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Characterization and modeling of composite Vacuum Infusion process: influence of fabric type, resin viscosity and strain rate

Claire-Isabelle Zénone¹, Philippe Le Grogne² and Chung Hae Park^{1*}

¹ IMT Lille Douai, Department of Polymers and Composites Technology and Mechanical Engineering, 941 rue Charles Bourseul, CS 10838, F-59508 Douai Cedex, France

² ENSTA Bretagne, Institut de Recherche Dupuy de Lôme, UMR CNRS 6027, 2 rue François Verny, F-29806 Brest Cedex 9, France

*chung-hae.park@imt-lille-douai.fr

Abstract. In Vacuum Infusion (VI) process, used to manufacture large composite structures, the fibrous preform undergoes large deformations during the impregnation due to the use of a flexible vacuum bag. Moreover, the resin pressure difference between the upstream and downstream sides of the preform leads to a non-uniform preform thickness during the mold filling process, which may degrade the part quality. Thus, the prediction of resin flow and preform thickness variations is a very important issue. However, fluid-structure interaction modeling is a difficult task, mainly due to the complex mechanical behavior of the preform. Indeed, the through-thickness deformation of fabrics depends on many factors such as loading type, fabric saturation and fabric type, and also on strain rate effects, as already observed in the literature. In this study, one focuses on the preform deformation during decompaction. Experimental measurements were performed using a universal testing machine with different strain rates, for two different types of fiberglass fabrics, i.e. a random mat and a twill weave fabric, in a dry or wet state saturated by liquids with different viscosities. From these fabric characterization tests, a constitutive model was deduced, which was subsequently implemented in a numerical software to simulate preform decompaction during VI process. Some VI process experiments were also conducted in order to measure the liquid pressure gradient and the preform thickness profile during the mold filling stage and validate the numerical results. It was found from fabric characterization tests that strain rate and viscosity have no significant impact on the preform response in decompaction, in the tested ranges of strain rate and viscosity, for both the random mat and twill weave fabric. However, the analysis of VI process experimental results highlights that, in the case of the twill weave fabric, a time lag appeared between the resin pressure rise and the preform thickness increase, which suggests that a viscoelastic behavior was nevertheless present; whereas in the case of the random mat, it seems thus sufficient to model the preform deformation occurring during the impregnation of VI process with a simple time-independent constitutive law.

1. Introduction

Composite manufacturing processes by Liquid Composite Molding (LCM) are closed-mold techniques where a liquid resin is impregnated into a dry fibrous reinforcement pre-placed in a mold. LCM processes offer some technical advantages such as applicability to complex part geometries, high

structural performance and low manufacturing cost. In addition, health risks to operators due to styrene vapors are eliminated contrary to open-mold techniques. Vacuum Infusion (VI) process, also known as Vacuum Assisted Resin Infusion (VARI) or Resin Infusion under Flexible Tooling (RIFT), is one of LCM processes particularly suitable for the production of large composite structures. Tooling cost is reduced by the use of a single side mold on which the preform is laid up. A thin plastic film, referred to as vacuum bag, replaces the upper rigid half mold [1].

Due to the flexibility of the vacuum bag, the fibrous preform undergoes large deformations during the process. Firstly, while air is extracted from the closed cavity by a vacuum pump before the resin infusion, the preform is compacted by the atmospheric pressure applied on the flexible vacuum bag; then, once the resin valve is opened, the liquid resin impregnates the compacted dry reinforcement and inlet resin pressure leads to a local decompaction state of the preform during the mold filling process. Compaction pressure on the fibrous reinforcement gradually reduces due to fluid pressure which increases as the resin flows, inducing variations in fiber volume fraction and therefore in permeability [2]. The differential pressure between the upstream and downstream sides of the preform may degrade the final part quality as it gives rise to non-uniform final thickness and fiber volume fraction distribution [3]; whereas permeability changes make it difficult to predict process cycle times [4]. Thus, this strong coupling between the resin flow and the fabric deformation has to be properly considered in the numerical simulation of the process to improve final part quality and optimize process cycle time. It is however a difficult task mainly due to the complex mechanical behavior of the preform. Indeed, the through-thickness deformation of fabrics is affected by many factors such as fiber architecture, loading type and saturation state. Furthermore, available results in the literature do not present a consistent agreement on the presence of significant viscoelastic effects during the mechanical response of preforms submitted to compaction pressure. Modeling of the mold filling stage of VI process is therefore challenging, due to the complex characterization of the mechanical behavior of preform throughout the impregnation. As a matter of fact, the preform is decompacted during the impregnation by the resin, i.e. in wet conditions; whereas it is initially dry when compacted at the pre-filling stage of VI process.

This study focuses on the factors which may influence the through-thickness behavior of the fabric during the VI process filling stage. Different effects on the mechanical response of the preform were examined, in particular during decompaction, such as the influence of strain rate, viscosity of the liquid resin and fabric architecture. The objective is to dispose of a more reliable characterization of fabrics behavior using a universal testing machine. The testing conditions may be chosen so as to reproduce at best the real conditions occurring during an impregnation experiment. The final purpose is to improve the modeling of VI process through the implementation of the most appropriate constitutive law for the mechanical behavior of the fabric into the numerical model.

