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NUMERICAL MODEL FOR FLUID INFUSION DURING INFUSION-BASED PROCESSES

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SUMMARY: A complete model of infusion-based processes (RFI, LRI) has been developed by Celle et al. [1, 2] and implemented using PRO-FLOT® libraries. This model is based on an updated lagrangian formulation for the dry preforms, and very stable mixed bubble elements for the fluid and saturated preforms response. This numerical model has shown its ability to deal with the infusion mechanism, for RFI as well as for LRI processes. Comparison of the predictions of this model with corresponding experiments is under progress (see Wang et al. and Drapier et al. in FPCM-9). Beyond the predictive ability of this model, it permits to evaluate inaccessible variables and assess the representation of the processing conditions. For the first time, the resin pressure can be evaluated in RFI processes, since only a global mechanical approach gives access to the resin pressure resulting from the transient equilibrium between the mechanical pressure applied over the preforms and the resin pressure induced in the preforms and in the pure resin (film) area. Moreover, this model is also used to demonstrate the strong influence of the representation of the vents and resin feeding onto the filling times and pressure distributions.

KEYWORDS: infusion, Stokes, Darcy, Finite Element Method (FEM), composite materials, Resin Transfer Molding (RTM), Liquid Resin Infusion (LRI), Resin Film Infusion (RFI)

INTRODUCTION

Infusion-based processes for composites are very promising provided models can help in designing these processes with low development costs. Indeed, if the interest of using such dry route processes is accepted, process optimization is still based on trial and errors principles.

We have demonstrated recently [1,2] that only a global approach can give access to the relevant physical parameters that control the complex mechanisms implied in these processes. Especially, it is clear that regarding the complexity of the transient mechanical equilibriums which characterize LRI (Liquid Resin Infusion) processes, but still more notably RFI (Resin Film Infusion) processes, almost no simplification can be reasonably achieved.

Although the numerical framework is still subject to improvements, the work presented here intends to demonstrate on simple cases the major information that only a global mechanical approach gives access to. Solving for the transient mechanical equilibrium of the resin infiltrating preforms undergoing external pressure is the key in getting qualitative results such as filling times and filling distributions, depending on the process mechanical boundary conditions.

MODEL OF INFUSION IN PREFORMS UNDERGOING COMPACTION

Overall Infusion Model

The overall model for infusion-based processes has been developed in [3] for 3D phenomena of thermo-reactive fluid infusion in porous media undergoing finite strains, and published later in [1] in this general form. In this model, the preforms/resin stacking is split into 3 distinct zones standing for the pure fluid resin, the dry preforms modeled and the wet preforms, connected using moving boundaries. This model formulated under an ALE form to take into account the fluid flow in the mobile preforms has then been degenerated, for direct use, to iterative couplings where an updated lagrangian scheme is adopted for the preform porous medium equilibrium. Resin is modeled through a Stokes approach and the resin / porous medium coupling is taken into account *via* a Terzaghi's model of the resin in the preforms while the preform deformations measured with the transformation gradient will modify the local porosity and consequently the corresponding permeability. It is one of the feature of this model to measure this porosity which results from the preform mechanical equilibrium. This permeability is, at the moment, represented as a Carman-Kozeny material, but a dependence of the permeability upon density and saturation can easily be integrated when material data are made available [4, 5].

Besides these models, boundary conditions have been formulated to couple the 3 zones with the outside of the preform/resin stacking, but also inside the stacking, at the level of the moving interfaces [1,3]. So called Beaver-Schaffman-Joseph conditions have been modified and integrated between the pure resin region and the wet preforms.

Bubble Finite Elements for Darcy and Stokes

Eventually, in order to get a stabilized resolution of this multi-physics problem, and so that incompressibility can be enforced while resin volume can be precisely measured, mixed velocity-pressure finite elements have been implemented [2, 3]. These P1+/P1 and P1-bubble/P1 elements are based on an additional velocity degree of freedom, introduced at the centre of every element in the mesh, which permits to satisfy the Brezzi Babuska stability condition [6].

