FDEVELOPMENT, CHARACTERIZATION, AND MODELING OF MULTI-DIRECTIONALLY REINFORCED POLYMER MATRIX COMPOSITES FOR STRUCTURAL APPLICATIONS

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ABSTRACT

Multi-directionally reinforced polymer matrix composites with unique architectural designs and no thickness limitations have been designed, developed, manufactured, and characterized for use in structural applications. Challenges to manufacturing these materials included implementation of single-step preform manufacture, managing thermal effects during densification, and process scale-up. Application of finite element analysis to translate raw materials and microstructural attributes to bulk material properties is being utilized. Modeling analysis to date have been utilized to accurately predict uniaxial test properties. Future goals include macrostructural property modeling, component performance simulation, alternative composite design to meet the demands of specific applications, as well as scale-up to the manufacture of cost effective products.

1. INTRODUCTION

The primary goal of this project was to develop a 3D structural composite material differentiated from traditional 2D and 3D crimped carbon epoxy systems that have limitations in fiber property translation, manufacturable thickness and inter-laminar properties. In order to design these materials to specific application requirements and predict structural performance, finite element analysis (FEA) modeling was also required. This paper discusses material design and manufacturing challenges, presents structural and thermal property characterization, and summarizes the microstructural performance modeling results to date. The research and results are intended to support advancement for engineers, designers, and technologists in composite applications where traditional 2D composite lay-ups, sandwich structures, or thin/crimped 3D forms/fabrics do not meet with size or performance requirements.

1.1 Multi-directionally Reinforced Composite Materials

Multi-directionally reinforced polymer matrix composite (PMC) materials are composites that include fibers outside of the traditional plane of reinforcement. Three-directionally reinforced (3D) orthogonal Cartesian PMC’s provide reinforcement in the three directions: X, Y, and Z. An un-crimped fiber containing weave provides the most complete translation of fiber properties to the composite since the fibers are subject to less complex stress components translating tension and compression loads to the fiber reinforcement directions [1-3]. Typical methods of
manufacture utilize a Jacquard loom to create the 3D orthogonal structure. This method utilizes a Z interlock fiber that imparts waviness, misalignment, and distortion of fibers near the top and bottom faces [4]. The equipment utilized for this investigation was a block loom design in which high uniformity fiber preform blocks were woven utilizing an array of pultruded rods for the Z-direction tows with placement of X and Y fibers via rapier similar to the method presented by R. W. King [5]. This array provides structure and uniformity to the preform allowing for high compression on the X and Y fibers with no significant distortion of the resulting structure. These preform structures are commonly utilized for carbon/carbon composites for high temperature thermal protection and propulsion applications, which contain carbon fibers within a graphite matrix. It was anticipated that 3D structures with polymer matrices could overcome many challenges that 2D materials face in applications replacing metals (e.g. titanium, aluminum), such as delamination and fracture failures. It was also anticipated that 3D structures would be able to meet challenges not ordinarily attempted by composite structures, particularly applications requiring high tension and shear strength across planes normal to the Z direction.

1.1.1 Preform Construction

3D preforms are fabricated using a loom with the Z fibers held in place mechanically while the X and Y fibers are woven between the Z fibers in alternating layers to create a tightly packed, un-crimped fiber block preform construction. This construction creates a unit cell with a pultruded rod in the Z-direction and square tows in the X and Y directions, represented in Figure 1.

![Figure 1. Single unit cell in a balanced weave architecture.](image)

Multidirectional composites almost always have lower fiber volumes than corresponding 2D composites due to architectural constraints. For this particular construction method, the primary variables dictating composite fiber volume are the width percent of the unit cell that the pultruded rod occupies (wZ), the fiber volume percent within the pultruded rod (FV%Z), and the fiber volume percent within the X and Y fiber tows (FV%X,Y). Increased fiber volume can be gained from using a ‘dry’ construction in which temporary rods used during the weaving process are replaced by un-impregnated fibers, thereby using the entire rectangular Z-direction tow space instead of the cylindrical rod that fits within it. Equations 1 - 3 describe fiber volume percent utilizing this construction method and identical X and Y tows. FV%max is the maximum amount of volume available for fiber to occupy, whereas FV%pultruded and FV%dry are the actual fiber volumes of the pultruded rod and dry constructions.