To this end, experimental measurements of preform compaction and decompaction were carried out on a universal testing machine, with different strain rates relevant to the impregnation experiments of VI process, for two different types of fiberglass fabrics, i.e. a random mat and a twill weave fabric, in a dry or wet state saturated by liquids with different viscosities. Some VI process experiments were performed in parallel in order to obtain the liquid pressure gradient within the fabric and the preform thickness profile during the mold filling stage. Fabric characterization experiments were performed in the same conditions as VI experiments, i.e. with the same fabric types, numbers of plies, compaction pressure and impregnating liquid. The liquid pressure gradient and the preform thickness profile were measured respectively by pressure transducers and by vertical displacement sensors, integrated into the mold set-up. Finally, these two data were compared to numerical results obtained with the previously characterized constitutive law.

2. Literature review

The mechanical behavior of fabrics has already been studied by many researchers with the objective to better understand the physics of VI process and to improve its modeling. Several authors performed

compaction experiments on fabrics so as to highlight the relevant factors which may influence their mechanical response. These main factors are listed below.

2.1. Fabric architecture

Many parameters affect the reinforcement behavior such as the fabric architecture, as seen in Chen et al. [5]. These authors conducted compaction experiments on three types of dry fiberglass preforms with different architectures, i.e. continuous strand mats, plain woven materials and unidirectional knitted fabrics. They pointed out the major factors contributing to the compaction behavior according to the reinforcement architecture, such as nesting, which was particularly dominant for woven fabrics but negligible for continuous strand mats.

2.2. Influence of loading type and saturation

The mechanical behavior of the preform is also dependent on the loading type. Correia et al. [6] identified different behaviors between compaction and decompaction of fiber reinforcements. Furthermore, they highlighted differences in fabric properties, according to whether experiments were carried out in dry or wet conditions. As an example, fiber friction coefficient is reduced by the lubrication effect in wet conditions, leading to a higher preform compaction degree at the same applied pressure as in dry conditions. Yenilmez and Sozer [7] reproduced and distinguished, in the same characterization experiment using a special set-up, fabric dry loading and fabric unloading once impregnated, to investigate fabric behavior during both the pre-filling and filling stages of VI process. Saunders et al. [8] analyzed the effect of saturation on the preform behavior, by testing three different resin viscosities on several woven fabrics. No significant differences were detected between the compaction data associated with the different resins, which indicated that the resin viscosity had probably no effect on the mechanical behavior of the preform in compaction. As experiments were not conducted for unloading cases, the conclusion cannot apply to the reinforcement mechanical behavior in decompaction.

2.3. Viscoelastic effects

In the literature, most of researchers assumed a time-independent relationship between compaction pressure and local fiber volume fraction, considering an instantaneous response of the preform when the applied pressure varies. Some authors, though, proposed a time-dependent model displaying a viscoelastic constitutive behavior for the preform. Saunders et al. [9] suggested that a time-independent relationship was only appropriate to describe the constitutive response of dry compaction (which does not exhibit dependence on the strain rate), and that it was not suitable in the case of wet hysteresis experiments which revealed viscoelasticity effects. The same authors [8-9] highlighted the influence of strain rate, which was proved to affect the wet plain weave compaction behavior. As the strain rate increased, a greater compaction pressure was needed to reach the same fiber volume fraction, suggesting that a part of the applied pressure was used to remove the resin. They interpreted that viscoelastic characteristics of wet compaction were mainly due to the resin flow and they developed a viscoelastic model which considered elastic and viscoelastic effects from the fiber preform, and also viscous effects from resin. Bickerton et al. [10] also investigated the apparent viscoelasticity of three dry common LCM reinforcements submitted to strain-rate dependent and hysteresis experiments. They observed that the stress could be generally expressed as a function of strain, strain rate and time, as formulated in Yenilmez et al. [11], where the authors described the behavior of a woven fabric during all stages of VI process by testing several viscoelastic models.

3. Materials and experimental procedures

Two sets of experiments were carried out: fabric decompaction characterization experiments and fabric impregnation experiments by VI process. The decompaction constitutive law of the impregnated preform derived from the characterization experiments will serve as an input in the subsequent numerical model.

3.1. Materials

3.1.1. *Fabrics.* Two types of fiberglass fabrics with different architectures were tested: a random mat and a twill weave fabric, whose main characteristics are presented in Table 1. The same number of plies was retained for both experiments, whatever the fabric considered. Each fabric was selected in such a way that both preforms display the same thickness when compacted with the same pressure of 0.09 MPa. Therefore, their behavior in decompaction should be compared easily.

Table 1. Fabric properties.