These elements were used both for preforms where a Darcy's flow prevails and for the pure resin zone where Stokes' flows occur. Using the same approach permits to simplify the coupling between the Stokes and Darcy zones and propose the same method to solve the flow in those two regions.

These developments were implemented in PRO-FLOT®, an Eulerian-based set of software libraries for composite manufacturing. The updated Lagrangian scheme along with the mixed FEs were completed with remeshing and field mapping capabilities using the GMSH freeware. At the moment, this model is used in its isothermal formulation in order to evaluate the accuracy of the predictions regarding the filling stage, compared with experimental validations (see Wang et al. and Drapier et al., FPCM-9).

INFUSION PROCESS MODELS

Using the numerical approach presented in [1, 2, 3] RFI and LRI processes were studied. In these models, the main difference between both processes comes from the location of the resin zone which is respectively placed on top of the preforms lay-up in LRI and then undergoes mechanical pressure from the vacuum bag (Fig. 1), while in RFI the neat resin is placed on the bottom of the stacking and then is submitted to a pressure resulting from the transient equilibrium of forces induced by the external pressure on top of the stacking (Fig. 2).

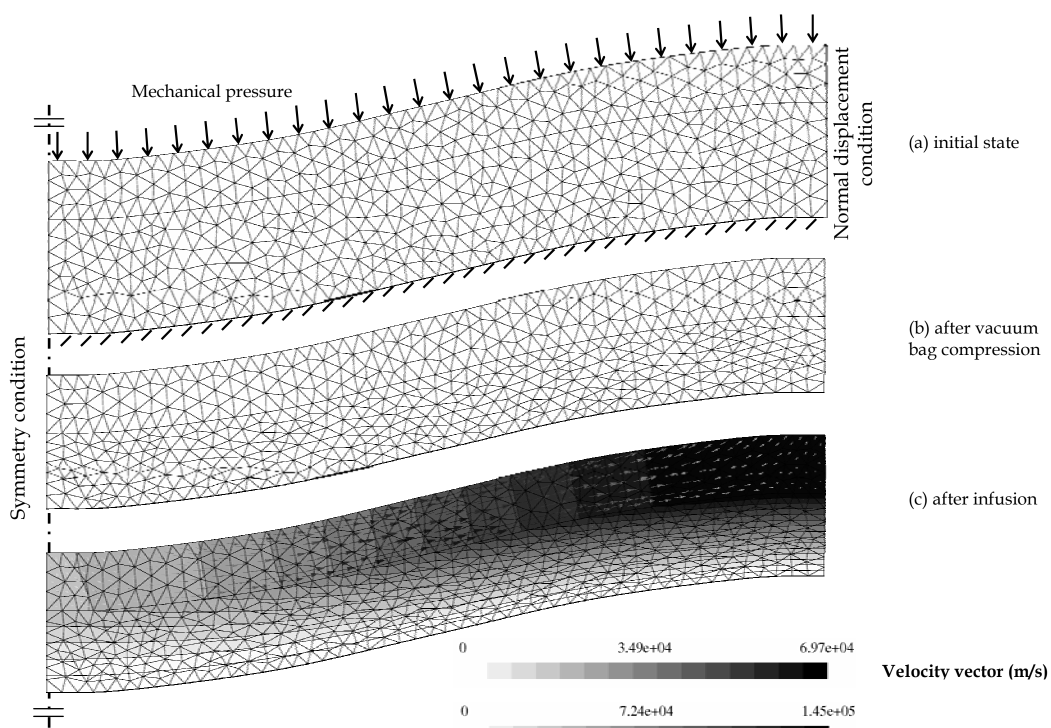

Fig. 1 Numerical simulation of LRI through the cross-section of a curved shell.

Running these simulations gives access to important data that one would like to evaluate in order to optimize the process parameters regarding both process requirements and the final properties targeted. For instance, pressure required to properly fill in the preforms and final dimensions of the piece elaborated can be computed (Fig. 1 and Fig. 2) since the global mechanical equilibrium is sought, resulting from the competition between preform compaction under mechanical loading and preform swelling due to resin infusion.

