SIMPLE MODELS FOR MOLD FILLING STAGE IN LIQUID COMPOSITE MOLDING AND THEIR APPLICATIONS TO STRUCTURE-PROCESS COUPLED OPTIMIZATION

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ABSTRACT: The current paper is composed of two parts. In the first part, we present the analytical and semi-analytical models to estimate mold filling time in Liquid Composite Molding processes. Their accuracy and efficiency are examined through a comparison with Control Volume / Finite Element simulations.
In the second part, we propose an integrated optimization of structural performance and manufacturing cost. The simple models are incorporated into the optimization procedure to investigate the couplings between structural performance and manufacturing costs. By considering manufacturing at the early stage of product design, excessive manufacturing costs which sometimes arise for the best structural performance can be avoided. In order to be cost effective, different manufacturing routes need to be selected depending on part dimensions, loading conditions and design criteria.

KEYWORDS: LCM (Liquid Composite Molding), Analytical model, Mold filling, Integrated optimization, Cost effective manufacturing

INTRODUCTION

LCM (Liquid Composite Molding) processes refers to composites manufacturing processes which employ liquid resin infiltration into a preform i.e. a dry fabric reinforcement put in the closed mold. LCM processes have been widely used in aeronautic industries, because of their advantages in terms of cost reduction, part integration and control of volatile problem.
From the manufacturing point of view, the main issues are reducing cost (part of which is process cycle time) and eliminating defects such as dry spots and micro/macro voids in the finished article. Thus, predicting resin flow kinetics and pressure distribution in the mold is essential to optimize the process. There have been numerous studies on numerical simulation of mold filling [1]. On the one hand, numerical simulations accurately predict the resin flow kinetics at the expense of a heavy computational cost,

and even more so when the simulations are repeated to optimize the process. For example, computational cost is a burden when simulating resin infusion with high permeability layer because the resin flows through the thickness as well as in planar directions which require three dimensional meshes. On the other hand, closed form models, which typically make more assumptions but are computationally more efficient than numerical simulations, may be preferred for design if their inaccuracy does not invalidate the final solutions. This is the case for the optimization of injection gates and vents.

From the viewpoint of design procedure, it has been a common practice to optimize process parameters only after the structural design is decided. In LCM processes, however, there exist strong couplings between mechanical performance and manufacturing. Fiber volume fraction and orientation are key parameters to structural performance such as stiffness and strength. On the other hand, they are also major factors influencing the preform permeability, a key parameter to productivity and manufacturability in LCM processes. Hence, this procedure, where the manufacturing is considered after the structural design is finalized, may require excessively high manufacturing cost or labor even if it may lead to the best structural performance. For example, it is acknowledged that up to 80% of the manufacturing cost of the structure is fixed once the preliminary structural configuration has been decided [2]. This dilemma calls for an optimization method that simultaneously considers structural performance and manufacturing cost. To investigate the couplings between mechanical performance and manufacturing and to consider many design solutions in the preliminary design stage, it is more efficient to use closed form models rather than numerical simulations.

Besides, this optimization approach can provide a good guideline for optimal selection of manufacturing route. In fact, the criteria for process selection are numerous: the complexity of part geometry, the environmental regulation, industrial strategies, level of part quality (quantity of residual void) etc. Arguably, cost effectiveness and manufacturability are the primary criteria among them. The cost of composite structures is composed of material cost, labor cost and tooling cost. Generally, it is not an easy task to accurately predict the total manufacturing cost, since it is affected by many factors such as labor rate, machine rate, factory lay-out, batch size, etc. However, it is evident that the mold filling time plays a major role in process cycle time since the polymer curing time is usually fixed for a specific resin. Hence, mold filing time can be a metric for the cost-effectiveness of manufacturing process. In addition, it can be a guide to estimate the manufacturability to prevent premature gelation of resin.

In the first part of this article, we present analytical and semi-analytical models for RTM, CRTM and LRI process. In the second part, using these models, a preliminary conceptual design is performed through simultaneous optimization of the structure and the process.

SIMPLE MODELS FOR LCM PROCESSES

Resin Transfer Molding

In RTM processes, analytical solutions are easily derived for the specific mold geometries such as linear channel-like injection and radial injection. To deal with general shaped mold, a simple model was developed for resin transfer molds containing thin flat preforms with isotropic permeabilities [3]. The time required to fill the mold can be calculated by treating the resin flow inside the mold as partly radial and partly channel-like flow. This simple model for mold fill time of two dimensional resin transfer molds with isotropic permeability can be applied to the preform with anisotropic permeability through the coordinate transformation [4].

