# 브레이드 프리폼의 투과율 계수 예측

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# Prediction of Permeability for Braided Preform

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## ABSTRACT

Complete prediction of second order permeability tensor for three dimensional circular braided preform is critical to understand the resin transfer molding process of composites. The permeability can be predicted by considering resin flow through the multi-axial fiber structure. In this study, permeability tensor for a 3-D circular braided preform is calculated by solving a boundary problem of a periodic unit cell. Flow field through the unit cell is obtained by using a 3-D finite volume method (FVM) and Darcy's law is utilized to obtain permeability tensor. Flow analysis for two cases that a fiber tow is regarded as impermeable solid and permeable porous medium is carried out respectively. It is found that the flow within the intra-tow region of the braided preform is negligible if inter-tow porosity is relatively high but the flow through the tow must be considered when the porosity is low. To avoid checkerboard pressure field and improve the efficiency of numerical computation, a new interpolation function for velocity variation is proposed on the basis of analytic solutions. Permeability of the braided preform is measured through a radial flow experiment and compared with the permeability predicted numerically.


## 1. Introduction

In this study, permeability tensor is computed for a three dimensional braided preform by applying a FVM to a unit cell. It is evident that resin will flow through the inter-tow and the intra-tow regions when pressure gradient is applied to the resin. The intra-tow region in the braided preform is regarded as not only an impermeable solid but also a permeable porous media. When the intra-tow region is excluded from domain of flow analysis in the case of the impermeable solid, the Stokes equation is computed for only inter-tow region. In the case of the porous media, the Stokes and the Brinkman equations are used to calculate flow field in the inter-tow and intra-tow regions, respectively. In order to obtain the permeability experimentally, a radial flow test is performed and the results are compared with numerically predicted values.

## 2. Geometric modeling

The braided preform is produced by using a 3-D circular braiding machine which has the compressed air mode and 11 machine pattern. 3-D circular braiding process is composed of two motions, beating and step motions. The beating motion makes the structure of yarn more solid-like by compacting the yarns in axis direction and the step motion comprises four steps to obtain the

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same arrangement of carriers. Based on the carrier motion, a geometric modeling is conducted. The braiding machine is composed of 12 carriers in radial direction and 48 carriers in circumferential direction, i.e., 1248 preform patterns are available. But 748 carriers are used in this study. The braided preform has a geometrical structure repeated per pitch length along cylindrical mandrel axis and the repeated structure again consists of the same 24 unit cells in the circumferential direction. As 7 carriers exist in the radial direction on the machine bed, each unit cell comprises 7 sub-unit cells, that is, 5 inner unit cells and 2 surface unit cells. Figure 1 shows the unit cell which is composed of the sub-unit cells. Most of the previous studies have used straight lines to describe yarn paths in the unit cell of the braided preform. In this work, however, the yarn paths are described as curved spline functions which are close to real geometry of the 3-D braided preform. In order to calculate permeabilities by using the numerical method, a curved unit cell is flattened.

## 3. Numerical analysis

### 3.1 Governing equation

In this study, flow in the inter-tow region is governed by both the continuity and the Stokes equations as follows.

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

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

As the tow of the braided preform is treated as a permeable porous medium, the flow within intra-tow region is modeled by using the Brinkman equation given by

$$\mu_e \nabla^2 < \mathbf{u} > - \mu \mathbf{K}^{-1} \cdot < \mathbf{u} > = \nabla < p >$$

where $\mathbf{K}^{-1}$ is the permeability tensor for the fiber tow and < > means volume averaged value. $\mu_e$ is the viscosity used in the porous medium. In order to examine contribution on overall flow of the flow through intra-tow region, the tow is also regarded as impermeable solid and the intra-tow region is excluded in the domain of the flow analysis. It is assumed that $\mu$ is equal to $\mu_e$ . Because the Brinkman equation contains permeability tensor of the intra-tow region, the permeability tensor is obtained from numerical flow analysis for the micro-unit cell which represents periodic structure of filaments inside the tow. The filaments are thought to be arranged in the hexagonal array owing to more acceptable than quadratic array. As the braided preform is compacted under pressure, the permeability of the intra-tow region is also varied as a function of intra-tow porosity. The permeability tensor of the intra-tow region is transversely isotropic for plane perpendicular to filament axis but each axes of lots filaments doesn't accord with the direction of global flow along which pressure gradient is imposed. The coordinate transformation between each direction of the tow composed of filaments and the direction of global flow is needed to conduct by using basis of direction vectors as follows.

$$\mathbf{K}_G = \mathbf{T}^T \mathbf{K}_L \mathbf{T}$$

where $\mathbf{K}_G$ represents the permeability tensor for the direction of global flow, global coordinate frame and $\mathbf{T}$ is the transformation matrix obtained from direction vectors and $\mathbf{K}_L$ is permeability tensor for the direction of the tow, local coordinate frame. The Brinkman equation needs to utilize the permeability tensor for global coordinate frame as an input.