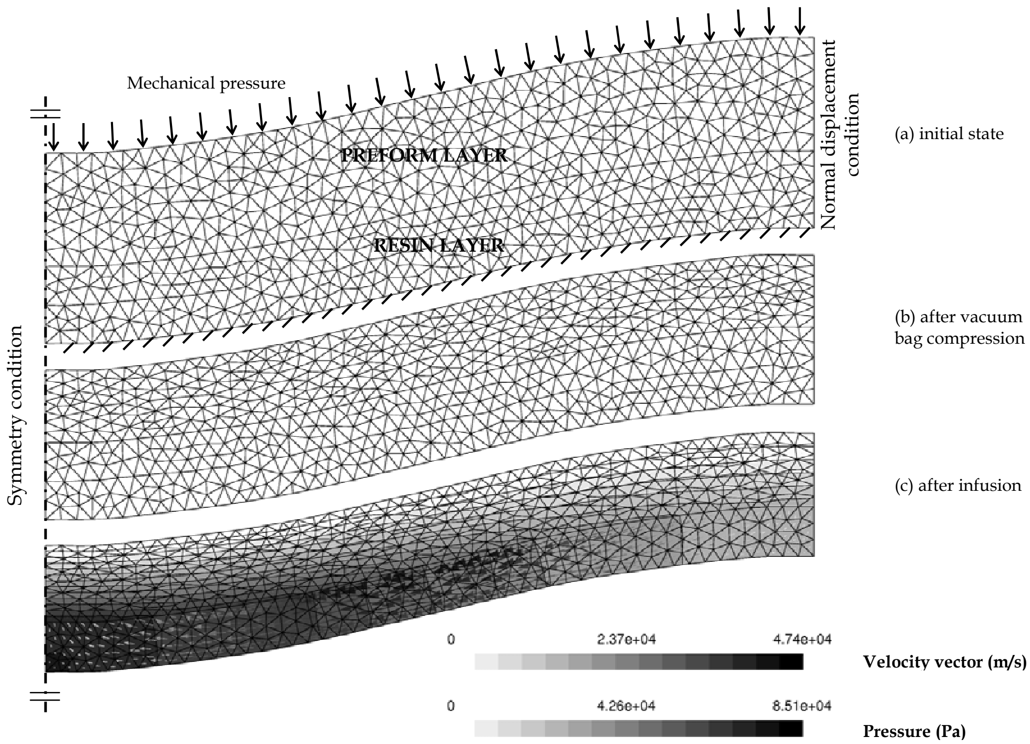

Fig. 2 Numerical simulation of RFI through the cross-section of a curved shell.

COMPARISON OF INFUSION PROCESS MODELS

Besides the lack of data upon certain material parameters such as permeability, realistic boundary conditions are missing even for standard processes. As a first illustration, the LRI process simulation under isothermal conditions has been carried out for NC2 materials $[0_6/90_6]$s using two boundary conditions for the resin at the interface between the dispersion medium (draining fabric), modeled as a purely fluid region, and the preforms (Fig. 3). The first boundary condition (Fig. 3a) corresponds to the external pressure prescribed on the vacuum bag, and represents the case where resin is placed in sufficient quantity prior to infusion. The second boundary condition type (Fig. 3b) is closer to processes, resin is fed in the stacking by pumping it from a heated pot and resin pressure results from the mechanical equilibrium solved. Obviously, these boundary conditions on the resin (velocity / pressure) are completed with mechanical boundary conditions on the preform (displacement / pressure).

