Effect of Layer Shifting on the Out-of-Plane Permeability of 0°/45° Alternative Multilayer Fabrics

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Keywords: Layer shifting; permeability; resin transfer molding;

Abstract. The shifting of layers has great effect on the permeability which is a key parameter in resin transfer molding (RTM). In this paper, a mathematical model was developed to predict the out-of-plane permeability of 0°/45° alternative multilayer fabrics with one extreme structure. The global permeability was modeled as a mixture of permeabilities of different zones with the electrical resistance analogy. And the modeling was accompanied by out-of-plane permeability measurements for different fabrics and a comparison of experimental data with the proposed model proved encouraging.

1.Introduction

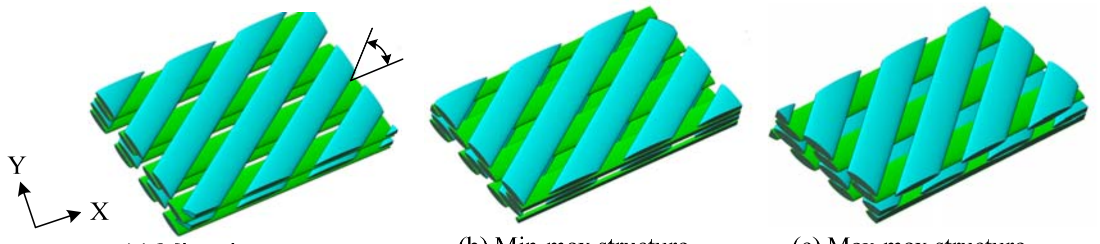
Processes of the Liquid Composite Molding (LCM) class are widely used in the automobile and aerospace industries. The permeability which measures the geometric resistance to flow by the reinforcement, governs resin impregnation and has a great influence on the quality and hence the performance of the final product [1-4]. Therefore, accurate characterization of preform permeability is vital to successful simulation, design, and optimization of the molding filling process in LCM [5, 6].

A considerable amount of past and present research has focused on the prediction of the permeability of textiles. However， for multilayer fabrics, layer shifting also plays an important role in determining the permeability behavior of the performs, especially the transverse permeability. Horizontal shifting can easily lead to layer nesting, which has been verified that this effect can change the resin flow path and contribute significantly to permeability variations [7]. To predict the permeability of textiles with layer shifting, Grujicic et al. [8, 9] and Lekakou et al. [10] developed numerical models. But the limitation of numerical calculations is the difficulty to define a periodic unit cell that would be representative of the fiber reinforcement.To possess a comprehensive understanding, the analytical modeling is worth performing to investigate the influence of geometrical fabric parameters on the out-of-plane permeability with layer shifting.

In this article, the effect of layer shifting on out-of-plane permeability was investigated experimentally and theoretically. Analytical models were developed to predict the out-of-plane permeability of 0°/45° alternative fabrics with one extreme ply stacking sequences-"min-min" structure.

2.Theoretical modeling

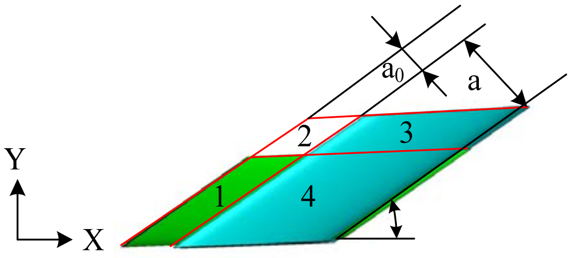
For 0°/45° alternative multilayer fabrics, layer shifting could increase complexity degree of fiber stacking and change the flow route through thickness. There are three extreme cases, as shown in Fig. 1: (1) the spaces between yarns align in thru-thickness direction along the layers with same ply angle, and the fiber arrangements of both 0° layers and 45° layers are similar to "minimum nesting" of unidirectional cloth, named "min-min" structure; (2) one of 0° layers is shifted relative to another in y direction and the axes of the yarns in upper layer are parallel to that of spaces between yarns in lower layers in x-z plane, this arrangement is similar to "maximum nesting" of unidirectional cloth. Meanwhile, for45° layers, the yarns align along the axes between upper and lower layers, similar to "minimum nesting" of unidirectional cloth. Then the arrangement of the whole perform is named "min-max" structure; (3) the axes of yarns in upper layers are coplanar with that of spaces between yarns in lower layers both for 0°and 45° layers, this arrangement is named “max-max” structure. Notice that the thickness of preform does not change with layer shifting, but this effect on out-of-plane permeability is great. In this paper, we concentrated on “min-min” structure and established the permeability model.



(a) Min-min structure (b) Min-max structure (c) Max-max structure

Fig. 1. Three extreme cases by layer shifting for a four-layer 0°/45° alternative fabric.

A representative unit cell for “min-min” structure is shown in Fig. 2, based on the assumption that cross section of the yarn is elliptical. Due to the specific characteristic of two-scale porosity, we divide the unit cell into four different zones, as described in Table 1.