	Random mat	Twill weave
Fabric reference	Unifilo® 450	1500 S3
Supplier	Vetrotex	Chomarat
Fabric pattern	Random	3/3 oblique pattern
Fiber type	E-glass	E-glass
Areal weight (g.m⁻²)	450	1500
Average ply thickness (mm)	2.40 ± 0.08	1.80 ± 0.07
Width and length plies for compaction test (mm x mm)	80 x 80	80 x 80
Width and length plies for infusion test (mm x mm)	150 x 300	150 x 300
Number of plies for both experiments	4	3
Average thickness of dry preform compacted at 0.09 MPa (mm)	2.81 ± 0.01	2.80 ± 0.08
Average fiber volume fraction of dry preform compacted at 0.09 MPa	0.24 ± 0.01	0.62 ± 0.02

3.1.2. *Liquids used to impregnation of fabrics.* Instead of synthetic resins classically used for VI process, two different mineral oils were chosen here so as to better evaluate the influence of viscosity on fiber lubrication and avoid resin polymerization during characterization and impregnation experiments: a low viscosity oil and a medium viscosity oil, whose viscosities are respectively in the range of 0.060-0.070 Pa.s and 0.250-0.350 Pa.s at room temperature (~ 20°C).

3.2. Fabric deformation characterization experiments

Fabric deformation characterization tests were performed on a universal testing machine (Zwick 1474). The experimental set-up in dry conditions consisted in two compression platens between which the dry preform was laid. In the case of wet experiments, the set-up was completed with a perforated compression platen, on which the preform was laid, allowing for the outflow of excess oil which was collected into a receptacle placed below. Two plastic films were put above and below the preform in order to ensure oil flow only from the side (Figure 1). The tested preforms were initially impregnated ply by ply using a syringe. In all compaction test cases listed in Table 2, the same loading pattern was used, namely a compressive loading at the chosen strain rate until the compaction state under 0.09 MPa, then a waiting period of 10 min in the compacted state and finally an unloading step until the fully decompacted state at the same strain rate as before. Each characterization experiment was performed three times so as to check repeatability.

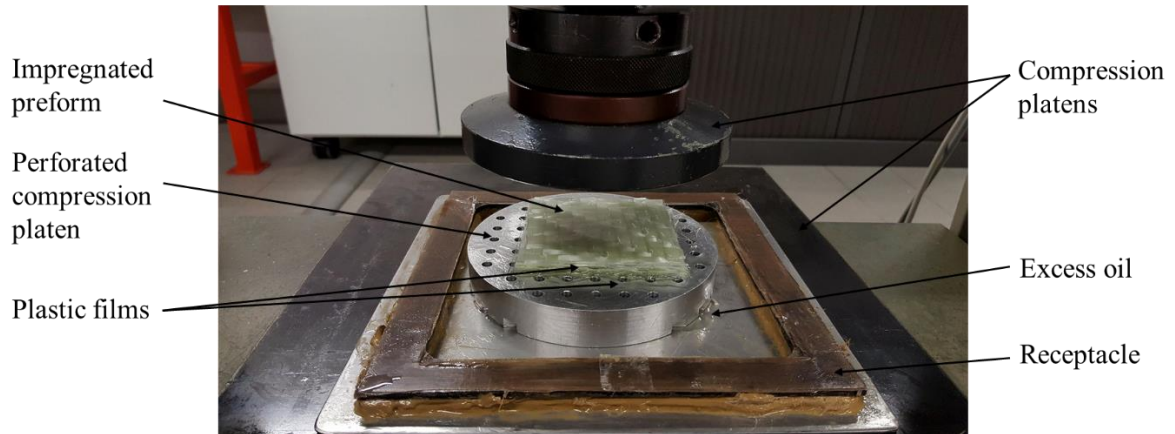


Figure 1. Set-up for characterization experiments on fabrics in wet conditions.

Table 2. Compaction experiment conditions.

	Fabric type	Saturation state	Viscosity (Pa.s)	Strain rate (mm.min ⁻¹)
Compaction 1	Random mat	Dry	-	0.2
Compaction 2	Random mat	Dry	-	1.0
Compaction 3	Random mat	Wet	0.300	0.2
Compaction 4	Random mat	Wet	0.300	1.0
Compaction 5	Random mat	Wet	0.070	0.2
Compaction 6	Random mat	Wet	0.070	1
Compaction 7	Twill weave	Dry	-	0.2
Compaction 8	Twill weave	Dry	-	1
Compaction 9	Twill weave	Wet	0.300	0.2
Compaction 10	Twill weave	Wet	0.300	1
Compaction 11	Twill weave	Wet	0.070	0.2
Compaction 12	Twill weave	Wet	0.070	1

