

GLOBAL OPTIMIZATION OF MOULD FILLING PARAMETERS DURING THE CONSTANT SPEED INJECTION COMPRESSION MOULDING PROCESS

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SUMMARY: Injection Compression Moulding (I/CM) is one of the many Liquid Composite Moulding (LCM) manufacturing processes for composite materials. In this study, process objective functions are defined and minimized using a global optimization technique which has been developed for this study. Different weighting values are assigned in the objective function to characterise the importance of process cycle time or clamping force requirements. The University of Auckland mould filling simulation software SimLCM has been used to simulate the I/CM process. Two different geometries are used for the optimization study, one planar and one non-planar, to demonstrate and verify the performance of the optimization algorithm. It is proven that the problem is non-convex indicating the existence of multiple local minima. The problem has been broken down into three sub-problems to locate the global minimum. Methods are presented which can be utilized by the manufacturer to decide upon the best combination of process parameters to suit specific desired outcomes.

KEYWORDS: injection compression moulding, Liquid Composite Moulding (LCM), global optimization

INTRODUCTION

Injection compression molding (I/CM) is becoming popular for its ability to produce complex geometries under low pressure operating conditions. The I/CM process involves the compaction of a dry fibrous preform within rigid mould pieces, resin injection to wet out a portion of the preform, and finally compression to the desired thickness which drives the resin through the remaining dry material. One of the advantages of the I/CM process over the more conventional Resin Transfer Moulding (RTM) method is the ability to achieve fast manufacturing times due to the relatively rapid initial fluid injection. As demand for more sophisticated products has increased, the issue of reducing manufacturing cost has become more important.

A number of process design parameters define an I/CM process cycle, for example fluid injection pressure, preform thickness at which fluid is injected, and mould closing speed. This study investigates the influence of these factors on the performance of the I/CM process. In particular, the effect on total mould clamping force and cycle time is explored, which in turn determine the required tooling and manufacturing cost and efficiency.

In general, it is difficult to locate the global minimum/maximum for any non-convex optimization problem. There are global search algorithms, such as genetic algorithms, which are commonly used to solve complicated optimization problems. However such algorithms do not solve all of the many kinds of problem that arise, limiting their use. In some cases, the only guaranteed method is to run an exhaustive search of the entire design space. With the increase in computing power in recent years, the number of problems which can be solved by this brute force method has dramatically increased. However, the I/CM problem under study here has a design space which is so large that such a method is impractical. A global optimization algorithm has been created for the I/CM process which locates the global minimum with a more than 95% reduction in simulation time when compared to the brute force method, for the case studies presented in this paper.

SIMULATION

Two different geometries (one planar and one non-planar) have been created and meshed using the Hypermesh software package. The planar geometry is a 200×40 mm rectangle with injection gates positioned along the left end resulting in a unidirectional flow. The non-planar geometry is shown in Fig. 1, and consists of a 100×150 mm flat plate on the top face, with four sides angled at 60° going 100 mm deep. Injection is at the centre of the top face, a 15 mm radius hole assumed to exist in the preform. Only one quarter of this geometry is modelled (Fig. 1b). A 450 g/m^2 chopped strand mat was used for both geometries.

