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# A 2.5D SIMULATION OF THE FILLING AND POST-FILLING STAGES OF THE RESIN INFUSION PROCESS

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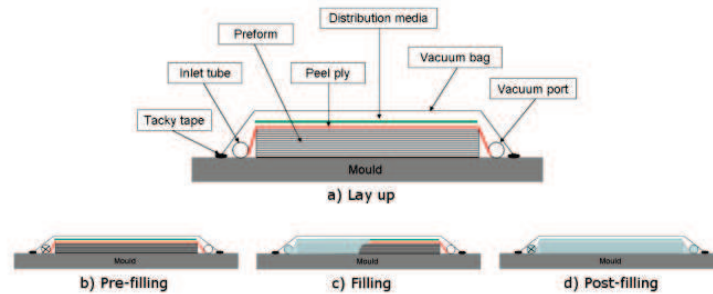
**ABSTRACT:** The Resin Infusion process (RI, also known as VARTM) is a subclass of the Liquid Composite Moulding (LCM) collective, which is increasingly applied in industry. As opposed to the other LCM processes, RI utilises only one rigid mould half, the upper mould half of the mould being a flexible plastic bag. This greatly reduces tooling costs, and makes the process suitable for medium to very large sized parts. However, the interaction between a flexible bag and the infusion of the laminate within, presents a significant challenge to model and understand. The University of Auckland LCM research group is developing SimLCM as a generic LCM mould filling simulation. SimLCM has recently been extended to simulate RI, focusing on resin flow and laminate thickness predictions throughout the process. To accurately predict filling times, and the evolution of fluid pressure and laminate thickness during filling and post-filling phases, a detailed knowledge is required of the complex compaction response of the fibre reinforcement. While significant research has been published on modelling of the filling in RI, the post-filling period has received much less attention. This phase is, however, significant as spatial variations in laminate thickness are removed, preferably before the infused resin gels. Extending on previous work on rectilinear filling, this paper will present a program of RI experiments in a range of 2D flow geometries and the results will be compared to the predictions made using SimLCM. Special attention is given to the post-filling stage, and the validation of the new models developed for SimLCM. A selection of radial, peripheral and more complex filling situations have been addressed.

**KEYWORDS:** *Resin Infusion, VARTM, Liquid Composite Moulding, simulation*

## INTRODUCTION

Resin Infusion (RI) is part of the Liquid Composite Moulding (LCM) process family. The term LCM describes the closed mould processes in which a liquid polymeric resin is impregnated through a fibrous reinforcement. Commonly applied LCM processes include Resin Transfer Moulding (RTM), Compression RTM (CRTM), RTMLight and Resin Infusion.

During manufacture with an LCM process, the operator typically has little control over the advancement of the flow, and successful process development by trial and error requires experience and can be long and expensive. Reduction of development costs requires a good understanding of the process physics, and can benefit from development of an accurate simulation tool. Significant effort has been placed into establishment of RTM and CRTM simulations that accurately predict fill time, flow front advancement and dry spot formation [1-4]. These two processes, through the use of rigid mould tools, allow for accurate control of the laminate thickness and therefore of the fibre volume fraction. A simulation tool therefore only requires an acceptable reinforcement permeability model to provide flow data.



**Figure 1:** Steps of the RI Process.

As opposed to RTM and CRTM, RI uses a single sided mould, the reinforcement being contained within a cavity formed and sealed by a vacuum bag. As the vacuum bag employed during the process provides minimal flexural rigidity, local compaction of the fibrous reinforcement is governed by the pressure difference between the inside of the cavity and the external atmospheric pressure. Local laminate thickness will vary in relation to the resin pressure inside the cavity, as will the reinforcement permeability which is governed by the local reinforcement architecture [5-9]. Not only is the resin flow affected by these changes in laminate properties, but it is also crucial to understand and simulate these variations in order to be able to predict and control the final part quality [9-12].

If infusion is to be used in the aeronautics industry as a replacement for prepregs and autoclave processes, simulation tools will have to not only predict the flow during the filling stage but also the evolution of the laminate throughout the filling and post-filling up to the curing of the resin. This paper presents experimental and numerical results, from a program aimed at developing SimLCM, a generic LCM process simulation.

