THE RTM-LIGHT MANUFACTURING PROCESS: EXPERIMENTATION AND MODELLING

O. Maclaren[1], J.M. Gan[2], C.M.D. Hickey[2], S. Bickerton[2], P.A. Kelly[1]
[1]Department of Engineering Science,
[2]Centre for Advanced Composite Materials, Department of Mechanical Engineering,
The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
pa.kelly@auckland.ac.nz

SUMMARY

An initial study was carried out to investigate key aspects of the RTM-Light process, in particular the effect of mould flexibility on process times, cavity thickness and pressure distributions. Radial and peripheral injection experiments have been performed, utilising mould platens of varied flexural stiffness. A simulation of these RTM-Light experiments was developed using an iterative coupling procedure to solve the fluid-mould interaction problem. Initial comparisons of experimental and numerical results are presented.

Keywords: Liquid Composite Moulding, RTM-Light, Resin Transfer Moulding, Tooling Forces, Simulation

INTRODUCTION

RTM-Light is one of the many Liquid Composite Moulding (LCM) closed-mould composites manufacturing processes. Its distinctive feature is that at least one side of the mould is made of a fairly flexible material, e.g. a plastic or composite, more flexible than the near-rigid moulds of conventional Resin Transfer Moulding (RTM), but not as flexible as the bags used in the Resin Infusion process (a.k.a. VARTM). The principal advantage of RTM-Light is that the mould can be closed and the fibrous preform can be compacted under a compaction-force which is much less than that required in RTM and this provides cost and time savings. The price one pays is that the mould deflection during compaction and filling may lead to a loss in part quality and process control. The goal of this study was to experimentally investigate some of the key aspects of the RTM-Light process, and to develop a modelling approach which can predict cavity thickness changes, pressure distributions and process fill times.

EXPERIMENTATION

The experimental set-up is illustrated schematically in Figure 1, and the 25 mm thick aluminium lower mould platen presented in Figure 2 [1]. The mould was designed to produce 450 mm diameter, 4 mm thick parts, in a manner consistent with industrial RTM-Light practice. Full vacuum is applied over the flange area between the outer wing seal and the inner seal to provide clamping force. 50 kPa of vacuum is applied to the central cavity to draw resin through the part, assisted by 30 kPa positive pressure inside the resin pot. Two polycarbonate plates (6 and 10 mm thick) were employed to provide upper mould plates of varying flexural stiffness. Significant care was taken to maintain a fixed boundary condition (i.e. zero slope) at the mould cavity edge.