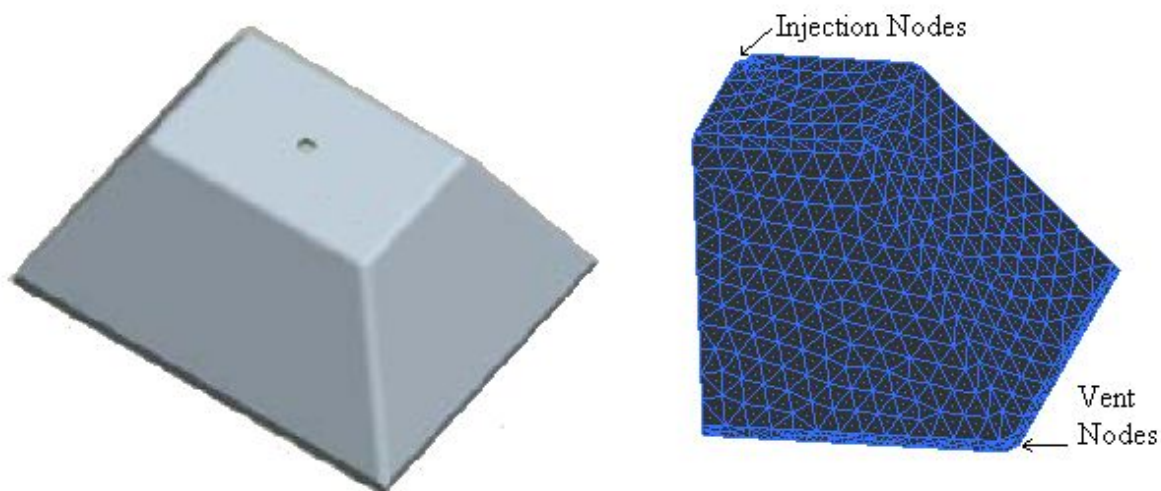


Fig. 1 Non-planar geometry, and quarter mesh of the component.

The mould filling software SimLCM is used to simulate the I/CM process. The user must define the input variables for this software, such as the viscosity of the resin, reinforcement properties, mould/preform friction coefficient, etc. Values for these variables have been collected from a number of experiments carried out at the University of Auckland [1, 2]. A “Mixed Elastic” model [3] was used to simulate the compaction behaviour of the material, and Darcy’s law combined with the continuity equation to model the resin flow. Values used for the viscosity of the resin and friction coefficient were 0.28 Pa.s at a room temperature of 20°C, and 0.21 respectively.

GLOBAL OPTIMIZATION

Objective Function

For this study, three design variables are used for the I/CM process. These are resin pressure at the injection gate during the fluid filling stage (P_{inj}), closing speed of the mould during the wet compaction phase (V_{wet}), and the injection cavity height during the filling stage (H_{inj}); this is the height *above* the final cavity thickness at which the resin is injected. Eqn.1 is the objective function which is used in this study. It consists of two terms; the first term is a measure of the total clamping forces arising in the mould. F is the force variable whereas F_{min} and F_{max} are the minimum and maximum forces to be expected in any given process, e.g. F_{min} is the force during a very slow compaction phase and F_{max} for a very rapid compaction process. The second term is a measure of the process cycle time. T is the fill time variable whereas T_{min} and T_{max} are the minimum and maximum fill times to be expected in any given process, e.g. T_{min} is the process cycle time with the fastest compaction phase and highest injection pressure, and T_{max} for the slowest compaction phase and lowest pressure. W_{force} and W_{time} are weight factors which can be altered to specify the relative importance of the total clamping force and the cycle time of the I/CM process, with $W_{force} + W_{time} = 1$. The values for normalized force and time in the objective function are functions of the three design variables.

$$Objective\ Function = W_{force} \left(\frac{F - F_{min}}{F_{max} - F_{min}} \right) + W_{time} \left(\frac{T - T_{min}}{T_{max} - T_{min}} \right) \quad (1)$$

For unidirectional I/CM filling of a flat plate, it can be shown that the optimisation problem is non-convex. This means that there are multiple local minima. With non-convex problems, using a local search method has a very low chance of locating the global optimal solution.

Global Optimization Algorithm

An algorithm has been created for this study which locates the global minimum of Eqn. 1. The non-convex problem has been broken down into three smaller sub-problems. The main idea of the algorithm is to keep two design variables constant and to change the remaining one in order to find the global minimum for that particular problem. When that optimum value has been found, the next step requires repeating the process with a different design variable that is changing, while keeping the other two design variables constant. After the three sub-problems have been solved, the algorithm repeats the process iteratively until the global minimum is achieved.

The algorithm can be stated as follows:

Step 1: Find optimum H_{inj} ; set V_{wet} and $P_{inj} = \text{minimum}$, by using an exhaustive search.

- Step 2:** Find optimum V_{wet} ; use P_{inj} and H_{inj} from last step, by using a proximity search.
Step 3: Find optimum P_{inj} ; Use H_{inj} and V_{wet} from last step, by using a proximity search.
Step 4: Find optimum H_{inj} ; Go to Step 1, (now we have new V_{wet} , P_{inj} values)
 *Stop when no significant improvements are made for 2 continuous steps.