We consider complex mold geometry (0.23m × 0.14m) with a circular insert in Fig. 1. Using the simple model, we estimate the mold filling times for 4 different injection gates: single gate at A, B, C and simultaneous injection at three gates. The injection pressure is 0.1MPa, and the injection gate radius is 1.5mm. The preform permeability is 10^{-10}m^2 and the resin viscosity is 0.1Pa s. The results are compared with those by numerical simulation by CV/FEM (Control Volume / Finite Element Method) [5]. Good agreements are observed even for the complex mold geometry with inserts (Fig.5).

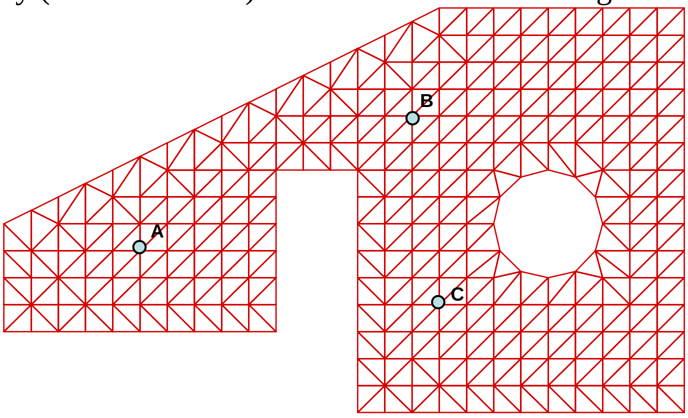

Fig. 1 Mold geometry for the validation of simple model for RTM

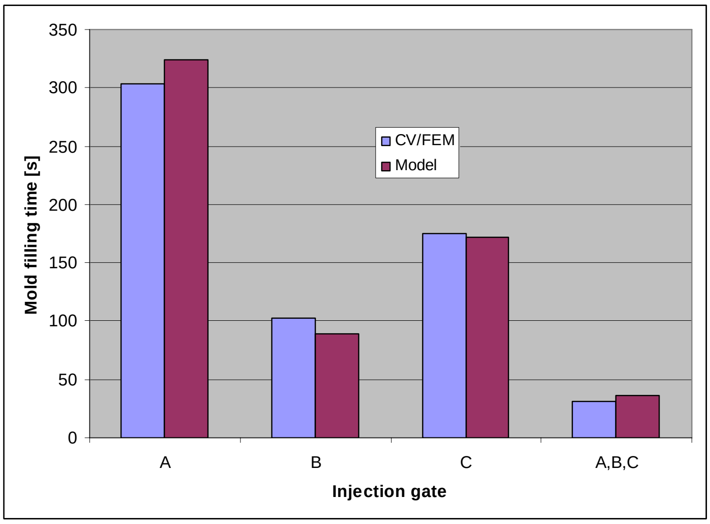

Fig. 2 Comparison of mold filling time in RTM

Compression Resin Transfer Molding

Saouab et al. proposed closed form solutions for CRTM processes [6]. In the present study, we consider separate injection and compression process: injection at constant pressure and compression at constant mold closing speed. For a linear flow condition (Fig. 3), we can derive the closed form solutions for total mold filling time as a sum of injection time (t_{inj}) and compression time (t_{comp}).

$$t_{inj} = \frac{\mu(1-V_f)L^2}{2KP_{inj}}\left(\frac{1-V_f}{V_f}\right)^4\left(\frac{V_{fo}}{1-V_{fo}}\right)^4, \quad t_{comp} = \frac{H}{U_c}\left(\frac{V_f}{V_{fo}}-1\right) \qquad (1)$$

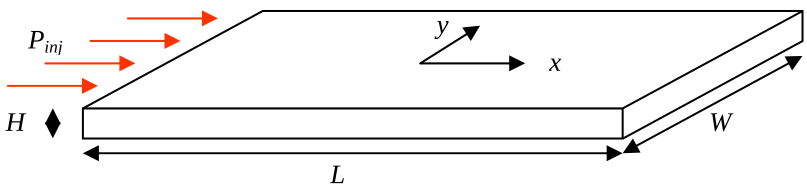

Fig. 3 Mold geometry and dimensions

We can see that the total mold filling time can be decided from U_c, mold closing speed, and the V_{fo}, fiber volume fraction at the moment when the injection ends and the compression begins. Mold closing speed is decided by the constraints of maximum pressure in the mold and the total mold clamping force which is the sum of resin pressure and compaction pressure by preform deformation. Then, we can obtain the V_{fo} to minimize the mold filling time.

