# ANALYSIS OF MOLD FILLING IN INJECTION-COMPRESSION

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**SUMMARY**: The consolidation in Compression Resin Transfer Molding (CRTM) and in flexible bladder process has been modeled by Pham et al. [1-3]. First the preform is partially filled by resin during the injection phase. Then it is compressed by the mobile part of the mold. The resin flow in the fiber bed is governed by Darcy's law. The consolidation of the saturated preform is described by the total mass conservation. A filling algorithm based on resin conservation on a deformable grid is used to advance the flow front at each time step. Resin pressure and velocity are calculated by the finite element method. The numerical model allows the calculation of the resin pressure distribution and the evolution of the preform thickness. Numerical results are compared to analytical solutions and experimental results.

**KEYWORDS**: CRTM, RTM, Consolidation, Injection-Compresssion, Finite Element, Filling Algorithm.

## INTRODUCTION

Recently, the analysis of resin flow through fiber reinforcements has arisen much interest especially in Liquid Composite Molding when the impregnation of the preform by the resin is facilitated by a compression. This approach is especially useful for high fiber volume fractions. After the preform has been partially filled by the resin during the injection phase, it is compressed in the second stage of the process by the mobile part of the mold. This compression phase may be controlled either by pressure or by displacement as shown in Figure 1.

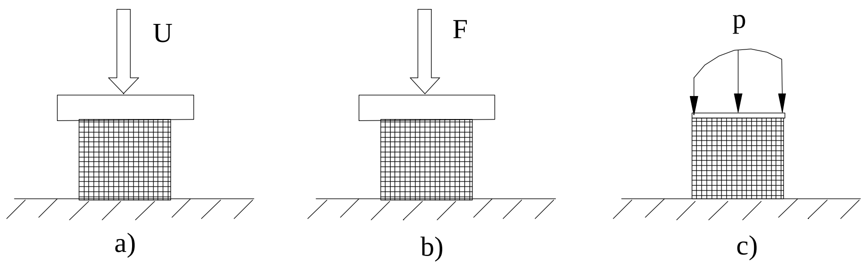



Figure. 1: Boundary conditions imposed on the mobile part of the mold during the compression phase: (a) displacement, (b) force F, (c) pressure p.

During the compression phase, the fiber reinforcement is deformed, the resin is squeezed out of the saturated preform, and the remaining dry reinforcement zone is gradually filled up. This phenomenon is called "consolidation". In this paper, the consolidation of the saturated preform is solved by the finite element method. Numerical results are compared with analytical solutions and/or experimental results.

## CONSOLIDATION THEORY

A review on the theory of the consolidation was presented by Pham et al. [1]. Fundamental consolidation models in soil mechanics can be found in Biot [9], Terzaghi [10] and so on. In composite manufacturing, many studies on the consolidation of the reinforcement were carried out by Phelan [4], Gutowski et al. [5-6], Dave et al. [7-8]. In these studies, the consolidation of the reinforcement in the direction of compaction was studied. Dave et al. [7-8] have used the same equations of consolidation as Biot [9]. On the other hand, Phelan [4] and Gutowski et al. [5-6] have proposed another form of continuity equation to model consolidation. Pham et al. [1] have showed that all of these equations are derived from a general form of the mass conservation.

The consolidation of a saturated fiber bed is governed by the following equations [1-3]:

- Equilibrium equation:

$$\sigma_{ij,j} + \rho\, f_i = 0\,, \tag{1}$$

where $\sigma_{ij}$ is the global stress, $f_i$ the body force and $\rho$ the specific mass of the medium.

- Stress relation:

$$\sigma_{ij} = \sigma'_{ij} + p\,\delta_{ij}\,, \tag{2}$$

where $\sigma_{ij}$ is the global stress, $\sigma'_{ij}$ the effective stress in the reinforcement, $p$ the resin pressure and $\delta_{ij}$ the Kronecker notation.