Step 1 uses an exhaustive search due to the non-convexity of the objective function for the case of variable H_{inj} . However, since the problem has been broken down, the search space is very small. It can be shown that the sub-problems involving changes in the variables V_{wet} and P_{inj} are convex and hence one can use a rapid proximity search in steps 2 and 3. The minimum possible values for V_{wet} and P_{inj} are chosen in Step 1 to maximize the efficiency of the algorithm. However, the starting point for the algorithm is arbitrary, in the sense that it does not have any influence on the identification of the true global minimum.

Algorithm Validation

The algorithm was tested on both the planar and non-planar geometries. For each shape, different weighting factors were chosen to validate the algorithm. Table 1 shows the range of the design variables, and the size of each iteration step. Different starting and increment values were selected for both geometries to demonstrate the robustness of the algorithm. For the planar case, the minimum possible value for the design variable H_{inj} is zero, i.e., a resin injection phase initiating at the final part thickness, corresponding to the Resin Transfer Moulding (RTM) process.

Table 1 Design variable parameters for planar and non-planar geometry

	Planar Geometry			Non-Planar Geometry		
	H_{inj} (mm)	V_{wet} (mm/min)	P_{inj} (kPa)	H_{inj} (mm)	V_{wet} (mm/min)	P_{inj} (kPa)
Minimum	0.0	0.0	50	0.1	0.6	10
Maximum	4.8	25.32	750	4.7	5.4	500
Increment	0.1	1.2	70	0.2	0.6	70
Total no. steps	49	22	11	24	9	8

Planar Geometry

11 layers of chopped strand mat reinforcement was used in this case. The material is compacted to a final volume fraction of 0.46. The weight factors have been chosen with time being the more significant factor, at $W_{time} = 0.8$.

The optimization of the I/CM process is detailed here (refer to Figs. 2a and 2b)

Step 1: Find H_{inj} ; with $V_{wet} = 0.12$ mm/min and $P_{inj} = 50$ kPa. After 49 runs, $H_{inj} = 0.6$ mm

Step 2: Find V_{wet} ; with $P_{inj} = 50$ kPa and $H_{inj} = 0.6$ mm. After 3 runs, $V_{wet} = 2.52$ mm/min

Step 3: Find P_{inj} ; with $H_{inj} = 0.6$ mm and $V_{wet} = 2.52$ mm/min. After 10 runs, $P_{inj} = 750$ kPa

Step 4: Find new H_{inj} ; with 2.52 mm/min, $P_{inj} = 750$ kPa. After 49 runs, $H_{inj} = 0$ mm

Step 5: Find new V_{wet} ; after 2 runs, $V_{wet} = 3.72$ mm/min

- Step 6:** Find new P_{inj} ; after 1 run, no change is made. $P_{inj} = 750$ kPa
Step 7: Find new H_{inj} ; after 49 runs, $H_{inj} = 1.2$ mm
Step 8: Find new V_{wet} ; after 2 runs, $V_{wet} = 4.92$ mm/min
Step 9: Find new P_{inj} ; after 1 run, no change is made: $P_{inj} = 750$ kPa
Step 10: Find new H_{inj} ; after 49 runs, no change is made. $H_{inj} = 1.2$ mm
Convergence achieved. Algorithm terminated.

For this case, the algorithm has looped four times resulting in 215 runs of SimLCM in total. The global minimum was found at $V_{wet} = 4.92$ mm/min, $P_{inj} = 750$ kPa and $H_{inj} = 1.2$ mm.

