CHARACTERIZATION AND PREDICTION OF COMPACTION FORCE AND PREFORM PERMEABILITY OF WOVEN FABRICS DURING THE RESIN TRANSFER MOLDING PROCESS

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ABSTRACT

In resin transfer molding process, after a fabric mat is placed in a mold, the mold is closed and the fabric is compacted before resin is injected to impregnate the empty spaces between the fibers. Whether the resin will fill all the regions between the fiber will depend on the permeability of the compacted preform. The fiber mat permeability is a non-linear function of the degree of compaction. To model the resin impregnation process, one needs to know the mat permeability and the fiber volume fraction which depend on the compaction. A compaction model is formulated to estimate how the preform architecture deforms as a function of applied force. This result is coupled with a separate analytical model for permeability prediction, which is based on an approximated two-dimensional lubrication flow in open spaces between the fabric tows and the one-dimensional transverse Darcy's flow within the tows to predict the in-plane permeability of the compacted multi-layer fabric mat. The permeability model needs geometric information about the macroscopic architecture of the compacted and resin filled fabric mat which can be supplied from the compaction model or from experimental measurements. A unique experimental set-up was designed and fabricated to measure permeability of a preform as a function of compaction force and fiber volume fraction for the same preform.

INTRODUCTION

Among various composite-molding techniques, RTM is of very high potential. A number of factors in RTM process influence the properties of finished composites, and the compaction of the preform during tool closure is of major importance. A literature review of the compaction behavior of textile reinforcements in composite manufacturing has been conducted by Robitail and Gauvin [1]. A number of experimental works on the compaction behavior can be found in the open literature, for example, Matsudaira and Qin [2], Pearce and Summerscale [3], Sauders, Lekakou and Bader [4], Parnas, Howard, Luce, and Advani [5,6]. However, few investigations have focused on modeling the preform compaction behavior theoretically, in spite of the fact that various regression relations for fabric preforms have been proposed based upon experimental results. Recently Chen and Chou [7,8] have conducted a theoretical study of the compaction of plain-weave fabric preforms. Simplified 3D micro-mechanical models for both single-layer and multiple-layer fabrics were developed for predicting the compaction behavior. These simplified models have been improved by considering the contacting pressure distribution between adjacent yarns and fabrics on the basis of compaction experiments [9]. The relations among the fiber volume fraction, the applied compressive force, and the preform thickness reduction, have been established. The proposed theoretical models [7,8] have been applied to predict the permeability of woven fabric preforms as a function of the degree of compaction.

COMPACTION MODELS OF PLAIN-WEAVE FABRIC PREFORMS

A typical pressure-thickness curve of woven fabrics is depicted in Figure 1. The curve can be divided into three parts: two linear parts and a non-linear part. Initially, preform compaction is primarily due to the reduction of pores and gaps among the fibers and yarns, while the last stage is dominated by the yarn bending deformation, as well as the yarn cross-section deformation and nesting. The image-processed sections of specimens at various degrees of compaction of Reference 4 give useful insights into the compaction process. The behavior of woven fabric preforms during the last stage of the compaction curve shown in Figure 1 has been examined recently. The modeling of this linear portion of the curve initiates at the point $(2h_y, p_0)$, namely, the previously applied pressure has brought the preform thickness down to $2h_y$ through the elimination of pores and gaps among the fibers and among the yarns.

One of the assumptions adopted in our micro-mechanical model [7-9] is that yarn packing fraction remains constant. That is, during the compaction process, the yarn shape deforms, but the yarn cross-sectional area remains unchanged. The analyses focused on the *unit cell* of an orthogonal plain-weave fibrous preform, which is composed of two sets of mutually orthogonal yarns. One quarter of this unit cell model of a single-layer fabric at the initial stage of bending deformation is shown in Figure 2. The analysis of the nesting and elastic deformation during the compaction of multi-layer woven-fabric preforms has also been performed [8]. By taking into account the contacting pressure distribution between adjacent yarns and fabrics, the models proposed in [7,8] have recently been improved in [9].

