3D Permeability Characterization of Sheared Fiber Reinforcement for Liquid Composite Molding Process Simulation

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3D Permeability Characterization of Sheared Fiber Reinforcement for Liquid Composite Molding Process Simulation

Collin William Childs

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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Abstract

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Collin William Childs
Department of Mechanical Engineering, BYU
Master of Science

Resin transfer molding (RTM) is an infusion-based closed-mold manufacturing process where resin is injected into a preform of dry reinforcement to create a net shape part. Often, when a preform is draped over a mold with complex geometry, such as the double curvature of a dome, a reorientation of the fibers takes place in the form of in-plane shear. This deformation of the reinforcement structure has the potential to adversely affect the resin flow and the filling of the mold during RTM if the manufacturer fails to properly account for the shear effects.

Various process simulation tools are being developed and used to simulate infusions in a virtual environment and assist manufacturers in optimizing tooling features and process parameters before needing to invest in tooling or prototypes. Such simulation requires material characterization of the resin viscosity and reinforcement permeability. The latter is a function of the reinforcement architecture and is highly sensitive to perturbations such as shear. Permeability measurement is well represented in the literature, but for ideal fabric arrangements without the deformations caused by complex mold geometries typical to industrial parts. The purpose of this study is to develop the first method for measuring the three-dimensional (3D) permeability tensor of a sheared fiber reinforcement in a single test and empirical models to show the effect shear has on permeability. The method and models are intended to enhance the accuracy of infusion simulation and further advance the development of liquid composite molding processes.

Building off the work of previous researchers who have used trellis tools to induce uniform shear on fabric samples and 3D point-infusion tools for radial flow tests, these two methods were combined to measure the sheared permeability of a carbon fiber non-crimp fabric (NCF) in the x, y, and z directions. To mitigate the amount of spring-back that occurs when transferring the sheared preform from the trellis tool to the permeability tool, a method of incorporating an adhesive binder into the preform is presented. Lastly, the permeability data obtained from testing samples sheared at 0, 10, 20, 30, and 40 degrees is documented.

Mathematical models are provided based on the data gathered in this work that show the permeability of a NCF in the x, y, and z directions as a function of shear angle. The resulting models indicate an inverse correlation between permeability and shear due to the reorientation of the fibers and closure of preferential flow channels in the preform. These models can be used to predict the permeability for shear angles less than 40 degrees. To validate these results, theoretical shear permeability models are included for comparison. Recommendations for future studies involving the measurement of 3D sheared permeability are discussed.

Keywords: composites, liquid composite molding, RTM, permeability, 3D ellipsoidal flow, shear
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**NOTATION**
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Cross-sectional area, $\text{m}^2$</td>
</tr>
<tr>
<td>$a$</td>
<td>$K_x/K_x = 1$</td>
</tr>
<tr>
<td>$b$</td>
<td>$K_y/K_x$</td>
</tr>
<tr>
<td>$b_i$</td>
<td>Flow inlet radius in the $i$-direction, mm</td>
</tr>
<tr>
<td>$b_T$</td>
<td>Tube radius, mm</td>
</tr>
<tr>
<td>$c_v$</td>
<td>Coefficient of variation</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus, GPa</td>
</tr>
<tr>
<td>$E_{geo}$</td>
<td>Corrective factor for the in-plane and out-of-plane fiber reorientations</td>
</tr>
<tr>
<td>$F_{Vf}$</td>
<td>Corrective factor for the change in fiber volume fraction</td>
</tr>
<tr>
<td>$h$</td>
<td>Cavity height, mm</td>
</tr>
<tr>
<td>$h_k$</td>
<td>Ply thickness, mm</td>
</tr>
<tr>
<td>$i$</td>
<td>Directional index</td>
</tr>
<tr>
<td>$K$</td>
<td>Permeability tensor, $\text{m}^2$</td>
</tr>
<tr>
<td>$K_e$</td>
<td>Equivalent isotropic permeability, $\text{m}^2$</td>
</tr>
<tr>
<td>$K_i$</td>
<td>Principal permeability in the $i$-direction, $\text{m}^2$</td>
</tr>
<tr>
<td>$K_o$</td>
<td>Unsheared Permeability, $\text{m}^2$</td>
</tr>
<tr>
<td>$k$</td>
<td>Kozeny-Carman constant, $\text{m}^2$</td>
</tr>
<tr>
<td>$L$</td>
<td>Length, m</td>
</tr>
<tr>
<td>$M$</td>
<td>Major axis of resin ellipse, cm</td>
</tr>
<tr>
<td>$m$</td>
<td>Minor axis of resin ellipse, cm</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of plies used in each preform</td>
</tr>
</tbody>
</table>
\( P \) Pressure, Pa
\( \Delta P \) Pressure difference, Pa
\( Q \) Volumetric flowrate, m\(^3\)/s
\( R^2 \) Coefficient of determination
\( r_i \) Principal flow radius in the \( i \)-direction, cm
\( S_o \) Areal weight, g/m\(^2\)
\( T \) Temperature, °C
\( t \) time, sec
\( V_f \) Fiber volume fraction
\( V_{f_0} \) Unsheared fiber volume fraction
\( v \) Velocity, m/s

\( \alpha \) Angle between fabric’s white-colored stitching fibers and the fiber tows, deg (°)
\( \beta \) Rotation angle of the principal flow direction, deg (°)
\( \beta_o \) Rotation angle of the principal flow direction for an unsheared sample, deg (°)
\( \gamma \) Shear angle, deg (°)
\( \theta \) Rotation angle of the coordinate systems, deg (°)
\( \mu \) Viscosity, Pa·s
\( \rho \) Density, kg/m\(^3\)
\( \rho_f \) Fiber density, kg/m\(^3\)
\( \varphi \) Porosity
\( \varphi_o \) Unsheared porosity
1 INTRODUCTION

A typical composite material is comprised of a matrix material, e.g., polyester or epoxy resin, that surrounds a reinforcement, e.g., carbon, glass, or aramid fibers. Compared to traditional plastics and metals, composites have superior specific strength and stiffness characteristics, i.e., when nominalized by the density of the material (see Figure 1-1, created using CES EduPack 2019, ANSYS Granta © 2020 Granta Design) [1].

![Figure 1-1: Ashby Plot of Young’s modulus vs. Density](image)

Most composites are heterogeneous and anisotropic, that is, the properties of the matrix are different from the fiber, and the overall homogenized composite properties change depending on which direction they are measured in. In general, the mechanical properties of a composite, e.g.,
strength and stiffness, are dominated by the fibers. By increasing the number of fibers in certain orientations, engineers can modify the structure of the material, add stiffness in certain directions, and design parts for a particular application [2]. Many companies in the aerospace and automotive industries are taking advantage of this and using composite materials to build parts that are lightweight and contribute to greater fuel efficiency. As the time/cost associated with composite manufacturing is reduced, other industries will surely look to tap into the superb strength-to-weight ratio and design benefits composites offer, and composite materials will become more widely used [3].

1.1 Problem Statement

At this time, advanced composite parts are primarily made from pre-impregnated reinforcement materials (prepreg) using an autoclave oven for the cure of the thermoset matrix. Because the cycle times are slow, and the processing and material costs associated with the autoclave and prepreg are high, alternative manufacturing processes are being developed and used based on the infusion of dry fabrics with low-viscosity matrix materials. These infusion-based processes, a.k.a., liquid composite molding (LCM) processes, include vacuum infusion (VI) and resin transfer molding (RTM). The former (VI) involves inexpensive one-sided tooling with a vacuum bag and is capable of producing larger parts than an autoclave allows. The latter (RTM) involves expensive double-sided metal tooling and can produce parts much quicker than an autoclave cycle. In all forms of LCM processing, it is possible to produce parts that require little to no post-processing after being cured. This is done by assembling preforms ahead of time, i.e., layers of dry fabric (plies) that are cut and stacked into the shape of the final part [2].
A major challenge associated with LCM processes, especially RTM, is predicting how the resin will flow through the preform during infusion [4]. RTM is a closed-mold process, and often requires costly trial-and-error prototyping to determine process parameters that guarantee a complete infusion of the preform. Such process parameters include inlet and vent gate locations, as well as the applied pressure and temperature. An incomplete infusion can result in dry spots in the part after it cures and a consequent loss of mechanical properties. To optimize processing parameters, limit the amount of trial-and-error prototyping, and bring products to market faster, various modeling and simulation tools for LCM are being developed. Similar to the simulation tools commonly used for thermoplastic injection molding, researchers are generating predictive models for software programs like ESI PAM-RTM™ that simulate LCM in a virtual environment. Having LCM simulation software that can virtually predict optimal processing parameters, without expensive prototyping, is a critical step in making higher quality parts with LCM manufacturing processes [5].

Permeability is an LCM processing parameter that expresses the ease of flow through a fiber reinforcement (fabric) and is used to predict how long it will take to fill a mold [6, 7]. The permeability of a fabric is highly dependent on the fabric’s architecture, i.e., how the fiber tows are held together and arranged. Although there have been many studies done to understand and model the permeability of fabrics with different architectures, most of the work up to this point has considered the reinforcement in its ideal configuration as coming off the production roll [8-12]. Shear is commonly induced in the reinforcement architecture, either from handling before molding, or from the mold geometry itself if double curvature is present. Such shear deformation significantly alters the geometry of the resin paths between the fibers, thus affecting both part mechanics and the permeability of the reinforcement [13, 14].
High-performance parts, such as parts of an airplane wing structure, typically have a complex geometry including double curvature. When the reinforcement is laid into the mold, it is deformed and sheared to match the part geometry. When double curvature is present, the main mode of deformation occurs in the form of in-plane shear (trellis shear) [15]. As shown in Figure 1-2, trellis shear changes the angle between tows and minimizes inter-tow gaps. Given how sensitive permeability is to a fabric’s fiber arrangement, if a manufacturer making a part with double curvature fails to account for how the preform will deform inside the mold, then there is potential for shear deformation to have an adverse effect on the resin flow and give rise to dry spots in the part.

