FLOW MODELING OF THE COMPRESSION RESIN TRANSFER MOLDING PROCESS

Jeffrey M. Lawrence[1], Pavel Simacek[1], Susanna Laurenzi[2] and Suresh G. Advani[1]

[1]*Center for Composite Materials and Department of Mechanical Engineering*
University of Delaware, Newark, DE 19716
[2]*School of Aerospace Engineering, University of Rome La Sapienza, via Eudossiana 18, 00184 Rome, Italy*

ABSTRACT: The automotive industry has been reluctant in the use of advanced composite components due to long cycle times associated with their manufacturing processes. Recently, a promising Liquid Composite Molding (LCM) process coined as Compression Resin Transfer Molding has attracted interest. In this process, the fiber preform is placed in the mold in the same manner as in Resin Transfer Molding, but the mold is not closed entirely, creating a fiber-free channel on top of the preform. The measured amount of resin is injected into the mold which first fills this channel due to its high permeability. Then, the mold is closed, thus forcing the resin to infuse the preform. The final stage of the process compacts the preform to its final part thickness, hopefully saturating the entire perform with resin. Due to its similarity with compression molding process and injection through the thin thickness of the part, short processing times can be achieved. The goal in this process not unlike all LCM processes is to ensure resin does fill all the empty spaces between the fibers. However, this process introduces several new issues that must be addressed in the flow model. The first issue is to account for the compaction of fiber preform, both when it is dry and when it is saturated with resin. Literature has shown that fiber compaction is not only non-linear, but exhibits visco-elastic behavior as well. Furthermore, the through thickness flow behavior under compression with perform serving as one wall will require one to couple flow in reducing gap with impregnation inside a perform. Finally, with a complex mold, visualization of the flow progression can be difficult, so a new method of sensing is desired. This paper will describe how these issues can be addressed, and presents the results of an experimental study conducted on a small, lab-scale molding apparatus. The compaction behavior of the fabric is explored and will be incorporated in the modeling and simulation of the compression resin transfer molding.

KEYWORDS: Liquid Composite Molding, Compression Resin Transfer Molding, Mold Design

1. INTRODUCTION

Composite materials can be tailored to have better mechanical properties than metals, but their use can only increase by developing new cost- effective manufacturing technologies. One of the promising technologies available today is the Compression Resin Transfer Molding (CRTM). It can manufacture parts with high fiber volume fraction, high surface quality and excellent tolerance control of net shape and is suitable for high volume production. However, it requires initial investment in expensive equipment which the industry can recuperate with medium-high volume production. For this reasons, one of the potential main users of compression molding is the automotive industry with production runs of between 1000 and 10,000 parts per year requiring a good surface finish [1]. Therefore, developments are necessary to improve production times and part quality, including new compression press systems. The aim of this research is to propose and validate a new cost effective press. Compaction behavior [2-4] of fabrics was investigated because compression modifies the processability by altering permeability to resin flow.

2. Modeling the Compression Resin Transfer Molding Process

To achieve fast, repeatable and reliable process one needs to acquire some predictive modeling capability to simulate the resin flow within the gap and preform during the injection. This capability is readily available for RTM process modeling, but to model the CRTM flow, it has to be somewhat extended. For modeling purposes, the injection can be divided into three phases. First, the resin is injected into the partially open mold cavity. This phase can be modeled directly by RTM simulations by treating the gap as a layer of high permeability distribution media, similar to DM in other RTM variations [1, 2]. In the second phase, the mold is being closed but there is still a gap between mold surfaces and preform. The squeezing of the gap part already filled with the resin will drive the resin into (i) the remaining unfilled gap regions and (ii) the preform. In the last phase, the mold is in full contact with the preform and the preform gets compacted to its target thickness. Some preform regions are already saturated with resin. The resin may be squeezed out from filled regions and be driven into regions that are still unsaturated. Practically, the individual phases may overlap. To model the second and third phase of the process with RTM simulation is nontrivial, but possible [5]. Essentially, the "squeezed" saturated regions – in gap or in preform – have to be replaced by a proper flow rate source and its magnitude must be modified with the time. Simultaneously, the material parameters must be continuously updated as the fiber volume fraction and permeability of the preform vary with the deformation. We were able to model these stages within our RTM simulation package, LIMS [6, 7], by taking advantage of its scripting and control capabilities [5]. It is, nonetheless, admitted that the resulting scheme is suitable for academic research but hardly for immediate industrial deployment and more robust approaches are in development.

