

# SPATIAL COMPACTION AND SATURATED PERMEABILITY VARIATIONS OF FIBRE REINFORCEMENTS

S. Bickerton<sup>1,3</sup>, S. Comas-Cardona<sup>2</sup>, I. Razali<sup>1</sup>, M. Deléglise<sup>2</sup>, W. A. Walbran<sup>1</sup>, C. Binétruy<sup>2</sup>,  
and P. Krawczak<sup>2</sup>

<sup>1</sup> *Centre for Advanced Composite Materials, Department of Mechanical Engineering  
The University of Auckland, Private Bag 92019, Auckland, New Zealand*

<sup>2</sup> *Department of Polymers and Composites Technology & Mechanical Engineering  
Ecole des Mines de Douai, 941, rue Charles Bourseul, 59508 Douai Cedex, France*

<sup>3</sup> *Corresponding author's E-mail:s.bickerton@auckland.ac.nz*

**SUMMARY:** Composite manufacturing techniques are subject to a range of disturbances, due to material and processing variability. Properties of fibre reinforcements such as compaction response and permeability are very influential, as is variability in these quantities. A compaction study of four reinforcements is presented, spatial stress variations quantified using the Tekscan distributed pressure measurement system. Variability in the average stress has been explored, considering basic statistics of the spatial variation over repeated experiments, and with increasing fabric layers in the sample. Two types of behaviour have been noted, chopped strand mat and twill weave reducing the magnitude of peak stresses as additional layers are added, resulting in reduced variability in average stress between samples. The plain weave and biaxial stitched fabrics maintained peak stresses with the addition of layers, and exhibited increasing variability. The noted spatial variability has been used to specify a model permeability field for a single layer of twill weave. Random fluctuations have been imposed on this field, and 1000 permeability fields have been generated for a 4 layer preform. The upper and lower permeability bounds have been used to predict injection pressure histories for unidirectional filling, results correlating well with observed experimental variability. This study shows that if reinforcement is well known in terms of statistical variations, a simulation can be more predictive in terms of injection responses.

**KEYWORDS:** spatial variability, compaction, permeability, fibre reinforcements, LCM.

## INTRODUCTION


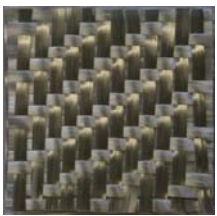


Liquid composite molding processes are known to be strongly dependent on fluctuations in various parameters (e.g., temperature, material batches, preforming consistency), which can induce poor process reproducibility. Fibre reinforcement properties such as compaction response

and permeability govern mould filling, and variability (global and spatial) in these quantities can be very influential [1]. Average compaction response has been shown to be complex [2,3], while little work has been done on the spatial distribution of compaction stress exerted on a mould. As an initial investigation of this issue, a compaction study on four different glass fibre reinforcements is presented. The Tekscan 2-D pressure mapping system has been employed, exploring the influence of increasing fabric layers (1, 3, 5, and 10), and issues of repeatability. In parallel a permeability variability study has been realized on one of the same reinforcements (a twill weave fabric), using a constant injection pressure permeability bench. The inlet pressure histories recorded during each experiment show variations that are related to saturated permeability spatial variation. From initial observations of the spatial compaction response, a spatially varying permeability field for a single layer of fabric has been proposed. Random fluctuations have been imposed on the parameters that define this field, and the permeability field for a 4 layer sample has been found through a numerical stacking process. Variability of nesting has been accounted for by allowing random variation in layer placement, this process being repeated 1000 times to establish bounds on the average permeability response. The long term goal of this work is to more clearly establish the link between spatial variability in compaction response and permeability, and better understand their influence on processing.

## COMPACTION STUDIES

A series of compaction experiments have been performed using parallel plates mounted in an Instron universal testing machine. The Tekscan distributed pressure measurement system has been used to measure spatial variation of compaction stress exerted on the platen, during a period of constant speed compaction (1.0 mm/min) to a target fibre volume fraction ( $V_f$ ). This study utilised square sensors (50 mm by 50 mm) having a fine grid of 44 by 44 sensels, and a pressure range of 0 to 2125 kPa. 100 mm square samples of the reinforcement were cut, the Tekscan sensor being placed at the centre of the sample, fixed to the lower mould platen. Significant care was taken to ensure target cavity thicknesses were achieved with very good accuracy. Four E glass fibre reinforcements have been considered, and are described in Table 1. Experiments have been performed using samples composed of 1, 3, 5 and 10 layers. Three repeats were performed in each case, with the exception of five layers, for which ten experiments were performed.

