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Numerical modelling of liquid infusion into fibrous media undergoing compaction

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Abstract

In the present paper, an overall model for the study of a non isothermal fluid flow across a highly compressible porous medium is proposed, in order to be included into a finite element software. This model can be applied to a wide range of activities, and as an application it is used here to model dry route composite manufacturing processes. Indeed, it is to be noted that the spreading of these promising processes fails due to the absence of a numerical model able to capture the resin infusion across the compressed preform thickness. The main difficulty being that this infusion results from a pressure prescribed over the deformable preform/resin stacking involved. From the modelling point of view, problems of this multi-physical analysis are two fold. First the coupling of liquid regions, ruled by Stokes equations, with the fibrous

preform regions governed by a Darcy's law, yield badly posed boundary conditions. Second, the interaction phenomena due to the resin flow in the highly compressible preform are not classical. The model developed here includes a modified Beaver-Shaffman-Joseph condition to couple Stokes and Darcy zones, and is based on an ALE formulation of the liquid flow across the deformable porous medium in which finite strains are accounted for with an updated Lagrangian scheme. These mechanical models are also coupled with thermo-chemical models, accounting for resin reticulation under the temperature cycle prescribed by the processing equipment.

Key words: infusion – Stokes – Darcy – ALE formulation – finite element – RFI: Resin Film Infusion – LRI: Liquid resin infusion – computational modelling – finite strains

1 Introduction

Studies of non isothermal fluid flow through a porous medium undergoing finite strains have become more and more demanded over the past few years to understand and predict wet porous media behaviour (*see* for instance Thimus et al. (1998) and following editions). In a large body of literature, experimental studies have been achieved in order to understand more precisely the interaction between the fluid flow, and the deformation of the wet porous media. From there, some empirical models have been drawn. However, these models are limited to specific fluid and porous material, and specific boundary conditions and regimes, usually depending on the field of application in scope. Intrinsically, from the macro/mesoscopical empirical approaches, the physical properties of the components during the flow and the interaction between the fluid and the structure cannot be studied precisely.

On the contrary, some numerical tools have been developed specifically for fluid/porous media interaction to predict liquid flows (Schrefler and Scotta (2001), Advani and Bruschke (1994), . . .). However, the porous medium de-

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formations are still poorly understood and represented while it is the key to understand many physical phenomena. As an illustration, dry composite manufacturing processes by infusion, *i.e.* involving mainly the direction normal to the fabric plane (Figure 1), will be considered to highlight the capability of the present model to represent the interaction between a fluid flow and porous medium compressibility. This numerical model is a part of a more exhaustive approach focusing on infusion-based processes.

More precisely, in these LRI (Liquid Resin Infusion) and RFI (Resin Film Infusion) processes, the fluid flow (liquid resin infusion) is induced across the compressed preform thickness, as a result of a pressure prescribed over the preform/resin stacking (Figure 1). This mixing of reinforcements and resin during the manufacturing stage leads to cost reductions while avoiding potential filling problems, but turns out to raise major difficulties in controlling the final part characteristics (geometry and physical properties) which result from the interaction between the porous medium mechanical response and the resulting fluid flow. This is the key to understand, and hence control, these cheap and simple-to-use but complex-to-understand processes. However, as stated previously, no satisfactory model exists and only a global predictive model would be a proper candidate to help in developing and finalizing new composite solutions.

[Figure 1 about here]

Establishing such a complete model of deformation/infusion implies solving three types of difficulties. First, one has to account both for the fluid flow into the deforming porous medium and conversely for the flow modifying the mechanical response of the wet solid. Second, the boundary conditions between the wet porous area and the liquid outside the solid component are not clearly established. Last, current methods to deal with fluid front tracking have shown some mass conservation problems which are not acceptable in the present

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approach where the amount of resin transferred into the preform must be accurately described to couple fluid mechanics with poro-elasticity.

1.1 Fluid / porous medium interaction

In most infusion processes, the pressure distribution of the fluid (resin) in the solid porous material (fibrous preform) is controlled by the permeability which depends both on solid phase porosity (Park and Kang (2003)) and fluid saturation (Acheson et al. (2004)). If the saturation can be related to some physical-chemical interactions, the porosity of the solid phase depends on the latter's mechanical response, *i.e.* is a function of its deformation. In our dry manufacturing processes these deformations of the preform during infusion results from the transient equilibrium between both pressure loading applied on the part itself, and pressure prescribed by the viscous liquid contained in the compressed saturated fabrics (Gutowski et al. (1987), Drapier et al. (2002), ...). However, viscous liquid infusion simulations are usually performed without taking into account the deformations.

Several approaches have been proposed to improve these models. Preziosi et al. (1996) and Ambrosi et al. (2002) dealt with the problem of injection in an elastic porous preform for one-dimensional problems thanks to a modified momentum balance equation for the fluid and the solid phase. Other studies postulate for the wet preform behavior a Terzaghi's response, where the liquid contribution is introduced through its hydrostatic pressure, and an experimental law is used for the fiber compaction (Park and Kang (2003)). More recently Joubaud et al. (2002) studied numerically the effect, on the stress distribution, of the bag compression after the filling of the preform for SCRIMP$^{©}$ processes. However, in these studies conservation equations are not clearly established except for one dimensional problems. A more systematic way should be employed to establish these modified (coupling) equations and couple them together.

Eventually, another important issue appears when the flow is considered also outside the porous medium. Then further conditions must be established to relate the liquid behavior inside and outside the porous media.

1.2 Interaction between fluid flow in the porous medium and purely fluid regions

For the fluid, the interface problem between the porous saturated medium and the fluid medium has not been studied in the literature dedicated to composite materials. This complex condition has been simplified by prescribing constant pressure or velocity at the porous medium / fluid boundary (Park and Kang (2003)). For soil behaviors, on the contrary, literature gives an overview of conditions which can be applied to ensure continuities on the porous medium/fluid interface, namely the Beaver-Joseph-Shaffman conditions (Rivière and Yotov (2005), Layton et al. (2003)). However, these soil mechanics studies deal with non deformable media. These boundary conditions do not take into account the mechanical action of the solid area onto the fluid behavior in the purely fluid area.

1.3 Flow front tracking and mass balance inaccuracies

For composite manufacturing simulations, the fluid front tracking remains an important issue, even for injection phenomena without deformations, since the quantity of resin required for filling is a major information for end-users. The Finite Element / Control Volume method (FE/CV) has been widely used for fluid front tracking during infusion or injection (Lim and Lee (2000), Advani and Bruschke (1994)). However, these techniques raise problems related to the mass-balance on the flow front (Joshi et al. (2000)). The non-structured finite element method introduced by Trochu et al. (1997) avoid the further meshing

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of FE/CV with Voronoï cells in counterpart of a discontinuous pressure field but a better mass balance. These methods require some mesh refinement for proper flow front locations. Some papers present other methods to improve the accuracy of FE/CV method such as flow refinement (Kang and Lee (1999)), improvement of mass balance (Joshi et al. (2000)), or implicit integration (Lin et al. (1998)), but a numerical improvement is still to be performed.