- Elastic constitutive law of the reinforcement:

$$\sigma'_{ij} = E_{ijkl}\,\varepsilon_{kl}\,, \tag{3}$$

where $\sigma'_{ij}$ is the effective stress, $E_{ijkl}$ the stiffness tensor and $\varepsilon_{kl}$ the deformation of the reinforcement.

- Darcy's equation (to model the resin flow through the fiber reinforcement):

$$v_i^{\,r} = -\frac{K_{ij}}{\omega\mu}\,p_{,j}\,, \tag{4}$$

where $v_i{}'$ is the interstitial velocity of the resin relative to the fiber grid, $\mu$ the viscosity of the resin, $p$ the resin pressure, $K_{ij}$ the permeability tensor and $\omega$ the porosity of the reinforcement.

- Continuity equation

$$div\,(\omega\vec{v}^{\,r}) + div\,\vec{v}^{\,s} = 0 \tag{5}$$

where $\vec{v}^r$, the relative resin velocity with respect to the fiber grid, is given by Eqn 4 and $\vec{v}^s$ is the velocity of the fiber grid particle. The second term of Eqn 5 may be developed as follows:

$$div\,\vec{v}^s = -\frac{dV}{dv}\frac{d}{dt}\left(\frac{dv}{dV}\right), \tag{6}$$

where $dv$ is the elementary volume in the deformed configuration and $dV$ the elementary volume in the initial configuration. By substituting Eqns 4 and 6 in Eqn 5, the continuity equation of the resin flow in the deformable reinforcement is obtained:

$$\nabla.\left(-\frac{K}{\mu}\vec{\nabla}p\right) = -\frac{1}{dv}\frac{d(dv)}{dt} \tag{7}$$

where $K$ denotes the permeability tensor of the reinforcement. Refer to [1] for more details about the equations of consolidation.

## INJECTION-COMPRESSION MODEL

### Displacement control model

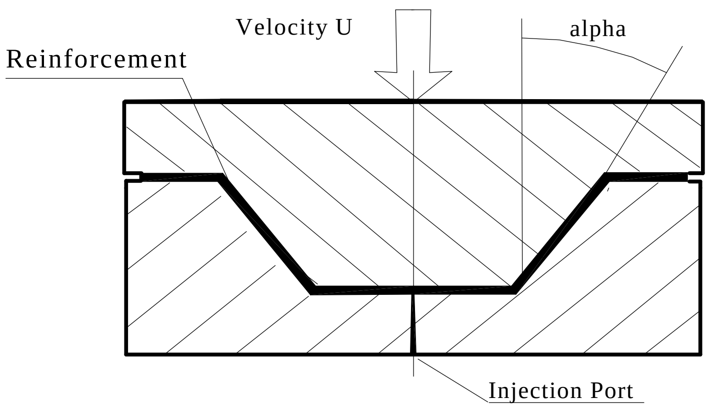



Fig. 1: Schematics of the CRTM process.

Figure 1 depicts the schematics of the CRTM process for a thin composite part with displacement control. During the injection phase, a given quantity of resin is injected into the mold through the injection gate. Then the preform is compressed under a higher pressure by the displacement of the upper part of the mold.

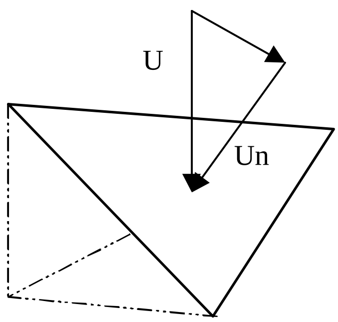



Fig. 2: Compaction speed $U_n$ of each element.