\[
FV\%_{pultruded} = \frac{\pi}{4} \cdot FV\%_{Z} \cdot w_{Z}^2 - FV\%_{X,Y} \cdot w_{Z} + FV\%_{X,Y}
\]  

[1]
Figure 2 illustrates the effect of the Z-fiber unit cell width on the total fiber volume of the composite. In Figure 2, the top curve (solid line) represents the architecture fiber volume at 100% packing efficiency into all rectangular tow spaces. The middle curve (double dash line) represents the actual fiber volume considering the packing efficiency of thousands of filaments into rectangular tow spaces and the typical process used to fabricate the construction, which is taken as 62.5%. The lowest line (single dash) represents the fiber volume of the composite with the pultruded rods used in the single-step preform fabrication process instead of rectangular Z-direction tows used in the dry construction.

![Figure 2: Effect of architecture on fiber volume within a 3D composite preform.](image)

For this investigation, a balanced weave architectural design was fabricated and tested. In a balanced weave, each reinforcement direction contains equal fiber volume, which occurs at roughly 50% \( w_z \). Figure 2 shows that the resulting total fiber volume (\( FV_T \)) is roughly 44%. Figure 3 illustrates alternate weave architectures also achievable in the block loom, with varying \( FV_T \), \( FV_{%Z} \), and X/Y fiber spacing or layer thickness, as tuning parameters to tailor the architecture and thus the properties. This illustration contains the following models (clockwise starting with top, middle image): balanced weave with medium layer thickness, low \( FV_{%Z} \) with low layer thickness, low \( FV_{%Z} \) with high layer thickness, high \( FV_{%Z} \) with high layer thickness, and high \( FV_{%Z} \) with low layer thickness. It is noted that while this investigation focused on the balanced weave, its fiber volume is at the minimum of the curve shown in Figure 2; meaning that the four models to the left and right in Figure 3 all represent \( FV_{%T} \) greater than the balanced weave at 44%. \( FV_{%T} \) can range upwards beyond 50% and approaching 60% with very low or very high Z fiber loading, represented on the left and right of Figure 2 respectively. In addition to the capability of adjusting \( FV_{%T} \) by adjusting \( FV_{%Z} \), the same loom has the capability to produce a range of layer thickness, which affects the weaving time and cost.
1.2 Introduction to FEA for Multi-directionally Reinforced PMC’s

FEA is used to simulate the effects of composite microstructure and materials on its properties and in components/systems to design materials for specific applications. In general, FEA can be performed in two ways for a composite material, at the microscale and the macroscale. At the microscale, it is used to simulate the effect of fiber, resin, and architecture on the bulk properties of the composite. Those bulk properties are then fed into the macroscale (or homogenization) modeling, to simulate the component or system level. Details of the microstructure are ignored, which is adequate if the bulk properties are well approximated. Modeling is typically performed in these two ways separately since capturing both scales in one simulation requires computational resources that are not accessible for everyday design.

There are a number of papers that provide a good overview of FEA for traditional 2D composites. However, this study is focused on multi-dimensionally reinforced composites, and so the literature review will be restricted to this area. Properties for different resin and fiber systems are reported either by the manufacturer but are also reported in several literature studies [6-10]. Failure/damage models that capture failure mechanisms, have also been described. For example, work has been performed to simulate matrix or yarn failure in either tension, compression, shear, or some combination of them in multiaxial loading [6-11]. Work has also been performed to simulate matrix microcracking, which is driven by both Von Mises and hydrostatic stresses [6-11].