Table 1 Description of the reinforcement materials

	Chopped Strand Mat (CSM)	Twill Weave Fabric (TWF)	Plain Weave Fabric (PWF)	Biaxial Stitched Fabric (BSF)
Areal mass ( $\text{g/m}^2$ )	450	1500	800	825
Target $V_f$	0.5	0.6	0.6	0.6
Image of 100 mm square samples				

## Repeatability between Individual Layup Events

The compaction stress distributions considered are at the instant the target  $V_f$  was reached. To demonstrate typical variability between layups, four distributions recorded for five layers of CSM and PW are shown in Fig. 1. Note that compaction stress is plotted using an exponential scale, as peak stresses dominate if a linear scale is used. The influence of layup variations between experiments is clear. The random nature of CSM is evident, peak compaction stresses following no geometric pattern. While the periodicity of the TWF has been captured, the variability in magnitude and position of the peak compaction stresses is significant. This is due to variability in the structure of a single layer, and variability introduced by subsequent placement of additional layers. For the larger weaves (TWF and PWF) maximal nesting was introduced into each layup, the warp and weft tows of each additional layer being positioned between the previous. Despite these relatively controlled conditions, significant variability was noted between experiments.

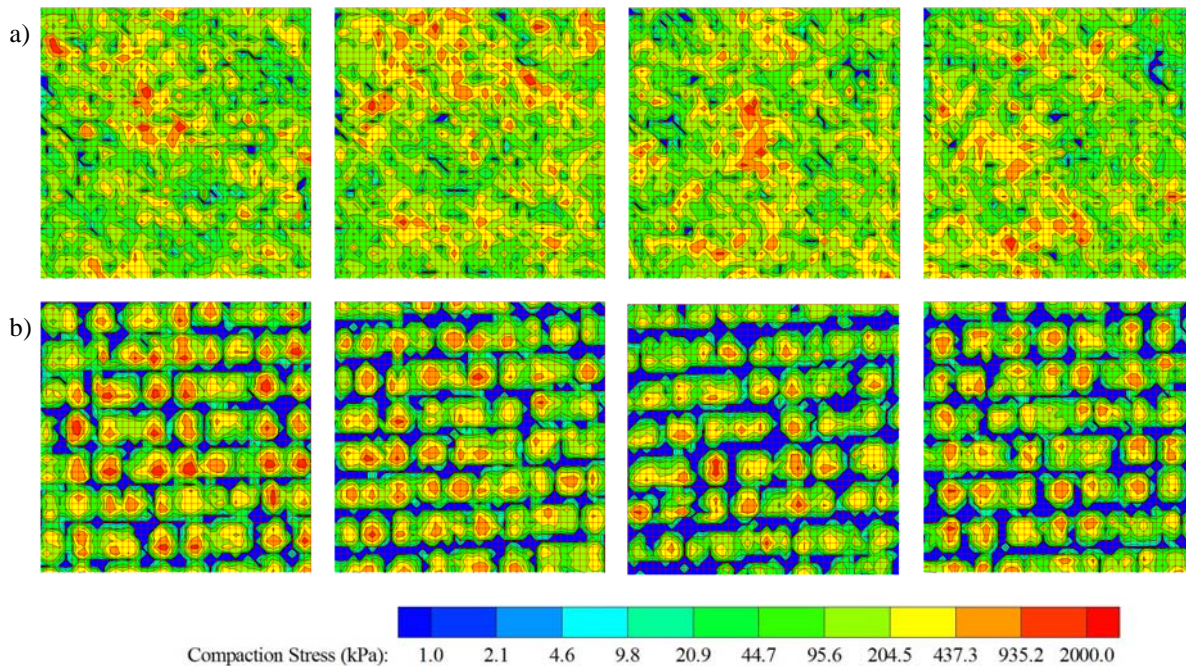


Fig. 1 Sample stress distributions for 5 layer samples, a) CSM, and b) TWF.

