The 8th International Conference on Flow Processes in Composite Materials (FPCM8)
Douai, FRANCE - 11 – 13 July 2006

MECHANICAL PROPERTIES AND PERMEABILITY MEASUREMENTS OF FIBRE REINFORCEMENTS: A CONTINUOUS METHOD

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ABSTRACT: Composites manufacturing using LCM (Liquid Composite Molding) involves resin flow and sometimes further compression or unloading of the fiber reinforcements. Therefore a proper modeling of such processes requires a model for fiber reinforcement in compression. Several mechanical models are available, but none of them includes permanent deformation. Moreover saturated permeabilities of fiber reinforcements are essential parameters for LCM simulations. A common way of measuring such permeabilities relies on liquid injection techniques that induce uncertainties and a wide scattering of the results. This paper proposes an experimental methodology to measure permanent deformations involved with unidirectional compression of fiber reinforcements. Compression tests are further exploited to propose a reliable and generic measurement method that provides the in-plane and through-thickness permeabilities. Characterization results are given for a glass twill-weave fabric and a non-crimp fabric.

KEYWORDS: compression, fiber reinforcements, permanent deformation, permeability

INTRODUCTION

Structural composite materials are increasingly produced using one of the Liquid Composite Molding (LCM) processing techniques. The common feature of such processes is that a liquid resin is forced through fiber reinforcements. During infusion processes, the fiber reinforcement may unload and eventually, when the injection is completed, it may not fully recover [1]. A proper modeling of LCM processes, especially estimating the final thicknesses of the manufactured parts requires to have models for compression of fiber reinforcements that include permanent deformation. Numerous previous studies focused on fiber reinforcement compression modeling [2,3], but none of them seemed to include permanent deformations. Modeling LCM manufacturing processes also requires to input accurate fiber reinforcement permeabilities. Most techniques rely on fluid injection experiments that require an injection equipment, a mold and any device able to sense the flow. Other limitations are common errors associated with the measurement such as the deflection of the mold or edge effects [4]. Another in-plane permeability measurement method is based on the compression of saturated fiber reinforcements [5,6]. It limits the equipment required to a material testing machine to continuously measure in-plane permeability with respect to fiber volume fraction.

This article deals with an experimental methodology to measure permanent deformations during unidirectional compression of dry and impregnated fiber reinforcements. That compression setup is further exploited in this paper to propose a reliable and generic measurement method that provides the in-plane and through-thickness permeabilities for a wide range of fiber volume fractions and materials. Characterization results are given for a glass twill-weave fabric and a carbon non-crimp fabric (NCF).

EXPERIMENTAL SETUP

Unidirectional compression tests on fiber reinforcement samples are carried out on a material testing machine with force cells of 10 kN and 100kN. For the compression of dry fabrics, the sample is simply inserted between two platens (Fig. 1). Force and crosshead position (sample height) are recorded during the compression test.

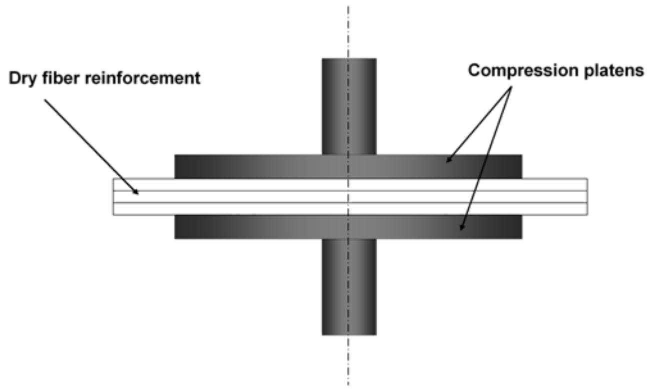

Fig. 1 Experimental setup for dry fiber reinforcement compression tests.

