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MYRTM: AN APPROACH FOR THE SIMULATION OF RESIN TRANSFER MOULDING (RTM) PROCESSES BASED ON CELLULAR AUTOMATA

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Abstract. *Liquid Composite Moulding (LCM) covers a class of manufacturing processes of high quality fibre reinforced composites, where the liquid resin is injected under pressure into the dry fibre reinforcement placed in a rigid cavity. Finite Element Methods (FEM) allow the optimisation of liquid moulding of composite parts by virtual process simulation, however due to costs and feature drawbacks, they are hardly used in practise. myRTM is a simulation software based on the principle of Cellular Automata to predict resin injection processes and serve as a preliminary process design tool. Simulation results are compared against sLIP, a mathematically correct finite element simulation software. The results show a good agreement in terms of filling pattern and the prediction of potential air entrapments. Fill time and pressure distribution are not accurately predicted and therefore still object of research for future releases of myRTM.*

1 INTRODUCTION

Liquid Composite Moulding (LCM) covers a class of manufacturing processes of high quality fibre reinforced composites for various applications. LCM processes are closed processes, i.e. during injection the mould cavity is open only to the vacuum vent and the injection point where liquid resin mix is flowing in. Finite Element Methods (FEM) allow the optimisation of liquid moulding of composite parts by virtual process simulation. In real life liquid moulding may be influenced by many additional effects, which are hard to consider in numerical simulations. Mainly race tracking effects in areas of low porosity are dominating the propagation of the flow front. Because of those reasons it is crucial, that the user of the software has deep knowledge on liquid moulding processes. Additionally, many of the features of commercial software may have minor influence on most infusion processes and are therefore not useful. For these reasons process simulation it is seldom used in practice. In particular in small and medium size enterprises the process simulation is not applied, because of the high license costs for the software, missing material data and the lack of knowledge of the engineers in application of simulation tools.

Cellular Automats were first proposed in 1940 by John von Neumann, Stanislav Ulam and Alan Turing at Los Alamos [1]. In order that cellular automats may be used to simulate physical phenomena that are described by sets of differential equations, they must be approximated either by the top down or by the bottom-up method. In the case under consideration a middle way is preferred, whereby in the bottom-up approach the algorithm is based on the influence of the individual parameters according to Darcy's law [2], which describes flow processes through porous media (Eq. 1):

$$q = \frac{[K]}{\mu} \cdot \nabla p \tag{1}$$

q means the flux (superficial flow front velocity), [K] is the permeability tensor, μ the resin viscosity and ∇p is the pressure gradient. The cellular automat presented here was developed specifically for hollow shell-shaped components – "2½ dimensional" – which is often the form of fibre-reinforced plastic structures, though the algorithm can in principle also be used for true three-dimensional structures. The algorithm calculates the state of the pressure distribution in a cell during filling from the pressure in the cell itself as well as that in the neighbouring cells, and from the properties of the cells in that region at that time, according to Eq. 2:

$$p_{t+1} = p_t + \left(\frac{K}{\bar{K}}\right)^q \cdot \frac{1}{m} \cdot \sum_{i=1}^{m} \left(\frac{d_i \cdot \Phi_i}{d \cdot \Phi}\right)^r \cdot \left(\frac{\bar{l}}{l_i}\right)^s \cdot \left(p_{i,t} - p_t\right) \tag{2}$$

where p is the pressure of the cell, K is the permeability ($\bar{K}$ the average permeability), p is the porosity, d is the cavity height, l is the distance to the neighbouring cell ($\bar{l}$ the average distance), q, r and s are weighting factors and m is the number of neighbouring cells taken into account [3].

2 MYRTM BENCHMARK WITH SLIP

The objective of this study is to benchmark the "quick & dirty" myRTM approach with a mathematically correct and established finite element solution (sLIP [4] of ETH Zurich) and provide suggestions for improvement. myRTM will however still be used for preliminary process design, with ease of use and fast generation of results as its main features; this study and the related suggestions will help to improve and interpret the simulation results.

Two sets of phenomena are taken into account: on the one hand, global effects which affect the whole part geometry; on the other hand, local effects that occur just in a fraction of the part geometry, but which might have significant influence on the global filling procedure. A simple rectangular geometry is chosen for that purpose. All results are scaled to match the (relative) fill times at 10, 25, 50 and 75% of the total fill time. Absolute time values are provided to compare the fill time prediction.

The standard parameters for all filling simulations are summarized in Table 1. The individual simulations derive in one or more parameters from this basic modelling.

Parameter	Abbrev.	Value	Unit
Dimensions of cavity			
Length	l	0.3	[m]
Width	b	0.3	[m]
Height	h	0.02	[m]
Injection pressure	p_i	500’000	[Pa]
Vacuum pressure	p_v	10’000	[Pa]
Permeability	K	$2 \cdot 10^{-9}$	[m^2]
Porosity	ϕ	50	[%]
Viscosity	μ	0.1	[Pa s]
Cell distance/mesh size	d	~0.01	[m]
Inlet position		Top mid	

Table 1: Basic parameters for RTM simulation.