3. Lab Scale Press Mechanism

One of the drawbacks of this process is the cost associated with the press / mold necessary to make composite components with this process. This cost will be recuperated by either high production yields typical of the automotive industry or the high cost of sophisticated parts in the aerospace industry. However, this benefit can not be realized in a laboratory setting. Therefore, it was desired to design and build a simple, inexpensive lab-scale press and mold in order to initiate research in this field. The first area to consider is the closing mechanism. Industrial presses and other clamping devices, such as Instron testing machines make injection and vent egress difficult [8]. It was desired to develop a closing mechanism independent of such a device that would allow for a lab-scale press with the ability to have tubing egress for resin injection and venting. The injection / compression molding process consists of a rapid traveling of the platens over a relatively short distance. Therefore it was decided to close the press using a heavy-duty hose. The hose is to be placed between two platens, and the inflation of the hose will raise the traveling plate, as seen in Figure 1.

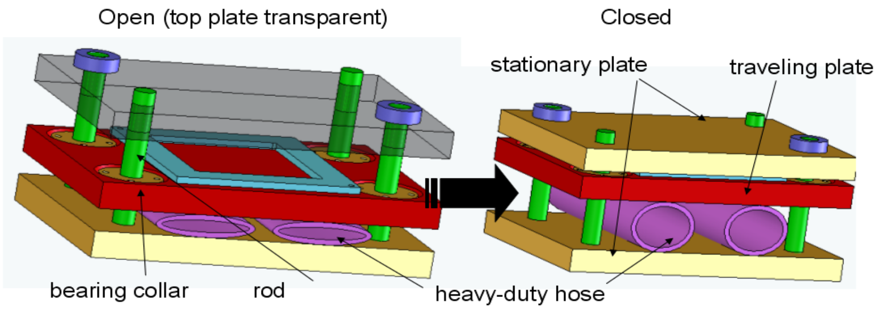

Figure 1: The inflation of a heavy-duty hose between two platens will generate the clamping of the press

3.1. Investigation of closing speeds /forces

The hose, of radius r_h, will have a circumference of $2\pi r_h$. This total perimeter will remain constant as the hose is inflated / deflated. At the state depicted in Figure 2, the hose is under an internal pressure of p_i, separates the lower (fixed) plate from the traveling plate by a distance d, and is in contact with the plates along a distance of l.
The hose, when placed in between the two plates and pressurized with fluid will contour to a rectangular geometry in the middle of the plate. At the ends, the unconstrained hose will assume the shape of a semi-circle. Therefore, the total perimeter in this configuration will be equal to the circumference of the original hose:

$$\text{cirm}=2l+\pi d = 2\pi r_h$$
$$\therefore l = \frac{\pi}{2}\left(2r_h - d\right) \tag{1}$$

Therefore there is a geometric constraint between the contact length (l) and the separation distance (d). There will be three forces counteracting the pressure in the hose: the weight of the traveling plate, the compaction pressure of the fabric, and the fluid pressure of the injecting resin.