Let $U$ be the compaction velocity of the moving upper part of the mold. As the thickness of the preform is small, when the cavity is discretized into a large number of elements, we can consider that each element is compressed independently by the velocity component $U_n$ normal to the surface of the preform as illustrated in Figure 2. If we note *h(t)* the preform thickness at time *t*, Eqn 7 becomes

$$\nabla . \left( -\frac{K}{\mu} \vec{\nabla} p \right) = -\frac{U_n}{h(t)} \tag{8}$$

**Pressure control model**

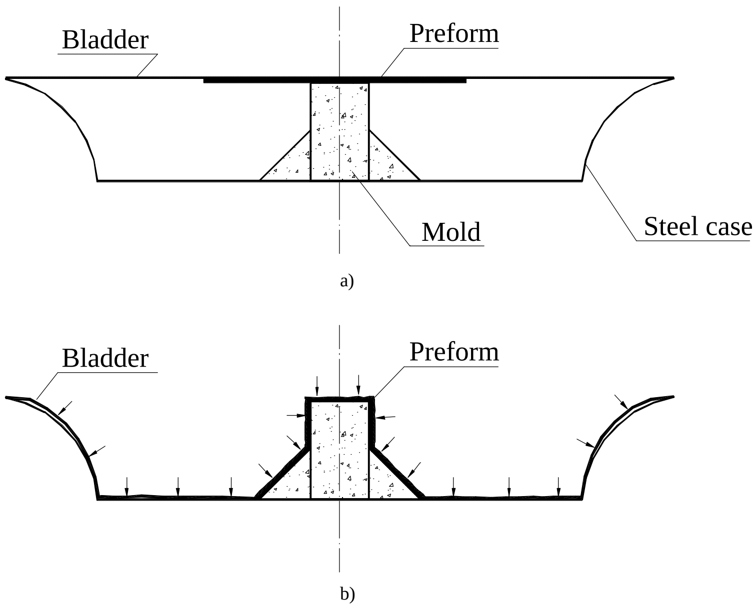



Fig. 3: Schematics of the flexible bladder process:
a) initial configuration, (b) deformed configuration

"*Flexible bladder*" is a LCM process variant for composite manufacturing. In this technique, a saturated preform is first set on a mold which is placed in a steel case covered by a flexible bladder, then the preform is compressed by means of this bladder as shown in Figure 3. The bladder used in this technique must be thin, soft and flexible so that the pressure can be considered as applied uniformly on the preform. Under the effect of pressure, the reinforcement takes the shape of the mold and reaches a certain thickness. The composite part is cured and moved out of the device.

There are two ways to compress the preform. In the first case, vacuum is created in the steel case. Consequently, the bladder is deformed and forces the preform to take the shape of the mold. It is evident that the maximum pressure gradient that can be reached in this technique is the atmospheric pressure. In the second case, the steel mold including the preform and the flexible bladder are placed in an autoclave. The difference here is that the pressure in autoclave may be very higher than the atmospheric pressure. The autoclave technique is more efficient and of course, more expensive.

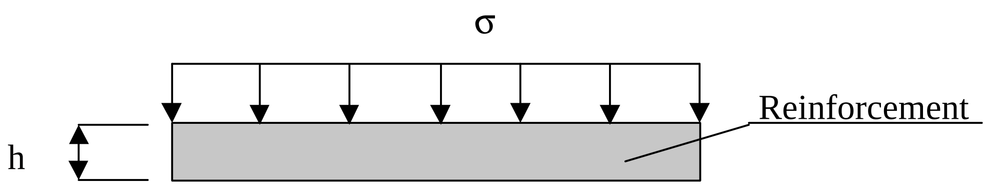



Fig. 4: Schematics of thin composite consolidation

The consolidation of a thin saturated preform under an external constraint $\sigma$ in the plane surface is presented in Figure 4. As the thickness of the preform is small, the resin flow is two-dimensional in the plane of the cavity and the consolidation happens through the thickness of the reinforcement. Then the continuity equation (Eqn 7) can be written as follows:

$$\nabla . \left( -\frac{K}{\mu} \vec{\nabla} p \right) + \frac{h_0}{h\,E} \frac{dp}{dt} = \frac{h_0}{h\,E} \frac{d\sigma}{dt} \qquad (9)$$

where $E$, the stiffness of the reinforcement in compaction, is evaluated as the slope of the compaction curve, and $h_0$ and $h$ are the initial and current thickness of the preform.