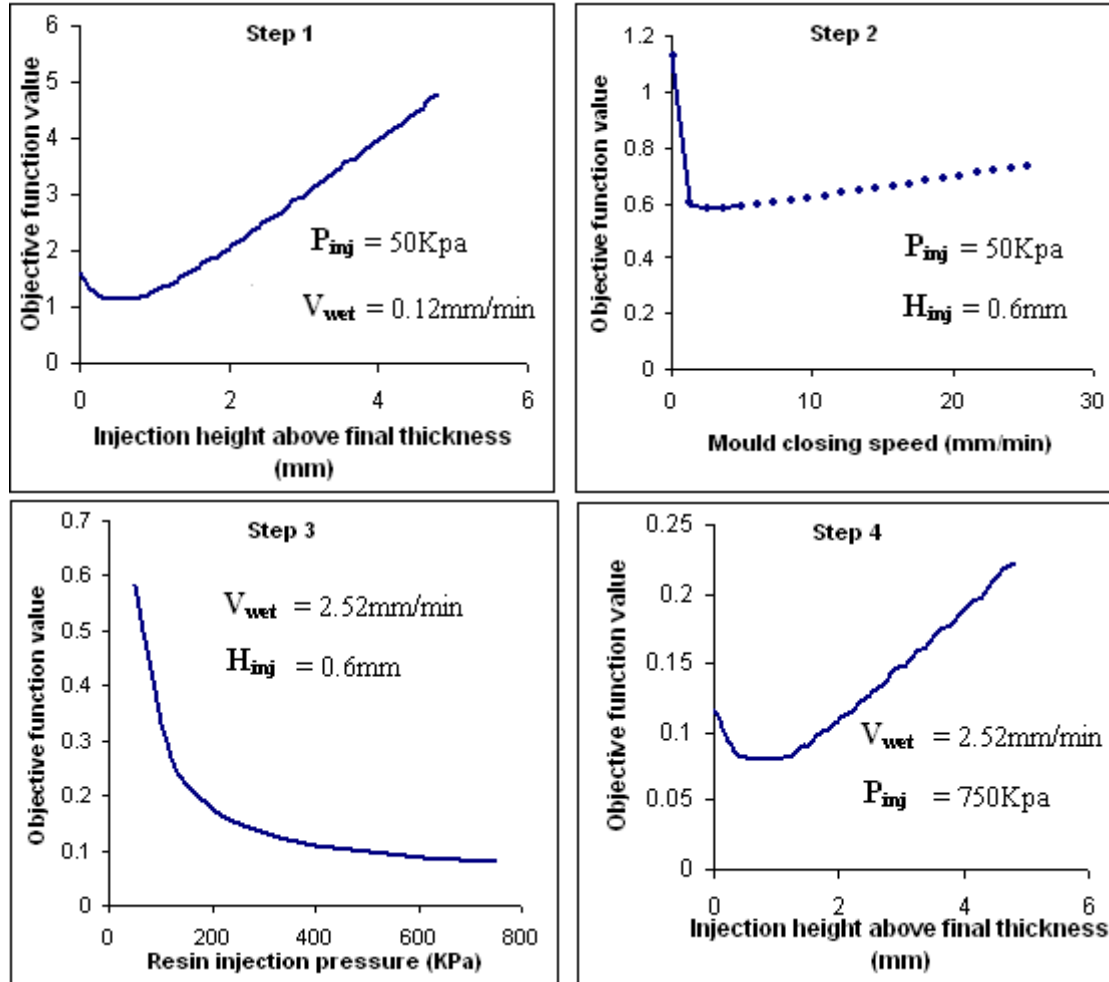


Fig. 2 Illustration of the algorithm for the planar geometry, steps 1 to 4.

To verify that the global minimum obtained by the algorithm was correct, an exhaustive search for this case was carried out, totaling 11858 runs (49 by 22 by 11). The global minimum was found to be at the same H_{inj} , V_{wet} and P_{inj} values. Note that the global optimum is located when $H_{inj} \neq 0$, indicating that the I/CM process here has achieved a better optimal solution than the corresponding RTM process for this case. The exhaustive search took 21738 s on a Pentium 4 CPU 3.00GHZ processor, and 221 s with the global optimization algorithm, which is a 98.2% reduction in time.

Non-Planar Geometry

11 layers of chopped strand mat were used for the non-planar simulation. The material is compressed to a final volume fraction of 0.46. The weight factors were again chosen with more importance on the time factor, with $W_{\text{time}} = 0.7$.