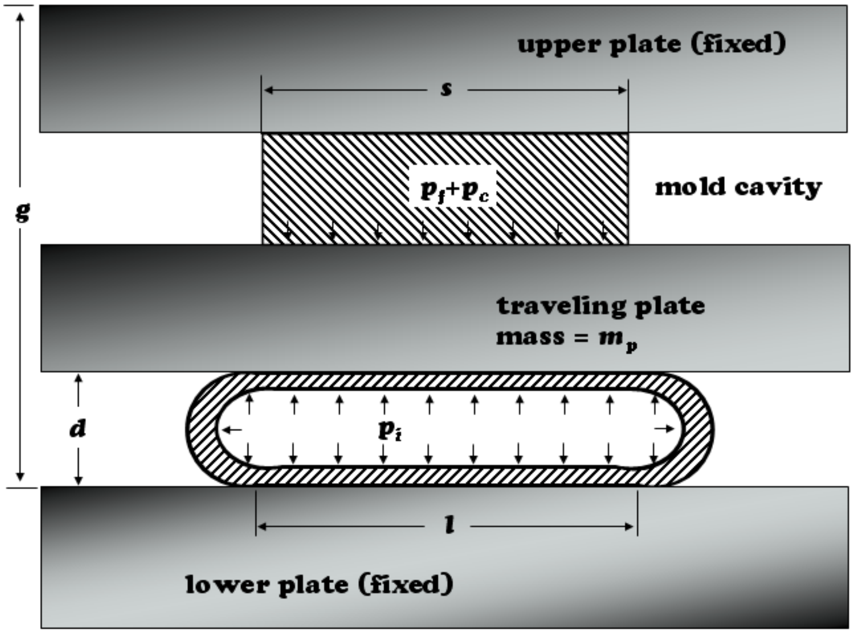

Figure 2: The internal pressure of the hose counteracts the weight of the traveling plate, the compaction pressure of the fabric, and the fluid pressure of the resin.

Force balance of the hose gives the following result:

$$p_i = \frac{2}{\pi} \frac{m_p + sh\left(p_f + p_c\right)}{h\left(2r_h - d\right)}, \quad d = 0..2r_h \tag{2}$$

Therefore, the internal pressure that is required to maintain the traveling plate with the fabric compaction and resin infusion can be found. Some analysis can be done to identify what type of water pump would be necessary to sustain typical manufacturing loads. One important factor to identify is the denominator term in equation (2). As the plate gets lifted to the point where the hose is fully inflated to a circle ($2r_h$=d), the required pressure would be infinite. Additionally, there is an exponential increase in the required internal pressure as the separation distance (d), approaches $2r_h$. This highlights the fact that this closing method is excellent for quick rising over a short distance, but is not adequate for lifting the plate over great distances. This formulation can be used to select an appropriate pressure source.

4. Compaction Testing

Different series of experiments were performed in order to highlight the viscoelastic behavior of preform during compression [9]. The first series of experiments consisted of evaluating the repeatability of the compaction process and the clamping force generated on dry preform. The second series of experiments investigated the material's hysteresis response under consecutive compression and the effects of the number of layers on the compression stress. The third series of experiments was performed to evaluate the effects of fluids on the preform response and compaction force.

