A NEW FORMULATION FOR THE INFUSION OF A THERMO-REACTIVE RESIN INTO A COMPOSITE DEFORMABLE MEDIUM

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ABSTRACT: Dry manufacturing composite processes consist in mixing reinforcements and resin during the final manufacturing stage, thus reducing storage and manufacturing cost. When furthermore, resin flow takes place in the through-thickness direction (infusion), it is possible to improve the quality of the final part and reduce tooling costs. However infusion processes are not fully predictable, mainly thickness and porosity are not straight to estimate. A numerical predictive model would be a proper candidate to help in developing and finalizing new composite solutions. In the present paper a complete model for the study of resin flow inside and outside a deformable porous medium is presented. This multi-physical model deals with mainly two types of problems. First, the interaction phenomena between the resin flow in a highly compressible preform, and second the coupling condition between this wet preform area and a purely fluid region.

KEYWORDS: infusion – Stokes – Darcy – FEM: Finite Element Method – composites materials – ALE Formulation – resin flow – LRI: Liquid Resin Infusion – RFI: Resin Film Infusion

INTRODUCTION

Resin Film Infusion (Figure 1-a) and Liquid Resin Infusion (Figure 1-b) consists in the infusion of a thermo-reactive resin in the preform transverse direction. Here, the RFI process is studied since its modeling leads to more exhaustive models than the LRI process. In this process, a dry fibrous preform is placed above a resin film. This assembly is enclosed in a vacuum bag, and a temperature cycle prescribed by an autoclave decreases the film resin viscosity until it becomes liquid. Then, vacuum induces a reaction pressure which leads to the impregnation of the preform by the resin in the transverse direction.

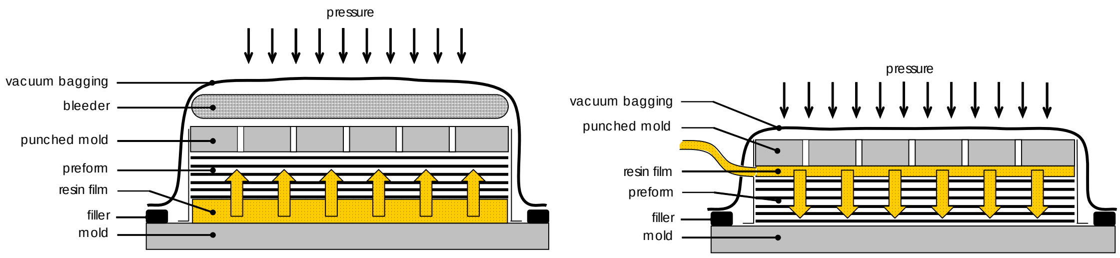

Fig. 1 Composite manufacturing processes by infusion – RFI (a) – LRI (b)

Infusion normal to the preform plane gives two advantages. First, time cycles are shorter due to the reduced distance resin has to travel. Second, the quality of impregnation is better when infusion of resin and its cure are dissociated. However, the thickness and the porosity of the finished part are not easily predictable. Currently in the literature there is no complete model able to describe the whole process due to complex mechanisms interacting. Here we propose a model able to describe the interaction phenomena between the porous medium and the fluid part, *i.e.* the flow in a deformable medium and conversely the modified mechanical response of the wet solid. This model is completed by a new boundary condition between the porous part and the purely fluid region.

THE PROPOSED MODEL

The following notation are used: a superscript is used to refer to the considered area (wet or dry preform f, resin r). An index is related to the component (fiber f, resin r or virtual domain d introduced to deal with ALE formulation). We write down x the material coordinates, X the initial coordinates, χ the reference coordinates used to tackle the ALE formulation.

The selected model

From industrial point of view, a macroscopical approach must be considered. This approach yields to reasonable computation times for such a heterogeneous structure. The proposed model relies on a homogenous representation of 3 regions connected with moving boundaries (see Figure 2): dry preform, wet preform and purely fluid region.

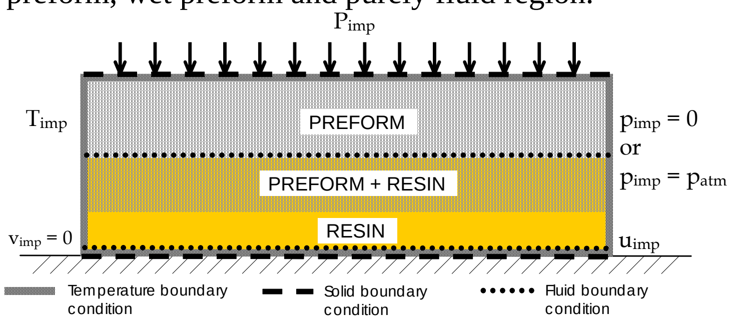

Fig. 2 Composite manufacturing processes by infusion – RFI (a) – LRI (b)

Macroscopical models for every component in each area are used to take into account the interactions between the components directly in mass balance and momentum conservation equations.