## DEVELOPMENT OF THE SIMULATION

SimLCM is a simulation tool developed at the University of Auckland, capable of simulating rigid moulding process such as RTM and CRTM. It is currently being developed for simulation of LCM processes using bags and semi-rigid tooling in order to offer a generic LCM process simulation tool. Laminate thickness evolution is coupled strongly with mould deflections and fluid pressure. It affects the permeability of the reinforcement and flow of the resin as well as the final mechanical properties of the composite. The simulation presented here aims to take into account those effects and offers prediction of the flow and laminate properties through both filling and post-filling, addressing what final laminate composition and thickness will settle to, and the time required. Comparisons are made here to the filling

and post-filling phases for infusion of moderately complex geometries. Empirical permeability and compaction models for the CSM have been described previously [7, 12].

### Theory

Resin flow through a fibrous reinforcement is usually described using Darcy's law;

$$\mathbf{q} = -\frac{\mathbf{K}}{\mu}\nabla P, \quad (1)$$

where  $\mathbf{q}$  represents the volume-averaged velocity,  $\mathbf{K}$  is the permeability tensor of the preform,  $\mu$  is the fluid viscosity and  $P$  is the local fluid pressure. The conservation of solid and fluid mass imposes:

$$\nabla(h\mathbf{q}) = -\frac{\partial h}{\partial t}, \quad (2)$$

where  $h$  is the local laminate thickness. Combining Eqns. 1 and 2 gives;

$$\nabla\left(\frac{\mathbf{K}}{\mu}h\nabla P\right) = -\frac{\partial h}{\partial t}. \quad (3)$$

### Solution strategy:

In Eqn. 3, the permeability is a coupled to the fibre volume fraction ( $V_f$ ) which can be expressed as a function of the thickness. The fluid pressure can also be linked to the thickness through Terzaghi's relation:

$$P = P_{ext} - \sigma_f, \quad (4)$$

where  $P_{ext}$  is the external pressure applied on the vacuum bag (in general atmospheric pressure), and  $\sigma_f$  is the stress taken by the fibrous preform which is related to the  $V_f$  through the reinforcement compaction model. Eqn. 3 can therefore be rewritten as:

$$\nabla\left(\frac{\mathbf{K}(h)}{\mu}h\frac{\partial P}{\partial h}\nabla h\right) = -\frac{\partial h}{\partial t}. \quad (5)$$

Eqn. 5 is then expressed in a matrix form as

$$\mathbf{K}_{el}(h^t) + \mathbf{C}_{el}(\dot{h}^t) = \mathbf{F}_{el}(h^t), \quad (6)$$

with  $\mathbf{K}_{el}$ , the elemental stiffness vector,  $\mathbf{C}_{el}$  the capacitance matrix, and  $\mathbf{F}_{el}$  the element force vector. To be solved using the Newton-Raphson Algorithm by using a backward finite difference approximation for the first derivative of the height:

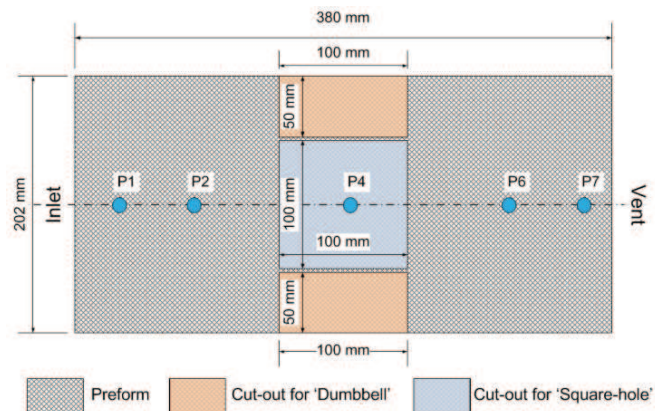
$$\frac{\partial h}{\partial t} \approx \frac{h^t - h^{t-\Delta t}}{\Delta t}, \quad (7)$$