The Von Mises stress ($\sigma_{VM}$) is calculated from the principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) in Equation 4. Hydrostatic stress ($\sigma_H$) is calculated from the principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) in Equation 5. For matrix failure, the dilatational failure criterion assumes matrix failure is driven by hydrostatic stress, which causes cracks to initiate under cavitation [8-10]. Crack initiation occurs when the hydrostatic stress exceeds a critical value estimated from experiments (Equation 6). The parabolic failure criterion assumes the failure envelope encompasses a parabola, and is calculated from both the Von Mises stress and hydrostatic stress (Equation 7), where the Von Mises has a square dependence and the hydrostatic stress component has a coefficient. Both $A$ and $B$ are material dependent and can be found from experimental data, for example uniaxial tension and compression tests [8-10].
The Drucker-Prager failure criteria, also known as Bauwens \[12\], is calculated from both the Von Mises stress and the hydrostatic stress (Equation 8). Both C and D are material dependent and can be found from experimental data, for example uniaxial tension and compression tests [8-10]. For tows, failure could occur by either tension along the tow direction (subscripted 11) as in Equation 9, tension along the transverse direction (subscripted 22), or shear (subscripted 12, 13) [6]. For tension in the tow direction or transverse to the tow direction, failure is assumed to occur when stress exceeds a critical value for either of the directions (Equation 10). For shear, failure is assumed to occur when stress exceeds a critical value (Equation 11).

\[
\sigma_{VM} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad [4]
\]

\[
\sigma_H = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad [5]
\]

\[
\sigma_H \leq \sigma_{H}^{critical} \quad [6]
\]

\[
\sigma_{VM}^2 + A\sigma_H \leq B \quad [7]
\]

The application of these failure models to FEA simulations is discussed and demonstrated in Tsukrov et al. [8-10] and Green et al. [6]. The available published work has shed light on the challenges with modeling multidimensional composites, especially with respect to the input data needed and assumptions needed to make the simulation solvable. However, the work has revealed a number of important insights, including the prediction of matrix, fiber, and composite failures by different mechanisms, and matrix microcracking during resin curing. For example, Tsukrov et al. [8-10] predicted matrix microcracking during the curing process by comparing different failure models for their resin and tow system. Green et al. [6] predicted failure in composites by analyzing potential failure in either the matrix or tow.

2. EXPERIMENTATION

2.1 Materials, Fabrication, and Evaluation

3D orthogonal preforms with dimension of 14 cm x 14 cm x 62 cm were woven using Hexcel AS-4 6K fibers in all three (X, Y, and Z) directions, resulting in a balanced weave architecture (equal fiber volume in all three directions). The Z fiber was set up through tooling in the block loom as pultruded rods, each comprised of single tow of AS4 6K fiber cast in Resin System A (Bisphenol-F resin, MTHPA hardener, copper catalyst). The X and Y fibers were woven within the rod array by automated rapier movements. Compaction occurs between layers, similar to the beat up process utilized in 2D weaving, allowing for higher fiber volumes to be achieved. The
resulting preforms contained approximately 44% fiber volume. Maximum size utilization of the applicable loom design results in preform dimensions of 37 cm x 37 cm x 62 cm.

The preforms were infused with Resin System B (a Bisphenol-A resin and a Cycloaliphatic polyamine hardener) using an adapted RTM process to ensure a void free infusion. Resulting bulk density was measured as 1.42 g/cm³. The Resin System B is considered a high-temperature epoxy, with glass transition temperature exceeding 200°C. Sample materials were removed and evaluated for microcracking and porosity using a standard stereoscope with fiber optic illumination (Figure 4).

![Figure 4. Micrographs of composite structure used for generating test data. Views from X-direction (4a) and Z-direction (4b).](image)

2.1.1 Challenges to Composite Fabrication: Matrix Infusion

Many consolidation techniques for 2D composites exist that cannot be used for a thick 3D composites materials. From the techniques available, resin transfer molding (RTM) is demonstrated to produce a highly consolidated 3D composite with minimal voids. Gas entrapment was minimized through a combination of initial vacuum and final pressure in conjunction with a rigid closed mold to ensure repeatable process results [13].