$$F_{mold} = F_{resin} + F_{fiber} = \frac{U_c \mu L^3 W}{3KH} + A_s \frac{\sqrt{V_f / V_o} - 1}{\left(\sqrt{V_{max} / V_f} - 1\right)^4} LW \qquad (2)$$

Liquid Resin Infusion

A striking difference of LRI from conventional RTM process is the adoption of High Permeability Layer (HPL or High Permeability Medium, HPM) to facilities the resin flow and to reduce the infusion time. The resin flow in HPM leads much faster than in reinforcement, due to the big difference in permeability. This preferential flow in HPM induces the through thickness resin flow. Hence, a new approach is required considering cross flow. The mold filling process in LRI can be divided into 3 steps (Fig. 4).

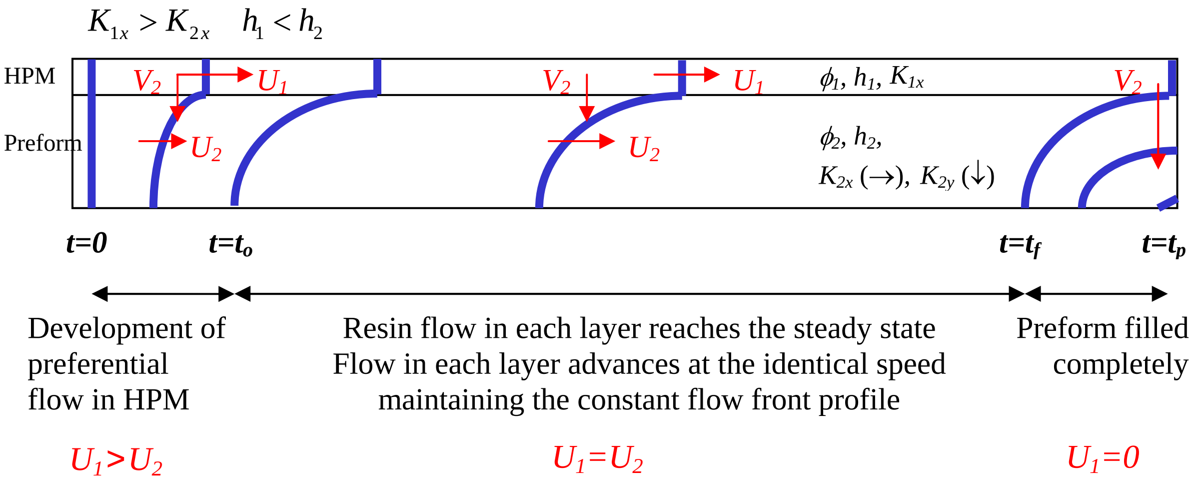

Fig. 4 Mold filling process in LRI

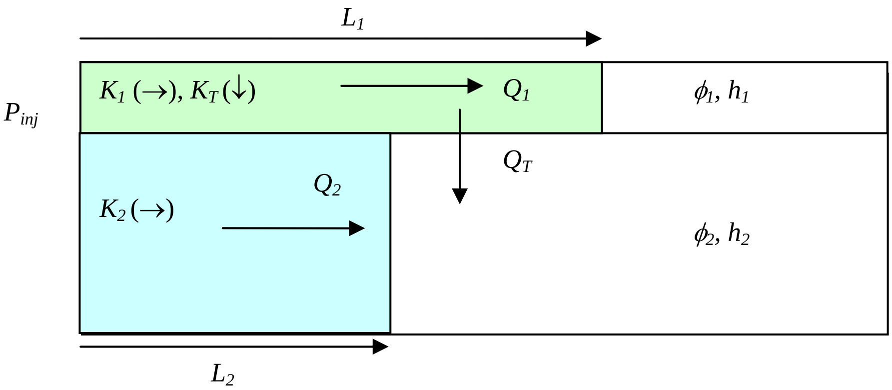

Fig. 5 Flow kinetics in LRI ($0<t<t_f$)

Until the flow reaches the end of HPM ($t=t_f$), it is assumed that the pressure distribution is linear at each layer (Fig. 5). From these pressure distributions, we can obtain average pressure of transverse flow from HPM to fiber preform $P_m = \frac{P_{inj}}{L_1} \frac{L_1 - L_2}{2}$.