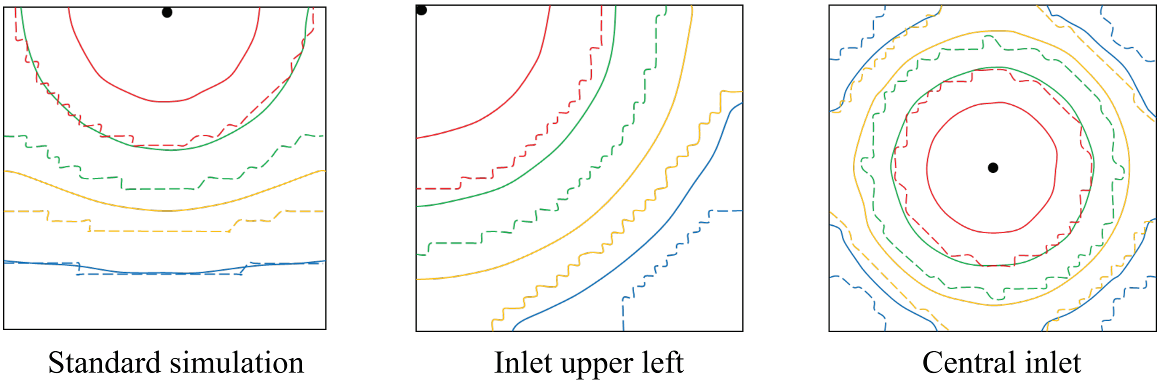
In myRTM, the weighting factors q, r and s are set to their standard values 1, 1 and 2, respectively (see Eq. 1). 8 relevant neighbouring cells are taken into account.

2.1 Global phenomena

Injection position

Test arrangement: The inlet is place in the middle of a cavity edge, in a corner or in the centre.

Results: The results of the filling stages are illustrated in Figure 1. Solid lines stand for the fill front as predicted with SLIP, dashed lines with myRTM. The lines represent the filling stages at 10%, 25%, 50% and 75% of total filling time.



Standard simulation

Inlet upper left

Central inlet

Figure 1: Filling pattern comparison for different inlet position

Whereas filling pattern generally shows a good agreement, filling times differ (Table 2). Flow front progression is faster in myRTM, however absolute filling time is lower in sLIP.

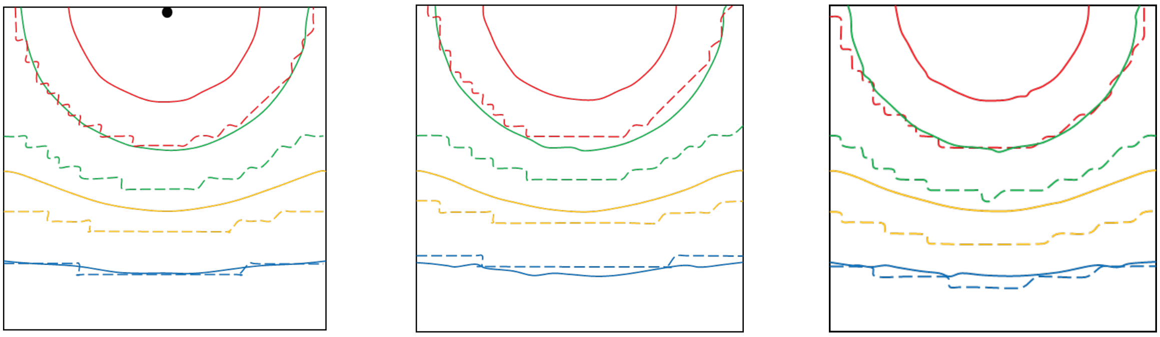
Simulation description	Fill time sLIP	Fill time myRTM	Deviation of myRTM
Central edge inlet	39s	93s	+138%
Corner inlet	76s	143s	+88%
Central inlet	16s	36s	+125%

Table 2: Fill time comparison for different inlet position

Injection pressure

Test arrangement: For the central edge injection, pressures of 2.5, 5 (standard) and 10bar are investigated.

Result: Filling patterns relative to total injection time are acceptably matching. Whereas sLIP predicts a linear dependence of the total injection time on injection pressure (as expected), myRTM overestimates this effect (Table 3).



