0)$, such as $\mathbf{a} = \mathbf{p}\otimes\mathbf{p}$. Reader should note that $||\mathbf{p}|| = 1$. $\mathbf{D}$ is the rate of strain tensor, symmetric component of the velocity gradient.

The inextensibility constraint can be noted by :

$$\mathbf{p}^T \cdot \nabla\mathbf{v}\cdot\mathbf{p} = 0 \tag{4}$$

while the conservation of mass reads:

$$\nabla\cdot\mathbf{v} = 0 \tag{5}$$

To satisfy Eqs. 4 and 5 we will use a double penalty formulation. Penalty formulations were successfully considered within the PGD framework in [7, 16]. Therefore we introduce two penalty coefficients λ and ξ such as :

$$\begin{aligned} &\nabla\cdot\mathbf{v} + \lambda P = 0 \\ &\nabla\mathbf{v} : a + \xi T = 0 \end{aligned} \tag{6}$$

with λ and ξ small enough. Taking into account the symmetry of $\mathbf{a}$, Eq. 6 leads to:

$$\begin{aligned} P &= -\tfrac{\nabla\cdot\mathbf{v}}{\lambda} = -\tfrac{1}{\lambda}Tr\left(\mathbf{D}\right) \\ T &= -\tfrac{\nabla\mathbf{v}:\mathbf{a}}{\xi} = -\tfrac{1}{\xi}\mathbf{D}:\mathbf{a} \end{aligned} \tag{7}$$

Now introducing Eqs. 7 into the linear momentum balance equation $\nabla\cdot\sigma = 0$ along with the Ericksen constitutive equation given in Eq. 3, the problem weak form results:

$$\int_{\Omega\times\mathcal{I}} \left\{ \frac{\mathrm{Tr}(\mathbf{D}^*)\cdot\mathrm{Tr}(\mathbf{D})}{\lambda} - \frac{(\mathbf{D}^*:\mathbf{a})\cdot(\mathbf{D}:\mathbf{a})}{\xi} + \eta_T\mathbf{D}^*:\mathbf{D} + (\eta_L-\eta_T)\mathbf{D}^*:(\mathbf{D}\cdot\mathbf{a}+\mathbf{a}\cdot\mathbf{D}) \right\} d\mathbf{x}\, dz = 0. \tag{8}$$

We can note that for $\mathbf{a} = 0$, Eq. 8 is reduced to the classical Stokes problem.

2.3. Multilayered laminate inserts

To represent laminates we introduce a characteristic function for each ply according to:

$$\mathcal{X}_i(z) = \begin{cases} 1 \text{ if } z \in [(i-1)h, ih] \\ 0 \text{ elsewhere} \end{cases} \tag{9}$$

where h is the ply thickness.

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2.4. Fabrics

In the case of fabrics we must add a new orientation vector $\mathbf{q}$ similar to the previous one $\mathbf{p}$. In the case of orthogonal fabrics $\mathbf{p}$ defines the orientation of fibres assumed aligned along the x direction, and then $\mathbf{q}$ defines de orientation of fibers aligned in the y direction. We can define matrix $\mathbf{b}$ such as $\mathbf{b} = \mathbf{q} \otimes \mathbf{q}$.

A new term appears therefore in the Ericksen fluid flow model when considering fabrics:

$$\sigma = -P\mathbf{I} + T_x\mathbf{a} + T_y\mathbf{b} + 2\eta_T\mathbf{D} + 2\left(\eta_L - \eta_T\right)\left(\mathbf{D}\cdot\mathbf{a} + \mathbf{a}\cdot\mathbf{D}\right) + 2\left(\eta_L - \eta_T\right)\left(\mathbf{D}\cdot\mathbf{b} + \mathbf{b}\cdot\mathbf{D}\right) \qquad (10)$$

where the same longitudinal and transversal viscosities are considered for the sake of simplicity.

3. Numerical results

In this section we show the solution of the flow resulting of layered strands immersed in a resin as shown in figure 1. Figure 2 depicts the deformation of the multilayered strands.

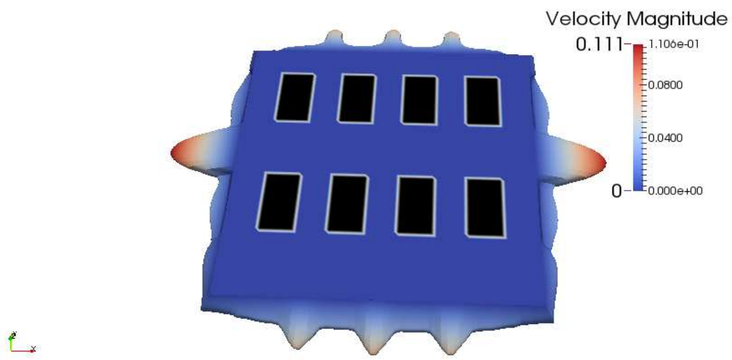

Figure 1. Distribution of composite inserts where only the external plies oriented at 0° are represented. The black regions represent the inserts.