![Figure 1-2: Trellis Shear](image)

1.2 Research Objectives

In effort to build off the models and methods researchers have used in the past for sheared permeability and gain further insight into the affect shear deformation has on three-dimensional (3D) resin flow patterns and fabric permeability, this research had the following objectives:
• For testing purposes, find a viable method of shearing a preform comprised of multiple layers of a fiber reinforcement, that mitigates the amount of spring-back (tendency of fibers to shift back into their semi-original shape) that occurs in the preform as it is transferred from the tool used to induce trellis shear to a testing device like a 3D permeability tool.

• Develop a test method to measure the full permeability tensor of a sheared preform by adapting a 3D test method used by Nedanov and Advani [16] for measuring the permeability of a non-sheared preform. This is the first known methodology for measurement of through-thickness permeability of sheared composite reinforcements.

• Compare and fit the permeability data obtained to create mathematical models that predict the permeability of the fabric based on the shear angle.

• Validate the models by characterizing the 3D sheared permeability of the VectorUltra™ C-BX 1800 +45°/-45° double bias carbon fiber non-crimp fabric (NCF).

• Propose other various techniques to implement the method and models and improve the accuracy of LCM process simulation.

1.3 Research Motivation

This work is meant to assist others who seek to characterize the permeability of a sheared fabric and inevitably enhance the accuracy of LCM simulation software packages by incorporating the characterized data. With robust LCM simulation software that accounts for
fabric shear, manufacturers would be able to produce higher quality parts, and LCM would become viable for a significantly wider range of industries.
2 LITERATURE REVIEW

2.1 Darcy’s Law

Darcy’s Law is an equation developed in the mid-1800’s by Henry Darcy, a French engineer, who studied the flow of water through saturated sand [6]. It describes the flow of a Newtonian fluid through a porous medium and is given by:

\[
Q = -\frac{KA \Delta P}{\mu L}
\]  

(2-1)

In this equation, \( Q \) (m\(^3\)/s) is the volumetric flowrate, \( K \) (m\(^2\)) is the permeability of the media, \( A \) (m\(^2\)) is the cross-sectional area of the flow, \( \Delta P \) (Pa) is the pressure difference (\( P_{out} - P_{in} \)) over a length \( L \) (m) of the porous media, and \( \mu \) (Pa·s) is the incompressible fluid viscosity. As \( P_{out} \) is less than \( P_{in} \), the minus sign in the equation is required for a positive flowrate.

Studies on resin infusion have found that Darcy’s Law can be modified to predict the transient instantaneous velocity (\( v \), m/s) of a resin as it flows through a fiber reinforcement [17], such that:

\[
v = -\frac{K \Delta P}{\varphi \mu L}
\]  

(2-2)

In this equation, \( \varphi \) is an added term that represents the porosity of the fiber reinforcement. Permeability, porosity, and viscosity are all material properties that must be determined empirically before the velocity can be calculated and used in a mold filling simulation. In
isotropic materials, like sand, permeability is constant and independent of direction; however, in composites materials where anisotropy is present, permeability becomes a second-order tensor that is used to quantify the resin velocity in three principal directions. When three mutually perpendicular axes of symmetry (orthotropy) are present, the permeability tensor reduces to its diagonalized equivalent where $K_x$, $K_y$, and $K_z$ are the principal permeabilities [18], such that:

\[
\begin{bmatrix}
    v_x \\
    v_y \\
    v_z
\end{bmatrix} = -\frac{1}{\varphi \mu} \begin{bmatrix}
    K_{xx} & K_{xy} & K_{xz} \\
    K_{yx} & K_{yy} & K_{yz} \\
    K_{zx} & K_{zy} & K_{zz}
\end{bmatrix} \begin{bmatrix}
    \frac{\partial P}{\partial x} \\
    \frac{\partial P}{\partial y} \\
    \frac{\partial P}{\partial z}
\end{bmatrix} = -\frac{1}{\varphi \mu} \begin{bmatrix}
    K_x & 0 & 0 \\
    0 & K_y & 0 \\
    0 & 0 & K_z
\end{bmatrix} \begin{bmatrix}
    \frac{\partial P}{\partial x} \\
    \frac{\partial P}{\partial y} \\
    \frac{\partial P}{\partial z}
\end{bmatrix}
\]

(2-3)

### 2.2 Permeability Characterization

The principal permeabilities are derived from analytical solutions using data obtained by monitoring the flow during an infusion. Often the direction of the principal permeabilities do not align with the fibers, and the fully populated permeability tensor is needed to characterize the permeability of a preform and calculate resin velocities for flow simulation. Below is a simple trigonometric transformation that can be used to rotate the coordinate system of the principal permeabilities to a new reference frame where anisotropic properties exist (see Figure 2-1).

![Figure 2-1: Rotation of the coordinate systems](image)
\[
\begin{bmatrix}
K_{x'}x' & K_{x'y'} & K_{x'z'} \\
K_{y'}x' & K_{y'y'} & K_{y'z'} \\
K_{z'}x' & K_{z'y'} & K_{z'z'}
\end{bmatrix} = [T]
\begin{bmatrix}
K_x & 0 & 0 \\
0 & K_y & 0 \\
0 & 0 & K_z
\end{bmatrix} [T]^T
\] 

(2-4)

\[
[T] = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & 2 \cos \theta \sin \theta \\
\sin^2 \theta & \cos^2 \theta & -2 \cos \theta \sin \theta \\
-\cos \theta \sin \theta & \cos \theta \sin \theta & \cos^2 \theta - \sin^2 \theta
\end{bmatrix}
\] 

(2-5)

Organizations like the National Institute of Standards and Technology aim to create a database of permeability data for a variety of materials to give people the ability to perform mold filling simulation without having to do their own experimental material characterization [19, 20]. Before a database like this can be established, a standardized test method is needed for permeability measurement.

2.3 Permeability Measurement Methods

Finding a standardized permeability measurement method for the purpose of permeability characterization and infusion simulation has been an on-going endeavor by researchers across the globe [21]. Various 1D, 2D, and 3D flow tests have been explored to identify permeability measurement methods where sample preparation, data acquisition, and data interpretation is simple and precise. In-plane permeability and out-of-plane permeability, a.k.a., through-thickness permeability, are usually measured independently, and because most composite parts are processed as thin shell-like structures [22], in-plane permeability and 1D and 2D flow tests have been extensively discussed. Following several notable benchmark studies conducted by international research groups, 1D and 2D flow tests were found to provide comparable in-plane permeability results, but each configuration has its own advantages and disadvantages to consider [8-11].

Although neglecting through-thickness permeability and averaging all flow characteristics into the in-plane permeability components is an efficient way to simplify infusion simulation [23, 24], as composite parts become thicker, more complex geometrically, and inhomogeneous, i.e., adjacent plies have different in-plane permeability values, understanding 3D flow and characterizing through-thickness permeability has become more pertinent [25, 26]. Consequently, a recent attempt has been made by another team of international researchers to benchmark and find a standardizable method for through-thickness permeability measurement [12]. In this study, the through-thickness permeability was measured by 26 institutions using the test procedure, sample dimensions, and data analysis method they deemed appropriate. The results showed a variability of two orders of magnitude between participants. This scatter was attributed to possible experimental errors and the complex micro-geometry variation that exists in the transverse direction. Although the data gathered from this study was inconclusive, the overall demonstration and evaluation of different through-thickness permeability measurement methods has set the course for future researchers to do more controlled experimentation and formulate a through-thickness permeability testing standard.

It is worth noting that permeability measurement is not limited to separate in-plane and out-of-plane measurement methods, and several studies have been carried out using 3D measurement techniques where all components of permeability were obtained from a single experiment [16, 27-29]. The permeability measurement method presented in this thesis for sheared fabrics is adapted from these techniques and reinforces the notion that unsaturated 3D flow tests are more universal and apt for standardization than 1D or 2D flow tests.
2.3.1 1D Flow Test

The general configuration for a 1D flow test involves a fluid being forced through a confined fabric in its lengthwise direction. To characterize the permeability of a fabric using a 1D flow test, the flow must be restricted in two of the three principal directions; consequently, at least three tests in different flow directions (usually $0^\circ$, $45^\circ$, and $90^\circ$) must be performed to calculate the 2D permeability components ($K_x$, $K_y$, and $\beta$) [30].

Some 1D flow tools are setup to monitor the steady-state flow of an already saturated fabric. To calculate permeability from a saturated 1D flow test, the pressure difference inside the tool is evaluated against the resultant flow velocity. While saturated flow tests are more repeatable than unsaturated flow tests, as well as more reconcilable with Darcy’s Law, they are not an accurate representation of the flow that occurs during an industrial infusion [31, 32].

To mimic the flow front progression that occurs during an infusion, 1D flow tests have been adapted to measure the permeability of an unsaturated reinforcement. In this permeability measurement method, a tool with a clear panel is used to infuse a strip of dry fabric; such that, photographs can be taken to record the position of the flow front as a function of time [33, 34].

The major challenge associated with 1D flow tests is race-tracking, i.e., movement of the resin that occurs in the gap between the tooling and sample edge (see Figure 2-2) [35, 36]. This unrestricted flow can make it difficult to ascertain the true flow front position and will often skew 1D flow permeability measurements. Attempts have been made to suppress race-tracking by using automated cutting tables to cut samples with a precise shape and incorporating a rubber or silicon seal inside the infusion tool to close off all gaps between the sample and tool [37-41].
2.3.2 2D Flow Test

An unsaturated 2D flow test and an unsaturated 1D flow test are similar in that an infusion tool with a clear panel is usually used so photographs can be taken of the progression of the in-plane flow front for subsequent permeability calculation. The main difference between a 2D and a 1D flow test is that the fluid is injected into the preform from a central point and the flow front is radial or elliptical depending on if the fabric is isotropic or anisotropic. This allows for the 2D permeability components to be measured from a single test [42, 43]. To isolate the flow to 2D and ensure that the flow is uniform across the thickness of the preform, a hole is cut through the center of the preform at the location of the inlet.