## RESULTS AND DISCUSSION

### Case 1

The objective of this test case is first to validate the consolidation model used in injection-compression by comparing the analytical and experimental results, and secondly to evaluate the accuracy of the numerical simulations in terms of filling time and pressure distribution. Wirth et al. [11] have carried out a series of CRTM experiments in the rectangular cavity shown in Figure 5. Three layers of continuous strand mat OCF-8610 were set up in the mold with an initial thickness of 5.1 mm, a length of 60 cm and an initial fiber volume ratio *Vf* of 11%. A polyester resin having a viscosity of 0.16 Pa.s, a density of 1.1 and a gel time of 20 minutes at $25^{o}$C was injected in the mold. The resin was injected in the mold and simultaneously, the preform was compacted by the upper part of the mold moving with a constant speed of 0.09 mm/sec. The injection lasted around 20 seconds. The advancement of the resin in the mold was captured along the length of the mold. On the other hand, the resin pressure was measured by six sensors.

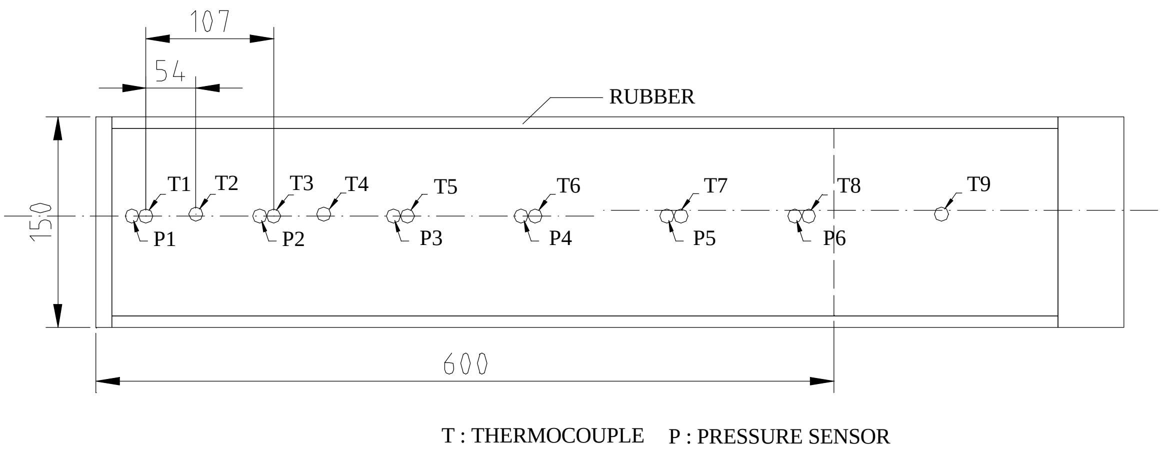



Fig. 5: Schematics of the frame cavity with sensor locations on the bottom plate
(from Wirth et al. [11])

Figure 6 shows the saturated length in function of time for the numerical, analytical and experimental results. A good agreement is observed between the analytical and experimental curves. The numerical and analytical solutions have both predicted correctly the experimental results in terms of filling time. The filling algorithm was able to capture precisely the progression of the resin front. The finer is the mesh, the closest are the numerical results to the analytical solution. Both results obtained with the regular and non regular 4x20 meshes fit well with the analytical solution.