Algorithm execution

Step 1: Find H_{inj} ; with $V_{\text{wet}} = 0.6$ mm/min and $P_{\text{inj}} = 10$ kPa. After 24 runs, $H_{\text{inj}} = 4.7$ mm

Step 2: Find V_{wet} ; with $P_{\text{inj}} = 10$ kPa and $H = 4.7$ mm. After 9 runs, $V_{\text{wet}} = 4.8$ mm/min

Step 3: Find P_{inj} ; with $H_{\text{inj}} = 4.7$ mm and $V_{\text{wet}} = 4.8$ mm/min. After 8 runs, $P_{\text{inj}} = 500$ kPa

Step 4: Find new H_{inj} ; with 4.8 mm/min, $P_{\text{inj}} = 500$ kPa. After 24 runs, $H_{\text{inj}} = 3.9$ mm

Step 5: Find new V_{wet} ; no change, V_{wet} value stays the same after 2 runs

Step 6: Find new P_{inj} ; no change, P_{inj} value stays the same after 1 run

Algorithm Terminated with $H_{\text{inj}} = 3.9$ mm, $V_{\text{wet}} = 4.8$ mm/min, $P_{\text{inj}} = 500$ kPa.

To verify the solution, an exhaustive search was carried out for this case with 1728 SimLCM runs. The global minimum was essentially the same solution as achieved by the optimization algorithm. The algorithm used 60 runs of SimLCM to locate the global minimum, which represents a 96.5% reduction in time as compared to the exhaustive search. The exhaustive search took 64539 s on a Pentium 4 CPU 3.00GHZ processor.

Predicted clamping force evolutions for the optimum I/CM process are presented in Fig. 3a. The total clamping force is plotted through initial mould closure ($-20 < t < 0$ s), injection ($0 < t < 8.1$ s), compression ($8.1 < t < 55.4$ s), and post-filling stages ($t > 55.4$ s). The force components due to fluid pressure and reinforcement compaction are also presented. For comparison, similar plots are provided for the RTM case with P_{inj} of 500 kPa (Fig. 3b), and for I/CM using the maximum design parameters ($H_{\text{inj}} = 4.7$ mm, $P_{\text{inj}} = 500$ kPa, $V_{\text{wet}} = 5.6$ mm/min, Fig. 3c). The optimal solution (as defined by the choice of weight factors) provides a fill time of 55.4 s, as compared to 191.8 s for the fastest RTM case, and 56.7 s for the I/CM case with maximum parameters. Both I/CM solutions provide clear improvement over RTM with regards fill time, with a compromise in increased maximum clamping force. The optimum solution represents a nearly fivefold increase in maximum clamping force over the RTM case. The I/CM case with maximum parameters provides a small increase in fill time, and small reduction in force, when compared to the optimal solution. This is the result of applying a high emphasis on minimizing fill time ($W_{\text{time}} = 0.7$, $W_{\text{force}} = 0.3$).

To further demonstrate the capabilities of SimLCM with respect to local tooling forces, several plots on the quarter mesh are presented in Fig. 4. Fig. 4a presents the evolution of the resin flow front in time, demonstrating the rapid progress of the flow front during the injection phase. Fig. 4b and 4c present the local normal stress distributions due to the fluid and reinforcement compaction, at $t = 49$ s. Fig. 4d represents the addition of these two components, being the distribution of the total normal stress exerted on the mould. This and the tangential stress distribution (due to friction between the reinforcement and mould surface) are integrated to determine the total clamping forces presented in Fig. 3.

CONCLUSIONS

An algorithm has been successfully created which locates the global minimum (the best solution possible) by breaking down the non-convex I/CM problem into three sub-problems. The algorithm has been applied to two geometries with different weighting values for each case. The optimal solutions found by the algorithm were the same as that achieved using exhaustive searches. Over 95% of a reduction in time was achieved using the proposed algorithm, when compared to the exhaustive search for both cases studied.