The primary benefit of running a 2D flow test is that the influence of race-tracking is eliminated as long as the preform is properly constrained to the required height inside the tool [11]. During infusion, the flow should be uninhibited and continually spread throughout the preform until it is close to touching the perimeter edges of the preform. This will result in more consistent wetting effects and permeability measurements.
One disadvantage of a 2D flow test that is frequently discussed in the literature is the deflection that often occurs in the transparent glass or plastic mold material from the high pressure of the fluid injection. At a pressure of 3 bar, the deflection of a PMMA cover at the center of a large point-injection mold was observed to be about 30% of the cavity thickness [33]. If metallic materials were used instead, there would be a reduced amount of deflection; however, the trade-off for using a metal mold would be the obstructed view of the flow front. Embedded pressure sensors [44, 45], ultrasound [46, 47], and x-ray radioscopy [48] are non-optical test methods that have also been used to monitor flow progression. The drawbacks of these approaches are that they require expensive equipment and calibration to work, and sensors are sometimes obtrusive enough to disturb the flow front.

2.3.3 3D Flow Test

3D flow tests are used to measure the through-thickness permeability of a reinforcement. Depending on which 3D flow test is used, the through-thickness permeability can be measured independent of or in addition to the in-plane permeabilities. In some instances, a preform can be so intricately braided, woven, or stitched that the in-plane and through-thickness permeabilities of the preform are dependent upon each other, and the 3D elements of the permeability tensor should be extracted simultaneously [18].

Through-thickness permeability values are typically one to two orders of magnitude less than in-plane values, and because transverse flow is slower during an infusion and harder to visualize than in-plane flow, a part that is saturated on the surface could very well remain unsaturated underneath. This is especially true during a SCRIMP (Seemann Composites Resin
Infusion Molding Process) infusion where the resin is distributed across the top of the reinforcement before impregnating the material transversely [49].

Although it is not considered a 3D flow test, the first attempts to measure and characterize the transverse permeability of a stack of fabrics involved summing the individual permeabilities of each layer to give a global laminate value [25, 50]. As shown in the equation below, this approach is similar to the method used in classical laminate theory to accumulate ply stiffnesses and strengths where \( h_k \) is the thickness of each layer \( k \) in a total of \( n \) layers.

\[
(K_z)_{Average} = \frac{\sum_{k=1}^{n} (K_z)_k h_k}{\sum_{k=1}^{n} h_k} \tag{2-6}
\]

Considering that this estimate for through-thickness permeability \( K_z \) does not account for fiber nesting between the layers of fabric and the overall 3D flow behavior in the laminate, more accurate permeability measurements can be obtained by preforming tests on actual fabric stacks at an expected fiber volume fraction.

At this time, no standard test method has been established for through-thickness permeability; however, in the literature, several different test methods and procedures have been presented as candidates for standardization [12]. In general, the test methods used to measure through-thickness permeability involve injecting a fluid through a stack of compressed fabrics from one surface, using either constant pressure for dry fabrics or a pressure gradient for saturated fabrics. When dry fabrics are used, the flow is often monitored visually; in saturated flow experiments, the flow rate is often monitored using a flow meter. As was the case when measuring the in-plane permeabilities from a 1D flow test, when \( K_z \) is measured using a 1D flow test, the effects of race-tracking are hard to suppress and often skew the resulting data [41]. Because the number of layers in a sample is much greater in a 1D flow test for through-thickness
flow than in a 1D flow test for in-plane flow, race-tracking is exacerbated, and greater care is required to match the reinforcement edges with the mold [51]. When examining through-thickness flow, it is also difficult to visualize the evolution of the flow front in the transverse direction due to the obstructed view the fabric itself creates. These challenges have promoted the use of saturated 1D flow tests for through-thickness permeability measurement where there is no need to visualize the flow front [52]. While the results from saturated 1D flow tests for through-thickness permeability measurement are more repeatable than wetting flow and more reconcilable with Darcy’s Law, they do not fully capture the fluid dynamics that occur during industrial LCM processing [23, 24]. In a saturated 1D flow test, it is also impossible to obtain both in-plane and through-thickness permeability data from a single test; thus, complicating the experimentation required to characterize the permeability of a material.

A true 3D flow test for permeability measurement is like an unsaturated 2D flow test in that a fluid is injected into a stack of dry fabrics (preform) from a central point to allow for the flow front to evolve radially or elliptically depending on if the fabric used is isotropic or anisotropic; however, in a 3D flow test, a hole is not cut through the center of the preform and the flow transversely infiltrates the preform layer by layer. In a 3D perspective, this type of flow will appear hemispherical or semi-ellipsoidal, depending on whether the permeability is isotropic (hemispherical) or anisotropic (semi-ellipsoidal). The benefit of a 3D flow test is that the in-plane and through-thickness permeability components can be measured from a single test. Like in a 2D flow test, the in-plane flow front that propagates across the top surface of the preform can be visually monitored for flow rate measurement and permeability calculation if the top mold-half is made from a clear material like acrylic, PMMA, or glass. The same type of time dependent flow rate measurement and permeability calculation is possible in the through-
thickness direction if the bottom mold-half is also made from a clear material [16, 27-29]. This is
done by watching the bottom surface of the preform and recording how long it takes the resin
ellipsoid to fully penetrate through the preform. Depending on how much pressure is used to
push the test fluid though the preform and the number of plies used in the perform that is tested,
the experiment can take several minutes.

One drawback of a 3D flow test is the point singularity error caused by the circular inlet
tube. When a circular inlet tube is used, the initial shape of the 3D flow front will be
hemispherical rather than semi-ellipsoidal. Assuming most reinforcement are dual-scale fabrics
that have different flow patterns and permeabilities in the $x$, $y$, and $z$ directions that will cause the
eventual 3D flow front to be semi-ellipsoidal, an initial 3D flow front that is hemispherical is an
inadequate flow representation for permeability measurement. Studies have found as the flow
protrudes away from the inlet, the point singularity error reduces, and the correct flow front
shape will naturally develop [53, 54]. For this reason, when conducting a 3D flow test, it is
pertinent to size the preform and use appropriate tooling to give the flow sufficient time to
develop into its correct semi-ellipsoidal shape.

3D flow tests for permeability measurement are commonly criticized for the taxing
mathematical calculations required to simultaneously determine all three principal permeability
components. In a study done by Lystrup [55], the mathematical solutions presented by Nedanov
and Advani [16], Ahn et al. [27], and Mekic, Akhatov and Ulvenare [28], for permeability
characterization from a 3D flow test, are assessed. In an effort to simplify and reduce the
dimensionality of these solutions, Lystrup also proposed a modified solution that reduced the
number of unknown variables from three to one. There is little experimental data available to
evaluate Lystrup’s simplified solution; thus, fueling the pursuit of this research to obtain quality data from 3D flow tests to substantiate this method of permeability characterization.

2.4 Permeability of Deformed Reinforcements

Although the permeability of many composite reinforcement materials has been successfully characterized, a significant challenge to permeability characterization that remains is measuring the variable permeability that is found in actual part geometries. Most permeability testing involves preforms made from undeformed materials with flat geometry. This may be valuable for benchmark data and method standardization; however, if the overall goal is to increase the viability of LCM processes in industry, then the bends, thickness changes, and curves found in industrial parts must be addressed. Infusion simulation software cannot account for such architectural effect on the flow behavior during an infusion without permeability data for deformed media [56].

While it is evident that any change to a reinforcement material’s structure will have an effect on its permeability, it is infeasible to test and obtain permeability data for every possible alteration. This is not only due to the repetitiveness of testing many permutations, but also the inability to measure the permeability of reinforcements in certain configurations. Recent work has focused on the permeability of reinforcements with shear deformation. In-plane shear deformation occurs in the reinforcement anytime doubly curved geometry is present (see Figure 2-3); consequently, shear is the main mode of deformation when draping fabrics over complex molds [57], and the topic of interest in this study.
Normal methods for permeability characterization do not work well for sheared geometries because shear introduces changes in areal density, orthotropy, flow direction, local and macroscopic bending, fiber tension, and crimping. Attempts have been made to characterize the permeability of sheared preforms numerically and geometrically [59-67]; however, very little experimental data is available to validate these theoretical models.

In the studies where experimental data for shear permeability has been obtained, a 2D flow test is most often used for permeability measurement [67-76]. No research has been done using a 3D flow test to simultaneously obtain the in-plane permeabilities and through-thickness permeability of a sheared fabric for characterization of the full permeability tensor; in fact, no sheared through-thickness permeability data of any kind was found in the literature. In these studies that conducted flow experiments, there is a clear indication that every fiber reinforcement affects flow differently; where some studies report that as shear increases, permeability decreases [67-71], others show that as shear increases, permeability increases [72-76]. In addition to unique fabric architectures, the inconsistency observed could also be a product of different shearing and testing methods used during experimentation. To validate and establish a standardized practice
for characterizing the effects shear deformation has on the permeability of a reinforcement, more shear permeability data must be acquired [71].

The aim of this study is to combine recent efforts at 1) development of a 3D flow test where the components of the full permeability tensor are obtained in a single test, and 2) characterization of the effects shear deformation has on permeability. The end goal is to provide a novel methodology to characterize the full 3D permeability tensor for sheared reinforcements, thus allowing simpler permeability characterization and more accurate LCM process simulation.
3 METHODOLOGY

3.1 Overview

This study involves the measurement and analysis of the effects of shear deformation on resin flow patterns and fabric permeability. A method of measuring the full 3D permeability tensor of a sheared preform in a single test was explored. From the data gathered experimentally, a mathematical model was created that predicts the permeability of the fabric based on the shear angle. The model developed is intended for LCM simulation and could be used by others to characterize the permeability of similar sheared fabrics or reinforcements.

Experiments were conducted to measure the permeability of preforms with 0, 10, 20, 30, and 40 degrees of shear. These shear orientations were selected for a wide distribution of data representative of the typical range seen in industrial processing. To validate results and increase the accuracy of the subsequent model, each shear orientation was tested twice.

3.2 Preform Materials and Preparation

3.2.1 Plies

The fiber reinforcement used in this work, VectorUltra™ C-BX 1800, is a +45°/-45° double bias carbon fiber NCF that is typically used for high-performance aerospace and automotive applications. The areal weight of this fabric is 623 g/m². This fabric was donated to
the Brigham Young University Plastic & Composite Materials Lab by VectorPly® for academic research.

Each ply was cut into a 10 x 10 in. (254 x 254 mm) square with 2 x 2 in. (50.8 x 50.8 mm) squares cut away from the four corners (see Figure 3-1). This was done to allow the plies to be placed into the trellis tool and sheared without bunching at the corners.