## EXPERIMENTAL OBSERVATIONS

### Plan of Experiments

To provide challenging validation cases for SimLCM, three different 2D shapes were infused. Two shapes were based on a 380x202 mm rectangular preform. The ‘Square-hole’ shape has a 100x100 mm square removed at the centre; the ‘Dumbbell’ has 100x50 mm cut-outs on each side halfway along the length. Schematics and dimensions of the preform shapes are depicted in **Error! Reference source not found..** The third geometry chosen was a disc with a 225 mm outer radius and a 7.5 mm inner radius, infusions were performed with radial divergent flow and peripheral convergent flow as presented in [13, 14]. The ‘dumbbell’ and ‘square-hole’ are identical regards simulation. Completing both experiments allows for pressure data to be taken along two paths, without adding more pressure transducers to the mould.

All experiments were performed with the inlet at atmospheric pressure, and the vent at 4.7 mbar. The preform consisted of 10 layers of a 450 g/m<sup>2</sup> Chopped Strand Mat (CSM) that was characterised for compaction and permeability [9,10]. The test fluid was a mineral oil, Mobil DTE Heavy, with a viscosity of 0.2 Pa.s at 20°C.



**Figure 2:** Schematic description of the preform shapes.

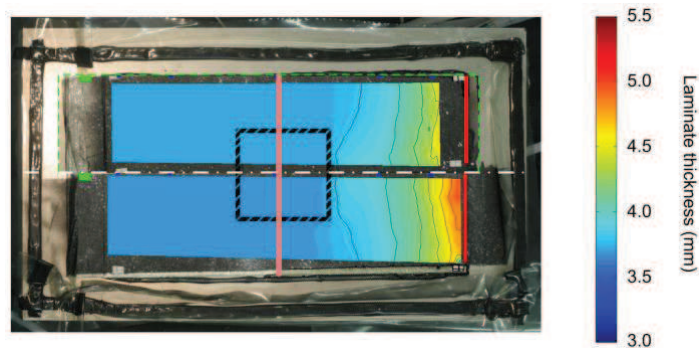
### Setup

The RI monitoring setup used for the experiments presented here was described in [7, 12, 14]. As well as recording inlet and vent pressure, fluid pressure was recorded at five points along the laminate (35, 90, 200, 310, and 365 mm from the inlet, P1, P2, P3, P4, and P5 respectively) for the rectangular infusion and three points along the laminate for the circular preform (56, 113 and 169 mm from the centre for P1, P2 P3 respectively), using 6001A4-FL pressure transducers. Laminate thickness was measured across the whole surface using a stereophotogrammetry system [6,8].

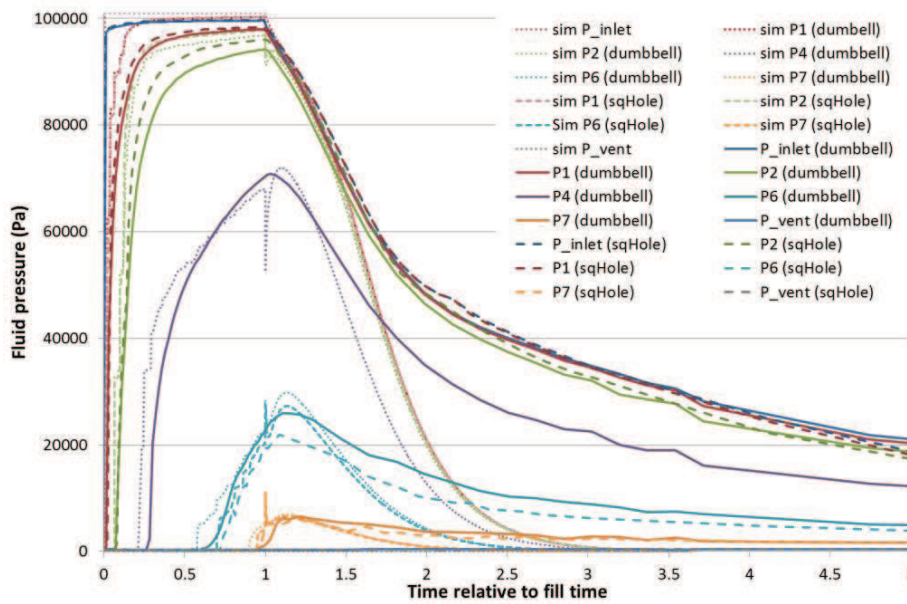
### Observations

When comparing the ‘square-hole’ and ‘dumbbell’ at the same relative fill time, it is observed that the thickness distribution and flow front shape and position are very similar. In Figure 3, the thickness map of the ‘dumbbell’ experiment (top) was overlaid on the processed image of the ‘square-hole’ experiment (bottom), lining up the cut-out of the dumbbell with the top half

