NUMERICAL METHODS FOR 3D COMPRESSIVE RTM SIMULATIONS

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Keywords: Compressive RTM, Fluid/Solid coupling, Composites virtual manufacturing, Process simulation

Abstract

The extensive use of composite materials in automotive structural components with high mechanical requirements is today limited by different concerns such as production rates. The compressive resin transfer molding process (C-RTM) is one amongst others composites manufacturing processes which could overcome this limitation enabling the reduction of the production time of composite parts.
Today, several simulation tools are used in the industry to perform LCM process simulations such as PAM-RTM™. Nevertheless, some functionalities are still missing to address advanced manufacturing processes such as C-RTM. Indeed, for C-RTM simulation, two main issues need to be tackled:

- the resin gap evolution during the forming due to the moving tool;
- the preform deformation due to compression and resin flow.

This paper presents advanced numerical methods for 3D compressive compressive RTM simulations developped by ESI Group in partnership with HONDA R&D.

1. Introduction

As lightweight design becomes a critical concern, automotive industry struggles to be more weight efficient and achieve lower levels of emissions mandated by continuously evolving regulations worldwide.
Vehicle weight reduction is often achieved by introducing new materials and assembly techniques. Car designers are using combination of metal alloys, such as high strength steel and hot formed steel, as well as lighter materials, such as continuous fibres reinforced composites.
The extensive use of composite materials in automotive structural components with high mechanical requirements is today limited by different concerns such as production rates. The compressive resin transfer molding process (C-RTM) is one amongst others composites manufacturing processes which could overcome this limitation enabling the reduction of the production time of composite parts.
This process is a two steps process:

- first resin is injected in a gap located between mold and preform;
- then, in a second stage, resin injection is closed and top mold begins its displacement in order to close the gap and compress the preform until final desired thickness is reached.

Excerpt from ISBN 978-3-00-053387-7

To address the resin gap vanishing issue, the Inter-Penetrating Meshes functionality uses one mesh representing the solid tool which can move through the fluid mesh and displace the resin as it moves. The position of the tool face needs to be very accurately determined so as to identify the fluid nodes in front of or behind the tool. Also, it is required to calculate the available fluid volume for the partially cut elements.
To address the fluid/structure interaction issue, a coupling and chaining framework was utilized. The framework connects independent solvers, sequences the coupling iterations and provides a mechanism for seamless exchange of interaction data. This enabled accurate prediction of preform deformation and its effect on permeability and fibre fraction variations [2; 3; 4]. Indeed, the deformation of the preform occurs during the first phase of the closing, when the resin in the gap is pushed in the preform, and during the second phase of the closing, when the tool is in direct contact with the preform.
The combination of those two unique functionalities enables C-RTM process optimization using simulation.

2. Compressive Resin Transfer Molding

Today, several simulation tools are used in the industry to perform LCM process simulations based on Darcy equation (1) such as PAM-RTMTM.

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

where $\vec{q}$ is the fluid velocity, $\overline{\overline{K}}$ the permeability, μ the resin viscosity, $\vec{\nabla}P$ the pressure gradient [1].

Nevertheless, some functionalities are still missing to address advanced manufacturing processes such as compressive RTM (figure 1).

Figure 1. Compressive RTM process schematics

The main difference of compressive RTM resides in the facts that this manufacturing process can be phased in two stages:

1. Resin injection in gap;
2. Mold displacement inducing resin compression and reinforcement preform impregnation as gap vanishes.

If resin injection simulation is considered as standard in LCM (Liquid Composites Molding) manufacturing process simulation tools, it is not the case for the second step on the C-RTM process. Indeed, no simulation software solution exists on the market to solve precisely the compression phase with vanishing gap and preform deformation due to tool compression.
Even though a dedicated C-RTM module exist in PAM-RTMTM since 2010, it is limited to 2D shells only and does not permit to model through thickness flows which are of prime importance during compression stage.

The objective of our work is to develop advanced functionalities allowing the use of 3 dimensional volumic elements.

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3. Specific software developments

This new three dimensional compressive resin transfer molding simulation tool is based on PAM-RTM™, a finite element code which solves Darcy's equation. The adaptation of current software solution to compressive RTM implies the addition of two main capabilities:

- vanishing gap;
- compression stage during which preform deforms under the action of resin and mold pressure.