PERMEABILITY PREDICTION MODEL

Permeability of compacted single or multi-layer fabric preforms is predicted by using an analytical model PERM [10,11] developed at the University of Delaware. The model is based on an approximated two-dimensional lubrication flow in open spaces between the fabric tows and one-dimensional transverse Darcy's flow within the tows. The model has been used for predicting the permeability of sheared and/or compacted fabrics [12-15]. The comparisons of the predicted and the experimentally measured permeabilities show that PERM does a fairly good job if the architectural detail of the deformed fabric is measured and used as input for the model. The bundle permeability and the tow architecture (in terms of tow and resin channel thickness) are used as input to the model. The tow dimensions are measured from compacted and resin-filled fabric samples. Alternatively, using the compaction model [7-9], the tow architecture is predicted and used in the permeability prediction model.

CASE STUDIES

Case studies were conducted on a balanced weave fabric with a length a and width b of the unit cell, $a = b = 6.11$ mm, and the yarn thickness $h_y = 0.318$ mm which is one half of the fabric thickness per layer.

Thickness Reduction Predictions due to Compaction

The compaction model predict the last part of the pressure-thickness curve and simulate the deformation during compaction. The fiber volume fraction as a function of the preform thickness reduction as well as the applied compressive force can be obtained explicitly using the models. At the same time, the location of the fabrics and the voids among yarns and fabric-layers as a function of the thickness reduction can also be determined. Using the compaction models, the non-dimensional thickness for a multi-layer fabric mat was predicted as a function of non-dimensional compaction force, and is shown in Figure 3 for a two-layer fabric with different nesting.

Data Input for Permeability Predictions Using the Compaction Model

PERM model will be used to predict permeabilities for single and 2-, 3-, 5-, 10- and 20-layer of plain-woven fabric preforms. The ratio of the thickness reduction (r_z) per layer to the original fabric layer thickness ($2h_y$) are taken as: 0%, 2%, 4%, … , 18%. The compaction model was used to generate the architectural data of the compacted preform, and then used as input in the permeability prediction model.

Permeability Predictions

Before investigating the change in the permeability of a woven fabric preform due to compaction, we studied the mold wall effects on the preform permeability. The motivation was to show that permeability of a compacted preform is not only dependent on the fiber volume fraction, but also on the total thickness and hence the mold effects. Under fixed fiber volume fraction, the permeabilities of 1-, 2-,3-, 5-, 10- and 20-layer preforms (see Figure 4) were predicted. Although the nesting is not considered here in this study, the model PERM is capable of handling nesting (Figure 5), in-plane shift of the layers, and the shearing deformation if the structural data is supplied.

The thickness of all fabric layers and all resin channels between them are used as input to the code. The side view of a schematic 5-layer fabric mat, and corresponding five fabric layer sub-domains and six resin channel sub-domains are shown in Figure 6. Within a unit cell of a two-layer fabric mat, the thickness input data is shown in a graphical form in Figure 7.

Under constant fiber volume fraction, the permeability of the selected balanced weave fabric was predicted using PERM and is shown in Figure 8. As the number of layers increase, the permeability rises; the wall effect weakens and the permeability converges for a mat with more than about 10 layers.

Now, we can investigate the compaction and permeability relation for the selected balanced fabric. First, the structural deformation is predicted using the compaction model that has been briefly mention earlier for thickness reductions of 0%, 2%, 4%, …, 18%. Under compaction, some sections of the tows will be flattened. The architecture of the deformed unit cell is stored in a data file and made ready for the permeability predictor model PERM. The predicted permeability is plotted in Figure 9 as a function of thickness reduction for 1, 2, 3, 5, 10 and 20 layers. As the thickness-reduction increases, the fiber volume fraction increases and consequently the permeability decreases. The permeability of a mat under 18% thickness-reduction is about 1/3 of the original permeability. For this fabric with no nesting, the best curve fittings show that the permeability is proportional to 1 over fiber volume fraction to the power of 6. Once again, the convergence of the permeability under fixed fiber volume fraction is clearly seen in Figure 9 as the number of layers increase.