of the square hole. It is therefore possible to assume pressures measured along the centreline of the ‘square-hole’ infusion are equivalent to those along the outside edge of the ‘dumbbell’ infusion, and vice-versa.



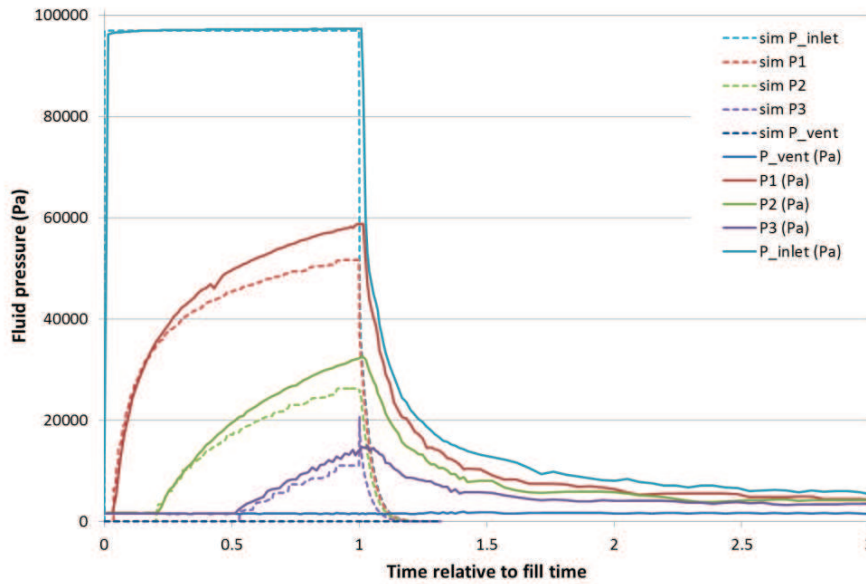
**Figure 3:** Comparison of the thickness distribution in the ‘dumbbell’ (top) and ‘square-hole’ (bottom) when the flow front (in pink) reaches 200 mm from the inlet.



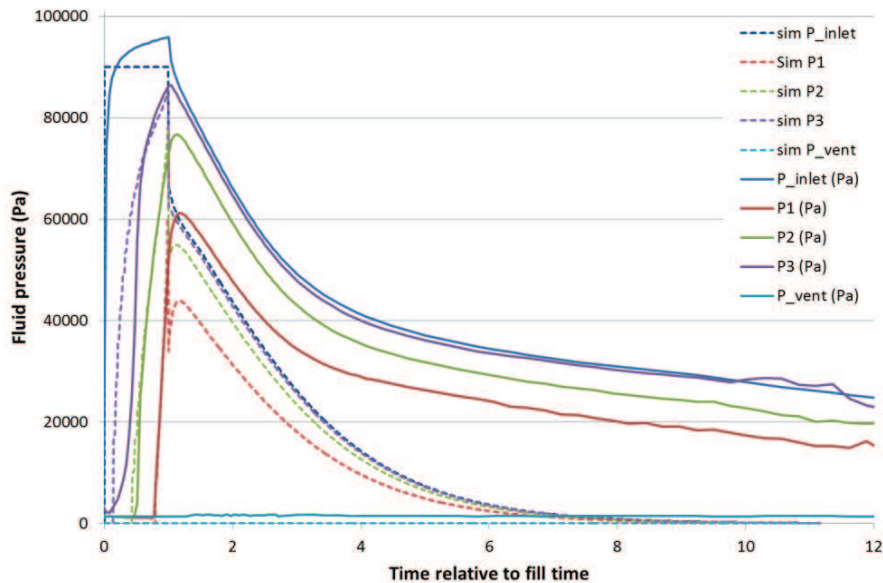
**Figure 4:** Comparison of the fluid pressure evolution in the rectangular infusion experiments and simulation.

