XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

ADVANCED MODELING OF THE OUT-OF-AUTOCLAVE THERMOPLASTICS PREPREG CONSOLIDATION

CHADY GHNATIOS* AND FRANCISCO CHINESTA†

* IRT JULES VERNE
Chemin du chaffault
44340 Bouguenais
e-mail: chady.ghnatios@irt-jules-verne.fr

†GeM UMR CNRS - ECN
Ecole Centrale Nantes
1 rue de la Noe, 44321 Nantes
e-mail: francisco.chinesta@ec-nantes.fr

Key words: Thermoplastic consolidation, squeeze flow, coupled models, Brinkman equations

Abstract. Nowadays, composite materials are replacing metallic ones thanks to their excellent mechanical performances and reduced weight. However, many difficulties are encountered during composite forming processes. In fact, autoclave curing process is too expensive and limits the part size to the autoclave dimensions. Out-Of-Autoclave processes reduce substantially the cost of forming processes. However, the absence of autoclave pressure in out-of-autoclave manufacturing processes leads nowadays to high porosity and poor consolidation at the interface between the tows [1]. Moreover, the effect of the process parameters on the consolidation is still unknown and thus controlling the final parts quality is not obvious. Despite the high potential offered by the Out-of-Autoclave processes, only few researches has been made in the last few years, in order to quantify the consolidation of the tows while using such processes [2]. In fact, only few models addressing void dynamics in thermoplastic composites has been carried out [3, 4]. In this work, we are using a novel coupled approach involving modeling and simulation in order to quantify the consolidation in Out-of-Autoclave processes. Advanced model reduction techniques (POD, PGD ...) are employed in order to predict thermal fields during manufacturing processes and coupled to the subsequent squeeze flow.

1 INTRODUCTION

For long time, engineers relied on experience in order to define optimal process parameters for manufacturing good parts. However, the high demand on composite thermoplastic parts requires a better modeling of the consolidation process. The thermoplastic consolidation is a complex process, coupling many physics silultaneously. Few works focused in this topic from the 80's [5], where Lee and Springer modeled the interface between thermoplastic composite tows. Later, in [6], a heating model was proposed. The coupling between the viscosity of the matrix and the heating temperature was addressed in the 90's [7]. However, the 3D simulation of the thermal and mechanical processes encountered in thermoplastic consolidation was never performed due to the excessive computational complexity that such a simulation involves.

Recently, the PGD – Proper Generalized Decomposition – became an appealing alternative for treating complex 3D models defined in degenerated domains (plate or shell geometries, involving eventually several layers in the thickness direction) [8, 9]. The PGD reduces the computational complexity by performing a space separated representation of the different fields involved in the models. For example in the case of plate geometries, instead of solving a 3D problem, we only need solving some 2D and 1D problems when performing an in-plane-out-of-plane separated representation, or even a sequence of 1D problems in hexahedral domains.

In this work, first of all we solve the thermal problem inside a composite part. Afterwards, the viscosity of the matrix is computed, in order to simulate the squeeze flow of the matrix inside the composite. The squeeze flow is classically modeled using the lubrication assumptions [10]. However, we show that this approach fails to model the squeeze flow in composite laminates. Thus, a fully 3D simulation becomes compulsory. We consider in this work the fully 3D solutions of the Stokes and Brinkman equations for describing the squeeze flow in multilayered laminates.

2 SIMULATION OF THE THERMAL FIELDS

In this work composite laminates are modeled as shown in figure 1. We consider the composite part placed between two plates through which the heat flux vanishes. The composite part is heated by convection through its lateral surfaces.

The governing equation is given by :

$$\rho \cdot C_p \frac{\partial U}{\partial t} - \nabla \left(\mathbf{K} \cdot \nabla U \right) = 0 \tag{1}$$

where ρ is the density, C_p the specific heat, $\mathbf{K}$ the conductivity tensor, t the time and U the temperature.