## The Effect of a Varying Number of Layers

The mean compaction stress over the sensor area is plotted against layers in Fig. 2a, the data representing averages over each set of experiments. Three of the reinforcements exhibit increasing stress with number of layers, the trend flattening after 3 or 5 layers. The TWF shows the opposite trend, additional layers being accommodated with lower compaction force. Repeatability between individual layups is demonstrated by the average stress standard deviations presented in Fig. 2b. Both the CSM and BSF demonstrate greater variability for compaction of a single layer, the effect of additional layers serving to reduce variability between layups. The TWF and PWF exhibit increasing variability, particularly when layups exceed a single layer, and the PWF shows greatest variability amongst the fabrics studied. It is clear that different mechanisms control average compaction stress, and it's variability, for each fabric.

Fig. 3 presents typical stress distributions (using an exponential scale) recorded as the number of layers was increased. Single layer distributions for all materials exhibit strong spatial variation in both the magnitude and location of peak stresses. While the TWF, PWF, and BSF have ordered structures, strong spatial variability exists, which is tempered to some extent as additional layers are added. Stress frequency plots have been constructed for each experiment, and an average frequency distribution determined for each set of experiments (set of 3, or 10 repeats). This frequency data is presented in Fig. 4, demonstrating how the distribution of stress magnitudes changes with additional fabric layers.

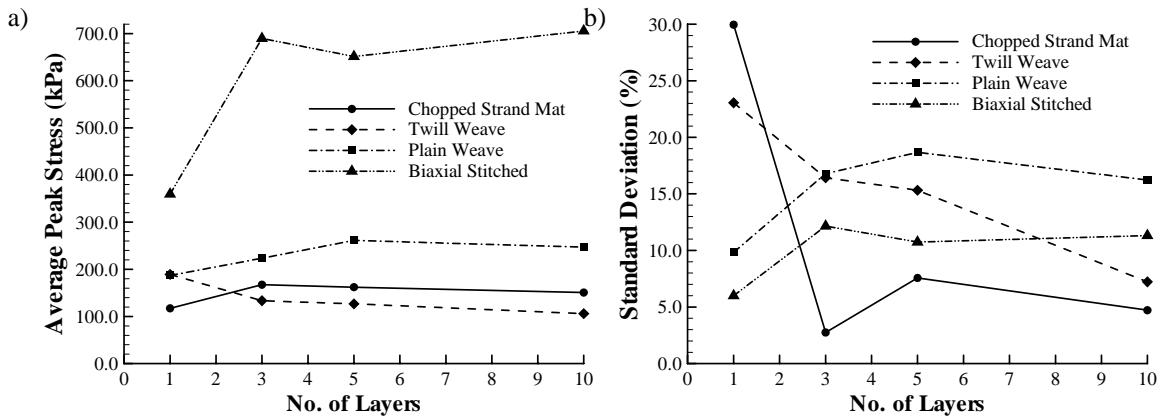


Fig. 2 a) Spatially averaged stress at the target  $V_f$ , and b) standard deviation for each set of repeat experiments.

Examining Figs. 3a and 4a a single layer of CSM exhibits localised regions of high stress, due to higher density fibre clusters, and large areas in which stress was below the measurable threshold. As additional layers are added, the fibre clusters in each layer are distributed across the sampling area, and the associated peak stresses reduced by lower fibre density in adjacent layers. The reduction in frequency of higher stresses is confirmed by Fig. 4a. Considering Fig. 4b the TWF exhibits similar behaviour, additional layers serving to reduce the influence of high stress regions generated by a single layer. For stress levels below 500 kPa the frequency plots are very similar, while above this level significant reductions in higher stresses are evident with increasing layers. It should be noted that CSM and TWF are the materials that exhibited reducing variability with increasing layers (see Fig. 2b).

In contrast, PWF shows no significant reduction in the occurrence of high compaction stresses, frequencies levels remaining relatively constant with increasing layers (Fig. 4c). The plots are very similar for 3 layers or above, with a redistribution to lower stresses for a single layer. For this material, stacking multiple layers serves to increase the average compaction stress, and variability of this quantity (see Fig. 2b). These quantities appear to level off at 5 layers. Similar observations can be made about the BSF, which exhibits a doubling of average compaction stress from 1 to 3 layers, with the standard deviation following a similar trend. Both Figs. 3d and 4d exhibit significantly different behaviour for 1 and 3 layer samples. There is a significant reduction of low and below threshold stresses for 3 layer samples, and a significant increase of high stress occurrences of 500 kPa or higher. As additional layers are added, this trend continues

to a smaller extent. As opposed to CSM and TWF, the PWF and BSF maintain the high stress regions as the number of layers is increased, and show greater variability with additional layers. The different behaviours of each group of materials must be related to how an individual layer interacts with the mould platens, and/or adjacent layers of material.

