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Experimental and numerical modelling of LRI process

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Abstract. The aim of this study is to gain knowledge concerning the process and its physics, as well as to become able to optimize the fabrication of large and complex composite parts in aeronautics applications. Composite materials have many advantages and the use of this technology is increasing in the aeronautic industry. In the L.R.I. process, dry textile preforms are impregnated by a thermoset liquid resin. All the elements are enclosed in a vacuum bag of known pressure. Once preforms are totally impregnated, the resin system begins the curing reaction to obtain the composite part. This study contains two major sections. Firstly, numerical modeling was done with the Pam- Rtm finite element code to determine the evolution of the flow front during the infusion. Simulations were performed to analyze the infusion of sandwich composite parts with perforate foam, which allows the inferior skin to be impregnated in the same operation. Secondly, experimental work was conducted to confirm the numerical results.

Introduction

Composite materials have many advantages over classical materials used in aeronautic industry. That's why, since few years, composite manufacturing processes have changed in many ways. Different new processes were developed in relation with the aeronautic manufacturing constraints. Among them, the composite liquid processes have been significantly developed: Resin Transfer Molding (RTM), Liquid Resin Infusion (LRI), Resin Film Infusion (RFI), etc... [1] The _ability of these processes is ever too weak to optimize the manufacturing of parts in composite materials by the liquid way. Many authors have already worked this subject [1, 2, 3, 4]. The key issue to achieve a realistic modeling of liquid composite processes is the determination of permeability values. Many experimental setup and method have been developed to make accurate permeability measurement [5, 6]. Some paper deals with also the permeability evaluation but by the numerical way, to save experimental cost and improve numerical models. [7, 8] Authors have also treated LRI simulation by the hydro-mechanical coupling between resin propagation through a compacted fiber preform. In this paper, a numerical work associated to the developpement of an exeprimental method allows to evaluate different issues in association with the LRI process understanding.

1 Numerical modelling

This chapter deals with the numerical modeling of LRI process on monolithic and sandwich composite parts. PAM-RTM is based on the following Darcy's Law.

$$\vec{V} = -\frac{[K]}{\mu} \cdot \vec{\nabla P} \quad (1)$$

In the Darcy's law, v (m/s) is the fluid velocity, K (m^2) is the permeability tensor of the fiber preform, μ (Pa.s) is the fluid viscosity, ∇P is the gradient between injection point and event. The method employed to simulate the manufacturing of these parts will be developed and so, the main difficulties in relation with the LRI numerical modelling will be exposed.

1.1 Infusion of a monolithic specimen. The monolithic specimen is the first simulation. It is a simple model, which allows understanding the simulation of LRI process. First simulation works concern the development of a model to simulate the LRI process on a monolithic part. The program used to perform these simulations is PAMRTM[®] edited by Esi-Group. This monolithic part has a very simple geometry, to easily make the correlation with the experimental results. The used geometry is a plate of dimensions 500x200x2mm. The boundary conditions applied during this modelling are two: pressure inlet and event. The mesh of this plate have been performed with I-DEAS[®] program, and it was build with 2D triangular elements, which are the only accepted by PAM-RTM[®]. In regard to the materials used, the properties are those of carbon fiber UDC300 and SR1710 resin, manufactured by SICOMIN. The mesh used in this model is represented by the following Figure 1. Table 1 presents numerical parameters of these simulations.

Parameters (unit)	Value
Relative Inlet pressure (mbar)	0 (P_{atm})
Vaccum pressure (mbar)	600
Fiber permeability (m^2)	1,00E-09
Nominal weight (g/m^2)	300
Temperature d'injection($^{\circ}C$)	45
Resin viscosity (cP)	91