3.1. Inter-Penetrating Meshes

A new functionality called Inter-Penetrating Meshes was developed in order to model the compression phase of the process. It uses two independent meshes (figure 2), one mesh representing the solid tool and another mesh modelling the gap and the preform to be filled. The tool mesh can move through the fluid mesh and displace the resin as it moves. The position of the tool face needs to be very accurately determined so as to identify which elements of the fluid mesh are supposed to be filled by the resin or not. Also, it is required to calculate the available fluid volume for the partially cut elements.

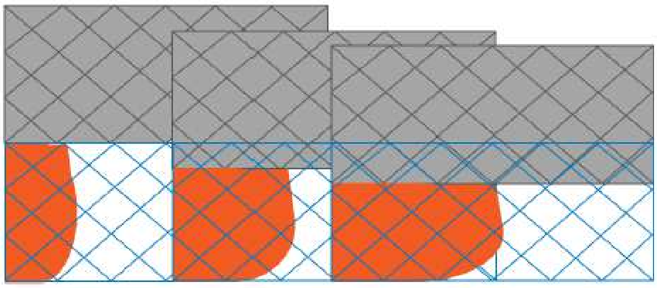

Figure 2. Inter-Penetrating Meshes technology

One of the main assumption resides in the fact that the resin flow in the gap is governed by Darcy's equation as it is in the preform region. Indeed equivalent permeability tensor values based on Poiseuille flow need to be defined for this gap region in order to represent adequately the resin flow.

3.2. Fluid/Solid coupled solver

During compression stage, the preform is deformed as a result of a competition between contact forces (resin layer and /or mold when gap has vanished) and hydrostatic loads due to resin flow.

Several projects have been studying the effect of resin pressure on mechanical behaviour and geometry of the perform [2, 3]. It appears that when the preform thickens due to resin arrival, the permeability values arise inducing an increase of flow front velocities. In C-RTM process, the effect is usually inverse and with gap closing, the preform tends to reduce its thickness. This thickness reduction causes a reduction of in-plane and transverse permeabilities slowing the flow front progression.

In order to take into account this mechanical behaviour of the preform, we leveraged the coupling framework's capability to exchange data between solvers. It enabled fluid solver of PAM-RTM™ to exchange informations with an ESI solid mechanics solver. With this Fluid/Solid coupled solver, we are able to capture the deformation of preform mesh during compression stage and send back to the fluid solver updated permeability values for the deformed elements of the 3D mesh used in the simulation. The fluid solver can then use those updated permeability values to compute the flow front velocities in 3 dimensions.

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A quasi-static approach is used in the fluid/solid coupling algorithm by a weak iterative coupling. First, the fluid problem using Darcy is solved on a fixed grid (i.e. for rigid preforms). Terzaghi's law (2) is used to predict the influence of the resin on the fibers through the hydrostatic pressure.

$$\bar{\bar{\sigma}}_{overall}(\bar{\bar{\varepsilon}}) = \bar{\bar{\sigma}}_{fib}(\bar{\bar{\varepsilon}}) + p\bar{\bar{I}} \tag{2}$$

with $\bar{\bar{\sigma}}_{overall}(\bar{\bar{\varepsilon}})$the overall stress applied to the system, $\bar{\bar{\sigma}}_{fib}(\bar{\bar{\varepsilon}})$ the effective stress in the preforms and $\bar{\bar{I}}$ the unit tensor.
The non-linear finite strain problem is then solved for a given pressure field (and therefore for an equivalent Terzaghi's behavior), the influence of deformations being taken into account through porosity variations which affects the permeability of the medium. The permeability can be computed with any porosity dependent measurement or model. Here, for the example, the Carman-Kozeny's law (3) can be considered:

$$\bar{\bar{K}} = \frac{{d_f}^2}{16\overline{\overline{h_k}}} \frac{\emptyset^3}{(1-\emptyset)^2} \tag{3}$$

with d_f the average fiber diameter, $\overline{\overline{h_k}}$ Kozeny constants and $\emptyset$ the porosity.