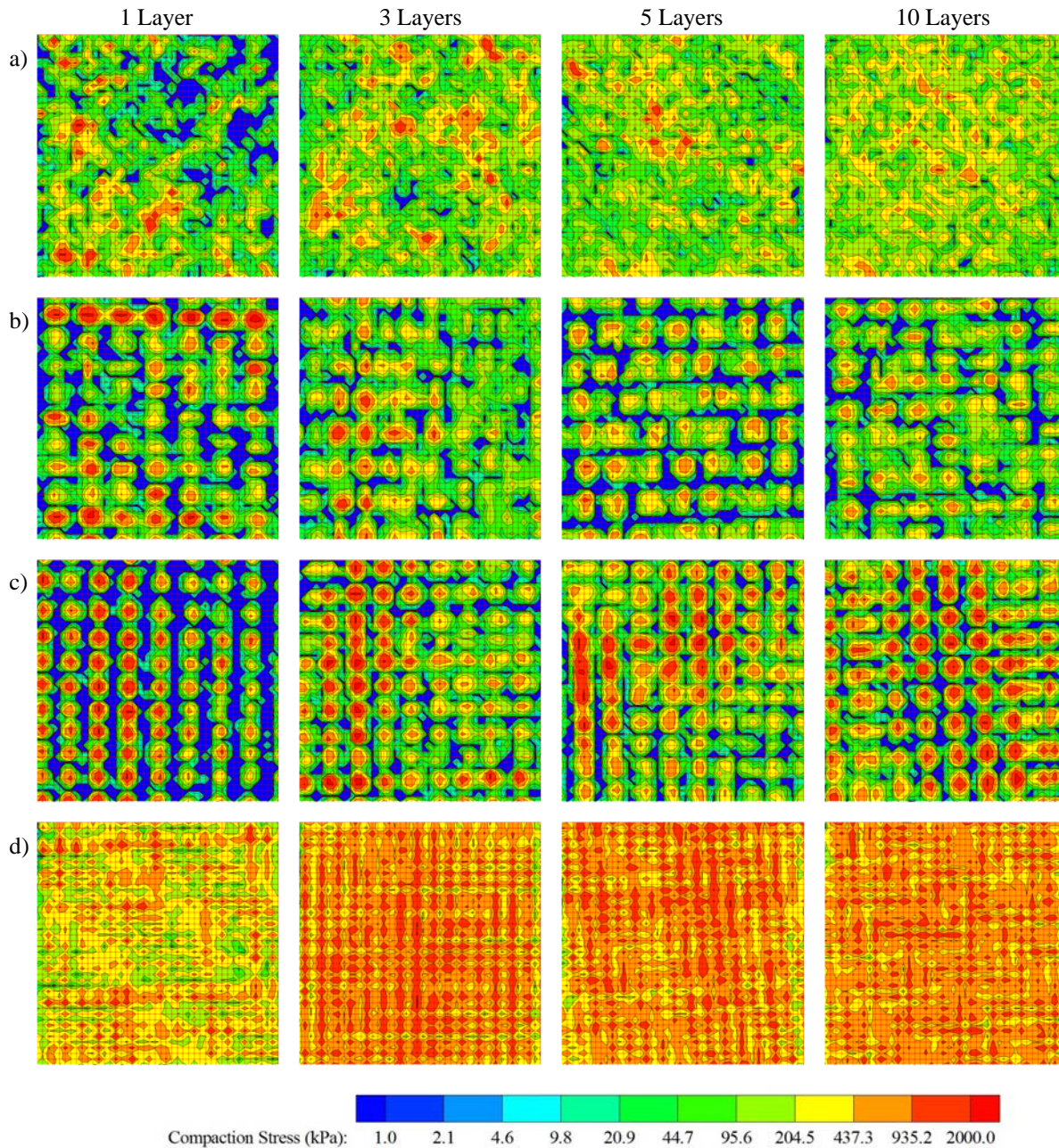


Fig. 3 Stress distributions for samples of increasing layers a) CSM, b) TWF, c) PWF, d) BSF.