PERMEABILITY MEASUREMENT AS A FUNCTION OF COMPACTION

Classical one-dimensional permeability measurement experiments require one experiment at each particular fiber volume fraction within the desired fiber volume fraction range. These experiments are time consuming and must be performed carefully so that no significant racetracking exists between the preform and the mold walls. Between each experiment, the mold is opened, the preformed is removed, a new preform is placed into the mold, and then the mold is closed with a different mold thickness. A new apparatus and experimental procedure are introduced here. This set-up allows us to measure the permeability of the preform at different fiber volume fractions in a continuous experiment using only one preform and without opening and closing the mold in between the experiment. The mold set-up, shown in Figure 10, was designed by P. J. Graham and S. Bickerton [16], here at the University of Delaware. The preforms are stacked on the bottom plate of the mold, and between the two sealing materials as shown in Figure 10. The injection gate and the vent are at the opposite sides of the preform. There is an empty channel between the fabric and the injection gate creating a one-dimensional resin flow. After steady state flow is achieved, using the two pressure transducers at the two ends of the mold, the pressure drop is measured. The permeability is calculated by using one-dimensional Darcy law

$$K_{xx} = \frac{\eta L}{wh} \frac{Q}{\Delta p}, \tag{1}$$

where K_{xx} is the permeability along the resin flow direction, η is the fluid viscosity, and L is the distance between the pressure transducers, w and h are the width and the thickness of the mold gap, Q is the flow rate, and Δp is the pressure drop. The permeability measurement procedure is repeated by changing only the mold thickness to obtain the next desired fiber volume fraction. The compaction load in the Instron machine is adjusted, and the excess sealing material is extruded from the mold through the holes along the two sides of the mold not to cause a disturbance at the edge of the preform.

Another advantage of the new procedure is to have a consistent nesting architecture throughout the continuous experiment. In classical permeability measurement procedures, the fabric preforms will not have the same architecture because of the inconsistency in the fabric cutting and stacking and hence different amount of nesting. How much of the permeability change is purely because of the fiber volume fraction, but not because of the change of nesting structure will not be known from the classical procedure.

The set-up and the procedure were applied to measure the permeability of felt and random fabrics so far [16]. For ten different fiber volume fractions of the felt fabric, the flow rate versus pressure drop is plotted in Figure 11. Using the 1-D Darcy's law given in (1), the permeability component of the fabric along the flow direction was calculated and plotted in

Figure 12 with circles. For test purposes, the same fabric was used in the "classical permeability measurement mold" under three different fiber volume fractions and shown with diamonds. In near future, we will use the new procedure for the woven fabric to verify our predictions as well.

CONCLUDING REMARKS

Compaction of a preform has a major influence on the processing and the final properties of the composite. Two different models were integrated to investigate the compaction effects on the structural deformation and permeability change of a balanced woven fabric preform. The compaction model predicts the thickness reduction and the architectural deformation of a multi-layer preform as a function of compaction load. This analytical model is for balanced woven fabric preforms. The architecture of the compacted and deformed preform supplies data about the thickness of the fabric and resin channel sub-domains. This is used as input for the second model, permeability predictor PERM. For a given architecture of the unit cell and bundle permeability, the in-plane permeability tensor of the preform is predicted. This model assumes in-plane lubrication flow in the resin channel sub-domains, and one-dimensional Darcy flow in the fabric sub-domains. PERM was first used for the investigation of mold wall effects. At fixed fiber volume fraction, permeabilities of 1-, 2-, 3-, 5-, 10- and 20-layer preforms were predicted using the architectural data files obtained by the compaction model. Calculations show that permeability of the preforms converges as the number of fabric layers increase. The deformed structure of the preform was predicted by the compaction model for thickness reductions of up to 18%, and then was used as an input for permeability prediction model PERM. As the thickness reduction increases as a result of increasing compaction load, the permeability decreases. Under 18% thickness-reduction, the permeability of the preform is about 1/3 of the original permeability. A new apparatus and experimental procedure are introduced to measure the permeability of a preform at different fiber volume fractions in a continuous experiment using the same preform and without re-opening the mold as the preform is compressed. This new procedure saves considerable experimental time and preform, and eliminates the inconsistency of the preform structure (different racetracking and nesting effects from one experiment to next). The procedure was applied to preforms with felt material, and will be used for the woven fabrics in the near future to verify the predicted relationship between the compaction load and the thickness reduction and to verify the predicted permeability of the deformed preform.

