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SIMULATION OF RTM PROCESSES INCLUDING STOCHASTIC DISTURBANCES

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SUMMARY: Detailed filling information can be obtained from injection simulations of RTM processes. Due to better process comprehension development time can be saved, part quality can be improved, and development costs can be reduced. Although the precision of fill simulation is very good for carefully prepared injection there are severe variations in real filling processes on the one hand and differences between fill simulations and real filling processes on the other hand. Those differences are supposed to result mainly from general preform disturbances induced by handling and from flow channels at geometrically predestined locations like edges for example. Considering these influences will allow more realistic fill simulations. Therefore a disturbance cell concept (Fig. 1) has been developed. It allows applying disturbances stochastically within a defined range of values, including disturbances of the fiber volume content, the permeability values as well as K_{plus}, a permeability supplement to model runners. This concept has been implemented in our in house developed simulation software sLIP and can be used in simulations with Monte Carlo initialization. Finally, simulation results of a complex shell component including stochastic disturbances are presented. Even for small (narrow) runners a strong reduction of the filling time could be observed (Fig. 8). General disturbances such as in the fiber volume content of up to ±10% showed a comparatively small influence.

KEYWORDS: Resin Transfer Molding (RTM), flow simulation, stochastic disturbances, scrap rate, runner

INTRODUCTION AND RESEARCH GOAL

Resin Transfer Molding (RTM) processes are capable to manufacture complex fiber reinforced parts with high fiber volume content and well orientated fibers. Due to comparably low cost of the raw materials and preforming technologies it is applicable for medium and large manufacturing series of structural parts. The process needs to be designed with respect to gate locations and vent locations. However disturbances of the process are unavoidable and RTM processes are often sensitive to these disturbances. Inappropriate selection of those locations may cause long cycle times leading to higher production costs. In the worst case a poor laminate quality or even gas entrapments may occur and scrap parts may result.

Today the development of RTM applications mostly relies on experience and trial-and-error procedures. This is a very expensive and a time-consuming process, which cannot even guaranty a good part quality, since already slight changes in the process parameters can significantly influence the RTM-process. Another critical issue for economical success is robustness of RTM the process:

- minimized scrap rate and thus reduced expenses for raw materials and labor;
- constant high part quality minimizes the finishing work;
- reliability of production ensures meeting production targets.

Our in house developed simulation software of liquid impregnation processes (sLIP) uses a finite element / control volume modeling of to calculate flow information like pressures and velocities and the advancement of the flow front. Although a very good precision of fill simulation can be obtained for carefully prepared injections, in industrial applications there are severe variations in the preparation of the injection, resulting in severe differences between fill simulations on the one hand and the real filling processes on the other hand. Those differences are supposed to result mainly from general preform disturbances due to handling and from flow channels at geometrically predestined locations such as edges for example [2].

SIMULATION

Parametric Model

A parametric simulation model has been developed allowing applying disturbances stochastically within a defined range (Fig. 1). It allows fast and automated application of model disturbances on the finite elements. Zones where a uniform influence of a disturbance can be expected are defined, influencing all covered finite elements. Examples of such zones are regions geometrically defined by one module of a modular tool or runners at component edges. Disturbance zones may overlap, and therefore add or compensate their influence.

Statistic information about distribution and ranges of disturbances needs to be given. Distribution functions can differ for different types (or sources, resp.) of disturbances. Then, a initialization number $s_{init} \in [0,1]$ with rectangular probability distribution is used to initialize the disturbance values in according to the range and distribution function of the disturbance (Fig. 2).

Variations of Permeability

As it is well known from literature there is a noticeable variation in permeability even under laboratory conditions. Depending on the fabric it is in the range of 10 to 20 % [4]. Their distribution function for permeability variance can be approximated by a normal distribution rather well. To account for permeability variations the principal values K_1, K_2 and K_3 and their directions described by φ, θ and ψ can be influenced by disturbance cells.