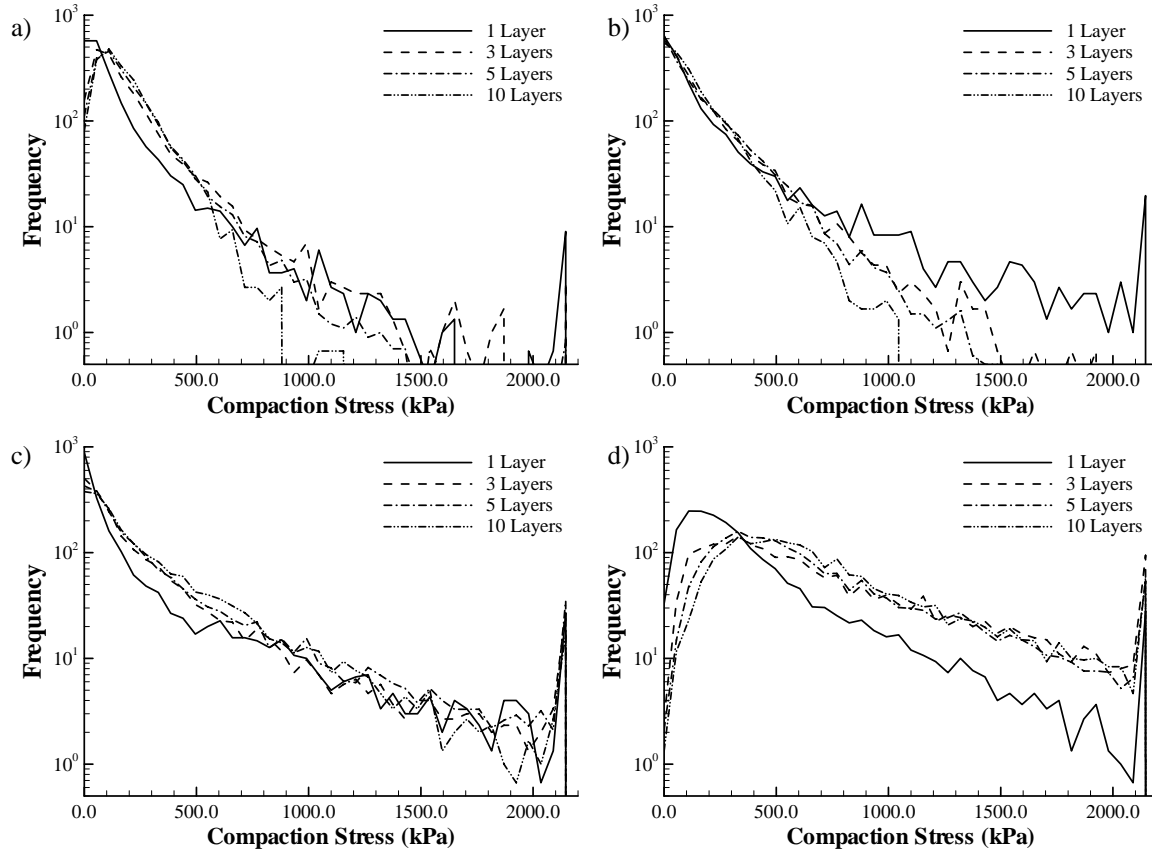


Fig. 4 Stress frequency plots, averages taken among each set of repeat experiments. a) CSM, b) TWF, c) PWF, and d) BSF.

## INFLUENCE OF PERMEABILITY VARIATIONS ON MANUFACTURING

The first part of this study has shown that fibre reinforcement architectures exhibit strong differences in terms of local variations and average levels of stress response when submitted to unidirectional transverse compression. The question that arises is: what would be the effect of these variations when infusing (during Resin Transfer Moulding for instance) a preform composed of such fibre reinforcements? When injecting a resin through a fibrous material, resin pressure  $p$  and interstitial flow velocity  $v$  are related through Darcy's law:

$$v = \frac{-K}{\phi\mu} \nabla p, \quad (1)$$

where  $K$  is the reinforcement permeability,  $\phi$  the porosity and  $\mu$  the resin viscosity. Eqn. 1 shows that permeability variations directly impact on the resin pressure  $p$  when constant flow velocity (flow rate) is used as an injection strategy.