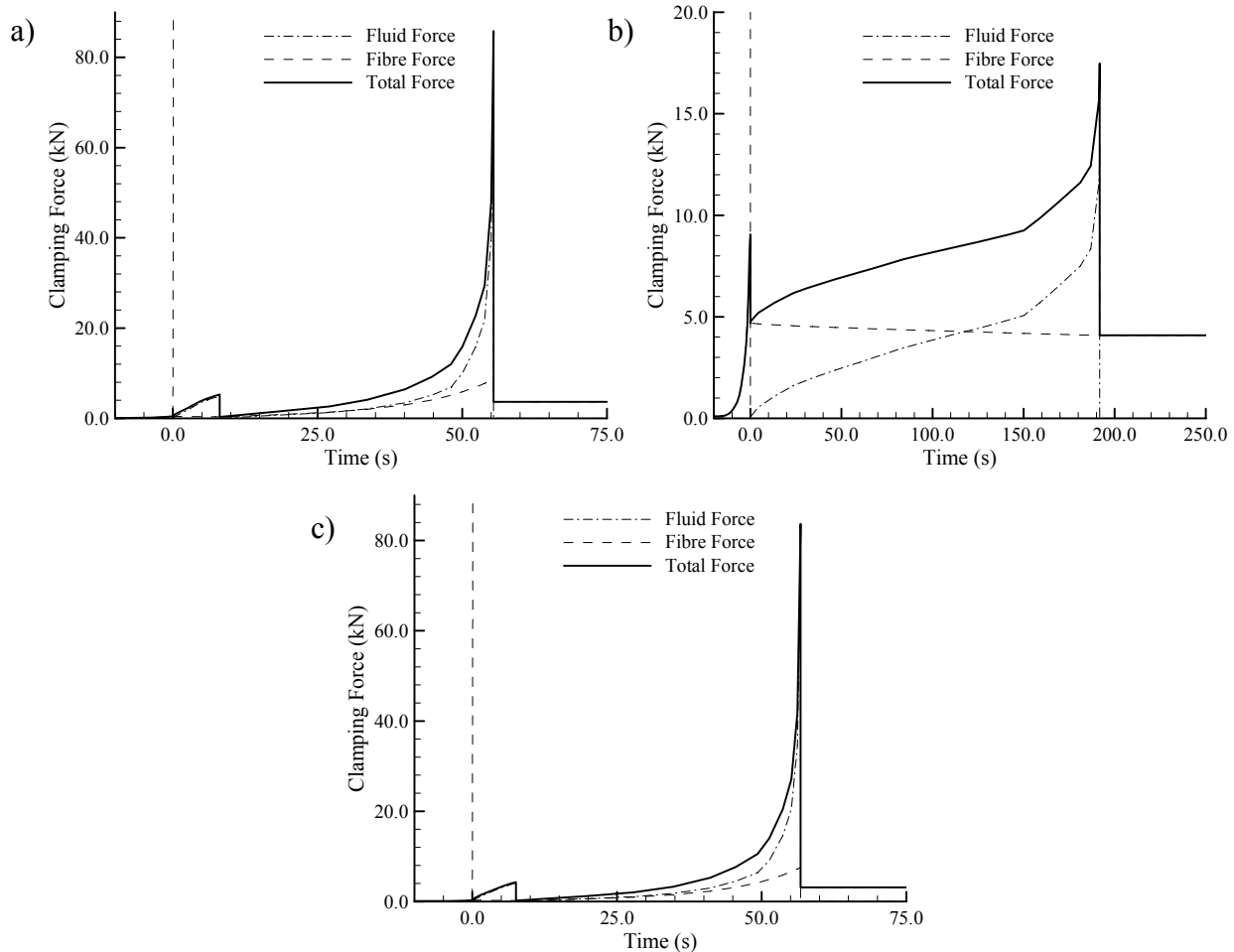


Fig. 3 Predicted mould clamping force traces for, a) the identified optimum solution, b) the fastest RTM cycle, and c) I/CM utilizing maximum design parameters.

The optimal values for the resin injection pressure were found in both cases reported in this study to be the maximum possible values. However, this is not always the case in general. Cases with more emphasis on minimizing the force requirement result in optimal injection pressures which are less than the maximum allowable. The optimal height at which the resin is to be injected is quite different in both cases, as were the optimal mould closing speeds (as a percentage of maximum allowable). This shows that the optimal design variables cannot be predicted intuitively, and demonstrates the advantage of the optimization methodology proposed here.

