A comparison between numerical simulation and experimental characterization of a Liquid Resin Infusion test under industrial conditions

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ABSTRACT: Liquid Resin Infusion (LRI) processes are promising manufacturing routes to produce large, thick or complex structural parts. They are based on the resin flow induced across its thickness by pressure applied onto a preform / resin stacking. However, both thickness and fibre volume fraction of the final piece are not well controlled since they result from complex mechanisms which drive the transient mechanical equilibria leading to the final geometrical configuration. In order to optimize both design and manufacturing parameters, but also to monitor the LRI process, an isothermal numerical model has been developed which describes the mechanical interaction between the deformations of the porous medium and the resin flow during infusion [1]. With this numerical model, it is possible to investigate the LRI process with classical industrial piece shapes. To validate the numerical model and to improve the knowledge of the LRI process, the present study details a comparison of the major process parameters between numerical simulations and an experimental study of a plate infusion test carried out by LRI process under industrial conditions. Moreover, these two approaches are both good ways to explore and improve our knowledge on the resin infusion processes, and finally, to develop simulation tools for the design of advanced composite parts.

KEYWORDS: Liquid Resin Infusion, numerical simulation, experimental study, comparison, industrial conditions.

INTRODUCTION

During the last decade, the resin infusion processes have become popular for the manufacturing of structural polymer-based composites. As such, Liquid Resin Infusion (LRI) process seems quite promising. In this process (see Fig.1), resin is distributed through a highly permeable flow enhancement fabric placed on top of the fibres preform. Thanks to a pressure differential created by a vacuum at the vent of the system, resin impregnates across the compressible performs, *i.e.* in the direction transverse to the preform 'plane'. The LRI process leads to final part quality improvement since resin flow and cure are distinct. On the contrary, the thickness and fibre volume fraction of the final piece are not well controlled during the process because, first, of the use of a vacuum bag instead of a rigid mould and second, due to the large preform deformation when vacuum and pressure are applied. Therefore, the final properties of the composite parts strongly depend on the process parameters. In order to optimize both design and manufacturing parameters, a numerical model has been developed which describes the mechanical interaction between the deformations of the preform and the resin flow during infusion stage [1]. To validate the numerical model and to improve the knowledge of the LRI process, this research work will deal with a comparison of the major process parameters between numerical simulations and experimental study of a plate infusion test carried out by LRI process under industrial conditions.

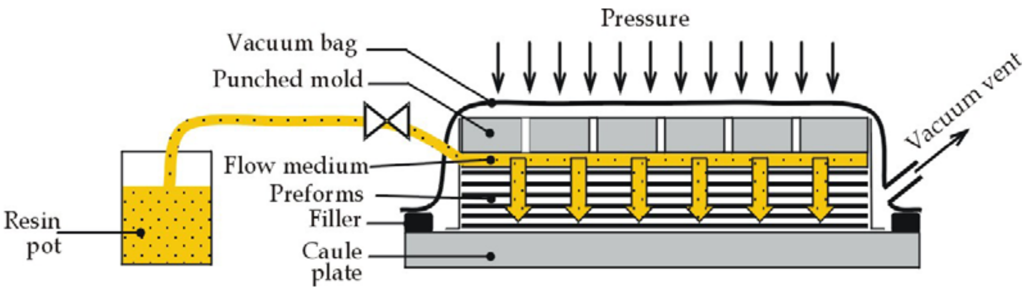

Fig. 1 Principle of LRI process

NUMERICAL MODEL OF THE LRI PROCESSES

Recently, a complete model for the study of a reactive fluid flow through highly compressible porous media such as fibrous preforms has been proposed by Celle *et al*. [1]. In this infusion-based process, liquid resin is supposed to flow across the compressed preform thickness, as a result of the difference between the permeability of the flow enhancement fabric and the perform. From the modelling point of view, problems of this multi-physical analysis are two fold. Firstly, one faces ill-posed boundary conditions regarding the coupling of liquid regions, where a Stokes flow prevails, with the wet fibrous preform regions modeled as porous media governed by the Darcy's law and a non-linear mechanical response. Secondly, the interaction phenomena due to the resin flow in the highly compressible preform are not classical. Using this numerical model, the simulations can bring a series of important process parameters values, like the filling time, resin mass, preform thickness, fibre volume fraction etc.