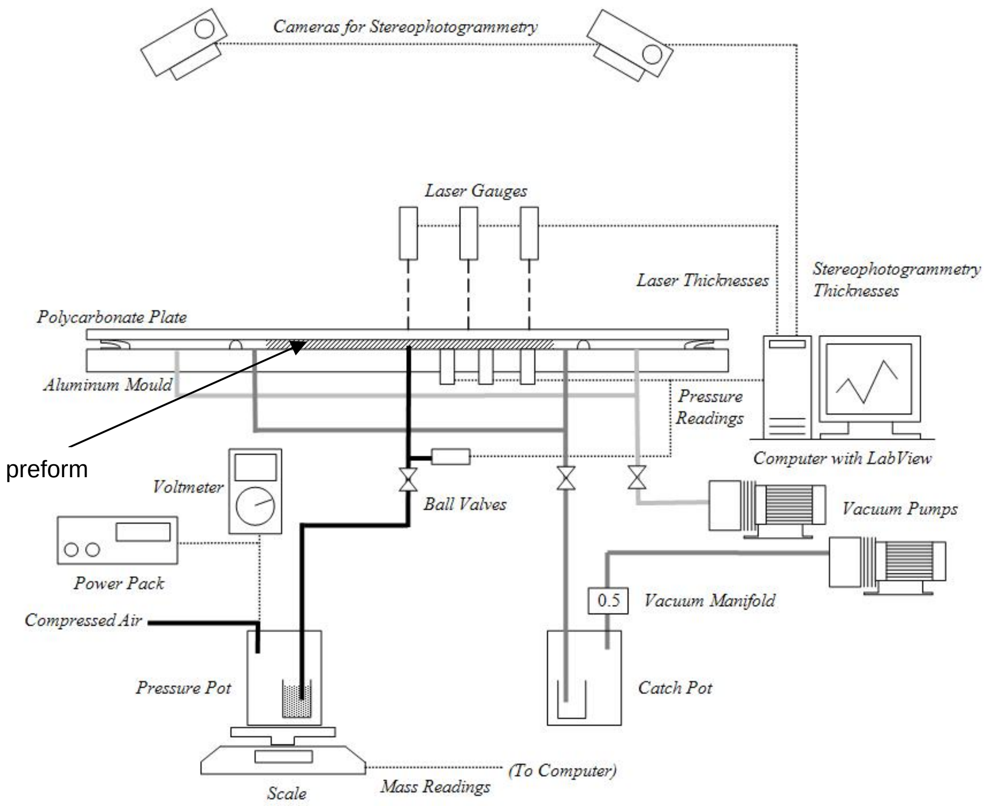

Figure 1: Schematic of complete experimental set-up.

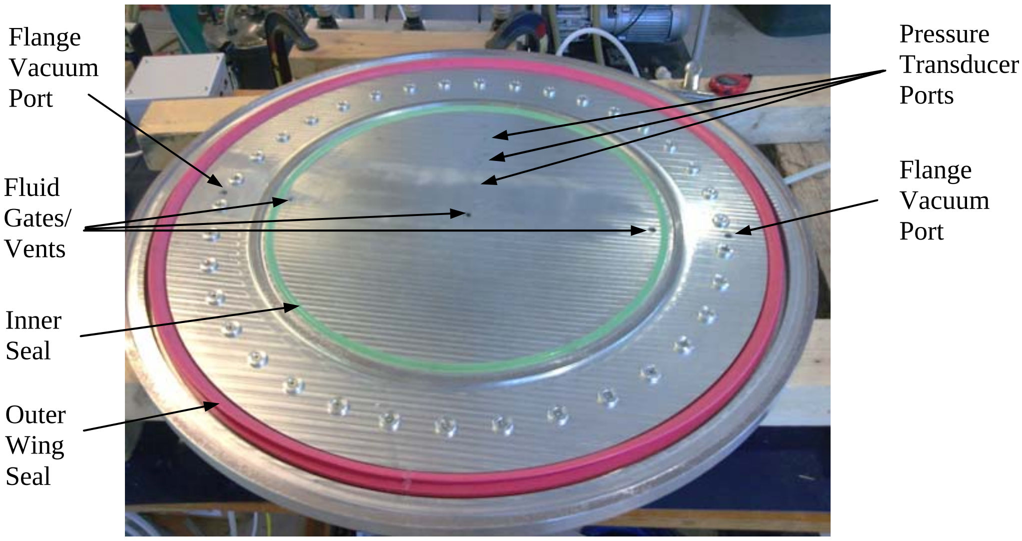

Figure 2: Photograph of aluminium lower mould platen.

Several reinforcements have been studied, although only data for a 450 g/m^2 chopped strand mat is presented here. Separate permeability and compaction tests were carried out to provide permeability/volume fraction and volume fraction/compaction stress data.

A Mobil DTE Light mineral oil (0.08 Pa.s at 20°C) has been used as the test fluid, injected radially from the mould centre, or peripherally via a 20 mm wide channel around the outer edge of a perform. Resin pressures have been monitored via transducers (at radii of 0, 56.3, 112.5, and 168.8 mm), and mould cavity thickness via laser gauges (at radii of 0, 75.0, and 150.0 mm). For peripheral filling, the transducer that was at the plate-centre was moved to the outer injection line. Data has been recorded through the "pre-filling" (initial application of vacuum to flange and cavity), "filling" (progression of flow front), and "post-filling" (after closure of the injection gate) process phases. Photographs presented in Figure 3 demonstrate radial and peripheral injection, and show the placement of the laser gauges.

a) b)

