SIMULATION AND VALIDATION OF 3D COMPRESSION RESIN TRANSFER MOULDING

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ABSTRACT

In recent years, resin manufacturers have been formulating thermoset resins with a decrease in cure time. This has helped to shorten the process cycle times and paved the way for the use of cost-effective compression resin transfer moulding (CRTM) process to produce high performance composite parts. However, highly reactive resins pose a major challenge in producing high quality parts. Currently, many researchers have been working on the process simulation of CRTM process. However, there is still a large gap to be addressed in terms of coupling between heat transfer, cure kinetics, resin flow and compaction (thermal-chemical-mechanical) during the CRTM process especially for 3D structures. The main objective of this work is to perform thermal-chemical-mechanical coupled CRTM simulation for a flat 3D part. The work involved development of resin and fibre material models. The material models developed were implemented to perform the simulations. These simulations were validated using interrupted resin flow CRTM experiments.

1 INTRODUCTION

In recent years, lightweighting has become increasingly necessary in the automotive industry. According to a study, a 5-8 % reduction in fuel consumption is possible with a 10 % decrease in vehicle weight [1-3]. Weight savings have been achieved predominantly by using fibre reinforced composite materials. However, adopting fibre reinforced composites comes with an added challenge [1]: (i) use of carbon fibres to produce automotive parts is a costly process and (ii) currently available manufacturing methods do not meet the industry requirement of large-scale production (2-5 minutes cycle time). Therefore, it is extremely important to develop cost-effect production techniques and produce high-quality parts.

Recent years have seen many material suppliers work on the development of fast curing thermoset resin systems. These were engineered to target short cycle times required by the automotive industry. Therefore, it is extremely important to develop a manufacturing process that can meet the short cycle time requirement [4]. Resin transfer moulding (RTM) and prepreg compression moulding appear to have the best potential to produce high standard parts with fast curing resins. Compression resin transfer moulding (CRTM), a variant of RTM, has been seen as the most ideal candidate to produce high-quality parts meeting the industrial requirement of 2-5 minute process cycle time [5]. CRTM process involves injecting dry fibre reinforcement with liquid resin in a closed mould. The injection can be done from the top or the bottom mould. During injection, the top mould is partially kept open to facilitate

the fast flow of resin and the complete filling is achieved through compression sequence of the top mould. Figure 1 shows the steps involved in the CRTM process

During the CRTM process, four main physical phenomena occur: heat transfer, resin cure, flow and compaction. It is crucial to understand each physical phenomenon and its coupling to perform CRTM simulation accurately. Over the years, many researchers have worked on the simulation of CRTM. However, most of the work revolves around 2.5 D simulations and there is a lack of information available about 3D coupled CRTM simulation.

CRTM process modelling mainly involves solving two major problems [6-7]: (i) coupling between heat transfer and resin curing reaction and (ii) coupling between resin flow and reinforced fibre compaction. Therefore, this paper aims at performing 3D CRTM process with the help of simulation followed by an in-depth analysis of thermal-chemical-mechanical coupling during the process. The following steps were performed in this work: (i) implementation of resin cure kinetic and viscosity model (ii) implementation of preform permeability and compaction model (iii) 3D simulation of coupled CRTM process and (iv) validation using a demonstrator part. The simulations were performed using PAM RTM™.

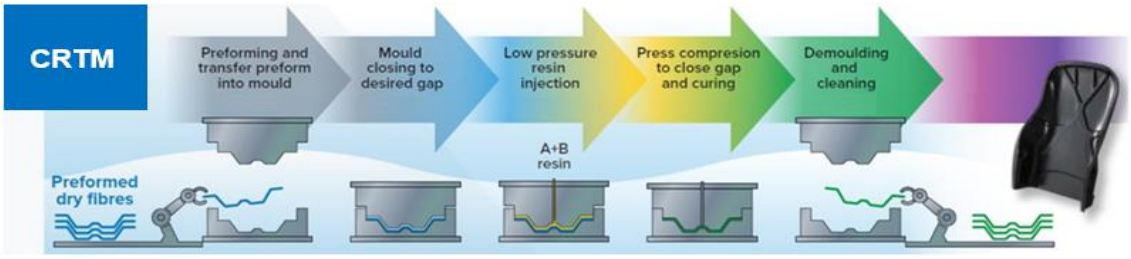


Figure 1. CRTM Process [3].