4. Application

4.1. Simulation input

Several material parameters are to be defined for running 3D C-RTM simulations. Alongside traditional RTM input data such as resin viscosity and cure behaviour as well as reinforcement permeability tensor, the fluid/solid coupled solver requires mechanical compression data. As in standard RTM process, the C-RTM simulaton tool developed can be used for isothermal and non-isothermal simulations including pre-heating, heated C-RTM and curing simulations.
Moreover, in C-RTM simulations, reinforcement permeability tensor values Kx, Ky and Kz have to be defined as a function of fiber volume content to capture with significant precision the effect of reinforcement compression on flow front evolution.

Our tests cases are using a non-crimp fabric for which experimental measurements of permeability values have been done for several fiber volume content. The variations of permeability tensor values are given in figure 3.

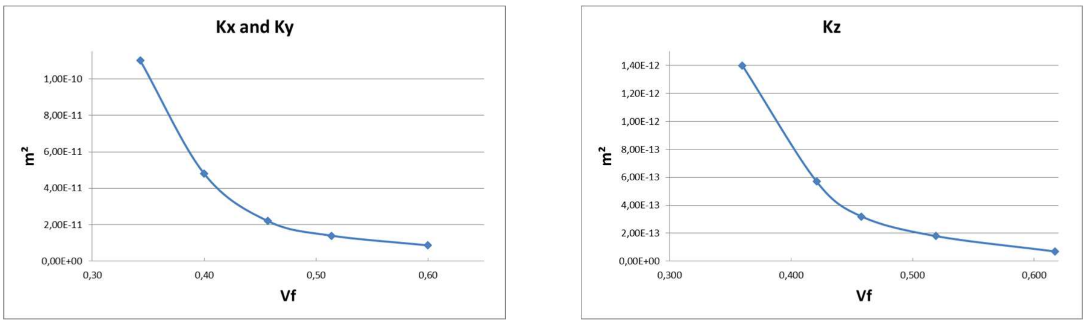

Figure 3. NCF permeability tensor values evolution with Vf

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Regarding meshing, standard meshing recommendations are to be used. PAM-RTM™ support both 2D (shell elements) and 3D (solid elements) modeling. Filling and heated filling simulations support triangle and tetra elements for permeable parts, triangle, quad, tetra, penta and hexa elements for non-permeable parts (core or mold). Of course our focus being on 3D C-RTM simulations, the mesh to be used will be based on solid elements. The use of 3D models allows the following effects to be taken into account:

- Temperature gradient through the thickness
- Transverse resin flow through the thickness
- Heat exchange with mold (if mold is meshed), convection exchange with air…

Please note that 3D C-RTM simulations require reinforcement zones and gap areas to have connected mesh to allow resin transfert in between those two zones. On the contrary, the gap and mold meshes should be disconnected to allow Inter-Penetrating Meshes functionality working properly.

Figure 4 presents the mesh used in the simple validation test case consisting in a simple 200x20x3 mm^3 plate. The mesh uses 3400 solid elements with tetrahedrons repreenting the fluid domain (gap and preform) and bricks for the mold. Resin inlet is defined on the right side of the gap. During injection, the mold remains fixed. After 10 seconds, compression stage starts, the resin inlet is closed and the mold velocity is set to 0.5 mm/s.

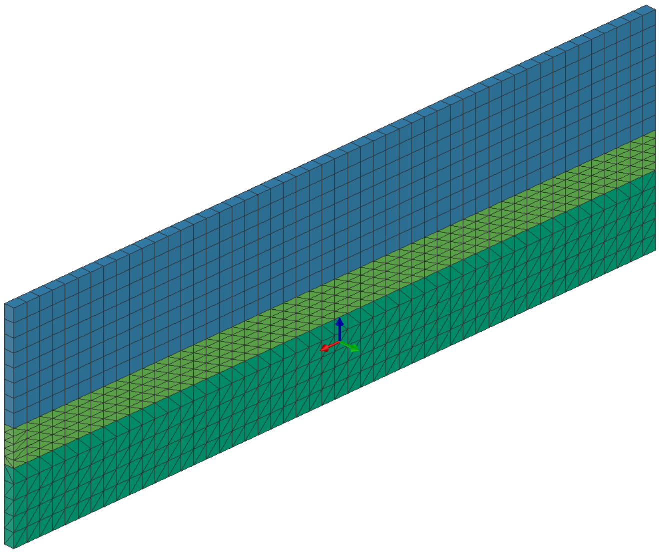

Figure 4. Solid mesh for C-RTM simulation showing Mold (blue), initial gap (light green) and preform (dark green)

4.2. Simulation results

Following pages show simulation results. Flow front evolution is displayed on figure 5. It can be noticed that resin flow initially within the gap due to the much higher permeability value when compared with preform permeability values. Once the total amount of resin needed to manufacture the part at the desired fiber volume content is injected (after 10s), the inlet is closed and the mold begins its displacement. Figure 6 shows mesh displacement and preform compression during the process.

