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SIMULTANEOUS IDENTIFICATION OF PREFORM PERMEABILITY AND COMPRESSIBILITY

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1 Introduction

In recent years, a need for composite materials for primary structural applications has been continually increasing. Liquid composites moulding (LCM) processes such as the RTM (Resin Transfer Moulding) process, are used to manufacture high quality and complex-shaped fibre reinforced polymer composite parts particularly in the aeronautic industry.

The RTM process consists of filling a closed mould cavity with preplaced dry reinforcements and injecting a resin through one, or several points. A unique feature of the RTM processing technique is that liquid resin has to flow a long distance to impregnate the dry fibres. However, this process is not well adapted in the case of large part manufacturing because of expensive tooling cost.

On the other hand, in resin infusion processes such as the RFI (Resin Film Infusion), dry textile preform is infiltrated in the transverse direction (Fig. 1) by a semi-cured resin [1, 2] that is consolidated and cured in a single step, eliminating the labour of laying-up of prepreg tapes. The process set up is usually placed in an autoclave to control the temperature cycle and to apply a homogeneous compression stress.

The reinforcement compressibility and the resin flow occur simultaneously and there is thus a mutual influence between the two "solid and liquid" phases. A strong coupling between the reinforcement deformation and the resin flow takes place and needs to be taken into account in the modelling of the RFI process [3, 4].

In the simulation of LCM processes, resin flow through dry fibres is conventionally modelled as a Newtonian flow through porous media, where Darcy's law is used. Some researchers have studied the resin infiltration in deformable preforms under different conditions [5-8]. However, viscous liquid infusion simulations are usually performed under an assumption that the fabric is supposed to be uniformly deformed in the direction of applied stress. In resin infusion processes such as the RFI, the principal resin flow and fabric deformation occur in the same direction. The resin pressure and the fabric compaction stress are not uniform along the thickness direction. As a consequence, the fabric is not uniformly deformed and the fiber volume fraction is not uniform either, in the direction of applied stress, during the resin flow in the RFI process.

For a more precise description of this hydro-mechanical coupling in the RFI process, Ouahbi et al. [3] proposed a numerical modelling of resin infusion taking into account the differential pressure and compaction stresses in the thickness direction.

Modelling the liquid composite moulding (LCM) manufacturing processes requires an accurate material data like resin viscosity, reinforcement compressibility and reinforcement permeability. The identification of the transverse properties of fabrics is becoming an important topic, as the transverse flow is significant in advanced liquid composite moulding processes such as the resin film infusion (RFI), the vacuum assisted resin transfer moulding (VARTM) process and the compression resin transfer moulding (CRTM) process. However, it is not easy to characterize the transverse permeability

and the compressibility of preform, since the fluid flow and the mechanical deformation of the fabrics simultaneously occur in the out-of-plane direction. Due to the strong hydro-mechanical coupling, hence, it has been a common approach to identify these two transverse properties separately either under the simplified assumption (uniform fibre volume fraction in the thickness direction) or under the ideal condition where the closed form solution is known.

In the previous work, we developed a computer code to simulate the resin film infusion process [3] and an experimental device for the measurement by a continuous technique of transverse compressibility and saturated permeability [9]. In this work, we characterize simultaneously the material behaviours in the transverse direction (permeability and compressibility) by incorporating the mathematical models into the full numerical simulation of an actual filling process. To identify the model coefficients, an inverse method is applied with experimental data.

2 Experimental Procedures

2.1 Experimental Device

We use a device to observe liquid flow in the transverse direction through the fabric under various injection conditions such as inlet pressure or flow rate and under various compaction conditions such as stress or displacement control by universal testing machine. A schematic of the device is shown in Fig.2.

2.2 Hydro-Mechanical Coupling under Imposed Displacement

Fibrous reinforcement layers are placed between two perforated grids and a test fluid is injected at a constant flow rate. At the same time, the mobile grid moves down, at a constant speed, to compact the fabrics. The time evolution of the pressure measured at the liquid inlet and the total stress applied to compress the reinforcement layers is given in fig. 3.