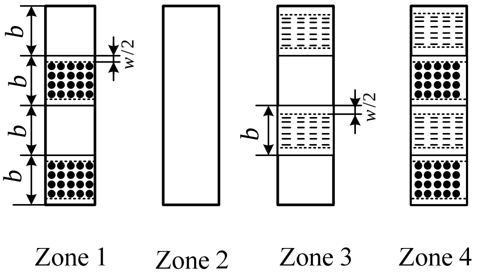


Fig. 2. Unit cell of “min-min” structure.

Fig. 3. the local through-thickness fiber arrangement.

The permeability of the unit cell can be modeled as a mixture of permeabilities of different zones with the electrical resistance analogy. In z-direction, the liquid flows through the four regions at the same time, therefore the flow resistances (equivalent to$1/K$) are in parallel. Then the out-of-plane permeability of the unit cell can be estimated as：

$$K_{\min-\min} = \frac{aa_0}{(a+a_0)^2}K_{zone\ 1} + \frac{a_0^2}{(a+a_0)^2}K_{zone\ 2} + \frac{aa_0}{(a+a_0)^2}K_{zone\ 3} + \frac{a^2}{(a+a_0)^2}K_{zone\ 4} \tag{1}$$

where $K_{zone\ 1}$, $K_{zone\ 2}$, $K_{zone\ 3}$ and $K_{zone\ 4}$ are the out-of-plane permeability values of zone 1, zone 2, zone 3 and zone 4, respectively. a is long axis of the yarn cross-section and a_0 is width of space between yarns.

For each zone in the decomposed unit cell, the local through-thickness fiber arrangement is approximated as illustrated in Fig. 3. To calculate the value of $K_{zone\ 1}$, we assume that the liquid flows through the yarns and spaces in succession. Then the resistances of them are in series. $K_{zone\ 1}$ can be expressed as follows:

$$K_{zone\ 1} = \left(\frac{\mathbf{b}-Dw}{2\mathbf{b}}\frac{1}{K_{yarn\ \wedge}} + \frac{b+Dw}{2b}\frac{1}{K_{void\ 1}}\right)^{-1} \tag{2}$$

With the same method, the permeability values of zone 2, zone 3 and zone 4 can be given as

$$K_{zone\ \mathbf{2}} = \frac{a_0^2}{12} \tag{3}$$

$$K_{zone\ \mathbf{3}} = \left(\frac{b-Dw}{2\mathbf{b}}\frac{1}{K_{yarn\ \wedge}} + \frac{b+Dw}{2b}\frac{1}{K_{void\ 3}}\right)^{-1} \tag{4}$$

$$K_{zone\ \mathbf{4}} = (\frac{b-\mathrm{D}w}{b}\frac{1}{K_{yarn\ \wedge}} + \frac{\mathrm{D}w}{b}\frac{1}{K_{void\ \mathbf{4}}})^{-1} \tag{5}$$

For the permeability of the yarn, equations proposed by Gebart [11], are employed:

$$K_{yarn\ \perp} = C_{\perp} r_f^2 (\sqrt{\frac{V_{b,\max}}{V_b}} - 1)^{5/2} \tag{6}$$

where $K_{yarn\ \perp}$ is the permeability of the flow perpendicular to the filament axis. V_b is the fiber volume fraction of a fiber bundle. $C_{\perp}$ and $V_{b,\max}$ are constants for the two types of fiber arrangement summarized in Table 1. The hexagonal fiber arrangement is used in the present analysis.

Substituting Eqs. (2-6) into Eq. (1), the out-of-plane permeability of “min-min” structure can be obtained. Notice that Eq. (1) reflects the influences of local permeability of different zones on global permeability of the unit cell.

Table 1. Parameter values of permeability equations.

Fiber arrangement	$C_{\perp}$	$V_{b,\max}$
Quadratic	$\frac{16}{9\pi\sqrt{2}}$	$\frac{\pi}{4}$
Hexagonal	$\frac{16}{9\pi\sqrt{6}}$	$\frac{\pi}{2\sqrt{3}}$

3.Experiment

Two types of unidirectional fabrics were used as presented in Table 2 and the epoxy resin 2511 was used as the model fluid in the permeability runs, with a viscosity of 800 mPas at the room temperature.

Table 2. Test material data.

Material	CFW-300	TET-450
Areal density (g/m2)	300	450
diameter of fiber filament (µ)	7	17
filament count	12000	2000

Table 3. Relationships between theoretical fiber volume fraction and the cavity height fixing at four layers.

cavity height (mm)	theoretical fiber volume fraction CFW-300	TET-450
1.1	56.0%	60.0%
1.2	51.3%	55.0%
1.3	47.4%	50.8%
1.4	44.0%	47.1%

A design of the proposed transverse permeability measurement tool is shown in Fig. 4. The fabrics were held between two aluminium honeycombs adjusted to fit in a cylindrical flow channel of 80 mm inner diameter. To prevent any leakage of the test fluid and guarantee a flow strictly through the fabrics and not along the mould walls, the samples were prepared by precision cutting with Laser Cutter SL120 and the stacking sequence is 0°/45°/0°/45°. Pressure was measured at the inlet and the outlet of the mold. The epoxy resin 2511was injected in the transverse direction through the fabrics under a constant inlet pressure. And a video camera was used to record the increase of liquid mass. More detailed explanation is given in the previous study [12].