In the case of the compression of impregnated fabrics, the setup is modified as shown in Fig. 2. The fabric, impregnated with silicone oil, is inserted between the platens. The combination of a low viscosity fluid, a low crosshead speed and a perforated compression platen allows to limit pressures due to the expelled fluid flow and therefore to measure the mechanical response of the impregnated fabric in drained conditions.

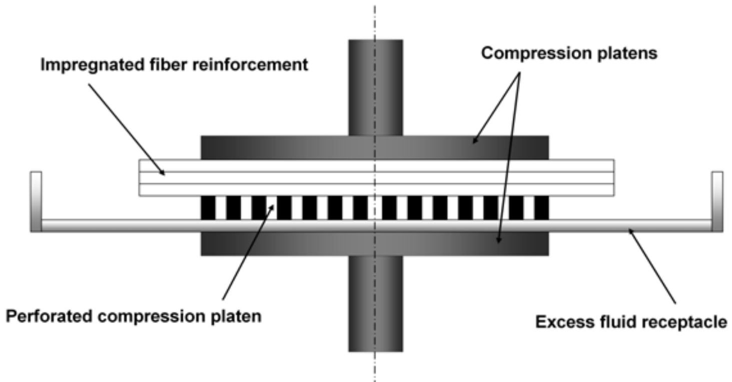

Fig. 2 Experimental setup for impregnated fiber reinforcement compression tests under drained conditions.

To measure permanent deformations (plasticity), the sample is loaded up to a maximum strain $\varepsilon^{\max}$, and subsequently unloaded to provide the amount of permanent deformation retained in the sample ε^{p} (Fig. 3). Each cycle gives a point of the plastic strain vs. total strain curve. Engineering strain is calculated as $\varepsilon = (h_o - h)/h_o$ and stress as $\sigma = F/A$ where h is the height of the sample, h_o the initial height of the sample, F the force applied to the sample and A the area of the sample in contact with the compression platens.

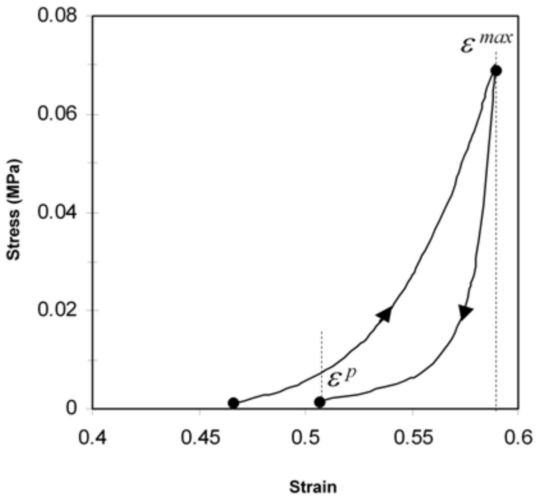

Fig 3 Example of loading-unloading compression test response that allows to extract plasticity.

Material	Glass twill-weave fabric	Carbon NCF
Areal weight	1500 g/m^2	230 g/m^2
Number of plies	4	10
Stacking sequence	[0°,90°,90°,0°]	[+45°,0°,0°,-45°,90°,90°, -45°,0°,0°,+45°]
Initial sample height	6.8 mm	4.5 mm
Crosshead speed	0.5 mm/min	0.5 mm/min
Silicone oil viscosity (21°C)	0.1 Pa.s	0.1 Pa.s

Table 1 Experimental conditions and material properties.

PERMANENT DEFORMATIONS

For the glass twill-weave fabric considered in this study (Tab. 1), the plastic strain develops linearly and represents 60% of the total strain (Fig. 4). Plasticity is influenced by the impregnation: lubrication facilitates yarn and fiber imbrications. However, for the carbon NCF (Fig. 5), the presence of fluid does seem to influence permanent deformations developing in the fabric. That difference of behavior may be due to the difference of textile architecture between the two materials. For twill-weave fabric permanent deformations are governed by nesting (yarn/yarn interactions) and fiber/fiber interactions whereas for NCF only fiber/fiber interactions are present.