![Figure 3-1: Ply dimensions and shape](image)

The plies used in this work were cut free of cost using an automated cutting table owned and operated by Murray Manufacturing in Murray, Utah. Compared to cutting out each ply out by hand, the increase cutting speed and precision of the automated cutting table with its reciprocating knife greatly benefited this work. Typically, when using a hand tool like a cutting wheel to cut into the fabric, the tool will cause the fabric to shear along the edges. Also, the plies are susceptible to shear whenever the edges are lifted or touched. For this reason, using an automated cutting table to cut out plies for the permeability tests was a highly effective way to reduce and prevent shear deformation during the cutting process.
3.2.2 Thermoplastic Binder

The preforms made for testing were comprised of 18 plies stacked on top of each other. Plies were stacked with the loops of the chain stitch always facing up and in the same direction to ensure that the fiber orientation of each ply was the same. For the sheared preforms, strips of a thermoplastic binder material were placed in between each of the plies. The binder material was used to fuse together the plies and prevent spring-back in the preform after the trellis tool was removed. Pellon® 807 Wonder-Web™ Tape was found to be an excellent binder material that adhered well to the carbon fiber fabric after a short amount of time in the oven. The tape was 5/8 in. wide and cut into 6.5 in. (165.1 mm) strips. As shown in Figure 3-2, these strips were placed along the perimeter edges of the plies, with a slight amount of overlap, to maintain enough space for uninhibited formation of the resin ellipse. The thickness of the tape was negligible, and after it was melted it absorbed into the fibers without producing a significant increase in the thickness of the preform. The use of Pellon® 987F Fusible Fleece™ as a binder material was also explored; however, due to its increased thickness and higher melting point than the 807 Wonder-Web™, it was dismissed as suitable binder material for this study.

Figure 3-2: Placement of thermoplastic binder between layers
For the preforms tested at 0°, i.e., no shear, there was no need to use the thermoplastic binder and trellis tool to create the preform. A stack of non-sheared plies was simply placed into the 3D permeability tool and infused.

### 3.2.3 Trellis Tool

The trellis tool used in this study (see Figure 3-3, adapted from Lystrup [55]) was machined out of 6063 aluminum and designed to grip a non-sheared preform in such a way that a uniform amount of shear could be applied to the entire preform without any pullout or deformation in the layers of fabric. To assemble the preform in the trellis tool, the following procedure was followed:

1. Place the preform on top of a square 10 x 10 in. (254 x 254 mm), 1/4 in. ply piece of plywood to prevent the center of the preform from drooping down while being mounted into the trellis tool
2. Situate the eight aluminum arms of the trellis tool underneath, on top of, and around the preform
3. Hammer a nail through each of the holes on the trellis tool arms and through the preform to create holes in the preform for the machine screws
4. Insert 1.5 in. (38.1 mm) 10-32 machine screws into each of the holes on the trellis tool arms to connect and align the arms of the tool
5. Place wing nuts onto the screws and tighten each one by alternating from one side of the tool to the other to fasten the preform in the tool with uniform pressure
6. With the preform securely fastened into the trellis tool, push down on bottom right corner of the tool to force the tool to change from the shape of a square to a rhombus. Apply force until the proper amount of shear deformation is achieved.

7. To hold the tool in the proper position, insert a 1/4 in. diamond-shaped steel template (Figure 3-3, right) with the appropriate shear angle into the tool.

![Figure 3-3: Trellis tool, non-sheared (left) and sheared (middle) with a preform and steel plate inside the tool, and example steel plate (right)](image)

Some out-of-plane deformation occurred in the preforms sheared with the trellis tool, due to shear-induced buckling of the fibers; however, this deformation was reduced by shearing groups of plies rather than all 18 at the same time. Groups of plies greater than five buckled out-of-plane and were too difficult to manually shear to angles greater than 40°. For this reason, two groups of four plies and two groups of five plies were sheared to the same angle using the trellis tool and then combined to create an 18-ply preform. The small amount of residual out-of-plane deformation existent in the combined preform dissipated later when the preform was compressed to a constant thickness in the 3D permeability tool.

To melt the thermoplastic binder, the preform, shear holding template, and trellis tool, were all placed inside an oven for 15 minutes at 400°F (204°C). Then, to solidify the binder and fix the preform in its sheared orientation, the preform was removed from the oven and allowed to
cool at room temperature for 15 minutes before being removed from the trellis tool. After the preform was removed from the trellis tool, it was then transferred to the 3D permeability tool.

Often, the shape of the sheared preforms would interfere with the 3D permeability tool’s bolt holes and the position of the thickness spacers in such a way that it was necessary to trim away the corners of the preform to make it more rectangular. Large knife-edge shears were used to cut through the stack of plies. Great care was taken to limit the amount of cutting that occurred in the regions of the preform with binder material. If too much of the binder material was removed, then the preform would spring back into its non-sheared shape.

3.3 Infusion Equipment and Preparation

3.3.1 3D Permeability Tool

A 3D permeability tool was used to radially infuse the preforms that were examined in this study and is shown to the left in Figure 3-4.

Figure 3-4: A preform being infused inside the 3D permeability tool with the following features: (a) inlet port, (b) vent, (c) mold clamping bolts, (d) gauge steel (left) and a mirror and flashlight used to visualize when the through-thickness flow reached the bottom of the preform (right)
The 3D permeability tool used was made previously for experiments done by George et al. [77]. A key feature of this tool, that made it possible to measure the permeability of a preform in all three principal directions, was that the two mold-halves were made from acrylic and polished to be transparent. The dimensions of both mold-halves were 12 x 12 x 3 in. (305 x 305 x 76.2 mm) with a planar tolerance of 0.2 mm on the inside surfaces. The advantage of using pieces of acrylic this thick was that the mold deflection was negligible at the levels of sample compression and applied pressure used in this study.

As shown in Figure 3-4 (left), the tool has an inlet port (a) in the center and a vent (b) in one corner of the top mold-half. To ensure uniform compaction of the preform inside the tool, the tool had 8, 7.5 in. (191 mm) long 9/16 in. bolts (c) that surrounded the preform. With a preform in place, these bolts were tightened using a torque wrench set to 15 ft-lbs. The numbers written next to each bolt hole were used to orient the top mold-half in relation to the bottom and provide an order for how the bolts should be tightened for uniform compaction. To maintain the proper cavity thickness, 10.7 mm, between the two mold-halves, strips of gauge steel (d) were used as spacers and placed along the outside perimeter near the bolts. To test for uniform compaction and check the cavity thickness, attempts were made to move the strips of gauge steel inside the tool after the bolts were tightened. It was assumed that if the strips of gauge steel were immovable, then the cavity thickness was indeed 10.7 mm. A 5 in. (12.7 cm) strip of ruler tape (not pictured in Figure 3-4 (left)) was placed near the edge of the preform to later define the pixel to centimeter ratio in the photos captured during experimentation. No gasket or sealant tape was used to surround the preform inside the tool because vacuum pressure was not used in these experiments and the flow never surpassed the edges of the preform. To visualize when the
through-thickness flow reached the bottom of the preform, a small mirror and flashlight were placed underneath the tool (Figure 3-4, right).

### 3.3.2 Pressure Pot System

A Central Pneumatic® 2.5-gal air pressure paint pot was used to transfer the test fluid to the 3D permeability tool. The pressure pot was outfitted with a pressure gauge, a quick-connect fitting for the air inlet, an 8 mm (diameter) hose fitting for the outlet, and an adjustable valve to regulate the pressure inside the pot. Prior to infusion, an open container of the test fluid was placed inside the pressure pot. The height of the fluid in relation to the bottom of its container was then measured, for later analysis of any potential effects from the hydrostatic head pressure of fluid flow between different heights. From the bottom of the test fluid container, a 1 m long tube with an 8 mm OD (6 mm ID) was extended through the pressure pot, out the hose fitting, and into the inlet located on the top mold-half of the 3D permeability tool. The pot was then sealed shut, the tube clamped shut, and an air hose was connected to the inlet of the paint pot. To generate a constant pressure of 1.0 bar inside the pot from the pressurized air, the regulator valve had to be adjusted several times to stabilize at that pressure. Once the system had demonstrated that it could hold 1.0 bar for at least 10 minutes, the system was ready for infusion and the clamp preventing test fluid from entering the tool could be released.

### 3.3.3 Test Fluid

In this study, canola oil was used in place of an infusion grade epoxy resin because it costs less, is easier to clean up after running an infusion, and has similar chemical properties to an epoxy. Although other oils could have been used, canola oil was selected because of its similar viscosity and surface energy (e.g., contact angle and surface tension) to an infusion grade epoxy
resin. Given that the permeability of a reinforcement is highly dependent upon the viscosity of the fluid it is being infused with, the viscosity of the canola oil was measured before each infusion using a Brookfield DV-E viscometer. The average viscosity of the batch of canola oil used during experimentation was 50.36 mPa-s. The ambient laboratory temperature at the beginning of each infusion was also measured, and the temperature to viscosity relationship is plotted in Figure 3-5. The actual measured viscosity for each test was used in subsequent calculations.

![Figure 3-5: Canola Oil Viscosity vs. Temperature](image)

3.3.4 Camera System

During each infusion, pictures were taken using a Sony SLT-A77 camera with a Sigma 50 mm f/2.8 EX DG macro lens. Pictures were taken to capture the flow shape, size, patterns, and movement for later permeability calculation. A remote was connected to the camera to easily release the shutter while the camera was suspended over the 3D permeability tool. The camera
was positioned directly over the center of the preform inside the tool using a tripod. Great care was taken to fit the entire preform in the camera window and adjust the focus such that the preform fibers were clearly visible. Once the camera was properly adjusted and in place, a lab coat was draped over the top of the camera and around the 3D permeability tool to eliminate the glare the overhead lights in the room created on the top surface of tool.