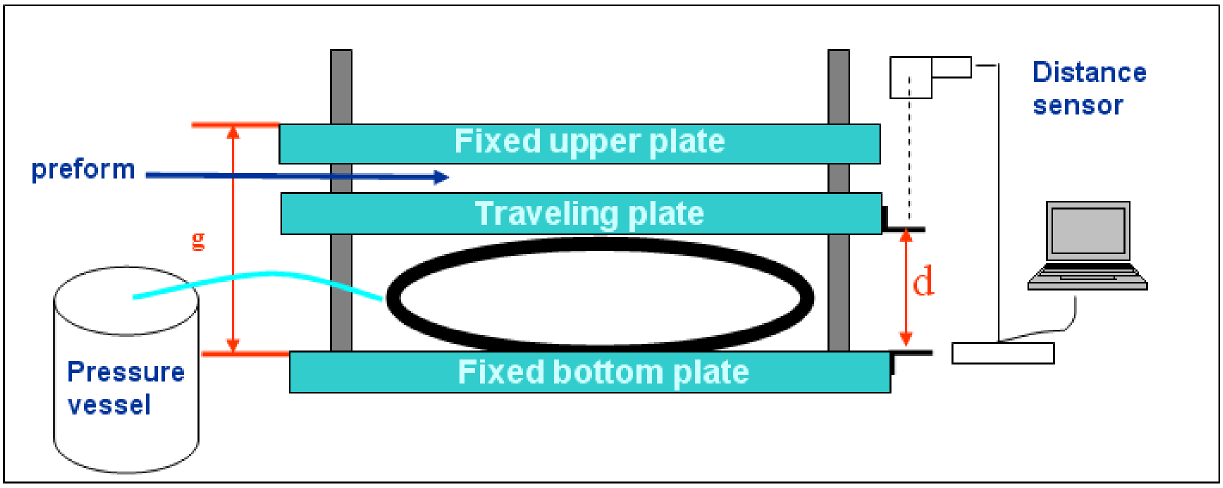

Figure 3: Schematic representation of set-up used for compaction tests

4.2. Experimental procedures

The set-up used for the compaction experiments is shown in Figure 3. The upper plate is fixed at determine height s, the layers are placed in the middle of traveling plate and the hose is inflated using a pressure vessel. The hose pushes the middle plate towards the upper fixed plate, compressing the material. When the distance d does not vary anymore, the maximum compression is reached. The measurement of both distances d and s is performed with a laser sensor having zero reference on the bottom plate. Knowing d and g, the clamping force is estimated from the calibration curve (equation (2) with correction) and the ultimate thickness *h* of the preform is calculated using simple geometric relations. The clamping force is increased during the experiment by increasing the pressure inside the hose. In each experiment the pressure varied from 35kPa to 310kPa. The experiments were performed with both 5 and 10 layers of 12.7cm x 12.7 cm square pieces. In each experiment a new sample was used. In case of plain weave, during the lay-up step, particular attention was given to match warp to warp and weft to weft direction as best as possible. For experimental series of repeated compressions on the same sample, layers were separated and left without constriction between two consecutive compressions in order to allow recovery of any elastic deformation of fibers. For experimental series performed to evaluate the effects of fluids on compaction behavior, the stacking sequences were prepared by wetting and assembling layers as a classic hand lay-up process with no rolling.

4.3. Results and discussion

The repeatability of the compression process, verified during the calibration test, was confirmed with the first experimental series, obtaining similar value of fiber volume fraction for the same clamping force. The trend of fiber volume fraction of woven fabric and random mat was similar. Both material show a power law trend as reported in literature by other authors [4]. The curves obtained for woven show modest power exponent compared to the random, which means the volume fraction increases much more slowly with the increment of force as compared to the case of random. The results are reported in Figure 4: hysteresis due to permanent deformation is presented for both materials. The compression reduces the gaps among fibers and yarns and the fibers find new collocation. In case of random mat, the interlayer packing seems to be the most important factor causing the enhancement of fiber volume fraction. In fact, a bigger percentage increment of volume fraction has been carried out for 10 layers than 5 layers. In the case of woven, the hysteresis behavior is principally due to the nesting and intra-packing phenomena that globally increases the fiber volume fraction.