3.3. VI process experiments

The experimental set-up for the infusion tests is shown in Figure 2. The test bench consisted in a special set-up, whose bottom was a PMMA platen with five aligned holes to insert pressure transducers and two other holes for an oil inlet and an air outlet. The preform, composed of several plies (Table 1), was laid on the bottom platen. A thick distribution medium was placed between the oil inlet and preform, and also between the air outlet and the preform, in order to ensure a straight oil flow front and avoid pressure losses. The oil inlet was connected by pipes to the oil pot and the air outlet to a vacuum pump. Valves on the inlet and outlet pipes allowed to control the start time of the preform compaction and oil impregnation. A vacuum bag was laid on the preform and the mold was closed by a sealing tape positioned between the bottom platen and the vacuum bag. One pressure transducer (sensor 0) measured the oil pressure just before the tip of the preform and the other ones were placed respectively at 20 mm (sensor 1), 60 mm (sensor 2), 95 mm (sensor 3) and 135 mm (sensor 4) from the tip of the preform. Four vertical displacement sensors, supported by a metallic structure, were put in contact with the top surface of the mold, i.e. the vacuum bag, and were positioned at the same planar locations as the pressure transducers. Three VI experiments were carried out, whose characteristics (oil viscosity and filling time) are listed in Table 3. Both types of fabric were tested

with the two different oils, but only the data listed in Table 3 were recorded, because the impregnation of random mat was too fast to obtain meaningful measurement data with the low viscosity oil. Thus, the twill weave fabric has been tested using both low and medium viscosity oils, whereas the random mat was tested only with the medium viscosity oil. For all experiments, vacuum pressure was -0.09 MPa, which was equivalent to a compaction pressure of 0.09 MPa on the top surface of the preform. Vacuum was applied during 10 min so as to obtain a stable and homogenous compaction of the preform.

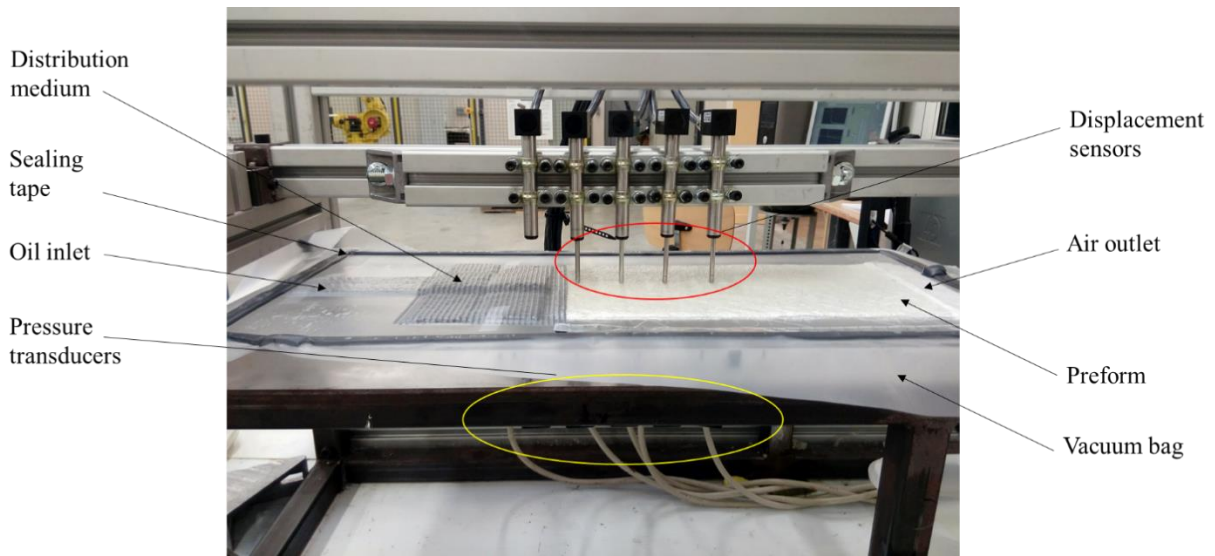


Figure 2. Test bench of vacuum infusion experiments.

Table 3. Vacuum infusion experiment conditions.

	Fabric type	Oil viscosity (Pa.s)	Filling time (s)
Infusion 1	Random mat	0.264	63
Infusion 2	Twill weave	0.249	853
Infusion 3	Twill weave	0.070	229

4. Results and discussion

Owing to the non-uniformity in fiber structure of fabrics, each set of characterization experiment was conducted at least three times. In each case, the average value of $h/h_{\text{compacted}}$ is depicted vs. the compaction pressure, where h is the current thickness measured instantaneously in response to the compaction pressure and $h_{\text{compacted}}$ is the thickness of the specimen measured just before decompaction. Only the decompaction stage of fabrics will be studied in the sequel.

Experimental results for random mat characterization are shown in **Erreur ! Source du renvoi introuvable.**, for all values of saturation and strain rate. All the curves present a very similar tendency. At strain rates of $1 \text{ mm}\cdot\text{min}^{-1}$ and $0.2 \text{ mm}\cdot\text{min}^{-1}$, the random mat shows the same decompaction behavior, regardless of saturation, which means that viscosity, in the considered range, has no significant impact on the decompaction behavior.