3 Material Characterization

3.1 Numerical Modelling

We present the set of equations needed for the modelling of Hydro-Mechanical (HM) coupling in

the transverse direction. The basis of all models is the mass conservation equation (1), where q is the relative resin velocity, V_f the fibre volume fraction and u_{si} the solid velocity. This mass conservation equation is derived from mass conservation equations of resin and fibre [3].

$$\nabla \cdot q = \frac{1}{V_f} \left(\frac{\partial V_f}{\partial t} + u_{si} \nabla V_f \right) \quad (1)$$

The resin flow through the fibre system is a typical example of flow through a porous media, which, on the macroscopic scale, is well described by the Darcy's law (2) relating linearly the fluid velocity q to the pressure gradient ∇p by the resin viscosity μ and the transverse permeability of fibrous reinforcements K_z .

$$\nabla P = - \frac{\mu}{K_z(V_f)} q \quad (2)$$

Terzaghi's Law is used to consider the coupling between the resin pressure and the stress imposed to the preform.

$$\sigma_{tot} = \sigma' + P \quad (3)$$

where σ_{tot} is the total external stress applied to the fabric stack, σ' is the effective fibre deformation stress and P is the resin pressure.

The compressibility and permeability behaviours of the fibrous reinforcement are given by:

$$\sigma' = c V_f^d \quad \text{and} \quad K_z = a V_f^b \quad (4)$$

where K_z and V_f are the transverse permeability and the fibre volume fraction respectively. a, b, c and d are the model constants.

3.2 Identification of Models Parameters

3.2.1 Inverse method

We present an inverse method to obtain the model constants (a, b, c and d). In general, the parameters in a model are fitted by experimental data. The deviation between the measured and the

computational values is expressed by a least square form (5).

$$S(a, b, c, d) = \frac{1}{2} \sum_{i=1}^N \left[\frac{\sigma_i^c - \sigma_i^m}{\sigma_i^m} \right]^2 + \left[\frac{P_i^c - P_i^m}{P_i^m} \right]^2 \quad (5)$$

where σ_i^c and σ_i^m are the computational and the measured total stress at the i th time step. P_i^c and P_i^m are the computational and the measured pressure (at the bottom of the preform) at the i th time step. N is the number of measurement data.

The model parameters $\langle a, b, c, d \rangle$ can be obtained by minimizing the function defined in equation (5). The computed total stress and resin pressure at the liquid inlet are obtained repeatedly changing the model parameters values iteratively through the optimization procedure.

3.2.2 Optimization algorithm

In this work, the optimization problem is solved by the Levenberg-Marquardt method [10]. This method takes the advantages of Gauss-Newton method and the gradient method, while it covers the disadvantages of both methods. The current optimization algorithm is as follows:

- From initial values of $\{a, b, c, d\}$ we compute $S(a, b, c, d)$ (from experimental measurements and numerical results of part thickness).

- New parameters are generated:
 $\{a, b, c, d\}^{(k+1)} = \{a, b, c, d\}^{(k)} + \{\delta\}^{(k)}$

Where $\{\delta\}^{(k)}$ is given by:

$$\left(\{A\}^{(k)} + \lambda \{I\} \right) \{\delta\}^{(k)} = \{g\}^{(k)}$$

$\{I\}$ is the identity matrix,

$\{A\}^{(k)}$ is the hessian matrix of S,

$\{g\}^{(k)}$ is the gradient vector of S.

- We compute $S(\{a, b, c, d\}^{(k+1)})$, then we compare $S(\{a, b, c, d\}^{(k+1)})$ and $S(\{a, b, c, d\}^{(k)})$:
 - If $S(\{a, b, c, d\}^{(k+1)}) < S(\{a, b, c, d\}^{(k)})$: decrease λ by a preassigned factor (say 10)
 - If $S(\{a, b, c, d\}^{(k+1)}) \geq S(\{a, b, c, d\}^{(k)})$: increase λ by a preassigned factor (say 10), update the vector of parameters $\{c, d\}^{(k+1)}$.

3.3 Results and Discussion

The inverse method is applied to the experimental data (Fig. 3). Fig. 4 shows the preform saturated permeability and compressibility corresponding to the identified parameters:

$$(a = 1.4 \cdot 10^{-14}, b = -7.8, c = 8 \cdot 10^6 \text{ and } d = 6)$$

The measured total stress (respectively resin pressure) is compared with the computed total stress (respectively resin pressure) and a good agreement is observed (Fig. 5).

4 Conclusion

An experimental device developed at Le Havre is used with a continuous technique to perform a simultaneous identification of the preform (permeability and compressibility) in the transverse direction by an inverse method. By the current technique we can take into account the hydro-mechanical coupling and the differential pressure and compaction stresses in the thickness direction.

