L. Simulation of Compression Resin-Transfer-Molding Process for Manufacturing Net-Shape Structures

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Objective

- The principal objective in this phase is to build fundamental understanding of flow-compression coupling in CRTM process and to identify the issues to be addressed in the subsequent analytic, experimental and numerical work.

Approach

- We extended, streamlined and analyzed the existing approach to model compression resin-transfer molding (CRTM). The scheme was utilized to analyze several parts with certain degree of success, but two drawbacks were revealed: low computational performance and limited accuracy. To answer these concerns, extended problem descriptions which include fiber-tow saturation and preform deformation were developed to be implemented in future modeling efforts.

Accomplishments

- An existing RTM simulation package was utilized to model the CRTM process with limited success and some parametric studies were performed. The approach was streamlined and most limitations (such as the requirement that the compression is kinematically driven) were alleviated.
- New governing relations for the general liquid composite molding (LCM) and, in particular, for CRTM have been developed and implemented in a simple numerical scheme. The scheme is currently being tested and, if successful, will be implemented in a finite-element-based simulation and will overcome the limitations of the current modeling approach.

Future Direction

The following tasks are planned:

- Verify the current model by comparison with laboratory experiments.
- Study the influence of processing and material parameters – including multiple constitutive relations – using the current solution as well as the extended model which is currently being tested.
- Develop and experimentally validate the numerical simulation of CRTM based on the extended model to address processing of complex, large-scale structures.

Introduction

All liquid composite molding (LCM) processes require one to place a fibrous preform inside the mold. The mold is sealed and a liquid resin (typically a thermosetting resin, due to its low viscosity) is injected to saturate the preform. The fibers in the preform and the preform itself are usually stationary or may undergo slow and infinitesimal deformations during the injection process. Next, the resin is allowed to cure. During the curing process, the resin cross-links and hardens. Once the resin has sufficiently solidified, the mold is opened and the part is removed. Two commonly used techniques in this process are RTM and vacuum-assisted resin-transfer molding (VARTM), but there are several other processes of interest, such as RTM "Light" and the subject of this report, CRTM. Figure 1 schematically compares these processes.

In all these variations, the flow of the resin through the preform is important. If particular sections of the preform remain dry after the injection is complete, the resulting void will seriously compromise the composite properties. This may, for example, happen if the inlets or vents are poorly placed. As it is not possible to visualize the resin flow inside a closed mold, this created a need to simulate the filling process using a science-based process model. For conventional RTM process, many reliable computer simulation tools have been established and validated with experiments [1-14]. They have been used to verify designs and, more recently, for the purposes of process optimization and control [15-20]. When other LCM variations in the process are involved, the modeling tools are scarce and RTM tools are usually adapted [21-22], though the results are sometimes not quite satisfactory. In this report, we analyze the adaptation of RTM modeling package to CRTM modeling.

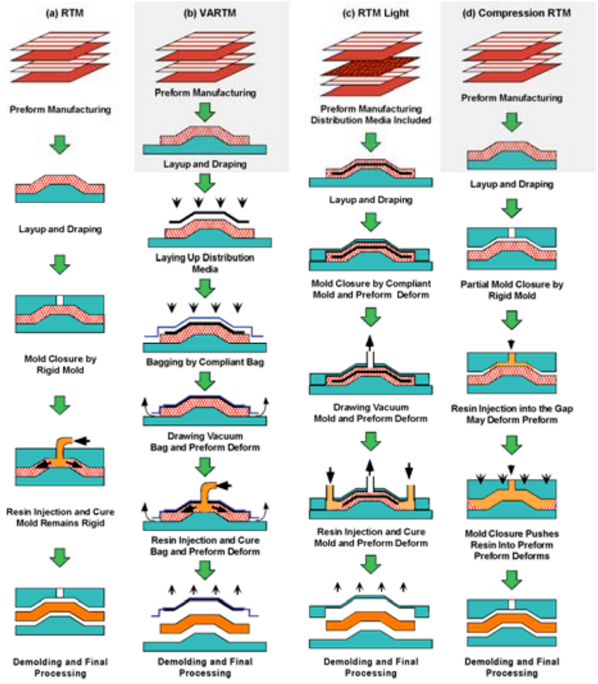

Figure 1. Comparison of several important LCM variations which includes CRTM.

CRTM Process

Traditionally, LCM processes are considered for small- to medium-production batches. The major limit to adaptation of this process to large-scale production is its cycle time. This may be overcome with a new process variation, CRTM, in combination with near-shape preform manufacturing, particularly the programmable powdered preform process (P4). This process combines resin injection into a preform in a partially-open mold, subsequently closing the mold to squeeze the resin into the preform and simultaneously compacting the preform to increase the fiber volume content, which is necessary for structural components. This process offers the potential to manufacture moderately-sized structures in a few minutes while preserving the advantages of RTM, namely, net-shape manufacturing of complex curvatures with class A surface finish.

