검사체적 방법을 이용한 평직의 투과율 계수 예측

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Permeability prediction of plain woven fabric by using control volume finite element method

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Key Words : permeability, plain woven fabric, unit cell, control volume finite element method

ABSTRACT

The accurate permeability for preform is critical to model and design the impregnation of fluid resin in the composite manufacturing process. In this study, the in-plane and transverse permeability for a woven fabric are predicted numerically through the coupled flow model which combines microscopic with macroscopic flow. The microscopic and macroscopic flow which are flows within the micro-unit and macro-unit cell, respectively, are calculated by using 3-D CVFEM(control volume finite element method). To avoid checker-board pressure field and improve the efficiency on numerical computation, A new interpolation function for velocity is proposed on the basis of analytic solutions. The permeability of plain woven fabric is measured through unidirectional flow experiment and compared with the permeability calculated numerically. Based on the good agreement of the results, the relationships between the permeability and the structures of preform such as the fiber volume fraction and stacking effect can be understood. The reverse and the simple stacking are taken in account. Unlike past literatures, this study is based on more realistic unit cell and the improved prediction of permeability can be achieved. It is observed that in-plane flow is more dominant than transverse flow in the real flow through preform and the stacking effect of multi-layered preform is negligible. Consequently, the proposed coupled flow model can be applied to modeling of real composite materials processing.

1. Introduction

In the resin transfer molding, there are many advantages such as high volume, high performance, and low cost. The permeability is essential in the design and operation of the process. Traditionally, the determination of permeability can be divided as three methods, which are experimental measurement, analytical, and numerical prediction using the Darcy's law.

In this study, the permeability in the microscopic level is first computed on the square-packing and hexagonal packing structures of the filaments inside the yarn by using CVFEM. Also the permeability of macroscopic unit cell which represents the plain woven fabric but excludes the yarns is calculated through the same numerical method. Then using the proposed coupled flow model, the permeability is predicted for the real woven fabric and compare with experiment of Kevlar plain woven. Unlike past efforts in modeling the microstructure for determining the permeability, the present study considers more realistic representation of the three-dimensional fabric architecture which includes tow crimp, spacing, stacking, and the like.

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2. Theory

2.1 Coupled flow model

The porous flow in the plain woven has microscopic and macroscopic flow, i.e. intra-tow and inter-tow flow, respectively. In the coupled micro- and macroscopic flow model, referred as the coupled flow model as coupled flow model, instead of calculating the Brinkman equation, the concept such as the rule of mixture is used to determine the permeability. Fig. 1. depicts the thought regarding the real plain woven unit cell as the several rectangular parallelepipeds which retain original volumes.

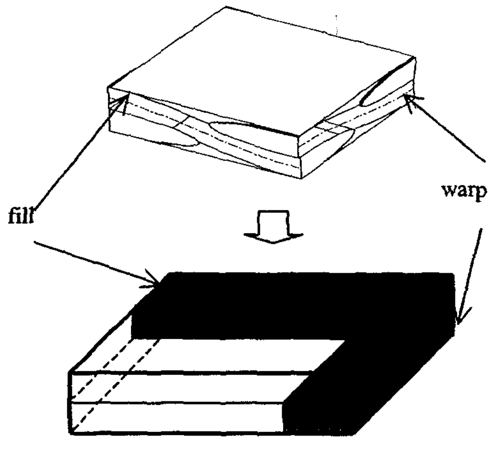


Fig. 1. Schematic diagram showing the concept of the coupled flow model

It is assumed that the cross-section of yarn is the ellipse whose major axis is constant. Through some geometrical considerations, The fiber volume fraction within a bundle, $V_{f,micro}$ and the volume fraction of fiber bundles, $V_{b,macro}$ are given as

$$V_{f,micro} = \frac{Nr_f^2}{ab},\ V_{b,macro} = \frac{V_f}{V_{f,micro}}$$

Where N is the number of filaments in a bundle, r is the radius of fiber and a and b are the major axis and minor axis of ellipse respectively. Finally The total permeability can be given as following equations.

$$K = K_{matrix} + \frac{1}{2}V_{b,macro}K_f + \frac{1}{2V_{b,macro}}K_w \quad (1)$$

where K_{matrix}, K_f, and K_w are the permeabilities in the only matrix, fill, and warp yarn part, respectively.