Standard simulation (5bar) 2.5bar injection pressure 10bar injection pressure

Figure 2: Filling pattern comparison for different injection pressure

Simulation description	Fill time sLIP	Fill time myRTM	Deviation of myRTM
2.5bar injection pressure	78s	232s	+197%
5bar injection pressure (std)	39s	93s	+138%
10bar injection pressure	19s	38s	+50%

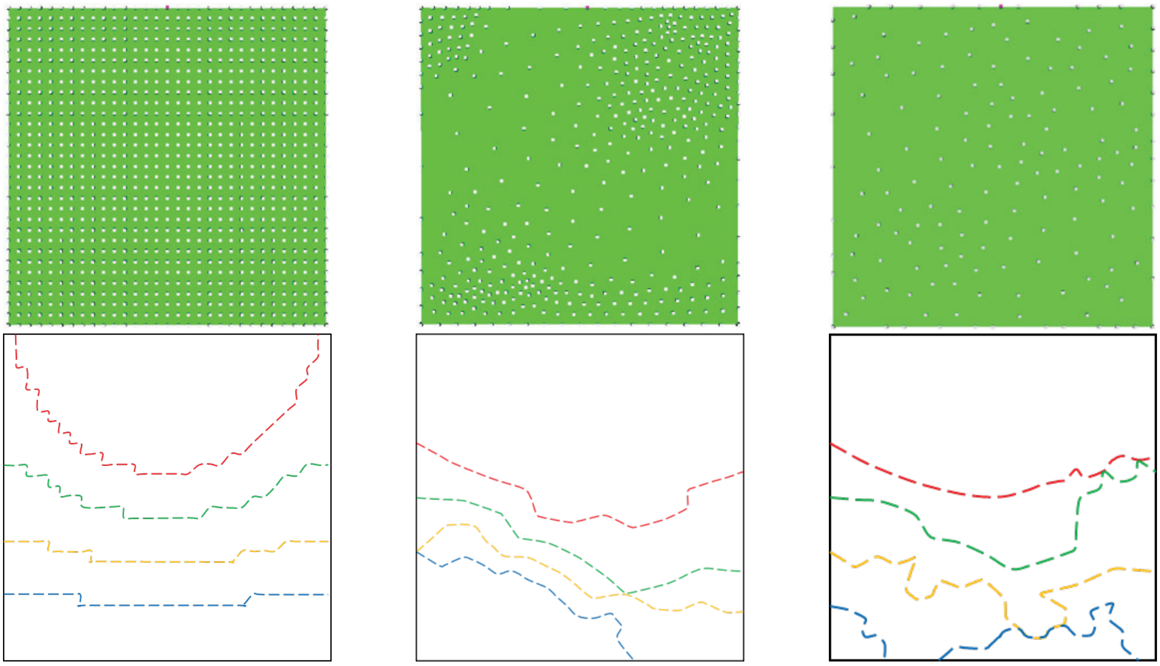
Table 3: Fill time comparison for different injection pressure

Cell distribution (within myRTM) and cell distance

Test arrangement: Cellular automata calculations are based on the status of neighbouring cells. Thus, the distribution of these neighbours has an influence on the results. Two configurations are investigated (Figure 3):

- Randomly odd cell distribution
- Gradually distributed cells

Result: A strong dependence of the simulation results on cell distribution can be observed. myRTM has therefore an integrated “sweep” function to delete so called “cancer nodes”. Although an ideally homogeneous distribution is not achieved, the simulation enhances with deleted cancer nodes (Figure 3, third column). However, there is still a strong dependence on cell distribution, and the results significantly differ from the ideal case.



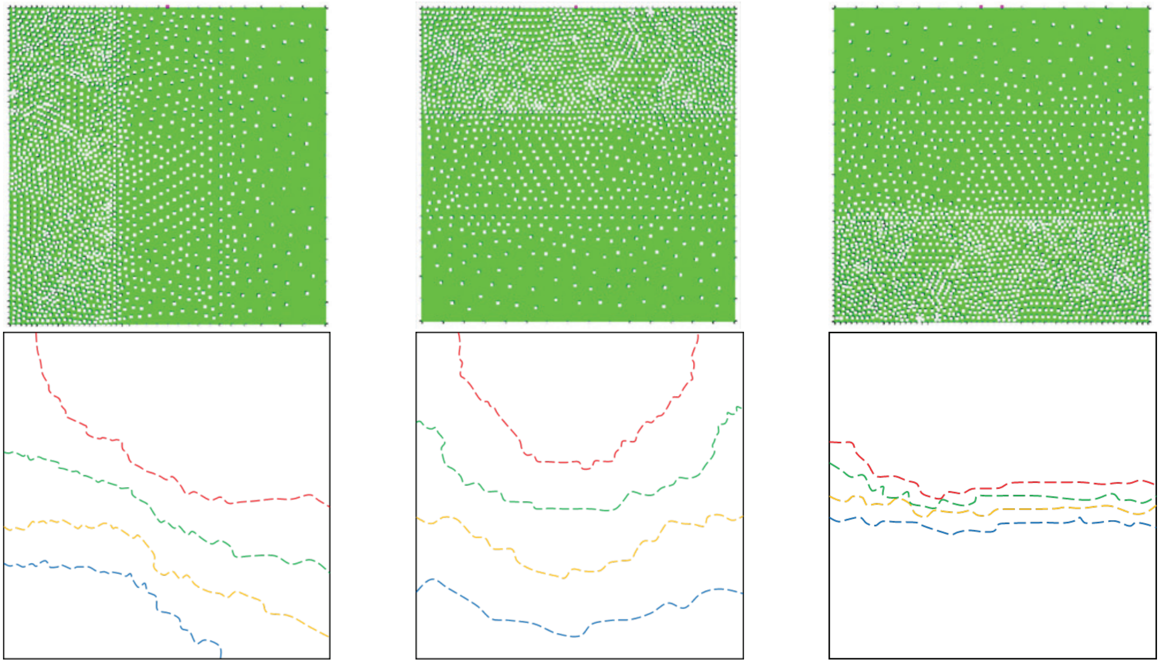
Standard simulation (homogeneous distribution)