1.4 Proposed solution

In the present paper, a fully coupled model is set, in a general framework, for the simulation of non-isothermal infusion processes. Globally, to model this family of infusion mechanisms, two types of problems must be tackled. The first problem is a thermo-physico-chemical one which involves the coupling between heat transfer and resin curing, but which can be solved in a rather straight manner (*see* § 2.3 below). The second problem, the very heart of our approach, is mechanical and it requires to characterize simultaneously both resin flow, inside and outside the preform, and fibers network compression during the resin infusion.

The proposed solution has been constructed by taking into account the inter-actions between all the solid and fluid components directly in mass balance and momentum conservation equations, as in the method proposed by Schre-fler and Scotta (2001) for non-moving media but with two-gas flows. Here, to develop these new equations, an ALE formulation is introduced to handle the action of the fibrous medium response onto the fluid flow, and a Terzaghi's law is used to take into account the fluid pressure onto the preform mechanical response. This study also deals with the coupling condition between the pure resin region and wet preforms. Complementary, mass transfers between these 2 regions must be carefully controlled. This is of prime importance for a global model of infusion processes. Therefore, a mixed formulation between velocity

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and pressure fields leading to accurate mass balance is used to study the fluid flow both inside the pure resin region and the porous medium (wet preforms).

2   Modelling infusion processes

2.1   The selected model

Here, the modeling of the RFI process is studied since LRI processes can be seen as a derivation of the latter. To model the various phenomena encountered, one first has to select the relevant scale of observation. If a local approach is chosen, a very fine description can be proposed. But local data are quite tricky to assess and a geometrical description of the (fiber) network must be realized, inducing very costly computations (Bechtold and Ye (2003)). In turn, one can try to represent, for instance, the void formation during infusion (Lim et al. (1999)). However, from an industrial point of view, macroscopical approaches are more easily considered, yielding reasonable computation times. The drawback of such approaches is to rely on macroscopical properties which may be hard to assess, since they depend on local properties, and quite often represented through semi-empirical laws.

A macroscopical approach is hence chosen, even if some material parameters, such as the preform permeabilities (Breard et al. (1999), Drapier et al. (2002), ...), are on their own complex to acquire. Then, simulation of the infusion processes will rely on a representation of the resin/preform stacking through 3 homogeneous regions, each standing for the dry preforms, the wet preform, and the resin, as depicted in Figure 2. These three domains are connected with moving boundaries through specific conditions described subsequently.

[Figure 2 about here]

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2.2 Mechanical modelling

The fibers network compressibility during the resin flow is controlled by both resin pore pressure and mechanical external pressures. The rsult is that the liquid and porous media will be described by different models depending whether resin and preform stand alone, respectively in the fiber-free domain and dry preform domain, or are mixed in the wet preform area (*see* Figure 2). The second difficulty of the present approach concerns the proper selection of boundary conditions on moving interfaces. In order to provide a systematic model, the mechanical behavior of both fluid and preform media is described directly through mass-balance (continuity equation), and momentum equations.

2.2.1 Resin flow

2.2.1.1 ALE formulation for fluid flow in a mobile domain   The Arbitrary Lagrangian Eulerian Approach (ALE) is an excellent way to study flows in deformable moving domains (Rabier and Medale (2003)). This enriched formulation requires a virtual intermediary mobile domain, called subsequently reference domain $\hat{\Omega}$, where computations are performed and which must undergo topological variations to account for the real material domain changes such as mechanical and physical properties changes (Belytschko et al. (2000)). In our case an ALE formulation allows a precise flow front tracking while fluid sources can be represented.

There are mainly two problems with this ALE formulation. First, implementation difficulties arise in the momentum balance equation because it is expressed in terms of a non symmetrical stress tensor. Second, constitutive laws for fluid behaviour (Newtonian incompressible fluid) are known in terms of Cauchy stress tensor ($\boldsymbol{\sigma}$). Classically:

$$\boldsymbol{\sigma}\left(\mathbf{x}, t\right) = 2\,\eta\,\mathbf{D}\left(\mathbf{x}, t\right) - p\left(\mathbf{x}, t\right)\,\mathbf{I} \tag{1}$$

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with η the fluid dynamic viscosity, $\mathbf{D}(\mathbf{x}, t)$ the strain rate tensor, $p(\mathbf{x}, t)$ the hydrostatic pressure, $\mathbf{x}$ is the current position in the material frame Ω and $\mathbf{I}$ the second-order identity tensor.

Therefore, for the sake of simplicity, the momentum balance equation should be expressed in the material configuration Ω with the corresponding material derivative. However, this Eulerian formulation must be modified to yield an appropriate ALE formulation, *i.e.* include a reference domain displacement. The relationship between the Eulerian formulation and the ALE one appears through the time material derivative which can be rewritten in terms of an Eulerian gradient $\boldsymbol{\nabla}_{\mathbf{x}}$, *i.e.* calculated with respect to the material frame. This is achieved by introducing the convective particles velocity $\mathbf{c}(\mathbf{x}, t) = \mathbf{v}(\mathbf{x}, t) - \hat{\mathbf{v}}(\boldsymbol{\chi}, t)$, equal to the difference between the particles velocity $\mathbf{v}(\mathbf{x}, t)$ measured in the initial frame Ω_0 and the reference frame velocity itself $\hat{\mathbf{v}}(\boldsymbol{\chi}, t)$. An ALE material derivative for the function f writes:

$$\frac{Df(\boldsymbol{\chi}, t)}{Dt} = \left.\frac{\partial f(\boldsymbol{\chi}, t)}{\partial t}\right|_{\boldsymbol{\chi}} + \mathbf{c}(\mathbf{x}, t) \cdot \boldsymbol{\nabla}_{\mathbf{x}} f(\mathbf{x}, t) \tag{2}$$

where $\boldsymbol{\chi}$ is the current position in the reference domain $\hat{\Omega}$ and t is time.