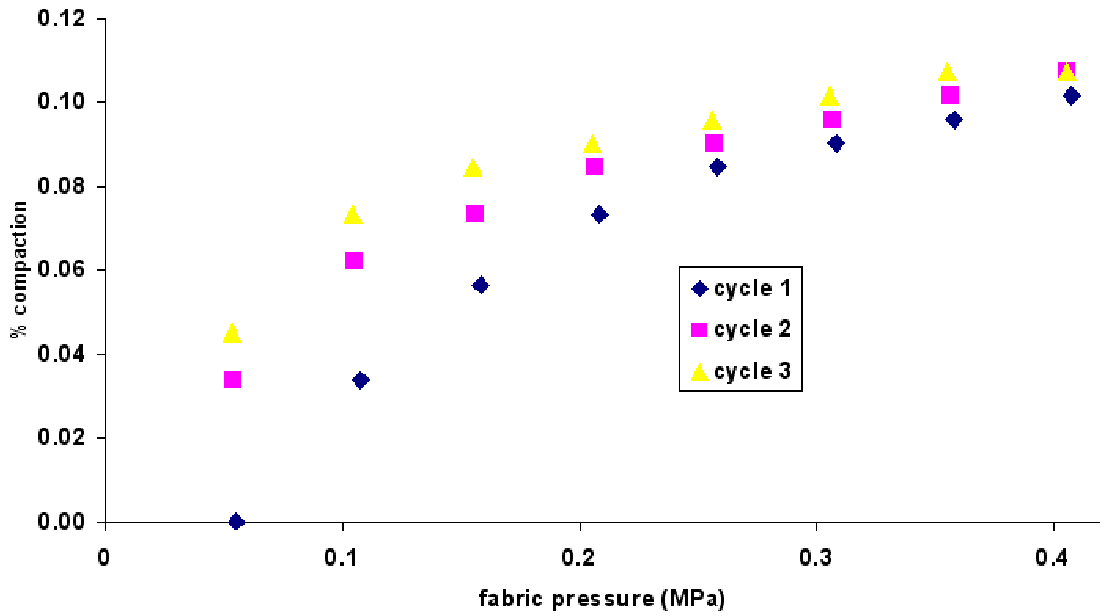

Figure 4: Percent compaction as a function of compaction pressure for three consecutive compressions performed on the same sample of random mat glass

In order to highlight the phenomenon of nesting, the thickness per layer as function of fabric pressure has been plotted. As shown in Figure 5, nesting exists at beginning of compression for woven but not for random.

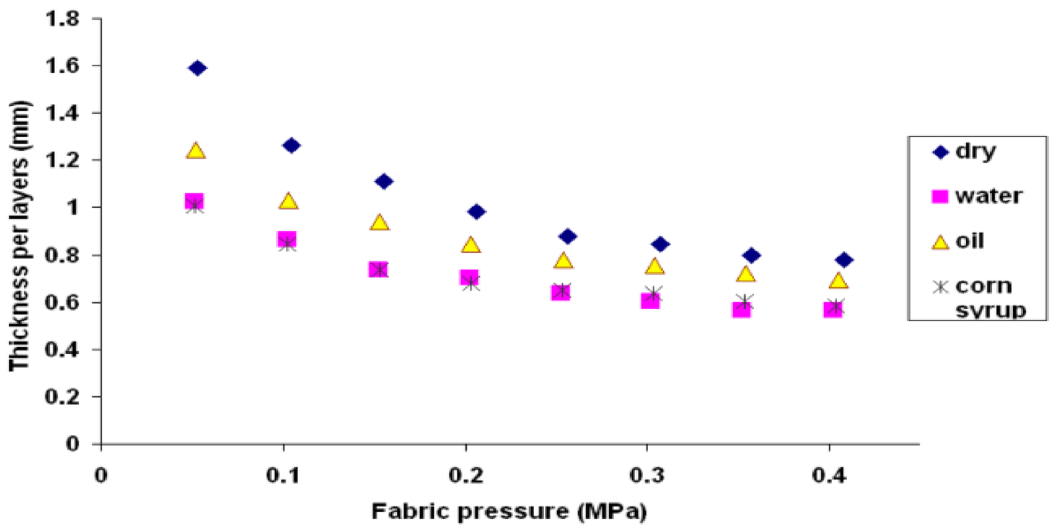

Figure 5: Thickness per layer versus fabric pressure for random mat glass. The viscosity of oil is 54 cps and the viscosity of corn syrup is 146 cps.

The dry preform shows the highest thickness per layer, comparing results obtained for dry assemblies and wetted assemblies. This phenomenon should be expected because of the friction between tows. The fluid serves to lubricate the fibers making the settling during the compression easier. Therefore, a lower compression force is required to obtain the same thickness (fiber volume fraction). Comparing the curves obtained using liquids, the curves with water show the lowest required compression force. This result could be due to both lubrication and wettability of water.