Table 1: Numerical simulation parameters

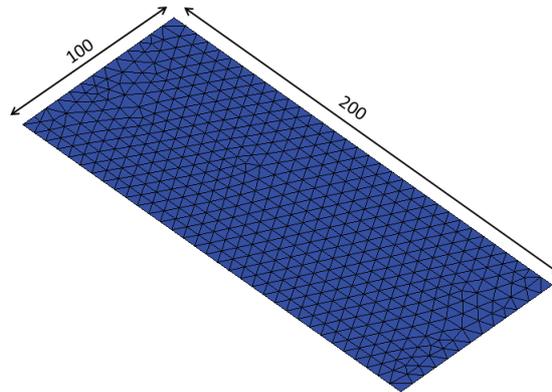


Figure 1: Mesh of monolithic model

1.1.1 Boundary conditions. Two kinds of boundary conditions have been used to perform these simulations. The first is the pressure of the fluid during the process. Its value is fixed to 0.6 bar, a classical value for composite made by LRI process. The second boundary condition is the event of the process, equal to the atmospheric pressure. The Figure 2 shows the geometry with the applied boundary conditions. Concerning the parameters in PAM-RTM[®], the permeability value is the most complicated to give. Indeed, the determination of the 3D permeability tensor $[K]$ can be done only by the experimental way. The measurement method is complicated and expensive. This problem has been bypassed by a sensibility study in relation with the experimental results. Starting with the experimental filling time, the value of $1.10^{-9}m^2$ is kept in PAM-RTM[®].

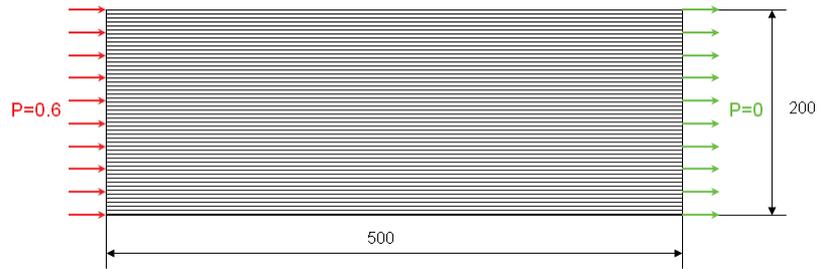


Figure 2: Boundary conditions of monolithic model

1.1.2 Results. PAM-RTM® gives the filling evolution of the considered part with a good precision. This simulation allows plotting the evolution of the fluid speed against time, as shown with Figure 3. This plot must be related to the different parameters of the modeling: fiber rate, permeability, charge loss. This graph shows that the resin speed decreases with time, in function of the charge loss. This fact is amplified if the permeability is more important. That is why the determination of the permeability tensor is critical for the filling time prediction. [10] This is one of the most important problematic in the LRI process study.

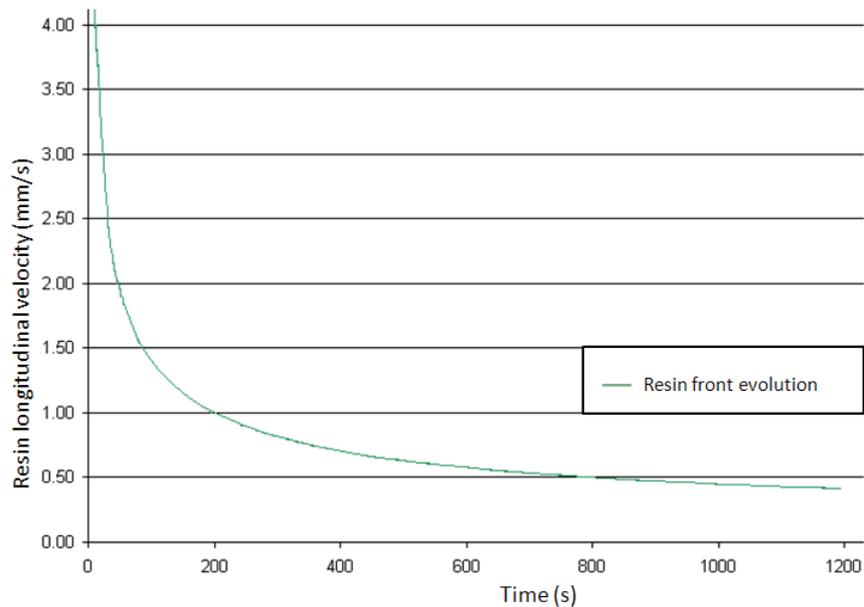


Figure 3: Resin speed evolution during monolithic infusion simulation

1.2 Infusion of a sandwich specimen. The sandwich simulation is interesting because, there are many differences in the interpretation of results. The infusion of sandwich generates specifically problem to consider, like the delay between the impregnation of the upper layer and the bottom layer.