ACKNOWLEDGEMENTS

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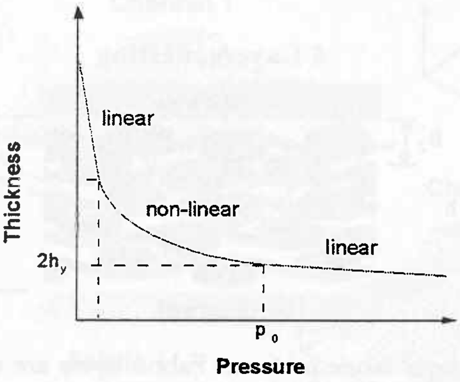

Fig. 1. Typical pressure-thickness curve of woven fabrics under compaction.

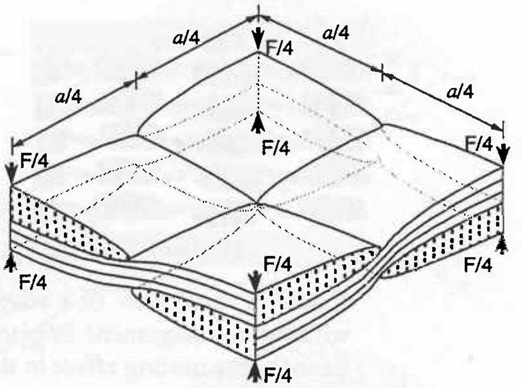

Fig. 2. One quarter of 3D unit cell of a plain-weave fibrous preform.

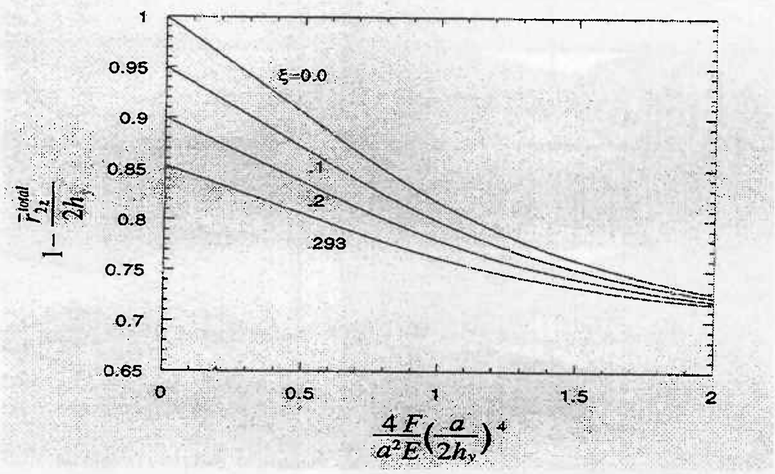

Figure 3. Non-dimensional compressive force (y-axis) versus non-dimensional thickness for a two-layer fabric mat.

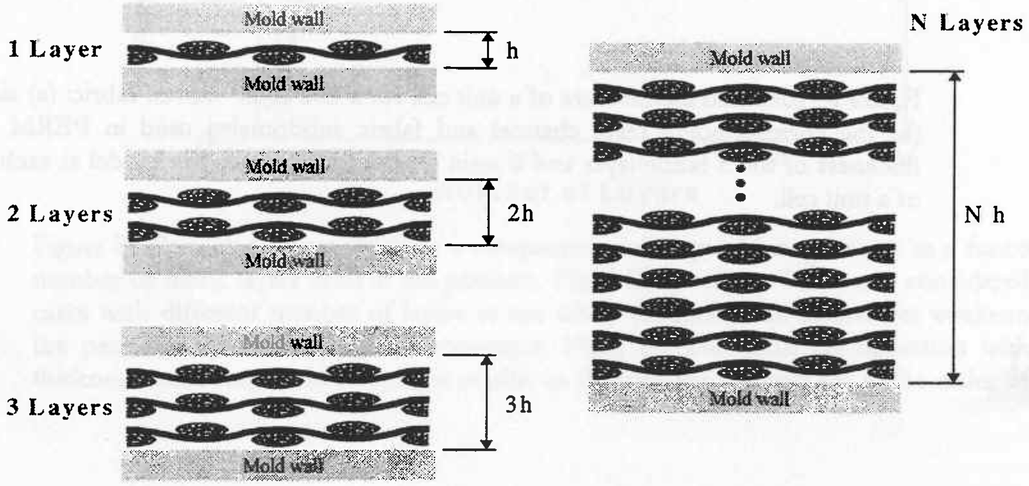

Figure 4. Multi-layer fabric preforms at fixed fiber volume fraction, V_f. Ideal architecture is assumed.

