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CONTINUOUS TRANSVERSE PERMEABILITY OF FIBROUS MEDIA

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SUMMARY: The manufacturing of large composite parts in the field of aeronautics is increasingly important. LCM processes (Liquid Composite Molding) are currently used. Infusion processes such as the Resin Film Infusion (RFI) are more and more used for the manufacturing of large parts. During this process, the resin flows through the fibrous medium under the stress created by a flexible membrane in the transverse direction of the reinforcement's plane. The compaction of the preforms and the flow of resin through the fibrous network take place simultaneously. There is, therefore, a coupled loading of the porous reinforcements. In order to better control this process, it is necessary to optimize resin pressure and fabric compression by using the appropriate simulating tools. It is also necessary to clarify which laws are suitable to model the process. To this objective, a new experimental device is set up to impose combinations of hydraulic and mechanical loadings (Hydro-Mechanical loadings) to fibrous preforms. The device is used to evaluate the transverse permeability in a continuous manner for a flax mat and a glass satin weave. For low compression speed the continuous technique give similar values than the "classical technique". Increasing the compression speed seems to give decreasing continuous transverse permeability values.

KEYWORDS: **i**nfusion, continuous transverse permeability, hydro-mechanical coupling

INTRODUCTION

The need for manufacturing large composite parts in the field of the aeronautic industry is increasingly important. Processes of the Liquid Composite Molding (LCM) class are widely used. These processes such as Resin Transfer Molding (RTM) consist in injecting a liquid thermosetting resin through some layers of dry and shaped preform. However, these processes are not well adapted in the case of large part manufacturing because of large tooling cost. Some void formation may also appear when the resin travels large distances as its viscosity may increase before the part is completely filled as a result of partial curing [1]. The infusion processes such as

RFI [2] consists in transmitting a stress with a vacuum bag on a stack of semi-cured liquid resin film and dry preforms (Fig. 1). The whole set up is generally placed in an autoclave to ensure the correct compression stress and to control the temperature cycle. The resin flows through the preform in the direction of the applied bag's stress. The reinforcement compressibility and the resin flow occur simultaneously and there is thus a mutual influence between the two ‘‘solid and liquid’’ phases. A strong coupling between the reinforcement compaction and the resin flow takes place and needs to be taken into account for the modelling of the process.

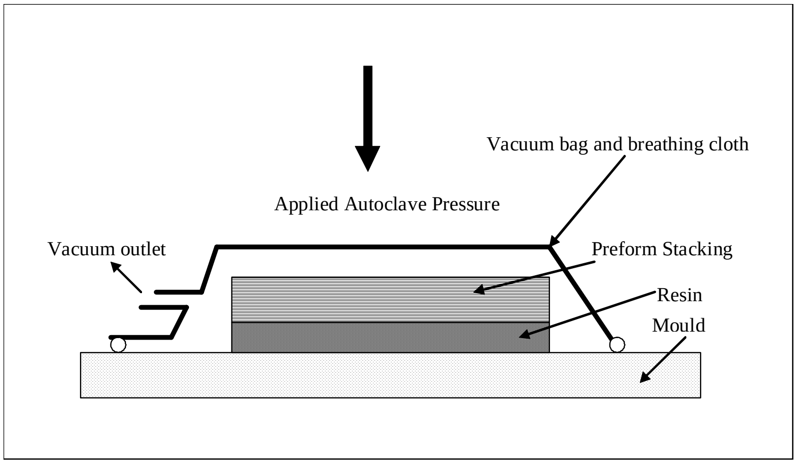

Fig. 1 Schematic of the Resin Film Infusion (RFI) process.

Studies dealing with the modelling of resin infiltration in deformable preforms under different conditions have been published [3-5]. The fabric is supposed to be uniformly deformed in the direction of applied stress. In processes such as RFI, the principal resin flow and fabric deformation occur in the same direction. The resin pressure and the fabric compaction stress are not uniform within the thickness direction. The differential pressure and compaction stresses in the *z* direction are taken into account in the modelling of the RFI process proposed by Ouahbi et al. [6] and Terzaghi's law is used to couple the resin pressure and the mechanical stress imposed to the preform.