The, so-called "quasi-Eulerian" momentum and mass balance conservation equations are obtained using this new expression of the time derivative (Folch Duran (2000)):

$$\mathbf{div}_{\mathbf{x}} \boldsymbol{\sigma} + \mathbf{f}_{\mathbf{v}} = \rho(\mathbf{x}, t) \left.\frac{\partial \mathbf{v}(\boldsymbol{\chi}, t)}{\partial t}\right|_{\boldsymbol{\chi}} + \rho(\mathbf{x}, t) \, \mathbf{c}(\mathbf{x}, t) \cdot \boldsymbol{\nabla}_{\mathbf{x}} \mathbf{v}(\mathbf{x}, t)$$

$$\tag{3}$$

$$\left.\frac{\partial \rho(\boldsymbol{\chi}, t)}{\partial t}\right|_{\boldsymbol{\chi}} + \mathbf{c}(\mathbf{x}, t) \cdot \boldsymbol{\nabla}_{\mathbf{x}} \rho(\mathbf{x}, t) + \rho(\mathbf{x}, t) \, \mathrm{div}_{\mathbf{x}} \mathbf{v} = 0$$

where $\mathbf{f}_{\mathbf{v}}$ are the volumetric external forces and ρ is the medium density. Eventually, the reference domain motion has to be defined, for instance with an elastic constitutive law (Belytschko et al. (2000)). In our case, this domain is

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totally arbitrary for resin films (regions) and coincide with preforms in case of a Darcy's zone.

2.2.1.2 Resin model in the resin domain The resin infusion processes duration may be quite long, for instance more than half an hour for a 40 mm thickness T-panel (Han et al. (2003)). Furthermore, resin behaves as a Newtonian incompressible fluid (Yang et al. (2000)). The result is that low resin Reynolds numbers can be considered at a macroscopic level. Hence, in this particular framework, inertial forces are negligible compared with viscous forces (Kaviany (1995), Loos and MacRae (1996)). More generally, except for the use of a "quasi-Eulerian" formulation, the modelling of resin in this domain is similar to classical formulations. Neglecting volumetric forces allows the Stokes equations to be written as follows (momentum and continuity equations):

$$\rho_r^r \, \mathbf{c}_r^r \cdot \boldsymbol{\nabla}_{\mathbf{x}} \, \mathbf{v}_r^r = -\boldsymbol{\nabla}_{\mathbf{x}} \, p_r^r + \eta \, \boldsymbol{\Delta}_{\mathbf{x}} \, \mathbf{v}_r^r \tag{4a}$$

$$\left. \frac{\partial \rho_r^r \, (\boldsymbol{\chi}, t)}{\partial t} \right|_{\boldsymbol{\chi}} + \mathbf{c}_r^r \cdot \boldsymbol{\nabla}_{\mathbf{x}} \, \rho_r^r + \rho_r^r \, \mathrm{div}_{\mathbf{x}} \, \mathbf{v}_r^r = 0 \tag{4b}$$

where variables are now defined for a zone (superscript r = pure resin, f = wet or dry fiber preform) and medium (subscript r = resin, f = fiber, d = reference domain), $\mathbf{c}_r^r = \mathbf{v}_r^r - \mathbf{v}_d^r$ is the resin convective velocity in the purely fluid region, *i.e.* the differential velocity between the material velocity $\mathbf{v}_r^r$ and the reference domain velocity $\mathbf{v}_d^r$ which results from the domain deformation prescribed to map its boundaries displacements (Celle (2006)). When RFI process is considered, the resin film fading is followed with a remeshing of the resin area (Figure 1-b).

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2.2.1.3   Resin model in the preform   On top of the assumptions made for the resin in the fiber free domain (purely fluid), in the wet preform region capillarity effects between fibers and resin can be neglected since the applied external pressures override surface tension effects (Ahn et al. (1990)).

Then, as classically achieved, the fluid flow across the preform is represented through a Darcy's approach. In this macroscopic model, Darcy (1856) showed a constant proportionality law between the superficial velocity $\bar{\mathbf{v}}$ and pressure differential for a fluid flowing across a sand bed. This was later extended to a 3D law based on the liquid pressure gradient $\boldsymbol{\nabla}p$. However, Darcy's law fails in representing properly sticking conditions for a macroscopical viscous flow. A solution was proposed in 1947, by Brinkman, as a generalization of the Stokes equation for flows inside porous media. An additional correction term accounts for transitional flow between boundaries, it leads to Brinkman's equation:

$$\mathbf{f_v} - \frac{\eta}{\mathbf{K}} \cdot \bar{\mathbf{c}}_r^f - \boldsymbol{\nabla}_\mathbf{x}\, p_r^f + \eta\, \boldsymbol{\Delta}_\mathbf{x}\, \bar{\mathbf{v}}_r^f = 0 \tag{5}$$

where $\mathbf{K}$ is the porous medium permeability tensor, $\bar{\mathbf{v}}_r^f = \phi s \mathbf{v}_r^f$ is a superficial or average velocity, ϕ is the porosity, s is the saturation and $\bar{\mathbf{c}}_r^f = \phi\, s\, \mathbf{c}_r^f$ is a superficial or average convective velocity. Considering a low permeability, the $\frac{\eta}{\mathbf{K}} \cdot \bar{\mathbf{c}}_r^f$ term becomes more significant compared with the advection and the diffusion terms (Farina and Preziosi (2000a), Preziosi and Farina (2002)). Then Brinkman's equation (Eq. 5) equates the classical Darcy's equation. As for the mass continuity equation, the ALE formulation yields the same form as Stokes and Darcy mass continuity equation (Eq. 4b).

It can be shown that Darcy's law is a good assumption of Brinkman's relation (Eq. 5) for a permeability lower than $10^{-3}\ m^2$ (Celle (2006)) in the case of infusion processes. For components with larger permeability Brinkman's equation should be used, for instance in the draining fabric (resin layer) for Liquid Resin Infusion processes (Figure 1-a).

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One can eventually point out that the quality of the experimental determination of the permeability tensor will strongly influence the reliability of the results obtained. Recently, several studies were conducted on techniques to accurately measure the permeability tensor (Buntain and Bickerton (2003), Drapier et al. (2005), ...) and showed a strong dependence on the porosity and the saturation level, *i.e.* the filling level of the volume part considered. Clearly, the permeability measurement is a major problem since saturated and unsaturated permeabilities may differ by a factor 6 to 10 for multiaxial stitched fabrics for instance and may also depend on the face receiving the fluid (Drapier et al. (2005)). In the present study, as a first approximation Carman Kozeny's equation has been employed to relate permeability and porosity (Park and Kang (2003)):

$$K_{ij} = \frac{d_f^2}{16\,h_{k_{ij}}}\,\frac{\phi^3}{(1-\phi)^2} \tag{6}$$

where d_f is the fiber diameter and $h_{k_{ij}}$ is the Kozeny's constant. However, the Carman Kozeny model remains a coarse assumption of the permeability as the saturation is not taken into account. When reliable expressions for permeability variation according to porosity and saturation are released from experimental studies, the proposed model can be updated in a quite straight manner.