2 NUMERICAL TREATMENT

2.1 Resin Flow Behaviour

PAM RTM™ uses Darcy's law to evaluate resin flow through the fibre reinforcement and the gap. The governing equation is given as follows:

$$\vec{v} = -\frac{\overline{\overline{K}}}{\mu}.\nabla P \tag{1}$$

where $\vec{v}$ is Darcy's velocity, $\overline{\overline{K}}$ is the permeability of the reinforcement, μ is the resin viscosity and P is the resin pressure. The resin is assumed to be incompressible while solving RTM problems. This leads to the mass conservation equation as:

$$\nabla.\vec{v} = 0. \tag{2}$$

By combining (1) and (2):

$$\nabla.\left(-\frac{\overline{\overline{K}}}{\mu}.\nabla P\right) = 0. \tag{3}$$

Nonconforming finite element formulation has been used by the PAM RTM™ solver to solve the above equation [4].

2.2 Reinforcement Behaviour

The fibre reinforcement was considered as a deformable medium. The large stresses and strains experienced by the reinforcement during the compression sequence cause a large change in porosity. This behaviour is captured by momentum conservation equation as [5]:

$$\nabla.\bar{\bar{\sigma}}(\vec{u}) = f_v \tag{4}$$

where $\bar{\bar{\sigma}}$ is the Cauchy stress tensor, $\vec{u}$ is the displacement and f_v are the body forces. Traditionally, porosity change was related to applied stress using semi-empirical laws [8]. However, here we use the approach proposed by Cielle et al. [6], where the porous domain is represented as an orthotropic homogenous medium composed of incompressible rigid fibres. Therefore, a Lagrangian formulation was used [7]:

$$J(\vec{x}, t + \Delta t)\big(1 - \emptyset(\vec{x}, t + \Delta t)\big) = J(\vec{x}, t)(1 - \emptyset(\vec{x}, t)) \tag{5}$$

where $\vec{x}$ is the position vector, $\emptyset$ is the porosity of the fibre reinforcement, J is the Jacobian of the transformation at times t and with time step Δt.

2.3 Thermal-Chemical Coupling

Fast curing resins undergo a polymerization reaction causing the degree of cure of the resin to increase. As a result, there is an increase in temperature which causes a rise in viscosity. This has been modelled using the first law of thermodynamics to take into effects of heat transfer between the resin and the fibre reinforcement:

$$\rho_c C_{pc} \frac{\partial T}{\partial t} + \rho_r C_{pr}(\vec{v}.\nabla T) = \nabla.\left(\bar{\bar{k}}\nabla T\right) + \emptyset\rho_r H_{tot} \frac{\partial \alpha}{\partial t} \tag{6}$$

where ρ_c represents the composite density, C_{pc} and C_{pr} are the heat capacity of the composite and resin respectively, and $\bar{\bar{k}}$ is the effective thermal conductivity tensor. The last term on the right-hand side of the equation takes into account the effect of the reaction kinetics of the resin. H_{tot} is the total heat of reaction and α is the degree of cure of the resin. The following equations can be used to calculate the averaged material properties. Here r and f represent resin and fibre respectively:

$$\rho_c C_{pc} = \emptyset\rho_r C_{pr} + (1 - \emptyset)\rho_f C_{pf} \tag{7}$$

$$\frac{1}{k} = \frac{\emptyset}{k_r} + \frac{(1 - \emptyset)}{k_f}. \tag{8}$$

The curing reaction of the resin during CRTM process is defined by the following equation [10]:

$$\frac{d\alpha}{dt} + \nabla.\vec{v} = R_\alpha \tag{9}$$

where R_α is the reaction rate. The reaction rate takes several forms depending on the type of resin you are characterizing. A simple model described in [11] can be used as:

$$R_\alpha = K.\exp\left(\frac{E_{act}}{RT}\right).\alpha^m.(1 - \alpha)^n \tag{10}$$

where R is the universal gas constant and K is the Arrhenius function of temperature. E_{act}, m and n are material constants. Eq. (10) is used in Eq.(6) to couple evolution of temperature with cure.

2.4 Resin Flow-Fibre Compaction Coupling

The resin pressure is coupled with the fibre reinforcement compaction using Terzaghi's relationship [5]:

$$\bar{\bar{\sigma}} = \bar{\bar{\sigma}}_f + P\bar{\bar{I}} \tag{11}$$

where $\bar{\bar{\sigma}}$ is the overall stress applied, $\bar{\bar{\sigma}}_f$ is the fibre reinforcement stress, P is the hydrostatic resin pressure and $\bar{\bar{I}}$ is the unit tensor. The pressure is calculated on a fixed 3D finite element configuration. The pressure data is then linked with the fibre stress which is used to compute displacements ($\vec{u}$). This deformation causes a change in porosity (∅) which is linked to the permeability through a semi-empirical law [6].

2.5 Themal-Chemical-Mechanical Coupling

Thermochemical coupling with mechanical phenomena is achieved through the viscosity of the resin [6]. Therefore, it is extremely important to model the viscosity which is a function of temperature and degree of cure. The resin viscosity can be modelled using the relationship used by Khoun et al. [12]:

$$\mu = A_\mu \exp\left(\frac{E_\mu}{RT}\right)\left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^{a+b\alpha} \tag{12}$$

where T is the resin temperature, R is the universal gas constant, α_g is the degree of cure at gelation and E_μ, A_μ, a and b can be calculated experimentally.

3 MATERIALS AND EXPERIMENTAL SETUP

3.1 Material Description

Gurit Standard SPX26528/26373 fast curing epoxy resin was used to perform the validation experiment. The resin system used here is a one-part epoxy and one part hardener mixed in the ratio 100:25 by weight. It was injected at room temperature with a viscosity of 0.05 Pa s. In terms of fibre reinforcement, TG15N glass non crimp fibre (NCF) from Texonic Inc. was used. It has an areal density of 518 g/m^2 and each fabric layer has an approximate thickness of 0.45 mm.

3.2 Equipment Description

The experimental set up to test CRTM is made from P20 steel plaque as shown in Figure 2 a). The tool was placed in a 1250 tons compression press from PEI (Pinette Emidecau Industries). The flat plate tool to make parts with dimensions of 350 x 350 mm with a thickness range of 1-10 mm was designed at the National Research Council (NRC). A pinch area was designed on the bottom mould whose thickness is 0.65 mm lower than the rest of the mould. This is designed to help keep the fibre reinforcement in place when the resin is injected. Injection gate is located at the centre of the bottom mould.

a) b)

Figure 2. a) CRTM mould setup used for the model validation, b) TG15N NCF glass fibre preform.

3.3 Preform Preparation

The preform was prepared with 8 plies with a layup sequence of $[(0/90)]_{4s}$. A 350 x 350 mm template was used to draw the preform boundaries and the NCF was cut using a simple utility blade (Figure 2 b)). The Epikote 06720 epoxy thermoplastic powder binder was then applied on the preform. The preform was then vacuum bagged and placed on the oven at 100 ^{o}C for 15 minutes. This helped the preform to remain in the required shape.