The previously mentioned models are based on experimentally determined material properties. The permeability behaviour of the preform and especially the transverse permeability evaluated in the *z* direction is a key parameter for process modelling. The saturated transverse permeability of fibrous composite reinforcements has been evaluated by several authors (see Drapier *et al.* [1], and Merhi *et al.* [7]). This “classical” approach consists of evaluating pressure/flow rate couples after injecting a test fluid through the fibrous preforms. This technique consumes a large amount of time as a set of pressure/flow rate couples has to be determined for every fibre volume fraction of interest. Moreover, pressure stabilisation due to changes of imposed flow rate may also take time particularly for high fibre volume fraction preforms [8]. Scholz *et al.* [9] developed a continuous technique to measure the transverse permeability during compaction to reduce the experimental time. It consists of injecting a Newtonian liquid or a gas through the preform while it is compacted continuously. Results obtained by injecting a liquid or a gas were compared.

During the RFI process, a strong coupling takes place between the compaction of the preform and the flow of resin. During the process, the permeability of the fibrous medium varies simultaneously according to the evolution of preform compaction. As a consequence, the values of the transverse permeability measured using a continuous technique that better reflects the coupling phenomenon between the flow of test fluid and the compaction of the preform may not be similar to the values determined using the “classical” method where fibre rearrangement may take place after each compaction step.

This work suggests investigating the effect of the continuous compaction upon the transverse permeability. Particularly, a comparison between the continuous measurement technique and the technique consisting of obtaining pressure/flow rate couples for a given fibre volume fraction is carried out for two different fibrous reinforcements. An experimental device was set up at Le Havre University to apply hydro-mechanical loads to fibrous media. Different combinations of fluid flow rates and mechanical stresses can be imposed to fibrous preforms.

EXPERIMENTAL PROCEDURE

Experimental Device

A device to establish simultaneous hydraulic and mechanical loads (Hydro-Mechanical coupling loads) to the fibrous preforms was set up at Le Havre University (Fig. 2). This apparatus consists of a stainless steel cylindrical pot within which a guided piston induces the exact amount of fibres compaction in the transverse direction. The device is mounted on a universal testing machine (Instron 8802) to control both the displacement of the piston ($\dot{\varepsilon}$) and the force (σ) applied to the fibrous medium. The fluid is guided in the transverse direction by perforated bronze grids. A pressure transducer is placed below the lower grid. Test samples of fibrous preforms are placed between the two grids. A 6 litre syringe is placed on an Instron 5867 universal testing machine in order to apply a controlled flow rate of silicon oil to the fibrous reinforcement. The magnitude of the flow rate is controlled by the Instron 5867 crosshead speed. When a Newtonian test fluid such as silicon oil is injected at a constant flow rate through the fibrous reinforcement, a pressure rise at the reinforcement entry is measured by the pressure sensor. The transverse permeability K_z is calculated using Darcy’s law [10]. Since the piston compresses the fibrous medium at a constant speed, K_z is measured in a continuous manner as a function of the increasing fibre volume fraction. The tested silicon oil has a viscosity of 0.1 Pa.s. The flax mats and the glass satin weaves are cut into 100 mm diameter discs by a specially made cutter. Stacks of twenty layers of flax or glass mats are compressed at 1 mm/min and submitted to a flow rate of 0.67 cm^3/s.

Experimental Set-up

A preliminary study to quantify the pressure rise due to the fluid flow going through the bronze grid was carried out for different flow rates. The rise of pressure due to the grid for each flow rate is then deducted when Hydro-Mechanical loads are imposed to fibrous preforms. Another study was also carried out to determine if race tracking was taking place along the walls of the cylinder despite the fact that a silicon joint is used to avoid this phenomenon. To reach this objective, different flow rates were imposed to fibrous preforms of constant fibre volume fraction and the corresponding rises of pressure were recorded. Fig. 3 shows a clear linear trend. If race tracking takes place along the cylinder walls, the rise in pressure would not be proportional anymore to the imposed flow rate. In this case, the pressure rise would be “slower” than the rise of flow rate.