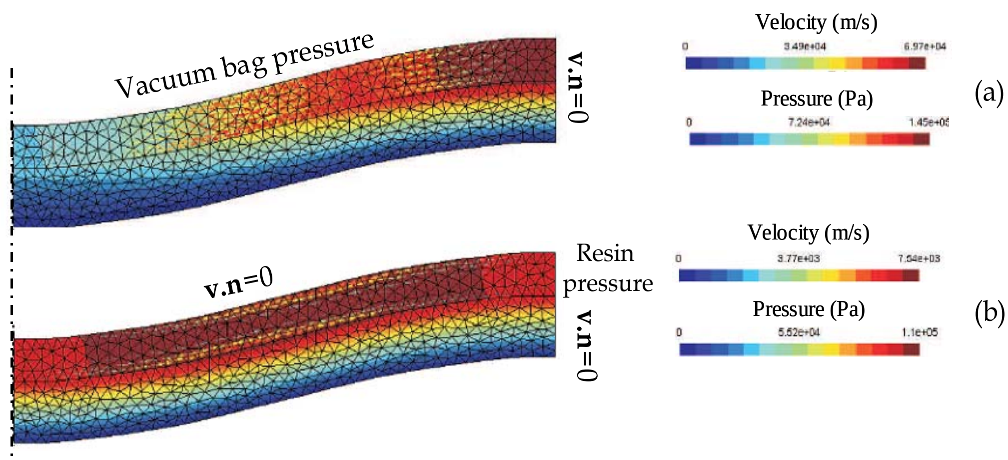

Fig. 3 Resin velocity and pressure in LRI through the cross-section of a curved shell: boundary condition at the fluid/preform interface (a) resin sucked in due to vacuum in the resin circuit; (b) resin placed in sufficient quantity prior to infusion.

Results of these simulations (Fig. 4) show that resin pressure and velocities are not distributed in the same manner for both boundary conditions. Resin tends to spread homogeneously over the preform when resin is fed in, while it concentrates on the upper region close to the impervious condition when resin is placed in the stacking prior to vacuum application. Regarding the resulting material parameters, porosities appear to change in the same manner for both types of boundary conditions while filling times differ. The heterogeneous resin velocity/pressure distribution in the draining fabric for the second boundary condition (Fig. 3a and Fig. 4a) implies that the curve zone of the part will be saturated later than with the second boundary condition (Fig. 3b and Fig. 4b).

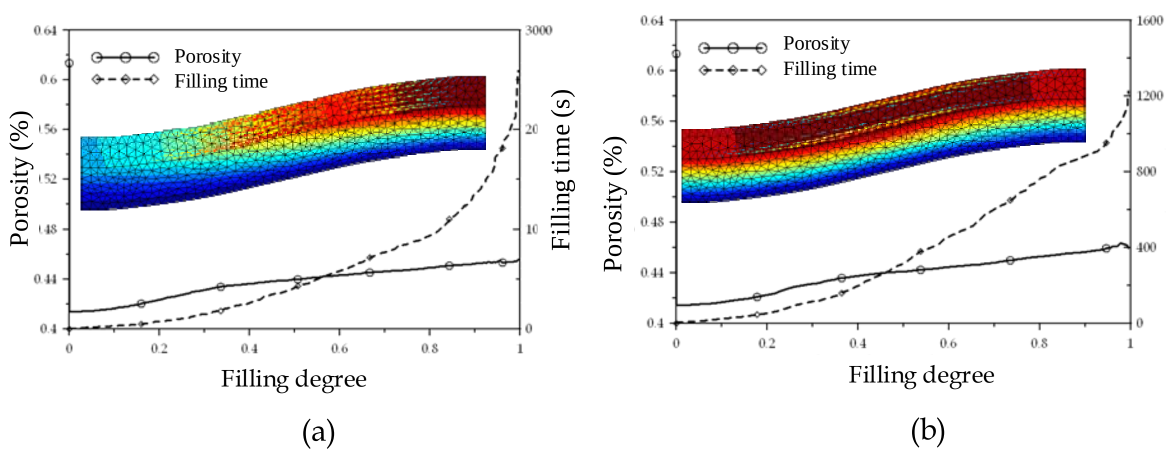

Fig. 4 Porosity and filling times in LRI for both boundary conditions.