In order to compare the results obtained experimentally regarding the filling stage of composite structure, flat plates are considered in this paper. Let us simulate first, the filling of such simple geometrics. Following the simulations proposed by Celle *et al*. [1], the flow distribution medium is represented as a purely fluid region governed by the Stokes law, and infinitely stiff from a solid mechanics point of view, in which resin flows first, prior to infuse gradually through the thickness of the preform. Even if the thermo-chemical modelling has been proposed in Celle's numerical model, as the real infusion processes involve complex mechanical situations on which we focus, isothermal situations were considered corresponding to constant resin viscosity. On the other hand, permeability of the preform is always a key parameter in LCM (Liquid Composite Molding) processes, quite tricky to assess event if some recent progress permit to anticipate its introduction in realistic simulations [2]. As a first approximation, Carman-Kozeny's equation has been employed to determine the permeability tensor which will be varied accordingly to the preform mechanical state of deformation.

EXPERIMENTAL APPROACH

Experiments were conducted with 48 plies composite plates $[0_6\ 90_6]_{2s}$, made up of "UD fabric" reference G1157 produced by Hexcel Corp. The preform dimensions are 335 mm × 335 mm × 20 mm and its mass is 1.56 kg before infusion. The experimental setup is shown in Fig. 2. This infusion test is carried out in standard industrial conditions, using a heating plate with an upper lid to guarantee homogenous thermal conditions. The entry and exit of the resin are presented also in Fig. 2, and a balance is proposed to measure the resin mass absorbed by the whole system during the infusion stage. A micro-thermocouple (TC1) is inserted in the middle of the entry tube to monitor the resin temperature and detect the initial infusion time. To initiate the measurement of the resin mass, another micro-thermocouple (TC2) associated with the mass capture unit is placed in the same location as the previous thermocouple (TC1). In the outlet pipe, a micro-thermocouple (TC7) is used to control the temperature change of the resin outlet and therefore to determine the filling time. To detect the temperature of the preform and the resin front during the filling stage [3], 4 micro-thermocouples (TC3-TC6) are placed across the thickness of the preform, at the center of ply 10, ply 25, ply 40 and ply 46. The order of ply number is defined from the flow enhancement fabric towards the bottom of the preform (heating plate). All the thermocouples are located at the center of the ply, along the same direction as for the carbon fibre to minimize intrusivity.

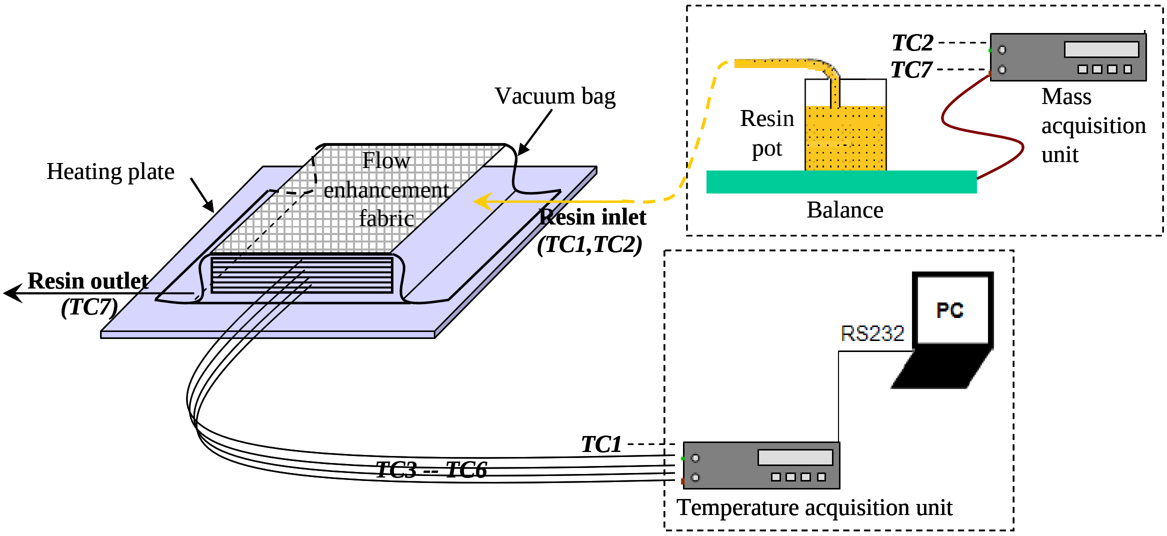

Fig. 2 Experimental set-up of a plate infusion test

RESULTS AND DISCUSSIONS

After numerical and experimental analysis to the filling stage of this same resin infusion test, a comparison has been made between the results of these two studies and presented in Table 1. Simulations have been realized with 1458 triangle mixed velocity-pressure elements. Adequate boundary conditions were used to represent, as properly as possible, the industrial environment. Experimentally, resin infusion has been performed under a vacuum pressure of 1.4 mbar. Generally, a good agreement can be observed between these two studies for the major parameters, except for the filling time which depends strongly on both permeability and resin viscosity.