From Darcy's law we can relate the resin pressure with flow rate. Considering mass conservation of each layer, we can describe the next governing equations.

$$\begin{cases} \frac{K_1}{\mu}\frac{P_{inj}}{L_1}h_1 - \frac{K_T}{\mu}\frac{P_{inj}}{h_1}\frac{(L_1-L_2)^2}{2L_1} = \phi_1 h_1 \frac{dL_1}{dt} \\ \frac{K_2}{\mu}\frac{P_{inj}}{L_2}h_2 + \frac{K_T}{\mu}\frac{P_{inj}}{h_1}\frac{(L_1-L_2)^2}{2L_1} = \phi_2 h_2 \frac{dL_2}{dt} \end{cases} \quad (3)$$

Once the flow reaches the tip of HPM, the transverse flow from HPM to preform and the longitudinal flow in preform fill the remaining dry preform (Fig. 6).

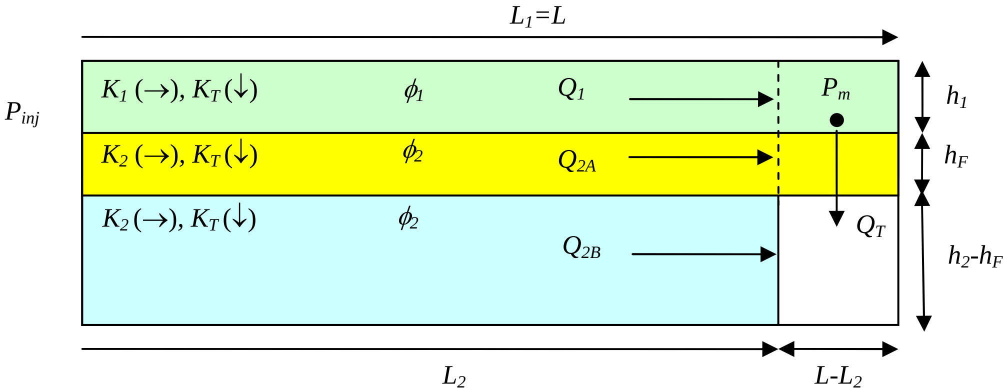

Fig. 6 Flow kinetics in LRI ($t_f < t < t_p$)

We adopt the assumption of linear pressure distribution again. P_m is the average pressure in the zone of (L-L_2) and (h_1+h_F). From Darcy's law, we can describe the relations of each flow rate. Taking into consideration the mass conservation of each zone, we can derive the governing equations.

$$\begin{cases} Q_1 + Q_{2A} = Q_T \\ Q_{2B} + Q_T = -\phi_2 \frac{d((h_2 - h_F)(L - L_2))}{dt} \end{cases} \quad (4)$$

We introduce an assumption that the unfilled zone (L-L_2 and h_2-h_F) of preform maintains the constant aspect ratio. These set of coupled PDEs can be solved by simple numerical integration scheme such as Runge-Kutta method. We present the comparison of the results by models and CV/FEM simulations in Tables 1~2 and Fig. 7.

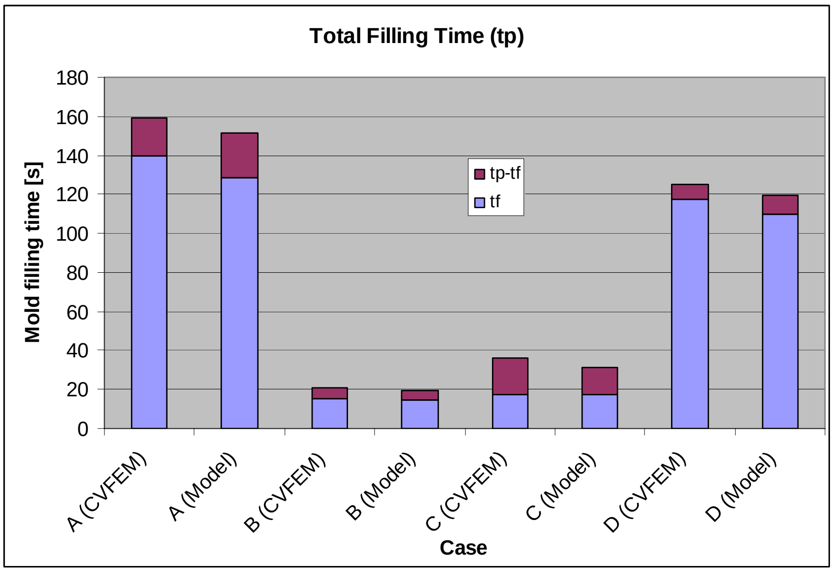

Fig. 7 Comparison of mold filling time in LRI

Even though it is not a closed form solution, the proposed model shows a much better numerical efficiency than numerical simulation. A CV/FEM simulation with 3507 nodes and 6000 triangular elements takes 1897 seconds of CPU time with Pentium 4 processor of 2.6GHz. With the same CPU, on the contrary, the simple model needs only

1.2 second for one calculation (120 seconds for 100 calculations) using the time increasing step of 10^{-4} second in Runge-Kutta method.