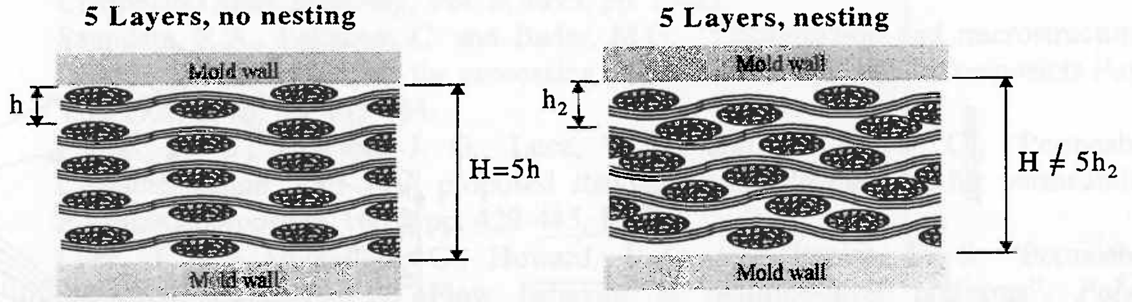

Figure 5. Side view of a schematic 5-layer fabric preform. Fabric layers are stacked up (a) without any alignment in-plane directions, and (b) with alignment in-plane directions and hence some nesting effect in the transverse direction.

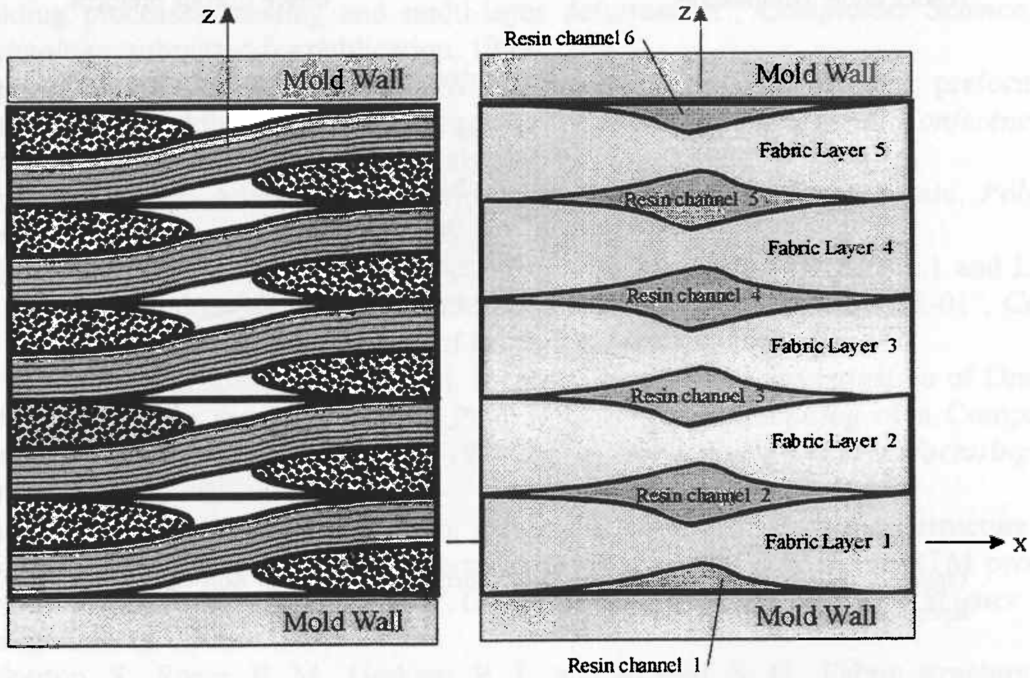

Figure 6. Idealized architecture of a unit cell for a five-layer woven fabric: (a) side view, and (b) the corresponding resin channel and fabric subdomains used in PERM model. The thickness of the 5 fabric layer and 6 resin channels is input to the model at each nodal point of a unit cell.