Using the PGD, we can compute the 3D transient solution in the separated form:

$$U(x, y, z, t) \approx \sum_{i=1}^{i=N} X_i(x) \cdot Y_i(y) \cdot Z_i(z) \cdot T_i(t) \tag{2}$$

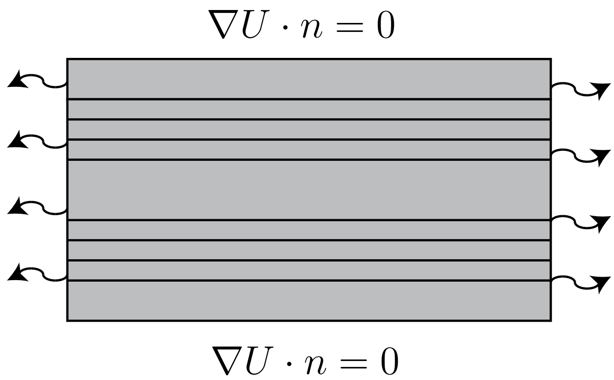


Figure 1: Sketch of the thermal model

The solution of the thermal model is shown in figure 2 on the middle surface at different times.

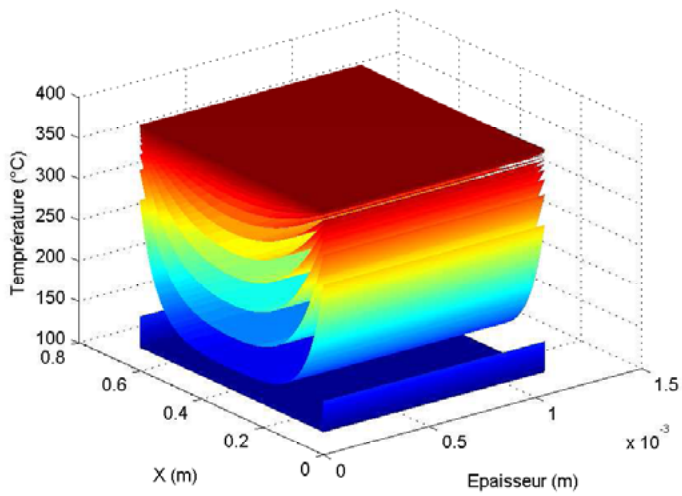


Figure 2: Thermal transient solution (each layer corresponds to a different time instant)

At each time and position the resin viscosity can be calculated from the temperature by using the relation:

$$\eta = A \cdot e^{\frac{B}{U}} \tag{3}$$

Figure 3 depicts the viscosities at each position and time associated with the thermal history shown in Fig. 2.

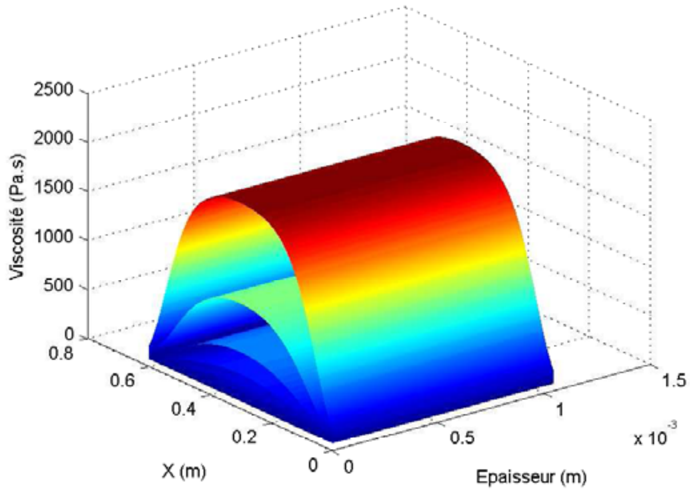


Figure 3: Viscosity of the matrix in the simulated part at each time instant related to Fig. 2

3 SQUEEZE FLOW

When applying a pressure on the upper plate the heated resin flows. This squeeze flow occurs typically during composites consolidation. In what follow we analyze the validity of three different approaches for solving the model depicted in Fig. 4.