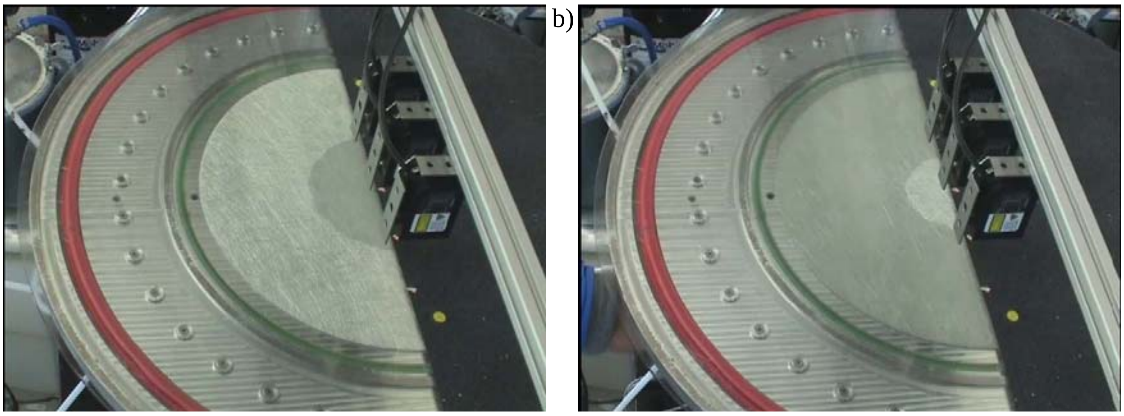

Figure 3: Sample images recorded during filling, for a) radial, and b) peripheral injection.

SIMULATION

The RTM-Light process was simulated using an iterative procedure to solve the coupled fluid-flow/structural problem, as outlined in Figure 4 [2].

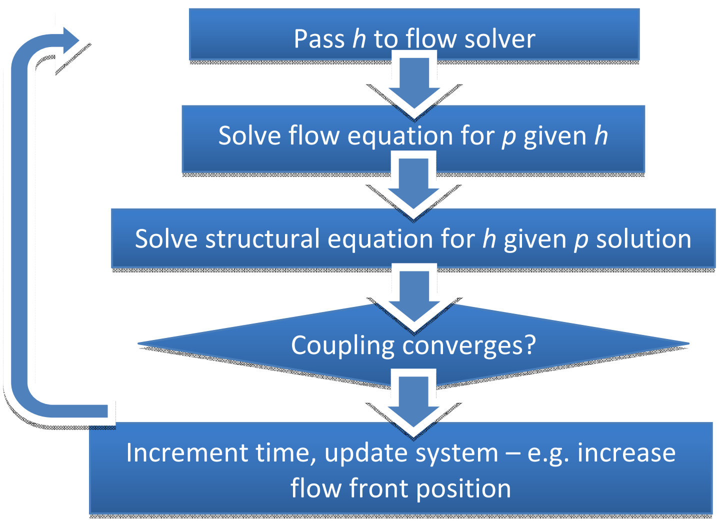

Figure 4: Procedure used to solve the coupled fluid-structure interaction problem.

Fluid Flow Problem

For the fluid-flow problem, flow was modelled using Darcy's law: the governing equation for Darcy flow through a porous medium of permeability **K**, incorporating conservation of fluid and preform mass, is

$$\nabla \cdot \left(\frac{h}{\mu} \mathbf{K} \nabla p \right) = \frac{\partial h}{\partial t}, \tag{1}$$

where h is the preform thickness, μ is the fluid viscosity, and p is the fluid pressure. Empirical relations were used to fit the experimentally obtained permeability/volume fraction data, so that **K** could be considered a function of h. Thus, given the thickness h, Eqn. (1) could be solved for the pressure, over the fluid-filled domain. A Finite Element scheme was used for this purpose. The term $\partial h / \partial t$ in (1) was evaluated using a backward difference scheme. Boundary conditions were specified on the pressure and/or fluid flux at the injection ports and the pressure was set to vacuum at the flow front. The flow solver was tested and verified using known analytical solutions for RTM.