Modeling of the fluid flow

In this process, the resin flow is laminar (low Reynolds numbers). This resin behaves as a Newtonian incompressible fluid. Hence, inertial forces are negligible compared to viscous forces. The two areas concerned by the resin flow (wet preform and purely fluid region) undergo large rotations and deformations during the flow which prevent the model from using an Eulerian formulation to deal with the fluid flow.

ALE Formulation

The Aribitrary Lagrangian Eulerian formulation is an excellent way to study moving boundary problems for fluid flow. The formulation combines the best aspects of Lagrangian and Eulerian schemes, by introducing a reference domain where computations are performed. Hence, this formulation allows to study flows in a deformable area since this reference domain (coordinate χ) is attached to the mobile domain where fluid flow occurs. Moreover, this formulation permits to represent any change of properties (mechanical, compaction …) of the mobile domain and its consequence on the fluid flow. From a computational point of view, the quasi-Eulerian formulation is often used as the Cauchy stress tensor is employed instead of the First Piola Kirchhoff tensor. This formulation gives a new expression for the material derivative of any function f which has to be used in Eulerian conservations equations [2]:

$$\frac{Df\left(\vec{\chi},t\right)}{Dt} = \left.\frac{\partial f\left(\vec{\chi},t\right)}{\partial t}\right|_{\vec{\chi}} + \vec{c}\left(\vec{x},t\right)\cdot\vec{\nabla}_x f\left(\vec{x},t\right) \tag{1}$$

where $\vec{c}\left(\vec{x},t\right)$ is the convective velocity, *i.e.* the relative velocity between the resin particle $\vec{v}_r\left(\vec{x},t\right)$ and the velocity of the corresponding virtual domain $\vec{v}_d\left(\vec{x},t\right)$.

Flow in the wet preform

The capillary effects between fibers and resin can be neglected since it is reckoned that applied external pressure overrides surface tension effects. A macroscopical Darcy law is used to take into account the fluid flow in the compressible preform. In this law, inertial terms and volumic forces are neglected. This macroscopical model introduces the permeability tensor $\overline{\overline{K}}$ which has to be determined precisely in order to provide accurate results for the flow [4]. Recently, many studies have been conducted to accurately measure the permeability tensor [6]. The Darcy law is reliable as soon as the permeability remains low. The Darcy's equation [5] (mass balance and momentum conservation) expressed in terms of ALE formulation writes:

$$\begin{aligned} &\phi\, s\left(\vec{v}_r^{\,f} - \vec{v}_d^{\,f}\right) = -\frac{\overline{\overline{K}}}{\eta}\cdot\vec{\nabla}_x\, p_r^f \\ &\frac{\partial\rho_r^f\left(\vec{\chi},t\right)}{\partial t} + \vec{c}_r^{\,f}\cdot\vec{\nabla}_x\,\rho_r^f + \rho_r^f\, div_x\,\vec{v}_r^{\,f} = 0 \end{aligned} \tag{2}$$

where ϕ is the porosity, s is the saturation ratio, η is the resin kinematics viscosity, $\vec{\nabla}_x$ is the gradient operator with respect to x, p_r^f is the resin pore pressure and ρ_r^f is the resin density in the wet preform area and $\vec{c}_r^{\,f} = \vec{c}_r^{\,f} - \vec{c}_f^{\,f}$.

Flow in the purely fluid area

As well as in the wet preform, inertial effects are neglected. In this purely fluid region, Stokes equations are used to predict fluid flow. Expressed in terms of ALE formulation the Stokes equations can be written as follows:

$$\begin{aligned} &\rho_r^r\, \vec{c}_r^{\,r} \cdot \overline{\overline{grad}}_x\, \vec{v}_r^{\,r} = -\overrightarrow{grad}_x\, p_r^r + \eta\, \vec{\Delta}\, \vec{v}_r^{\,r} \\ &\left.\frac{\partial \rho_r^r\left(\vec{\chi},t\right)}{\partial t}\right|_{\vec{\chi}} + \vec{c}_r^{\,r} \cdot \overrightarrow{grad}_x\, \rho_r^r + \rho_r^r\, div_x\, \vec{v}_r^{\,r} = 0 \end{aligned} \tag{3}$$

Here the convective velocity $\vec{c}_r^{\,r}$ is the difference between the resin velocity $\vec{v}_r^{\,r}$ and the domain velocity $\vec{v}_d^{\,r}$, which has to be defined for instance with an elastic law.