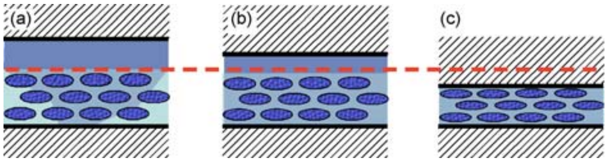

Figure 2. Three stages of CRTM process.

The resin flow in the CRTM process is more complex than any other LCM variations. It exhibits three distinct stages which are shown in Figure 2. All of the phases can be modeled as flow through porous media under different boundary and initial conditions.

The three stages are:

1. resin injection into the narrow gap between the mold platen and the fiber preform in the mold,
2. closing of the gap while squeezing the resin into the preform without direct contact between the movable tool part and the perform, and
3. compaction of the preform by the mold platen along with continuing resin impregnation.

Note that individual stages may overlap in time depending on tool geometry and kinematics. Also, a single composite structure may be undergoing different phases in different regions. For the sake of simplicity, we assume that these three stages follow each other. This assumption may be relaxed if necessary.

Stage 1: Resin Injection into the Narrow Gap

In the first stage, the resin is injected into the gap between the movable mold part and preform (Figure 2 (a)). It can readily spread through the gap, as its permeability is much higher than that of the preform. It also penetrates into the preform. This is analogous to the flow in traditional VARTM. In CRTM, the gap plays the role of the flow-enhancement layer known as the distribution media. As there is a pressure gradient across the preform thickness, the preform will undergo stress (compaction) to ensure equilibrium. However, the injection pressure is usually not particularly high to induce the resin to flow in the gap and hence one can neglect this compaction.

Stage 2: Closing the Gap

In the second stage (Figure 2 (b)), the resin injection is switched off and the mold platen moves to close the gap. The gap filled with the resin serves as a continuous resin source to impregnate the rest of the dry preform. The gap between the preform and the mold platen reduces as the mold closes and the resin is displaced and forced into the preform and in the unfilled regions of the gap. As the gap thickness reduces, so does its permeability. However, pressure increases, accelerating the resin flow into the preform. In this phase, as the resin pressure is higher, we expect higher deformation of the preform due to the pressure gradients, even though there is no mold-preform contact. For low-pressure compression molding one could assume that this physical phenomenon does not influence the flow significantly, but experimental verification of this assumption is highly desirable.

Stage 3: Preform Compaction

In the final stage (Figure 2 (c)), the gap between the preform and the mold platen vanishes, and the mold wall comes in contact with the preform and compresses the preform directly. Consequently, the resin is forced from already-filled regions which serve as a resin source to impregnate the unfilled regions in the mold. The preform compaction can be described reliably if the mold kinematics are known. Then, the volume fraction, permeability, etc. of the preform can be predicted at any time during this stage. A notable exception to this rule is the case when the force required for compression is known, instead of the mold kinematics. The coupling between the mold closure and the pressure field would not significantly complicate the modeling if one could predict the stresses in the preform. These could be combined with known resin pressure using the Terzaghi equation [23]. Unfortunately, the stress/deformation relation of preforms is not well mapped despite a fair amount of research in this field [24-35].

Process Model

All three stages of the CRTM process described above are similar to other RTM variations as they represent a pressure-driven flow in porous medium. This should allow one to create a modeling algorithm utilizing the existing, well-developed RTM modeling software. We will show below an iterative scheme that is able to model the process and undeniably useful for researching the process but could be made efficient by modifying the governing equations.

RTM Modeling

First, we should briefly examine the traditional RTM modeling approach. The resin flow into a thin, closed-mold cavity can be represented as flow through porous media, usually with negligible inertial effects due to the high viscosity of the resin [3]. To describe the physics of such a flow one usually uses the Darcy's law

$$\langle \mathbf{v} \rangle = -\frac{\mathbf{K}}{\eta} \cdot \nabla p \qquad (1)$$

and the continuity equation

$$\nabla \cdot \langle \mathbf{v} \rangle = 0 \qquad (2)$$

to formulate the governing equation. Here $\langle \mathbf{v} \rangle$ is the volume-averaged flow velocity, ∇p is the pressure gradient in the impregnating fluid, and η is the viscosity of the fluid. The positively-definite tensor **K** describes the permeability of the fibrous porous media. The continuity equation reflects the fact that no preform deformation takes place.

Substitution of equation (1) in the continuity equation (2), results in the following governing equation:

$$\nabla \cdot \left(\frac{\mathbf{K}}{\eta} \cdot \nabla p \right) = 0 \qquad (3)$$

This equation is usually solved to provide the pressure field for a given configuration. Flow velocity is then computed from equation (1) to provide description of the flow. Modeling flow of the viscous liquid into the mold involves a moving boundary. There are several ways to numerically simulate the filling process [1-14]. In our package, LIMS (Liquid Injection Molding Simulation), we utilize the common finite-element/control volume (FE/CV) solution scheme described elsewhere [3, 9, 36].