Structural Problem

The upper-mould was assumed to deflect according to the Kirchhoff elastic plate theory, the governing equation for which is [3]

$$\nabla^4 h = -\frac{q}{D}, \quad D = \frac{Et^3}{12\left(1-\nu^2\right)}, \tag{2}$$

where q is the (net) pressure distribution over the plate, E is the Young's modulus, ν the Poisson's ration and t the plate thickness. Terzaghi's law was assumed to hold: $\sigma_0 = \sigma_f + p$, where σ_0 is the stress applied to the (fluid filled or dry) preform and σ_f is the compaction stress taken up by the preform alone. If p_a is the (known) stress applied to the upper mould, then

$$q = p_a - \sigma_0 = p_a - (\sigma_f + p) \tag{3}$$

Empirical relations were used to fit the experimentally obtained volume fraction/compaction stress data, so that σ_f could be considered a function of h. Then, given the fluid pressure p, Eqns (2,3) could be solved for the thickness h. To this end, a Galerkin Finite Element procedure was used, to reduce (2,3) to a system of non-linear (due to the non-linear function $\sigma_f(h)$) algebraic equations, which were then solved using a Newton-Raphson procedure. Boundary conditions were specified on the thickness h, the slope (e.g. dh/dr in an axisymmetric system), the mould moment $\left(\propto \nabla^2 h\right)$ and the mould shear force $\left(\propto \nabla^3 h\right)$, two of these four at any boundary point. The structural solver was tested and verified using known analytical solutions, e.g. that of a clamped circular plate subjected to a uniform load.

In both the fluid-flow and structural problems, cubic-Hermite interpolations were used, for the pressure and thickness respectively, i.e. interpolations were based on nodal values of p and h, but also on their derivatives. This was necessary for the solution of

(2), since its weak form contains second derivatives, for which linear interpolations are zero. Cubic-Hermite elements provide the advantage also of having boundary conditions not only on *p* and *h* to be of the essential type, but also conditions on their derivatives (including fluid velocity). Further, the fluid velocity could be evaluated from (1) with the same accuracy as the pressure; this was advantageous since the velocity is used to evaluate times for flow-front advancement. Once convergence was achieved for the fluid pressure and cavity thickness, a simple explicit scheme was used in conjunction with Darcy's law to advance the flow front.

The simulation can be started under the physically correct assumption of a flat plate under zero load, and then the known loads can be applied to determine the initial fluid-free mould-profile. Alternatively, one can begin with an estimation of the initial profile for the upper mould, based on the known boundary conditions, applied load and preform stress dependence on thickness. The structural solver then brings this estimate to equilibrium with the applied loads. This latter approach is often preferable, due to difficulties caused by the very low compaction stresses at the relatively low initial volume fractions, and the rapid rise in this stress over small changes in volume fraction.

RESULTS AND DISCUSSION

Experimental Observations

Experiments presented utilised 7 layers of the CSM, representing a fibre volume fraction of 0.30 at 4 mm part thickness. Radial and peripheral filling are considered, for the 6 and 10 mm upper mould platens. Figure 5 presents pressure and cavity thickness traces using the 6 mm platen, for both radial and peripheral filling. In all experiments cavity thicknesses significantly lower than 4 mm were observed, due to the relatively low flexural stiffness of the polycarbonate plates, and the large span attempted without additional reinforcement. Throughout the complete study, significantly large thickness deflections have been noted through filling and post-filling.

Considering Figure 5a, fluid pressure at the gate rises quickly to 130 kPa, and filling occurs in 277.5 s. Changes in cavity thickness are noted only for radii less then 150 mm throughout filling and post-filling. The post-filling period appears to be complete within 100 s, a relatively small portion of the filling time. In comparison, peripheral filling is complete in 65.5 s, and significant thickness increases are noted even at central vent. Post-filling occurs very slowly, pressures and thicknesses arguably still settling 500 s after completion of filling. In industry, peripheral filling is preferred due to significantly shorter fill times. However, these experiments highlight the length of time over which cavity thicknesses continue to evolve, which may lead to variation in final part thickness. The slow progression during post-filling can be attributed to the fact that excess fluid is driven in a converging flow to the vent, and that large cavity increases near the periphery result in significant amounts of excess fluid injected during filling.