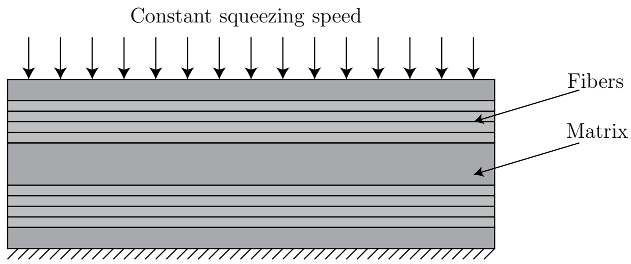


Figure 4: Squeeze flow model

3.1 Modeling based on the lubrification hypotheses

The most natural way to model the squeeze flow is by using the lubrication assumptions. In fact, the thickness of usual composite laminates is much lower that the characteristic in-plane dimensions. This fact suggests the introduction of the so-called lubrification hypotheses:

$$\begin{cases} \frac{\partial u}{\partial z} \gg \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial z} \gg \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y} \\ w = 0 \end{cases} \tag{4}$$

where u, v and w are the velocity components. By considering these hypotheses the momentum balance reduces to:

$$\begin{cases} \frac{\partial p}{\partial x} = \frac{\partial}{\partial z}\left(\eta \frac{\partial u}{\partial z}\right) \\ \frac{\partial p}{\partial y} = \frac{\partial}{\partial z}\left(\eta \frac{\partial v}{\partial z}\right) \\ \frac{\partial p}{\partial z} = 0 \end{cases} \tag{5}$$

where $p = p(x, y)$ is the pressure field and η the resin viscosity.

Integrating equations 5 twice with respect to z, taking into account the non-slipping flow conditions, we can derive the expression of the velocity that allows computing the flow rate $\mathbf{q}$ and then by enforcing the mass balance

$$\dot{h} = \nabla \cdot \mathbf{q} \tag{6}$$

for deriving the second order partial differential equation governing the pressure distribution. Fibrous layers were modeled from a viscous enough pseudo-fluid. The computed results are shown in figure 5 for Newtonian and power-law fluids, both with temperature dependent viscosities.

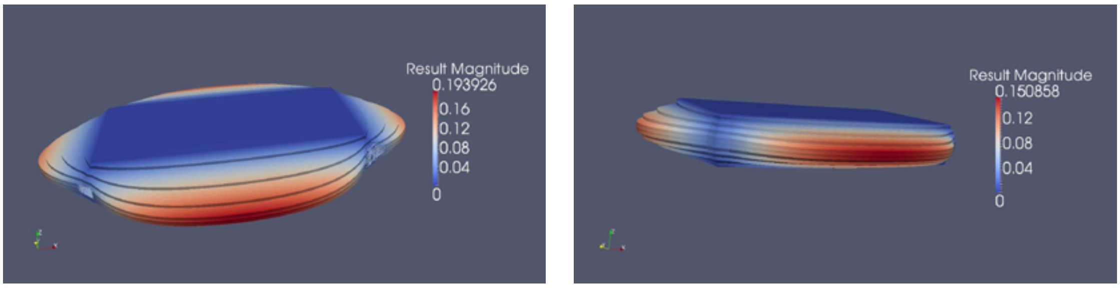


Figure 5: Velocity field within the lubrication framework for a Newtonian fluid (left) and a power-law fluid (right)

The resulting velocity are unphysical. It is easy noticing that the large viscosity assumed in the reinforcement layers limits its shearing but accommodates an elongational flow that is not described within the standard lubrification hypotheses. A fully 3D solution of the momentum and mass balances seems compulsory for simulating squeeze flow in multilayered laminates.

3.2 Fully 3D solutions

We just proved than in the case of laminates composed of several layers of fluids with very different viscosities standard lubrification hypotheses fail for describing the flow kinematics. In that case fully 3D solutions seem compulsory. Even if there is no major conceptual difficulties in considering the fully 3D Stokes problem, from the numerical point of view the situation is radically different because we should consider a mesh fine enough for representing the viscosity evolution in the thickness direction and its induced effects on the flow kinematics. Such a discretization will imply an extremely large number of degrees of freedom to avoid too distorted elements in the mesh.