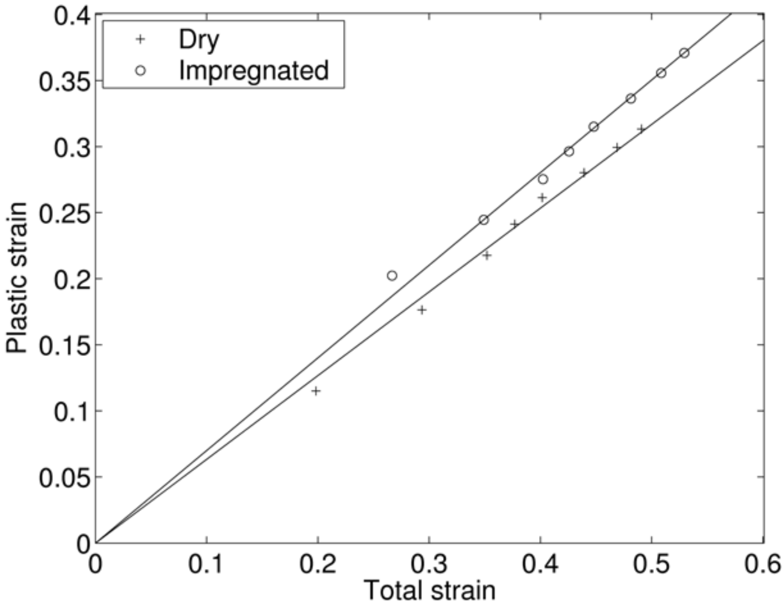

Fig. 4 Permanent deformations of the glass twill-weave in dry and impregnated states.

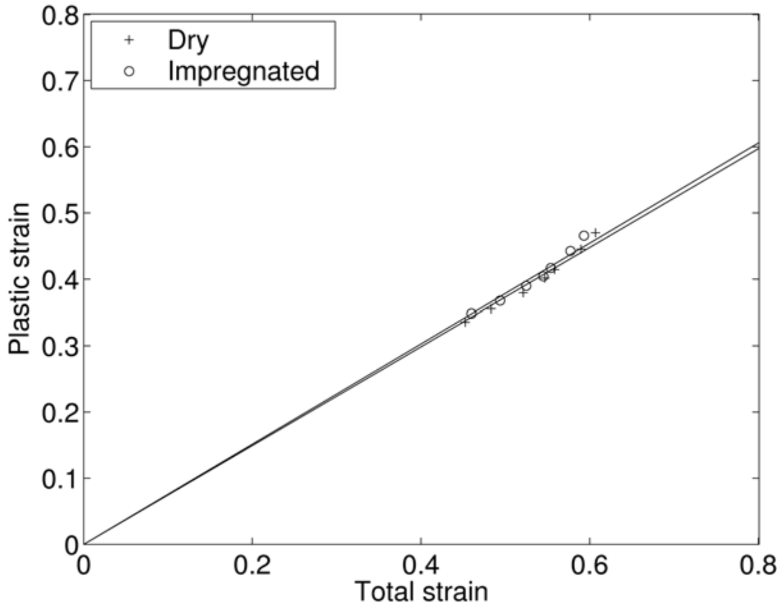

Fig. 5 Permanent deformations of the carbon NCF in dry and impregnated states.

PERMEABILITY MEASUREMENTS

So far, for permanent deformation measurement, the aim of the compression tests has been to limit the fluid pressure. From now on, in order to measure permeabilities, the purpose of the measurement method [8] is to generate fluid flow and fluid pressure within the sample using proper compression speeds and fluid viscosities. For in-plane permeability measurement, in-plane flow is generated using the setup depicted in Fig. 1

with an impregnated sample and a receptacle. For through-thickness permeability measurement, the generation of a purely transverse flow using a compression test is difficult to achieve. However, using the setup shown in Fig. 2, fabric compression forces the fluid out, in the three directions of the sample. Those two types of compression tests induce fluid pressure and fiber effective stress response. In order to extract the fluid pressure out of those experiments, the fiber effective stress has to be measured and subtracted to the previous experiments.