5. Injection of Parts

Now that the compaction tests have been conducted, and it is known that this apparatus can sufficiently compact the preform to appropriate levels, the next step is to use it to manufacture composite components. Previous sections of the paper described the design and construction of the press system. This was used to conduct the compaction tests. Next, a mold apparatus needs to be added in order to manufacture composite parts. For initial testing, it was decided to construct a mold to manufacture circular parts. The reason for this is the ease in which a circular mold can open / close and not bind up during operation. The mold was designed much like a piston system, with a ring and plunger.

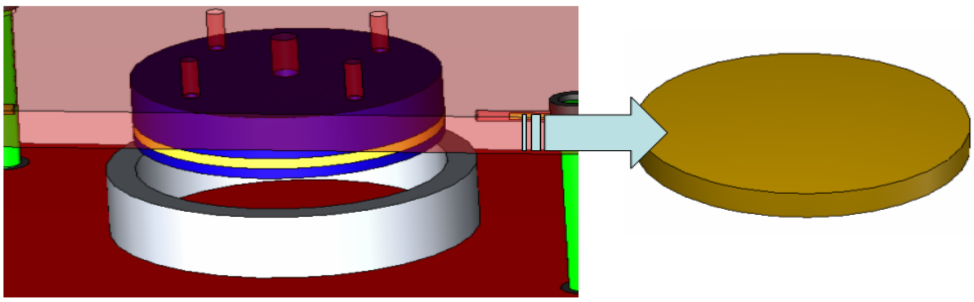

Figure 6: The mold was designed to manufacture circular disks to facilitate in the operation of the press

5.4. Manufacturing of parts

The procedure was as follows. First, the preform is placed inside the cavity. Then, the hose is inflated to raise the traveling plate such that the volume between the top of the preform stack and the top of the mold is equal to the volume of resin to be ultimately injected. Once the desired thickness is reached, the resin is poured into the mold. Next, the traveling plate is again raised, compacting the preform, until the laminate reaches the required fiber volume fraction. During this compaction process the thickness is monitoring by a distance sensor. When the final part thickness is achieved, the gate and vent are clamped, and the part is allowed to cure. The fiber volume fraction is determined by the following:

$$v_f = \frac{A_w n}{\rho_f h} \tag{3}$$

In equation (3), Aw is the weight per unit area of the fabric, n is the number of layers, ρ_f is the average fiber density, h is the thickness of the preform. The total volume of resin required in the cavity to impregnate the preform is:

$$V_{\text{resin}} = (1 - v_f)\pi R^2 h_{final} \tag{4}$$

In this, h_{final} is the thickness of the preform for a given number of layers to obtain the fiber volume fraction v_f; R is the radius of the cavity. Using the compaction curve as a rule of thumb establishes h_{final} for a given fiber volume fraction. The ultimate hose pressure can be determined in two ways. First, if there is no compaction curve available, the pressure inside the hose can be increased slowly until the ultimate preform thickness is achieved. The second way is to use the compaction curve for establishing the force required for compaction and therefore the pressure in the hose.

