Experimental and Numerical Analyses of the In-plane Permeability of 2.5D-woven Carbon Fabric Preforms with Compressive Deformation

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Abstract. The radial flow method is applied to obtain the in-plane permeability of a kind of 2.5D-woven carbon fabrics with various compression ratios. Geometrical parameters of weft, filling warp and binder warp yarns are measured by using computed tomography (CT) technology while the cross-sectional shape of fiber bundles and the orientation of yarns under certain compact effects are fully considered. Regarding the fiber bundle region as porous media, an unit cell model of the 2.5D-woven carbon fabrics is set up, and resin flow process is simulated by Computational Fluid Dynamics (CFD) method. The simulation results of the in-plane permeability are proved to be well consistent with the experimental data. Finally, using this method, the in-plane permeability of 2.5D-woven carbon fabrics with different fiber volume fractions ($\phi_v$) are predicted, and the changing tendency under different compressive deformation are analysed.

1. Introduction
Resin transfer molding (RTM) is an important processing technology of composite materials that is capable of fabricating extremely complex parts and three-dimensional (3D) reinforced composite structures. In RTM process, a dry preform is placed in a closed mold, impregnated with injected liquid resin and cured in the mold. To avoid the insufficient mold filling defects, finite element method (FEM) analysis tools is conventionally used to simulate the mold filling process and assist the mould design. The permeability of woven fabric preform is the key parameter for the processing simulation [1-3]. There are three main methods for obtaining permeability: experimental method, theoretical analysis method, and numerical simulation method. The permeability of fiber preform is generally obtained by experimental method and numerical simulation method [4]. The radial flow with flow visualization technique has become the main experimental method [5]. There are three basic types of numerical simulation method: Homogenization method, Lattice-Boltzmann method and Cell method [6]. More and more scholars obtain the permeability by using cell method.
In early researches, most scholars used the unit cell model with simplified cross-section of yarns. The influences of real texture of fabrics was neglected. To improve the accuracy of the simulation results, getting the actual feature size of the minimum periodic unit by image processing way is the most advanced method. Recently, by using the electron microscope, Endruweit [7] established the unit cell model which is similar to the actual fabric microstructure. Zeng [8] used the CT scan image to create a geometric unit cell model of the three-dimensional fabric and got a good result of the yarn cross-section. Isart [9] characterized the geometry of the fabric structure by using optical micrographs.
As for the numerical prediction of permeability, the Stokes Equation and the Brinkman Equation were used to describe the resin flow of unit cell respectively by Wu [10]. They used the finite element method to solve the permeability of the fabric. Verleye [11] used a meso-scale simulation tools to compute the permeability on the unit cell of textiles. Both He [12] and Wang [13] used the coupled flow model of resin flow with Darcy’s law to establish a unit cell of plain fabric and predict the permeability. Based on Darcy Law, Dong [14] finished simulation of resin flow in the unit cell which was based on a two-scale porous medium. Zeng [8] used Darcy law and Navier-Stokes Equation to describe the resin flow of inter-yarn and intra-yarn respectively. The unit cell was considered as porous media to simulate the permeability. Kang [15] verified the reliability of porous medium and used the method of porous media replacing yarn bundle regions to calculate the permeability of unit cell.

It’s found that during modeling, the unit cell model can’t characterize accurate section structure and orientation of yarns so that the influence which was caused by these variations on the permeability was neglected. Besides, the two-scale flow in inter-yarn and intra-yarn has a great influence on prediction results. So, considering the accurate model of yarns and resin flow in intra-yarn is absolutely necessary.

This paper is divided into three parts: (1) Radial flow experiments and CT tests were conducted. (2) Based on the CT image, the fabric’s minimum periodic feature was obtained. Then, a nearly realistic unit cell model was established and Computational Fluid Dynamics was used for simulation of resin flow with the method of porous media model replacing fabric bundle regions model. (3) The actual cross-section feature size and orientation of yarns with different compression ratios were got and deformation of yarns was analyzed. The permeability of 2.5D fabrics under compression was obtained by dealing with experimental data, and the effects of compression degrees on the permeability were investigated. The simulation results were compared with experimental data and the feasibility of the modeling and simulation methods was verified. At last, the permeabilities of preforms with four kinds of fiber volume fractions were predicted by using this method.

2. Experiment

In order to get the geometrical parameters and permeability of 2.5D-woven fabric preforms with compressive deformation, the CT and radial flow experiment were conducted respectively.

2.1. CT Test

The interior geometry of the fabric was characterized at different compaction levels by Computed Tomography (CT) analysis. The fabric was compressed by customized acrylic fixture. The CT instrument is Precision II CT scanner of YXLON.