Odd cell distribution

After “sweep” within myRTM

Figure 3: Filling pattern for different cell distribution

With complex geometries, standard meshers tend to model simple zones with relatively large, homogeneous elements, whereas in zones with radii or other features, the elements become small and sometimes misshapen. For this purpose, a gradual distribution of cells is evaluated (Figure 4).



Gradual horizontal distribution with decreasing density

Gradual vertical distribution with decreasing density

Gradual vertical distribution with increasing density

Figure 4: Filling pattern for gradually different cell distribution

myRTM shows a very strong dependence on cell density. Simulation results differ significantly and may render unusable, if an inhomogeneous mesh is used. For very close meshed cells, simulation even stops. Therefore, it is crucial to control and optimize the cell distribution prior to simulation start – either using a finite element modeller or the integrated "sweep" function.

Permeability (absolute value, whole cavity)

The variation of the global permeability within the cavity does not change the filling pattern. The injection time rises linear with a decrease in permeability, in both sLIP and myRTM.

Part thickness

For injections with constant pressure, a change in the part thickness (cavity height) does not change the filling pattern or the filling time, as long as enough resin is pumped (in reality).

Viscosity

Changes in the resin viscosity linearly influence the filling time (in both sLIP and myRTM), as expected.

Pressure level and vacuum pressure

The pressure gradient is the driving force of the resin flow. In myRTM, the fill status of a cell is calculated according to a threshold pressure based on the difference between inlet and outlet. If this value is exceeded, a cell is filled. The threshold depends on injection pressure and vacuum. This procedure might lead to errors if injection and vacuum pressure are sufficiently close.

2.2 Local phenomena

To be able to realize local variations, the cavity is divided in 9 squares of 0.1 x 0.1m dimension.