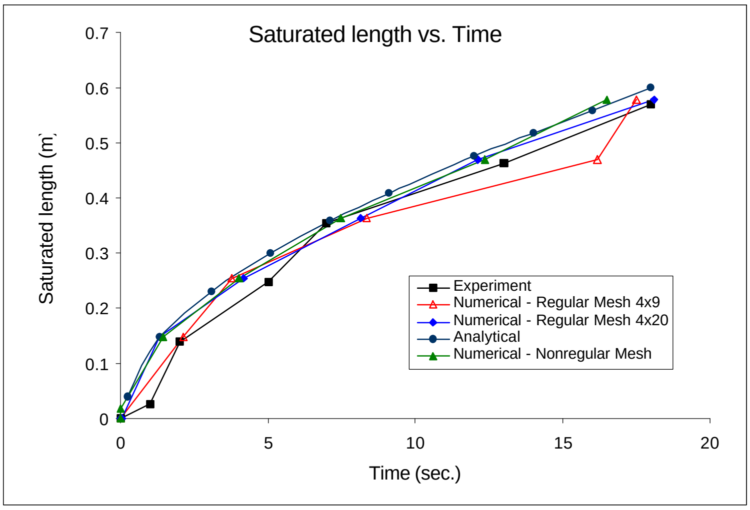
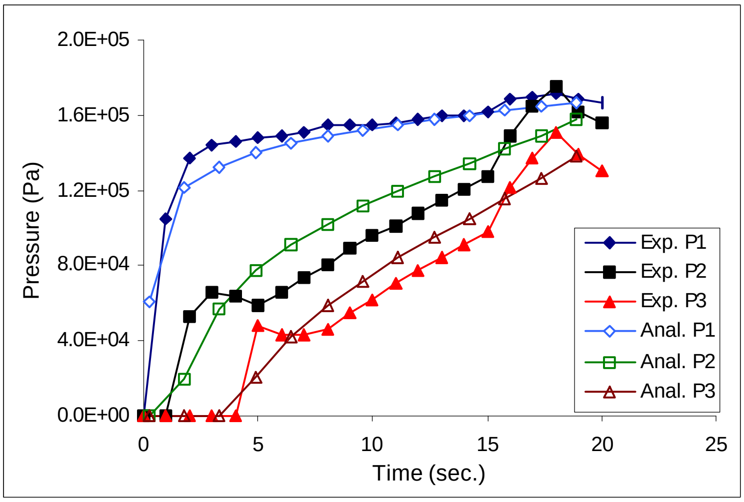
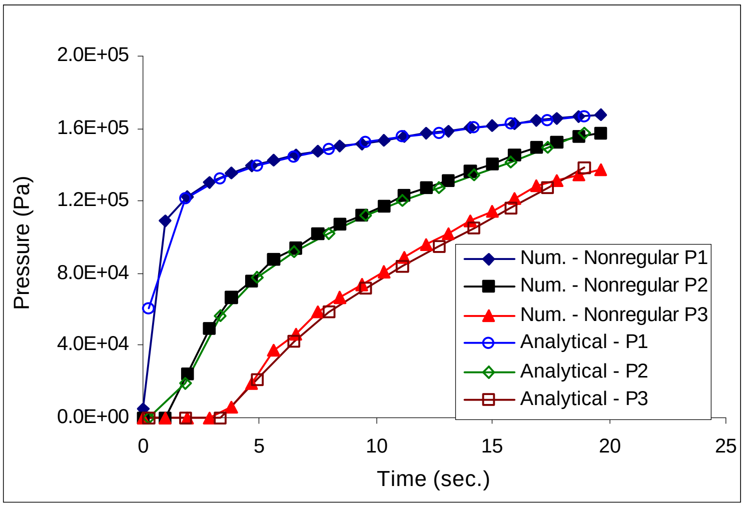



Fig. 6: Comparison of saturated length over time




a)

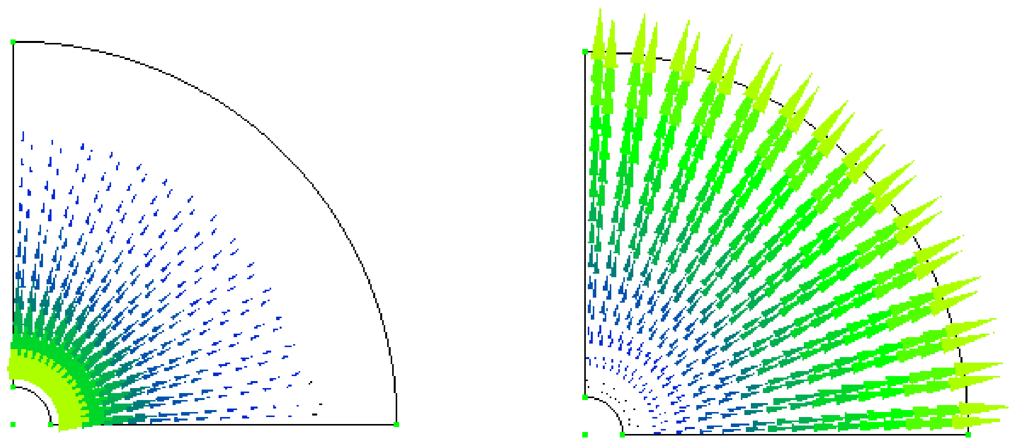



b)

Fig. 7: Comparison of pressure distribution:
(a) experimental and analytical results and (b) numerical and analytical results.