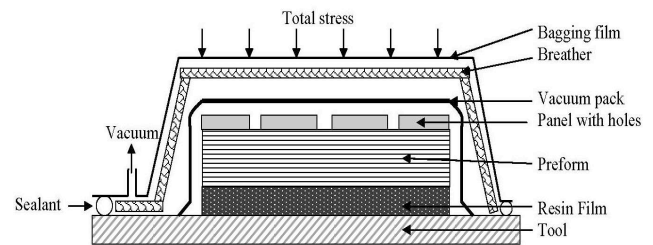


Fig.1. Schematic of the resin film infusion process.

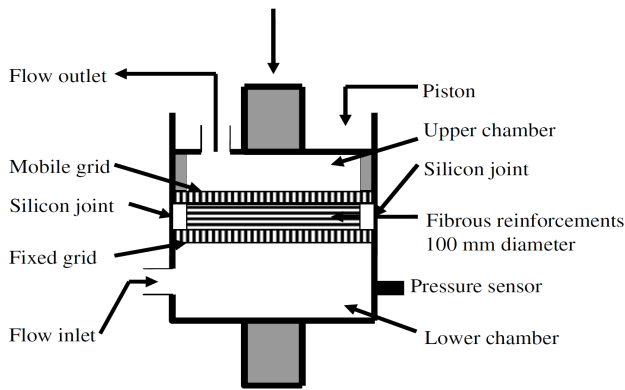


Fig.2. Schematic of the hydro-mechanical loading device.

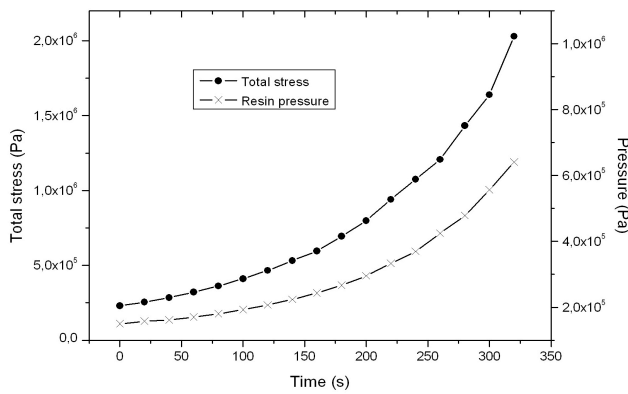


Fig.3. Experimental time evolution of the pressure and the total stress.

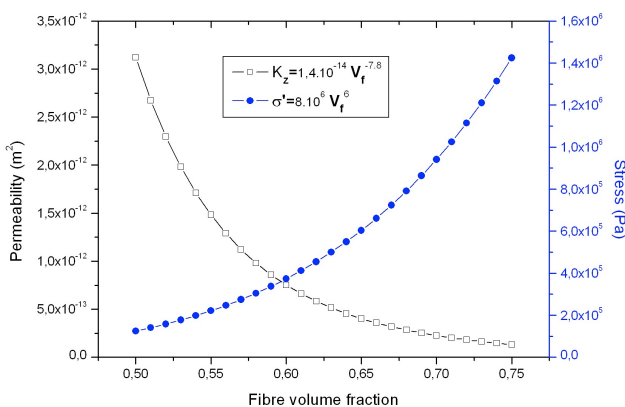


Fig.4. Preform permeability and compressibility obtained simultaneously by inverse method.

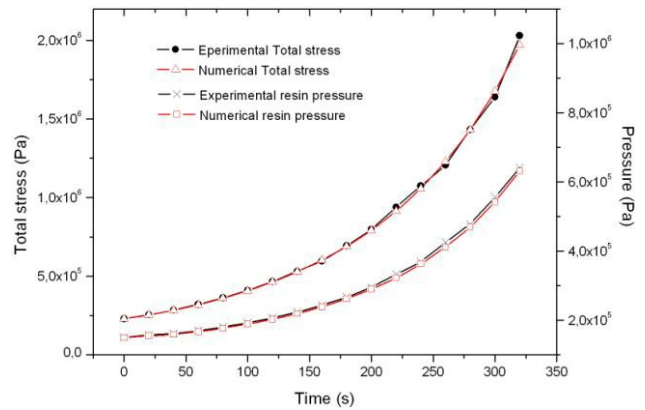


Fig. 5. Comparison of measured pressure and total stress with computed pressure and total stress.

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