Challenge of Deformable Preform

The conservation of mass, equation (2), assumes that the porous medium does not deform. Once the control volume associated with the porous medium starts changing during the flow, a new source term appears in this equation. For modest deformation, one can use infinitesimal volumetric strain rate $\dot{\varepsilon}$ and a coordinate system fixed to the porous media:

$$\nabla . \langle \mathbf{v} \rangle = -\dot{\varepsilon} \qquad (4)$$

The infinitesimal strain can be replaced by other strain measure as needed. The rigorous evaluation of the deformation field requires a known stress-strain relation in the fibrous preform and evaluation of this stress field. This is impossible to accomplish within a RTM modeling package as one would need to couple the flow computation with stress/strain analysis (of poorly characterized material). One can, however, make several acceptable assumptions to simplify the solution:

1. The preform deforms through the thickness only.
2. The preform deforms uniformly through the thickness.
3. The preform does not deform without tool contact.

The first assumption is true for most variations of LCM which deform the preform. The second assumption relies on use of similar material in all layers of the preform and limited through-the-thickness pressure gradient. The last assumption is generally tied to the second one and depends on pressure gradient through the thickness not deforming the material (at least not significantly). With these assumptions, we can replace the strain rate by the rate of change of preform thickness *h(**x**,t)*. For linear strain it is:

$$\nabla . \langle \mathbf{v} \rangle = -\frac{\dot{h}(\mathbf{x},t)}{h_0(\mathbf{x})} \qquad (5)$$

where h_0 is the original preform thickness, before the mold platen starts compressing it. Utilizing Darcy's law, we can obtain the governing elliptic partial differential equation (PDE) for pressure as follows

$$\nabla . \left\langle \frac{\mathbf{K}(h)}{\eta} \cdot \nabla p \right\rangle = \frac{\dot{h}(\mathbf{x},t)}{h_0(\mathbf{x})} \qquad (6)$$

This equation looks similar to those for compressible preforms [21, 22]. However, the thickness variation is generally known as a function of time (and location) from the kinematics of the tooling. Note that even if the compaction force is prescribed in lieu of the closing speed, the closing direction is known; but, we will return to this case later. This means that neither the source term on the right-hand side, nor the permeability value K on the left-hand side is coupled with the unknown pressure field. The pressure field is related only to the fluid pressure averaged over the pores. Thus, we still have a linear partial differential equation (PDE) for pressure, only its coefficients are transient. Note that the compressive force cannot be evaluated unless an additional constitutive model is introduced for preform stress-strain relations.

Note that if the linearized deformation is not acceptable, one can replace the right-side term in (6) with a more appropriate one.

The usual, explicitly-integrated, quasi-static solution of the RTM flow [3] may be modified to solve equation (6) using the following steps:

1. At a particular time step, the filled region represents the solution domain. Permeability and the rate of deformation are known. The rate of deformation allows one to compute the source term on the right side of equation (6) and set these as injection rates at filled nodes. Then, the equation is solved to determine the pressure. Flow rates are determined using Darcy's law and current permeability values. The flow is advanced accordingly by explicit time integration over a selected time step to include more filled control volumes in the solution domain just like in traditional RTM modeling [3].

2. Thickness is changed accordingly to the compaction rate and new permeability values are computed.

At this point, we should return to the case of prescribed compression force and unknown compression rate. As equation (6) is linear in pressure and closing rate, one can evaluate the necessary strain rate as follows:

1. Estimate the closure rate and evaluate the pressure field.

2. Compute the total force from resin pressure and compare it to the prescribed force minus whatever force is exerted by the compressed preform.

3. Multiply the closing rate by the ratio, recompute pressures, and advance the flow as described above.

This approach is restricted to linearized strain and preform stress/strain behavior to elastoplastic.

Permeability and Deformation

Besides creating the "source" effect, preform deformation also changes the preform properties necessary to compute pressure field and flow, most importantly, the permeability and porosity (fiber volume fraction).

The dependence of permeability on the fiber volume fraction K*(vf)* has been studied for various cases, but there seems to be no generally accepted, physically meaningful formula. The Karman-Kozeny equation

$$\mathbf{K}\left(v_f\right)=\mathbf{k}\frac{\left(1-v_f\right)^3}{v_f^2} \qquad (7)$$

is commonly being used for this purpose, often as a curve-fitting tool, because of its simplicity. The results are usually acceptable, though it may be possible to achieve a better fit using other formulas in individual cases [37].

Modeling CRTM with RTM Simulation Package

A sensible approach to the solution of equation (6) would require one to rewrite the solution package. The conventional RTM modeling packages do not allow one to change the part volume. Additionally, the solution is optimized for constant permeability and limited number of inlets [9]. Moreover, a brand new approach would allow one to relax the assumptions of uniform deformation through the thickness of the preform.