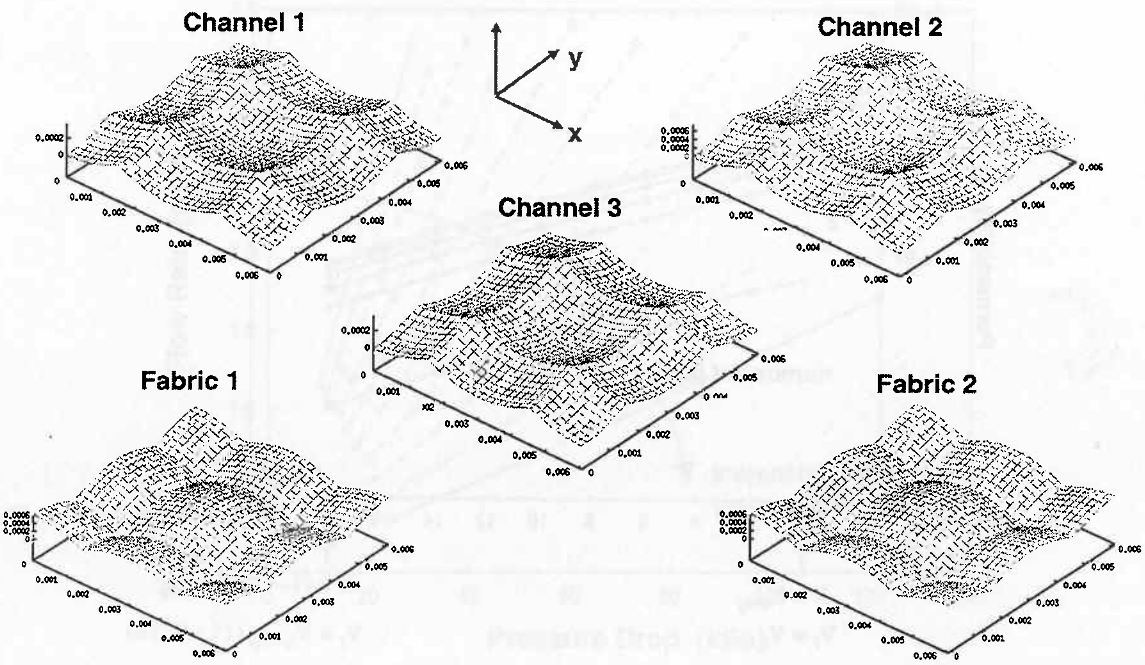

Figure 7. The input data to the permeability predictor code PERM for a 2 layer fabric mat case. Two fabric and three resin channel domain is input to the model

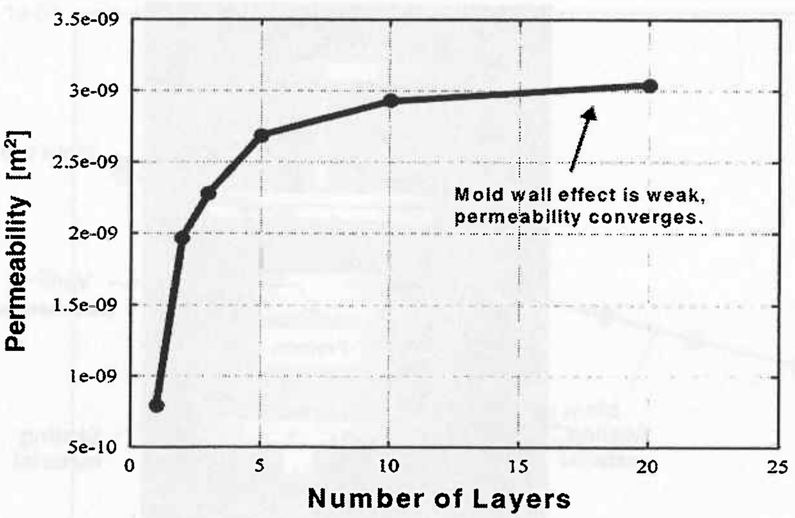

Figure 8. Predicted permeability of a compacted multi-layer fabric preform as a function of number of fabric layers used in the preform. Fixed fiber volume fraction is considered in all cases with different number of layers to see when the mold wall effects get weakened and the permeability of the preform converges. Here, for the initial configuration with zero thickness reduction, mold effects get smaller as the number of layers get in the order of 10's.