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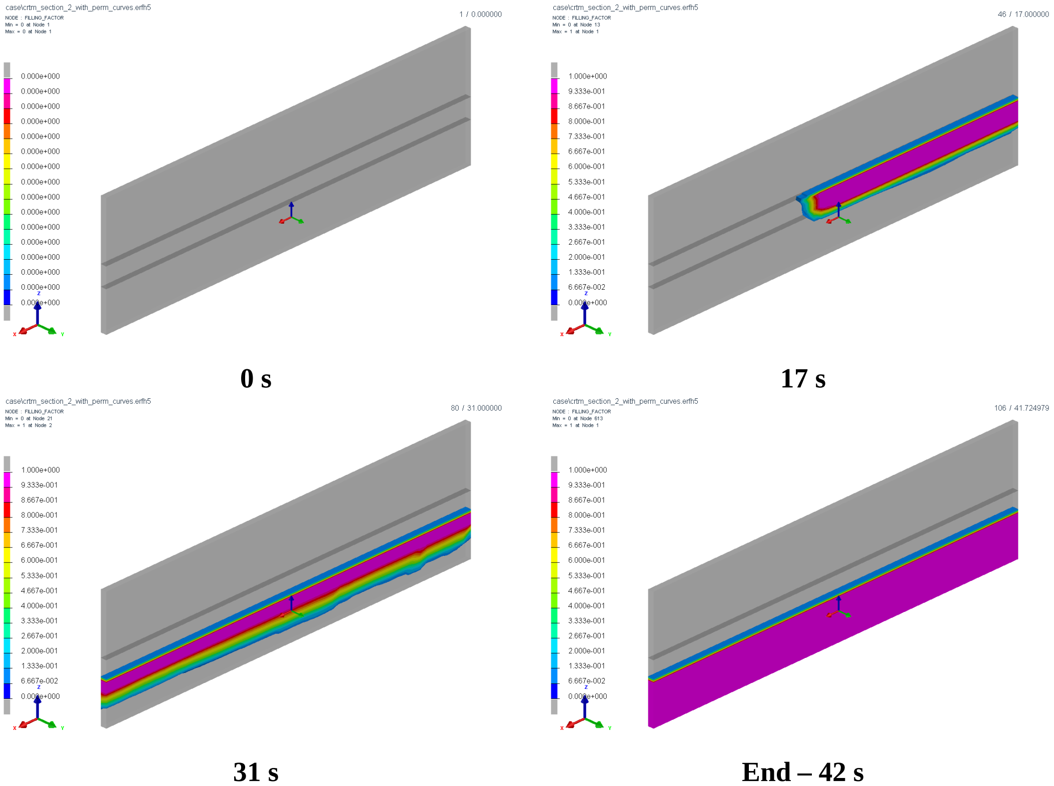