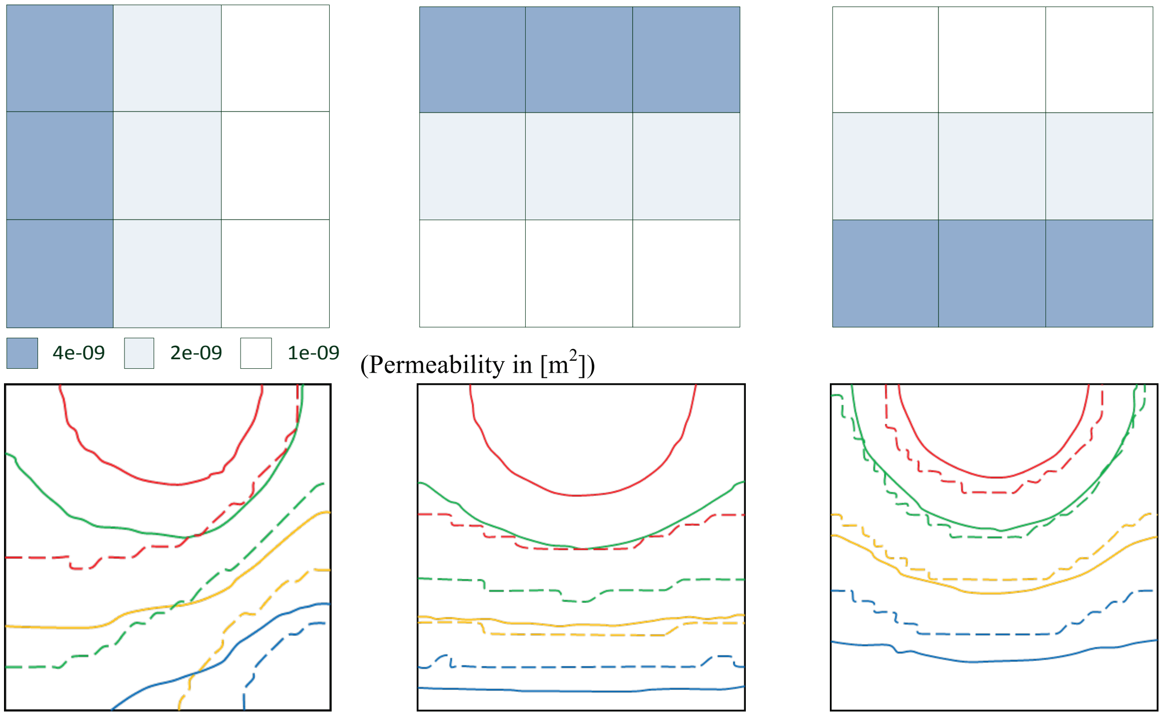
Permeability

Test arrangement: Besides intended variation of the permeability depending on lay-up sequence or number of layers, local permeability may vary in a mould due to effects like local compression, fibre washing or fibre distortion because of mould closing. These effects are however difficult to predict and therefore only of limited use in simulation, unless implemented using stochastical variations to eventually obtain a robust filling process [4]. Three zones of different permeability values are defined within the cavity (Figure 5). Resin injection starts in the standard configuration (central edge injection).

Result: The filling patterns in sLIP and myRTM reasonably agree, however the fill time change in myRTM is opposite to sLIP (Table 4). The term for the ratio of local to global permeability in Eq. 2 needs modification to correct this effect.

Simulation description	Fill time sLIP	Fill time myRTM	Deviation of myRTM
Decreasing from left to right	43s	150s	+249%
Decreasing from top to bottom	27s	111s	+311%
Increasing from top to bottom	74s	78s	+5%

Table 4: Fill time comparison for local permeability changes



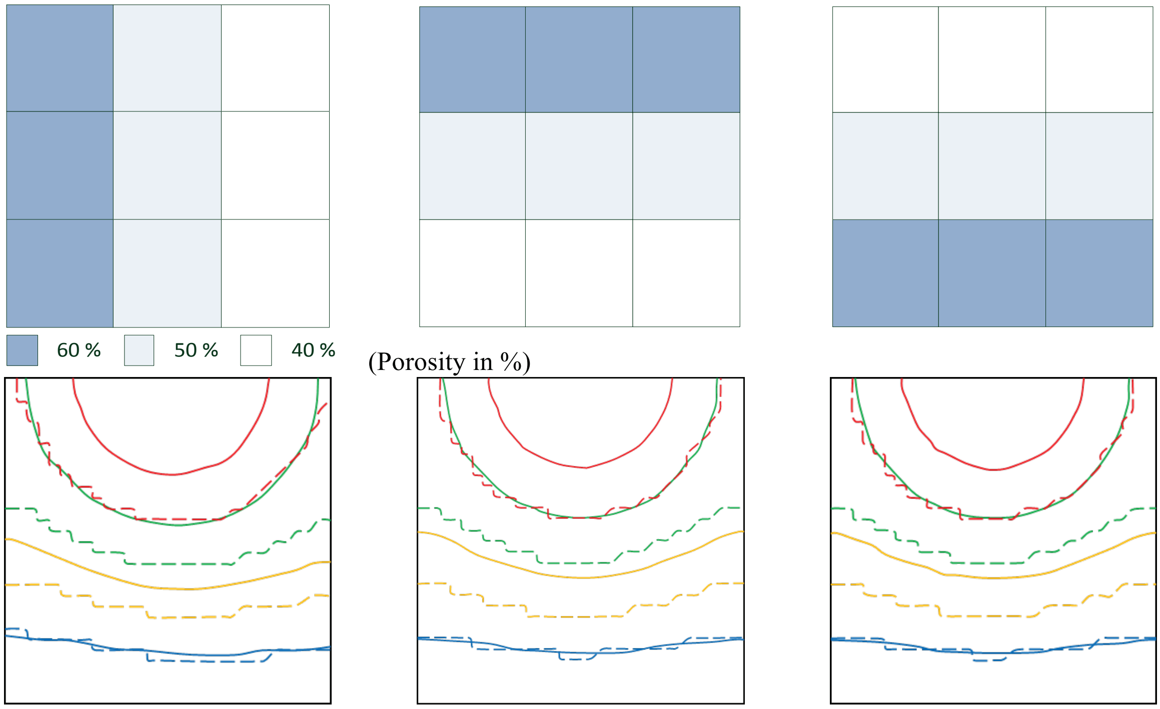
Decreasing from left to right Decreasing from top to bottom Increasing from top to bottom

Figure 5: Filling pattern for local permeability changes

Porosity

Porosity changes may occur if more than one fabric material is used. It is important to envision the context of fibre volume content ε, porosity ϕ and permeability K: Porosity is defined as 1-ε; permeability is a function of porosity ϕ (because it is a function of fibre volume content ε). For the same porosity, the permeability varies between different reinforcements. Thus if permeability is constant, a change in porosity means another fabric is used.

Generally, a porosity reduction means an acceleration of the flow front (at unchanged injection pressure). This effect is slightly visible in Figure 6, first column. The basic filling pattern between myRTM and sLIP matches. Filling times differ but remain at equal difference according to the standard simulation.