The pressure curves evaluated at positions P1, P2 and P3 for the experimental and analytical results are presented in Figure 7a. The results show a good correlation of the analytical model with the experiment except at locations P2 and P3, where some slight fluctuations are observed in the experimental pressure. On the other hand, in Figure 7b the analytical solution and the numerical results obtained with the non regular mesh fit very well together at all locations P1, P2 and P3. This analysis demonstrates that the numerical and analytical solutions based on the consolidation theory correspond well to the experimental results of Wirth et al. [11] and that the numerical simulations using triangular elements allow to simulate adequately injection-compression.

**Case 2**



a) b)

Fig. 8: Resin velocity on the flow front: (a) injection phase, (b) compression phase

A numerical simulation in a quarter of circle has also been performed to study the effect of the compression. Three layers of continuous strand mat OCF-8610 are set in the mold with an initial thickness of 5.1 mm and an initial fiber volume ratio $V_f$ of 11%. Resin is injected at a constant pressure of 0.2 MPa during the injection phase. After the necessary resin volume is injected, the injection gate is closed and the preform is compressed by the upper part of the mold with a constant speed of 0.5 mm/s until a final thickness of 3.1 mm is reached.

The numerical simulations are performed with regular and non regular meshes using both conforming and non conforming 3 nodes triangular elements. Results show that during the injection phase, the pressure curve has a logarithmic form. The pressure gradient on the resin front is small. During the compression phase, a much larger pressure gradient will facilitate the progression of the resin. The pressure gradient on the front is larger than during the injection phase. The pressure grows up quickly and the resin pressure on the resin front increases remarkably in time. Figure 8 shows clearly the effect of compression on the velocity of the flow front. In this figure, the velocity vector is represented by arrows. It is seen that the compression creates a larger velocity on the flow front during the compression than during the injection phase. As a result, the filling time in injection-compression is much shorter than for RTM without compression.

**Case 3**

A folder geometry, as shown in Figure 9 with L = 0.5 m, is used as example of thin composite part in order to analyze the evolution of the resin pressure and the thickness of the preform during injection with a flexible bladder. A series of numerical simulations are performed with different parameters such as the loading curve, the boundary conditions and the size of the composite part to study the effect of the compression on the behavior of flexible bladder process. The important process parameters that must be studied here are the final thickness of the part and the time necessary to obtain a uniform thickness. A preform of twelve layers of fabric NCS 81053 has an initial thickness $h_0$ and initial fiber volume ratio $Vf^0$ as indicated in Table 1. The preform is saturated with a resin of viscosity 0.16 Pa.s.

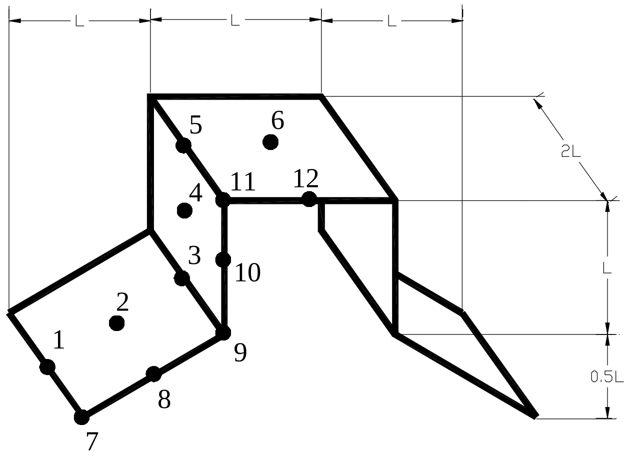



Fig. 9: Geometry of the folder and sensor positions.