Several other factors are known to have also an influence on the actual permeability. For instance there is a dependence of permeability on the resin's flow velocity [1]. Draping of the preform will cause even higher disturbances. The orthotropic ratio K_1/K_2 will be affected as well as the orientation of the principal flow directions. Modeling all these effects is costly and requires much input data, so most flow simulations don't usually take these influences into account. However, it is possible to estimate the range of these influences, add it to the actual permeability variation and thus include these effects in the flow simulation.

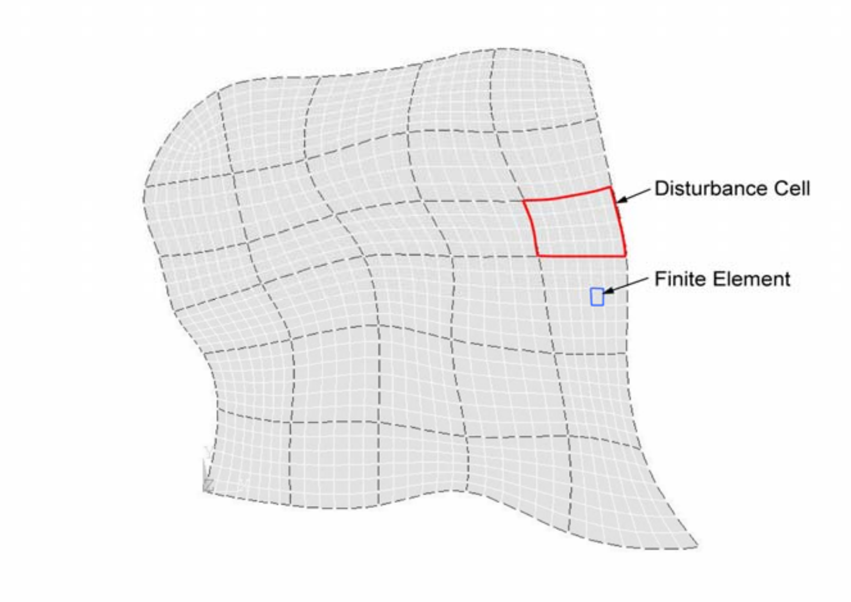

Fig. 1 Finite element mesh and disturbance cells.

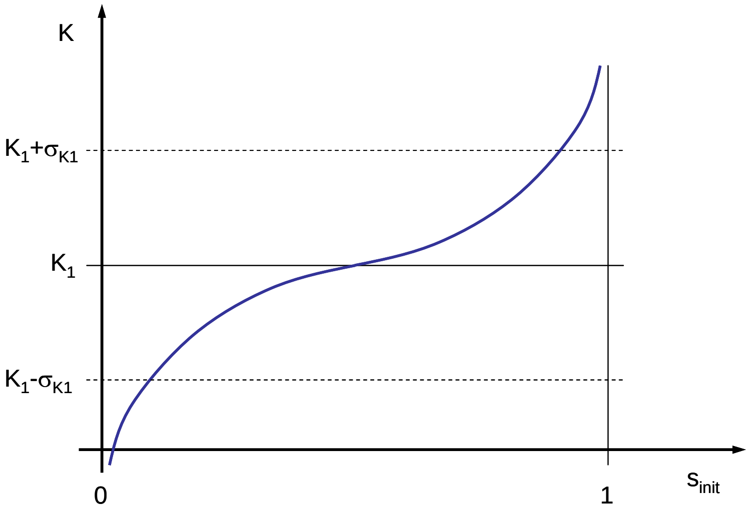

Fig. 2 Initialization of disturbance cell with normal distributed permeability.

Variations of Fiber Volume Content

Disturbance cells can also influence the fiber volume content. Variations of the fiber volume content depend highly on the tool's precision and stiffness. Particularly for large thin walled parts this can become important. Laminates of 1 mm thickness can easily be affected by a variation of \pm0.1 mm, resulting in a ±10% relative variation and a 2.5-fold Permeability variation (equation of Kozeny-Carman). FVC depends on manual treating and draping as well. Draping will often cause local thinner and thicker preform, respectively.