Resin processing and final use are often at odds. High temperature polymer systems such as polyimides and bis-maleimides (BMI) often have high viscosity or contain solvents to lower the processing viscosity. Many have short pot lives that necessitate a fast infusion, limiting part size. This investigation used polymers with viscosities lower than 1000 cP and pot life greater than 2 hours for processing ease, while also having relatively high Tg (>200°C) and use temperature.

2.1.2 Challenges to Composite Fabrication: Pultruded Rod Quality and Adhesion

Fabricating a robust composite utilizing pultruded rods required that load transfer between the matrix resin and the pultruded rod be as predictable as possible. To ensure this, a bond must occur between the two. Additionally, the pultruded rods must be fully consolidated. Otherwise, they propagate microcracking or create inefficient load transfer within the tow. Pultrusion resin used in other applications did not have the appropriate chemistry to remain bonded to the PMC matrix following the curing processes. Figure 5a shows pultruded rods not fully consolidated, Figure 5b shows porous pultruded rods propagating from matrix micro-cracking, and Figure 5c shows pultruded rods that did not remain fully bonded to the matrix following matrix cure. For manufacture of these materials, a new pultrusion resin was formulated. Handling requirements were modified in order to better ensure reliable bonding surfaces. Figures 4b and 5f show well bonded and consolidated rods developed for 3D PMC applications.
2.1.3 Challenges to Composite Fabrication: Matrix Microcracking

Matrix pocket microcracking can result from tri-axial stresses within the matrix caused by either shrinkage or differential thermal expansion. Thermal gradients within a thick composite add a level of complexity to the challenge. Figures 5d and 5e show extensive and mild micro-cracking, respectively, in 3D composites. In 2D composite fabrication, curing resin is constrained in two directions but can relieve stress by shrinking in the through-thickness direction as during debulking. In this investigation, the resin was fully constrained in three dimensions with the closed mold process preventing stress relief. The resin must have sufficient strength and toughness. Additionally, the curing process must generate minimal stresses. A combination of low shrinkage, good mechanical property buildup, and low gel temperature were needed to result in the matrix microcrack-free structure presented in Figures 4 and 5f.

![Figure 5](image)

Figure 5. (a) Porous pultruded rods without matrix micro-cracking, (b) porous pultruded rods propagating from matrix micro-cracking, (c) dis-bonded pultruded rods (d) extensive microcracking, (e) mild microcracking, (f) no anomalies present

2.2 Composite Design Variables

This paper was focused on a balanced weave 3D orthogonal Cartesian carbon-epoxy PMC material with approximately 1.25 mm layer thickness in all three directions. There are many design variables that may be changed to refine the composite system to produce specific properties for specific applications. Among those variables are weave architecture geometry, weave spacing, fiber volume by direction, fiber type, and resin. In addition to 3D orthogonal, weave geometries include 4D (U/V/W in-plane fiber 60° apart and Z), 3D cylindrical (circumferential, radial, and axial fibers), and others. Weave spacing can be tailored between ultra-fine (~0.75 mm layer thickness) to ultra-coarse (~4 mm layer thickness) in each direction. Total fiber volume and fiber volume by direction can be adjusted with very wide constraints, for example Z fiber volume can range from 5% to 80% of the overall fiber volume. Different fibers can be used, including carbon, glass, quartz, and others. Resin types utilized in this 3D weave include standard epoxy, high-temperature epoxy, phenolic, benzoxazine, cyanate ester, and polyimide resins.
3. RESULTS AND DISCUSSION