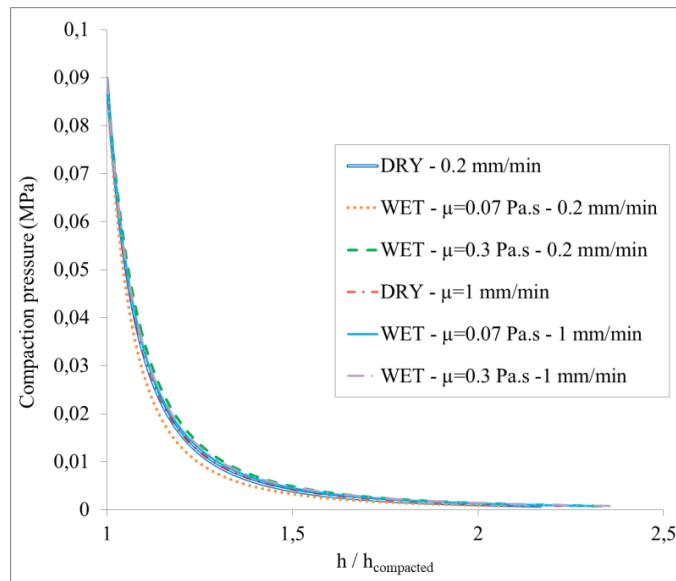


Figure 3. Decompression test results for random mat with strain rates of $0.2 \text{ mm}\cdot\text{min}^{-1}$ and $1 \text{ mm}\cdot\text{min}^{-1}$ for all the saturation cases.

The same conclusion can be drawn for experimental results concerning twill weave fabric characterization presented in **Erreur ! Source du renvoi introuvable.**. No significant effect of strain rate or viscosity appears to affect the mechanical behavior during the decompression of the twill weave fabric in the chosen ranges.

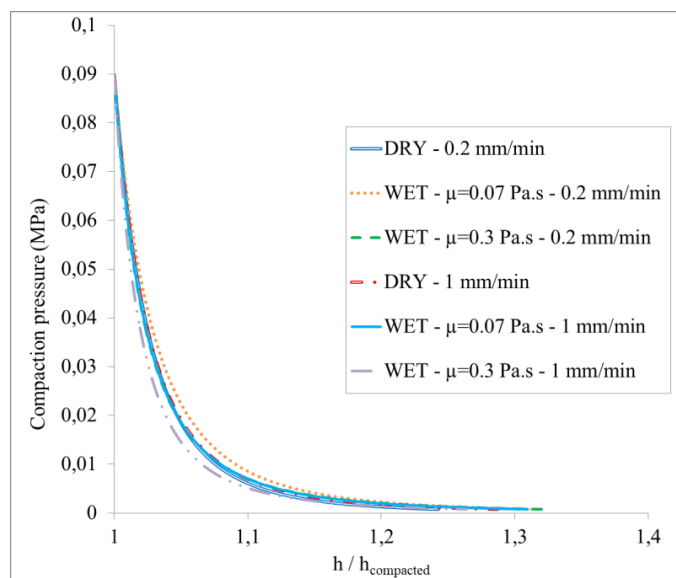


Figure 4. Decompression test results for twill weave fabric with strain rates of $0.2 \text{ mm}\cdot\text{min}^{-1}$ and $1 \text{ mm}\cdot\text{min}^{-1}$ for all the saturation cases.

Comparison between **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.** reveals however that the two fabrics (with different architectures) exhibit a different behavior in decompression even if both fiberglass fabrics were unusually compacted to the same

thickness (see Table 1). The final thickness of the specimens were 6.45 mm for random mat and 3.65 mm for twill weave fabric at the end of the tests, which shows that fabric type architecture strongly influences the mechanical response in decompaction.

The characterization of both fabrics is not affected by any change in strain rate and saturation, at least in the considered ranges of infusion experimental conditions. Then, the average mechanical behavior of random mat and twill weave fabric in decompaction can be compared with the results of infusion experiments, namely the thickness and pressure values measured during infusion experiments by sensor 1 (Figure 5 and Figure 6).

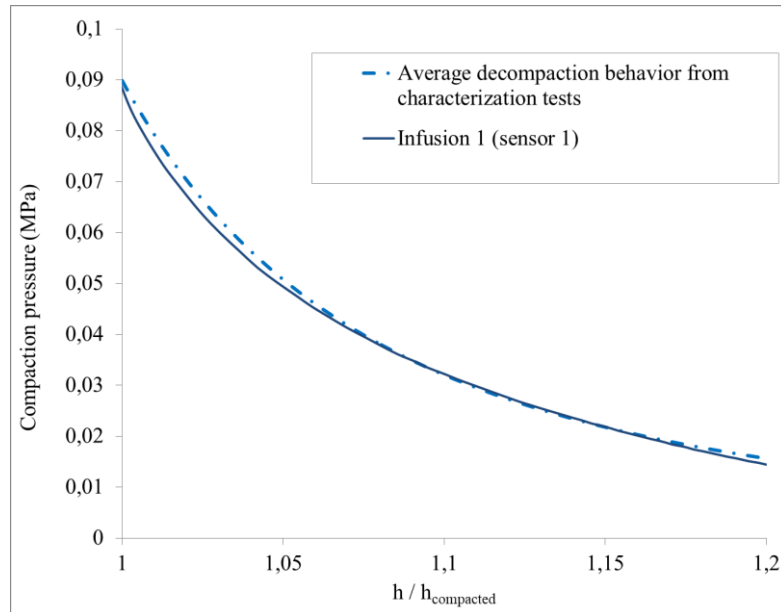


Figure 5. Comparison between the average mechanical behavior of random mat specimens obtained by characterization experiments and the mechanical behavior of random mat measured during impregnation tests.