### 3.2 Flow analysis for unit cell

When the tow is regarded as permeable porous medium, flow simulation is performed simultaneously for both the inter-tow and intra-tow regions within a unit cell shown in Fig. 2. but in the case that the tow is thought as impermeable solid, the flow analysis domain is only the inter-tow region and the flow simulation is carried out the region.

A single tow is composed of about 9000 filaments whose diameter is about 9 μm. As the braided preform is compacted, both the intra-tow and the inter-tow porosities are varied. Three dimensional numerical analysis is carried out for the flow along the plane and the flow perpendicular to the plane of the unit cell by using the CVFEM described above. When the braided preform is compacted, minor axis of elliptic cross-section in the unit cell is reduced while the major axis is assumed to be constant. The governing equations, the Stokes equation and the Brinkman equation, can be solved by assuming appropriate boundary conditions for the in-plane flow and for the flow perpendicular to the plane. Pressure is imposed at the inlet and the outlet planes of the unit cell and periodic boundary conditions are given along the planes. It is also assumed that velocity is zero on tow surfaces. The velocity and pressure fields are obtained for the unit cell and total flow rate, $Q$, is calculated for each direction. Then the permeability, $K$, for each direction of the unit cell is obtained through the following equation.

$$K = \frac{Q\mu}{A\Delta p}$$

where $A$ is the cross-sectional area including both fluid and fibers. As a result, the second order permeability tensor for the braided preform is obtained.

## 4. Results and discussion

The velocity and pressure distributions obtained from the numerical calculation are used to predict the permeability tensor of the braided preform with above equation. Based on the experimental results, principal directions of the permeability tensor are determined as the x, y, and z directions of the unit cell, which are circumferential, mandrel axis, and thickness directions of the preform. As the braided preform is compacted under the applied pressure in the mold, thickness and porosity of the preform are reduced. The permeability for each principal direction is obtained numerically with respect to the entire porosity as shown in Fig. 3 (a). The permeability increases with the increase in the entire porosity and the permeability for y direction has the highest value. The results are explained if geometrical architecture is examined. Because the average yarn orientation angle from the mandrel axis is 26, the flow in y direction will be dominant. The contribution on permeability tensor of the intra-tow flow (e.g., intra-tow permeability) can be neglected if the entire porosity is above about 0.6. In this case, it is sufficiently accurate that the tow is regarded as impermeable solid and is numerically much efficient. When the porosity is low, the permeabilities for thickness direction of the preform are different in two cases considering the tow as porous medium and solid. Therefore, the flow through the tow along the direction of thickness is important at low porosity and must be taken into account. The predicted permeability is compared with the experimental results as shown in Fig. 3 (b). When the thickness of the mold cavity is reduced much to achieve high fiber volume fraction, it is difficult to generate an FE mesh owing to high compaction and geometrical complexity, and large deformation of the transparent top plate of the mold is observed. Therefore, both the numerical prediction and experimental measurements are performed for the porosity higher than 50 %. There are some discrepancies between numerical and experimental results in the case of x direction. The differences may be attributed to the nesting and shifting effects of the layers between sub-unit cells, distortion of the unit cell during flattening the cylindrical preform, and coarseness of the FE mesh.

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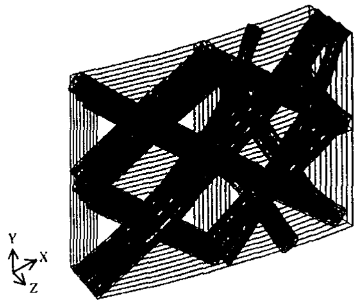
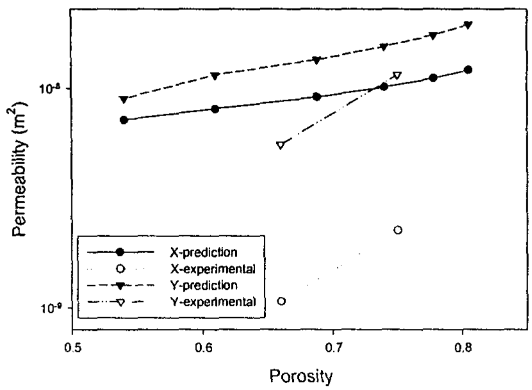
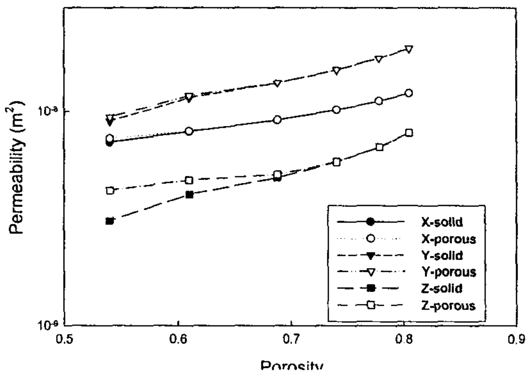



Fig. 1. Curved unit cell for 3-D circular braided preform


Fig. 2. Geometrical structure of flattened unit including sub-unit cell




(a)




(b)

Fig. 3. (a) Comparison of permeabilities predicted for each direction as a function of porosity, (b) Comparison of permeabilities predicted for each direction as a function of porosity