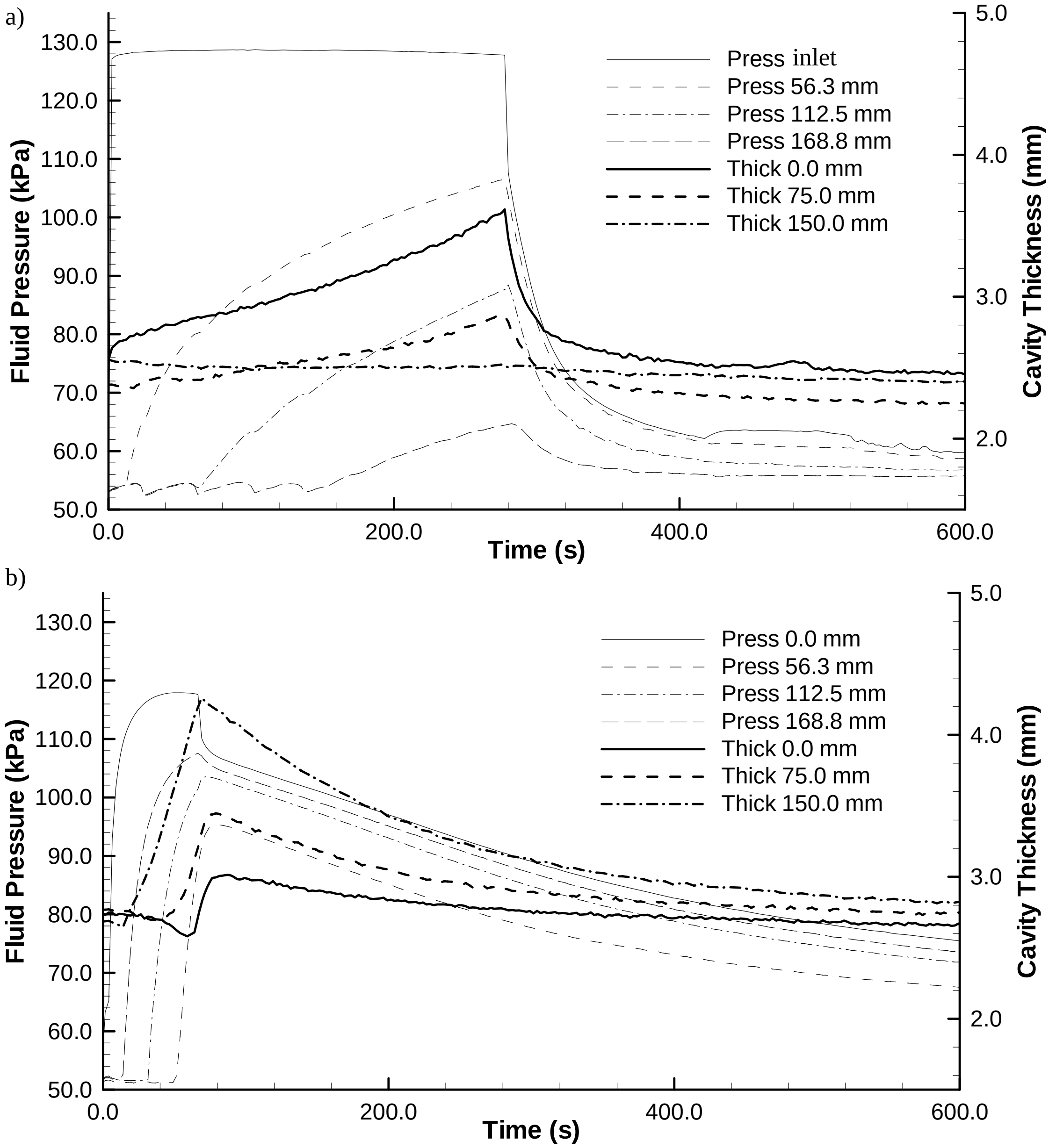

Figure 5: Experimental data traces for trials completed with the 6mm polycarbonate upper mould, a) radial filling, and b) peripheral filling.

Comparison to Simulation

A longer term aim of this project is to predict the evolution of the post-filling phase, but the current focus is currently upon filling. As simple measures of the performance of the simulation, experimental and predicted fill times and maximum mould deflections are presented in Table 1. Maximum deflections have been taken as the total increase in thickness at the mould centre for radial filling, and at a radius of 150 mm for peripheral filling. Predicted fill times are all significantly higher, though some trends in the experimental data have been captured. For radial filling increasing upper mould plate thickness results in an increased fill time. This can be attributed to the smaller mould deflections, and the resulting reductions in preform permeability. The simulation captures this basic trend, as well as the reduction in fill time for peripheral filling.