Table 2 presents the parameters used in the numerical simulations. Firstly, the pressure increases in the steel case linearly from zero to a certain value, then this pressure is held until the end of the process as shown in Figure 10a. The preform may be opened along only two edges (type 1 boundary condition) or on all sides (type 2 boundary condition). Figures 10b and 10c present the evolutions of resin pressure and preform thickness during simulation 1, for example. The resin pressure and the preform thickness are evaluated during the process at the positions indicated in Figure 9.

Table 1: Reinforcement parameters.

| **Reinforcement** | $h_0$ **(mm)** | $Vf^0$ | **Number of layers** |
|---|---|---|---|
| NCS 81053 | 6.62 | 0.42 | 12 |

Note that the final thickness depends on the maximum loading pressure. For a given reinforcement, the compaction curve provides the relation between the thickness and the loading pressure. Hence, in order to reach a given design thickness, it is necessary to set a predetermined pressure during the loading phase. This means that the flexible bladder process based on vacuum is valid for a relatively limited range of thickness, i.e., the fiber volume ratio achievable by this process is lower than in autoclave. In addition, these simulations show that the duration of the loading phase has little effect on the evolution of the thickness. Finally, the smaller is the maximum loading pressure, the longer it will take to reach a uniform thickness.

This time is called the “critical time”. During the consolidation process, before the thickness becomes uniform, the thickness at the center is always larger than at other locations. If polymerization happens more early than this critical time, the final composite part will not have a uniform thickness. Finally, the choice of the boundary conditions influences how the resin pressure decreases during the holding time and consequently, also the critical time.

Table 2: Results of the simulations with the folder geometry.

| **Simulation** | **Boundary conditions** | **Maximum loading pressure** | **Loading Time** | **Maximum thickness Difference** | **Final thickness** |
|---|---|---|---|---|---|
| Autoclave | | | | | |
| 1 | Type 1 | 0.5 MPa | 20 sec. | 2% at 1000 sec. | 4.80 mm |
| 2 | Type 2 | 0.5 MPa | 20 sec | 1% at 100 sec. | 4.80 mm |
| 3 | Type 1 | 0.8 MPa | 10 sec. | 2% at 925 sec. | 4.53 mm |
| 4 | Type 2 | 0.8 MPa | 10 sec. | 1% at 87 sec. | 4.53 mm |
| 5 | Type 1 | 1.5 MPa | 10 sec. | 2% at 900 sec. | 4.16 mm |
| 6 | Type 2 | 1.5 MPa | 10 sec. | 2% at 80 sec. | 4.16 mm |
| Vacuum | | | | | |
| 7 | Type 1 | 0.1 MPa | 10 sec. | 4% at 1000 sec. | 5.80 mm |
| 8 | Type 2 | 0.1 MPa | 10 sec. | 3% at 100 sec. | 5.80 mm |