We proposed recently and in-plane-out-of-plane separated representation that allows solving fully 3D models defined in plate geometries keeping a computational complexity characteristic of 2D simulations. This separated representation allows independent representations of the in-plane and the thickness fields dependencies. The main idea lies in the separated representation of the velocity field according to:

$$\mathbf{v} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} \approx \begin{pmatrix} \sum_{i=1}^{i=N} X_i^u(x,y) \cdot Z_i^u(z) \\ \sum_{i=1}^{i=N} X_i^v(x,y) \cdot Z_i^v(z) \\ \sum_{i=1}^{i=N} X_i^w(x,y) \cdot Z_i^w(z) \end{pmatrix} \tag{7}$$

that leads to a separated representation of the strain rate, that introduced into the Stokes problem weak form allows the calculation of functions $X_i(x,y)$ by solving the corresponding 2D equations and functions $Z_i(z)$ by solving the associated 1D equations. Because de one-dimensionality of problems defined in the laminate thickness we can use extremely fine descriptions along the thickness direction without a significant impact on the computational efficiency.

3.2.1 Stokes modeling

We consider the momentum equation and a penalty formulation of the mass balance:

$$\left\{ \begin{array}{l} \nabla p = \nabla \cdot (\eta \nabla \mathbf{v}) \\ \nabla \cdot \mathbf{v} + \lambda \cdot p = 0 \end{array} \right. \tag{8}$$

with the penalty parameter λ small enough.

Again fibrous layers are modeled by assuming a viscous enough pseudo-fluid. The solutions for a Newtonian and a power-law fluid are shown in Fig. 6. The velocity profiles along the laminate thickness are shown in figure 7. The power-law fluid exhibits a lower velocity around the middle plane because being the shear rate minimum the viscosity becomes maximum.

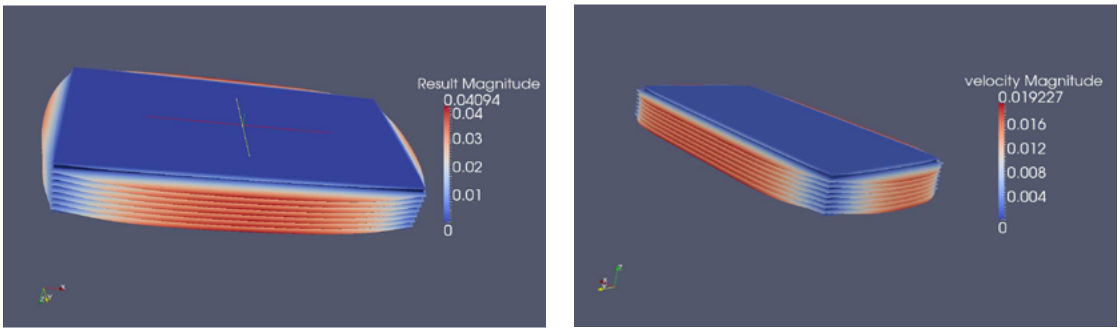
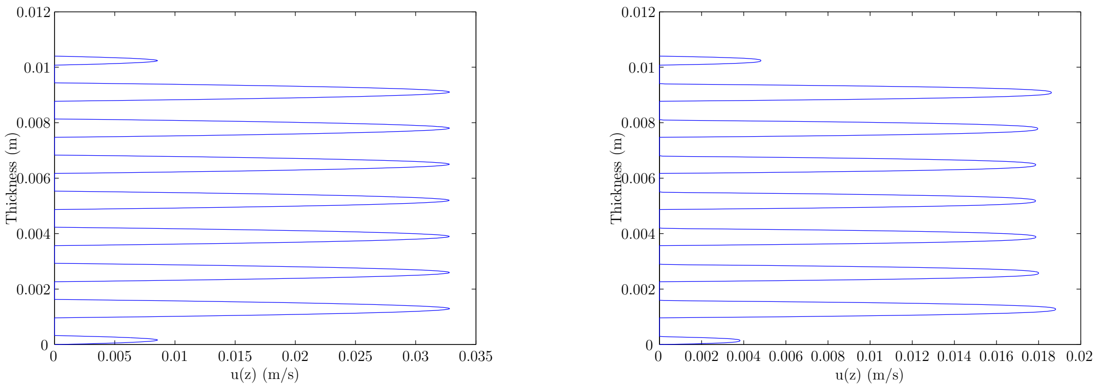