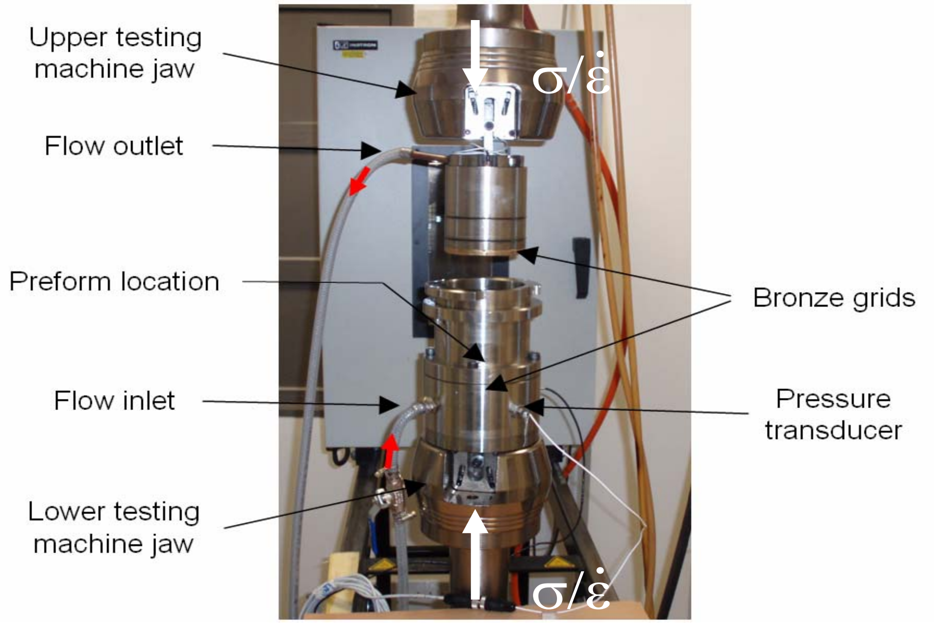

Fig. 2 Photograph of the continuous permeability device.

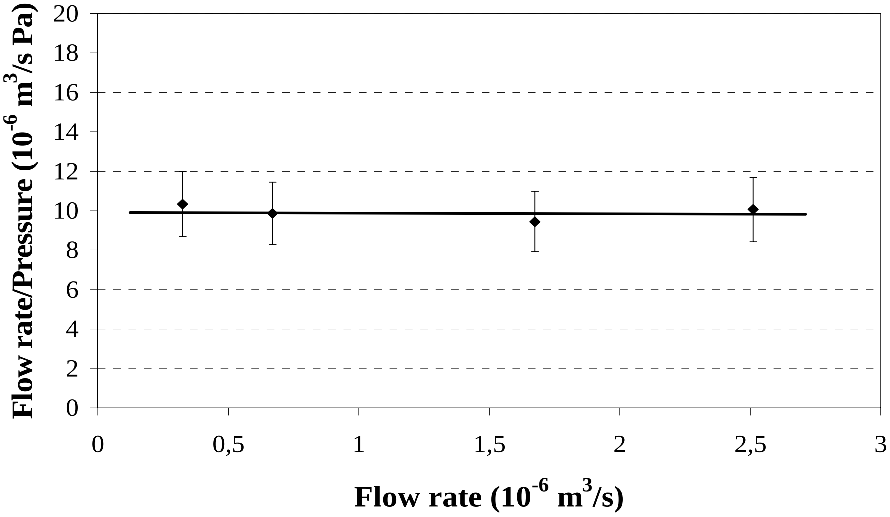

Fig. 3 Linearity of the pressure-flow rate relationship.