Increasing the upper mould thickness resulted in a relatively small decrease in both predicted and simulated fill time.

Although the predicted fill-times are much larger than those measured, it should be noted that these fill-times depend strongly on the permeability data used, and that a simple adjustment of this one set of data brings the simulation results very close to the experimental results.

Comparisons of predicted and simulated maximum deflections are better, particularly for radial filling. Radial predictions are in close agreement, while those for peripheral are 50% lower than the experiments. While providing a simple comparison, the maximum deflection and fill time values demonstrate that basic trends are being captured by the presented simulation. This paper represents a first attempt to experimentally characterise and simulate an industrially relevant RTM-Light process. The process is complicated, requiring the consideration of resin flow with a deforming fibrous media, coupled with large deformation structural response of the upper mould.

Table 1: Comparison of experimental and predicted fill times and maximum deflections.

	Radial Filling		Peripheral Filling	
	6 mm Mould	10 mm Mould	6 mm Mould	10 mm Mould
Experimental fill time (s)	277.5	356.0	65.5	59.5
Predicted fill time (s)	1353.5	2748.2	827.6	800.3
Experimental deflection (mm)	1.03	0.2	1.59	0.85
Predicted deflection (mm)	0.79	0.19	0.59	0.43

Comparison of fluid pressure and cavity thickness data is made in Figures 6 and 7 for the radial and peripheral cases respectively. For ease of comparison, both experimental and predicted data sets are plotted against normalised time. The time scale for each individual data set has been normalised against its own fill time.

Figures 6a and 6c compare traces at the three pressure transducers. On a normalised time scale, fluid arrival is predicted well at each location, as signified by a rapid rise in pressure. Pressure magnitudes are predicted reasonably well for the 6 mm mould plate case, up until a normalised time of 0.6. After this point the predicted curves flatten, and the pressures at completion of filling are underestimated. Differences between predicted and experimental fluid pressures are greater for the 10 mm mould plate. Similar observations can be made about the flattening of predicted cavity thickness data presented in Figures 6b and 6d. While qualitative differences exist between the predicted and measured thickness evolution, predicted maximum deflections are good considering the complex nature of the problem addressed.