Figure 6: Flow velocity from the 3D Stokes solution for a Newtonian fluid (left) and a power law fluid (right)



(a) Newtonian fluid

(b) Power-law fluid

Figure 7: Velocity profiles along the laminate thickness

3.2.2 Brinkman solution

As indicated before, resin impregnating fibers in the reinforcement layers also flows. A usual approach for evaluating the resin flow in such circumstances consists of solving the associated Darcy's model. It is well known that Darcy-Stokes coupling at the interlayers generates numerical instabilities because the localized boundary layers whose accurate description requires very rich representations (very fine meshes along the laminate thickness).

In this section we propose to use the Brinkman model that allows representing in an unified manner both the Darcy and the Stokes behaviors. In order to avoid numerical inaccuracies we are using a very fine representation along the thickness direction and for circumventing the exponential increase in the number of degrees of freedom that such a fine representation would imply when extended to the whole laminate domain, we are considering again the in-plane-out-of-plane separated representation previously introduced.

The Brinkman model is defined by:

$$\nabla p = \mu \cdot \mathbf{K}^{-1} \cdot \mathbf{v} + \eta \cdot \Delta \mathbf{v} \tag{9}$$

where μ is the dynamic viscosity, $\mathbf{K}$ the layer permeability and η the dynamic effective viscosity.

The 3D solution is shown in figure 8 and the velocity profile along the laminate thickness is depicted in figure 9.

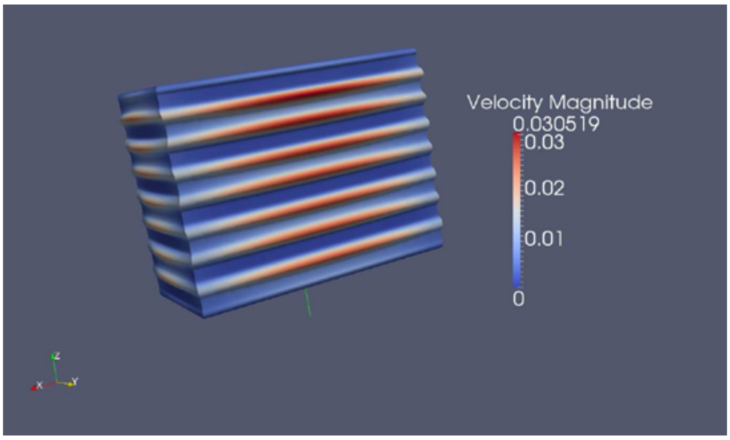


Figure 8: 3D Brinkman solution

Moreover, we compare in Fig. 10 the out-of-plane component of the velocity of both the Stokes and the Brinkman solutions. When considering the Stokes equation the velocity of the resin in the fibrous layers (modeled from a pseudo-fluid with large enough viscosity) was constant along the layer thickness (fibrous layers move like a rigid solid) whereas in the case of considering the Brinkman model this velocity evolves inside the fibrous layer proving the complex flow exchanges between the different layers.

4 CONCLUSIONS

In this work we analyzed the validity of lubrification approaches for addressing squeeze flows in composite laminates. When describing fibrous layers from a viscous enough pseudo-fluid the main conclusions are (for both Newtonian and power-law behaviors):

1. the solution obtained within the lubrification framework when addressing a laminate consisting of different layers of fluids with very different viscosities is definitively wrong;

2. when lubrification approaches fail the only valuable alternative consists of solving the fully 3D flow model. The efficient 3D solution is possible by applying the in-plane-out-of-plane separated representation.