Decreasing from left to right　Decreasing from top to bottom　Increasing from top to bottom

Figure 6: Filling pattern for local porosity change

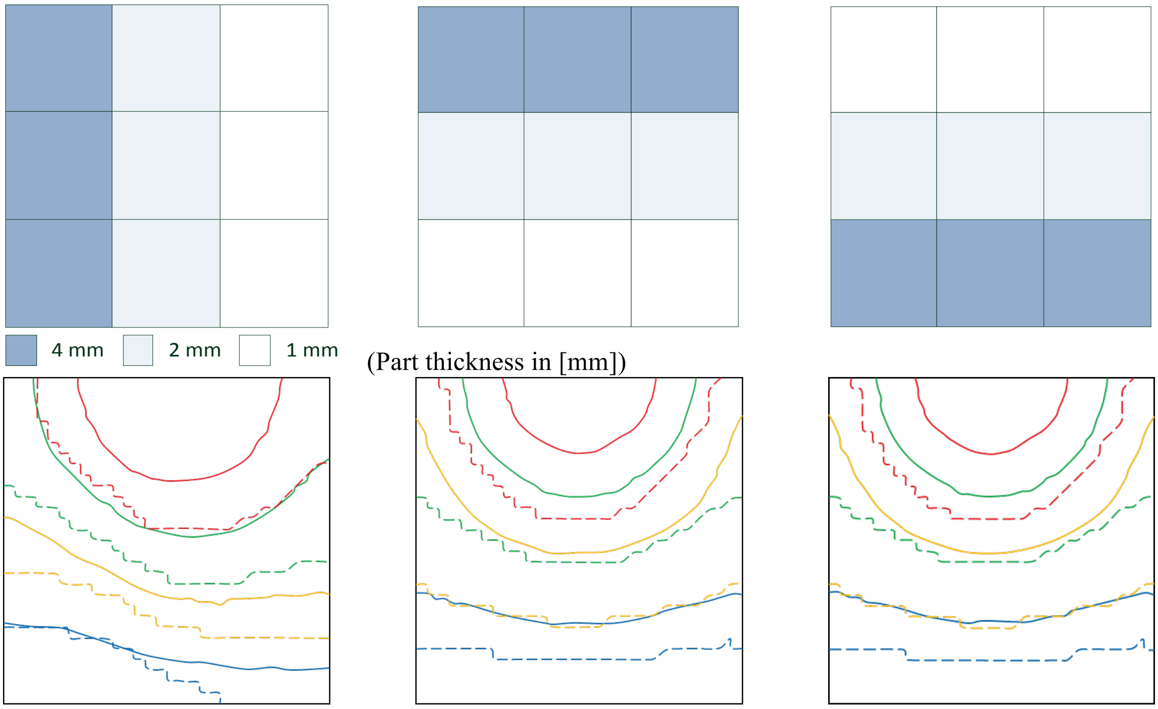
Part thickness

Test arrangement: Zones of different thicknesses are defined within the cavity. If part thickness changes, a different number of fabric layers is necessary to maintain fibre volume content and thus permeability. Filling time will vary because of the corresponding flow front velocities in the individual zones (faster flow in thinner part zones).

Result: This effect is reproducible in both myRTM and sLIP (Figure 7), however not to the same extend. The thickness/porosity-term in Eq. 2 determines the influence of part thickness within myRTM and needs adaption (Table 5).

Simulation description	Fill time sLIP	Fill time myRTM	Deviation of myRTM
Decreasing from left to right	45s	122s	+171%
Decreasing from top to bottom	23s	70s	+204%
Increasing from top to bottom	87s	197s	+126%

Table 5: Fill time comparison for local part thickness change

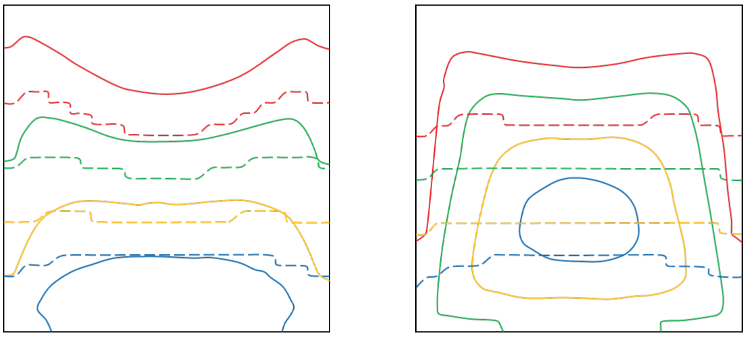


Decreasing from left to right | Decreasing from top to bottom | Increasing from top to bottom

Figure 7: Filling pattern for local part thickness change

Race tracking

Test arrangement: In reality, flow channels forming due to fibres not optimally placed in the cavity or distorted during mould closure are known as race tracking. To guarantee complete impregnation of the part, race tracking might be included in the simulation process, commonly as a small tube of higher permeability (typically up to 2 orders of magnitude). The definition of race tracking along the edges of the cavity is achieved by applying higher permeability values to cells (myRTM) and elements (sLIP) to the appropriate areas. To exaggerate the effect, the zone is set to 1cm width.



