PERMEABILITY FOR FLOW ALONG AND ACROSS FIBER BUNDLES: TESTING OF PERMEABILITY MODELS THROUGH TOW-SCALE EXPERIMENTS AND SIMULATIONS

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Introduction

Liquid Composite Molding (LCM) constitutes an important set of technologies for manufacturing polymer composites that include processes such as Resin Transfer Molding (RTM), Vacuum-Assisted Resin Transfer Molding (VARTM), etc. Several simulations of the LCM mold-filling processes have been developed by companies and academic institutions to reduce the LCM mold-design time.

There have been several studies/simulations involving sink effect as well as void formation in dual-scale fabrics that required modeling of microscopic flows in tows using Darcy's law, which in turn required estimating the tow permeability. Researchers have used theoretical models, such as the Gebart's model, for this purpose which often assume that the fibers are arranged parallel to each other in perfect square or hexagonal arrays. However, what is surprising is that despite being used so widely over last several decades, these models have *never been tested for their accuracy* by comparing their predictions with the permeability measured at the tow level using experiments.

In the current investigation, the permeability of glass-fiber tow at three different fiber-volume-fractions (60%, 55%, 50%) have been obtained by using different methods. The permeability of such porous media is determined by: a) an experimental method adapted for such tow-scale systems, b) theoretical models available in literature, and c) numerical simulations based on solving Stokes flow and Whitaker's closure formulation equations. The results derived from all these methods have been compared to find the degree of accuracy and agreement among them.

Permeability estimation methods

Theoretical models

The theoretical models for tow permeability are strong functions of fiber diameter and fiber volume fractions. The bundles/tows are often idealized as stacks of aligned parallel fibers which create a transversely-isotropic porous medium. The permeability models tested in our investigation are the models developed for the flow axial to parallel fibers (models by Berdichevski and Cai, and Gebart) and the models for the flow transverse to parallel fibers (models by Berdichevski and Cai, Gebart, and Bruschke and Advani).

Numerical simulation methods for permeability estimation

a. Stokes flow simulation (GeoDict)

Since we are interested in slow creeping flows through a porous medium, the particle-based Reynolds number has to be less than 1. In this such flow regime, the inertia terms in the Navier-Stokes equation can be neglected and the resulting Stokes equation representing momentum-balance is solved using a commercial software GeoDict popular in the geoscience area. Unit cells are created by randomly distributing aligned fibers (of measured average diameters) within the cells.

b. Closure formulation (COMSOL)

The formulation developed by Whitaker, based on the volume averaging method as employed to derive Darcy's law, is used for numerically estimating the tow permeability. The great advantage of the formulation being that the full permeability tensor can be obtained from a single simulation in the above mentioned unit cells. One solves the boundary value problem consisting of the transformed 'momentum' equation $-\nabla d_f + \nabla^2 D_f + I = 0$ and 'continuity' equation $\nabla . D_f = 0$. The closure tensor variable D_f used in the transformation is first estimated within the unit cell by solving the closure formulation as given by this boundary value problem. One can then estimate the permeability tensor, K, using the intrinsic phase-averaging relation $K = \varepsilon_f \langle D_f \rangle^f$. We solved the closure formulation using the multiphysics software COMSOL.

Experimental Method

For our glass-fiber tows, we choose to apply an adapted falling-head method to measure the permeability. The falling-head method is based on the flow of a liquid through a prepared sample of a bundle which is connected to a graduated duct. The setup is held vertical to enable the gravity-driven liquid flow through the porous bundle either axially or transversally. As the head at the inlet decreases, the inlet pressure driving the flow decreases with time. The duct is filled with a test liquid that has its density and viscosity measured. If the initial height of the liquid column in the burette is h_1 at time $t = t_1$, and the height reduces to h_2 at the end of the experiment at time $t = t_2$, then the permeability of the bundle, K, can be estimated through the formula $K = \frac{\mu a L}{\rho g A(t_2 - t_1)} \ln \frac{h_1}{h_2}$ where A is the cross-section area of the bundle sample while a is the cross-section area of the duct.

Result and Discussion Here the x and y axes are the two perpendicular directions transverse to the tow axial direction, the z axis.

FLOW ALONG TOW AXIS

As can be seen from Table 1, a remarkable closeness can be seen between the permeability predictions by the two numerical methods, and the experimental results. It is to be remembered that getting a match with in an order of magnitude is often considered quite creditable in any permeability study. Hence this effort of ours to simulate the permeability along the fibers can be considered to be quite accurate. However, surprisingly, the permeability obtained from the theoretical models is one order of magnitude greater than the numerical and experimental results.

FLOW TRANSVERSE TO TOW AXIS

First the permeability in the two transverse directions are obtained from the numerical methods and the analytical models, and later they are compared with the experimental values in Table 2. We observe that the K values predicted by the three analytical models (Berdichevski and Cai, Gebart, and Bruschke and Advani) are again rather lackluster—they are more than twice the experimental and numerical K values, though they achieve parity in the orders of magnitude. This time the Stokes flow simulation is more accurate than the closure formulation one. It is heartening to note that most of the models, whether numerical or analytical, furnish permeability values that fall within an order of magnitude of the experimental results. It is also worth noting that the transversal K_x and K_y values are fairly close to each other, as it should be.

An important takeaway from this research has been the good accuracy of the two numerical methods used to estimate the fiber-tow permeability. Also, this study highlights the need to develop more accurate analytical models for permeability for flow along the fibers in fiber-bundles and -tows. It also seems that microscopic effects such as fiber clustering and fiber length-wise crookedness need not be considered explicitly for enhancing the accuracy of the tow-scale permeability models.

Table 1: For flow along the tow axis, the permeability (K) values (Units: 10^{-11} m^2) obtained from the numerical simulations and theoretical models are compared with those from the experiments.

	K_z(Stokes flow)	K_z(Closure)	K_z (Experiments)	Berdichevski and Cai	Gebart
Fvf = 60%	1.09	1.2	2.09	35.6	18.6
Fvf = 55%	1.48	1.8	2.09	58.7	31.5
Fvf = 50%	3.29	2.67	5.65	94.5	52.3

Table 2: For flow transverse to the tow axis, a comparison of the permeability values (Units: 10^{-12} m^2) obtained from the numerical simulations and theoretical models with those from the experiment. The fiber volume fractions are of the same values and order as listed in Table 1.

K_y Stokes Flow	K_x Closure	K_y Closure	K_x Experiments	K_y Experiments	Gebart	Berdichevski -Cai	Bruschke –Advani Square unit cell	Bruschke –Advani Hexagonal unit cell
0.1	0.59	0.51	0.26	0.33	1.33	1.92	1.37	0.79
0.69	1.64	1.78	0.58	0.65	2.27	3.25	2.11	1.21
1.18	3.15	3.35	1.11	1.38	3.75	5.35	3.11	1.79