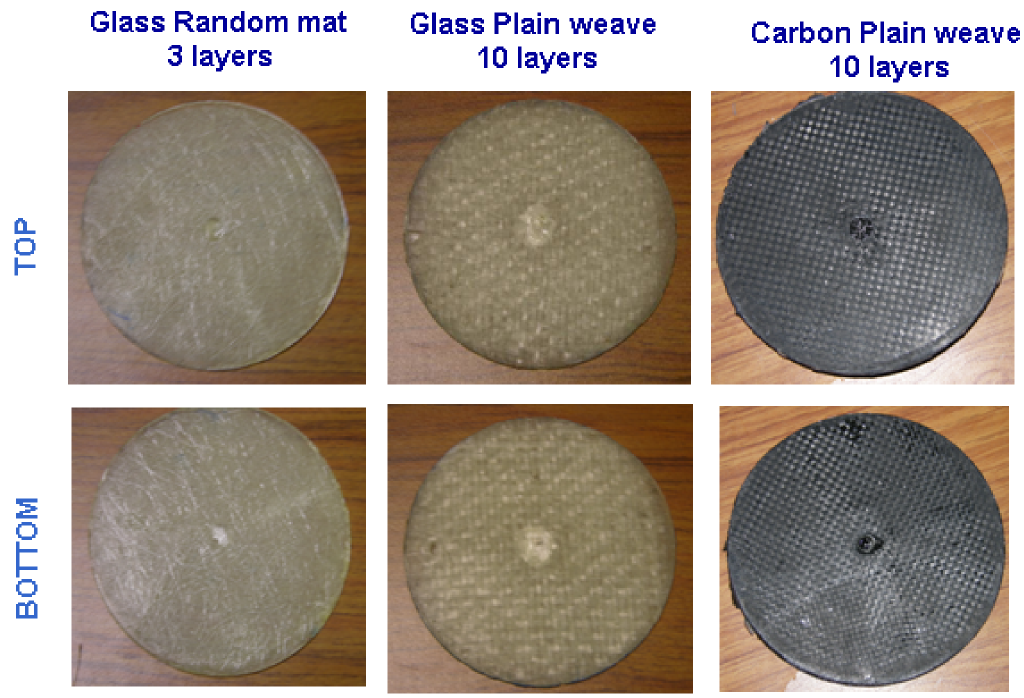

Figure 7: Examples of manufactured parts with the new low cost Compression RTM press

6. Conclusions

A simple mold was built to conduct exploratory experiments with the compression resin transfer molding process. The mold was designed to be very simple in operation, without the need of a press. Geometric and mathematical modeling was done to estimate the processing windows for the closing speeds and forces that could be realized. Once the press was built, compaction testing was done and compared to previous results. With this apparatus established as valid tool for investigation of compression RTM, a mold cavity was added, and compression RTM experiments were carried out. Circular disks of 4 inches in diameter were manufactured with E-glass random and plain weave fabric and also with carbon fabric. As predicted, the infusion time was very fast of the order of 5 seconds, and the resultant parts had fiber volume fraction in the range of 55-62 percent for woven fabric and 27-34% for continuous strand random mat.

7. Acknowledgments

The authors gratefully acknowledge the support provided by the Office of Naval Research (ONR) under Grant Number N00014-05-1-0832 for the “Advanced Materials Intelligent Processing Center” at the University of Delaware and by National Science Foundation and Department of Energy/National Energy Technology Laboratory under grant number DMI-0521789.

8. References

1. *Technology update: compression moulding.* Reinforced plastics. July-August 2003.
2. Chen, B., E.J. Lang, and T. Chou, *Experimental and theoretical studies of fabric compaction behavior*

in resin transfer molding. Materials Science and Engineering A, 2001. 317: p. 188–196.

3. Chen, B. and T. Chou, *Compaction of woven-fabric preforms: nesting and multi-layer deformation.* Composites Science and Technology, 200. 60: p. 2223-2231.
4. Saunders, R.A., C. Lekakou, and G. Bader, *Compression and microstructure of fibre plain woven cloths in the processing of polymers composites.* Composites, Part A, 1998. 29(a): p. 443-454.
5. Simacek, P. and S.G. Advani, *Simulating Three-Dimensional Flow in Compression Resin Transfer Molding Process.* Revue Europeenne des Elementes Finis, 2005. 14(6-7): p. 777-802.
6. Simacek, P. and S.G. Advani, *Desirable features in a Mold Filling Simulation for Liquid Molding Process.* Polymer Composites, 2004. 25(4): p. 355-367.
7. Simacek, P., S.G. Advani, and C. Binetruy. *Liquid Injection Molding Simulation (LIMS) A Comprehensive Tool to Design, Optimize and Control the Filling Process in Liquid Composite Molding*. in *JEC - Composites, n 8*. 2004. Paris, France.
8. Bickerton, S. and M.Z. Abdullah, *Modeling and evaluation of the filling stage of injection/compression moulding.* Composites Science and Technology, 2003. 63: p. 1359-1375.
9. Bickerton, S., M.J. Buntain, and A.A. Somashekar, *The viscoelastic compression behavior of liquid composite molding preforms.* Composites, Part A. 34: p. 431-444.