2.2.2 Preform response

2.2.2.1 Lagrangian-based formulation The Lagrangian formulation is suitable to follow the deformation of non-linear solids such as the preform stacking stage in our manufacturing processes. Numerically, this type of non-linear analysis is usually achieved through an iterative procedure which aims at solving the non-linear equilibrium as the ultimate solution of a sequence of linearized states. However, in such an incremental procedure, the configu-

ration chosen to compute the solution is not unique. The first method, the Total Lagrangian Formulation, consists in using the initial configuration to compute the solution. In this case, a second Piola-Kirchhoff tensor needs to be computed. The second method, the Updated Lagrangian formulation, consists in updating the geometry for every loading increment (the total loading is divided into sub-loadings). When the geometry update is made for every linearized state of the iterative scheme, the formulation is sometimes referred to as an Iterative Updated Lagrangian Formulation (Belytschko et al. (2000)). In our case, the choice of the formulation is driven by the representation of the action of the fluid on the solid media, and we shall use the fluid stresses to modify the solid medium mechanical response. Since working with fluid is much straighter when Cauchy stresses are considered (Eq. 1), this iterative updated material formulation is more suitable to assimilate the current Cauchy stress tensor to the stress tensor known in the last updated configuration (Zienkiewicz and Taylor (2006) and Bathe (1996)).

Another difficulty in this non-linear approach concerns the response of the preform under compression. A transversely isotropic behavior is considered. The preform stiffness in the plane direction is well-known and assumed constant. For the normal direction, in order to express a consistent constitutive law from experimental data, and because Cauchy stresses are necessary, the conjugated logarithmic strains are naturally chosen. Eventually, one has to ensure that a co-rotational formulation is used in order to deal with large rotations and large displacements (Celle (2006)).

2.2.2.2 Conservation equations In a material Lagrangian formulation mass balance is implicitly verified since both computational and material domains coincide. Then, the mass balance equations relates masses at times t and $t + \Delta t$ via the macroscopic preform density $\bar{\rho}_f^f$ and Jacobian of transformation J at these times. In our case the preforms are assumed to be deformable but

composed of incompressible fibers. This yields an explicit relationship between the deformation states and associated porosities ϕ:

$$J(\mathbf{x}, t + \Delta t)\ (1 - \phi(\mathbf{x}, t + \Delta t)) = J(\mathbf{x}, t)\ (1 - \phi(\mathbf{x}, t)) \tag{7}$$

This approach is an original feature of the proposed model compared to those exposed in literature where empirical approaches are used to relate the fiber fraction and the applied pressure (Farina and Preziosi (2000b), Gutowski et al. (1987), ...). For the current load increment, when the new configuration has been obtained with the Updated Lagrangian Formulation, the preform volume change gives the porosity variation assuming the incompressibility of the fibers.

As for the momentum balance equation without volumic forces, it is classically written in terms of Cauchy stresses in the preforms $\boldsymbol{\sigma}_f^f(\mathbf{x}, t)$:

$$\mathbf{div_x}\,\boldsymbol{\sigma}_f^f(\mathbf{x}, t) = 0 \tag{8}$$

The constitutive law of the wet preform will depend on the fiber network behavior but also on the resin flow type. Several authors studied the response of a wet preform under very particular boundary conditions and for specific fiber networks (Gutowski et al. (1987), Kessels et al. (2006)). However, for a general use, the constitutive law can be formulated following the Terzaghi's hypothesis. In this model, the influence of the resin on the preform response is taken into account through the hydrostatic resin pressure (Terzaghi et al. (1967), Gutowski et al. (1987), Kempner and Hahn (1998), ...):

$$\left| \begin{array}{ll} \boldsymbol{\sigma}_f^f = \boldsymbol{\sigma}_{e_f}^f - s\,p_r^f\,\mathbf{I} & \text{in the wet preform} \\ \\ \boldsymbol{\sigma}_f^f = \boldsymbol{\sigma}_{e_f}^f & \text{in the dry preform} \end{array} \right. \tag{9}$$

where $\boldsymbol{\sigma}_{e_f}^f$ is the effective stress of the preform skeleton, s is the saturation

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level, p_r^f is the resin pressure in the wet preform and $\mathbf{I}$ is the identity tensor. It can be pointed out that a Biot's model may also be considered. It does not change fundamentally the formulation presented here, but the a further coefficient introduced must be identified from proper experimental models. This can be integrated subsequently in the presented model.

2.2.3 Representing the preform filling

The main limitation encountered with traditional infusion or injection simulations is their inability in taking into account the change in saturation level. This lack may be due to the difficulty in measuring the saturation itself, defined as the ratio of pore volume occupied by resin. From a physical point of view, this saturation is likely to be progressive. According to Spaid et al. (1998) the relation between pressure and saturation is governed by tension-surface related effects. Therefore, in a transient approach a further relationship between the pressure field and the saturation degree must be characterized from saturated and unsaturated flow behaviors in porous media (Breard et al. (1999)). Currently, the lack of information concerning the relation between pressure and saturation leads to use the so-called "slug-flow" hypothesis. This assumption yields a direct binary relationship between the hydrostatic pressure $p_r(\mathbf{x}, t)$ and saturation level $s(\mathbf{x}, t)$ (Eq. 10).

$$
\left|
\begin{aligned}
s(\mathbf{x}, t) &= 1 \text{ for } p_r(\mathbf{x}, t) \neq 0 \\
s(\mathbf{x}, t) &= 0 \text{ for } p_r(\mathbf{x}, t) = 0
\end{aligned}
\right.
\tag{10}
$$

This hypothesis eliminates one degree of freedom in the Finite Element formulation (Michaud and Mortensen (2001)) and it is referred to as the "slug flow approach". This approach relies on a control volume associated with a degree of freedom in saturation (or pressure) which permits to determine the

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flux between the boundaries of this volume (Loos et al. (2002)). As stated in introduction, mainly two types of numerical methods are associated with the slug-flow approach. The non structured elements method, used in PAM-RTM$^{\text{TM}}$(Trochu et al. (1997)), relies on the existing finite element mesh but leads to discontinuous pressure fields. On the contrary, Finite Element / Control Volume is widely used since continuous pressure fields can be represented but require a further "mesh" with Voronoï cells, and more importantly yields mass balance problems. Some methods have been reported in the literature to solve these mass balance problems encountered. At the node/element numbering level, Joshi et al. (2000) proposed an element sorting, Kang and Lee (1999) suggested a refinement of the flow front by node replacement without any increase in the global system size. A mesh refinement can also be operated, such as suggested in the literature for other engineering fields: X-FEM (Chessa and Belytschko (2003)), ALE (Belytschko et al. (2000)), ...

However, in all these methods the fluid velocity field cannot be computed directly. In the present model, the quantity of resin must be assessed precisely, especially the amount of resin transferred from the resin zone to the preform zone. This is the key of the coupling between fluid and porous mechanics. For that reason, we have implemented a mixed formulation for the Darcy's equations which consists in computing simultaneously both pressure and velocity fields using P1/bubble or P1+/P1 finite elements (Celle et al., to appear).

2.2.4   Boundary and coupling conditions

The assessment of boundary conditions is a major problem, mainly on the moving boundary interface between resin and wet preforms. Figure 3 summarizes these boundary conditions at the structural scale. Coupling conditions between material regions are also reported in this figure.