3.4 Experimental Procedure

The preform was placed in the bottom mould cavity. The top mould was then brought down until there was a small gap of 1 mm between the mould and the preform. The resin/hardener mixture was injected at constant pressure through the injection gate located at the centre of the bottom mould. Once a known amount of resin is injected, the top mould moved down compressing the preform to a known thickness. Since the steel mould is opaque, it was impossible to make in situ measurements of the flow inside the preform. Therefore, an interrupted filling test was performed to check for the flow front at different times. Since the resin we use is fast curing in nature, the flow front stops within a minute after the resin injection is stopped. As a result, we can see a clearly defined flow front which can be used for validating CRTM simulation. The test matrix used for interrupted filling test is as shown in Table 1.

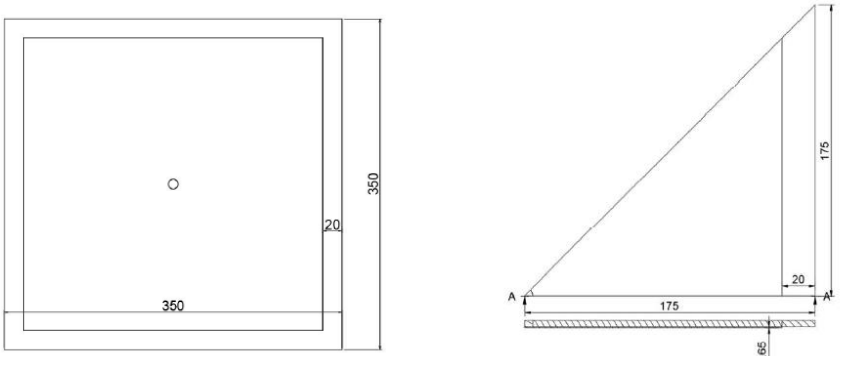
Table 1. Interrupted filling test matrix.

Test No.	Time (sec)
1	5
2	30
3	60 (End of injection)
4	End of compression

4 SIMULATION SETUP

4.1 Geometry Definition

The detailed dimension of the geometry is as shown in Figure 3 a). The dimensions are in mm and the resin injection gate has a diameter of 4.5 mm. Only 1/8th of the total part was used to reduce the computation time, as shown in Figure 3 b).

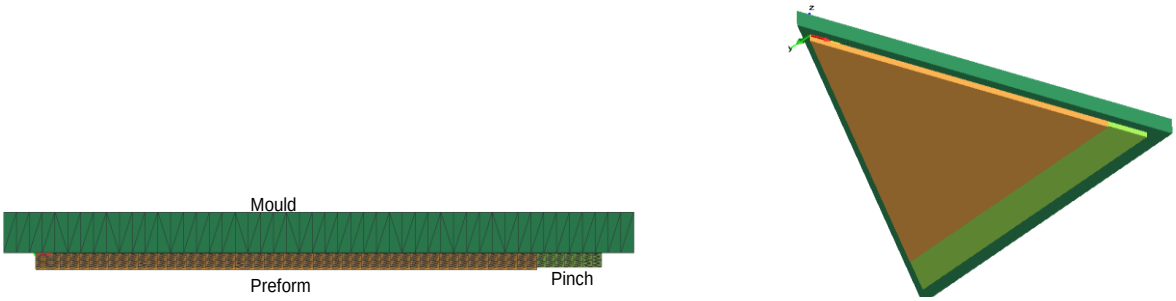


a) b)

Figure 3. CRTM mould schematic for: a) full dimension, b) 1/8th section. Dimensions are in millimetres.

A few simplification strategies are adopted in this work. In reality, there is a transition between pincher and the central mould in the form of an inclined surface. This work is simplified by assuming a flat mould pressing an already deformed reinforcement that has a step transition from central to pincher. Early methodology required definition of gap geometry. Later simplification assumes that the preform occupies the entire mould cavity. As a result, the preform geometry has greater thickness and will be defined with lower fibre volume fraction.