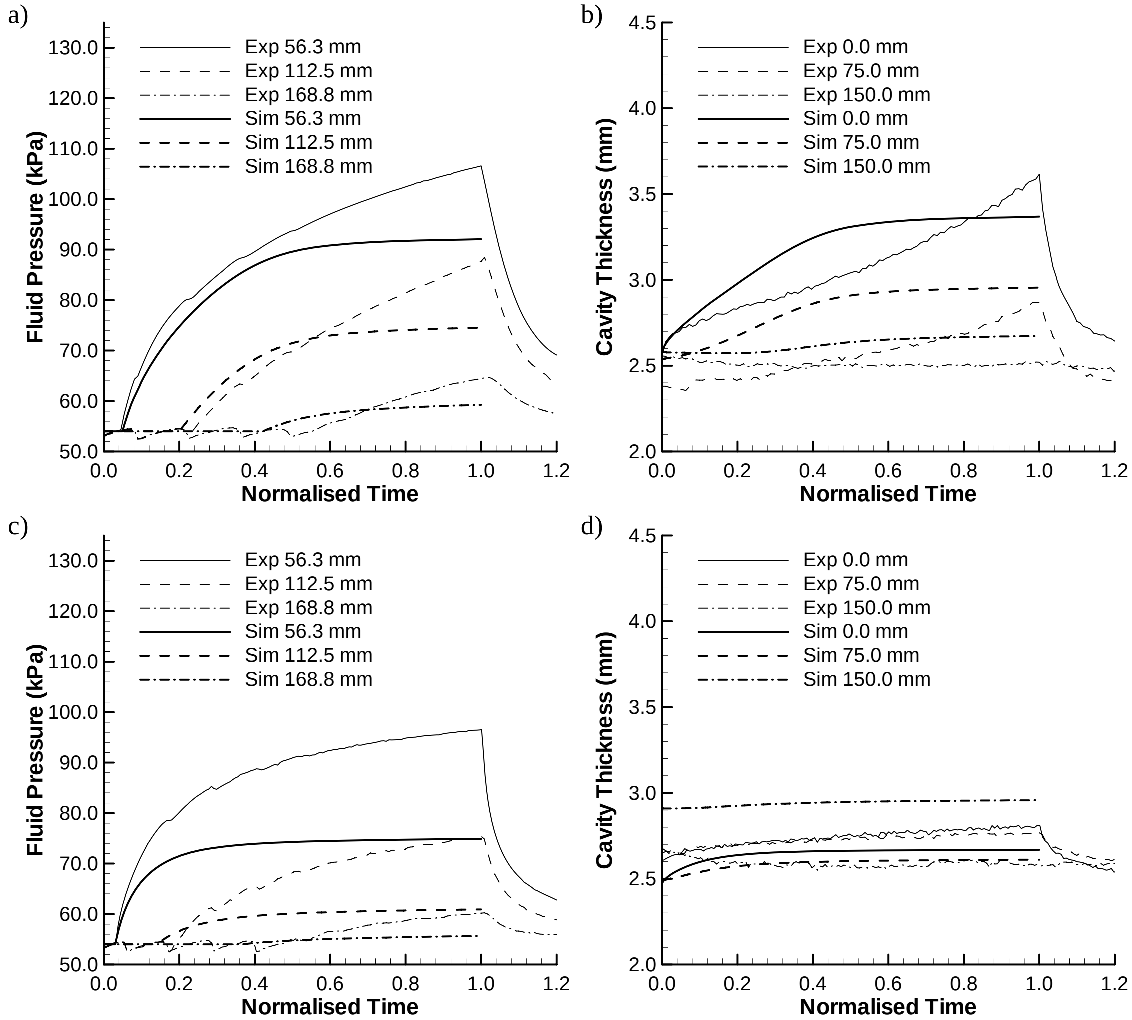

Figure 6: Comparison of experimental and simulated data for radial filling, with time normalised to the fill time. a) Pressure and b) thickness comparisons for the 6mm upper mould. c) Pressure and d) thickness comparisons for the 10 mm upper mould.

Figure 7 demonstrated that the thickness of the upper mould plate was less influential on the evolution of peripheral filling. The fluid pressure traces are similar in magnitude, shape, and timing, for both cases presented. As expected, the 6 mm plate deflected significantly more. The experimental data shows cavity thicknesses increasing steadily, resulting in a large excess of injected fluid that must be removed through the post-filling stage. As for radial filling, fluid pressure magnitudes are underestimated. It is also clear from the pressure data, that the simulated flow front advances quickly relative to the experiment. This is a consequence of a constant pressure boundary condition applied to the outer edge of the preform. In future work, the pressure drop from the fluid reservoir to the mould must be accounted for.