3.4 Infusion Process

With all the equipment setup, inspected, and the flow parameters recorded, the infusion process was ready to begin. To start the infusion process, the clamp was released from the inlet tubing to allow the oil to flow from the pressurized pot towards the ambient pressure throughout the mold. A timer was started, and a picture was taken, immediately when the oil first contacted the preform. From that point on, pictures were taken every 30 seconds to record the movement of the flow front. The timer was stopped, and the final picture was taken, when there was visual indication that the oil had permeated through the thickness of the preform. To facilitate recognition of this milestone, a light was shined onto the bottom surface of the tool to generate greater contrast between the saturated and unsaturated fibers (Figure 3-4, right). To mitigate false identification of the oil hitting the bottom, the timer and picture-taking were continued until there was no denying that the oil had permeated to the bottom of the preform. The point at which the oil first touches the bottom of the tool, signifies that the oil had fully permeated though the thickness of the preform, creating a half-ellipsoid shaped flow front just touching the bottom (see Figure 3-6).
To finish an infusion and clean up the tool for future experiments, the inlet tube was clamped again to stop the oil from flowing into the tool. Then, the bolts were loosened, the top mold-half was removed, and the preform was disposed of. Rather than using acetone to remove the oil from the surface of both mold-halves, soap and water were used because the tool was acrylic, and acetone would have dissolved the plastic. Lastly, the images captured during the infusion were copied over to a computer from the camera SD card to ensure data preservation.

3.5 Image Processing

The raw images captured from each test were analyzed in ImageJ to measure the lengths of the major and minor axes of the resin ellipse formed on the surface of the preform. ImageJ is a Java-based image processing program developed in the public domain by the National Institutes of Health and the Laboratory for Optical and Computational Instrumentation (LOCI) at the University of Wisconsin. ImageJ has features that allow the user to detect objects in an image using an intensity threshold and measure distances and angles based on user-defined selections and pixel value statistics. The key to using ImageJ is being consistent with the analysis.
technique. If too much variation is induced, then the amount of uncertainty in the results increases.

The steps used to process images in ImageJ are:

1. Open image in ImageJ
2. Set the scale to define the pixels/cm ratio using ruler tape captured in the image and the ImageJ measurement tool
3. Select the enhance contrast function
4. Set image type equal to 8-bit
5. Subtract the background using the create background and sliding paraboloid functions
6. Crop the image to only contain the ellipse
7. Use the color picker tool to select the color of the darkest region in the ellipse
8. Use the paintbrush tool to darken the lighter regions inside and along the edges of the ellipse
9. Adjust the threshold for maximum exposure and to create a binary black and white image
10. Duplicate the image
11. Select the analyze particles function with the show ellipses feature marked to create an image of a smooth ellipse that best fits the original
12. Compare the duplicated image to the image with the smooth ellipse to confirm that the smooth ellipse is an adequate representation of the original ellipse
13. Save resulting image and record the major and minor diameter measurements from the result summary
4 ANALYSIS & RESULTS

4.1 Elliptical Flow Shape and Orientation

Processing the raw images in ImageJ proved to be a beneficial way to measure the lengths of the major ($M$) and minor ($m$) axes of the resin ellipse formed on the top surface of the preform, and the rotation angle of the principal flow direction ($\beta$) in relation to the warp stitching. When locating the edges of the resin ellipse in ImageJ, approximations were made regarding where saturation truly occurred. To limit the error associated with this and increase the accuracy of the flow radii used in permeability calculation, preforms were made as large as the 3D permeability tool would allow, and as many plies were used as possible to maximize the size of the flow front ellipsoid before it touched the bottom. For example, if $r_x = 5$ cm, then $K_x = 2.23E-12$ m$^2$; and if $r_x = 5.2$ cm, a 2 mm difference, then $K_x = 2.52E-12$ m$^2$; this is a 11.5% difference in permeability. Alternatively, if the resin ellipse was small and $r_x = 2$ cm, then $K_x = 1.22E-13$ m$^2$; and if $r_x = 2.2$ cm, again, a 2 mm difference, then $K_x = 1.66E-13$ m$^2$; this is a 26.5% difference in permeability. Although a potential error of 11.5% is not ideal, it is much better than a number like 26.5%; also, in the benchmarking study where 19 institutions reported on their results from controlled radial flow tests, average coefficient of variation ($c_v$) between the participant’s results was 32% and 44% (non-crimp and woven fabric), while the average $c_v$ for individual participants was 8% and 12%, respectively [11].
Figure 4-1 shows an example image taken at the moment when the fluid first touched the top surface of the bottom mold-half, for an unsheared preform ($\gamma = 0^\circ$). The rotation angle $\beta$, appears to be in between the white-colored warp direction stitching fibers ($0^\circ$) and the bias direction of the fibers along the top surface of the reinforcement specimen ($45^\circ$). The flow during infusion of a textile reinforcement usually flows faster along the fibers, which in this case pushes the orientation of $M$ towards $\beta = 45^\circ$; however, the stitching fibers also create preferential flow channels, which tilts $\beta$ slightly towards $0^\circ$. Thus, the combination of preferential flow paths in both $45^\circ$ and $0^\circ$ causes $\beta$ to equal $33^\circ$ in this particular experiment. In Figure 4-2, all the other experimental images are shown for when the test fluid first touches the bottom of the preform, showing an increase in $\beta$ as increasing shear increases the angle between the fibers and the warp direction. The measured values of $\gamma_{actual}$, $M$, $m$, and $\beta$ for all experiments, are tabulated in Table 4-1.
Table 4-1: Elliptical flow shape and orientation for each permeability experiment

<table>
<thead>
<tr>
<th>$\gamma_{expected}$ (°)</th>
<th>$\gamma_{actual}$ (°)</th>
<th>$M$ (cm)</th>
<th>$m$ (cm)</th>
<th>$\beta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0†</td>
<td>0</td>
<td>10°</td>
<td>7°</td>
<td>30°</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>12.2</td>
<td>7.7</td>
<td>33.0</td>
</tr>
<tr>
<td>10†</td>
<td>9.8</td>
<td>9.2</td>
<td>8.5</td>
<td>52.9</td>
</tr>
<tr>
<td>10</td>
<td>9.0</td>
<td>13.2</td>
<td>9.8</td>
<td>78.7</td>
</tr>
<tr>
<td>20</td>
<td>18.8</td>
<td>8.9</td>
<td>6.3</td>
<td>58.4</td>
</tr>
<tr>
<td>20</td>
<td>19.6</td>
<td>10.3</td>
<td>7.5</td>
<td>60.9</td>
</tr>
<tr>
<td>30</td>
<td>27.8</td>
<td>10.1</td>
<td>7.0</td>
<td>67.6</td>
</tr>
<tr>
<td>30</td>
<td>29.0</td>
<td>10.8</td>
<td>7.2</td>
<td>61.1</td>
</tr>
<tr>
<td>40</td>
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<td>10.7</td>
<td>6.7</td>
<td>74.7</td>
</tr>
<tr>
<td>40</td>
<td>39.2</td>
<td>9.5</td>
<td>7.1</td>
<td>67.0</td>
</tr>
</tbody>
</table>

†16-ply experiment
*approximate

A mishap with the camera occurred when running the first experiment that resulted in undistinguishable images of the flow front ellipse. As a result, it was not possible to use ImageJ for the first $\gamma = 0°$ experiment and the data points for this test had to be approximated. Initially, 16 plies were used to make a preform; however, after two experiments with 16 plies, the decision was made to increase the number of plies to 18. With 16 plies, the $x$-$y$ in-plane flow front was fairly small compared to the preform dimensions. Ideally, the $x$-$y$ in-plane flow front shape
should start as a perfect circle coming out of the injection tube, and then slowly evolve into the ellipse over time due to the anisotropy of in-plane permeability. Once the flow front has traveled far enough away from the inlet to develop its true flow front shape, then any measurement after that should result in the same $K_x$, $K_y$, and $\beta$. Thus, an ideal experiment would take up as much of the sample surface area as possible without touching the sample edges. A larger flow front reduces the risk of error associated with the inlet flow front shape, but the flow front cannot be too large, because touching the sample edges would also invalidate the ellipsoid-based flow model. Thus, two more layers were added to later preforms to allow for more in-plane flow development before the flow touched the bottom of the preform.

If the results for the 16-ply experiments are fairly close to the 18-ply experiments, it would suggest that the flow front ellipse was large enough even with the 16-ply experiments. If the 16-ply experiments are significantly more circular ($M/m$ is smaller ratio, and $\beta$ more difficult to ascertain) then this would suggest that the flow front is still developing in the experiments with 16 plies, and maybe even in the ones with 18 plies.

Table 4-1 includes a comparison of the intended shear angles and the actual resultant shear angles. The following equation was used to calculate the actual shear angle from the experimental images:

$$\gamma_{actual} = 2\alpha - 90$$

(4-1)

In this equation, $\alpha$ is the angle between the white-colored stitching fibers in the warp direction and the fiber tows on the top surface of the reinforcement specimen. This angle was manually measured for each experiment in ImageJ using the angle measurement tool. Given that the average difference between $\gamma_{expected}$ and $\gamma_{actual}$ was $0.72^\circ$, it can be concluded that
incorporating a thermoplastic binder into the preforms was a satisfactory method to hold the preforms in their sheared orientation even when the shear angle was as extreme as 40°.

### 4.2 Porosity Calculation

The permeability of a preform is highly sensitive to changes in its fiber volume fraction \((V_f)\) and its corollary, the porosity \((\varphi)\). The porosity is the volume fraction of air in a dry composite reinforcement before it is infused with a resin. Both of these numbers are used in calculations of the permeability by Darcy’s Law and the Kozeny-Carman relation. Mass measurement [78], thickness measurement [79], solvent digestion [80], and combustion digestion [81] are all methods that can be used to measure the \(V_f\) of a composite.

With the 3D permeability tool’s cavity height \((h)\) fixed, the thickness measurement method was used to estimate the unsheared fiber volume fraction \((V_{fo})\) and porosity \((\varphi_o)\) using equations 4-2 and 4-3.

\[
V_{fo} = \frac{nS_o}{h\rho_f} \tag{4-2}
\]

\[
\varphi_o = 1 - V_{fo} \tag{4-3}
\]

In this study, the number of plies used in each preform \((n)\) was 16 or 18, the areal weight of the fabric \((S_o)\) was 623 g/m², and the fiber density \((\rho_f)\) was 1760 kg/m³. \(h\) was slightly modified to achieve a \(V_{fo}\) of 0.595 and a \(\varphi_o\) of 0.405, for either value of \(n\). \(S_o\) and \(\rho_f\) are both unique to the fabric tested and were provided in the manufacturer-supplied material data sheet [82].
4.3 Permeability Calculation

To characterize the permeability of a preform (see Section 2.2), the principal permeabilities \((K_x, K_y, K_z)\) must be known. The principal permeabilities are derived from the principal flow radii that dictate the ellipsoidal shape \((r_x, r_y, r_z)\) where \(r_x = M/2, r_y = m/2, r_z = h\).