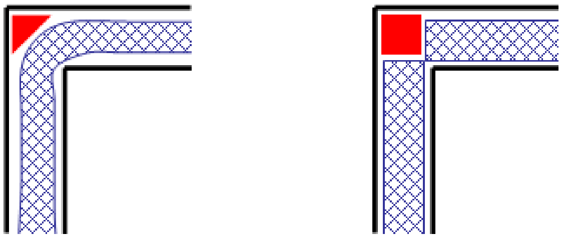

Fig. 3 Schematic of different runners shapes and sizes for bended and joining performs.

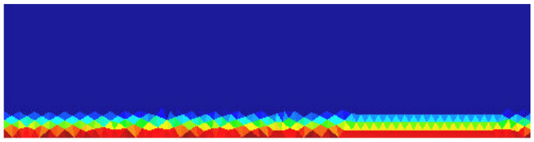

Fig. 4 Modeling a runner on the lower edge of the plate with permeability supplement K_{plus} .

Influence of Runners

Runners occur at geometrically exposed locations like component edges, steps in the number of layers, stitching lines, joint areas or bending corners (Fig. 3). Runners can also occur as runner areas instead of runner lines, e.g. when layers are displaced due to compression during a three-dimensional injection at low FVC and high injection pressure, respectively.

These runners can be modeled using a virtual permeability supplement K_{plus} , that is added locally added to the actual permeability of the used fabric, significantly increasing local permeability. According to the formulation of equivalent permeabilities described by [3], realistic values can be obtained from runner geometry.

Those permeability supplements are applied over a small region around the actual runner location. In order to obtain a smooth modeling in the FE model the runner influence decreases linearly to zero within a model dependent width (Fig. 4).

Initialization

All model parameter need to get initialized before simulations can be run. Those parameters are initialized using random numbers between 0 and 1 with a uniform probability distribution. As shown in Fig. 2 the disturbance values are set within the cells range of values. Several simulations are run (Monte Carlo Simulation) to evaluate the range of the output variables, e.g. fill time and fill degree. Compared to commonly used simulations without stochastic disturbances these output variables will not be a fixed number, but a range of expected values and their distribution.

Assuming independence of the disturbances, the initialization can be done using a plane Monte Carlo initialization (Fig. 5, left). However, coverage of the parameter space is not optimal for this initialization scheme. Some parameter combinations are emphasized, some other are not investigated. There may be a correlation in the parameter input values, resulting in artificial correlations in the simulation result. We suggest using Latin Hypercube initialization [5, 6]. Thus the parameter space is well covered and correlations are minimized.

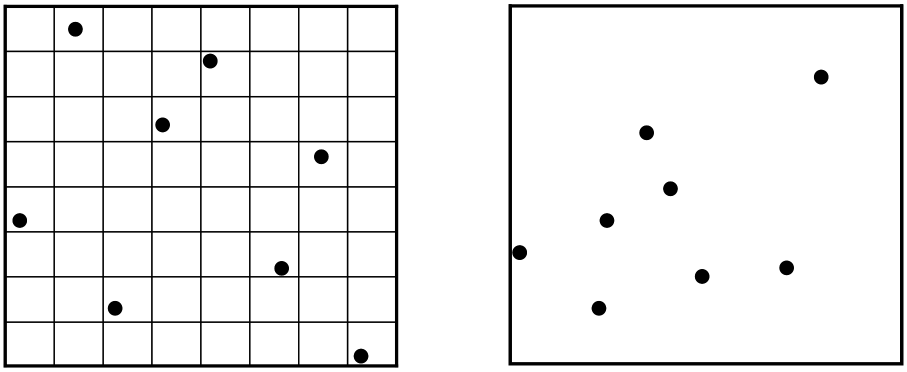

Fig. 5 Plain Monte-Carlo initialization (left) and latin hypercube initialization (right) of input parameters.