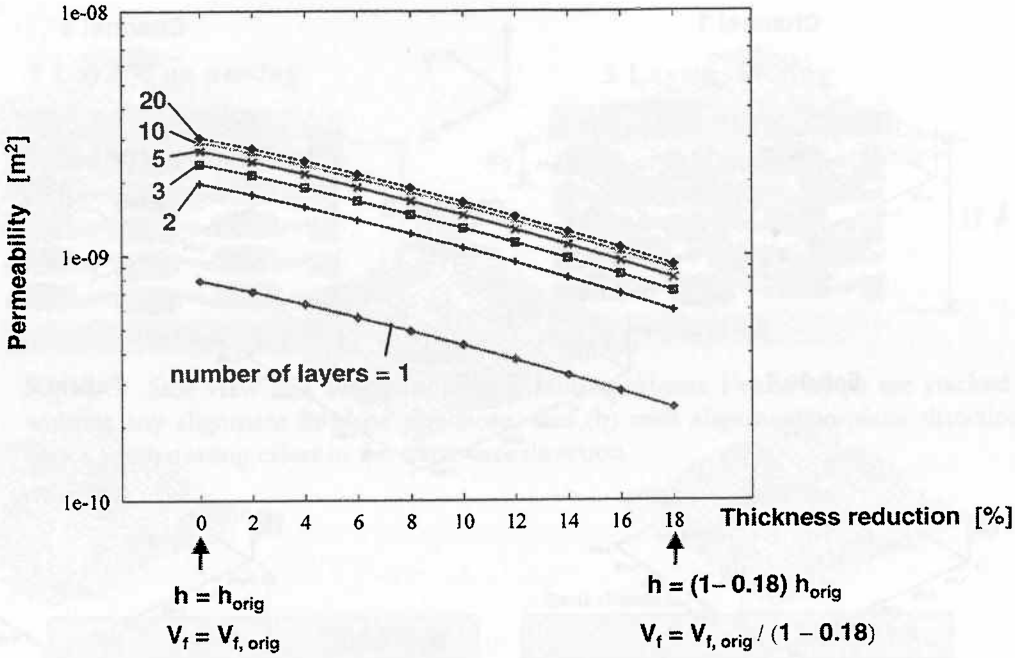

Figure 9. Predicted permeability of a compacted multi-layer fabric preform versus percentage thickness reduction.

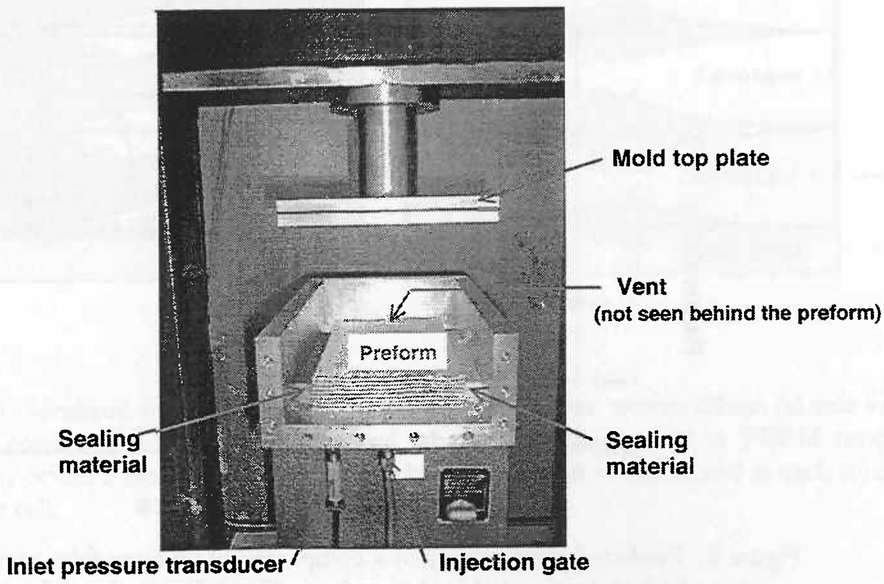

Figure 10. Mold setup for detailed permeability versus fiber volume fraction measurements. From one experiment to another, the compaction load is changed in the Instron machine without opening the mold and the permeability of the corresponding preform is measured.