1.2.1 The delay problem. The major difficulty in the modelling of the sandwich infusion is to control the impregnation of the upper and bottom layer. If the sandwich is made with foam, it is necessary to realize many holes through the thickness to let the resin flow to the bottom layer. [11] Indeed, the LRI process principle is to distribute the resin on the upper layer with a draining component, and then it is flowing to the bottom. Concerning the sandwich part, the thickness is generally more important than the monolithic composite. This important thickness generates the delay problem in sandwich materials infusion, because there is a significative time during which the resin flows through the foam by the micro-holes. The Figure 4 shows this problem.

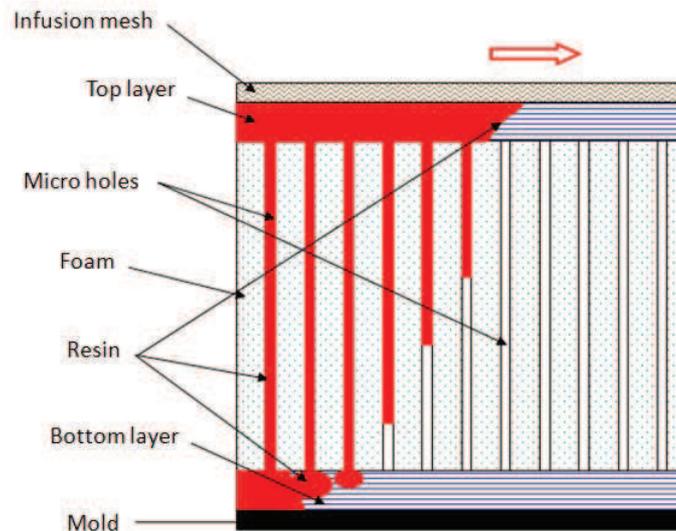


Figure 4: Problem of delay in sandwich infusion

1.2.2 Modelling. Sandwich infusion analysis was made with an elementary volume, which is representative of the foam, with micro-holes, upper and bottom layer. The layers and the foam are considered in two different areas, with different materials properties. Layers properties are the same as these used for monolithic simulations. Concerning the foam, it is an AIREX® R82. The dimensions of this model are a rectangular volume of 100x100x17mm. The thickness of the foam is 15mm, so each layer is 1mm thick. The particularity of this model is only the wall of the holes has been drawn. It is not necessary to model the foam, because there is no fluid flowing through. The simulation is concentrated on the flow behavior. Figure 5 presents this numerical modelling.

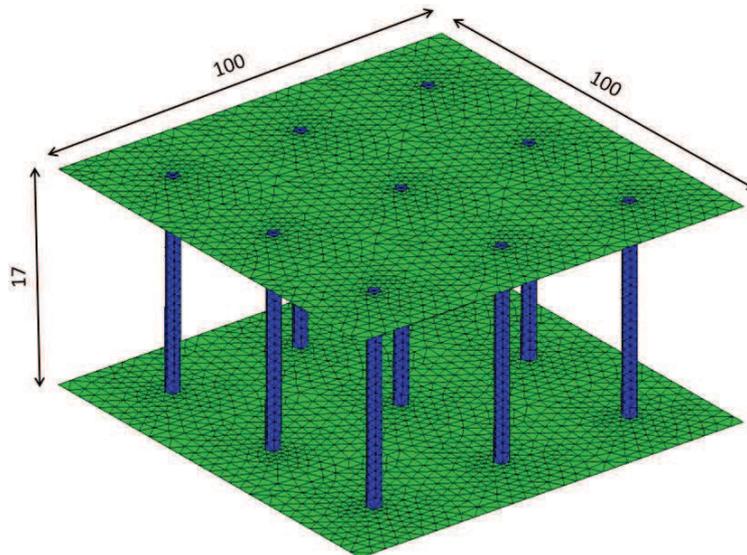


Figure 5: Mesh of sandwich model

1.2.3 Boundary conditions. The boundary conditions are the same as the monolithic model, except event is applied on upper and bottom layer, as shown by the Figure 6. The resin injection remains on the upper layer because of the draining fabric.