Saturation

Two types of approaches are commonly used in the literature to deal with change in saturation. The transient approach gives a further relation between the resin pressure and the saturation. But the lack of information concerning this relation leads to the slug flow approach. This hypothesis yields a direct binary relationship between the resin pressure and the saturation:

$$s\left(\vec{x},t\right)=1 \quad for \quad p\left(\vec{x},t\right)\neq 0 \quad et \quad s\left(\vec{x},t\right)=0 \quad for \quad p\left(\vec{x},t\right)=0 \tag{4}$$

Modeling of the preform compressibility

The main feature of the provided model is related with the compressibility of the preform during the resin infusion [7]. These deformations result from the transient equilibrium between the loadings applied on the part by the vacuum bag and the pressure induced by the viscous liquid contained in the compressed saturated fabrics. A material formulation such as a Total or an Updated Lagrangian Formulation is suitable for this type of behavior.

Mass balance

Mass balance of the preform allows following the preform density evolution. This equation relates mass at times t and $t+\Delta t$ via the density and the Jacobian of transformation J [5]. Here the preforms are assumed to be deformable but composed of incompressible fibers.

$$J\left(\vec{x},t+\Delta t\right)\left(1-\phi\left(\vec{x},t+\Delta t\right)\right)= J\left(\vec{x},t\right)\left(1-\phi\left(\vec{x},t\right)\right) \tag{5}$$

Momentum equation

The preform compressibility experimental data for saturated and unsaturated flows has been studied for very particular boundary conditions and specific fiber networks [8]. In this approach, for a general use, we choose to formulate the behavior of the preform by a Terzaghy's constitutive law. In this constitutive law, the effective stiffness of the preform $\overline{\overline{\sigma}}_{ef}^{\,f}$ is completed by the action of the resin pressure inside the porous medium's pores ($s\ p_r^f$). This approach gives a continuous model for the wet and dry preform *i.e.* there is a direct continuity of stresses on the flow front:

$$\overrightarrow{div}_x\, \overline{\overline{\sigma}}_f^{\,f}\left(\vec{X},t\right)=\vec{0} \quad \text{where} \quad \begin{cases} \overline{\overline{\sigma}}_f^{\,f} = \overline{\overline{\sigma}}_{ef}^{\,f} - s\ p_r^f\, \overline{\overline{I}} & \text{for wet preform} \\ \overline{\overline{\sigma}}_f^{\,f} = \overline{\overline{\sigma}}_{ef}^{\,f} & \text{for dry preform} \end{cases} \tag{6}$$

Boundary Conditions

Figure 3 summarizes both boundary conditions and interaction conditions between the two types of components (resin and preform) in the three area studied for the modeling of the RFI process. The interaction conditions are settled at the material scale between the wet preform and the resin in this wet preform. At the structural scale, the boundary conditions put together conditions imposed by the process itself and conditions prescribed on the interface to ensure the stress vector continuity.