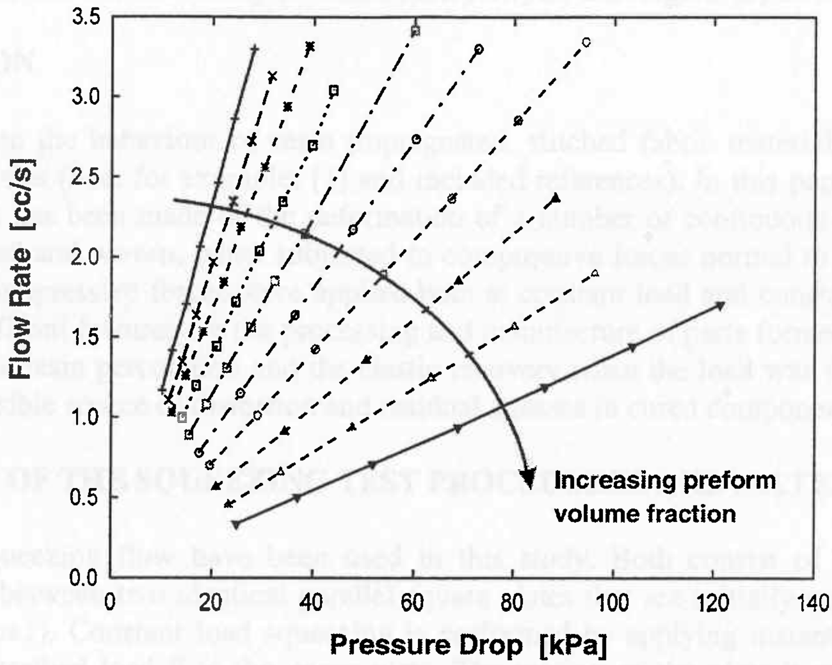

Figure 11. Flow rate versus pressure drop for a felt fabric mat at 10 different fiber volume fractions. The permeability is calculated by using the relation between the flow rate and the pressure drop in 1-D Darcy law, $Q = K(wh/\mu L)\Delta p$.

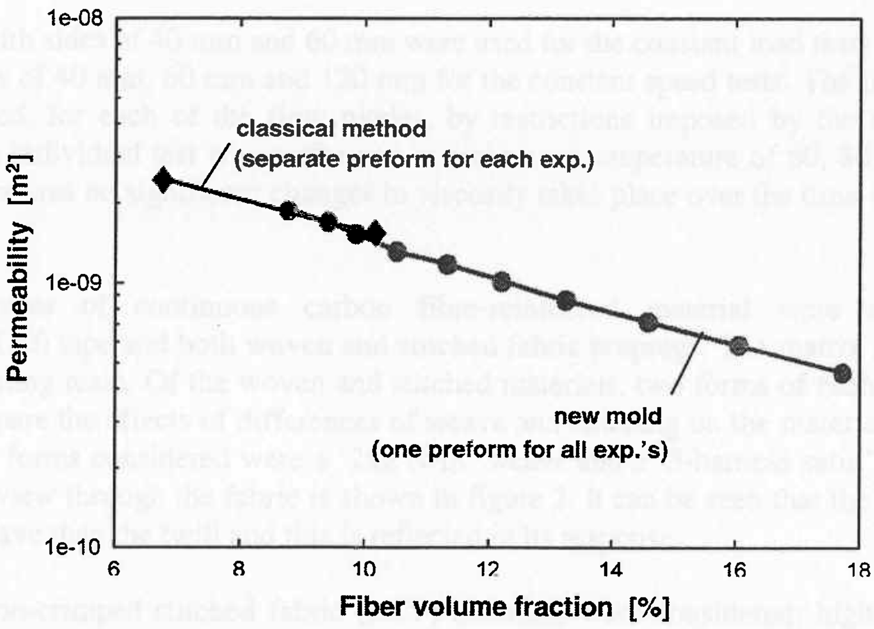

Figure 12. Measured permeability for the felt fabric mat at various fiber volume fractions. The circles are from the present mold setup, and the diamonds are from a different mold set-up using the classical method in which separate preform is used for each experiment.