Table 1 Material properties for simple LRI model

ϕ_1	ϕ_2	K_T [m^2]	K_2 [m^2]	μ [Pa s]	h_1 [m]	L [m]	P_{inj} [Pa]
0.99	0.5	1.47×10^{-11}	8.80×10^{-11}	0.1	0.002	0.3	1.00×10^{5}

Table 2 Sample cases for preform permeability and thickness

Case	K_1/K_2	h_2/h_1
A	10	10
B	100	5
C	100	10
D	10	5

STRUCTURE-PROCESS COUPLED OPTIMIZATION IN LCM

Integrated Optimization of Structural Performance and Manufacturing Process

We suggest an integrated optimization method simultaneously considering structural performance and manufacturing process. The design objective is the minimization of structural weight. We assign structural and process constraints at the same time. As a structural constraint, the stiffness is considered to constrain the strain under the load. As process constraints, the mold filling time, the mold clamping force and the maximal pressure are treated.
To achieve these purposes, four parameters are optimized: layer number, layer stacking sequence, final fiber volume fraction and final part thickness. Fiber orientation is selected from the pre-assigned angle set. In this work, we employ the 4 angle set composed of 0°, 45°, 90°, -45°. The layup of laminated plate is assumed to be symmetric. As the optimization scheme, we apply the genetic algorithm. To deal with the layer number variation, crossover and mutation operators are modified as in Park et al. [6]. Elastic moduli of composites can be obtained from the moduli of the constituents by the Halpin-Tsai equations. As a metric of the structural stiffness, we define the strain norm using classical lamination theory.

$$\varepsilon = Max_{top,\,bottom}\left[\sqrt{0.5\times(\varepsilon_1+\varepsilon_2)^2+0.5\times(\varepsilon_1-\varepsilon_2)^2}\right] \quad (5)$$

The permeability according to the fiber volume fraction variation is obtained using Kozeny-Carman equation. The anisotropic permeability tensor in each layer can be related to the principal permeabilities by tensor transformation equation. The gapwise averaged permeability model is applied to obtain the perform permeability composed of layers with different orientations, assuming that the in-plane permeabilities in principal directions are of the same order.

Sample Problem

As a design object, the rectangular plate under the flexural bending is regarded. The mold geometry and injection port location are illustrated in Fig. 3. We consider RTM, CRTM and LRI as a candidate for manufacturing route. The unidirectional carbon stitched mat (fiber density: 1.79g/cm^3, areal weight: 152g/m^2) is used as reinforcement. The in-plane permeabilities of mat are 10^{-9} m^2 in fiber direction and 1.33×10^{-10} m^2 in transverse direction at the fiber volume fraction of 0.4, while the permeability in the thickness direction is 1.33×10^{-13} m^2. For the sake of easy layup, four plies stacked in the same orientation make up one layer. The resin viscosity is 0.15Pa s. In RTM process, the injection pressure is maintained at 0.15MPa. In CRTM process, injection is performed under the constant pressure of 0.12MPa. Maximum allowable mold clamping force is 300kN and maximum allowable pressure is 0.15MPa. Mold closing speed should not exceed 1 mm/s. In LRI process, injection pressure is assumed to be 99.5kPa, the difference between atmospheric pressure (0.1MPa) and vacuum pressure (500Pa). HPM permeability is 10^{-8} m^2 and its thickness is 1 mm.

Results and Discussion

For the various loading conditions and plate dimensions, optimal material configurations are obtained for each manufacturing process (Tables 3~4).