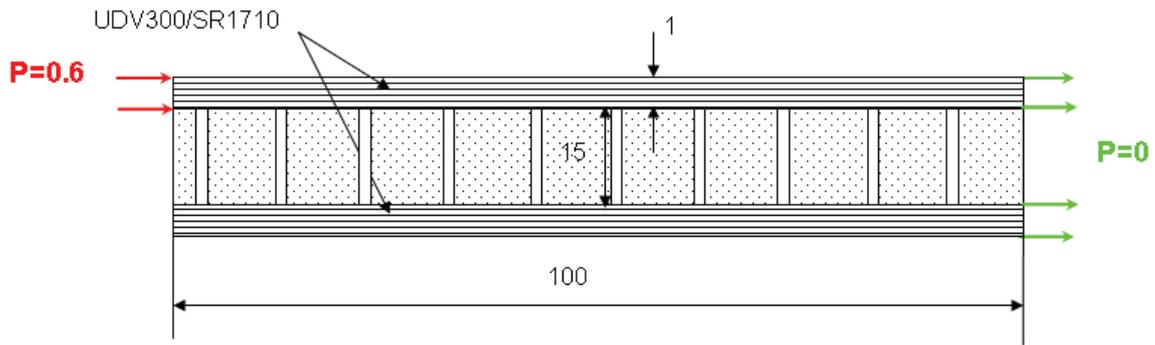


Figure 6: Boundary conditions of sandwich model

1.2.4 Results. One of major aim of these sandwich infusion simulations is to identify the delay between the upper layer and the bottom impregnation. This goal is reached, as we can see on the Figure 7, the upper layer is full (red color) before the bottom layer. This one is impregnated by growing points when the resin fills the holes.

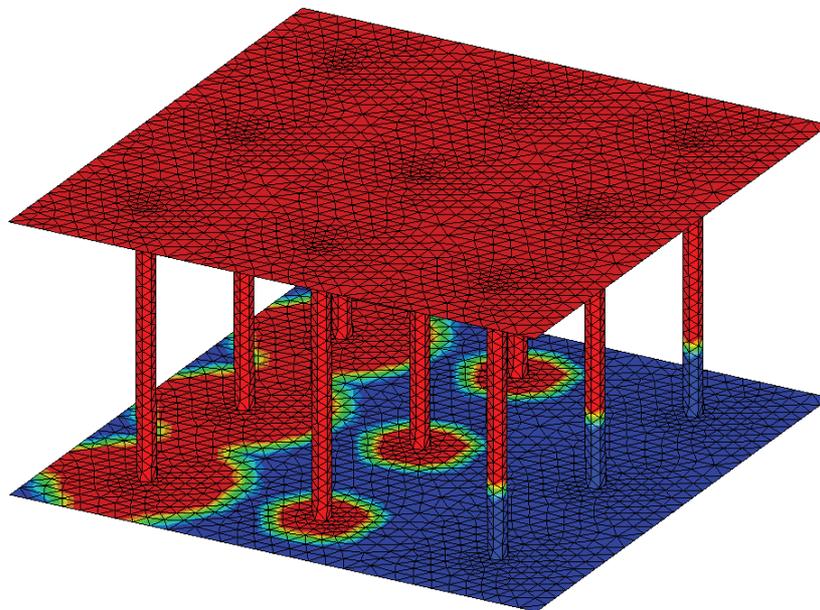


Figure 7: Sandwich simulation filling result

This fact is completely coherent with the experimental behavior. Nevertheless, there are some problems to analyze on the delay plot (Figure 8). Indeed, the delay is not constant in time. This is identified by rebounds on the curve. After 40s of infusion, rebounds disappear, which means that there is no delay after 40s. This is no coherent with real results, the delay is observed up to the end of the process. In simulation, after 40s, there is delay and at the end the resin flow by the two layers at the same time, which is impossible in real process. It means that the model do not transcribe the good behavior of sandwich infusion, for many reasons. First, if this phenomenon can be observed, it will be in very special permeability and draining conditions. Another reason is that draining product is not a parameter of the simulation, so PAM-RTM® considers in the same way the flow through the two extreme layers. Finally, this software considers infusion more than an injection under pressure with vacuum assistance (process VARTM) instead of the real LRI process.

