Out-of-plane permeability of multilayer $0^\circ/90^\circ$ non-crimp fabrics

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Abstract. Layer shift is the main source of the variations in permeability values for multilayer fabrics. This phenomenon could change the flow path and cause inadequate infiltration. In this paper, the out-of-plane permeability of multilayer $0^\circ/90^\circ$ non-crimp fabrics was analyzed statistically. Based on the prediction models of 2-layer fabrics, every two adjacent layers were regarded as porous media with different permeabilities. The out-of-plane permeability of multilayer fabrics was then modeled with the electrical resistance analogy. Analytical results were compared with experiment data. And the effect of number of layer on permeability was thoroughly researched based on the statistical point of view.

1. Introduction
Permeability is a key parameter in flow simulations for RTM (Resin Transfer Molding), which is used to optimize the injection process [1-3]. To predict the most accurate permeability values of fabrics, many studies have been done by analytical modeling or numerical prediction [4]. However, most models are only applied to an ideal stacking structure rather than a real stacking structure. As layer shift is a major source of the observed variations in permeability, the values could differ by a decimal order of magnitude [5]. In our previous studies [6], analytical models were developed to predict the permeability of two-layer fabrics. The results show that the less the number of layers, the greater the randomness of yarn arrangements.

For multilayer fabrics, stacking sequence of perform layers should be taken into account. Although some models were proposed considering the effect of layer shift on permeability, the layer shift must be given in advance to predict the permeability [7-9]. In fact, obtaining the information about shift between each layer is very difficult. Therefore, it is of great importance to predict permeabilities of multilayer fabrics without being given the layer shift values.

In this paper, the out-of-plane permeabilities of multilayer $0^\circ/90^\circ$ non-crimp fabrics were figured out based on the statistical point of view. Based on these models of two-layer $0^\circ/90^\circ$ non-crimp fabrics we proposed earlier, every two adjacent layers were regarded as different porous media. As the flow resistances are equivalent to the reciprocal of permeability $1/K$, the permeability of multilayer fabrics can be calculated by electrical resistance analogy. Statistical analysis was then carried out to study the effect of number of layers.

2. Theoretical modeling
$0^\circ/90^\circ$ non-crimp fabrics consist of yarns with two different orientations which are stitched together. The geometrical feature is schematically illustrated in Figure 1. In our previous study [6], the unit cell can be decomposed into sixteen different zones of different local fiber arrangement. With electrical...
resistance analogy, the permeability of unit cell can be modeled as a mixture of permeabilities of local zones. In z direction, the liquid flows through the local zones at the same time. Therefore the flow resistances are in parallel. For two-layer NCFs, the out-of-plane permeability of the unit cell can be estimated as

$$K_z = \sum_{i=1}^{16} K_z^i \frac{s_i}{s}$$  \hspace{1cm} (1)$$

where $s_i$ is the area of local zone $i$, $K_z^i$ is the out-of-plane permeability of local zone $i$.

As the architecture of unit cell changes with respect to layer shift. The local permeability is modeled as a function of layer shift in reference [6]. From above models, we can find that the permeability of two-layer NCFs can be predicted if the layer shift values $x$ and $y$ are given.

For multilayer fabrics, shift between adjacent layers varies in a large range and this parameter is independent and random. In addition, layer shift is difficult to obtain in actual process. In this paper, each pair of two adjacent layers is treated as a porous medium with different permeability, as shown in Figure 2. The flow resistances of all pairs are in parallel in z direction. With the electrical resistance analogy, the permeability of multilayer fabrics can be written as follows:

$$K = \left( \frac{1}{n/2} \sum_{j=1}^{n/2} \frac{1}{K_z^j} \right)^{-1}$$  \hspace{1cm} (2)$$

Where $n$ is the number of layers, $K_z^j$ is the out-of-plane permeability of pair $j$.

From the architecture of unit cell, it can be seen that the layer shift $x$ changes in interval $[0, a_{00} + e_{00}]$ and $y$ changes in interval $[0, a_{0} + e_{0}]$. The layer shift values are randomly selected from the interval under the same probability.

Assuming that $x$ can take $m_x$ and $y$ can take $m_y$ uniform random numbers if the step sizes are given, there may be $m_x m_y$ cases for the out-of-plane permeability of two-layer NCFs. 4-layer fabrics can be seemed as two pairs of adjacent layers. The permeability of each pair is one of $m_x m_y$ cases. Then the out-of-plane permeability can be calculated by Eq. 2. The statistical characteristics can be acquired if many calculations are carried out. With the same method, the distribution of out-of-plane permeability of multilayer fabrics can be obtained.