All cavity edges with 10 times higher permeability | All cavity edges with 100 times higher permeability

Figure 8: Filling pattern for race tracking effects

Result: The effect of race tracking is obvious in both simulation tools (Figure 8). Using a 100 times higher permeability in sLIP reduces the injection time (although leaving an air entrapment in the centre of the part) to 4s (Table 6). The actual fill time is not that relevant, as the simulation of race tracking is mainly used to identify potential problems and develop an appropriate injection strategy. As race tracking channels are usually reasonable small, the permeability might be further increased. Ni et al [5] propose to use a pipe model for the calculation of an equivalent permeability in the race tracking zone, calculated from:

$$K_{eq} = \frac{d^2}{32} \tag{3}$$

Thus, permeability K in the race tracking channel is $1.25 \cdot 10^{-7} m^2$. In myRTM, the definition of one row of cells set to this equivalent permeability delivers the desired effect. sLIP is able to use special race tracking elements to simulate this effect.

Simulation description	Fill time sLIP	Fill time myRTM
Standard simulation	39s	93s
Race tracking (10K)	14s	65s
Race tracking (100K)	4s	60s

Table 6: Fill time comparison for different inlet position

2.3 Summary of all test arrangements

The benchmark study has shown that myRTM is well suited for its intended purpose, to run preliminary simulations, which identify potential problems in mould filling. Thus, fill patterns generally agree well with the mathematical correct sLIP simulation. However, myRTM is not suited to predict filling times, which might lead to problems if effects that correlate with flow front velocities are included. Table 7 summarizes all tests and gives advices on how to interpret myRTM results.

Parameter	myRTM result	Conclusions/Solutions
Injection position	Appropriate prediction of fill pattern	
Injection pressure	Appropriate prediction of fill pattern	
Cell distribution	Strongly dependent on mesh uniformity	Revise mesh and use sweep function
Pressure gradient	Critical if pressure gradient is flat	Simulate with steeper gradient
Local permeability	Appropriate prediction of fill pattern	
Local porosity	Appropriate prediction of fill pattern	
Local part thickness	Appropriate prediction of fill pattern	
Race tracking	Dependent on width of race tracking zone and allocated permeability	Use small race tracking zone with significantly higher permeability

Table 7: Summary of tests and conclusions

3 PROCESS DEVELOPMENT FOR A TYPICAL RTM COMPONENT

The injection strategy for a white-water paddle shall be optimized by the use of simulation. Besides the placement of the inlet, race tracking along the edges of the blade has to be clarified. The bionic structure from the transition between blade and loom (Figure 9) is neglected for simulation purposes. The hollow loom (1.5mm wall thickness) transitions into a completely flat blade (2mm wall thickness).

Simulation is done in myRTM and in sLIP, to compare their application to an actual part. Within myRTM, the use of one or two inlets (cascade injection) is evaluated.

Figure 9: White-water paddle, manufactured with RTM process

3.1 General filling procedure

Several filling strategies are evaluated:

- Central resin injection (interface between blade and loom)
- Top injection (tip of loom)
- Bottom injection (tip of blade)
- Cascade injection (2 inlets; first at top of loom, second at interface loom/blade)

The fill patterns in myRTM and sLIP generally agree. Figure 10 illustrates the filling pattern after 47% of total filling time in both programs. As seen for the benchmark geometry, myRTM predicts a faster resin velocity in the blade (higher part thickness).

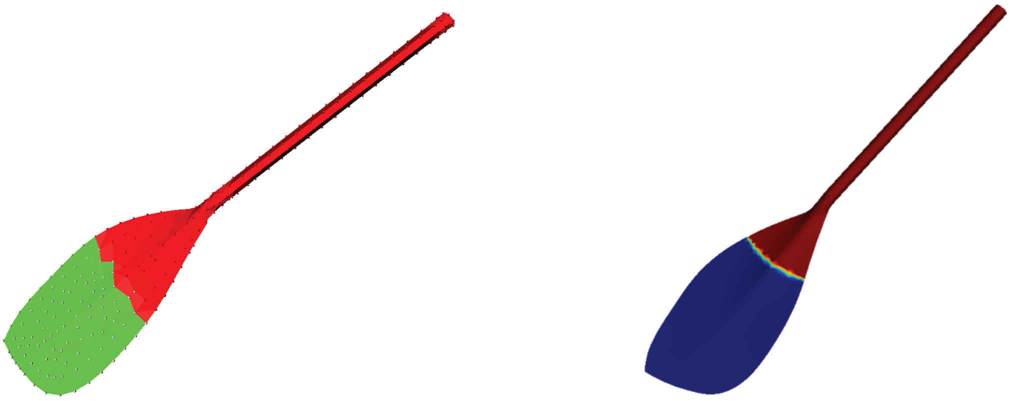


Figure 10: Filling comparison for top injection between myRTM (left) and sLIP (right) at 47% of total fill time (red: filled volume fraction)

Absolute filling time is 270s in sLIP and 213s in myRTM for the top injection process. As a highly reactive resin system will be used, a cascade process is evaluated to speed up the resin injection (see 3.3).

