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STUDY OF THE COMPACTION CHAMBER GEOMETRY FOR MANUFACTURING OF COMPOSITE BY FLEXIBLE INJECTION

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SUMMARY: The new technology of flexible injection with a compaction chamber belongs to the family of advanced composite manufacturing processes known as Liquid Composite Molding (LCM). This process requires a double cavity mold, i.e., two chambers separated by a silicone membrane. The fibrous reinforcement is laid down in the bottom cavity known as the injection chamber. The first step consists of introducing the resin by pressure in the injection chamber, and then, in a second step, silicone oil is injected in the compaction chamber in order to compact the saturated reinforcement and complete the filling of the bottom cavity. During the third and last step of the process, the saturated reinforcement is compacted, in order to consolidate the composite. The geometry of the compaction chamber represents a key feature of this new process. To understand the role of this cavity on the performance of flexible injection, this study aims to determine the best possible geometry of the compaction chamber when the reinforcement is a woven fabric. From this perspective, three different shapes are studied in a first experimental plan. A second plan will then focus on the shape that gave the best results, i.e., with long slopes. The two plans of experiments show the influence of the resin front position before the compaction fluid is injected in the part. In fact, as shown in this paper, the quality of impregnation depends on the position of the resin front and on the thickness of the composite.

KEY WORDS: flexible injection, compaction, woven fabric, impregnation, glass fibers, obstacle

INTRODUCTION

In this study, we move one step further in the analysis of flexible injection. Until now, this new process has been only used on mats reinforcement. Now it will be investigated for woven fabrics. A new flexible injection process has been studied since 2003 by the Chair on Composites of High Performance composites laboratories (CCHP) of École Polytechnique de Montréal. A flexible membrane is laid on a rigid mold cavity in order to create in the upper a second cavity called the compaction chamber. During the injection, a fluid is introduced into the upper cavity in order to reduce filling time and to increase composite consolidation after injection. After sealing of the mold, the flexible injection process includes the five following steps, as presented in Fig. 1:

(1) vacuum pulled in the chambers,
(2) injection of the exact resin quantity,
(3) injection of the compaction fluid to complete the reinforcement impregnation,
(4) composite polymerisation and consolidation,
(5) opening of the mold and removal of the part from the mold.

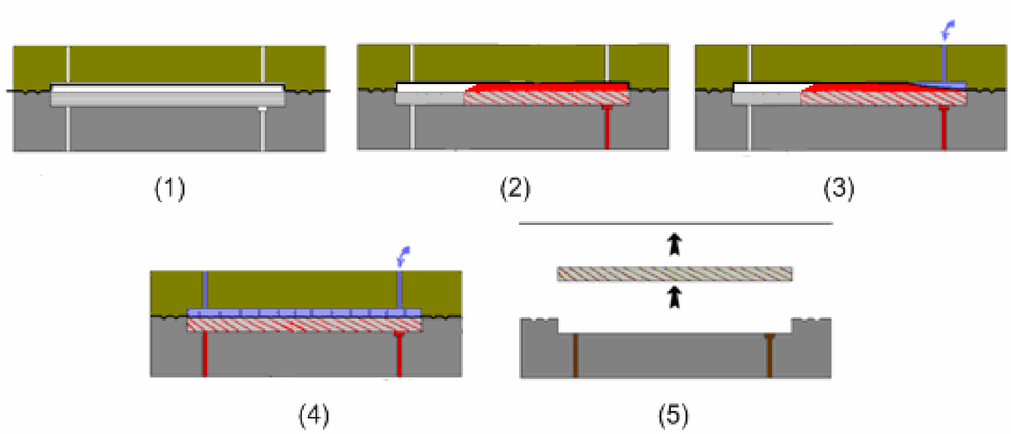


Fig. 1 Steps of flexible injection process.

Flexible injection belongs to the family of « Liquid Composite Molding » (LCM) processes as the RTM process (« Resin Transfer Molding ») or rigid mold injection has a limited output. For automotive applications, it is necessary to increase the production volume as compared to the RTM process in order to manufacture up to 20 000 parts per year.

Objective of the study

Since flexible injection has been used in previous studies only for glass fiber mat reinforcements, this investigation aims to understand the process behaviour for glass woven fabrics. To increase acknowledge on the process behaviour for glass woven fabrics, the compaction chamber geometry is under study in tow experimental plans.