The ideal 2.5D-woven fabric preform consists of filling warp, weft and binder warp yarns which are shuttled between two adjacent weft yarns. The centerline of the filling warp and weft yarns is straight, without bending deformation, as shown in Figure 1. The x-direction is the direction of the centerline of weft yarn, and the y-direction is the direction of the centerline of the filling warp yarn. Then by using the software of Digimier to process CT images, structural parameters of yarns can be obtained.

2.2. Radial Flow Experiment

The experimental equipment with the specifications listed in Table 1 is characterized in this work. The method of radial flow is applied to obtain the in-plane permeability of 2.5D-woven fabric preforms. The vacuum pump provides a stable negative pressure so that the resin flows from the middle inlet and gradually wets the preform. At the same time, the flow visualization technology is used to monitor the resin flow front. The resin flow in the thickness direction will have a negative influence on the in-plane permeability measurement. In order to avoid this problem, the hollow drill is used to open a straight hole in the middle of the preform to ensure that the resin flow front in the thickness direction is uniform during the wetting process.
Figure 1. The ideal model of 2.5D carbon fabric.

Table 1. Specifications of experimental equipment.

| Equipment                  | Specification                        |
|----------------------------|--------------------------------------|
| Vacuum Pump                | Shanghai Vacuum Pump: 2XZ             |
| 2.5D-woven preform         | 1/3 twill weave, T800 carbon fiber   |
| Rotating viscometer        | Bangxi Instrument: NDJ-8S             |
| Flow monitoring            | Apple Mngx2ch/a                      |
| Resin                      | Customization                        |
| Testing mold               | Customization                        |

Combined with the injection pressure and resin viscosity, the in-plane permeability and the deflection angle (δ) that between the X-direction of the principal permeability and the warp direction were calculated by using the two-dimensional in-plane permeability formula. The directions of principal permeability are defined as X-direction and Y-direction. The resin flow process is shown in Figure 2. The experimental parameters are shown in Table 2.

Table 2. Experimental parameters of the compressed preform.

| Serial number | Original thickness | Thickness after compression | $V_f$ (%) | Viscosity ($mP_0/s$) |
|---------------|-------------------|----------------------------|-----------|----------------------|
| C0            | H                 | H                          | 48.4      | 50                   |
| C1            | H                 | 0.86H                      | 54        | 50                   |
| C2            | H                 | 0.76H                      | 61        | 50                   |

Figure 2. Typical resin flow process of the preform.

The time and distance by processing the resin flow image are obtained. According to the formula of two-dimensional in-plane permeability (1), (2), the in-plane permeability can be gained [16].

$$K_x = \frac{\mu \varepsilon}{4 \Delta P} x_f^2 \left[2 \ln \left(\frac{R_0}{r_f}\right) - 1\right]$$ (1)

$$K_y = \frac{\mu \varepsilon}{4 \Delta P} y_f^2 \left[2 \ln \left(\frac{R_0}{r_f}\right) - 1\right]$$ (2)

Here, $K_x$ and $K_y$ are the X-direction and Y-direction of principal permeability respectively. $x_f$ and $y_f$ are the positions of flow front in two principal directions. $R_0$ denotes the radius of the injection port. $\mu$ is the viscosity of the resin, $\varepsilon$ is the porosity.
3. Numerical Analyses

3.1. Geometrical Modelling for 2.5D-woven Fabric Preforms

Structural parameters of yarns can be obtained by CT images. This paper uses the following assumptions when establishing the structure model of yarns:

1. The cross-section of the warp yarn is rectangular;
2. The weft yarns are divided into two types. Type I: The cross-section consists of two arcs which are at the top and bottom ends and the two arcs are connected by two straight lines respectively. Type II: The cross-section is a parallelogram. The cross-section area of these two kinds of weft is identical. The transition area between the two yarn cross-sections is ignored;
3. The centerline of the filling warp yarn is straight;
4. The cross-section of all yarns is consistent along the centerline;

The simplified dimension and structure of the preform are shown in Figure 3. The central part of the illustrated structure is weft yarn.

Here, \( W \) is the cell length, \( c \) is the cell width, and it indicates the length of the warp cross-section. \( B \) is the height of the interior cell, \( B_1 \) is the height of surface cell, \( a \) is the long semi-axle of Type I weft, and \( b \) is the height of the weft cross-section. \( f \) is the length of the straight line of the Type I weft. \( e \) and \( h \) are the length and height of the Type II bottom side respectively, and the cross-section areas of Type I and Type II are equal. \( d \) is the height of warp yarn, \( \alpha \) is the orientation angle of binder warp yarn which characterizes its variation trend. \( \beta \) is the orientation angle of weft yarn, formed by the intersection of the centerline of weft yarn and the positive direction of horizontal line.