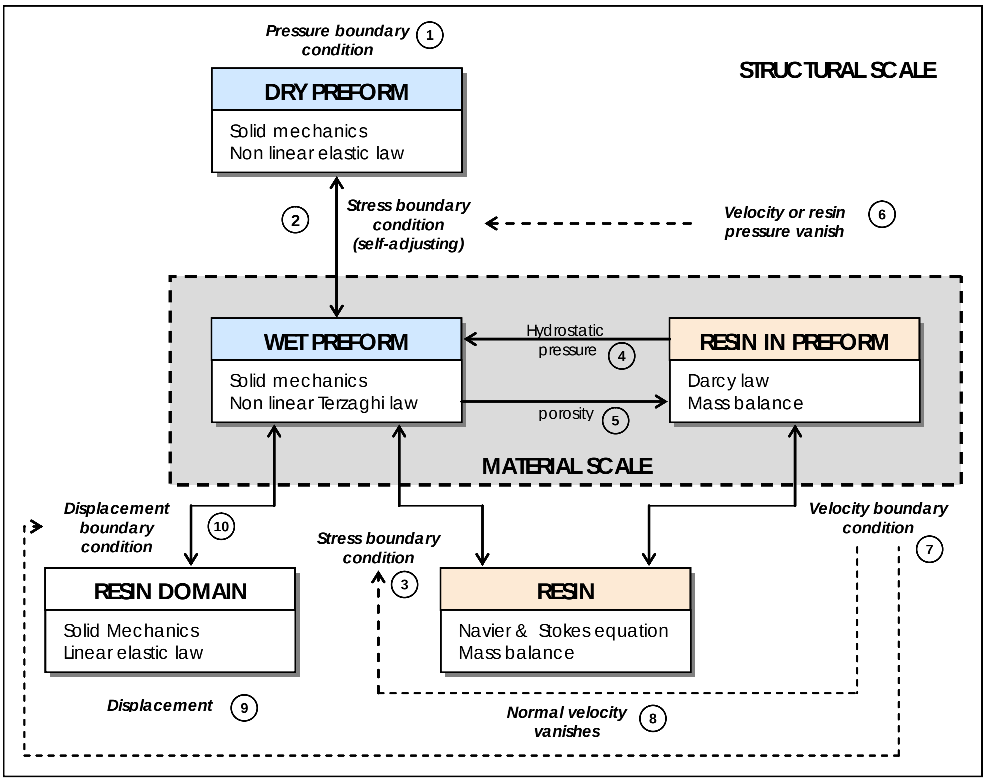

Fig. 3 Boundary conditions at structural scale and interaction at material scale

Thermo-chemical modeling

In this approach, unlike the mechanical modeling, three homogeneous domains are considered since resin flow is slow, *i.e.* fiber and resin temperature are very closed at a same spatial point. Two types of equations govern the thermo-physico-chemical phenomena. Heat transfer equation expresses the conservation of energy [3]:

$$\rho\, c\, \frac{DT}{Dt} = \overline{\overline{\sigma}} : \overline{\overline{D}} + div\left(\overline{\overline{\lambda}} \cdot \overrightarrow{grad}\, T\right) + \Delta H\, \frac{D\alpha}{Dt} \tag{5}$$

where c is the specific capacity, $\overline{\overline{\lambda}}$ is the thermal conductivity tensor, ΔH is the heat of reaction and α the curing degree.

The curing equation expresses the transport of the curing resin mass α.

$$\frac{D\alpha}{Dt} = \frac{D\alpha}{Dt} + \vec{v} \cdot \vec{\nabla}\alpha \tag{5}$$

There are many models in the literature for the material derivative $\frac{D\alpha}{Dt}$. These models are commonly constructed by coupling Arrhenius laws with power laws.

Review

Figure 4 summarizes the interactions between the behavior of the resin and preform in the wet preform. The bold boxes contain independent variables. Each variable is connected with conservation equations and physical laws.