Experimental plans description

Preliminary tests on woven fabrics, carried out with the same parameters as those used with fiber mat reinforcements showed the formation of a dry area close to the injection gate and an accumulation of resin near the vent. To solve this problem a proper processing window had to be determined for woven fabrics. In flexible injection the compaction chamber geometry appear like an important parameter. In a first stage, various geometries of the compaction chamber are studied. Then, the geometry whose give best results will be the subject of a deeper study. The experimental plans A and B respectively carry on the kind of obstacle in the compaction chamber (plan A) and on the utilisation of long slope in compaction chamber (plan B).

MATERIAL

In this study, the first generation mold of flexible injection has been chosen for its transparent upper mold. Thanks to the geometry of the frame, it is possible to change the compaction chamber geometry with transparent obstacles.

Experimental Mold

A first mold was devised to test flexible injection and visualise the different stages of a 125 x 355 mm sheet injection. The mold base is in aluminium 6061-T6 and the upper mold is in PMMA (polymethylmethacrylate or Plexiglas). Each part of the mold has its own injection port and event located in the injection chamber for the resin and in the compaction chamber for the compaction fluid. This first mold does not allow performing heated resin injections. Indeed, the acrylic cover of the mold can only be used at room temperature and with a pressure lower than 6 bars. The mold was designed by Briones [1] and used by Allard [2] for random fibers mats.

Monobloc Frame

Thicknesses of the tow chambers are determined by one frame. This type of frame is characterized by a step shape, what proved to hold the reinforcement during the manufacturing process. As illustrated in Fig. 2, the inferior part of the frame is larger and longer. This dimensional change is located at 1/3 of the total frame thickness. Five frames have been made with five different thicknesses: 3.175, 6.35, 7.64, 9.525 and 15.875 mm.

The reinforcement is laid on the base of the mold, it is coved by a membrane and then the frame is placed. The low compressibility of fabrics imposes a minimal thickness of frame. Also, when woven fabrics are used, this stack creates a clear space between the membrane and the upper mold.

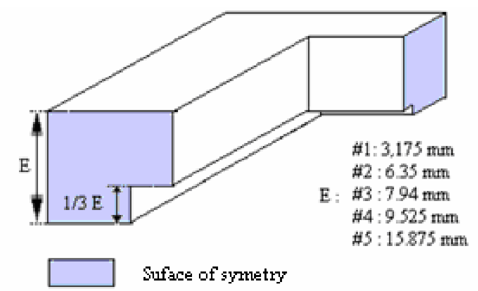


Fig. 2 Monobloc frame in PMMA.

Fabrication of the Obstacles Placed in the Compaction Chamber

Obstacles in a transparent resin of epoxy are used to change the compaction chamber shape. The transparency of the obstacles is important because this proved to see flows of resin and compaction fluid. The commercial resin, vitra-laque from Desser is put in a steel mold made by bending and welder. Two mold are made in order to fabric long and short obstacles. Those obstacles are stick on the upper mold thanks to a transparent double face tape.

OBSTACLES IN THE COMPACTION CHAMBER

Objectives

Obstacles are placed in the compaction chamber to change the direction of the pressure gradient created by the compaction fluid. Three geometries of obstacle have been tested to force the resin to impregnate transversally the reinforcement. The Fig. 3 presents the geometries: a long slope, a short slope and a rectangular obstacle. The long slope is placed over the entire reinforcement length. The two other geometries represent the half length of the composite.

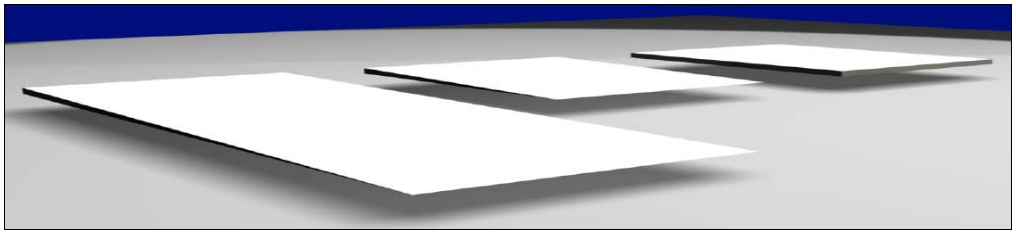


Fig. 3 Plan A (obstacles).

Description and Role of Obstacles

Only one frame is used in the experimental plan A, this is the frame # 4 of 9.5 mm thick. In this case, used obstacles change the geometry and also the volume of the compaction chamber.
Obstacles used in the different injections done in the plan A are referenced as follow:

- LS: long slope over the entire reinforcement length ;
- SS: short slope placed over the first half of the mold;
- RO: rectangular obstacle placed over the second half of the mold.