Here we focus on the unidirectional ( $x$ -direction) injection of a preform composed of four plies of the twill weave fabric defined earlier. Due to the nature of fibrous reinforcements, the compression response and therefore the permeability can vary:

- within a single ply,
- and from one ply to another.

First, concerning the variability within a single ply, the following permeability distribution in the  $(x, y)$  plane can be proposed. This is reasonable, due to the reinforcement's periodic architecture.

$$\frac{K(x, y)}{K_o} = \frac{\alpha}{2} \cdot \left[ \sin\left(\frac{-2\pi}{\lambda_x}(x - x_{off})\right) + \sin\left(\frac{-2\pi}{\lambda_y}(y - y_{off})\right) \right], \quad (2)$$

where  $K_o$  is the average permeability of the ply,  $\alpha$  its amplitude of variation,  $\lambda_x$  and  $\lambda_y$  the periodicity of the fabric in the  $x$  and  $y$  directions respectively. Also,  $x_{off}$  and  $y_{off}$  represent the possible offsets that occur between layers during the lay-up.

Table 2 Distribution, bounds, means and standard deviations of the parameters characterizing the TWF.

Parameter	Distribution	Bounds or Mean / Standard Deviation	Values
$K_o$	Gaussian	Mean	$2.9 \times 10^{-10} \text{ m}^2$
		Standard Deviation	$4.9 \times 10^{-11} \text{ m}^2$
$\lambda_x$	Gaussian	Mean	$6.7 \times 10^{-3} \text{ m}$
		Standard Deviation	$1.5 \times 10^{-3} \text{ m}$
$\lambda_y$	Gaussian	Mean	$7.1 \times 10^{-3} \text{ m}$
		Standard Deviation	$1.5 \times 10^{-3} \text{ m}$
$x_{off}$	Uniform	Min	0 m
		Max	$6.7 \times 10^{-3} \text{ m}$
$y_{off}$	Uniform	Min	0 m
		Max	$7.1 \times 10^{-3} \text{ m}$

The variability from one ply to another can be obtained by generating random (uniform or Gaussian distribution) values of the parameters of Eqn. 2 [4]. Table 2 describes distributions that have been chosen, their adequate bounds or mean, and the standard deviation.  $K_o$  has been measured from several fluid injection experiments. The fabric wavelengths,  $\lambda_{x,y}$ , were obtained from the compression tests run with the Tekscan sensor, measuring the length between maxima in both directions of the fabric. Permeability and wavelengths are considered to be normally distributed. Offsets between layers are due to the randomness of how an operator cuts and lays up the fabric. The amount of offset varies within the fabric wavelengths because of its periodicity. Therefore, the best mathematical description is obtained with a uniform distribution of offsets in both directions.

A sampling of each parameter is generated for each fabric ply. An example of the resulting permeability field is shown in Fig. 5. The preform permeability is then calculated while averaging across the width direction, and through the four plies in the preform as follows;

$$K_{preform}(x) = \frac{1}{4} \sum_{i=1}^4 K^i(x, y). \quad (3)$$

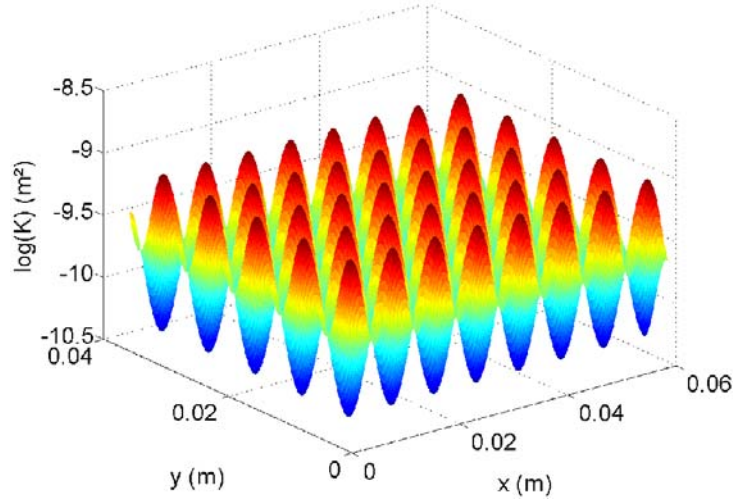


Fig. 5 Generation of the permeability within a ply.