Table 1 Comparison between numerical simulation and experimental studies of a standard plate infusion test carried out by LRI process

		Experimental	Simulation
After compaction	Thickness of the preform (mm)	13 ± 0.5	12.7
	Fibre volume fraction	60%	61%
After filling	Average thickness variation of the preform (mm)	/	1.25
	Fibre volume fraction	/	56%
	Mass of resin used during the infusion stage (g)	705	750
	Filling time of preform (s)	1000	890

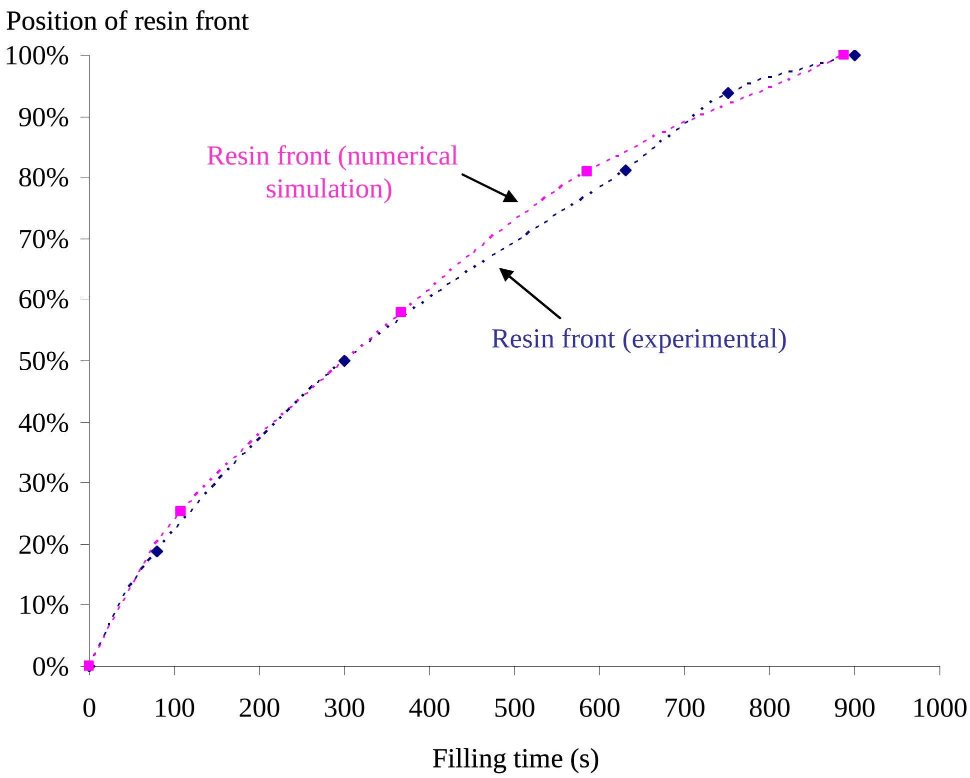

Fig. 3 Resin front position versus time for a standard plate infusion test by LRI process

Since we performed a standard plate infusion test with closed lid, the thickness variation of the preform could not be assessed. This comparison was performed in an open-lid infusion test second carried out to 24 plies G1157 composite plates. Here again, comparison is satisfactory, numerical simulations show an average thickness variation of 0.6 mm while experimentally 0.55 mm could be measured by a fringe pattern projection technique [4].

Fig. 3 presents the experimental and numerical results concerning the position of the resin front during the filling stage. For the numerical simulation results, to asses the flow front position 5 nodes were selected across the stacking thickness of the preform, on a same line corresponding to the TCs position (see Fig. 2). On the other hand, 4 micro-thermocouples (TC3-TC6) have been used to characterize the resin flow by measuring changes in temperature of the preform [2]. Time of resin arrival at position 100% corresponds to the time when resin is in contact with the heating plate at the bottom of infusion system. Comparing both curves, a good correlation can be found here for the estimates of resin front position in the middle of the preform.

CONCLUSIONS

In this present paper, we realized a general comparison between numerical simulation and experimental results based on a plate infusion test by LRI process under standard industrial conditions. From this comparison on the most important parameters, we consider that our numerical model is able to deal with the problem of interaction between resin flow and the deformations of the porous medium during resin infusion phase.

Although a good correlation can be obtained between numerical and experimental analysis, some problems remain to be solved both in the numerical computations and experimental measurements. One main problem corresponds to characterising the industrial conditions, such as the resin viscosity, the preform thickness before compaction, and more generally the thermal environment. The next step in this validation process will hence focus on thermal and chemical aspects of LRI processes.

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