Fig. 4 presents the expected influence of the utilisation of a long slope. This obstacle should help to impregnate the reinforcement during the resin injection and the compaction fluid introduction. The tow other short obstacles are under study to know if it is possible to prevent locally a bad impregnation of the reinforcement. The short slope is placed above the bad impregnated zone and the rectangular obstacle just after the defect of impregnation.

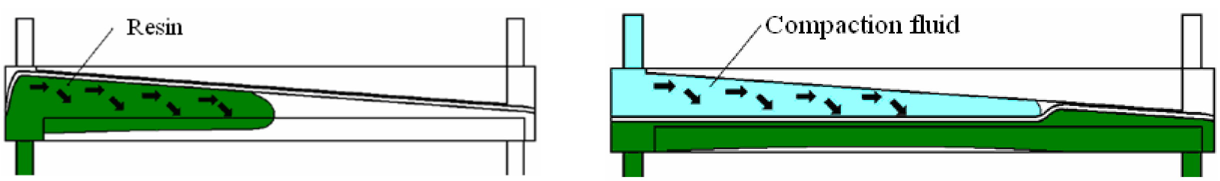


Fig. 4 Expected influence of long slope.

Materials

The reinforcement used is the Structex from Chomarat with a surface density of 1020 g/m^2. This multidirectional fabric is used as a 5 plies preform. The resin is the Derakane 411-350 from Ashland. This vinylester resin has a viscosity of 0.35 Pa.s.

To observe the resin and compaction fluid flows, the membrane should be transparent. The membrane EL1040T from TORR-TECHNOLOGY is a translucent silicone membrane of 0.061 inches thick. This is a good membrane for flexible injection applications because of its compatibility with silicone oils and good compressibility which ensures mold tightness. The compaction fluid is a transparent silicone oil from DOW CORNING with a viscosity of 1000 cSt.

Injection Setup

The resin is injected thanks to a pressure pot set to 3 bars. A plastic glass with 290 g of resin is placed in the pot. The injection is stopped when the first air bubble leave the pot. In this condition 120 g ±10 g of resin are injected. To inject the compaction fluid, a pressure of 6 bars is used. Two vacuum pots are connected to the vents. One of them applies a vacuum pressure of 1 bar in the compaction chamber. The vacuum pressure in the injection chamber is set to 0.25 bars.

Observations and Results

This experimental plan allowed us to understand more the role of the compaction chamber. The Table 1 describes observations done on the parts produced in the plan A. The position and the size of dry spots are indicated as well as resin accumulations.

Table 1 Description of composites (plan A)

Reference	Geo.	Visual characteristic
E06PF1_02	NO	Important dry spot: 40 mm from the injection port. Dry spot size: 70 mm on the base mold surface. Resin accumulation on the vent. Dimensions: 10 x 110 x 3 mm.
E06PF1_03	LS	No dry spot. Resin accumulation on the vent. Dimensions: 7 x 110 x 5 mm.
E06PF1_04	LS	Small dry spot: on the middle base mold surface. No resin accumulation.
E06PF1_05	SS	Medium dry spot: 90 mm from the vent. Dry spot size: 30 x 45 mm on both surfaces (more on base mold surface). Resin accumulation on the vent. Dimensions : 10 x 60 x 4 mm.
E06PF1_06	SS	Medium dry spot: 90 mm from the vent. Dry spot size: 118 x 30 mm on both surfaces. No resin accumulation.
E06PF1_07	RO	Small dry spot: 70 mm from the injection port. Dry spot size: 25 x 35 mm on the base mold surface. Small resin accumulation on the vent and on the sides (150 mm).
E06PF1_08	RO	Small dry spot: 70 mm from the injection port. Dry spot size: 25 x 35 mm on the base mold surface. Small resin accumulation on the vent and on the sides.

Table 1 shows that the utilisation of a long slope erases the concentred dry spot which appear without obstacle. The utilisation of a short slope creates a dry spot just after the obstacle. Finally, the rectangular geometry reduces the concentred dry spot without erases it completely.

CONCLUSIONS

The experimental plan A shows that the utilisation of a long slope obstacle allowed to improve reinforcement impregnation. For obstacles placed locally in the mold, the results are not clear. For those reasons, the second experimental plan focuses on the long slope geometry.

VARIATION OF THE ANGLE OF THE LONG SLOPE

Objectives

The experimental plan B aims to determine the influence of the slope angle on the reinforcement impregnation in function of the number of plies of fabric. In this plan 4 thicknesses of composite are studied and for each one, several angles of slope are used. The Table 2 gives dimensions of each obstacle. The Table 3 present the obstacle used in function of the number of plies and the thickness of the frame. For each combination of parameters, tow parts are produced.