For random mat, infusion experimental conditions correspond to the ranges of viscosities and strain rates employed during its characterization, i.e. the preform was impregnated with a medium viscosity oil ($\mu=0.264$ Pa.s) and the average strain rate was $0.6 \text{ mm}\cdot\text{min}^{-1}$ at sensor 1. The behavior of the preform measured at sensor 1 did not reach the fully decompacted state, due to the rapidity of oil impregnation into the random mat preform (the filling stage is only 63 s). However, the resin pressure reached the value of 0.07 MPa, equivalent to the compaction pressure of 0.2 MPa. Characterization results depicted in Figure 5 are consequently focused until this compaction pressure. These results reveal a good agreement with the decompaction behavior observed during infusion tests. Thus, a time-independent constitutive law seems to be appropriate for random mat and may be characterized by simple decompaction tests in the average conditions of viscosity and strain rate observed during the mold filling stage of VI process.

On the contrary, comparison between characterization tests and infusion experiments on twill weave fabric (Figure 6) shows strong discrepancies between both infusion tests (Infusion 2 and Infusion 3) and the average mechanical behavior provided by the compression testing machine. A constitutive law derived from characterization tests does not seem to be representative of the real behavior occurring during the impregnation of the twill weave fabric, even in experimental conditions close to infusion conditions. In addition, a higher viscosity appears to affect even more the mechanical behavior during infusion. As it has been shown (see **Erreur ! Source du renvoi introuvable.**) that

neither the viscosity nor the strain rate in the considered ranges have any effect on the mechanical behavior, the differences in fabric behavior are probably induced by another phenomenon. For example, the long filling time, which could result in some relaxation during the filling stage, may be responsible for this disagreement. Thus, it is not finally relevant to consider only a time-independent model to represent the mechanical behavior of twill weave fabric during infusion.

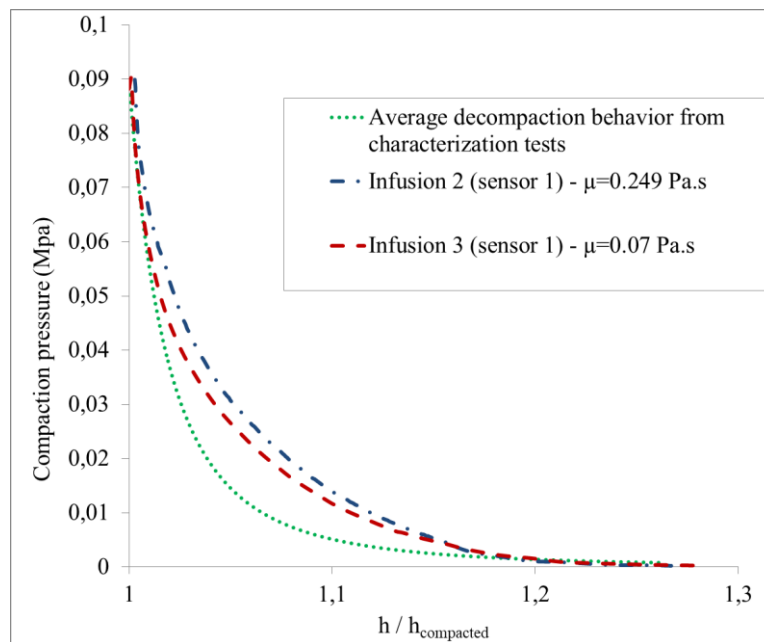


Figure 6. Comparison between the average mechanical behavior of twill weave fabric specimens obtained by characterization experiments and the mechanical behavior of twill weave fabric measured during impregnation tests.

5. Conclusion

The comparison between two fiberglass fabric types, a random mat and a twill weave fabric, whose thickness is the same in dry conditions and compacted at 0.09 MPa, demonstrated that the mechanical behavior in decompaction is highly influenced by the fabric architecture. Characterization of the decompaction behavior of these two fabrics using a universal testing machine, with two strain rates and two different viscosities, has highlighted that strain rate and viscosity had no particular effect on the response of the preform in decompaction, at least in the tested ranges of strain rate and viscosity. To identify the constitutive law of preforms undergoing transverse deformations in VI process, it seems therefore not necessary to reproduce strictly the same conditions of saturation and strain rate.