While a new solution is desirable and quite feasible, it is possible to simulate CRTM filling using the existing RTM simulation code, assuming that:

1. Preform properties such as permeability and porosity may be changed during the simulation execution.

2. There is no limit for the number of inlets.

It is not even necessary for the simulation code to modify parameters and set inlets on its own; an external program can be used to accomplish this. Our simulation does have the capability to evaluate and change material properties within the simulation and to set/close inlets as needed due to the scripting capability. This makes it possible for us to adopt this package to address CRTM flow under the above mentioned assumptions.

We decided to model the preform as a three-dimensional, porous solid with fixed dimensions. Three stages are modeled independently. A two-dimensional model is inadequate as the gap on top of the preform makes the flow three dimensional [36]. Dynamically-changing dimensions are a fact of the CRTM process, but cannot be implemented in the package. Instead, the thickness is tracked independently and porosity is adjusted to simulate the actual part volume. This does not correspond to either the original preform or to the compacted final part. Note that the preform is being compressed only in the third phase of the process, i.e., any deformation caused by resin pressure in previous phases is neglected. The permeability is modified according to Karman-Kozeny equation (7).

In phases I and II, the channel on top is modeled similarly as a standard distribution medium in VARTM, using two-dimensional elements [36, 38]. The only change relative to the way this model is used in VARTM for distribution media is that the equivalent permeability of the gap is approximated from the equations for creeping (lubrication) flow in a narrow channel of given height (thickness) as

$$K_{xx} = K_{yy} = \frac{h^2}{12} \tag{8}$$

This is obviously acceptable only if the thickness of the gap *h* is much smaller than the in-plane dimensions of the part. The thickness, *h*, is constant in the first stage, and then it continuously varies during the stage 2 from its original value to zero. The permeability of the gap must be modified accordingly. In the last phase, the gap is non-existent, which can be accomplished by setting its thickness and permeability to zero.

The mold is assumed to be rigid and its motion is described by the vector of its velocity **v**, with the displacement x(t). These values are known throughout the process. If the compression load is specified, it can be handled as described above. The model for all three stages is summarized in Figure 3.

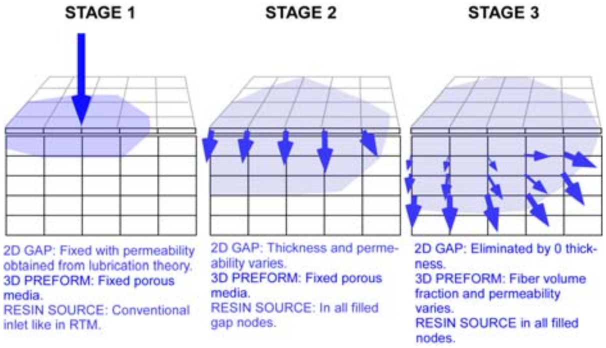

Figure 3. Modeling the three stages of CRTM process.

Modeling Algorithm: Stage 1

In the first stage, the mold is fixed. Resin is injected into the channel on top of the preform and is simulated as ordinary VARTM injection with distribution medium of thickness h, fiber volume fraction of 0 and permeability as described by Equation (8).

The simulation at this stage can predict the time required for injection of a required volume of resin, which is known as the final part dimensions and fiber volume fraction are known in advance. This is trivial if the simulation uses flow-rate control, but the simulation provides the flow rates at inlet(s) in any case, such as constant pressure or even mixed inlets. These can be integrated to provide the volume of resin injected during a certain time period.

The only assumption made at this stage is that the preform itself does not deform as the pressure continues to build. Since the resin pressure will cause some deformation, this may reduce the modeling accuracy by a certain degree, though the pressure build-up in the gap in this stage is likely to be small.

Modeling Algorithm: Stage 2

In this stage, the upper mold platen moves with speed **v**, while there is no resin injection into the mold and the injection gate is closed. If force is prescribed, one might evaluate **v** simply, as no forces in preform are involved at this stage. The thickness of the gap changes with time. Every saturated node in channel represents a control volume. The change of thickness in this area results in resin source that is applied at that node. This value might change with each time step. Even if the mold speed is constant, one still has to set new "inlets" in newly-filled control volumes with every time step. One also has to obtain the new thickness before each step and update the permeability in the channel whose gap is reducing due to the closure of the mold platen (equation 8) and update each gap element. The process is straightforward, but one must be careful to prevent generating elements with negative thickness of the channel due to the round-off error.

The only assumption made here is that the preform itself does not deform as the pressure builds. At this stage, this assumption might be more questionable, as higher resin pressure is expected and this could deform the preform. One could eliminate this error if we had the compaction data by following these steps: (i) compute the through-the-thickness deformation at each location, (ii) adjust the dimensions of the gap accordingly, (iii) adjust the properties of preform and (iv) create a flow source in the filled preform that is being compressed. The last two points are examined below in Stage 3.