3.2. Unit Cell

According to the above structural parameters, the ideal model of 2.5D-woven fabric preforms (Figure 1) is transformed into the unit cell model which is shown in Figure 4(a). The minimum periodic unit cell is divided into eight parts which are shown in Figure 4(b). Surface cells include SC1, SC2, SC3, and SC4. Interior cells include IC1, IC2, IC3 and IC4. According to the bending deformation, the weft yarns are divided into two types. One has a straight centerline, including SC1, SC2, SC3, IC1, IC2, and IC3, and the other has the orientation angle (\( \beta \)), including SC4 and IC4.
Figure 4. Structure model of carbon fabrics. ((a) Structure of periodic unit cell in carbon fabrics, (b) Eight cell models, green: weft yarn, yellow: warp yarn, gray: the gap region of bundles.)

3.3. Computation of Numerical Permeability
Considering the two-scale structure in inter-yarn and intra-yarn, a porous medium model is adopted. The parallel and vertical porous media regions are used to replace the parallel and vertical fiber yarns respectively. The computational fluid dynamics (CFD) software is used to simulate the resin flow in eight unit cells to obtain the data of mass flow. Then, according to the Darcy formula [17], the permeability values of the eight cells are obtained. The boundary nodes in the z-direction are set as the inlet, which is shown in Figure 4(a). The x-direction and y-direction permeability values of each cell are brought into the model. The resin flow is simulated by the software of PAM-RTM. According to the resin flow situation, the $\delta$, flow velocity and filling time can be obtained. Then, the in-plane permeability of preform would be obtained by using the Darcy formula.

4. Results and Discussion

4.1. Deformation of Fabric Preforms with Compressive Deformation
The actual cross-section feature size and orientation of yarns with different compression ratios are got by CT. The yarn orientation and cross-section shape are shown in Figure 5.

Figure 5. Fiber tow cross sections ((a) View from weft direction of binder warp zone, (b) View from weft direction of filling warp zone, (c) View from warp direction)

Compared with the ideal preform structure in Figure 1, it is found that the binder warp yarns between the upper and lower adjacent weft yarns, the filling warp yarn is not bent substantially and its centerline is straight. These two types of yarns are arranged at intervals. The weft direction and cross-section shape have changed, and micro-bending occurred at the same time. The cross-section shape and area of the weft and warp remain unchanged. The specific cell parameter information is shown in Table 3.

In these experiments, as the degree of compression increases, $\alpha$, $\beta$, b, and d decreased. This is because after weaving, the weft yarn is compressed by warp yarn, resulting in slight deformation. And the heights of weft and warp are both reduced with the decrease of fabric thickness. The yarns of the preform are gradually compacted, and the remaining parameters of yarns remain unchanged.
Table 3. Main parameters of unit cell under different compression.

| Serial number | Surface cell size(mm) | Interior cell size(mm) | α(°) | β(°) | b(mm) | d(mm) |
|---------------|-----------------------|------------------------|------|------|-------|-------|
|               | c/H                   | W/H                   | B1/H | c/H  | W/H   | B/H   |
| C0            | 0.119                 | 0.355                 | 0.147| 0.119| 0.355  | 0.141 |
|               |                       |                       |      |      |       |       |
| C1            | 0.119                 | 0.355                 | 0.130| 0.119| 0.355  | 0.120 |
|               |                       |                       |      |      |       |       |
| C2            | 0.119                 | 0.324                 | 0.118| 0.119| 0.324  | 0.105 |

4.2. In-plane Permeability

According to the formula of two-dimensional in-plane permeability, the in-plane permeability values can be gained. The calculation shows the time variation of in-plane permeability and deflection angle (δ) (Figure 6-7). $K_a$ and $K_b$ are reference standard value. $T_0$ is the total filling time, which represents the time from the beginning of the resin injection to the end. $T$ is the time from resin injection to calculate permeability.

![Figure 6. Principal permeability values of X and Y direction in three compression ratios.](image)

![Figure 7. Deflection angle (δ) values in three compression ratios.](image)

In the initial stage, due to the high flow rate and the big area ratio of the unsaturated region to the saturated region, the measured permeability values are large. As the resin flows continuously, the flow rate decreases and tends to be a constant value, the variation of measured permeability values has the similar tendency. The unsaturated flow in the 2.5D woven texture leads to the gradually expanding rough boundary of the saturated region, combined with the deviation in setting the resin boundary by using the software of Digimier, the measured δ values have larger fluctuation. The time range in which the permeability values and δ are relatively stable is selected to calculate the value of principal permeability, as shown in Table 4.