3.2 Race tracking effects

As race tracking might occur along the edges of the paddle, a zone with higher permeability is defined. As expected, the race tracking effect might lead to an accelerated resin flow and thus an air entrapment at the tip of the blade forms (Figure 11, right hand side).

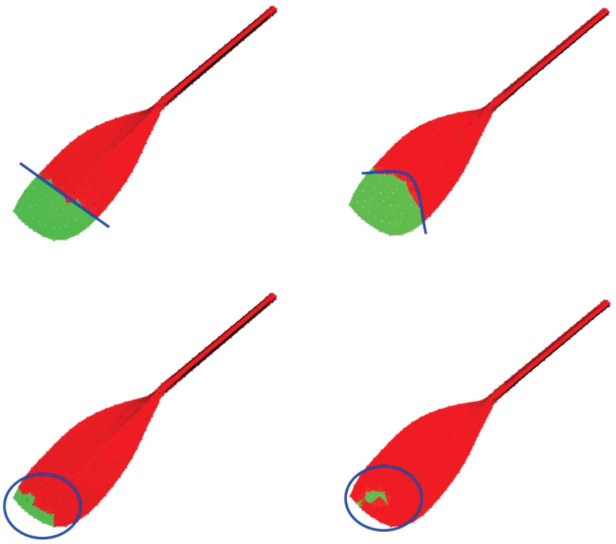


Figure 11: simulation without (left) and with (right) race tracking

3.3 Cascade injection

Using more than one resin inlet is a method of significantly speeding up the fill procedure. Especially when dealing with highly reactive resin systems, the use of two or more inlets might be inevitable. In myRTM, it is extremely simple to define a cascade injection process, as the simulation process might be stopped at any point in time and an additional inlet is defined at the flow front position. By resuming the simulation, both inlets are taken into account.

Figure 12 illustrates the difference in fill time between standard (top loom) and cascade injection: In only 99s, the paddle is completely filled using the cascade injection strategy. This corresponds to 46% of the standard injection time.

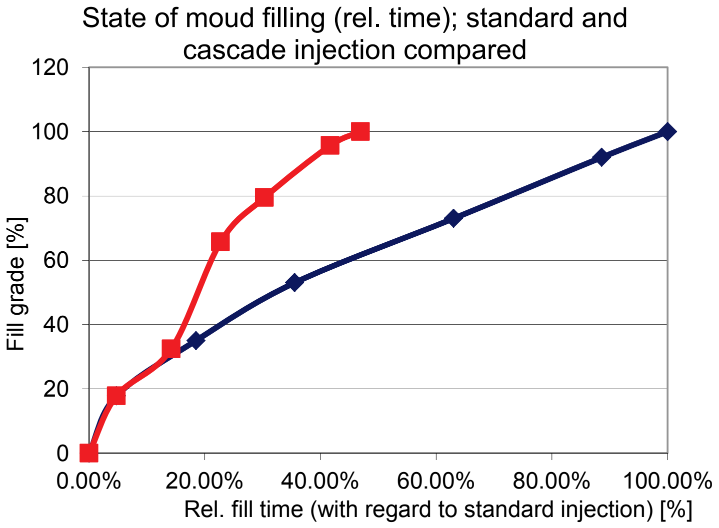


Figure 12: Comparison of standard (top loom) and cascade injection

3.4 Realized design

The cascade injection process is used to manufacture prototype parts (Figure 9). The injection of the second inlet (interface loom/blade) is started as soon as the resin reaches this point. This process is reproducibly robust and several paddles of adequate laminate quality are manufactured.

4 CONCLUSIONS

Both applications myRTM and sLIP have proven to be useful tools to develop injection strategies for RTM parts. The strengths of myRTM lie in the ease of use and the "time to market": Due to a very straightforward approach, simulations are realized in a few minutes. On the downside, some inaccuracies arise from the empiric approach, which the model is based upon: inhomogeneous cell distribution and applied pressure gradient may falsify the simulation results for complex parts.

sLIP as numerical correct Finite Element simulation software offers more features, but needs more training and experience to run. It is generally more complex than myRTM, but delivers more accurate results.

For so called applied simulation of quasi-isotropic, shell like RTM parts – as the majority still is today – myRTM is sufficiently accurate. The objective of shifting from trial-and-error procedures (with several mould modifications or even new moulds in the worst case) to a virtual optimisation route can be achieved.

For geometrically more complex parts with anisotropic fibre reinforcement, sLIP is better suited as it delivers more accurate results.

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