Additionally, we neglected the partially-filled volumes as sources. The fill-factor of these volumes should be updated as they get compressed and, if it reaches unity, the flow source should be introduced for that element. This results in net loss of resin volume during the simulation. This simplification may be alleviated at a cost of implementation complications. The accuracy is also affected by the explicit time integration over finite time steps, though this error should go to zero with mesh refinement.

Modeling Algorithm: Stage 3

In this phase, there is no resin being injected and no gap to provide a preferential flow path. The resin source is the preform itself that is being deformed by compaction. We cannot easily change the "thickness" of three-dimensional (3D) elements, but we can modify their properties to reflect the correct porosity and permeability [36].

The preform thickness and the normal (through-the-thickness) direction in the preform is not immediately obvious in three-dimensional meshes and one needs to perform substantial book-keeping to determine these values and to track them.

Then, we need to create the flow-rate gates in every filled control volume of the domain (Figure 3). In each time step, the closing speed **v** may change and one must set new inlets in the volume(s) just filled and modify the ones filled previously.

The deformation is "averaged" through the thickness, assuming that the deformation is uniform through the thickness. This assumption is fully justifiable only if the preform is fully saturated through the thickness. Otherwise, through-the-thickness pressure and saturation gradients will cause variations in deformation and deformation rates. However, to alleviate this problem one would need to solve a coupled elasto-visco-plastic deformation problem in the three-dimensional preform.

Also, the change of fill-factors in partially-saturated volumes in the preform was not accounted for during the previous stage. This introduces a small inaccuracy in the mass conservation of resin.

The entire modeling approach is summarized in the flowchart presented in Figure 4. The most important difficulty encountered with this model lies in the fact that the performance of the simulation is drastically reduced compared to the conventional RTM modeling. For realistic parts, it is formidable to conduct a parametric study or to try to optimize the injection.

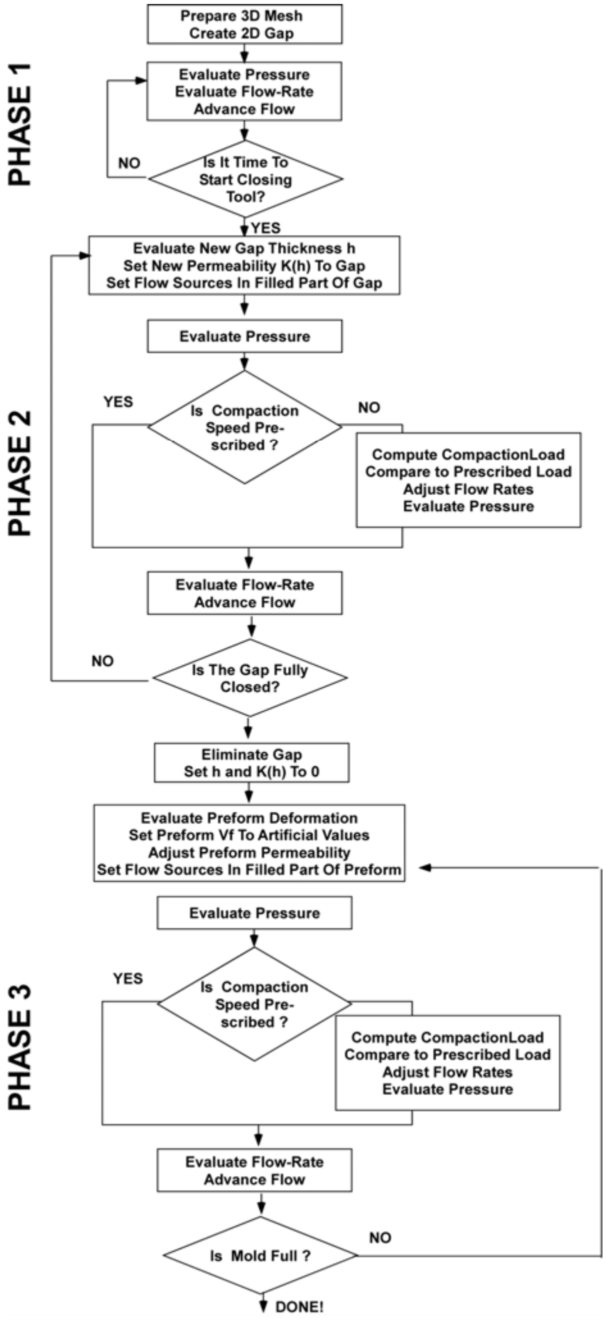

Figure 4. Simulating CRTM by RTM modeling package: The Flowchart.

Results and Discussion

Figure 5 shows the mesh used for the simulation of CRTM filling of a circular test part using LIMS. The radius of the part is 75 mm, the original material thickness is 10 mm and the original fiber volume fraction is 25%. In-plane permeability of the material at this fiber volume fraction is $7.40.10^{-10}$ m^2, the through-the-thickness permeability is $2.50.10^{-11}$ m^2. The in-plane permeability varies with the Kozeny-Karman equation (7). The material data correspond to those measured for a P4 preform. Only one quarter of the part is modeled because of symmetry.