3.1 Property Testing

Structural and thermal properties of the balanced weave 3D PMC are presented in Table 1. Unless noted, the tests were conducted at room temperature (25 +/- 3 °C) in air at the Energy Materials Test Laboratory (EMTL). Elevated temperature and thermal tests were conducted in nitrogen at 1 atm. ASTM testing standards were employed where applicable. Tension specimens had rectangular gage sections with enlarged tab ends. Shear testing utilized a double notched specimen design, while 4-pt flexure and compression test specimens were rectangular. For thermal conductivity, comparative rod analysis was used. For thermal expansion, a quartz dilatometer was employed. For the structural properties, the average of 3-5 replicates are reported (2 replicates for thermal properties). For each property, the fiber direction measurements are shown without parentheses. Generally, all three fiber directions (X/Y/Z) have exhibited statistically equivalent properties within measurement variation. The values in parenthesis represent the property in the 45° direction between two fiber directions XZ or YZ. Although the 45° direction typically yielded a different test result, compression testing was equivalent in the off-angle direction. For the elevated temperature compression testing, the material strength gradually decreased as the temperature approached the resin glass transition temperature with a decreasing slope; thus results beyond 150°C were not reported.

Table 1. Structural and Thermal properties of Balanced Weave 3D PMC Material.

<table>
<thead>
<tr>
<th>Property</th>
<th>Fiber Direction (45° Offset)</th>
<th>Property</th>
<th>Fiber Direction (45° Offset)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
<td>1400 kg/m³ (1.4 g/cc)</td>
<td>Flexural Strength</td>
<td>520 MPa</td>
</tr>
<tr>
<td>Compression Strength (20°C)</td>
<td>500 MPa (500 MPa)</td>
<td>Flexural Modulus</td>
<td>34 GPa</td>
</tr>
<tr>
<td>Compression Strength (150°C)</td>
<td>370 MPa (370 MPa)</td>
<td>Thermal Conductivity (20°C)</td>
<td>1.2 W/m-K</td>
</tr>
<tr>
<td>Compressive Modulus</td>
<td>37 GPa (9.0 GPa)</td>
<td>Thermal Conductivity (200°C)</td>
<td>1.6 W/m-K</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>570 MPa</td>
<td>Shear Strength</td>
<td>210 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>41 GPa</td>
<td>Coefficient of Thermal Expansion</td>
<td>4.0 x 10⁻⁶/K</td>
</tr>
<tr>
<td>Tensile Elongation</td>
<td>1.4 %</td>
<td></td>
<td>(5.8 x 10⁻⁶/K)</td>
</tr>
</tbody>
</table>

Figure 6 shows the results of room temperature Z-direction tensile fatigue testing, which was conducted in compliance with ASTM D 3479 (Procedure A) [14]. For this testing, first the tensile failure strength was determined for the fatigue test design (594 MPa). Next the tension cycling was conducted for each percent failure stress level (29 % to 91 %) at 3 Hz frequency until failure was observed or runout (1,000,000 cycles) was achieved. All tests with tensile loadings under 75% ultimate stress all achieved runout. These results are considered favorable in comparison to 2D glass and carbon epoxy composites and metals.
3.2 FEA Modeling Results

3.2.1 Phases and Properties

In defining phases and properties of the fiber tows and matrix resin, properties could be taken from manufacturers, literature, and actual test values. Composite materials are multi-scale: the resin-infused tow is actually a composite itself, at volume fractions of fiber and resin. A rule of mixtures approach was taken to compute the tow properties given the properties of the fibers and resin [8, 11, 15]. Resins were taken to be elastic, isotropic materials, thus the elastic modulus (E) and Poisson’s ratio (v) were used for modeling. Fiber tows were assumed to be transversely isotropic and linearly elastic; as such two elastic moduli and Poisson’s ratios were required, as well as the shear modulus (G). For strength modeling, material specific parameters for the given failure modeling was also needed [6-10]. For this simulation version, currently focusing on tension properties, the bond between the fiber and matrix were considered ideal, which has proven adequate. In other simulations, some interface properties will need to be applied.