However, the comparison between these constitutive behaviors identified through characterization experiments and the fabric response occurring during infusion experiments shows that only the experiments performed on random mat appear to be representative of the real fabric behavior during impregnation, whereas the twill weave infusion experiments reveal some differences in terms of thickness, when compared to characterization experiments, which are not due to lubrication or strain rate effects.

These observations were confirmed by numerical simulations, where the constitutive law of the average fabric behavior was implemented into a numerical model so as to simulate infusion experiments. Oil pressure gradient and preform thickness profile (Δh) were calculated numerically and compared to experimental values. These results are presented with respect to t^* , which is equivalent to

the ratio between current time and final filling time for an accurate comparison of thicknesses and pressures, regardless of time lag. The first case study was the impregnation of random mat (Figure 7), whose experimental filling time was 63 s and numerical filling time was 67 s; whereas the second case study was the impregnation of twill weave fabric (Figure 8), which presented an experimental filling time of 853 s and a numerical one of 766 s.

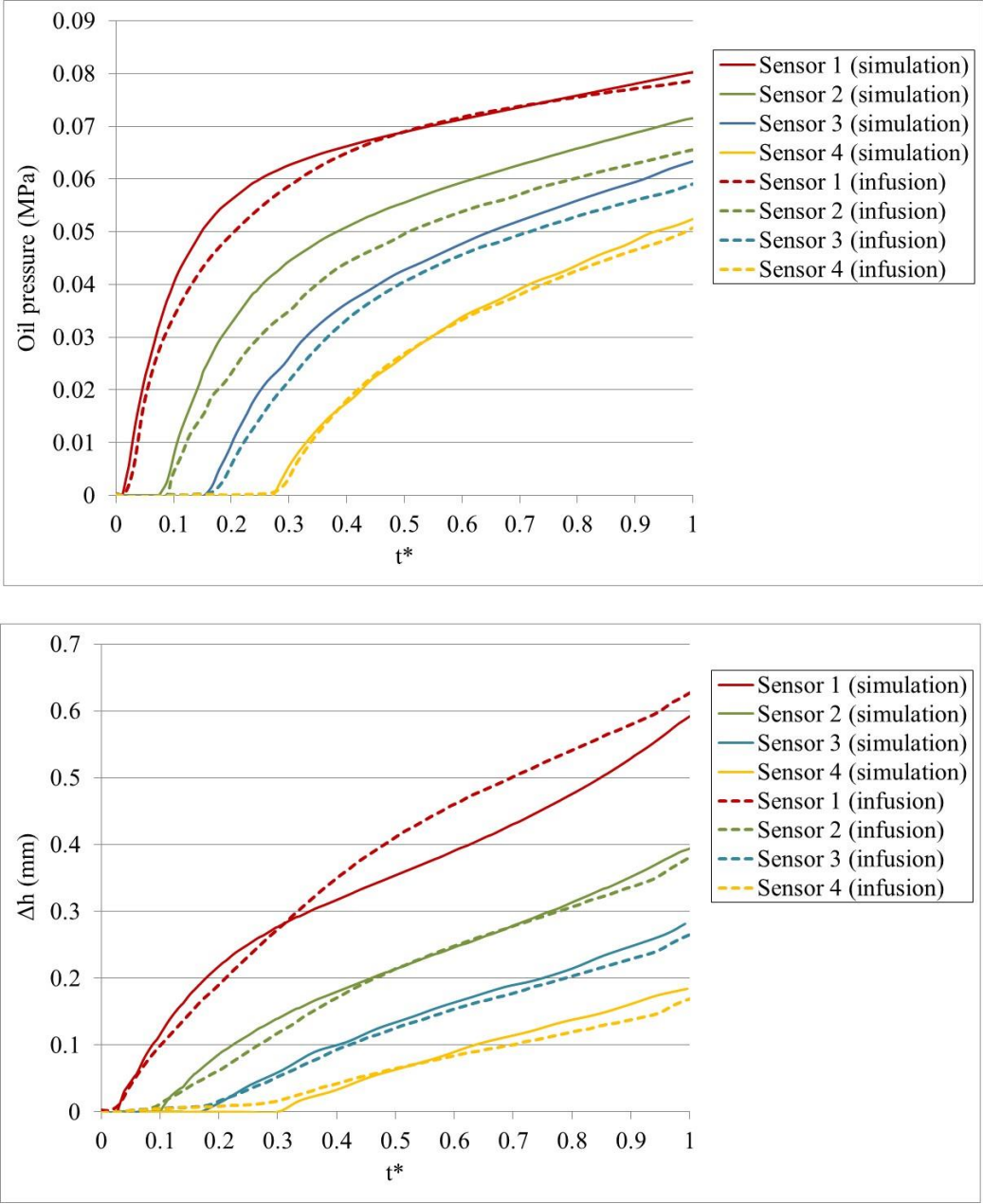


Figure 7. Comparison between experimental and numerical results of thickness and pressure for random mat impregnation ($\mu=0.264$ Pa.s)

