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Effect of relative ply orientation on the through-thickness permeability of unidirectional fabrics

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ABSTRACT

When unidirectional stitched fabrics are used as reinforcement in composites, plies are typically stacked on top of each other to build up the desired thickness. Strength and stiffness requirements dictate the orientation of individual layers and the accuracy of angular alignment is limited. A pressure differential across the thickness is used to distribute the resin, either from a pre-impregnated fabric or injected from a resin source, to occupy all of the empty spaces between the fibers. This process is commonly modeled using Darcy's law, which describes flow of resin through porous media in which the flow rate is directly proportional to the applied pressure differential by the through-thickness permeability of the fabric. A different orientation between layers or even a slight misalignment during the stacking can change the through-thickness permeability dramatically due the change of resin pathways. In this work, we characterize the through-thickness permeability of a series of unidirectional fabrics stacked in various orientations to address both the effect of stacking sequence and those of misalignment of the individual layers. We conduct numerical simulations to predict the effect of change in fiber orientation on the through-thickness permeability. The results from the numerical model are compared with experimental measurements. Our results show that averaging approach is not suitable to calculate the through-thickness permeability component when using unidirectional fabrics and that the stacking sequence of the unidirectional fabrics may significantly influence the through-thickness permeability. We also show that the effects of small misalignments between individual layers do not significantly modify the transverse flow.

1. Introduction

In Liquid Composite Manufacturing (LCM) processes, the resin is infused into stationary reinforcement under positive or atmospheric pressure to saturate the spaces between fibers to fabricate the composite material. In other processes, such as out-of-autoclave processing of partially saturated prepregs, the excess resin is displaced into empty spaces under pressure to fully saturate the spaces between the fibers although the transport distances may be much shorter. Obviously, full saturation is required. To accomplish it careful selection of process parameters such as injection pressure and inlet location is needed. One may apply simple relations or full blown numerical simulations (such as those for LCM process) to estimate time to fill the mold, to identify the optimal locations for placement of gates and vents, and to find regions which may be susceptible to formation of dry-spots. However, validity of the simulation or governing equation result completely depends on the fidelity of the material input data such as viscosity of the resin and the permeability of the fabric placed in the mold. Hence it is important to characterize the permeability (and other material data) accurately.

Permeability of a woven or stitched fabric is different in different directions. The impregnation of the resin into the fabric is modeled as flow through porous media due to the applied pressure difference generalizing Darcy's law which relates the average velocity of the fluid to the pressure gradient as shown below in Eq. (1)

$$\bar{\boldsymbol{u}} = -\frac{\boldsymbol{K}}{\mu} \cdot \nabla P \tag{1}$$

where $\bar{\boldsymbol{u}}$ is the volume averaged velocity, μ is the viscosity, ∇P is the pressure gradient and $\boldsymbol{K}$ is the symmetric, positively definite permeability tensor. The components of the permeability tensor, $\boldsymbol{K}$, as shown (in Cartesian coordinates) in Eq. (2), represent how easily resin can flow in the corresponding direction.

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$$\boldsymbol{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \tag{2}$$

There are several approaches to establish the in-plane permeability of a fabric [1–12] and a few ones to measure the through-the-thickness component [1,7,11,12]. The latter presents more difficulties as one needs to measure flow through very small thickness of these fiber preforms. To circumvent that issue, most modelers will use the series-averaged value to assign through-thickness permeability.

This work will analyze through-the thickness flow depending on relative orientation of individual reinforcement layers. It will show that such an averaging approach can result in large errors in calculation of the through-thickness components when the preform consists of layers of unidirectional fabrics stacked in different desired fiber orientations. It will be shown both experimentally and by modeling, that the stacking sequence can significantly influence the through-thickness flow and hence the transverse permeability. This study will, however, show that a limited misalignment between the neighboring layers – which can be attributed to inaccuracy of the layup process – does *not* significantly modify the through the thickness permeability.

We will numerically study a simplified model fabric, as shown in Fig. 1. Through-the-thickness direction is aligned with the z axis. We will assume that this is the principal direction of permeability and will not study the terms K_{yz} and K_{xz}. While this is generally (unless some symmetry is involved) an approximation, these components are usually insignificant. Fig. 1 shows a solid model of three unit cells along with the corresponding cross-section. Each unit cell has four layers of unidirectional fabrics with different fiber orientation sequence in the in plane direction. In Fig. 1a, all plies are aligned in the y-direction, while in Fig. 1b, all plies are still aligned but rotated by 10 degrees with respect to the y axis in the x–y plane, and in Fig. 1c plies are rotated by 10 degrees with respect to the previous ply in the x–y plane as they are stacked on top of each other so the fiber orientation sequence with respect to the y-axis will be 0/10/20/30 degrees. The change in orientation may arise from two sources: First, the design commonly requires that the unidirectional reinforcement is oriented with stacking sequence in pre-determined directions for desired strength and stiffness. This change of orientation from one layer to the next is usually in increments of 15 degrees or more even though several subsequent layers might have the same orientation. Second, the change in orientation may arise due to small unintentional misalignments. We address both these cases.