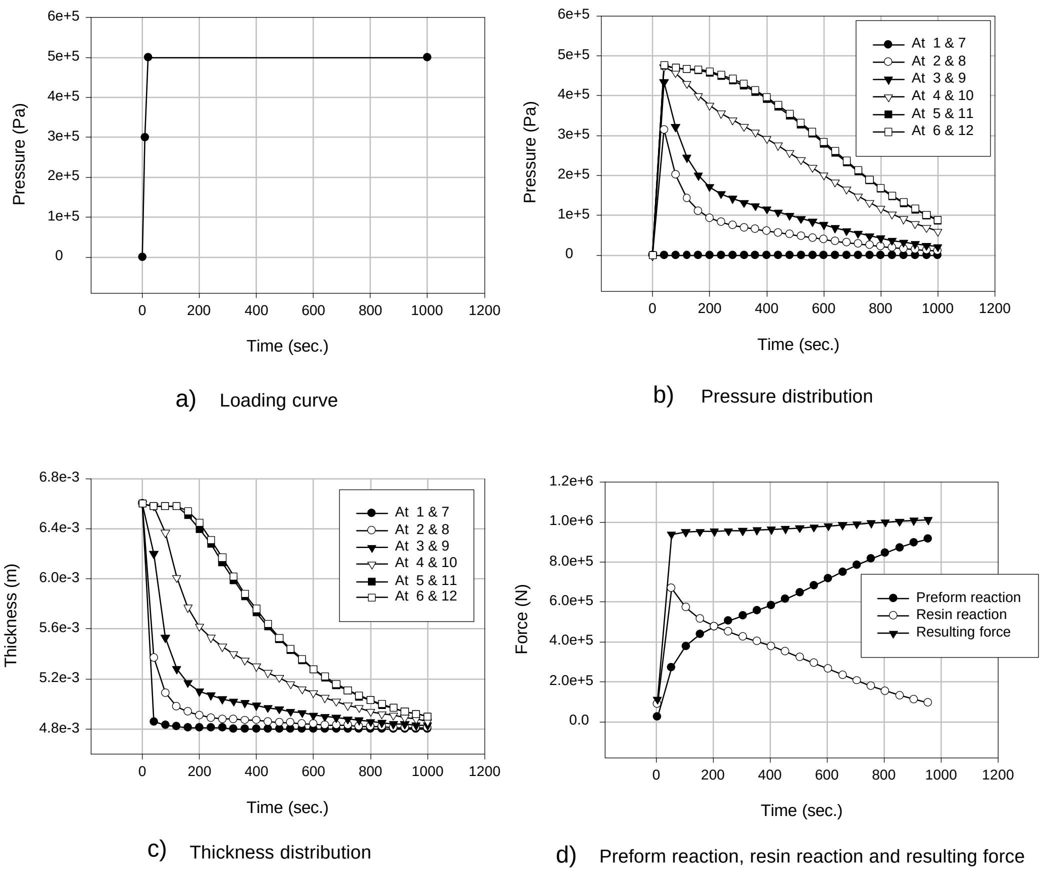



Fig. 10: Simulation 1 with autoclave.

Moreover, the dimension of the part plays an important role in this process. A series of simulations with a small folder are performed to study this effect. The dimensions of this part are shown in Figure 9 with L = 0.05 m. The consolidation behavior is strongly influenced by the size of the part. The maximum value of the resin pressure is very different from one simulation to the other. When the dimension is reduced, the maximum resin pressure and the critical time decrease considerably. The larger the loading pressure, the smaller is the final thickness, i.e., the higher becomes the fiber volume ratio.

## CONCLUSION

The effect of compression has been modeled when the resin saturated or partially saturated reinforcement is compressed either by a rigid plate (displacement control) or a flexible membrane (pressure control). The physical phenomenon that occurs here is called consolidation in the mechanical theory of porous media. The fiber reinforcement satisfies the equilibrium conditions during the deformation and the resin flow is governed by Darcy's equation. The continuity equation expresses the conservation of the resin mass during consolidation.

The numerical simulation is based on an iterative procedure. For each calculation step, the domain is modified and the physical parameters are updated. The finite element method is used to solve the equations of consolidation and calculate the resin pressure and velocity. The advancement of the resin front through the deformed reinforcement is based on a filling algorithm which respects the conservation of the resin mass. A good agreement has been found between the analytical, numerical and experimental results in terms of resin pressure and filling times. Both conforming and non conforming triangular elements have been used in the finite element approximation. The conforming element gave a very good approximation of the resin pressure. On the contrary, the non conforming element provided better results in terms of filling time.

The compression presents two important advantages in these types of processes. First, the composite part is forced by compression to take the shape of the mold and the fiber volume ratio obtained is much higher than the one of classical process such as RTM. Secondly, the compression creates a larger pressure gradient on the flow front. As a result, the resin flows more easily. The filling time is shorter and the final composite part is of better quality, more uniform, more homogeneous. The consolidation models described here allow to predict the distribution of the resin pressure, the filling time, the mold closing force, the evolution of the preform thickness and the time necessary to obtain a uniform thickness in the final product.

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