Material and Experimental Conditions

The materials used during this study are the following:

- An E glass 5 harness satin weave. This material has an areal weight of 620 g/m^2 and an initial fibre volume fraction of ~ 48 %. The thickness of an individual layer of fabric is ~ 0.5 mm.
- A flax mat of superficial density 116 g/m^2.

The fluid used in the experimental procedure is a silicon oil of viscosity 0.1 Pa.s. The size of the preforms is adjusted to the size of the cylindrical pot and a silicon joint is used to avoid preferential oil propagation on the edge of the samples. The different layers of fabric are superimposed and the yarns of each layers are disposed parallel to the corresponding yarns of the neighbouring fabric layer. Twenty layers of fabric are disposed for each test. The imposed compaction velocity is 0.5 mm/min. The influence of compaction speed was also considered and the compaction velocity ranged from 0. 5 to 5 mm/min. A constant flow rate (6.7 10^{-7} m^3/s) is forced through the preform by keeping the syringe speed constant.

RESULTS

Fig. 4 shows that the pressure measured at the flax preform entry raises as a function of the fibre volume fraction. As the flow rate is constant, the transverse permeability is deduced from the pressure data (Fig. 4) and Darcy's law. Fig. 5 shows the evolution of the transverse permeability of flax mat as a function of the fibre volume fraction. The increase of pressure and decrease of permeability is related to the reduction of the pores volume between the bundles and between the fibres.

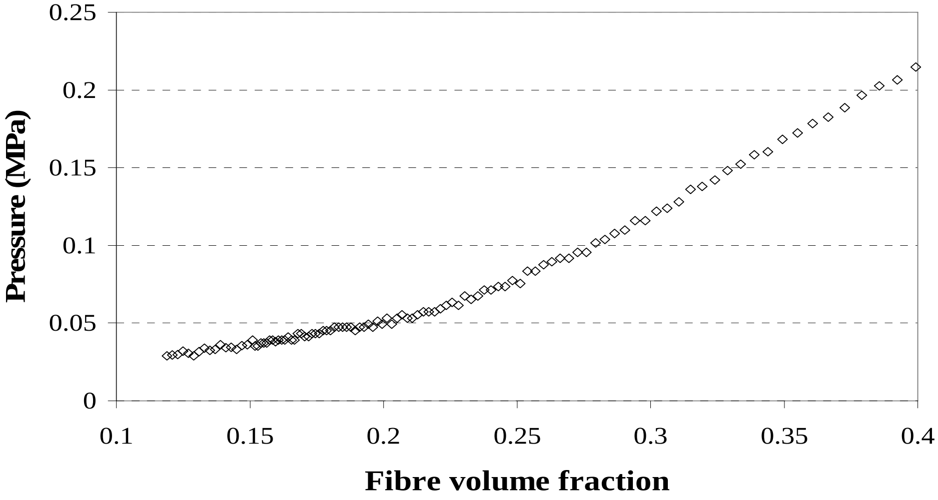

Fig. 4 Pressure evolution during compression of flax mat preform submitted to a constant flow rate.

Fig. 5 shows a comparison between the transverse permeability of flax mats determined by the classical method and the continuous technique. For both curves, a fast decrease in permeability is observed at low fibre volume fraction. For higher fibre volume fraction, the decrease in permeability slows down progressively. Fig. 5 also indicates that the transverse permeability results determined using the "classical" method and the continuous technique give data points situated in the same range of values.

Fig. 6 shows a comparison of the transverse permeability of a glass satin weave determined by the classical method and the continuous technique. The classical transverse permeability values are slightly higher than the values observed for the continuous transverse permeability determined using a compression speed of 0.5mm/min. However, the difference between the two curves is low and can be considered to be within the range of error of the classical technique. In this figure, the evolution of the continuous transverse permeability is plotted for 3 different compression speeds and the same constant imposed flow rate. The curves of Fig. 6 show that the continuous transverse permeability decreases for rising compression speeds during the test.