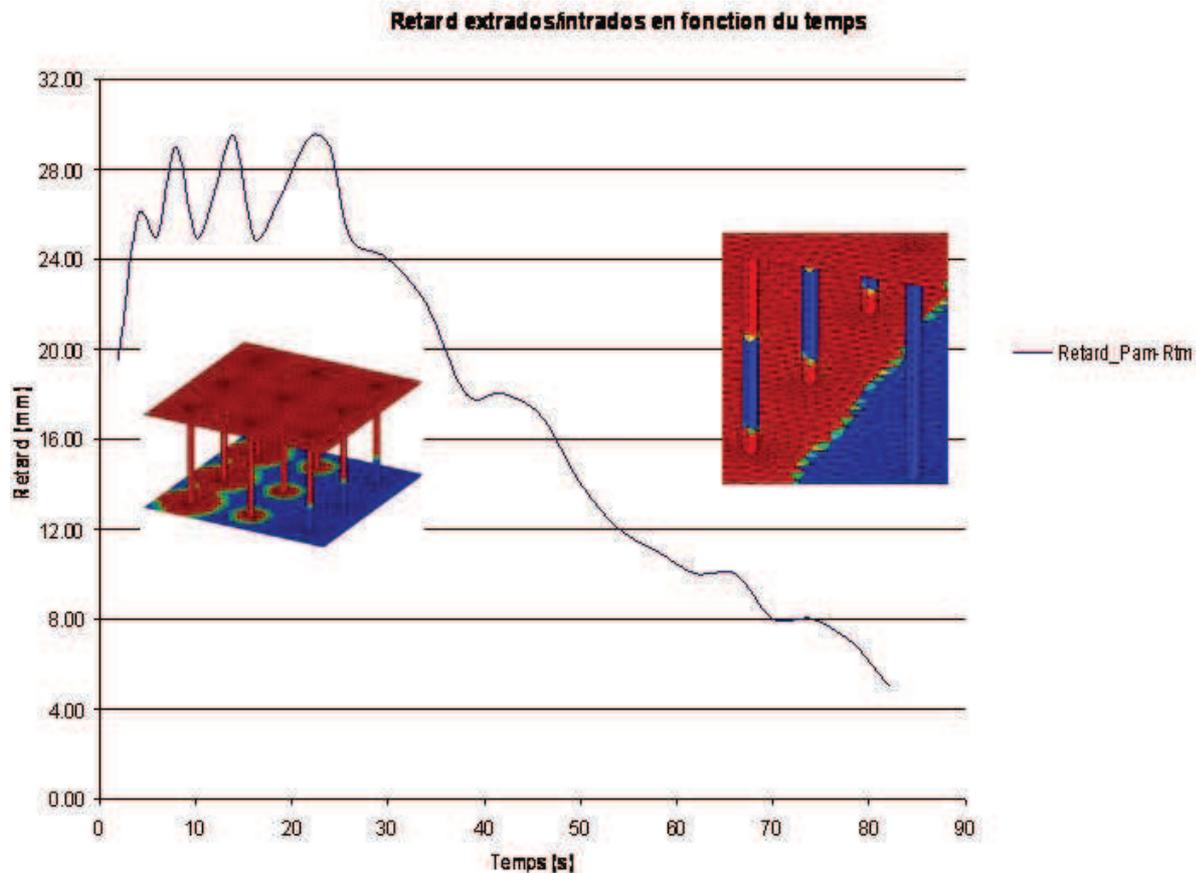


Figure 8: Evolution of delay in sandwich simulation

2 Experimental study

The goal of the experimental study is to be capable of measure significant parameters during a composite part infusion and make the correlation with numerical results to help understanding LRI process behavior. This correlation will allow identifying the major issues of this study.