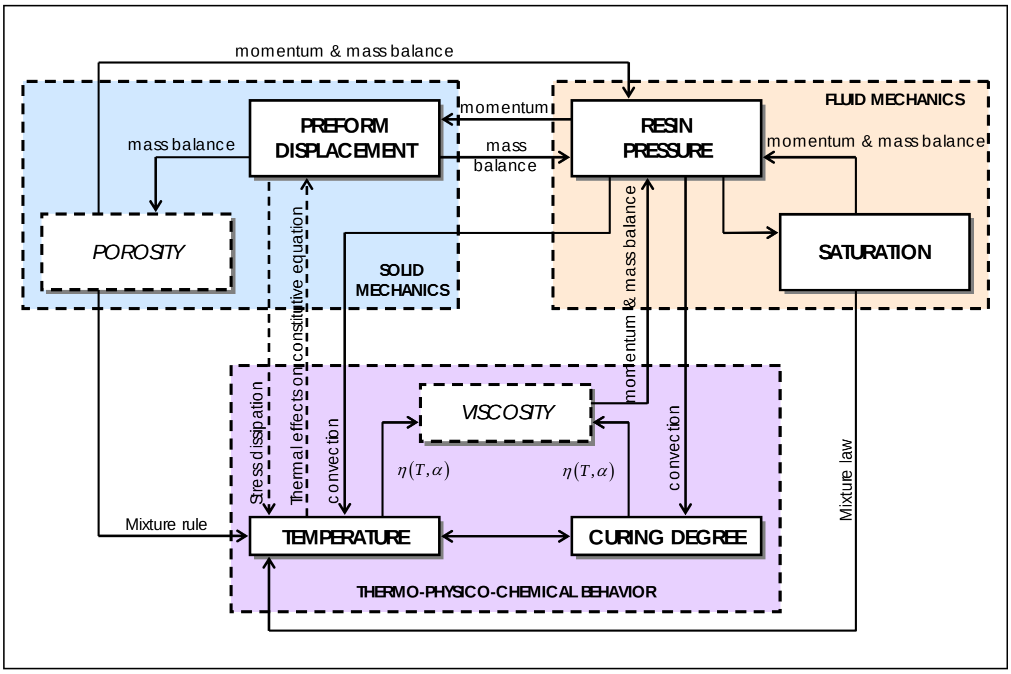

Fig. 4 Coupling between thermo-chemical, fluid and solid mechanical behavior

RESULTS

Mechanical interactions between the fluid and the solid part have been introduced in PAM RTM©. Here two types of numerical results are presented. The first one concerns the interactions phenomena in the wet preform. The purely fluid region is not taken into account, flow rate boundary conditions are used to feed in the preform. This modeling is suitable for a SCRIMP© like process. The second chosen example is a modeling of RFI process, the purely fluid region is introduced in the model.

Flow in a highly deformable media

This first result has been obtained with an exaggerated flow rate for a complex T-shape piece with permeability orientations. This exaggerated flow rate is prescribed in order to observe the porous medium deformations due to the internal pressure applied by the fluid inside the pores (Terzaghi hypothesis). The vacuum bag applies a mechanical pressure as presented in Figure 5-c. The proposed algorithm (Figure 5-a) uses an iterative scheme with a coupling between implicit Darcy and mechanical calculations until the filling of the part is complete (time explicit). Figure 5-c depicts the mesh of the T-shape piece with permeability orientations of the stacking. The core, *i.e.* the solid part without permeability orientations, is 10 times more permeable than the preform in the transverse direction. Figure 5-b shows the internal resin pressure obtained on the deformed configuration. The results obtained with this algorithm have been compared successfully on a simplest geometry with analytical results.

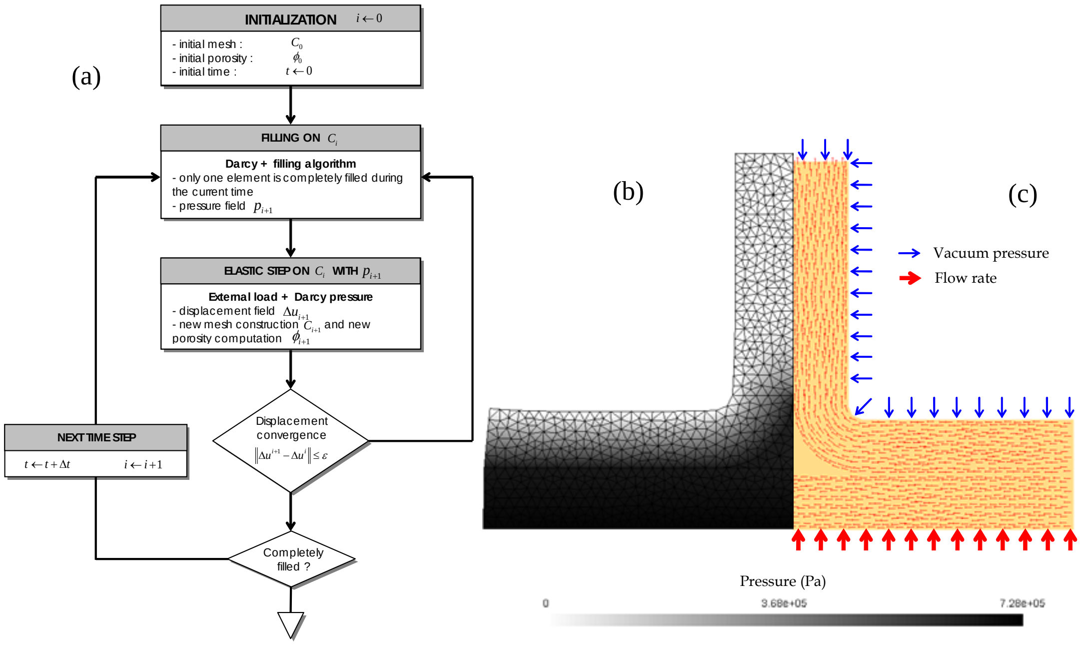

Fig. 5 Infusion of a T: (a) algorithm used - (b) pressure distribution (Pa) on the deformed configuration - (c) permeability orientation for the underformed configuration

Interaction between Darcy and Stokes Area

This second example adds the purely fluid domain in the previous algorithm.