Figure 4 presents the evolution of the fluid pressure along the centreline of both ‘dumbbell’ and ‘square hole’ experiments. To eliminate the variations in time due to variability of the process and fluid viscosity, the time was normalised to the fill time. Until 0.15 fill time, before the flow front reaches the cut-out, the fluid pressures in both experiments matches very well. After the flow front reaches the beginning of the cut-out, the fluid pressures at P1 and P2 diverges with a steeper rise and higher maximum along the centreline of the ‘square hole’ experiment, the rise being more pronounced at P2 that at P1. This effect can also be observed in Figure 3 where the thickness appears to be higher just upstream of the cut-out as compared to the area where the preform is continued. While there is a lag between the pressure rise at P6 between the two experiments, the pressure at the centreline of the ‘dumbbell’ experiment

rising earlier and to a higher peak than that of the ‘square hole’ experiment, the difference is not noticeable anymore at P7.



**Figure 5:** Comparison of the fluid pressure evolution during the radial infusion between the simulation and experiment.



**Figure 6:** Comparison of the fluid pressure evolution between the experiment and simulation for the peripheral infusion.

Figure 5 and Figure 6 present the fluid pressure evolution during the radial and peripheral infusions. Table 1 presents the fill time for all experiments and the corresponding simulation. It can be observed that while the peripheral infusion has a much reduced fill time, the time necessary for post-filling is much longer, in fact the total cycle time is slightly longer than in the radial infusion case. On the other hand while the radial infusion has a relatively long fill

time, the post-filling occurs much faster than for peripheral or linear infusion. It can also be observed that while the inlet pressure didn't reach a stable maximum during filling for the peripheral infusion, the pressures at P1, P2 and P3 reached a much higher peak as compared to the radial infusion.

**Table 1:** Comparison of the experimental and simulated fill time for all experiments

	Dumbbell	Square hole	Radial	Peripheral
experimental fill time (s)	1055	1660	1247	227
Simulation fill time (s)		1523	1180	249

### SIMULATION RESULTS

As was discussed in [12], fibrous reinforcements displays a complex compaction behaviour. The reinforcements do not behave in the same way in loading and unloading or when they are wet and or dry. Three compaction models were therefore implemented in the simulation, one representing the compaction of dry fibre, one representing the progressive unloading of a saturated reinforcement for the filling stage, and one modelling the compaction of saturated reinforcement during post-filling. However this causes some discontinuity in the pressure and laminate thickness at the onset of post-filling as can be seen in Figure 4 to 6.

It can be observed from Figure 4 to 6 that the simulation appears to capture very well the filling stage of the resin infusion process in various scenarios providing some level of complexity. The simulation of the post filling appears however to predict much quicker changes than what is observed during the experiments. The pressure profile across the parts however, appear to match relatively well. For the rectangular infusions, the rate of pressure decay predicted at the beginning of post-filling match relatively well that observed in the experiments. Once the fluid pressure reaches below 60000 Pa near the inlet however, the experimental rates of pressure decay decrease dramatically while the simulation does not pick this up. This could be the sign of a stiffening of the reinforcement that was not observed during the reinforcement characterisation. Another possible explanation could be due to small irregularities at the edges of the preform in the experiments that might reduce the flow out to the vent.

The developments of simLCM for the resin infusion can now also account for turning the inlet into a vent at the onset of post-filling, and the possibility of having multiple zones with different materials or number of layers is being implemented into the infusion model.

### CONCLUSION

This paper has presented recent development of the process simulation software SimLCM to address resin infusion. Several complex scenarios were presented, and compared to detailed experiments for validation. The simulation provides good predictions of flow progression and laminate thickness evolution, and provides a deeper analysis than that possible using a simple RTM simulation. While the experimental post-filling appears to be slower than forecasted by the simulation, it has to be noted that the post-filling simulation is very sensitive to the compaction behaviour model used; a refined compaction model could provide more



satisfactory results. On-going work is focused on amelioration of the predictions through the post-filling stage of RI and improvement of the reinforcement's compaction behaviour model.

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