N. Modeling and Simulation of Compression Resin Transfer Molding

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Objective

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

Approach

We analyzed the existing approach to modeling CRTM, and its shortcomings were examined. New governing equations are being developed. These equations describe all the necessary physical phenomena of the process.

Accomplishments

Analysis of the current modeling approach for CRTM, as well as for some of the physical phenomena involved in the process, such as preform deformation, revealed certain weaknesses in the numerical approach and, more importantly, significant gaps in fundamental understanding of underlying physics.

New governing relations for the general Liquid Composite Molding (LCM) and, in particular, for CRTM have been proposed. These relations describe the process in general and should help not only in process modeling but also in identifying the needs in material characterization.

Future Direction

The current development should be followed by several steps:

1. Build fundamental understanding of flow-compression coupling in the CRTM process with exploratory experiments and closed-form solutions.
2. Develop and experimentally validate the numerical simulation of CRTM to address processing of complex, large-scale structures.
3. Perform parametric studies to identify material and process parameters that significantly impact the process and the yield.

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 small deformation 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.

The resin flow during the preform saturation is of particular interest, as full preform saturation is mandatory to manufacture a successful part. Note that, for textile preforms, this implies *both* the saturation of macro-pores between the fiber tows and the saturation of the micro-pores in the fiber tows.

Flow modeling thus became an important part of the established variations of the LCM process, since, for non-trivial cases, it may defy the intuition of the process designer. For CRTM its importance may be even higher as fast, high-volume production is desired.

The CRTM Process

Unlike the other common variations of LCM, the resin flow during CRTM exhibits three distinct stages. These are shown in detail in Figure 1. All of the phases can be modeled as flow through porous media, but under distinctly different boundary and initial conditions. The three stages are:

(a) Resin injection in the narrow gap between the mold platen and the fiber preform in the mold.
(b) Closing of the gap without direct contact between the mold platen and the preform.
(c) Compaction of the preform by the mold platen along with resin impregnation.

Note that the first stage may overlap with the later ones and, depending on tool geometry and kinematics, a single composite structure may be undergoing different phases in different regions.

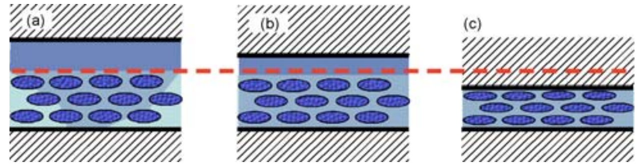

Figure 1. Three stages of CRTM process: (a) Resin injection into the gap. (b) Compression closing the gap, forcing the resin into preform. (c) Final preform compaction.

In the first stage, the resin is injected into the gap between the movable mold part and preform (Figure 1 (a)). It can readily spread through the gap, but it also slowly penetrates into the preform. This situation is similar to the flow in traditional LCM variations with distribution media. In this case, the gap plays the role of highly-permeable distribution media.

In the second stage (Figure 1(b)), the resin injection is discontinued and the mold closure is initiated. The gap between the preform and the mold platen reduces as the mold closes and the resin is displaced and forced into the preform. The gap serves as a flow channel and as a continuous resin source similar to traditional compression-molding squeezing a charge of resin. However, here the resin needs to fill the small gaps in between the fibers of the preform with possible preform compaction as well. As the gap thickness reduces, so does its resistance to the resin flow (permeability) and the resin-flow behavior changes accordingly.

In the final stage (Figure 1 (c)), the gap between the preform and the mold platen is closed, and the mold wall is in contact with the preform and compresses the preform directly. Consequently, the resin is forced out from already-filled regions in the preform to impregnate the remaining unfilled regions.

The averaged preform compaction can be described reliably if the closing speed is known, as the mold platen is in direct contact with the preform. In this case, the average volume fraction, permeability, etc., can be predicted at any time-step during this stage. However, there are currently no means to estimate whether there are local variations in these properties, much less to quantify those variations. Also, if the compaction is driven by applied load, the mold kinetics are unknown and should be predicted by the numerical model.

The advantage of CRTM, as related to more conventional RTM processes, is that it combines the net-shape, high-performance part with the fast cycle time compatible with rapid manufacturing process. In addition, the method inherits the capability to manufacture complex, near-shape part with good surface finish in one step, possibly eliminating a number of assembly steps. These advantages are offset by significant process complexity as demonstrated above.

Current Modeling of CRTM Process

The CRTM process combines elements of conventional RTM and of compression molding. Both these processes were successfully modeled, but the combination of the two is non-trivial. Also, some additional issues are introduced.

The compression creates a resin source in the filled volume and this source is modeled as a constant-flow-rate inlet in every node. It also changes the material properties of the preform.

Our existing model utilizes Liquid Injection Molding Simulation scripting to model the resin flow during CRTM process in 3D or combined 2D/3D. As there is coupling between preform deformation and flow, repetitive modification of both the material parameters and the resin "inlets" is accomplished by script that executes the simulation.

We were able to obtain predictions for simple geometry (Figure 2), but the resulting accuracy was poor. Generally, this method is not acceptable to meet industrial demands and was not accurate enough to install confidence.

Additional Issues to be Considered

There are several additional issues to consider when modeling CRTM which are not modeled by the current approach. The first one lies with possible replacement of kinematically-driven compression by a certain applied load.