Modeling Darcian flow through porous media in an ellipsoidal geometry is difficult; no closed-form solution that deals directly with this geometry has been presented thus far. Ahn et al. [27] presented a solution to ellipsoidal flow by isotropic transformation, defining a coordinate transformation that converts the ellipsoidal shape \((r_x, r_y, r_z)\) to spherical shape \((r'_x, r'_y, r'_z)\), based on the three directional components of the permeability tensor, \(K_x, K_y,\) and \(K_z\):

\[
    r'_x = r_x \left(\frac{K_e}{K_x}\right)^{1/2}, \quad r'_y = r_y \left(\frac{K_e}{K_y}\right)^{1/2}, \quad r'_z = r_z \left(\frac{K_e}{K_z}\right)^{1/2}, \quad K_e = \sqrt[3]{K_x K_y K_z}
\]

(4-4)
This transformation allowed for a derivation of a closed-form solution of Darcy’s Law. At
the flow front the isotropic flow radius (i.e., hemispherical in the new coordinates) is \( r_x' = r_y' = r_z' = R' \). The equivalent isotropic permeability, \( K_e \), determines the hemispherical flow in the
transformed coordinate system. Integration with boundary conditions (based on pressures at the
inlet and flow front) results in a closed form solution that is then transformed back to ellipsoidal
geometry by the inverse coordinate transformation. The resulting equations, 4-5, 4-6, and 4-7
provide the principal permeabilities at the flow front for a given time \( t \). \( \mu, \varphi, b, \) and \( \Delta P \)
respectively represent the fluid viscosity, porosity of the preform, radius of the flow front where
it first enters the preform from the tube, and the pressure difference from inlet to flow front.

\[
K_x = \frac{\mu \varphi b_x^2}{6 t \Delta P} \left[ 2 \left( \frac{r_x}{b_x} \right)^3 - 3 \left( \frac{r_x}{b_x} \right)^2 + 1 \right] \tag{4-5}
\]

\[
K_y = \frac{\mu \varphi b_y^2}{6 t \Delta P} \left[ 2 \left( \frac{r_y}{b_y} \right)^3 - 3 \left( \frac{r_y}{b_y} \right)^2 + 1 \right] \tag{4-6}
\]

\[
K_z = \frac{\mu \varphi b_z^2}{6 t \Delta P} \left[ 2 \left( \frac{r_z}{b_z} \right)^3 - 3 \left( \frac{r_z}{b_z} \right)^2 + 1 \right] \tag{4-7}
\]

Regarding the flow inlet radius shape, \( b_x, b_y, \) and \( b_z \), this solution requires the assumption
of a fictitious ellipsoidal inlet flow shape, whose aspect ratio is held constant as the flow
proceeds from the inlet through the reinforcement. In practice, such an inlet flow shape is
impossible to establish. The inlet tube inner radius (\( b_T = 3 \) mm) is not ellipsoidal as assumed for
anisotropic analysis, and \( b_z \) is not intuitive nor easy to measure. With such difficulties, \( b_T \approx b_x = b_y \)
is assumed in this study as in Ahn et al., causing an error arising from the difference between
the assumed elliptical shape and the actual initially hemispherical shape. This error decreases as
the flow front moves farther from the inlet. For the \( z \)-direction initial flow shape, to reduce the
error caused by inlet size assumptions, in this study \( b_z = b_T [r_z (r_x r_y)^{1/2}] \) was assumed for
Equation 4-7, based on the inverse of the isotropic transformation in Equation 4-4. All calculated values for the permeability tensor components are listed in Table 4-2.

Table 4-2: Calculated principal permeabilities and the time it took the flow to permeate through the thickness of each preform

<table>
<thead>
<tr>
<th>( \gamma_{\text{expected}} ) (°)</th>
<th>( \gamma_{\text{actual}} ) (°)</th>
<th>( K_x ) (m²)</th>
<th>( K_y ) (m²)</th>
<th>( K_z ) (m²)</th>
<th>( t ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0†</td>
<td>0</td>
<td>2.23E-12*</td>
<td>7.33E-13*</td>
<td>6.47E-14*</td>
<td>117*</td>
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<tr>
<td>0</td>
<td>0</td>
<td>9.54E-12</td>
<td>2.29E-12</td>
<td>2.30E-13</td>
<td>49</td>
</tr>
<tr>
<td>10†</td>
<td>9.8</td>
<td>9.97E-13</td>
<td>7.85E-13</td>
<td>5.19E-14</td>
<td>186</td>
</tr>
<tr>
<td>10</td>
<td>9.0</td>
<td>1.98E-12</td>
<td>7.92E-13</td>
<td>3.41E-14</td>
<td>308</td>
</tr>
<tr>
<td>20</td>
<td>18.8</td>
<td>4.87E-13</td>
<td>1.81E-13</td>
<td>1.77E-14</td>
<td>561</td>
</tr>
<tr>
<td>20</td>
<td>19.6</td>
<td>1.15E-12</td>
<td>3.95E-13</td>
<td>5.50E-14</td>
<td>143</td>
</tr>
<tr>
<td>30</td>
<td>27.8</td>
<td>3.21E-13</td>
<td>9.36E-14</td>
<td>1.02E-14</td>
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</tr>
<tr>
<td>30</td>
<td>29.0</td>
<td>3.90E-13</td>
<td>1.23E-13</td>
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<td>685</td>
</tr>
<tr>
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<td>1.20E-14</td>
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<td>2.80E-13</td>
<td>6.46E-14</td>
<td>8.68E-15</td>
<td>1128</td>
</tr>
</tbody>
</table>

†16-ply experiment
*approximate

4.4 Empirical Permeability Models

Figure 4-4: Principal permeabilities as a function of shear angle with corresponding regression lines. The experiments done with 16 plies are displayed as triangles where the hollow triangle is an approximated value from the experiment that malfunctioned.
Figure 4-4 displays the measured principal permeabilities as a function of the shear angle, as well as regression lines showing exponential decay in permeability as shear increases. These lines appear linear due to the logarithmic scaling of the $y$-axis. The negative correlation between permeability and shear is a result of fiber compaction and the closing of preferential flow channels as shear reorientates fiber directions.

Like empirical formulas deduced from experimental data in other studies, equations 4-8, 4-9, and 4-10 can be used to model the permeability of the VectorUltra™ C-BX 1800 fabric and potentially similar NCFs for shear angles less than $40^\circ$.

$$K_x = 3.00 \times 10^{-12} e^{-0.070\gamma} \quad (4-8)$$

$$K_y = 1.00 \times 10^{-12} e^{-0.074\gamma} \quad (4-9)$$

$$K_z = 1.00 \times 10^{-13} e^{-0.062\gamma} \quad (4-10)$$

The calculated coefficient of determination ($R^2$) for $K_x$, $K_y$, and $K_z$ was 0.45, 0.62, and 0.58, respectively. $R^2$ is a statistic commonly used to quantify how well a set of observed outcomes are replicated by a model. $R^2$ values normally range from 0 to 1, where a value of 1 would indicate that the regression model perfectly fits the data. The values seen here show that quite a bit of variability exists, and lurking variables may be present.

### 4.5 Empirical Model for the Rotation of the Principal Flow Direction

The evolution of how the principal flow direction rotates as the shear angle increases is presented in Figure 4-5. The experiments done with 16 plies are displayed as triangles where the hollow triangle is an approximated value from the experiment that malfunctioned. The uptick in $\beta$ for the experiment done with a shear angle of $10^\circ$ and 16 plies verifies that the anisotropic
flow front was indeed too circular and underdeveloped when only 16 plies were used. When the in-plane flow front is more circular than elliptic, it is difficult to discern the major and minor axes and ascertain $\beta$. For this reason, $\beta$ can widely swing in various directions for no particular reason.

![Figure 4-5: Rotation angle as a function of shear angle with corresponding regression line. The experiments done with 16 plies are displayed as triangles where the hollow triangle is an approximated value from the experiment that malfunctioned](image)

With the outliers from the 16-ply experiments excluded, one can see in Figure 4-5 that there is a positive correlation between $\beta$ and shear. This is an observation that can be used to validate the permeability data from the 18-ply experiments and prove that the errors associated with the circular inlet flow front shape are negligible, at least in regard to the rotation angle, $\beta$.

This dashed line in Figure 4-5 represents the exponential model fit to the data from the eight 18-ply experiments and is shown in Equation 4-12. $R^2$ for this model is 0.95, which indicates that the model accounts for 95% of the variability observed and fits the experimental data well.
\[
\beta(\gamma) = \beta_o \cos(2\gamma/3)^2
\] (4-11)

\[
\beta = 2.25\beta_o - 2.25\beta_o \cos[\gamma + \arccos[\ln(1.25\beta_o)/\ln(2.25\beta_o)]^{0.5}]^2
\] (4-12)

The models in Equation 4-11 and Equation 4-12 are a function of, \(\beta_o\), the rotation angle of the principal flow direction for an unsheared sample and \(\gamma\), the shear angle. Equation 4-12 was developed through a series of graphical transformations to a similar model, Equation 4-11, developed empirically by Demaría et al. [66]. This model could be used to predict \(\beta\) for any shear angle within the tested range, i.e., less than 40°. Like the permeability models above, this model for \(\beta\) is unique to the VectorUltra™ C-BX 1800 fabric used but is likely similar for other NCFs.

### 4.6 Validation of Theoretical Models

In a study done by Demaría et al., unidirectional infusions were conducted to characterize the in-plane permeability of a carbon fiber plain weave fabric, at various shear angles [68]. A plain weave has a similar biaxial fabric structure to the NCF used in this study, although the in-plane shear mechanism may be significantly different. The former involves loose tow-on-tow rotation and some sliding due to the woven crimps. The latter involves more shear resistance due to the chain stitching threads being in the bias direction to the fibers [83]. It is also important to note that no through-thickness sheared permeability was measured by Demaría et al.; a method to do so has not been presented in the literature before this study.