Table 3 Results of structure-process coupled optimization
(L=0.5m, W=0.5m, ε_c=0.001, t_c=240s)

Loading		Process	Weight [g]	Optimal configuration			
M_x [N]	M_y [N]			V_f	H [mm]	Stacking sequence (symmetric layup, ⎜s)	Layer number
0	10^3	RTM	2962.38	0.4145	8.20	$90^3\ 0^2$ ⎜s	10
		CRTM	2898.55	0.4255	7.99	$90^4\ 0$ ⎜s	10
		LRI	2898.55	0.4255	7.99	$90^4\ 0$ ⎜s	10
10^3	10^3	RTM	4340.88	0.4612	11.79	$90\ 0^2\ 90\ 0\ 90^2\ 0$ ⎜s	16
		CRTM	4197.28	0.5573	10.89	$90\ 45\ -45\ 0^6$ ⎜s	18
		LRI	4432.10	0.4496	12.10	$0\ 90\ 45\ –45\ 90\ 0^3$ ⎜s	16

**M_x and M_y denote the moment per unit length*

Table 4 Results of structure-process coupled optimization
(L=1.0m, W=0.5m, ε_c=0.001, t_c=600s)

Loading		Process	Weight [g]	Optimal configuration			
M_x [N]	M_y [N]			V_f	H [mm]	Stacking sequence (symmetric layup, ⎜s)	Layer number
0	10^3	RTM	6166.75	0.3951	8.61	$90^3\ 0^2$ ⎜s	10
		CRTM	5924.75	0.4145	8.20	$90^3\ 0^2$ ⎜s	10
		LRI	5797.11	0.4255	7.79	$90^4\ 0$ ⎜s	10
10^3	10^3	RTM	8780.60	0.4549	11.96	$90\ 0^2\ 90\ 0^4$ ⎜s	16
		CRTM	8681.87	0.4612	11.80	$0\ 90^2\ 0\ 90\ 0^3$ ⎜s	16
		LRI	8684.37	0.4611	11.80	90 0 45 -45 0 -45 45 0 ⎜s	16

We can see that optimal material configuration changes according to the manufacturing route as well as the loading conditions, the design constraints and the plate dimensions. Cost-effectiveness of each process can be investigated with the optimization results referring to the material cost and the batch size. For example, CRTM process results in lighter structure than LRI process does under the same design constraints, in some case (e.g. M_x=1000N, M_y=1000N, L=0.5m, W=0.5m). However, CRTM process needs more fiber mats (18) than LRI does (16) for each product. Furthermore, the total manufacturing cost also depends on the batch size. Since the equipment and tooling cost per product is critical, LRI may be better in terms of manufacturing cost, for the low production number. On the other hand, the equipment and tooling cost goes marginal, as the production number increases. Otherwise, we can assign different mold filling time constraints with the aid of more exact model for the total manufacturing cost evaluation.

CONCLUSIONS

Analytical and semi-analytical models have been proposed for Liquid Composite Moldings: Resin Transfer Molding, Compression Resin Transfer Molding and Liquid Resin Infusion. They are not only numerically efficient but also accurate enough to be applied in a global optimization procedure. The semi-analytical LCM models have been applied to the integrated optimization of structural performance and manufacturing process. In the preliminary design stage, this approach provides a good guideline to predict the cost-effectiveness of each process for given design criteria, structural size and loading conditions.

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REFERENCES

1. J. Mackerle, “Finite Element Analyses and Simulations of Manufacturing Processes of Composites and Their Mechanical Properties, A Bibliography (1985-2003),” *Computational Materials Science*, Vol. 31**,** 2004, pp. 187-219.

2. K. Wang, D. Kelly, and S. Dutton, “Multi-Objective Optimisation of Composite Aerospace Structures,” *Composite Structures*, Vol. 57, 2002, pp. 141-148.

3. A. Boccard, W. I. Lee, and G. S. Springer, “Model for Determining the Vent Locations and the Fill Time of Resin Transfer Molds,” *Journal of Composite Materials*, Vol. 29, No. 3, 1995, pp. 306-333

4. C. H. Park, W. I. Lee, W. S. Han and A. Vautrin, "Multi-Constraint Optimization of Composite Structures Manufactured by Resin Transfer Molding Process," *Journal of Composite Materials*, Vol. 39, No. 4, 2005, pp. 347-374.

5. M. K. Kang and W. I. Lee, “A Flow Front Refinement Technique for the Numerical Simulation of the Resin Transfer Molding Process,” *Composites Science and Technology*, Vol. 59, 1999, pp. 1663-1674.

6. A. Saouab and J. Bréard, “Analytical Modeling of CRTM and RTM Processes: Part A. General Mathematical Development,” *International Journal of Forming Processes*, Vol. 9, No. 3, 2006, in press