[Figure 3 about here]

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The structural boundary conditions can be divided into two different categories. The first type of boundary conditions is deduced directly from the physics of LRI/RFI process. Concerning the resin in the pure resin area, the mass balance implies continuity of the velocity field at the interface (⑦) with the wet preform domain, and a zero normal velocity on the bottom mould surface (⑧). The displacement continuity (⑩) is a consequence of the velocity continuity (⑦). The vacuum bag creates a mechanical boundary pressure on the surface of the dry preform (①), and this pressure must tend toward zero on the flow front (⑥). Finally, the resin domain in the pure resin area, introduced to take into account the flow of resin in a moving frame, is bounded with Dirichlet conditions in displacement (⑨ and ⑩).

The second type of conditions is specific to the stress vector continuity (② and ③). The interface conditions between the resin and the wet preform area are mentioned in the literature as Beaver-Joseph-Shaffman conditions for porous elastic soils. Classically, these conditions include the continuity of the normal velocity for the resin mass balance (⑦), and the stress vector continuity for the momentum conservation between the wet preform and the purely fluid area (③). A further condition is usually appended which concerns the sliding condition on the interface, *i.e.* the tangential velocity (Rivière and Yotov (2005), Layton et al. (2003), Jäger and Mikelic (2001)). Here, the sliding effect between both areas is not constrained since normal infusion dominates the flow. These Beaver-Joseph-Shaffman conditions are completed with a continuity of the resin hydrostatic pressure.

At the material scale, coupling conditions result from the ALE formulation of the mass conservation equation for Darcy/Brinkman, similar to Eq. 4b (④) and the use of a Terzaghi's or Biot's model where the influence of liquid is accounted for through its hydrostatic pressure (⑤).

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2.3 Thermo-chemical modelling

In the thermo-chemical modelling, unlike for the mechanical modeling, three homogeneous domains are considered. Currently, the wet preform is modelled as a single homogeneous equivalent material since the resin flow is very slow. The properties of this theoretical material are obtained using appropriate rule of mixtures (Loos et al. (2002), Hassanizadeh (1983a), Hassanizadeh (1983b)). From there, classically the thermo-chemical phenomena are governed by two macroscopic equations: a heat transfer equation and a curing equation.

2.3.1 Thermo-chemical equations

The heat transfer equation for LRI/RFI modelling is obtained from the first law of thermodynamics, by considering a Fourier's law for conduction, and convective terms. The source term represents the energy released by the curing reaction (Bergheau and Fortunier (2004)):

$$\rho\, c\, \frac{DT}{Dt} = \boldsymbol{\sigma} : \mathbf{D} + \operatorname{div}\left(\boldsymbol{\lambda} \cdot \boldsymbol{\nabla}\, T\right) + \Delta H\, \frac{D\alpha}{Dt} \qquad (11)$$

where T is the temperature, c is the specific capacity, ΔH is the heat of reaction, $\boldsymbol{\lambda}$ is the thermal conductivity tensor and α is the resin degree of cure. The mechanical dissipative term ($\boldsymbol{\sigma} : \mathbf{D}$) is usually neglected. The transport phenomena are taken into account to guarantee an accurate temperature distribution.

The curing equation expresses the transport of the curing resin mass. In the literature, several models have been used to express the material derivative of the resin degree of cure. They are constructed by coupling Arrhenius' laws with power laws. One of the most popular model is of Kamal-Sourour's type (Farina and Preziosi (2000b)):

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$$\frac{D\alpha}{Dt} = \frac{\partial \alpha}{\partial t} + \mathbf{v} \cdot \boldsymbol{\nabla} \alpha = \left(A_1 \, e^{-\frac{E_1}{RT}} + A_2 \, e^{-\frac{E_2}{RT}} \, \alpha^p \right) (1 - \alpha)^q \qquad (12)$$

where A_i are pre-exponential constants, E_i activation energies, and p and q are model constants.

Considering the heat transfer equation for each component, it is possible to determine equivalent thermo-mechanical parameters for the mixed area. The theory underlying these expressions is described precisely by Hassanizadeh (1983a).

2.3.2 Relation with mechanical problem and boundary conditions

Apart from the transport phenomena, the viscosity controls the coupling condition between the mechanical and the thermo-chemical phenomena. An empirical equation between temperature, degree of curing and viscosity allows for an explicit solution of the viscosity in terms of the other parameters (Park and Kang (2003)).

The boundary conditions for this thermo-chemical model are of two types: conditions imposed by the process itself and by the autoclave, *i.e.* the temperature of the autoclave, and conditions on the moving interfaces to guarantee the continuity of the temperature field. The degree of cure associated with the resin must be prescribed as an initial condition.

2.4 Review

Figure 4 schematically depicts a synthesis of the proposed model, for a better understanding of the relationships between the various phenomena described in the previous sections.

[Figure 4 about here]

The bold boxes contain independent variables, either scalar or vectorial. Each variable is connected with conservation equations and physical laws. The viscosity is not an independent variable since there is an explicit dependence upon temperature and degree of cure. Similarly, there is a direct dependence of the porosity on the displacement (Eq. 7). Summarizing, this model consists of 7 independent variables (3 displacements, resin pressure, saturation, temperature and degree of cure) for a three dimensional problem. It must be pointed out that solving simultaneously for non-linear solid as well as for fluid mechanics leads to severe numerical problems, mainly due to variable scaling difficulties.

Concerning the thermo-chemical problem the strong coupling between temperature and degree of cure with transport phenomena requires a suitable formulation to treat the convection-diffusion equation (Brooks and Hughes (1982)).

One of the innovative features of the presented model is the coupling between non-linear poro-elasticity and fluid mechanics, in a strong form. From this model, an updated Lagrangian formulation for solid mechanics has been implemented in PAM-RTM^{TM}, an Eulerian-based software, along with a Darcy ALE formulation for the fluid part which permits to study flows in a deformable medium. These updated Lagrangian and Darcy ALE formulations have been strongly coupled using an iterative method to study LRI/RFI processes, and a mixed ALE Stokes formulation has been employed to deal with fluid flow outside the porous media.

In the future, in order to improve the model an attempt will be made to reinforce this coupling. As for the strong coupling between mechanical and thermo-chemical aspects, it may be even more complex.

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3 Applications to RFI process

As an illustration of the current work, Figure 5 presents the results obtained with the RFI process simulation implemented for a simple curved piece for compaction and infusion stages. The simulation is achieved in plane strains, and transverse and planar permeabilities are distinct. The PRO-FLOT[TM] finite element library has been linked with GMSH[©] meshing free software in order to follow the non-linear mechanical response of the solid material and to observe velocity and pressure fields during the flow.