A finite difference method solver has been written to solve Eqn.1 in the case of a unidirectional ( $x$ -direction) injection with constant flow rate and variable local permeability. Table 3 shows the input parameters that have been applied here. The output of the simulation is the evolution of resin inlet pressure with respect to the flow front position.

Table 3 Input parameters used for both numerical and experimental injections

Input parameters	Values
Length $L$	0.295 m
Width $l$	0.18 m
Thickness $h$	0.0045 m
Flow rate $Q$	$1.67e^{-6} \text{ m}^3/\text{s}$
Viscosity $\mu$	0.1 Pa.s
Fiber volume fraction $V_f$	0.51

The filling simulation was repeated 1000 times while performing permeability sample generation. The inlet pressure evolutions, for all cases, fall in between the bounds depicted by the broken lines in Fig. 6. For comparison, five different experimental injection pressure responses are also presented in Fig. 6. The experimental injections exhibit variability that is not negligible and can be captured.



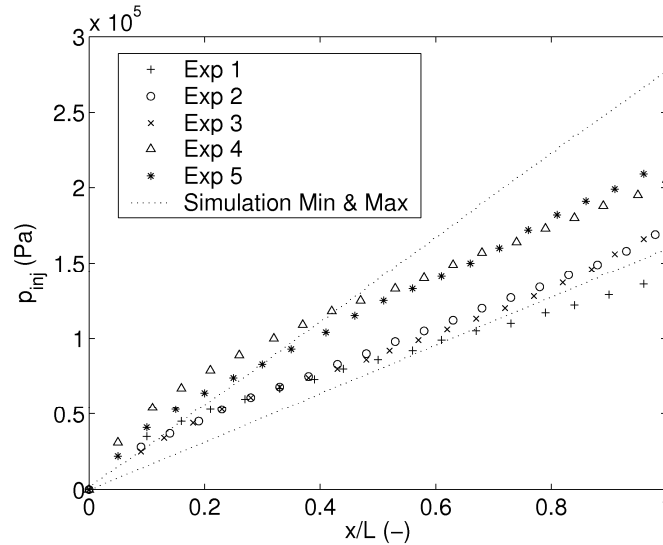


Fig. 6 Experimental pressure profiles compared to the predicted pressure bounds.

## CONCLUSIONS

Strong spatial variability in compaction response has been demonstrated for several glass fibre reinforcements. Trends in the spatially average compaction stress, and its variability, have been related to stress distributions as the number of layers was increased. Large peak stresses are generated by a single fabric layer, these peak values being reduced with the addition of layers, for two of the four materials studied. Compaction data has helped to specify a model permeability field for a single layer of twill weave, which has been used to realize 1000 fields for a 4 layer preform. This study has shown that when a reinforcing material is well known in terms of statistical variations, a simulation can be more predictive in terms of injection responses. Realistic bounds on pressure response could be used, for instance, to help designers optimise the strength of LCM moulds to withstand maximum pressures that could occur during resin injection.

## REFERENCES

1. K. Hoes, D. Dinescu, H. Sol, R. S. Parnas and S. Lomov, "Study of Nesting Induced Scatter of Permeability Values in Layered Reinforcement Fabrics", *Composites Part A*, Vol. 35, no. 12, 2004, pp. 1407.
2. A. A. Somashekar, S. Bickerton and D. Bhattacharyya, "Exploring the Non-Elastic Compression Deformation of Dry Glass Fibre Reinforcements", *Composites Science and Technology*, Vol. 67, no. 2, 2007, pp. 183.
3. S. Comas-Cardona, P. Le Grogne, C. Binetruy and P. Krawczak, "Unidirectional compression of fibre reinforcements. Part 1: A non-linear elastic-plastic behaviour", *Composites Science and Technology*, Vol. 67, no. 2, 2007, pp. 507.
4. G. E. P. Box and M. E. Muller, "A Note on the Generation of Random Normal Deviates", *Annals Math. Stat.*, Vol. 29, 1958, pp. 610.