The geometry was built using features available in PAM RTM™. The 3D model is as shown in the Figure 4. The top mould was 10 mm thick and was made wider to accommodate possible deformation during the compression sequence. The preform was divided into two parts: (i) the central preform region thicker than the preform region (orange) and (ii) pinch area (light green).



a) b)

Figure 4. a) Front view of 1/8th section with 3D tetrahedral mesh and, b) isometric view.

4.2 Material Model Implementation

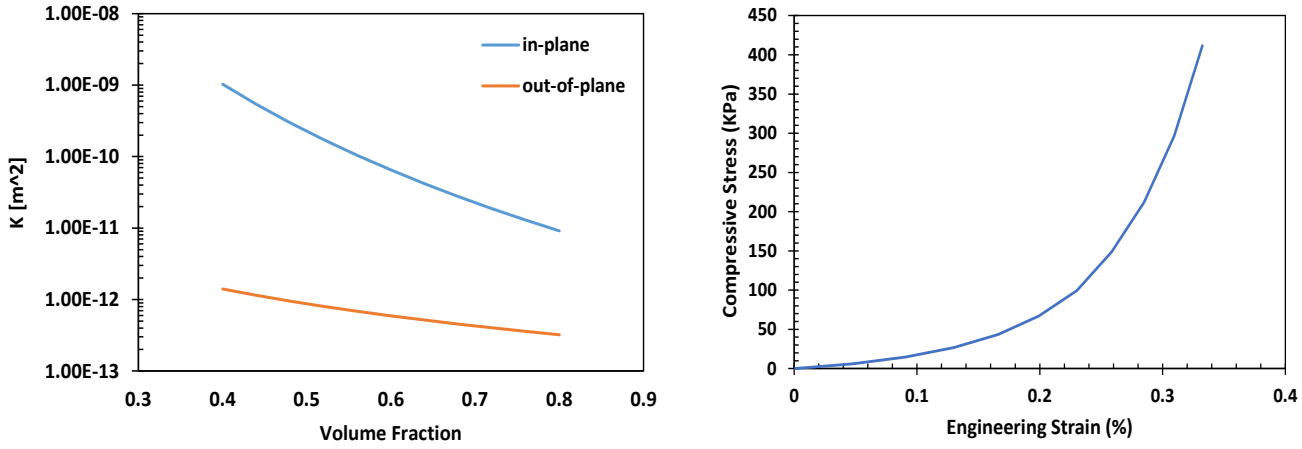
Cure kinetics and viscosity of Gurit Standard SPX26528/26373 fast curing resin was measured at 70, 80 and 90 °C. Based on the experimental data, semi-empirical models were developed. The models developed served as the input for the material database in PAM RTM™. Permeability of TG15N NCF was measured both in in-plane and out-of-plane direction using in-house lab equipment. Preform compaction was also measured using MTS insight 5kN universal testing machine. Permeability was implemented as a function of volume fraction as shown in Figure 5 a). The compaction pressure is implemented as a function of engineering strain as shown in Figure 5 b).

5 RESULTS AND DISCUSSION

The mould, preform and pinch were modelled with 125,347 tetrahedral 3D elements as shown in Figure 4 a). The resin was injected at 80 psi pressure at room temperature (25 °C) and vacuum was applied across the perimeter of

Table 2. Initial and boundary conditions.

Parameters	Value
Initial preform volume fraction	0.402
Initial pinch volume fraction	0.482
Top mould temperature	105 °C
Bottom mould temperature	100 °C



a) b)

Figure 5. a) Permeability curve, and b) compaction curve.

the part. The resin was injected for 60 seconds and then stopped. At this point, the compression sequence of the mould was activated at a constant closing speed of 0.5 mm/sec. The initial and boundary conditions used are summarized in Table 2.