[Figure 5 about here]

More complex geometries can be studied with the proposed model but this simple rectangular geometry has been studied in order to compare numerical and experimental results. For the same reason, *LRI* process simulations have been obtained but as an example *RFI* process is presented, it is more complex to achieve. The present model is limited to 2D simulation but all developments have been extended to 3D. At the moment, both preform behavior and Darcy mixed formulation have been qualified with 3D elements.

In order to solve this problem, material data are requested for the preform response. Some experiments have been performed at ENSM-SE[1] on NC2 dry fabrics (Drapier et al. (2002), Drapier et al. (2005)) and more recently with Hexcel Reinforcements to determine the constitutive relationship in the fabrics normal direction. The compression results show that dry fabrics have a non-linear reversible behavior (Figure 6). For plane directions, classical carbon fiber Young's modulus can be used as a first approximation relying on the fiber volume fraction (Berthelot (2005)).

[Figure 6 about here]

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[1] École Nationale Supérieure des Mines de Saint-Étienne

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The 2D RFI model is formulated in plane strains. The present model accounts for all mechanical phenomena described throughout this paper (solid and fluid mechanics in both purely fluid, and dry and wet preform areas). Boundary conditions correspond to those presented in section 2.1 and Figure 1-b but for a curved piece, they are also reported in Figure 5. In this study, the viscosity is assumed to be constant, equal to 0.027 $Pa.s$, (corresponding to RTM 6 resin manufactured by Hexcel Company). The initial porosity of the preform is equal to 61.3 % and the vacuum bag applies a mechanical pressure of 1.10^5 Pa (1 atm). Kozeny's constant (see Eq. 6) is equal to 100 and the carbon fiber diameter to 5.10^{-6} m. Poisson's effects have been neglected since during the compaction of the preform the in-plane deformations are negligible compared to transverse ones.

[Figure 7 about here]

In this approach a strong coupling between both solid and fluid mechanical behavior is used. For each time step, four implicit problems are computed to reach the displacement, the pressure and the velocity convergence (*see* figure 7). They represent Darcy's flow inside the porous media under finite strains, and Stokes flow in the assumed-elastic fictitious domain. The mass balance equation provides the resin amount transferred in the preform area and consequently the new thickness of the Stokes area. Figure 8 shows the filling time and porosity changes according to the saturation level.

[Figure 8 about here]

[Figure 9 about here]

For this test case, one can observe two steps. First the vacuum bag pressure leads to a pronounced porosity decrease due to the dry preform compaction (from 0.62 to 0.40). Then, during infusion, the resin pressure leads to the swelling of the preform and therefore the porosity increases from 0.40 to 0.42.

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It is well known that the filling time given with traditional filling algorithms is often far from real experimental values since some local phenomena are not taken into account. However, the filling time gives relevant information. Here, the large increase in filling time against the filling level during the resin film infusion process is related to the viscous force which increases along with the preform saturation. Figure 9 presents another view of the preform compaction (35 % initial decrease) and filling. One can observe the resin film thickness variation during the infusion process, simultaneously with the preform swelling due to the absorbtion of the corresponding resin quantity. The residual resin film shows that the resin film thickness was initially in excess, accordingly with real processes where vents ensure that the excess of resin will flow out the preform, hence decreasing the potential residual voids.

More complete parametric studies and confrontations with experimental results will be the purpose of a subsequent paper. Also, the direct strong coupling between solid and fluid mechanical with the ALE formulation would help in improving the CPU time requirements.

4 Conclusions

This paper presents a new model designed to simulate non-isothermal infusion processes in highly deformable porous media. This model can be applied to a wide range of activities from composite manufacturing processes, infiltration of water in concrete (Schrefler and Scotta (2001)) to all industrial processes involving infiltration in deformable porous materials. The presented model accounts for the porous medium deformation during the temperature and pressure cycles, this deformation results both from external loadings and internal pressure exerted by the fluid inside the solid material. The proposed model deals also with the influence of the preform deformation on permeability, and

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therefore on pressure distribution. The interaction between these two last phenomena which occurs in the solid part, is completed by complex interaction boundary conditions on the interface with the purely fluid domain. Finally, a thermo-chemical model accounts for viscosity changes during the infusion. The proposed model is quite general since it is based on conservation equations established for every component in every liquid, solid and mixed regions and at the moment is being released as a commercial version of PAM-RTM. More exhaustive results obtained with this new model, and the corresponding numerical difficulties, are to be published subsequently.

Acknowledgements

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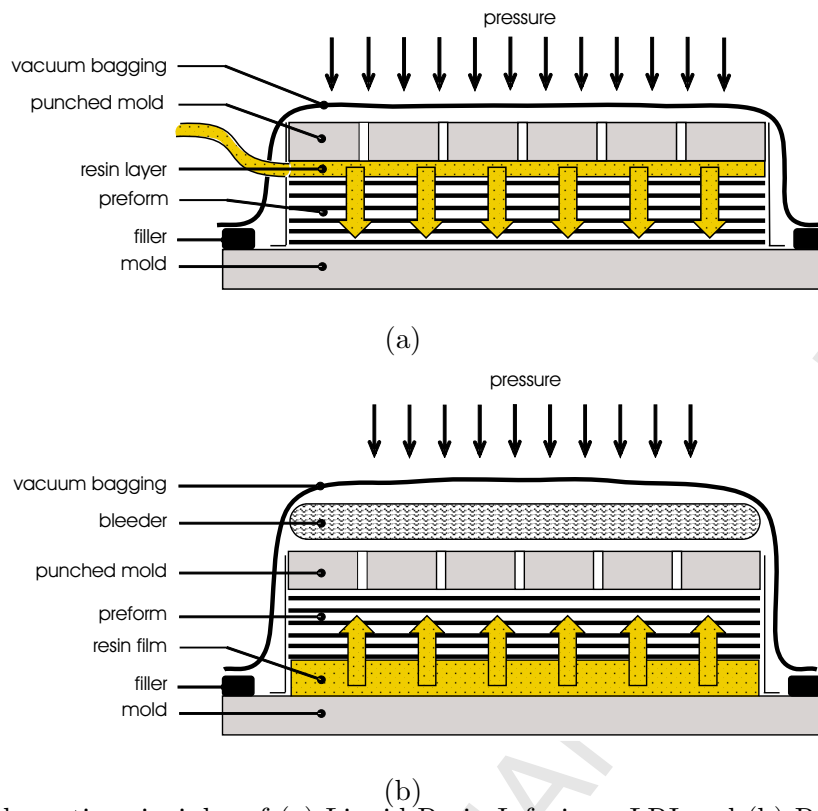
5   Figures