2.1 Experimental equipment. A test bench was made to realize measurements during monolithic and sandwich infusions. The mold which has been used is glass plate. All tests were performed with this very simple mold. To follow the resin front during impregnation, a camera and a ruler were installed on top and under the mold to take pictures at fixed time steps. The temperature was measured with thermocouples regularly distributed on the part. All sensors were connected with computers to make a real time acquisition of data. The test bench was also equipped with all injection equipment necessary to the LRI process: vacuum system, resin trap, etc... This test device is in a gray room, with controlled environmental conditions. The Figure 9 presents this test equipment.

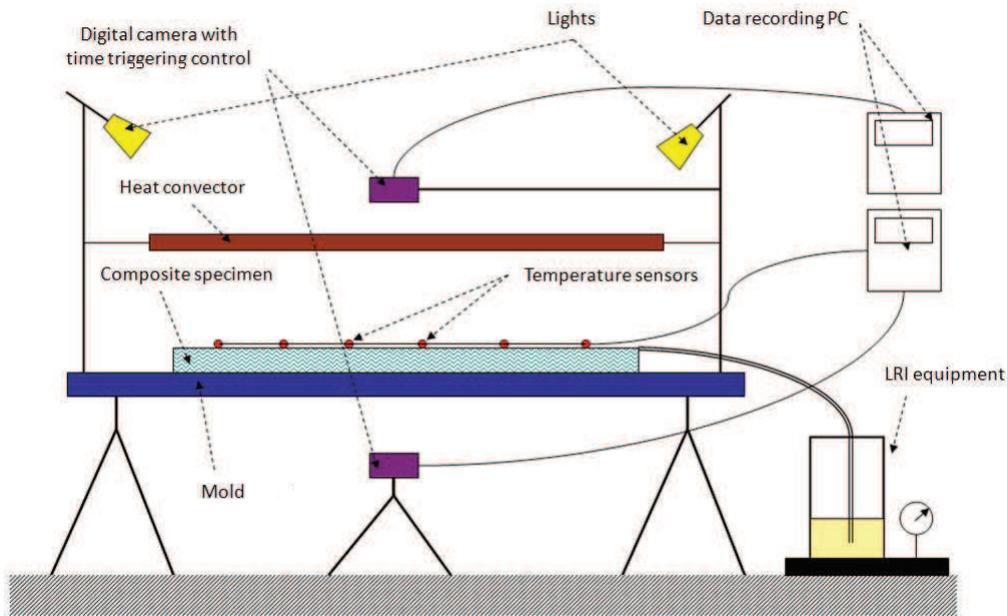


Figure 9: Experimental equipment

2.2 Experimental results. During experimental campaign, monolithic and sandwich infusions were performed, but only monolithic results are exploitable for a quantitative correlation, because not enough sandwich results were available.

2.2.1 Monolithics. These tests allow plotting the evolution of filling and fluid speed against time for monolithic infusion, represented by the Figure 10. It shows that the numerical and experimental results are similar. These plot mean also that carbon fiber have a permeability lower than glass fiber. This is important for the determination of LRI process parameters: resin viscosity, temperature, draining strategy, etc... The test bench allows also analyzing the evolution of temperature during the LRI process, to complete his understanding.