The effective stress response is measured combining a test with the setup in Fig. 2, a low compression speed, and a low fluid viscosity in order to zero the fluid pressure. That experiment called the reference compression is performed with a fluid viscosity of 0.1 Pa.s and a compression speed of 0.5 mm/min.

In-plane permeabilities

Once the experimental fluid pressure is measured, one can solve for the conservation of mass and Darcy's law in the sample. If the fiber reinforcement is transversely isotropic (K_x=K_y), an analytical solution exists (Tab. 2). But in most cases when the fiber reinforcement is anisotropic, an inverse method algorithm adjusts the permeability of the simulation results to match the simulated liquid pressure to the experimental liquid pressure. The anisotropy ratio is needed to calculate the two in-plane principal permeabilities. Results for the in-plane permeability, calculated for the glass and carbon fabrics, are in excellent agreement with the ones measured with the unidirectional or central injection methods (Figs. 8 and 9).

	Transverse isotropic fiber reinforcement		Anisotropic fiber reinforcement	
	In-plane permeability ($K_x = K_y$)	Through-thickness permeability K_z	In-plane permeabilities ($K_x \neq K_y$)	Through-thickness permeability K_z
Analytic	✓			
FDM (2D cylindrical)	✓	✓		
FEM	✓	✓	✓	✓

Table 2 Methods to extract permeabilities depending on the material anisotropy.

Through-thickness permeability

Once the in-plane permeabilities are known, the compression tests inducing through-thickness flow (Fig. 2) can be analyzed using an inverse method as detailed above. Results for glass twill-weave and carbon NCF are given in Figs. 6 and 7. No comparison with experimental data using injection techniques is given since such measurements are very difficult to realize. However, the orders of magnitude obtained are in a proper range for through-thickness permeability.

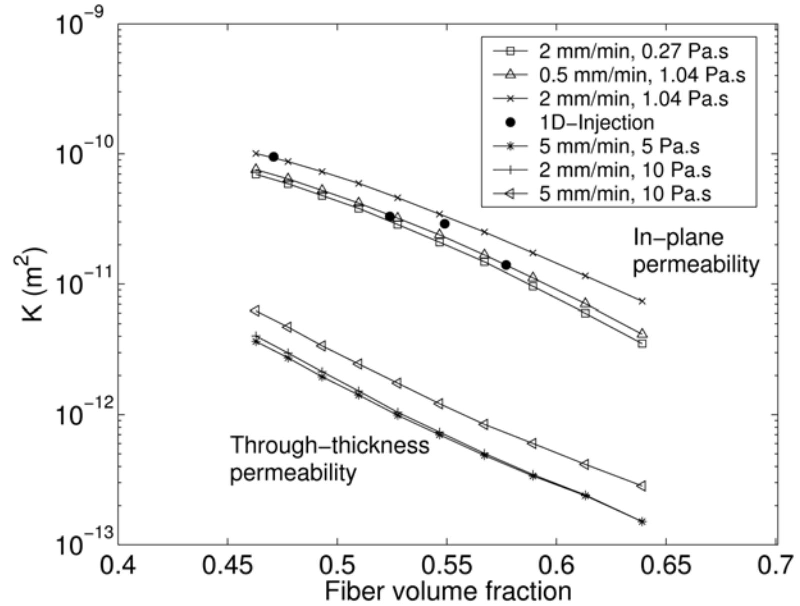

Fig. 6 In-plane and through-thickness permeabilities of the glass twill-weave fabric extracted from the compression tests. The black circles (●) are in-plane permeabilities obtained using the unidirectional injection method.