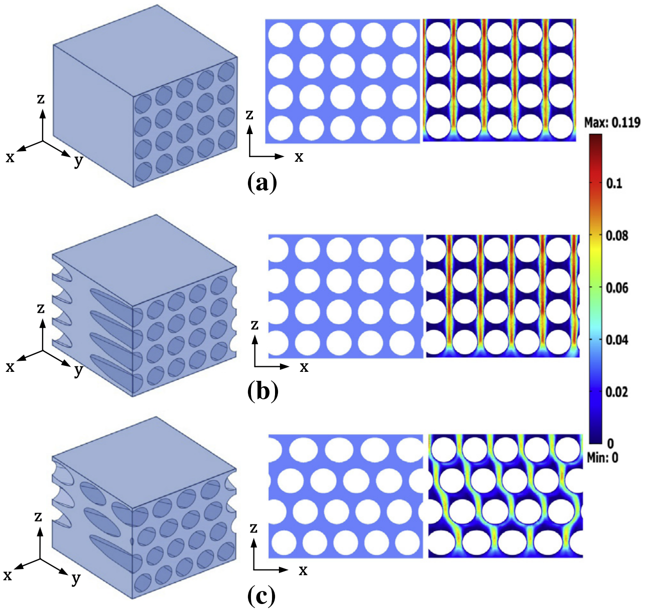

Fig. 1. Solid model of a unit cell and the corresponding cross-section of four unidirectional plies stacked on top of each other. (a) All plies aligned along the y-axis. (b) All plies are rotated by 10 degrees in the x–y plane with respect to the y-axis. (c) Each successive ply is rotated by 10 degrees resulting in a stacking sequence of 0/10/20/30 with respect to the y-axis with the corresponding cross-sections in the through-thickness direction, respectively.

Note that the cross-sectional area for the lay up in Fig. 1c has a very different profile for through-thickness flow of the resin compared to no rotation and rotation of the plies by the same rotation degree (Fig. 1a and b respectively). Thus, the in plane orientation of unidirectional fabrics and their stacking sequence can create different pathways for resin flow in through-thickness direction resulting in different through the thickness permeability values (K_{zz} component). In this study we investigate the effect of the pathways formed by different in plane orientations of the plies on the through-thickness component of the permeability tensor.

The simplified nature of the model is demonstrated by circular cross-sections of the fiber tows and by the absence of stitching which (Fig. 2) may actually form a very sparse "weft" layer. The only effect this stitching has in our model is that we do not allow any interpenetration of subsequent layers.

1.1. Effective permeability of preform stacks

Traditionally, the permeability tensor of a set of unidirectional plies stacked together to form the thickness of the composite is calculated by using the laminate analogy and the tensor transformation rules taking into account the orientation of the plies with respect to a coordinate system [9]. This approach serves reasonably well for two-dimensional (in-plane) permeability components, though some issues have been noted [1]. However, for the three-dimensional permeability tensor – mainly the through-the-thickness component(s), this method has two major shortcomings. First, many models conclude that the permeability component (K_{zz}) in the thickness direction will be the same irrespective of the layup and the stacking sequence [13,14]. This is definitely not the case for unidirectional fabrics. We will show that, for example, 6 plies of unidirectional fabric that are all in the zero direction, their K_{zz} value will be very different from the same 6 plies if they have 0/90 sequence repeated three times. Physically this is true because the permeability depends on easy pathways for flow which will change in the thickness direction as one changes the orientation layup. Secondly, even small layer misalignment could create a flow path which could dramatically increase the through-thickness permeability.

The effect of ply-angle misalignment has been studied in detail on in-plane permeability of woven textiles components, but these

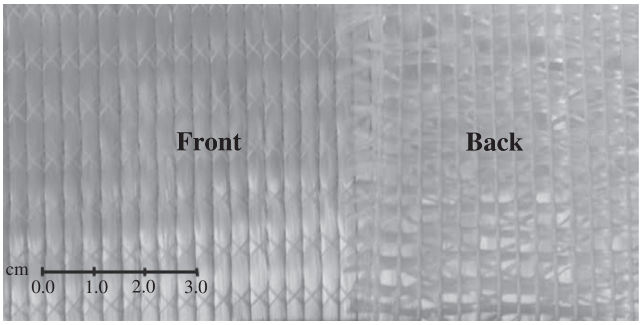

Fig. 2. Front and back sides of the unidirectional fabric.