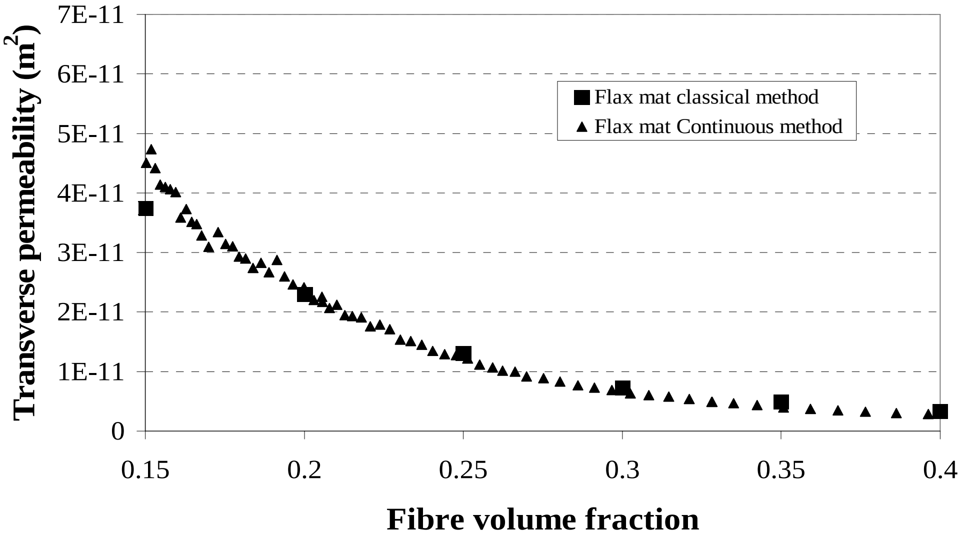

Fig. 5 Continuous and “classical” transverse permeability of flax mat.

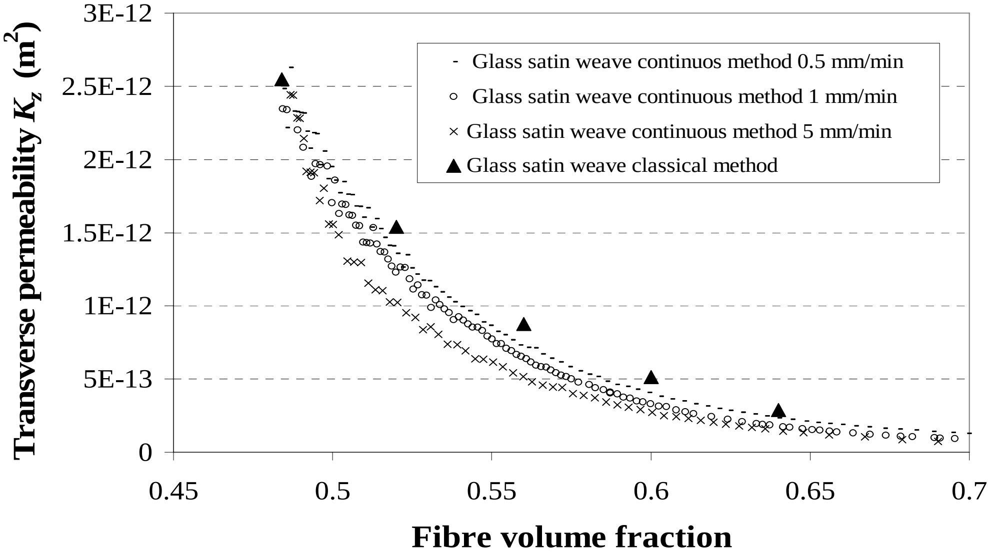

Fig. 6 Continuous and “classical” transverse permeability of flax mat.

CONCLUSIONS

A new experimental device was developed at Le Havre University to impose combinations of hydraulic and mechanical loads in order to investigate the transverse permeability determined by a continuous technique of a flax mat and glass satin weave. The continuous transverse permeability results determined at a low compression speed are situated in the same range of values than the results determined by the classical technique for both materials. Different compression speeds are used to evaluate the continuous transverse permeability of the glass satin weave. When the compression speed increases, the values of continuous transverse permeability decrease.

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