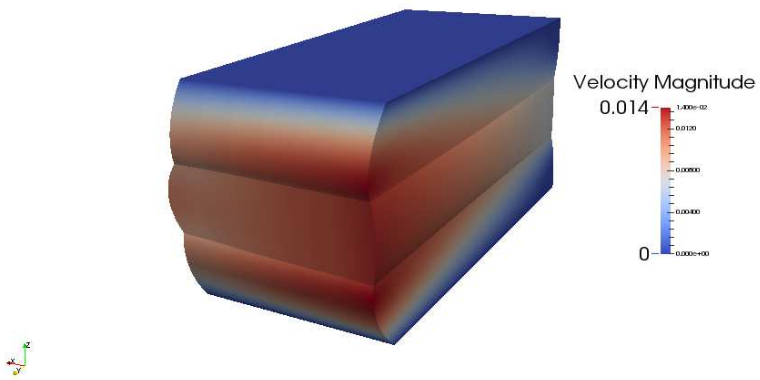

Figure 2. View of the deformed strands. The fiber orientation in the upper and lower strands is parallel to the x-axis, while in the middle one fibers align along the y-axis.

In figure 3, we show a $2cm \times 2cm$ incompressible fabric inside a $1m \times 1m$ viscous domain. The height of the fabric is $\frac{1}{3}$ the height H of the domain and it's center of gravity placed at $H/2$. We notice that the fabric velocity is relatively constant and that the fabric remains almost undeformed. However in figure 4

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we illustrate a compressible fabric having the same size located at the same position. In that last case the square fabric is deformed into a diamond as shown in figure 5.

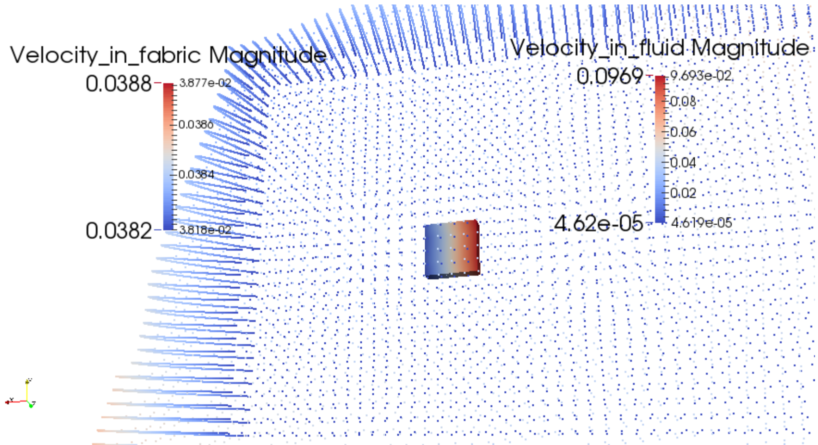

Figure 3. View of an incompressible fabric inside a viscous domain (shown in dots)

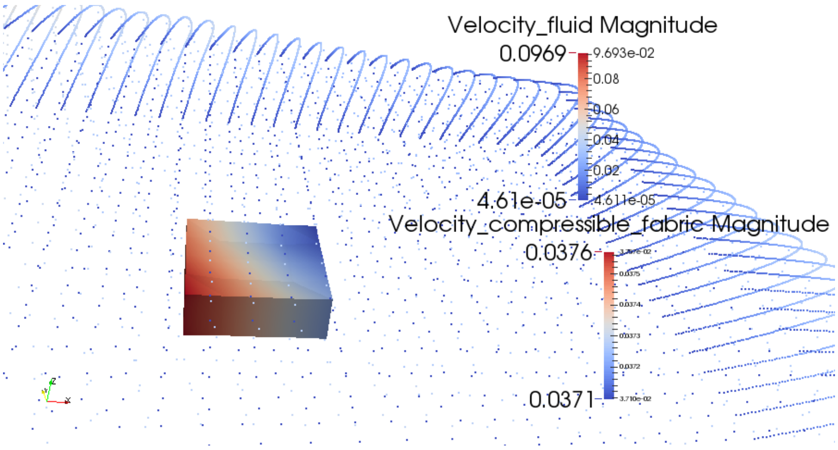

Figure 4. View of a compressible fabric inside a viscous domain (shown in dots)

4. Conclusion

In this work we successfully considered the deformation of composite inserts into a viscous resin in squeezing conditions. The PGD succeeded to solve the resulting 3D flow model while the inserts where assumed incompressible and inextensible in one or two directions.

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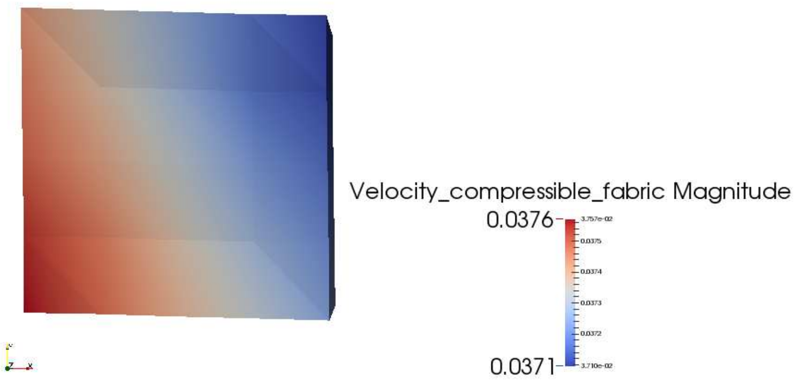

Figure 5. A top view a compressible fabric deformed by squeeze flow

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