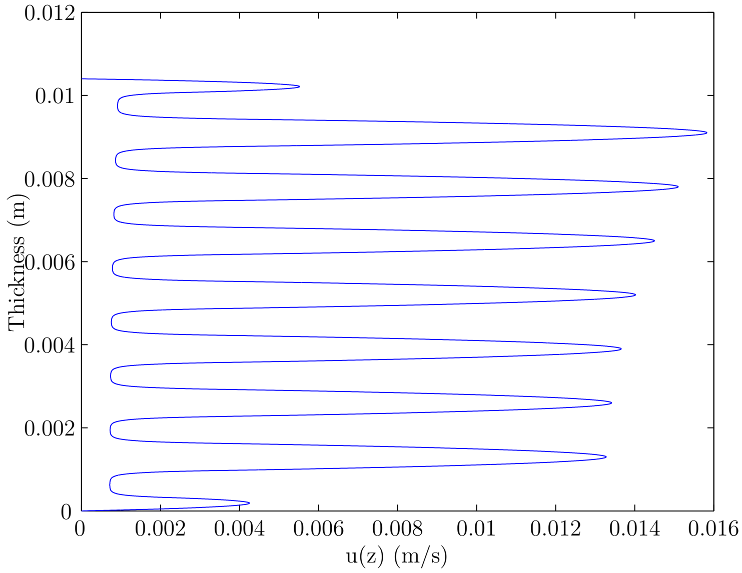


Figure 9: Velocity profile along the laminate thickness

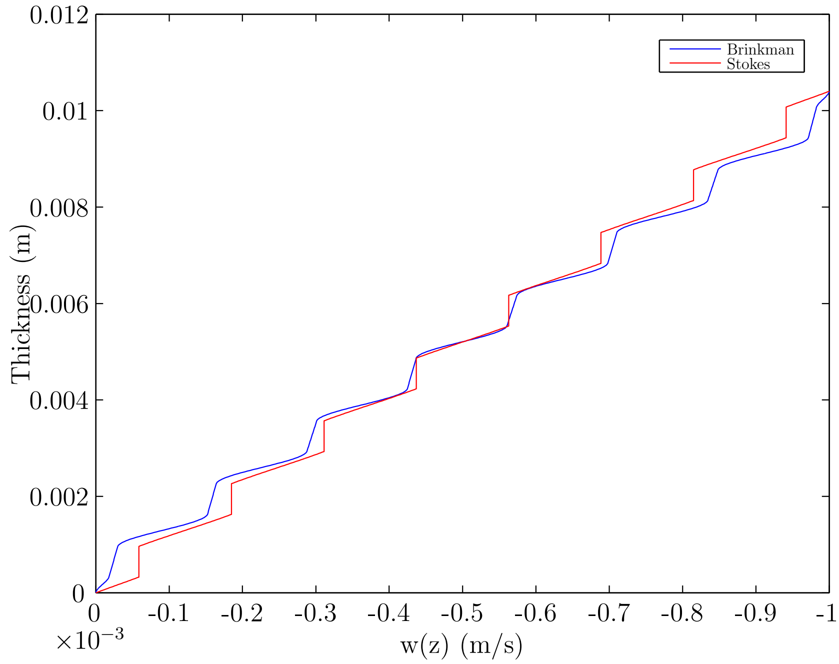


Figure 10: Out-of-plane velocity componet

Finally, the last section allowed considering finer descriptions based on a more realistic model of resin flow within the fibrous layers, consisting in the solution of the fully 3D Brinkman model that revealed a rich kinematics along the laminate thickness. This rich behavior requires a fine enough representation, that implies the necessity of using extremely fine discretizations in the thickness direction. This fact limits the applicability of standard 3D discretizations because the number of degrees of freedom increases too much, however when the solution is addressed by considering an in-plane-out-of-plane separated representation the fully 3D solution can be computed with a computational complexity characteristic of lubrfication models (2D).

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