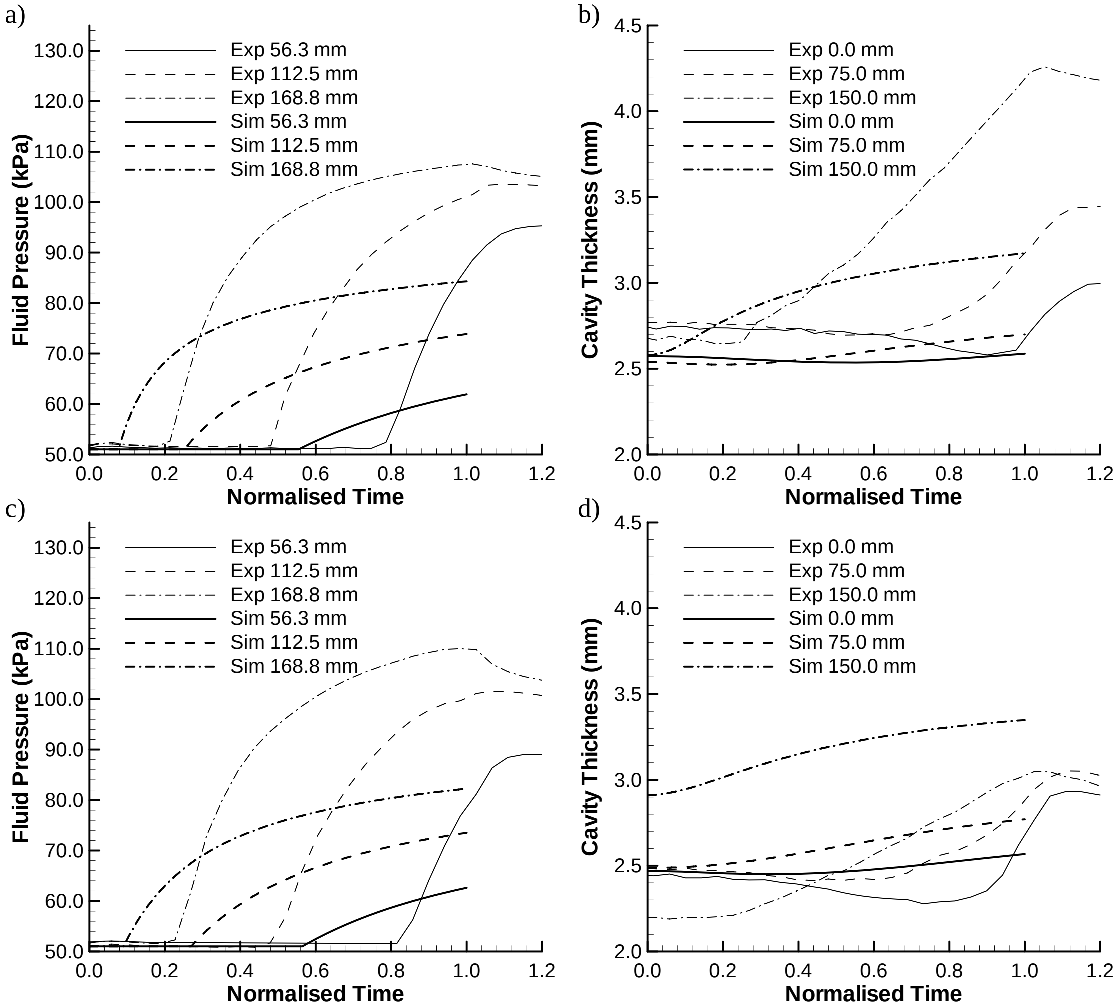

Figure 7: Comparison of experimental and simulated data for peripheral filling, with time normalised to the fill time. a) Pressure and b) thickness comparisons for the 6mm upper mould. c) Pressure and d) thickness comparisons for the 10 mm upper mould.

Discussion

Further work is being carried out to improve the reliability of experimental data, and to improve the accuracy of RTM-Light simulation. The validity of applying the Kirchhoff elastic plate theory to predict the large scale deflections of the upper mould will be checked, by applying various pressure conditions to the mould cavity without fibre reinforcement present. While Darcy’s law has been successfully applied to model resin in a wide range of LCM processes, the dependence of permeability on local cavity thickness significantly complicates prediction for RTM-Light. Cavity thickness is dependent on flexural stiffness of the mould, and the complex compaction response of the fibre reinforcement. Fibre reinforcements are commonly considered to be nonlinear elastic, but have also been shown to exhibit significant viscous effects, and permanent deformation. Time dependent relaxation or creep will be important, due to the low to moderate filling and post-filling times common with RTM-Light. Progressive softening of the reinforcement influences the process due to the cyclic nature of the applied compaction cycle (i.e. cavity thickness decreases during pre-filling, can decrease and then increase during filling, and finally decrease during post-filling). Fibre reinforcement compaction was modelled in this paper using a purely elastic model.

Compaction models involving elastic, viscous, and permanent deformation effects are under development at the University of Auckland, and will be a strength of improved RTM-Light simulations.

CONCLUSION

An initial study was carried out into the RTM-Light manufacturing process. A number of experiments involving the filling of circular preforms were carried out. Quite different results were obtained depending on whether the preforms were filled radially (from a central injection gate) or peripherally. The post-filling period (during which the filled preform continues to undergo thickness changes until equilibrium is reached) was seen to be much longer in the case of peripheral filling. Significant mould deflections were observed in all experiments. The process was modelled using a coupled fluid flow / structural Finite Element simulation. The simulation captured well the experimentally observed trends and gave excellent predictions for the maximum mould deflections during the process.

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