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Fig. 1. Schematic principles of (a) Liquid Resin Infusion - LRI and (b) Resin Film Infusion - RFI processes.
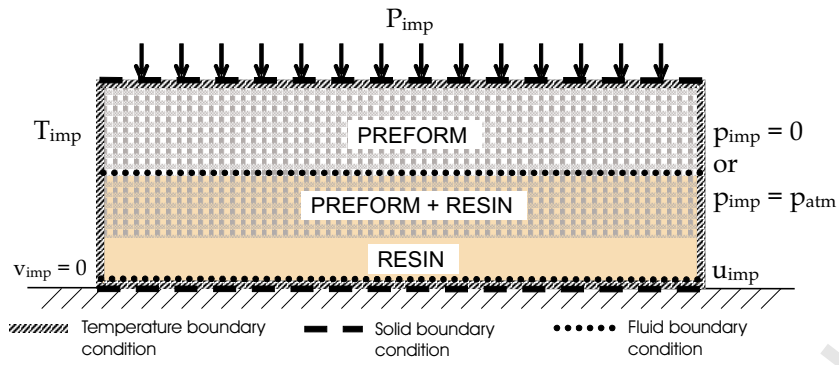
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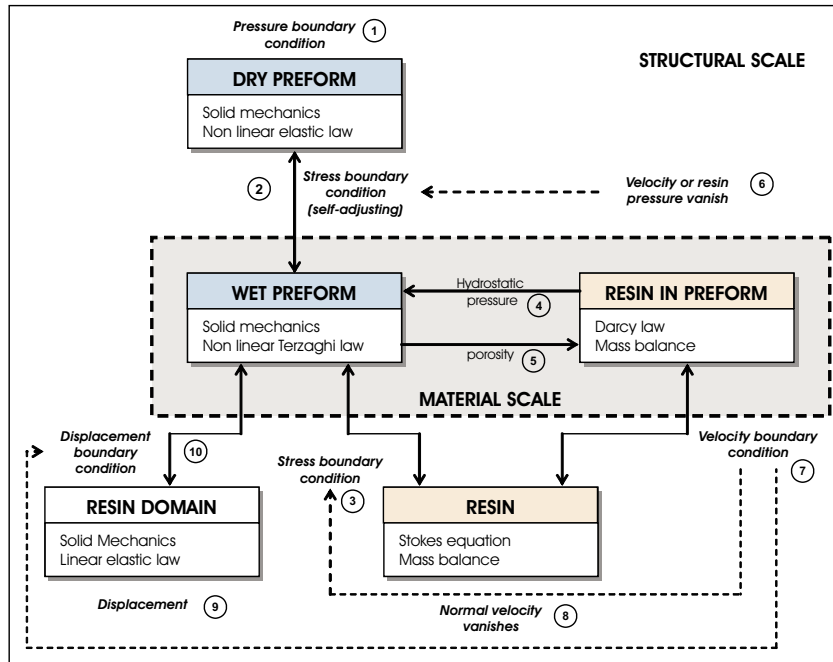
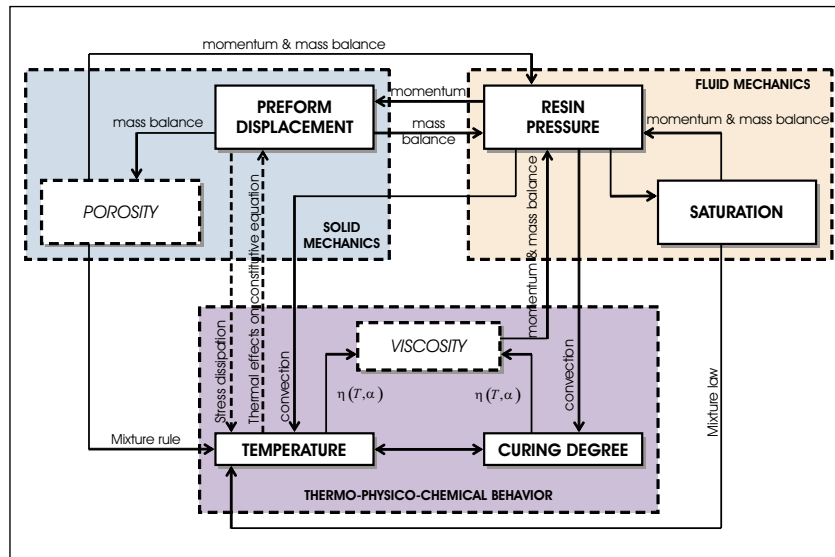Fig. 3. Boundary conditions and interactions at material and structural scale.

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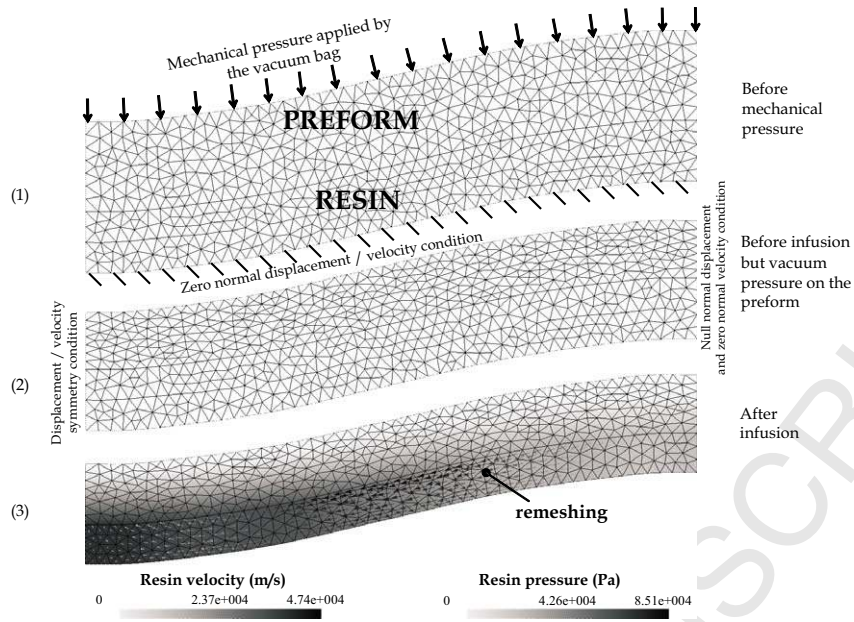
.