Table 2 Long slopes reference

Ref.	Max thickness (mm)	Length (mm)	Angle (°)
PL01	3,75	345	0,62
PL02	4,37	345	0,73
PL03	5,30	340	0,89
PL04	5,85	323	1,04
PL05	9,40	337	1,60
PL06	11,15	345	1,85
PL07	12,20	345	2,03

Table 3 Presentation of the plan B

Frame number	Frame thickness (mm)	2 plies	3 plies	4 plies	5 plies
#1	3,18	None			
#2	6,35	PL02	PL01		
#3	7,94	PL04	PL03	PL02	
#4	9,53		PL05	PL04	PL03
#5	15,88			PL07	PL06

Materials

The fabric used in the plan B is the unidirectional SaerUni from Saertex. This fabric replaces the fabric from Chomarat because its fiber orientation doesn't change the resin flow above the reinforcement. The flow remains 1D, what is not sure with the Structex reinforcement. The surface density of this reinforcement is 1020 g/m^2. The resin, the membrane and the compaction fluid don't change.

Injection setup

The quantity of resin varies with the numbers of plies to obtain composites with a fiber volume fraction of 50 %. For each thickness of composite the Table 4 gives the theoretical quantity of resin required.

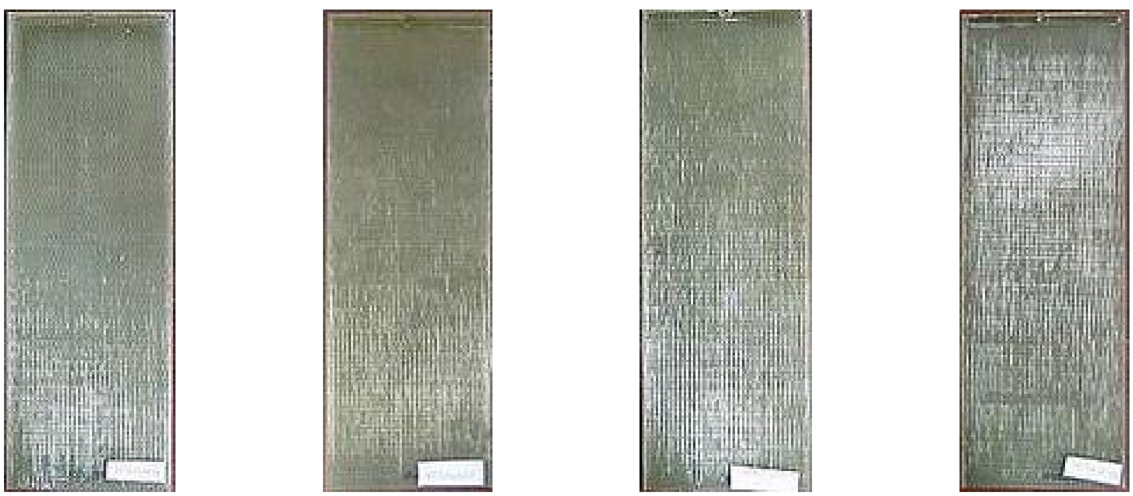
Table 4 Resin quantity in function of ply number

Ply number	Resin quantity (mL)
2	33,9
3	50,8
4	67,8
5	84,7

With a tensile testing machine a piston filled with resin is activated and gives a precision of ± 2 mL. The rest of the equipment is the same than in the plan A. The vacuum pressure in the compaction chamber is set to 1 bar and in the injection chamber to 0.25 bars.

Observations and Results

The good results obtained in plan A with the long slope geometry are not confirmed in plan B. The augmentation of the obstacle angle doesn't improve the reinforcement impregnation, on the contrary the entrapped air quantity increase. However, the impregnation is improved when for a same frame a slope is placed in the compaction chamber. Fig. 5 illustrates the influence of the angle slope for the 4 ply composites. For the three other thicknesses of reinforcement, the same results are noticed.



H07P4004 / None H07P4005 / PL02 H07P4011 / PL04 H07P4013 / PL07

Fig. 5 Influence of the long slope angle for 4 plies composites.

For each injection, Table 5 presents the position of the resin front as a function of the obstacle used. In the same table, a short description of the composite quality shows the important role of the resin front position before injection of the compaction fluid. In this table the presence of dry spots is given by tow information: the dry spot dispersion and position and also the dry spot size.
For the same number of plies the quantity of resin doesn't change and the increase of the slope angle enlarges the clear space above the reinforcement. For this reason, the resin front position changes with the type of obstacle used. When the slope angle increases, the resin front comes closer to the injection port (Fig. 6).