Table 4. The permeability of 2.5D-woven fabric preforms with different compression ratios.

| Serial number | $V_f$ (%) | $K_x (K_a \times 10^{-11}m^2)$ | $K_y (K_b \times 10^{-11}m^2)$ | δ(°) |
|---------------|-----------|-------------------------------|-------------------------------|------|
| C0            | 48.4      | 1.07                          | 1.12                          | 13.6 |
| C1            | 54        | 0.79                          | 0.73                          | 22.4 |
| C2            | 61        | 0.51                          | 0.42                          | 21.2 |

It is found that when the $V_f$ is 48%-61%, the principal permeability decreases with the increase of the compression degree. And the overall variation of permeability value is a linear tendency, while the value of δ is basically stable at 22 °after preform is compressed. As the degree of compression increases, the deformation of the preform mainly occurs in the z-direction. The yarns are gradually compacted, both of the cross-section height of the warp and weft yarns and the gap of inter-yarn and intra-yarn are reduced. These deformations are confirmed by CT, which gets the cross-section features of the preform. In summary, the compression leads to a reduction of the gap of inter-yarn and intra-yarn, which impedes the resin flow, resulting in the descent of the permeability.
4.3. Numerical Simulation

The in-plane permeability of preform are obtained by the Darcy formula, which is shown in Table 5.

Table 5. In-plane permeability of preform with different compression ratios.

| Serial number | \( \alpha \) (°) | Expt. | Simulation | \( K_x \) (\( K_a \times 10^{-11} \) m²) | Expt. | Simulation | \( K_y \) (\( K_b \times 10^{-11} \) m²) | Expt. | Simulation | \( \delta \) (°) |
|---------------|----------------|-------|------------|-------------------------------|-------|------------|-------------------------------|-------|------------|----------------|
| C0            | 26.5           | 1.07  | 2.09       | 1.12                          | 1.79  | 13.6       | 6.8                           |
| C1            | 25             | 0.79  | 1.50       | 0.73                          | 1.10  | 22.4       | 9.4                           |
| C2            | 23             | 0.51  | 0.96       | 0.42                          | 0.76  | 21.2       | 9.7                           |

Comparing the numerical simulation results with experimental measurement results, it can be concluded that the simulated values of principal permeability are larger than the experimental values, but both of them are at the same order of magnitude. The simulated value of the \( \delta \) is smaller than the experimental measurement, but the simulated value follows the same trend as the measured data. Besides the certain deviation of the experimental permeability to the actual permeability, the simulate setting of boundary conditions, in which the interaction between the two adjacent periodic unit cells is weaken, may mainly cause this problem. In the follow-up research, this aspect is meaningfully improved.

This numerical simulation method is used to predict the in-plane permeability of 2.5D-woven fabric preforms. The \( V_f \) of these four compressed fabrics are 50\%, 52\%, 56\%, and 58\%, respectively. Finally, the curve fitting results are shown in Figure 8 and Figure 9. It can be found that after the 2.5D-woven fabric preforms is compressed, the principal permeability decreases with the increase of the \( V_f \), and the \( \delta \) increases first and then gradually stabilizes, and its variation range is 6.8°-9.7°.

![Figure 8](image1.png)  ![Figure 9](image2.png)

Figure 8. Prediction curve of deflection angle (\( \delta \)) with fiber volume fraction.

Figure 9. Prediction curves of X-direction and X-direction permeability in different \( V_f \).

The major difficulty is that different regions of the carbon fiber fabric are subjected to different compressions during RTM molding, which makes it impossible to complete the experiment test and obtain the in-plane permeability by one test. However, the permeability values and \( \delta \) can be obtained by the prediction curve, which can offer a reference for subsequent RTM molding simulation, optimize the design of molds, avoid manufacturing defects and reduce costs.

5. Conclusions

Compared with previous permeability researches, accurate section structure and orientation of yarns are taken into consideration in this work of 1/3 twill 2.5D-woven fabric preforms. Besides, priority consideration is given to the two-scale flow in inter-yarn and intra-yarn in numerical simulation. And good results are obtained. The following conclusions were drawn:

1. The in-plane permeability coefficients of 2.5D-woven fabric preforms with various compression ratios are obtained by experiments. When the \( V_f \) is 48\%-61\%, the in-plane permeability decreases linearly with the increase of \( V_f \), but the \( \delta \) is stable at 22°.

2. The accurate geometric modeling and numerical prediction method for 2.5D-woven fabric preforms are validated. The permeability of compressed 1/3 twill 2.5D-woven fabric preforms whose \( V_f \) is 48\%-61\% can be predicted and the deviation is within an acceptable range.
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