Figure 5. C-RTM simulation – Flow front evolution – Fluid solver result

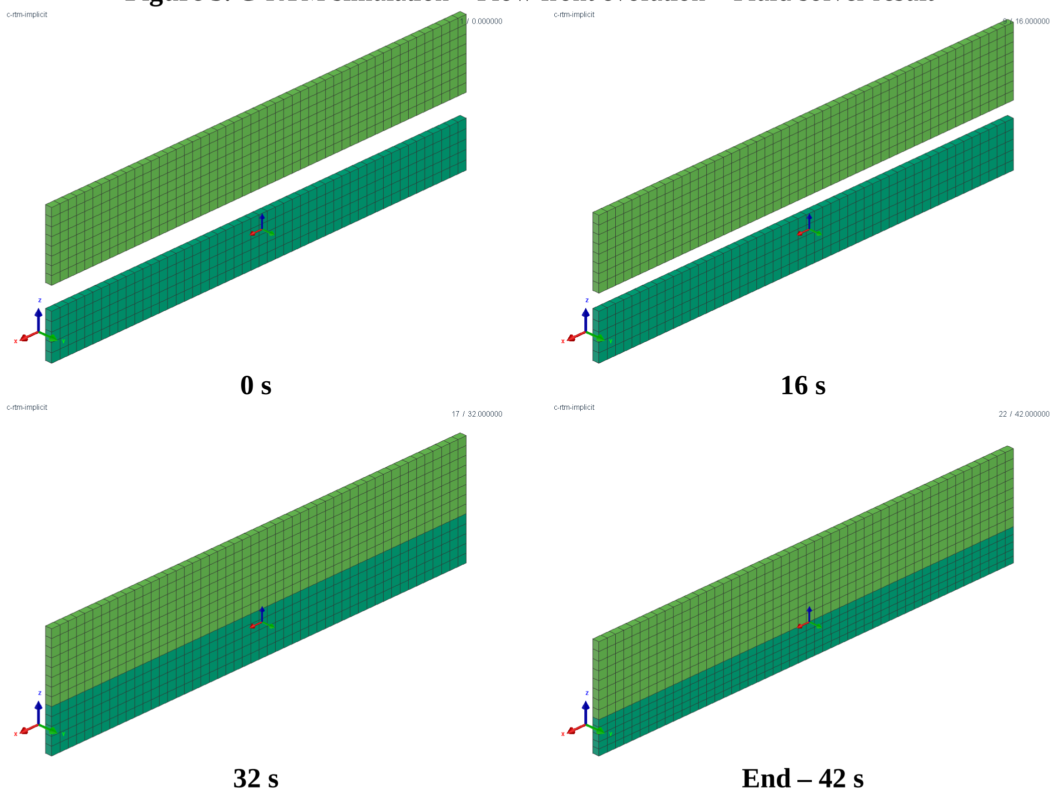

Figure 6. C-RTM simulation – Mesh deformation - Solid solver results

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Following figure 7 shows through thickness permeability value evolution with time and figure 8 shows evolution of fiber volume content. Of course, the Kz and Vf values in the gap do not evolve and maximum values stay constant at 1e-8 m² for Kz and 0 for fiber volume content.

On the other hand, the through thickness permeability value in the preform (minimum values) evolves from

- @ 0 s - Kz = 2.343e-12 m². Kz permeability for 30 % fiber volume content initial value.
- @ 17 s - Kz = 2.341e-12 m². The mold displacement has already began but preform compression is limited so far. Fiber volume content in the preform is still 30%.
- @ 31 s - Kz = 2.141e-12 m². Gap has just vanished but mold only slightly compress the preform yet. Fiber volume content in the preform is still 31.3%.
- @ 42s - Kz = 5.079e-13 m². The gap has vanished. The mold compresses the preform as the deformed mesh of figure 6 shows. Fiber volume content in the preform has increased to 44.6%.