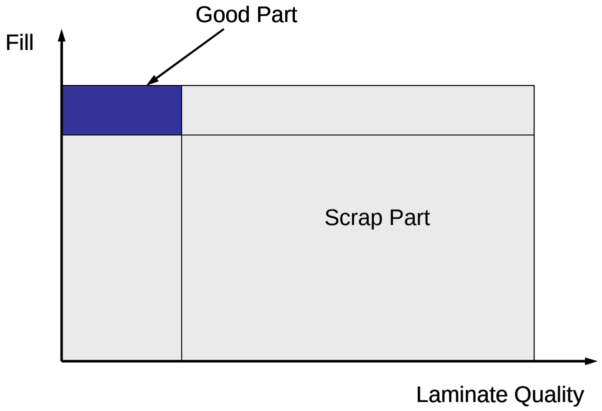

Fig. 6 Definition of scrap part based on fill degree (0...100%) and quality criterion (0 for good quality, 1 for poor quality).

Scrap Rate Estimation

A low scrap rate is an important objective of process development. Here, the definition of a scrap part is based on the fill degree and the laminate quality criterion (low values indicate good quality). Each criterion provides a single index number. If the fill degree is below a user defined threshold or the quality value is above a user defined threshold, the part is scrap (Fig. 6). So the scrap rate can be determined by integrating the distribution function over the area outside the threshold values. To keep simulation effort low a minimum number of simulations should be used. Having defined a suitable distribution function, simulation results can be used to adapt the distribution function using a maximum likelihood estimation.

However, since the distribution function of the output values is not known a priori, Monte-Carlo simulations with several hundred initializations are run in the current development of the method. Fig. 7 shows an ant hill plot of a simulation for two output parameters, the final fill degree and the quality criterion. Different distribution functions are fitted to the distribution and their approximation quality is determined. Different part geometries and different processing parameters can lead to different distributions. So, appropriate distribution functions have to be found, that match simulation results well in all cases.

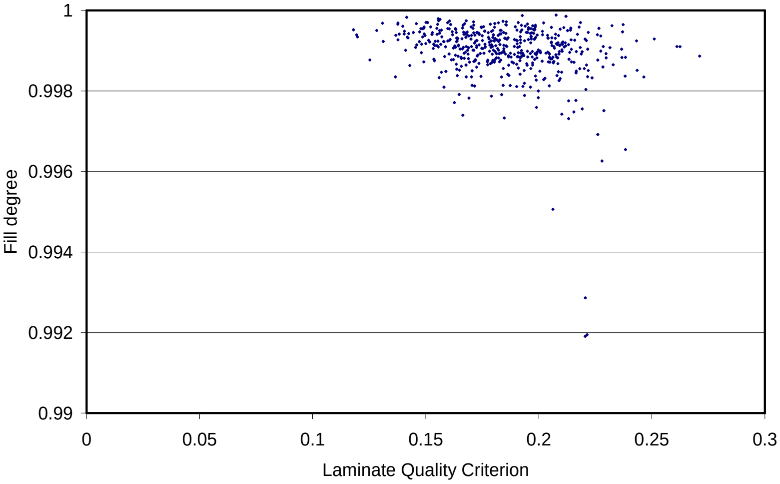

Fig. 7 Ant hill plot of fill degree and laminate quality for 500 simulations. The fill degree can range from 0 to 1, quality criterion ranges between 0 (good quality) and 1 (poor quality).

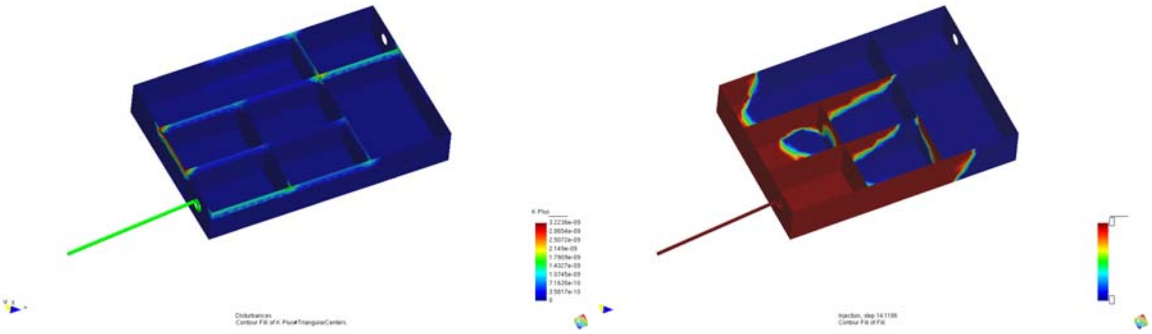

Fig. 8 Model disturbed by runners, stochastically initialized on base of 0.4 mm wide channels in maximum (left). Resulting fill pattern, showing race tracking effects on several part edges (right). The overall part size is 180 x 120 x 30 mm.