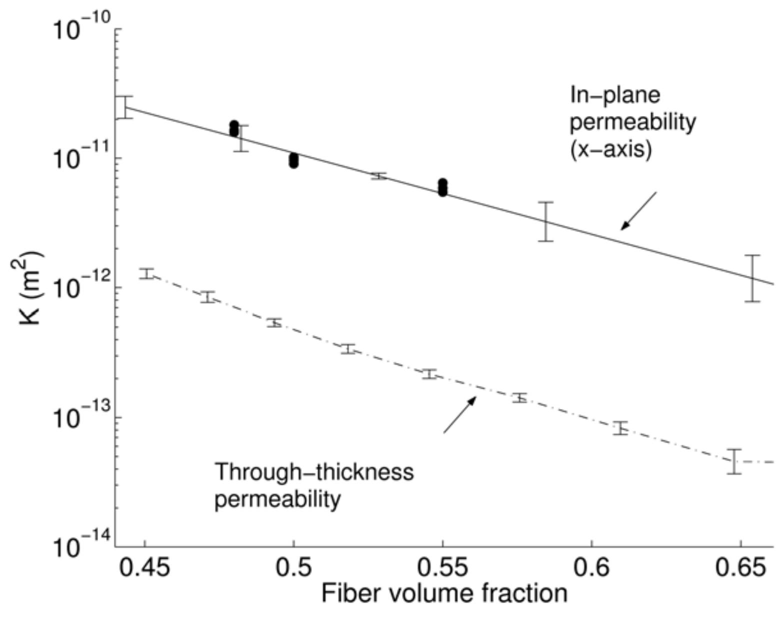

Fig. 7 In-plane and through-thickness permeabilities of the carbon NCF extracted from the compression tests. The black circles (●) are in-plane permeabilities obtained using the central injection method.

CONCLUSION

The results obtained for plasticity characterization show the importance of permanent deformations during unidirectional compression of the glass twill-weave fabric and carbon NCF studied. Also a methodology for fiber reinforcement permeability measurement using a compression test setup has been described. That method offers the main advantage of being continuous over a wide range of fiber volume fractions. Moreover, once the anisotropy ratio is known, the method allows the determination of the in-plane and through-thickness permeabilities. That method also eliminates lots of drawbacks present in the injection methods such as edge effects or mold deflection. This methodology can also be applied to fabrics that have been sheared prior to compression.

ACKNOWLEDGEMENTS

The authors would like to thank the Advanced Technologies Development Center, Dassault Aviations (France) for providing the carbon fiber reinforcements and funding part of the study.

REFERENCES

[1] Tackitt KD, Walsh SM, *Mat. Manufact. Processes*, 20 (2005), p. 607-27.

[2] Rudd CD, Bulmer LJ, Morris DJ, *Mat. Sci. Technol*, 12 (1996), p. 436-44

[3] Toll S, Manson JAE, In: Proc. of the FRC Conf. 1994, Newcastle upon Tyne, UK, p. 25/1-25/10.

[4] Lundstrom TS, Stenberg R, Bergstrom R, Partanen H, Birkeland PA, *Compos. Part A*, 31 (2000), p. 29-43.

[5] Ait si Ahmad M, Fasi-Ferhi O, Poitou A, Bojji C, *Mécaniques & Industries*, 3 (2002); p. 27-34.

[6] Buntain MJ, Bickerton S, *Compos. Part A*, 34 (2003), p. 445-57.

[7] Comas-Cardona S, Binetruy C, Krawczak P, Unidirectional compression of fibre reinforcements Part 1: A non-linear poro-elasto-plastic behaviour. Submitted to *Compos. Sci. Technol*. (2005)

[8] Comas-Cardona S, Binetruy C, Krawczak P, Unidirectional compression of fibre reinforcements Part 2: A continuous permeability tensor measurement. Submitted to *Compos. Sci. Technol*. (2005)