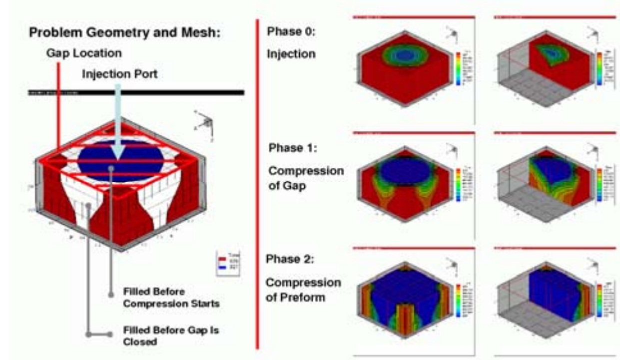

Figure 2. Numerical modeling of resin flow during CRTM injection into rectangular plate.

The prediction of compression forces is difficult even for the kinematically-driven compression as the load is a superposition of resin pressure – which the model predicts – and of forces within the deformed preform. As there are very limited material data and no reliable models for the latter, compression forces can not be predicted with any degree of accuracy. The model cannot, in its current form, predict flow during load-driven compression. While it is theoretically possible to extend it, the extension would compound the performance problems and is, in our opinion, a waste of time.

Another issue is the problem of fiber-tow saturation. The preform of choice consists of fiber-tow strands and the saturation of micro-voids within these strands is imperative. While we have successfully modeled fiber-tow saturation for conventional LCM processes (Figure 3), the approach is not quite suitable for the existing CRTM model because of performance issues.

Process Governing Equations

The preceding analysis indicates that there is a need to fundamentally modify the approach to the modeling. Instead of lumping corrections and "equivalent" properties into the existing model, we need to develop a more general governing equation for flow modeling and to use it in order to (a) create a numerical model and (b) analyze which material data are necessary for reasonably accurate process modeling.

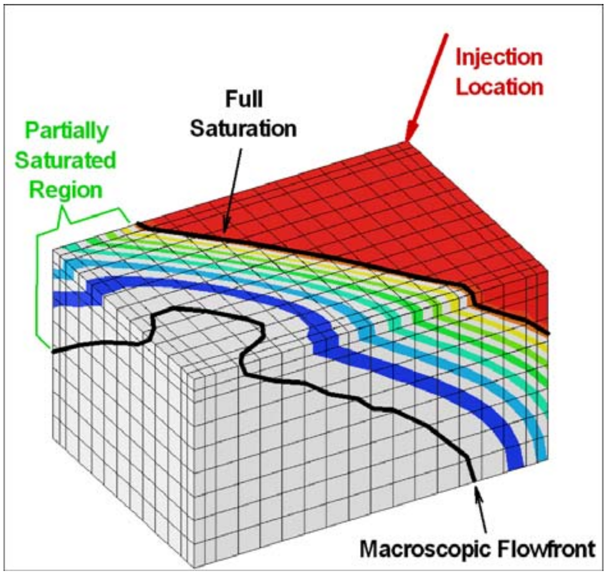

Figure 3. Numerical modeling of dual scale (saturated and unsaturated) flow during RTM resin injection into box-like structure.

The equation must include not only resin pressure and preform saturation that are commonly used to describe the flow in RTM, but also the following:

1. Description of preform deformation in time. This is necessary to obtain acceptable stress prediction for kinematically-driven compression and to model load-driven compression at all.
2. The saturation of micro-pores within fiber tows. This is necessary to predict if the process rate is to be as high as possible. In such a case, the heuristic remedy of conventional RTM of "ramping up pressure and wait" may be suboptimal.

This suggests substituting the usual LCM governing equation

$$\phi \cdot \frac{\partial s}{\partial t} = \nabla . \frac{\mathbf{K}}{\eta} . \nabla p$$

where ϕ is the material porosity (constant during the process), **K** its permeability (constant), η the resin viscosity, *p* the resin pressure and *s* the saturation by the more involved system.

$$\phi_M \cdot \frac{\partial s_M}{\partial t} + \frac{\partial \phi_M}{\partial t} . s_M + \phi_F \cdot \frac{\partial s_F}{\partial t} + \frac{\partial \phi_F}{\partial t} . s_F = \nabla . \frac{\mathbf{K}}{\eta} . \nabla p$$

$$\phi_M = f(p, \ldots)$$

$$\mathbf{K} = f(\phi_M)$$

$$\phi_f = f(\phi_M)$$

This system contains independent values for porosity and saturation in macro- and micro-pores (ϕ_M, s_M and ϕ_F, s_F) and additional constitutive equations that relate porosity and permeability with material state. One must also add the equation to govern the saturation of micro-pores in the form:

$$\frac{\partial s_M}{\partial t} = f(s_M, p, \ldots)$$

Note that the porosity may be used as the above-mentioned measure of deformation.

The constitutive equations are – apart from permeability-porosity relation $\mathbf{K}=f(\phi_M)$ – insufficiently explored, if explored at all.

Conclusions

The analysis of existing modeling capabilities for the CRTM process revealed weaknesses that cannot be overcome by evolutionary approach; based on the current solutions, a novel approach is needed to provide industry-strength modeling capability for the CRTM process.

A new, more involved, governing-equation system is suggested to include the relevant physical phenomena at a fundamental level, rather than adding them by correctional steps to what is basically an RTM solution.

This analysis also revealed a number of constitutive relations that should be studied to gain better insight into the flow mechanics during the CRTM process.