Using the experimental data collected from the unidirectional flow tests, Demaría et al. also introduced a theoretical model to predict the in-plane principal permeabilities of sheared fabrics [66]. Although other models have been proposed to predict the permeability of sheared
fabrics [67, 84], the model presented by Demaría et al. is most suitable for comparison because it can be used for all types of reinforcements and requires no additional characterization of the fabric architecture beyond the unsheared permeability, rotation angle, and fiber volume content. This model developed by Demaría et al. accounts for both changes in the fiber volume fraction and the in-plane and out-of-plane fiber orientations after shearing to any shear angle:

\[ K(\gamma) = K_o F_{V_f}(\gamma) F_{geo}(\gamma) \]  

(4-13)

In this equation, \( K_o \) is the unsheared permeability (found experimentally), \( F_{V_f} \) is the corrective factor used to account for the change in fiber volume fraction, and \( F_{geo} \) is the corrective factor for the in-plane and out-of-plane fiber reorientations.

\( F_{V_f} \) is derived from the Kozeny-Carman relation for unsheared (Equation 4-14) and sheared (Equation 4-15) fabrics, where Equation 4-16 is substituted in Equation 4-15, and equations 4-14 and 4-15 are combined to eliminate the Kozeny-Carman constant (\( k \)). Equation 4-17 is the resulting expression for sheared permeability where the corrective term, \( F_{V_f} \), becomes Equation 4-18.

\[ K_o = k \frac{\left(1-V_{f_o}\right)^3}{V_{f_o}^2} \]  

(4-14)

\[ K(\gamma) = k \frac{\left(1-V_f(\gamma)\right)^3}{V_f(\gamma)^2} \]  

(4-15)

\[ V_f(\gamma) = \frac{V_{f_o}}{\cos \gamma} \]  

(4-16)

\[ K(\gamma) = \frac{K_o}{\cos \gamma} \left(\frac{\cos \gamma - V_{f_o}}{1-V_{f_o}}\right)^3 \]  

(4-17)
Following the geometric analysis of a deformed fabric unit cell outlined by Endruweit and Ermanni [62], a relation for the correction factor, $F_{geo}$, is obtained. $F_{geo}$ is meant to reduce the overall reinforcement permeability as shear reduces the area of the fabric unit cell from the shape of a square to a rhombus.

$$F_{geo} = \frac{1 - \Delta r_2}{1 + \Delta r_1} = \frac{1 - \left(\frac{b}{\cos(90 - \beta_0)}\right) + \left(\frac{b \sin(90 - \gamma)}{\sin \beta_0}\right)}{1 + \left(\frac{a \cos(y)}{\sin(\beta_0 - \gamma)}\right) - \left(\frac{a}{\cos(90 - \beta_0)}\right)}$$  \hspace{1cm} (4-19)

In this equation for $F_{geo}$, $a = K_x/K_x = 1$ and $b = K_y/K_x$ where $a$ and $b$ are the normalized dimensions defined in terms of permeability of the undeformed fabric unit cell. From what was observed experimentally by Demaría et al., squaring the $F_{geo}$ term is necessary for the model in Equation 4-13 to agree with test measurements. An additional study done by Bear [85] argues that it is necessary to square the $F_{geo}$ an additional time for the minor direction, $K_y$, such that:

$$K_x = K_{x_0} \frac{1}{\cos(y)} \left(\frac{\cos y - V_{f_o}}{1 - V_{f_o}}\right)^3 \left(\frac{1 - \left(\frac{b}{\cos(90 - \beta_0)}\right) + \left(\frac{b \sin(90 - \gamma)}{\sin \beta_0}\right)}{1 + \left(\frac{a \cos(y)}{\sin(\beta_0 - \gamma)}\right) - \left(\frac{a}{\cos(90 - \beta_0)}\right)}\right)^2$$ \hspace{1cm} (4-20)

$$K_y = K_{y_0} \frac{1}{\cos(y)} \left(\frac{\cos y - V_{f_o}}{1 - V_{f_o}}\right)^3 \left(\frac{1 - \left(\frac{b}{\cos(90 - \beta_0)}\right) + \left(\frac{b \sin(90 - \gamma)}{\sin \beta_0}\right)}{1 + \left(\frac{a \cos(y)}{\sin(\beta_0 - \gamma)}\right) - \left(\frac{a}{\cos(90 - \beta_0)}\right)}\right)^4$$ \hspace{1cm} (4-21)

Figure 4-6 displays the in-plane principal permeability models (equations 4-20 and 4-21), as well as the $K_x$ and $K_y$ data obtained in this study. Although the theoretical models are not as accurate as the models obtained from the regression lines in Figure 4-4, the theoretical models from Demaría et al. do show some resemblance to this study’s experimental results. This is
confirmation that the theoretical models from Demaría et al. could be used to approximate the permeability of a sheared NCF if no empirical data is available.

Figure 4-6: Theoretical in-plane principal permeability models superimposed with experimental in-plane principal permeability data

In the work done by Demaría et al., the in-plane principal permeability data was derived from unidirectional infusions that were done in the direction of the in-plane components, $K_x$ and $K_y$. The analysis for the geometrical correction factor induced by shear ($F_{geo}$) has not yet been extended to the $z$-direction. To be specific, $F_{geo}$ cannot be used to model $K_z$ because the fabric unit cell is different in the $z$-direction. In theory, the Kozeny-Carman based correction for fiber volume ($F_{V_f}$) is still applicable, such that:

$$K_z(\gamma) = \frac{K_{zo}}{\cos \gamma \left( \frac{\cos \gamma - V_{f_o}}{1 - V_{f_o}} \right)^3}$$  \hspace{1cm} (4-22)

This equation is the sheared permeability model adapted to through-thickness flow, neglecting the shear effect on the fabric architecture. When compared to the $K_z$ data obtained
experimentally in this work (see Figure 4-7), it is evident that the total effects of shear are being underestimated when not accounting for $F_{geo}$, especially at low to mid-range shear values.

Given that the geometric correction term is the same for the $x$ and $y$ directions, the model in Equation 4-21 was adapted to explore the $z$-direction flow by simply replacing $K_{yo}$ with $K_{zo}$, and replacing $b \,(K_y/K_x)$ with $c \,(K_z/K_x)$, such that:

$$K_z(\gamma) = K_{zo} \frac{1}{\cos \gamma} \left( \frac{\cos \gamma - V_f o}{1-V_f o} \right)^3 \left( \frac{1-sin(90-\gamma)}{1+/\sum (\beta_0-\gamma)}/(\cos (\alpha_0-\gamma)) \right)^4$$

(4-23)

Although the exponent differences between Equations 4-20 and 4-21 play only a small role in the model appearance, using $F_{geo}^4$ in this equation offered a slightly better fit.

Looking at Figure 4-7, both models seem to underestimate the effects of shear, with the model in Equation 4-23 giving a slightly better fit, until it reaches 40° and begins to overestimate the effects of shear on the permeability. More research is needed to modify the Demaría et al.
model to predict the shear permeability more accurately for through-thickness flow. Analyzing
the 3D fabric unit cell with shear deformation to develop a similar corrective factor for through-
thickness flow is beyond the scope of this work; however, it would be a worthwhile pursuit to
improve the accuracy of the through-thickness shear permeability model.

In the work done by Demaría et al., an empirical formula was also included to describe the
rotation evolution of the principal flow direction as a function of the shear angle, $\beta$. Like the
empirical model proposed in this work (see Equation 4-12) for $\beta$, Equation 4-24 is a modified
exponential function with cosine squared in the exponent. The main difference between the
model in Equation 4-24 and the one in Equation 4-12, is that in Equation 4-24 the function is
decreasing and in 4-12 it is increasing. This is because in Equation 4-24, $\beta$ must lie in the
positive $x$-$y$ quadrant and be measured counter-clockwise from the warp direction. Since the
reinforcement used in this work was a NCF with the fiber tows oriented $+45^\circ/-45^\circ$ from the
fabric’s warp, and not a traditional weave like the reinforcement used by Demaría et al., a
transformation is required to compare the $\beta$ data obtained in this work to Equation 4-24.
Equation 4-25 denotes the transformation that was used.

\[
\beta(y) = \beta_o \cos^2(2y/\beta) \quad (4-24)
\]

\[
\beta_{\text{trans}} = 90 - \left| \beta + \frac{y}{2} - 45 \right| \quad (4-25)
\]
Figure 4-8 combines the theoretical model presented by Demaría et al. (Equation 4-24) with the transformed $\beta$ data obtained in this work. For the most part, this model fits the data well even though a NCF was tested in this work and not a woven fabric.

Pickett reported the Demaría et al. model does not work well for large shear angles [15], which is also observed here seeing that divergence begins to occur for shear angles greater than 30°. A similar trend was also observed in the permeability graphs (Figure 4-6 and Figure 4-7) where the models seem to over-predict the effects of shear at 40°. This could be a result of some microstructural changes in the fabric at these high shear angles, not accounted for by the model, that somehow allow for better flow than would be assumed. In this work, the preforms sheared to 40° exhibited high shear stiffness, where it seemed nearly impossible to shear them to any higher angle, suggesting that 40° correlates with the fabric shear locking angle, i.e., no higher shear is possible without buckling. To resolve this, it would worth examining the relationship between
trellis shear and fiber compaction to possibly develop a theoretical model for the orientation of the in-plane permeability tensor (\(\beta\)), which accounts for that shear locking angle.
5 CONCLUSION

5.1 Observations

5.1.1 Preparing Sheared Preforms

When developing the method used in this work to make sheared preforms for permeability testing, it was assumed that the fabric used, the VectorUltra™ C-BX 1800 +45°/-45° double bias carbon fiber NCF, would easily shear inside the trellis tool if plies of the fabric (see Figure 3-1) were cut orthogonal to the bottom edge of the production roll. This assumption was shortsighted in that this fabric’s top layer of tows run +45° and the bottom layer of tows run -45° from the bottom edge of the production roll. With the fibers already oriented +45°/-45°, when the trellis tool was mounted squarely onto the assembled preforms the fibers instantly buckled in and out of plane and an extreme amount of force had to be applied to the tool to even shear the preform 10° (see Figure 5-1).