The simulation was performed on Intel® Core™ i-7 4770 CPU using four cores. The total time taken to perform simulation was 45 minutes. Figures 6-9 show the comparison between experimental and simulation results for the CRTM process. First shot of resin was injected for 5 seconds and the results were compared with simulation. Since the injection gate was located at the bottom, flow front of the bottom surface was compared as shown in Figure 6. The flow front prediction is in good agreement with the experimental result. The difference between experiment and simulation was slightly higher as the injection proceeds as shown in Figures 7-8. The reason might be attributed to change is out of plane permeability due to addition of binders during preforming but still it was considered to be in good agreement. Figure 9 shows the end of the compression sequence. The experiment and simulation results were a perfect match.

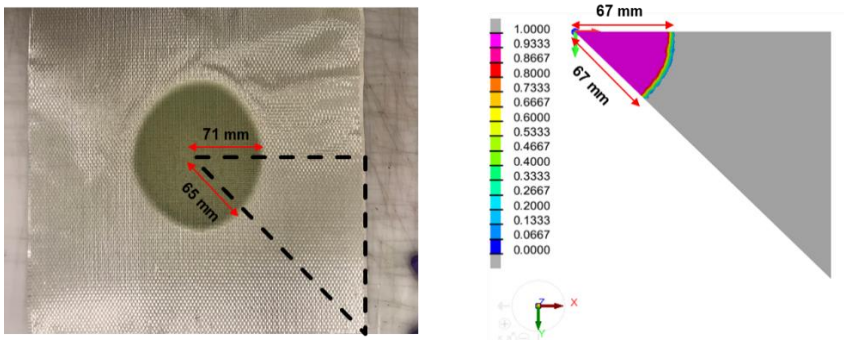


Figure 6. Experiment vs simulation after 5 seconds of Injection for 1/8th section.

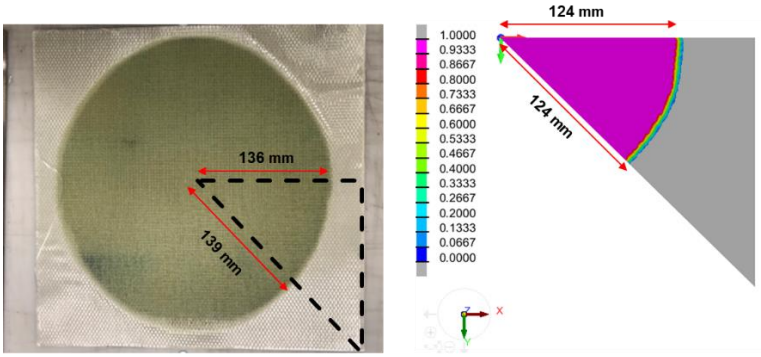


Figure 7. Experiment vs simulation after 30 seconds of Injection for 1/8th section.

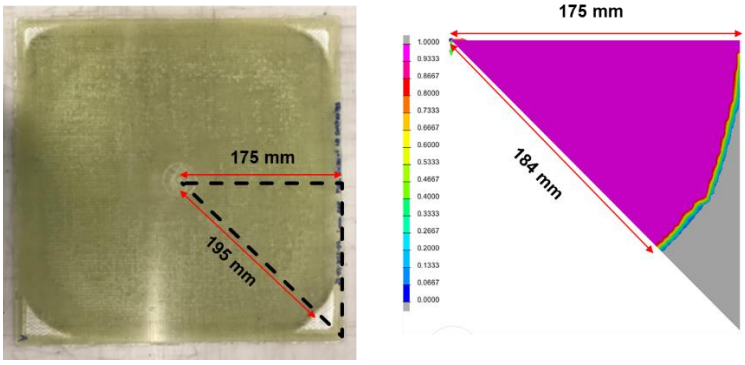


Figure 8. Experiment vs simulation after 60 seconds of Injection (end of injection).