3. Numerical analysis

3.1 Numerical method

In order to get the flow field, the continuity equation and stokes equation are solved by using CVFEM(Control-Volume Finite Element Method). The governing equations are as follows

$$\nabla \cdot \mathbf{u} = 0$$

$$\nabla P = \mu \nabla^2 \mathbf{u}$$

In each element, the velocity is interpolated as second order formula by considering pressure gradient as source which prevents checker board pressure and the pressure is interpolated linearly. The sub-control volume from the four-node tetrahedron which is used as the basic discretization element is made and treated.

$$u = Ax + By + Cz + D - \frac{1}{\mu}\frac{\partial p}{\partial x}\left[x - \frac{1}{4}(y^2 + z^2)\right]$$

$$P = A^p x + B^p y + C^p z + D^p$$

The components of y and z are similar with the above formula.

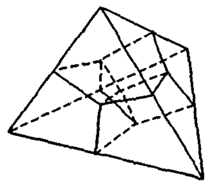


Fig. 2. Division of tetrahedral element into portions of polyhedral control volumes.

3.2 Microscopic flow simulation

It is considered that the filaments within the yarn is packed in the form of square and hexagonal structure. In each unit cell, the pressure gradient is given along flow direction and the symmetry boundary conditions are imposed along the planes of symmetry. Then the permeability is calculated by the following equation.

$$K = \frac{Q\mu}{A\Delta P}$$,where A is the cross-sectional area.

From the microscopic flow simulation, the axial and transverse permeabilities which can be regard as K_f and K_w is calculated.

3.3 Macroscopic flow simulation

As referred above, the governing equations can be solved by using proper boundary conditions which are non-slip at surfaces of yarn and symmetry conditions.

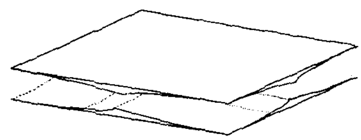
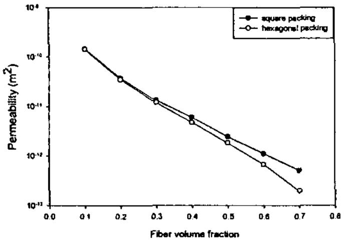


Fig. 3. the only matrix region of unit cell

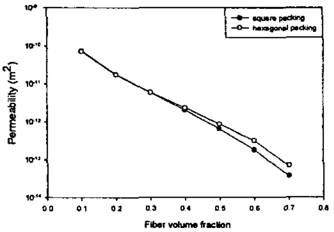
Through the same procedure with microscopic flow simulation, macroscopic permeability, K_{matrix} can be solved.

4. Results

4.1 Microscopic flow simulation



(a) axial flow

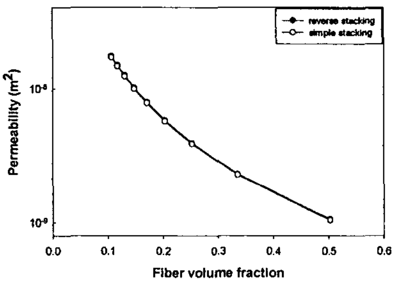


(b) transverse flow

Fig. 4. Permeability obtained by the microflow numerical analysis.

4.2 Coupled flow model

The permeability obtained by using equation (1) is a little higher than experimental value, because in this study, the fabric shift and yarn nesting effect is ignored.



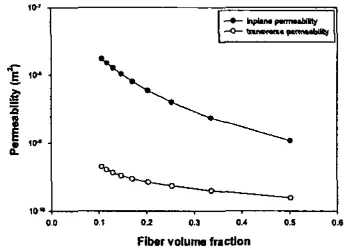


Fig. 5. Total permeability computed by using coupled flow model

5. Conclusions

The discrepancy between numerically obtained and experimentally measured permeability is due to non-uniformity present in the preform. To obtain more exact permeability, other structural characteristics such as the nesting and the phase shifting effect must be considered.

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