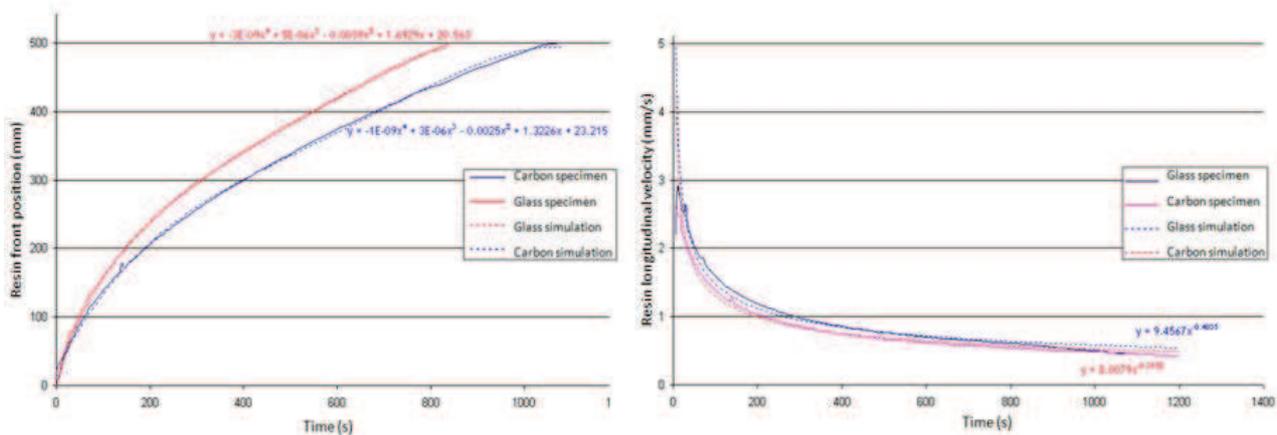


Figure 10: Evolution of filling and resin velocity evolution

2.2.2 Sandwiches. If there is not exploitable quantitative measure, some observations can be made during sandwich infusion tests. First, concerning the delay problematic, the experimental results confirm that resin fill the bottom layer by growing points, and then the impregnation front is circular, around micro-holes. It is the same behavior in sandwich infusion simulation, at the beginning of filling, which means this modeling is acceptable up to a limit of part length.

3 Correlation of results

This section deals with the comparison between numerical and experimental results. Also, some issues link to the LRI modelling will be identified to share on the study of this liquid composite process.

3.1 Simulation/Experience comparison. As it is shown on graph provided by previous chapters, the correlation of results is good. Indeed, concerning the monolithic results, the prediction of filling and the resin speed are close between the both evaluation techniques. For sandwich infusion, the results are also good, by visual observations.

These results allow validating many things. First, the monolithic modelling is completely exploitable, for 2D geometry. This tool can be used for the cycle prediction in the case of simple parts. Mathematic law can be identified on graph, and a further study is necessary to affine coefficients and identifies terms in physical LRI parameters.

3.2 Identification of new issues. This study allowed to identify many issues, which must be solved, to make an accurate prediction of the LRI process behavior. These issues can be divided in two categories, numerical and experimental issues.

3.2.1 Numerical issues. Concerning the numerical modelling, there are many ways to optimize the simulation results. Softwares will take in account draining component to be efficient in the prediction of LRI behavior, especially for sandwich modelling. Also, the modelling of flow through the micro-holes must be developed to solve errors in the impregnation delay prediction. The major work to be more efficient in LRI simulation is probably the permeability measure. It seems clear that it is the more influent parameter. All these modifications should allow developing a reliable numerical model.

3.2.2 Experimental issues. In the experimental study to, the major research axis is the permeability determination. That is a complicate measure, which requires many precautions:

- Side effect
- Flow control
- Injection section
- Pressure measurements

It will be interesting to measure the effect of fibers compression under the resin action, this parameter modify the preform permeability, and so the filling time [11]. An experimental technique which measures in real time the compression stress on fiber section would allow deepening LRI analysis.

Research axes are necessary to develop reliable techniques for LRI cycle predictions. This is a process more and more used in aeronautic industry, and so, many companies will be interested by the prediction of part made by LRI process in few years.

Conclusion

This six months study dealt with the experimental and the numerical modelling of LRI process, a liquid composite molding technique. The simulation work allows evaluating performance of PAM-RTM® software used to optimize RTM and LRI composite manufacturing. Different modelling have been realized, for monolithic and sandwich composites. The results of these models are the prediction of filling time and resin speed evolution, with an acceptable accuracy. The experimental campaign is the second research way to understand the LRI process. This one, by a test bench developed for this study, allows making a correlation with the numerical results, to validate PAM-RTM® models. The correlation was good for monolithic infusion, but the sandwich simulations gave errors at the end of process. The delay problem was not ideally modeled. The last part of this paper gives several ways to be developed for the numerical and experimental work, with the aim to be more efficient in the LRI process understanding and prediction.

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