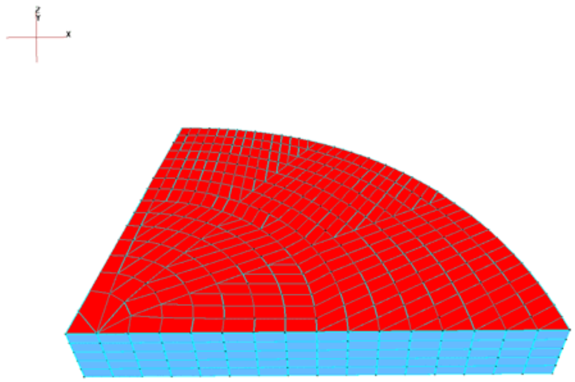

Figure 5. Mesh used for simulation of circular test part manufactured using CRTM.

For this mesh, the simulation takes only several minutes to execute, allowing one to conduct parametric studies varying the material parameters. The most obvious parameter to study is the original thickness of the gap. If the gap thickness is too large, the compression cycle will be extended as closing the gap takes time. If the thickness is too small, the injection cycle might get extended as the resin is effectively injected (with limited pressure) into the preform which has only limited permeability, creating a process close to RTM. Figure 6 shows the flow patterns during the injections with gradually reduced gap thickness.

The filling time goes from almost a minute for 5 mm gap to 35 s for 2.5 mm to 27 s for 1.25 mm gap. However, once the gap size decreases further to 0.625 mm, the fill time jumps to 35 s and the flow starts developing three-dimensional character.

Modeling complex, practical parts is quite feasible. Unfortunately, the time required for a single simulation run is increased to days, or at least many hours. This complicates the use for optimization purposes or even most parametric studies. We have simulated the process for I beams and full-body panels which involve thousands of nodes with this methodology to demonstrate the capability of the simulation. However, the simulation took over 52 hours and requires an expert to write the script to

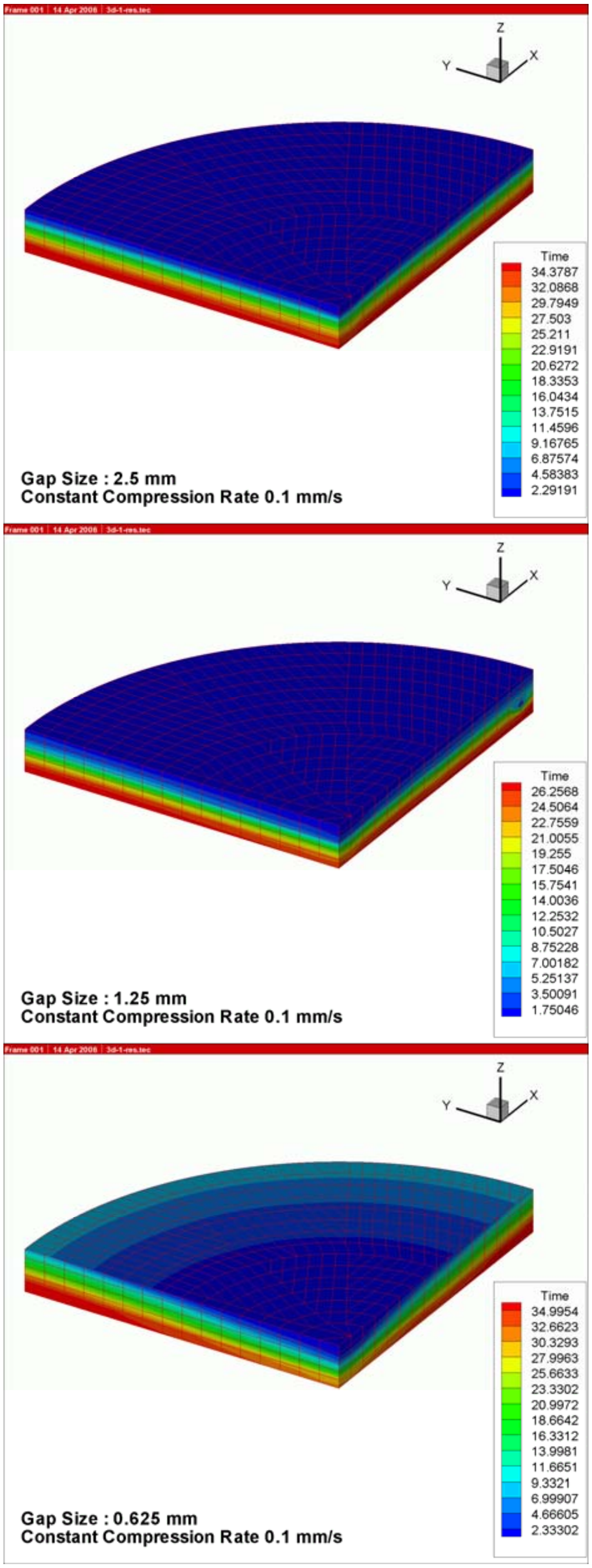

Figure 6. Filling of the test part with CRTM and varying original thickness of gap. The same shade of grayscale indicates regions filled at the same time.