![Figure 1](image_url)

**Figure 1.** Unit cell of 0°/90° non-crimp fabrics. $a_{00}$ and $a_{0}$ are the are long axes of the cross section of 0° and 90° yarns, respectively. $e_{0}$ is the width of channels between 0° yarns and $e_{00}$ is the spacing between 90° yarns. $x$ and $y$ are layer shift values in $x$ and $y$ directions, respectively.
3. Experiment

$0^\circ /90^\circ$ non-crimp glass fiber fabrics LT817 were used in modeling and experiments. Properties of the different yarns are listed in Table 1. The epoxy resin 2511 was used as the model fluid in the permeability runs, with a viscosity of 800 mPa s at the room temperature.

The apparatus used for measuring out-of-plane permeability was designed based on Darcy’s law for one-dimensional (1-D) flow:

$$Q = -\frac{K \cdot A \cdot dP}{\eta \cdot dz}$$

(3)

Where $Q$ is the volume flow rate, $P$ is the pressure distribution over the saturated preform, $A$ is the flow related preform area ($A$). The out-of-plane permeability can be obtained by

$$K_z = -\frac{Q \cdot \eta \cdot h}{\Delta P \cdot A}$$

(4)

Where $h$ is the preform thickness, $\Delta P$ is the pressure drop through the preform thickness.

The permeability tool used in this paper was depicted in Figure 3. The fabrics were held by two parallel porous circular plates. And the thickness of fabrics can be compressed to the desired value. After the samples were placed in the cylindrical mold, the epoxy resin 2511 was injected in the transverse direction by air compressor under a constant inlet pressure. A video camera was used to record the increase of liquid mass when the epoxy resin flowed out.

| Fabric code | Material  | Areal density (g/m2) | Filament diameter | Number of filaments in a yarn |
|-------------|-----------|----------------------|-------------------|-----------------------------|
| LT817       | E-glass   | 817                  | 16                | 2200                        |

4. Results and discussion

To validate the analytical model proposed for predicting the out-of-plane permeability of 2-layer NCFs, experiments were carried out with 4 different layer shift cases: (1) $x = 0$ and $y = 0$; (2) $x = 0$ and $y = e^0$; (3) $x = e^{90}$ and $y = 0$; (4) $x = e^{90}$ and $y = e^0$. The comparison between theoretical and experimental results was shown in Figure 4. Good agreement can be found for the last three cases.
There existed great differences for the first case. A possible reason may be that the yarns were not aligned perfectly during stacking fabrics.

**Figure 4.** Predicted and measured out-of-plane permeabilities with four different cases.

To validate the analytical model applied for multilayer fabrics, i.e. Eq. 2, permeabilities with 2, 4, 6, 8 and 10 layers were analyzed statistically. The average thickness per layer was fixed at 0.7mm. 1,000 analytical calculations for each of the layer numbers were chosen. Figures. 5-7 present the distributions of out-of-plane permeability of 2, 4, 6, 8 and 10 layers. It can be seen that the permeabilities of 2-, 4- and 6-layer preforms are distributed scatterly. The permeability values could differ by a decimal order of magnitude. With increasing the number of layers, the histogram of permeability takes the shape close to a typical distribution. In addition, the average permeability values of 8 and 10 layers are close to each other. The standard deviation of 10 layers is smaller than that of 8 layers. This means that the distributions of permeability become narrow when increasing the number of layers.

Figure 8 presents the comparison between experimental and analytical results when the average thickness per layer was fixed at 0.7mm. For 2-layer fabrics, the average permeability obtained theoretically is very different from experimental value. The reason is that the stacking structure changes greatly due to the effect of layer shift. However the differences become less significant as the number of layers increases. This means that the more the number of layers, the lower the scatter level of permeabilities.

**Figure 5.** Distributions of out-of-plane permeability for 2, 4 and 6 layers.  
**Figure 6.** Distribution of out-of-plane permeability for 8 layers.
5. Conclusions
Based on the permeability model of two-layer NCFs, each pair of two adjacent layers is treated as a porous medium with different permeability. An analytical model was then developed in this paper to predict the permeability of multilayer NCFs with the electrical resistance analogy. Without given the layer shift values, this model can be used to examine statistical features of the out-of-plane permeability. It was found that the histogram of permeability takes the shape close to a typical distribution and the distributions become narrow with increasing the number of layers.

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