After the measurements were performed，the permeability through the preform thickness can be obtained by applying Darcy’s law:

$$K=-\frac{hLQ}{SDP} \quad (7)$$

where h is the value of the fluid viscosity, S is the cross-section of the cylinder, and L is the height of fabrics. The flow rate can be obtained by

$$Q=\frac{m}{r\,t} \quad (8)$$

where r is the density of the liquid.

To investigate the effect of layer shifting on the permeability changes with the fiber volume fraction, the number of layers was fixed at 4 and four different fiber volume fractions were obtained by appropriate adjustment of the cavity height, as shown in Table 3.

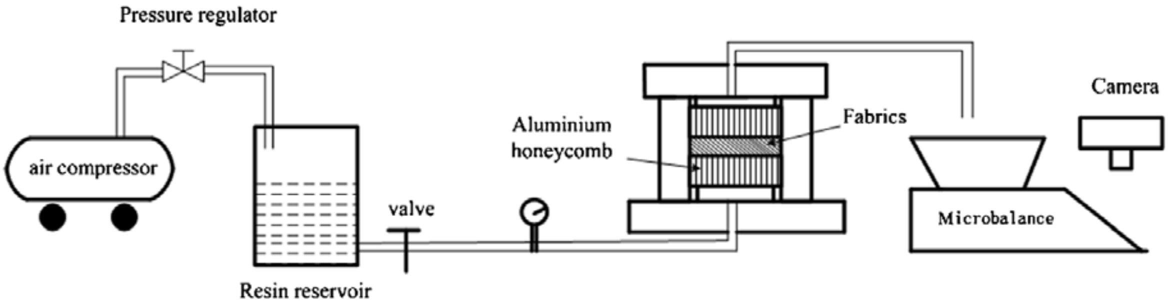


Fig. 4. Experimental setup

4.Results and discussion

Figure 5 and Figure 6 present the out-of-plane permeability for fabrics TET-450 and CFW-300 with respect to the fiber volume fractions, respectively. As expected, the permeability decreases at an ever decreasing rate with increasing fiber volume fractions. And the analytical model yields the results satisfactory enough to describe this behavior. The predictions also compare well with experimental results. In z-direction, the flow is dominated by compression of the yarns and reduction of gaps size. And the out-of-plane permeability decreases with increasing V_f regardless the shifting of layers

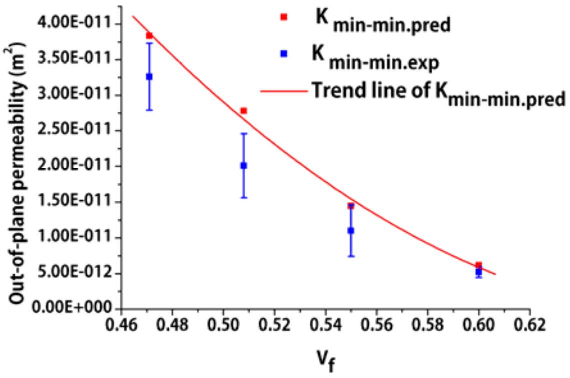


Fig.5. Out-of-plane permeability of TET-450 with "min-min"structure.

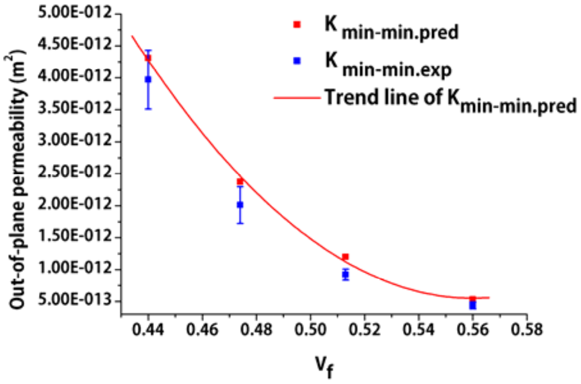


Fig.6. Out-of-plane permeability of CFW-300 with "min-min"structure.

5.Conclusions

This paper investigated the effect of layer shifting on the out-of-plane permeability. one extreme case-"min-min structure" was investigated. For predictive estimation of the out-of-plane permeability, the fabric unit cell was decomposed into different zones of characteristic yarn arrangement. A set of equations was derived allowing description of the local permeability of each zone as a function of geometrical yarn parameters. The overall permeability can be modeled as a mixture of permeabilities of different zones with the electrical resistance analogy. For verification of the model, two different kinds of fabrics CFW-300 and TET-450 were tested. It was found that the analytical results were in agreement with experimental ones.

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