manage the three phases. Hence, our objectives will be to develop efficient algorithms to speed up the calculations as we can do for RTM (of the order of minutes) and to develop a user-friendly interface to make it truly useful for Industry

Discussions and Conclusions

It was demonstrated by adapting the existing RTM simulation software that one can model and simulate CRTM process with certain success, although experimental comparisons are yet to be carried out. This modeling capability is useful to provide some insight into process parameters and, in absence of better models, it may even be used to model injection into complex structure.

However, there are two drawbacks of this methodology that cannot be overcome by an evolutionary approach based on the current solutions. First, the assumption of uniform deformation is uncertain, but it can be overcome only by a different system of governing equations that includes the preform deformation. Second, the computational performance is not quite satisfactory and it is certainly not adequate for the task of process design and optimization in industrial settings. A novel approach is needed to provide industry-strength modeling capability for CRTM process. Discretization of the governing equation system and development of a solver rather than adding many correctional steps to an existing RTM solver will help overcome these shortcomings and are planned for the future.

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References

1. C.A. Hieber, S.F. Shen, "A finite element/finite difference simulation of the injection mold filling process," J. Non-Newtonian Fluid Mech. 7, pp. 1-31, (1980).
2. T.A. Osswald, C.L. Tucker, Polymer Eng. & Sci. 28, pp. 413-420, (1988).

3. M. Bruschke, S.G. Advani, "Finite Element/Control Volume Approach to Mold Filling in Anisotropic Porous Media," Polymer. Composites 11, pp. 398-405, (1990).
4. R.W. Lewis, A.S. Usmani, J.T. Cross, "Finite Element Modeling of Mold Filling," Finite Elements in the 90's, ed. by E. Onate, J. Periaux and A. Samuelsson, Springer-Verlag/CIMNE, Barcelona, (1991).
5. V.R. Voller, Y.F. Chen, "Prediction of Filling Times of Porous Cavities," International Journal Numerical Methods 10, (1995).
6. N.D. Ngo, R.V. Mohan, P.W. Chung, K.K. Tamma, "Recent Developments Encompassing Non-Isothermal/Isothermal Liquid Composite Molding Process Modeling/Analysis: Physically Accurate, Computationally Effective, and Affordable Simulations and Validations," Journal of Thermoplastic Composite Materials 6, pp. 493-532, (1998).
7. F. Trochu, R. Gauvin, D.-M. Gao, "Numerical Analysis of the Resin Transfer Molding Process by the Finite Element Method." Advances in Polymer Technology 12(4), pp. 329-342, (1993).
8. B. Minaie, Y.F. Chen, A.M. Mescher, "A Methodology to Obtain a Desired Pattern During Resin Transfer Molding," Journal of Composite Material, 14, pp. 1677-1692, (2002).
9. R.S. Maier, T.F. Rohaly, S.G. Advani, K.D. Fickie, K.D. "A Fast Numerical Method for Isothermal Resin Transfer Mold Filling," International Journal of Numerical Methods in Engineering 39, (1996).
10. M.K. Kang, W.I. Lee, J.Y. Yoo and S.M. Cho, "Simulation of Mold Filling Process During Resin Transfer Molding," Journal of Materials Processing and Manufacturing Science, 3, pp. 297-313, 1995.
11. W.B. Young, "Three-Dimensional Nonisothermal Mold Filling Simulations in Resin Transfer Molding," Polymer Composites, 2, pp. 118-127, 1994.
12. O. Mal, A. Couniot and F. Dupret, "Non-Isothermal Simulation of the Resin Transfer Moulding Process," Composites Part A: Applied Science and Manufacturing, 1-2, pp. 189-198, 1998.
13. M. V. Bruschke and S. G. Advani, "A Numerical Approach to Model Non-isothermal, Viscous Flow with Free Surfaces through Fibrous Media," International Journal of Numerical Methods in Fluids, 19, pp. 575-603 (1994).
14. P. Simacek and S.G. Advani, "Approximate numerical method for prediction of temperature distribution in flow through narrow gaps containing porous media," Computational Mechanics, v 32, n 1-2, September, pp. 1-9 (2003).
15. M.Y. Lin, M.J. Murphy, H.T. Hahn, "Resin transfer molding process optimization," Composites: Part A 31, pp. 361-371, (2000).
16. R. Mathur, B.K. Fink, S.G. Advani, "Use of Genetic Algorithms to Optimize Gate and Vent Locations for the Resin Transfer Molding Process," Polymer Composites 2, pp. 167-178, (1999).
17. E.M. Sozer, S. Bickerton, S.G. Advani, "Use of Sensors and Simulations for Strategic Control of Liquid Composite Mold Filling Process," SME Technical Paper, Composite Manufacturing and Tooling 2000, (2000).
18. B.Y. Kim, G.J. Nam, J.W. Lee, "Optimization of Filling Process in RTM Using a Genetic Algorithm and Experimental Design Method," Polymer Composites, 1, pp. 72-86, (2002).
19. S. Bickerton , H.C. Stadtfeld , K.V.Steiner, S.G.Advani, "Design and application of actively controlled injection schemes for resin-transfer molding," Composites Science and Technology, v 61 n11, pp. 1625-1637 (2001).
20. D.R. Nielsen, R. Pitchman, "Closed-loop Flow Control in Resin Transfer Molding Using Real-time Numerical Process Simulation," Composite Science and Technology, 2, pp. 283-298, (2002).