Figure 5-1: Three different views of the preliminary attempt to shear a preform to 10°
Not being able to shear the preforms as expected was discouraging and required a reassessment of the shearing method developed in this work. After inspecting the root cause of the problem and learning that the fabric’s tows needed to be aligned in parallel with the sides of the shear tool to be properly sheared, it was found that the plies that were already cut could still be used and the assembled preforms could easily be sheared by rotating them 45° before mounting them inside the trellis tool (see Figure 5-2).

![Figure 5-2: Improved method of shearing preforms with the trellis tool](image)

After resolving the problem with orientation of the fibers, another problem was encountered when attempting to shear an entire preform (18 plies of fabric) by hand to an angle of 20°. The thickness of the preform caused it to be too stiff to be sheared. Although a tensile test machine could have been used to apply increased force and shear a preform no matter its thickness, the trellis tool was only designed to be sheared by hand, and the bolts used as pin joints in the frame of the trellis tool were not robust enough to withstand the amount of force a tensile test machine would apply. To resolve this issue, smaller groups of plies were sheared and then combined into a single preform rather than shearing an entire preform at once. Not only did this make it easier to shear preforms by hand, but it also reduced the amount of in and out of plane bucking that occurred during the shearing process to provide more consistent results.
After overcoming these technical difficulties, the method used in this work to create sheared preforms for permeability testing worked very well. Incorporating the Pellon® 807 Wonder-Web™ Tape into the preforms as a binder material and placing the entire preform, trellis tool, and steel plate into an oven to melt this thermoplastic binder material proved to be an excellent way to create a sheared preform for permeability testing. Very little spring-back of the fibers occurred after the binder material cooled and the trellis tool and steel plate were removed, only an average of 0.72°. It was also observed that the binder material had no significant effect on the overall thickness of the preform after it had solidified into the fibers, and by placing it on the outer edges of the preform, there was still ample room for the resin ellipse to develop naturally without any interference from the binder material. Given how inexpensive and simple it was to incorporate this Pellon® 807 Wonder-Web™ Tape into the preforms for shear permeability characterization, this material could easily be used in future studies to create preforms with shear, bending, or other forms of deformation that influence a composite reinforcement’s permeability.

5.1.2 3D Permeability Measurement Method

Given that this research had a limited amount of fabric and testing materials available, there was little to no opportunity to repeat a 3D flow test if one were to go wrong and provide insufficient data. To combat this, a very thorough checklist for experimentation was drafted. This checklist was used to make sure that the preforms were oriented and placed into the 3D permeability measurement tool properly, the pressure pot was set to the right pressure, the inlet tube was clamped down and test fluid was ready for injection, and the camera was turned on, in focus, and positioned so a full unobstructed view of the preform could be captured during testing. Despite taking all the necessary precautions outlined by the checklist, during the first test
the lens cover of the camera was never removed, and as a result the images captured during this experiment were indistinguishable and the measurements of the major and minor axes of the resin ellipse that formed on the surface of the preform had to be estimated. The lesson learned from this mistake was to double check every aspect of the experimental design to make sure nothing went wrong again.

The parameters that were recorded during each of the ten 3D flow tests included: the date of experimentation, the shear angle of the preform being tested, the number of plies used in the preform, the thickness of the gauge steel, the pressure inside the pressure pot, the temperature and viscosity of the test fluid (canola oil), how long the infusion lasted from the time the oil first touched the top of the preform to the time it first soaked through the bottom of the preform, and the estimated lengths of the major and minor axes of the ellipse that had formed on the surface of the preform at the instant in time when the infusion was stopped. Recording this last parameter ended up being very beneficial when the mishap with the lens cover occurred during the first experiment to still have some quantifiable data for permeability calculation.

During experimentation, no race-tracking of the oil was observed between the preforms and tool. This indicates that the binder material placed around the edges and in between the plies did not significantly increase the thickness of the preform. If the sheared preforms that were constructed using the binder material and trellis tool were indeed thicker at the edges than at the center, during an infusion the oil would have pooled up and race-tracking would have been visible near the inlet. Although inclusion of the binder material did create spatial and material variation in the preform where it was used, it did not have an effect on the flow characteristics of the preform, i.e., permeability and saturation, because no resin ellipse ever reached the edges of a preform where the binder material was present (see Figure 4-2). In the permeability tool, the
strips of gauge steel that surrounded the preform provided uniform spacing and compaction that made the fiber volume content, porosity, and permeability of the preform constant.

A critical component of the permeability measurement method presented in this work is knowing when to stop the timer and take a picture of the saturated in-plane ellipse. In each experiment only one measurement in the $z$-direction could be obtained. Obtaining an accurate data point for $K_z$ hinged on knowing the exact moment in time when the test fluid had penetrated through the preform and first contacted the bottom mold-half of the tool. This is the moment when the timer had to be stopped and a photograph needed to be taken. Pinpointing when the oil had reached the bottom of the preform was difficult, because the carbon fiber fabric used was opaque, it did not easily show signs of saturation. To improve the visibility of the test fluid in the fibers, a LED flashlight was shined onto the bottom surface of the bottom-mold-half and a mirror was placed directly underneath the tool to more easily see when it was time to take a picture and stop the timer. This detection method was not fool-proof, and obtaining accurate data still necessitated user awareness. In future work it might be worthwhile to mix an ultraviolet dye into the test fluid and use a blacklight instead of a LED flashlight. A method like this is presented in a thesis done by Perry [86], and would help reduce the user error that occurs when determining when to stop the 3D flow experiment.

5.1.3 Modeling Variable Permeability

From the permeability data that was obtained experimentally, empirical models were created that predict permeability as a function of shear. These empirical models are limited to shear angles less than or equal to $40^\circ$ and are only truly accurate for the fabric used in this work; however, the fabric used was a traditional carbon fiber NCF common to the aerospace and
automotive industries, and because the permeability characteristics of this fabric may be similar to other fabrics, the empirical models presented may be representative of other $+45^\circ/-45^\circ$ double bias NCFs. Considering that the primary focus of this work was to develop a novel measurement method for 3D characterization of sheared fabrics, and not necessarily a study on the specific permeability characteristics of the VectorUltra™ C-BX 1800 $+45^\circ/-45^\circ$ double bias carbon fiber NCF used, these empirical models should not be referenced for simulation. Equations for these empirical models are included to assist other researcher as they seek to examine the effects of shear, especially in the through-thickness direction. Up until now, no models for through-thickness permeability versus shear angle have been published.

The theoretical models for in-plane permeability and orientation angle of the in-plane ellipse versus shear developed by Demaría et al. proved to be excellent for comparison when validating the experimental data and solution for permeability calculation presented in this work. Although these models were made from a woven fabric and not a NCF, the theory practice used, based on the Kozeny-Carman relation for changes in the fiber volume content and geometric analysis of a shear fabric unit cell, was relevant and required no additional material characterization other than the principle in-plane permeability values, the shear angle, the orientation angle, and fiber volume content. Slight adjustments had to be made graphically to accommodate this work’s experimental data on the orientation angle of the in-plane ellipse to Demaria et al.’s model; however, great agreeance was found between the two which indicates that the flow evolved equally even though the architecture of the fabrics used were different.

To assess the experimental sheared through-thickness permeability data obtained in this work and see if the theory behind Demaría et al.’s theoretical permeability model could be extended to permeability in the $z$-direction, liberty was taken to modify Demaría et al.’s model
with z-measurements. Although the correction factor in Demaría et al.’s model that accounts for the geomatic analysis of a shear unit fabric cell does not lend particularly well to what is actually going on in the z-direction when a preform is sheared, it was still a correction factor that improved the models fit for $K_z$. Apart from Demaría et al.’s work and the observations that the permeability of a sheared preform in the through-thickness direction behaves similarly to and is one to two orders of magnitude less than permeability values of a sheared preform in the in-plane direction, which is seen in the literature for non-sheared through-thickness versus in-plane permeability values [16], there is little way to further validate theses $K_z$ results. Ideally, other researchers who attempt full 3D sheared permeability characterization would benefit from this data and follow the suggestions presented herein for experimental testing.

5.2 Future Recommendations

With the advancements in finite element methods and process simulation that have been made in the last ten years [87, 88], there is a pressing need for research and development of standardized methods for measuring material properties like permeability. In particular, a standardized method for through-thickness permeability characterization is needed to simulate the SCRIMP manufacturing process where flow media is used, and through-thickness flow dominates the resin infusion. Steps have already been taken by research teams to find a through-thickness permeability measurement method appropriate for standardization [11]; however, more method validation and testing needs to be done on different reinforcement materials to develop databases of permeability data that can be used in process simulation.

There are also modelling challenges, like the effects of localized permeability variation due to shear deformation of the preform, that need to be further explored and addressed [89].
Although shear is the main mode of deformation and frequently discussed in the literature, it is not the only abnormality that can occur inside a mold. Tests for the effects of race-tracking, bending, and compaction also need to be conducted to fully understand, model, and characterize the permeability of a reinforcement.

5.3 Summary

In this study, a method of measuring the full three-dimensional permeability tensor of a sheared preform in a single test was presented. From the data gathered experimentally, empirical models were created to characterize the principal permeabilities of a carbon fiber non-crimp fabric for shear angles less than 40°. It was found that a negative correlation between permeability and shear exists; such that, the permeability of a preform decreases as the shear angle increases due to the closure of preferential flow channels and reorientation of fiber directions. This is the first known published characterization of through-thickness permeability in a sheared state.

In effort to validate this novel permeability measurement method, the experimental data obtained was compared to theoretical models developed by Demaria et al. [66, 68]. Given that Demaria et al. did not measure or explore through-thickness permeability, an attempt was made to adapt their in-plane theoretical models to through-thickness permeability. As a whole, the theoretical models fit the experimental data well. The methods and models presented herein are intended to assist individuals interested in obtaining shear permeability data of their own; where at a minimum, shear permeability characterization can be done from unsheared permeability values.
REFERENCES