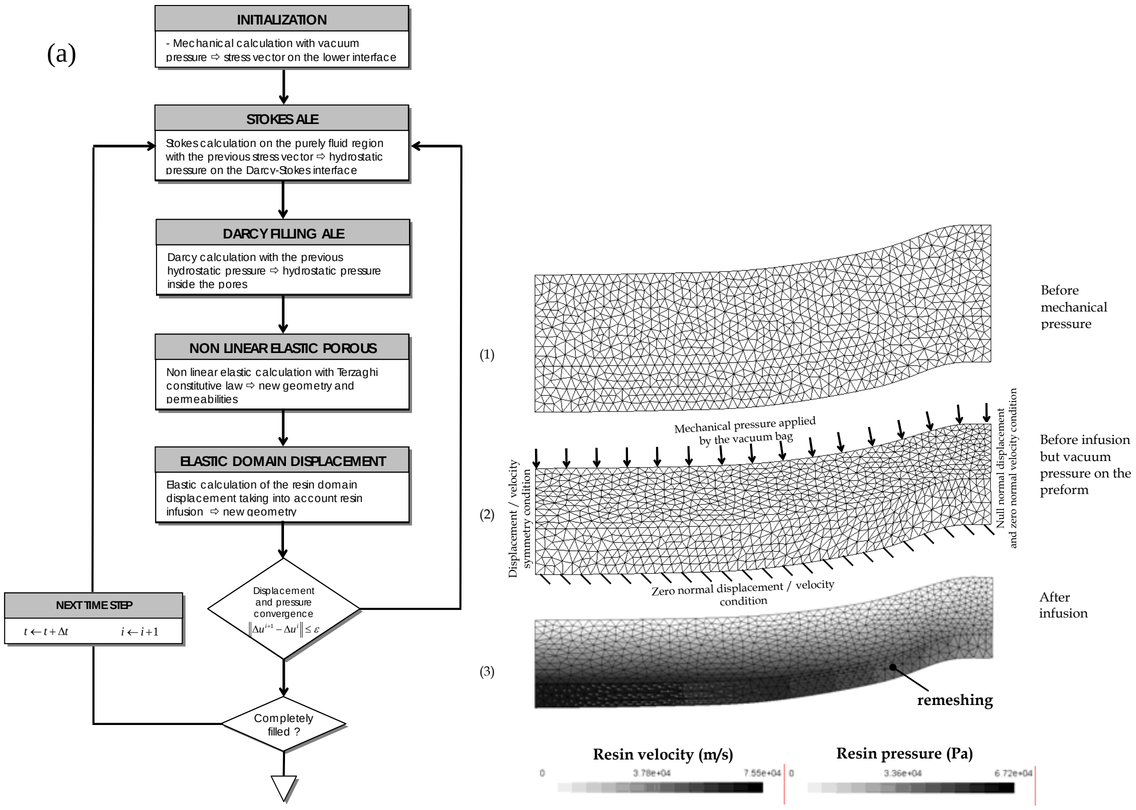

Fig. 6 Resin Film Infusion (RFI) of a curved panel – (a) proposed algorithm – (b) results at initial time (1), compression time (2), final stage (3)

A modified Beaver-Joseph-Saffman condition has been used to couple the Darcy and Stokes areas. This condition has been completed with a continuity of hydrostatic pressure on the interface. The proposed algorithm consists in a filling iterative scheme made of four implicit problems: fluid and solid mechanics in the porous area and fluid and domain displacement in the purely fluid region. This iteration loop is based upon a pressure, displacement and velocity criterion convergence. The Darcy and Stokes problems use an ALE formulation in order to observe an accurate mass balance. In the present results (see Figure 6-a,b,c) finite strains of the preform can be observed. Moreover, border and curvature effects give a non-constant pressure field that would be constant for a plane plate. The velocity pressure formulation for the Stokes problems and Darcy problems has been solved here by the Bubble Element formulation [1].

CONCLUSIONS

In this paper, a new model conceived to simulate non-isothermal resin infusion in a highly compressible preform was presented. This model can be applied in a large range of activities for all industrial processes involving infiltration in deformable porous media. Currently, experimental validations of the proposed RFI model have been carried out with Hexcel Reinforcement to provide a reliable tool. It is important to underline here that the lack of information and experimental data is the major drawback met for industrial use, mainly for the permeability measurement in the transverse direction in saturated and unsaturated regimes.

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