Table 5 Resin front position and impregnation quality

Reference	Ply number	Long slope	Resin front position	Impregnation quality	Dry spots
H07P2003	2	None	17,7	very good	quasi inexistent
H07P2004	2	None	17,2	very good	quasi inexistent
H07P2005	2	PL02	8,9	quite good	dispersed, medium
H07P2006	2	PL02	8,7	quite good	dispersed, medium
H07P2011	2	PL04	6,0	bad	dispersed, big
H07P2012	2	PL04	5,8	bad	dispersed, big
H07P3013	3	None	14,2	quite bad	dispersed +light concentration 2/3, small
H07P3014	3	None	13,9	quite bad	dispersed +light concentration 2/3, small
H07P3009	3	PL01	17,8	good	dispersed, small
H07P3010	3	PL01	17,8	good	dispersed, small
H07P3005	3	PL03	11,8	quite bad	dispersed +concentration 1/3, medium
H07P3006	3	PL03	11,0	quite bad	dispersed +concentration 1/3, medium
H07P3011	3	PL05	9,8	bad	dispersed +concentration 1/3, big
H07P3012	3	PL05	8,6	bad	dispersed +concentration 1/3, big
H07P4001	4	None	16,0	bad	concentrated 1/4, big
H07P4004	4	None	16,5	bad	concentrated 1/4, big
H07P4005	4	PL02	18,9	quite good	concentrated 1/4, medium
H07P4006	4	PL02	18,5	quite bad	concentrated 1/3, big
H07P4009	4	PL04	11,8	very bad	concentrated 1/3, big
H07P4010	4	PL04	12,7	very bad	concentrated 1/3, big
H07P4013	4	PL07	9,8	very bad	concentrated 2/3, very big
H07P4014	4	PL07	9.6	very bad	concentrated 2/3, very big
H07P5001	5	None	19,2	very bad	concentrated 1/2, very big
H07P5002	5	None	19,8	bad	concentrated 1/3, big
H07P5005	5	PL03	22,6	quite good	concentrated 1/4, medium
H07P5006	5	PL03	22,8	quite good	concentrated 1/4, medium
H07P5009	5	PL06	11,6	very bad	concentrated 1/3, very big
H07P5010	5	PL06	11,4	very bad	concentrated 1/3, very big

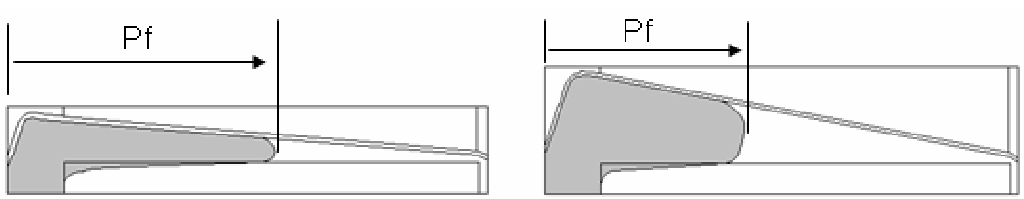


Fig. 6 Resin front position as a function of the long slope angle.

When the resin does not cover a great part of the preform after its injection, the introduction of the compaction fluid pushes the resin to the end of the mold and leaves a great part of the reinforcement dry. Then the resin accumulated in the end of the mold block the vent and the pressure applied by the compaction fluid force the resin to impregnate the reinforcement. This mode of impregnation creates an important and concentrated dry spot. Fig. 6 shows that the uncovered zone of the reinforcement increases with the slope angle. This has the effect of increasing the quantity of air entrapped in the reinforcement, and consequently composite quality drops down.

CONCLUSIONS

This study shows the role of the resin front position before the compaction fluid entrance. It seems very important that during its injection, the resin go further as possible in the mold. This observation orients research toward the study of the compaction chamber thickness. Indeed, it should be interesting to change the compaction chamber thickness to play on the resin front position. This potential study could allow us to differentiate influence of the chamber thickness and slope angle and to confirm the role of the resin front position before the compaction fluid injection. The utilisation of a long slope is not necessary to be banned from flexible injection. As the experimental plan A shows, for a fixed compaction chamber thickness it is possible to improve the composite impregnation by adding a long slope in the compaction chamber. Among other parameters that govern flexible injection, membrane thickness, the viscosity of the compaction fluid and the fiber volume fraction play also a role. The influence of those parameters could be the topic of future investigations.

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