Fig. 5. Modeling of a half curved piece with the proposed simulation - (1) preform and resin at initial time - (2) compression time - (3) final stage of infusion.
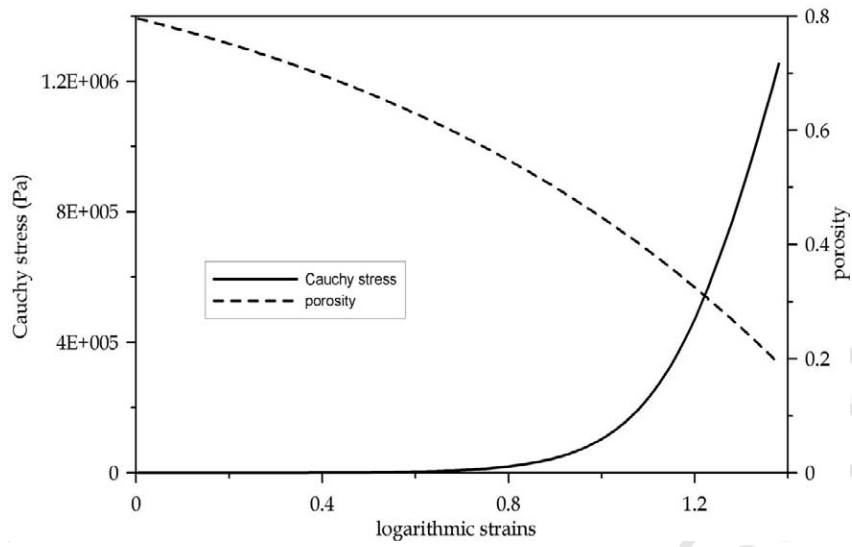
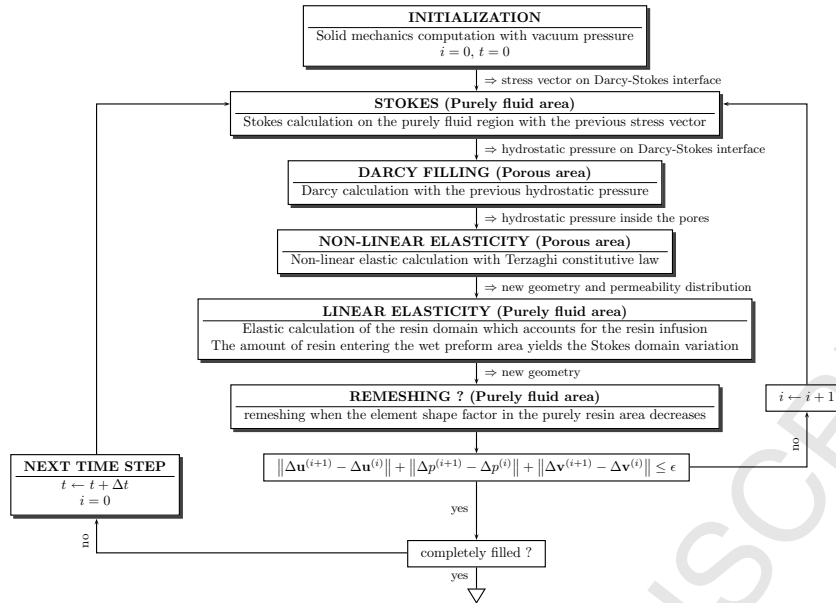Fig. 6. Compression curve for dry NC2 fabrics.

INITIALIZATION
Solid mechanics computation with vacuum pressure
$i = 0$, $t = 0$

STOKES (Purely fluid area)
Stokes calculation on the purely fluid region with the previous stress vector

DARCY FILLING (Porous area)
Darcy calculation with the previous hydrostatic pressure

NON-LINEAR ELASTICITY (Porous area)
Non-linear elastic calculation with Terzaghi constitutive law

LINEAR ELASTICITY (Purely fluid area)
Elastic calculation of the resin domain which accounts for the resin infusion
The amount of resin entering the wet preform area yields the Stokes domain variation

REMESHING ? (Purely fluid area)
remeshing when the element shape factor in the purely resin area decreases

NEXT TIME STEP
$t \leftarrow t + \Delta t$
$i = 0$

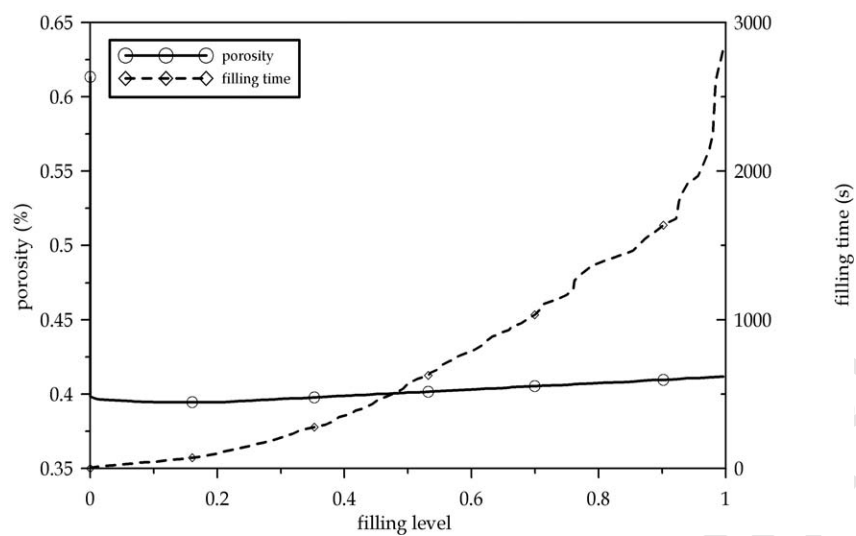Fig. 7. Proposed algorithm for the Resin Film Infusion modeling.

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Fig. 8. Porosity and filing time according to the filling level, *i.e.* the ratio of the resin volume over the pore volume.
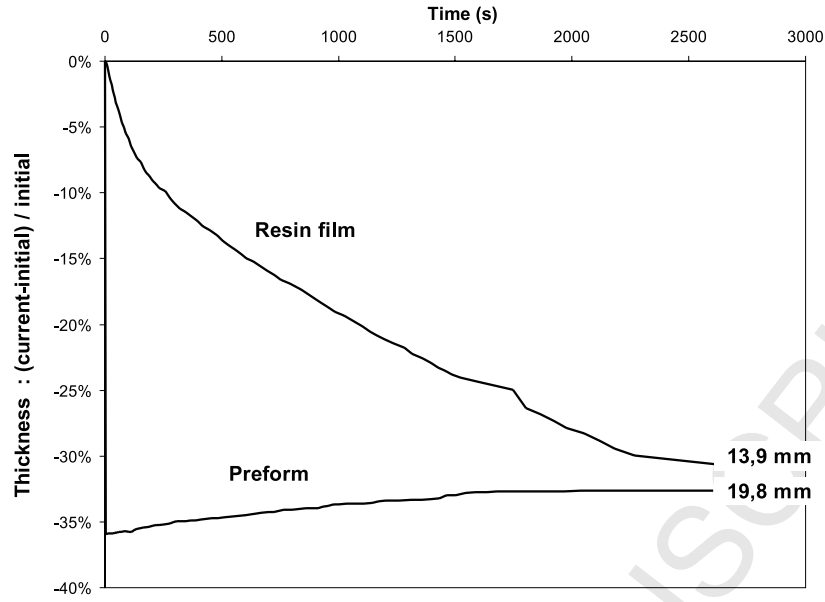
Fig. 9. Preform and resin film thickness variation during the infusion process.