21. Acheson, Jeffrey A.; Simacek, Pavel; Advani, Suresh G., "The implications of fiber compaction and saturation on fully coupled VARTM simulation" Composites Part A: Applied Science and Manufacturing, v 35, n 2, February, pp. 159-169 (2004).
22. Correia, N.C., Robitaille, F., Long, A.C., Rudd, C.D., Simacek, P. and Advani, S.G., "Use of Resin Transfer Molding Simulation to Predict Flow, Saturation and Compaction in the VARTM Process," Journal of Fluids Engineering, Vol 126, March, pp. 1-6 (2004).
23. Terzaghi, K., and Peck, R. B., "Soil Mechanics in Engineering Practice," 2nd, ed., John Wiley & Sons, New York (1967).
24. Carnaby, G.A. and Pan, N. "Theory of Compression Hysteresis of Fibrous Assemblies," Textile Research Journal 27 (1989).
25. Batch, G.L. and Macosco, C.W. "A Model For Two-Stage Fiber Deformation In Composite Processing," 20th Internationa SAMPE Technical Conference, 1988 (1988).
26. Komori, T., Itoh, M. and Takaku, A. "A Model Analysis of the Compressibility of Fiber Assemblies," Textile Research Journal 10, pp. 567-574 (1992).
27. Hearle, I.W. and Shanahan, W.J. "11-An Energy Method for Calculations in Fabric Mechanics; Part I: Principles of the Method," Journal of Textile Institute 4, pp. 81-91 (1978).
28. Shanahan, W.J. and Hearle, I.W. "12-An Energy Method for Calculations in Fabric Mechanics; Part II: Examples of Application of the Method to Woven Fabrics," Journal of Textile Institute, pp. 93-100 (1977).
29. Simacek, P. and Karbhari, V. M., "Notes on the Modeling of Preform Compaction: I - Micromechanics at the Fiber Bundle Level," Journal of Reinforced Plastics and Composites 1, pp. 86-122 (1996).
30. Karbhari, V. M. and Simacek, P. "Notes on the Modeling of Preform Compaction: II - Effect of Sizing on Fiber Bundle Micromechanics," Journal of Reinforced Plastics and Composites 8, pp. 837-861 (1996).
31. Gutowski, T.G. and Dillon, G., "The Elastic Deformation of Lubricated Carbon Fiber Bundles: Comparison of Theory and Experiments," Journal of Composite Materials 16, pp. 2330-2347 (1992).
32. Cai, Z. and Gutowski, T., "The 3-D Deformation Behavior of A Lubricated Fiber Bundle," Journal of Composite Materials 8, pp. 1207-1237 (1992).
33. A.A. Somashekar, S. Bickerton and D.B. Bhattacharya, "Non-elastic Effects during Compression of Fiber Reinforcements," International Conference on Flow Processes in Composite Materials, FPCM 7, 413-418 (2004).
34. T. Kruckenberg and R. Patton, "Compaction of Dry and Lubricated Reinforcements," International Conference on Flow Processes in Composite Materials, FPCM 7, 425-436 (2004).
35. P.A. Kelly and R. Umer, "Modeling the Viscoelastic Behavior of Fiber Reinforcing Fabrics," International Conference on Flow Processes in Composite Materials, FPCM 7, 443-446 (2004).
36. Simacek, P. and S.G. Advani, "Desirable Features in Mold Filling Simulations for Liquid Molding Processes," Polymer Composites, 25, pp. 355-367 (2004).
37. Bruschke, M., Advani, S.G., "Flow of generalized Newtonian fluids across a periodic array of cylinders," Journal of Rheology, 37(3), pp. 479-498 (1993).
38. Modi, D., Simacek, P., Advani, S.G., "Numerical Issues in Mold Filling Simulations of Liquid Composites Processing," Proceedings of 10th US-Japan Conference on Composite Materials (2002).