The same type of boundary condition simplifications can be proposed for the RFI process. One can let the pressure at the interface between saturated preforms and resin area result naturally from the transient equilibrium solving, or simply consider that resin must equilibrate, on its own, the mechanical pressure applied on top of the preform-resin stacking. It can be verified in Fig. 5

that in RFI processes the resin pressure computed is not constant at all during the whole infusion process, and moreover is totally different from the external pressure applied onto the vacuum bag. Again, the resin pressure results from the transient equilibrium between the external mechanical pressure and the pressure loss induced by the progression of the resin into the preforms. The first drop of the resin pressure in Fig. 5 corresponds to the stacking compaction; it is followed by a continuous resin decrease. In RFI processes, the driving force is the mechanical pressure used to force the resin into the preforms. As the filling progresses, the pressure loss increases, and hence filling times increase in the same manner. This explains also why thick preforms may not be properly saturated.

RFI process simulations may not be achieved properly relying on the very coarse assumption that the resin area can be replaced by a resin pressure equal to the mechanical pressure applied on top of the stacking. This simplification leads to filling times which may be half of those for the complete resin-preform models, and most importantly overestimating the resin pressure may lead to evaluate the ability of thick stackings to be properly filled while they may not be saturated in reality.

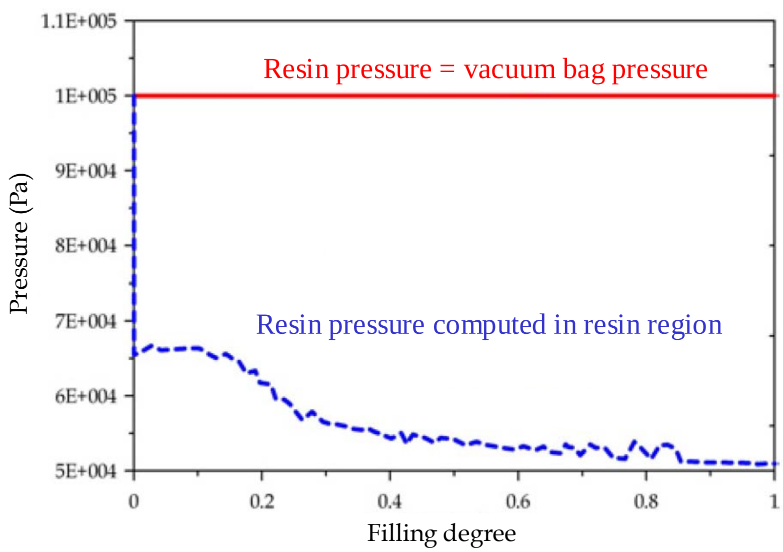

Fig. 5 Evolution of resin pressure in time during LRI for both types of boundary conditions: pressure applied by the vacuum bag and computed mean hydrostatic resin pressure.

REMARKS AND CONCLUSIONS

A general computational framework has been developed to simulate the infusion-based processes. It was used here to simulate the filling stage of LRI-and FRI-like processes and has permitted to show that boundary conditions are of the utmost importance in capturing the main physical parameters controlling isothermal infusion. Especially, besides permeability, resin pressure will control the filling time as well as the ability of the preform to be properly saturated. As presented in the papers of Wang et al. and Drapier et al. presented in FPCM-9, the simulation of LRI can be achieved with this model for simple parts. The calculated thickness as well as the mass content (hence porosity) correlate well experimental measurements. This is the very first step in validating the present numerical models.

As it can be noticed in velocity scales in Fig. 1 to 4, extremely high velocities, some peaks, appear at the interfaces. In fact, one faces high gradients in some properties such as permeability, and specific numerical methods must be implemented to manage this. Also, filling times are not satisfactory at the moment, compared to experiments; they tend to be mesh-dependent. Obviously, filling times depend also on resin viscosity, which is constant for the moment. Consequently, non-isothermal simulations must be realized in the future for full validation.

More generally, such a numerical framework will give an insight into the mechanisms implied in this complex process of infusion, and may be extended to predict residual stresses and distortions or void formation-transport. Eventually, permeability is still a key issue for the simulation of these processes, and numerical models can be ideally coupled with permeability measurements to provide an embedded approach of transient as well as stationary permeability.

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