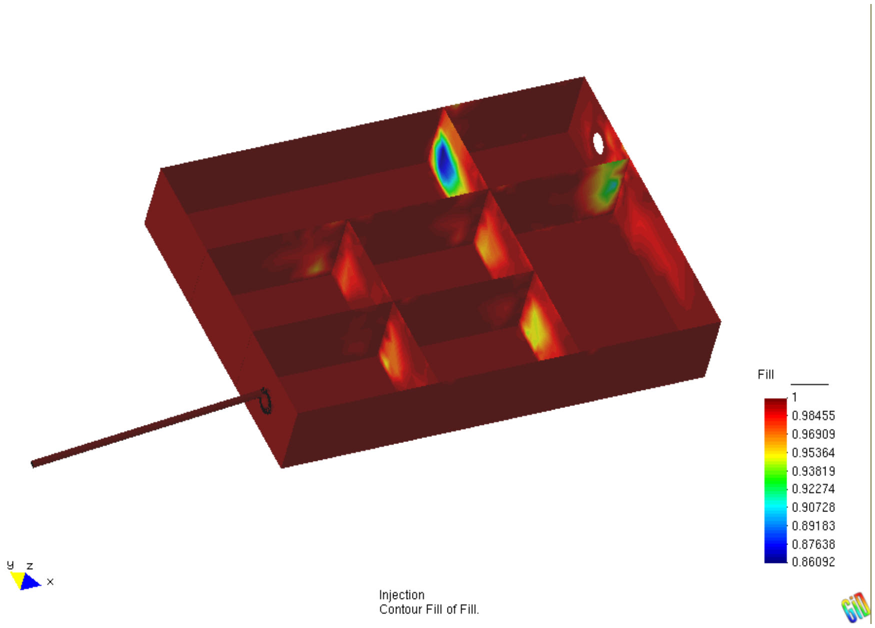

Fig. 9 Averaged fill degree after 500 simulations, indicating areas where dry spots can be expected.

Preliminary Results

Simulation results of a complex shaped shell component including stochastic disturbances are presented. The effect of runners on the fill pattern is shown in Fig. 8. Even for small (narrow) runners a strong reduction of the filling time could be observed on the one side. On the other side general disturbances like a disturbance of the fiber volume content of ±10 % showed a comparatively low influence on the filling pattern and the fill time. Finally, Fig. 9 shows the final fill degree averaged over 500 simulations. This illustration does not contain all information of every simulation, but it shows the areas where high probabilities of unfilled spots are to be expected at a glance.

The diagrams in Fig. 10 show the distribution of the output variables fill time, final fill degree and laminate quality. These diagrams were generated on the same data base like the ant hill plot in Fig. 7. Normal distribution might be used to approximate the output variables fill time and laminate quality. Log-normal or gamma-distribution could be used to approximate the fill degree distribution. The fill time for the model without disturbances is 78 s and therefore longer than the averaged fill time.