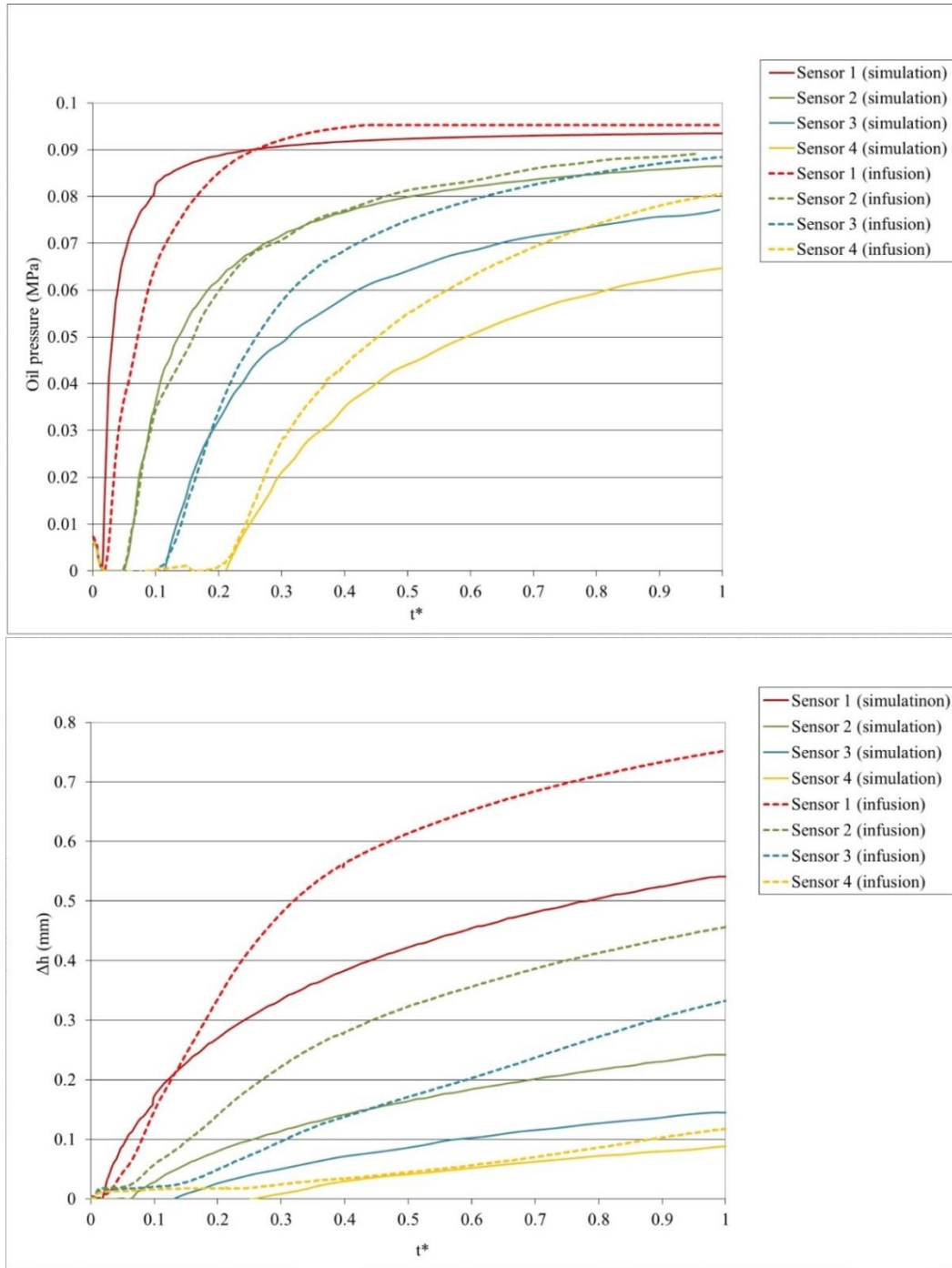


Figure 8. Comparison between experimental and numerical results of thickness and pressure for twill weave fabric impregnation ($\mu=0.249$ Pa.s)

As expected, numerical results obtained for random mat are close to corresponding experimental results, whereas the discrepancies observed for the twill weave fabric confirm that the constitutive law implemented into the numerical model is not sufficient to reproduce the real behavior of such a fabric

during infusion. The calculated pressures of twill weave fabric are slightly lower than the experimental ones in particular for sensors 3 and 4, whereas sensors 1 and 2 lead to a good agreement. However, the analysis of experimental curves of the first two sensors highlights a time lag between the resin pressure rise and the preform thickness increase. It means that viscoelastic effects may occur during impregnation of the twill weave fabric, which are not directly due to viscosity or strain rate effects, as analyzed in **Erreur ! Source du renvoi introuvable.** The long filling time in that case may induce some relaxation during the process, increasing thus the deformation of the preform. Therefore, considering viscoelastic effects in the numerical model could improve the prediction of the mechanical behavior occurring during VI process, in particular for fabrics with low permeability.

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