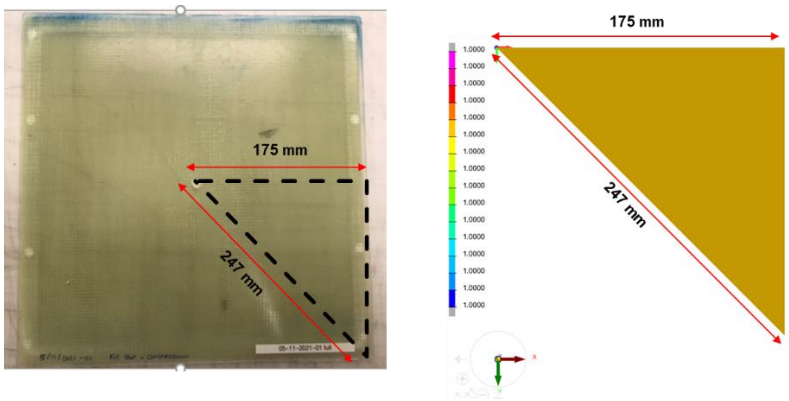


Figure 9. Experiment vs simulation at the end of the compression.

The experimental data of the mass of resin injected was also compared with the simulation. Figure 10 shows the comparison between experimental and simulation results. Furthermore, the resin degree of cure progression has also been reported as shown in Figure 11.

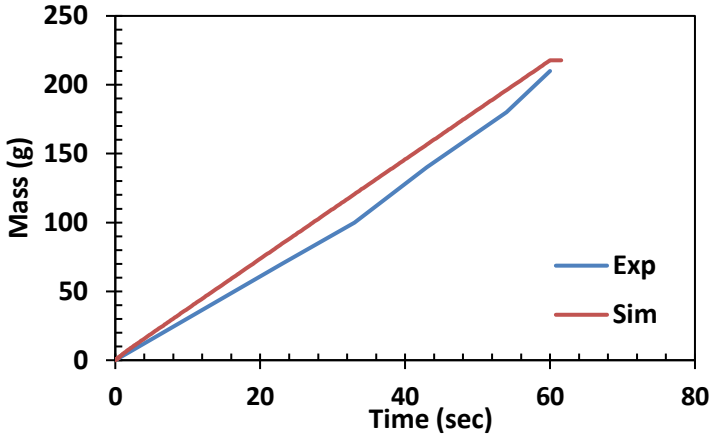


Figure 10. Experimental vs Simulation showing mass of resin injected.

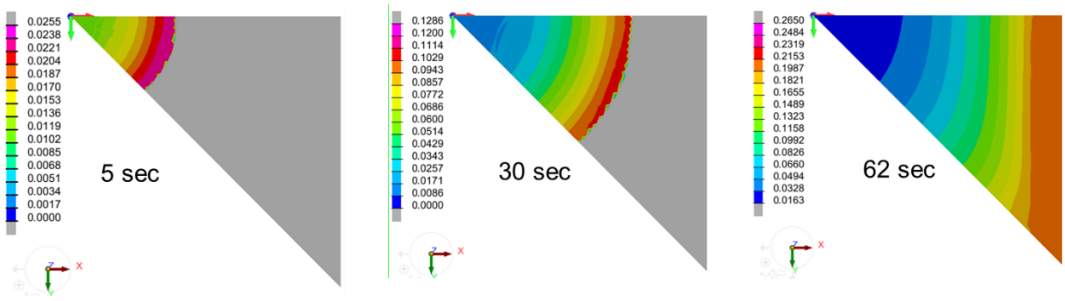


Figure 11. Degree-of-cure progression during the CRTM process.

6 CONCLUSION

Thermal-chemical-mechanical simulation of 3D CRTM process was performed in this work. The results from the simulation were compared with the experimental test results conducted at NRC. The coupling between different physics involved in CRTM process was explained in detail. The results from interrupted filling tests were in good agreement with the simulation results. Future work will involve incorporating temperature sensors inside the mould at different locations to compare the temperature and degree-of-cure profile during the CRTM process with the simulation results. Furthermore, sensitivity analysis will be performed on the process.

7 ACKNOWLEDGEMENTS

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