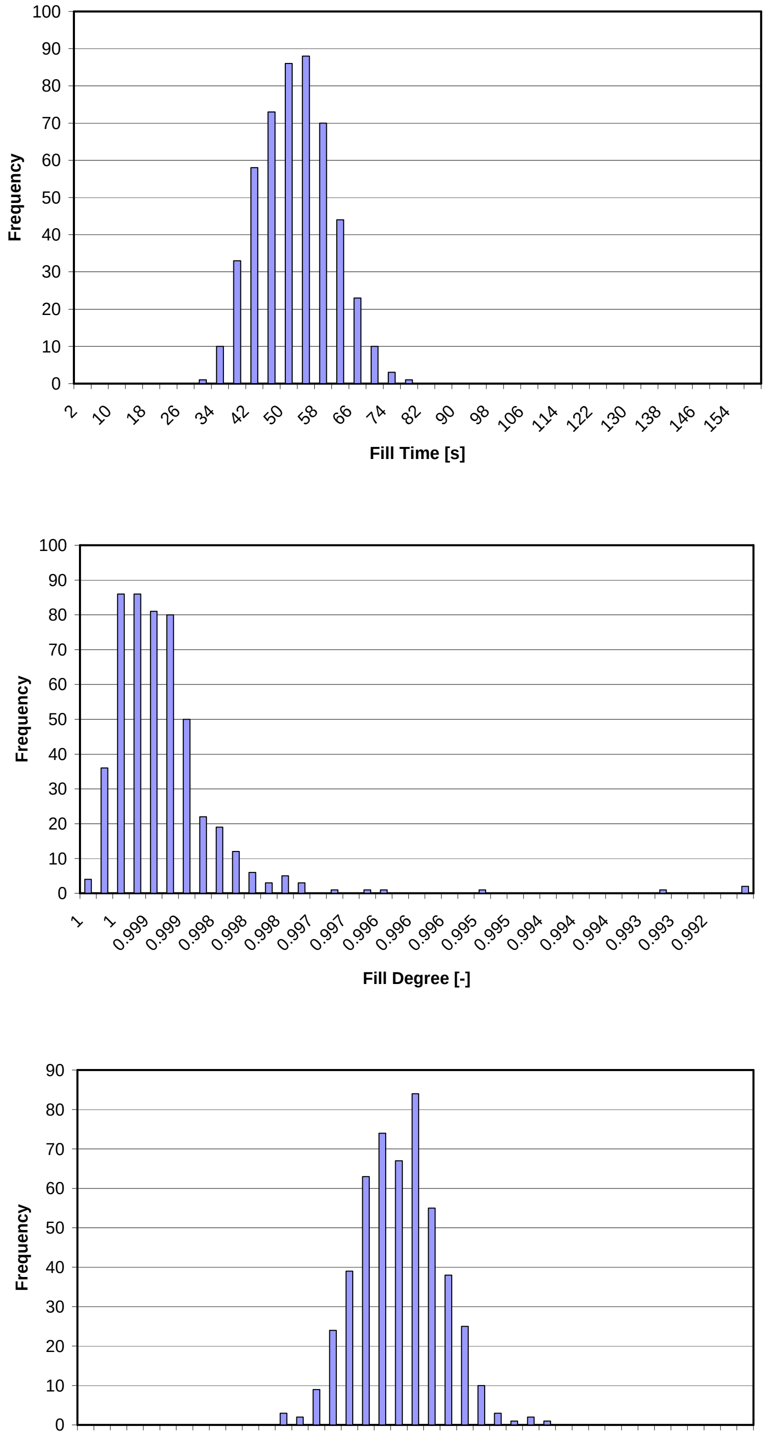

Fig. 10 Variation of the simulation output parameters fill time, final fill degree and laminate quality.

CONCLUSION AND OUTLOOK

A parametric model has been implemented to allow simulating the effects of stochastic disturbances on the resin flow. The influence of disturbances is significant, particularly on runner fill patterns and fill times. This is in good agreement with experimental observations. Depending on the process, different variations have been observed in the simulation output. This is a useful criterion to estimate process robustness, which is a critical issue in RTM applications. Based on suitable criteria a scrap rate can be estimated.

A critical issue remains the appropriate initialization of disturbances. This may depend on the particular situation, but basic reoccurring classes can be identified. For instance bending layers at a corner will generate certain flow channels, and different flow patterns may occur when two cut layers are joined at a corner. Current investigations are carried out on this issue. We aim in the future to be able to estimate the scrap rate by numerical optimization in order to assist in the development of fast and robust manufacturing processes.

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