The I/CM process has been shown to be a more efficient process than RTM for the particular objective function employed in this study. Even if the fastest dry compaction speed is applied for RTM, the time taken to complete the resin injection phase is much longer than for I/CM, significantly increasing the objective function value. More importantly, the increased complexity of I/CM process control has been demonstrated, which relative to RTM, requires the process designer to specify a greater number of design variables.

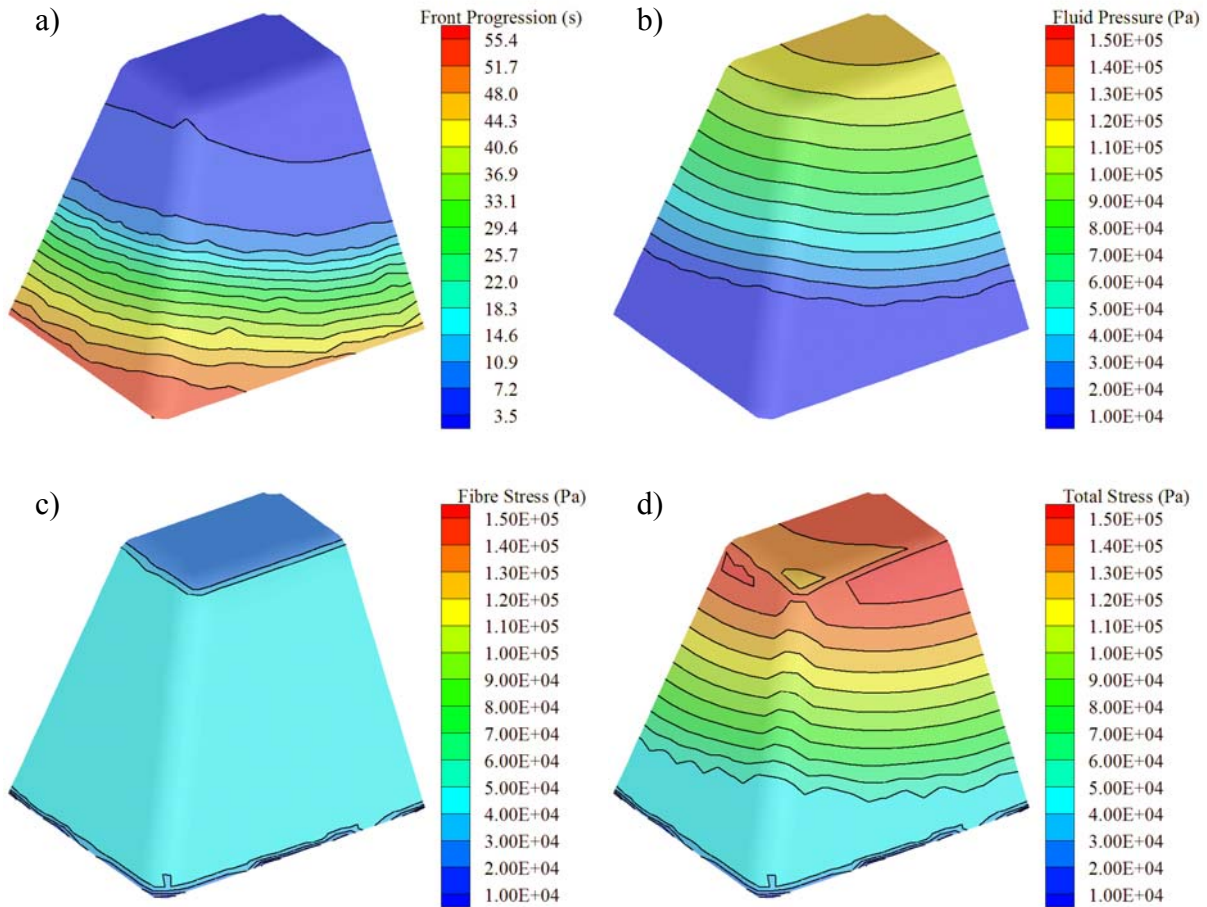


Fig. 4 Various predictions for the optimal solution: a) flow front progression; b) fluid pressure; c) reinforcement compaction stress; and d) total normal stress at $t = 49$ s.

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