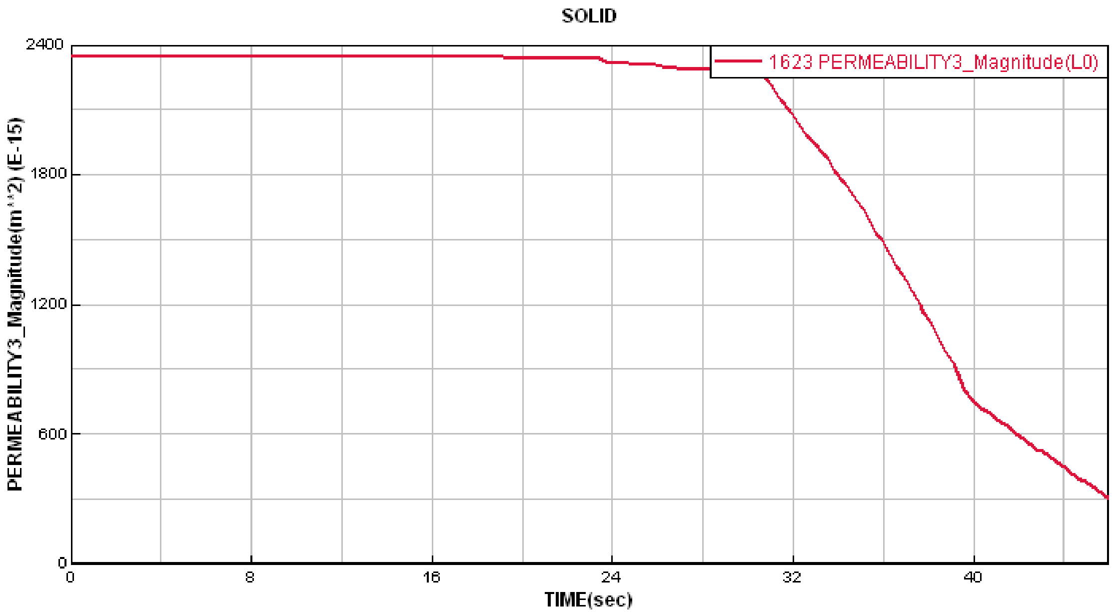

Figure 7. C-RTM simulation – Kz evolution with time – Fluid solver results

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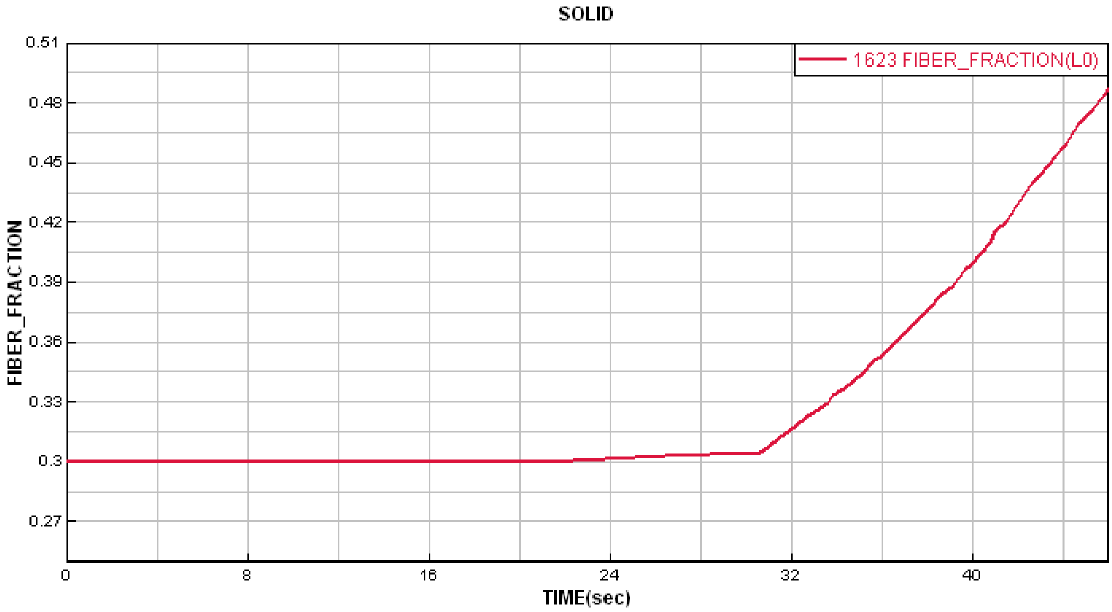

Figure 7. C-RTM simulation – Fiber volume content evolution with time – Fluid solver results

This 3400 elements simulation took 184 seconds on a 64 bits Windows computer running 1 Intel Core i7-3740 QM CPU @ 2.7GHz processor with 16Go RAM. Please note that current software version version is still in prototype mode and optimization has not been done yet.

5. Conclusions and perspectives

Future steps of this work include industrialization of those development in order to make it possible to use them on large parts and industry acceptable computation times. Additional industrial validation of current developments is also to be done. Overcoming the current limitation of Darcy description of resin flow in the gap should also be carried out in the coming months using advanced Stokes-Darcy coupling. Simulation of several other LCM processes might also benefit from those new functionalities. During infusion process, the resin is not pushed by a moving tool controlled by an external pressure applied on a deformable membrane. Resin arrival often causes a thickening of the preform with unneglectable effect on permeability values, resin flow velocities and filling times.

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