There has been discussion on both the Chamis approach [15] and the Tsukrov et al. approach to calculating the resin-infused tow properties, which were assumed to be transversely isotropic. The Chamis equations for resin-infused tow properties are expressed in Equations 12-18, where the subscripts $m$ and $f$ refer to matrix and fiber respectively.

$$E_{11} = V_f E_{11}^f + (1 - V_f) E_m$$ \hspace{1cm}[12]

$$E_{22} = E_3 = \frac{E_m}{1 - V_f \left(1 - \frac{E_m}{E_{22}^f}\right)}$$ \hspace{1cm}[13]

$$E_{22} = E_3 = \frac{E_m}{1 - \sqrt{V_f \left(1 - \frac{E_m}{E_{22}^f}\right)}}$$ \hspace{1cm}[14]
Tsukrov et al. derived their own equations as an alternative to the Chamis equations, citing concerns that the Chamis equations did not satisfy bounding criteria. For this simulation work, the properties of the resin, carbon fiber, and resin-infused tow are shown in Table 2. The resin properties were taken from the manufacturer’s reported values supplemented with literature. The carbon fiber properties were taken from the manufacturer and literature, and the resin-infused tow properties were calculated from Chamis and Tsukrov et al. methods respectively. It can be seen that the $E_{11}$ prediction is the same for Chamis and Tsukrov et al, but the predictions from them are different for $E_{22}$, $\nu$, and $G$.

Table 2. Properties of Resin, Carbon Fiber, Tow, and Pultruded Rod.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$\nu_{12}$ (-)</th>
<th>$\nu_{23}$ (-)</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin System B (matrix resin)</td>
<td>3.0</td>
<td>3.0</td>
<td>0.35</td>
<td>0.35</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Resin System A (pultruded rods)</td>
<td>3.5</td>
<td>3.5</td>
<td>0.34</td>
<td>0.34</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>AS-4 (6k) carbon fiber</td>
<td>230</td>
<td>13</td>
<td>0.20</td>
<td>0.20</td>
<td>13</td>
<td>4.0</td>
</tr>
<tr>
<td>Tow *</td>
<td>143</td>
<td>7.0</td>
<td>0.26</td>
<td>0.46</td>
<td>3.7</td>
<td>-</td>
</tr>
<tr>
<td>Pultruded rod*</td>
<td>155</td>
<td>8.3</td>
<td>0.24</td>
<td>0.50</td>
<td>5.2</td>
<td>-</td>
</tr>
<tr>
<td>Tow**</td>
<td>143</td>
<td>6.8</td>
<td>0.25</td>
<td>0.53</td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>Pultruded rod**</td>
<td>155</td>
<td>8.3</td>
<td>0.24</td>
<td>0.55</td>
<td>4.7</td>
<td>-</td>
</tr>
</tbody>
</table>

*Chamis equations, **Tsukrov et al. equations

In addition to the elastic properties above, it was noted that the tensile strength of Resin System B is given in published reports as 40 MPa. The tensile strength of AS-4 fibers (6k) is given as 4.4 GPa in published reports.

3.2.2 Microstructure Model

The microstructural arrangement of the fibers and tow in the composite were used to define the representative volume element (RVE); refer to Figure 7. The RVE is not a single unit cell but several, and was chosen to suit the model and failure mechanisms. The goal of the RVE was to have a statistically representative set of homogenized “bulk” properties, requiring enough features and interactions between features. For this simulation, the Digimat-FE commercial
software program was used (Digimat-FE, Version 6.0.1, MSC Software, Newport Beach, CA). Mesh nodes and elements were sized to capture enough detail in key areas while controlling degrees-of-freedom and thus computational power requirements, resulting in 54,000 elements in the RVE. The RVE of the composite with mesh, unloaded, is shown in Figure 7a; and the non-crimp orthogonal fiber preform is shown in Figure 7b. Each tow is shown a different color to clarify the phases, with the Z-fiber pultruded rods blue, X-direction tows red, Y-direction tows green, and matrix yellow.

After meshing, the next step was to add loading and boundary conditions. For this study, uniaxial tension simulations were performed at strain levels of 0.25 %, 0.50 %, 0.75 %, 1.00 %, 1.25 %, and 1.50 % along the x-direction. Periodic boundary conditions were applied. The simulation was run using an iterative solver, with results post-processed for further analysis.

### 3.2.3 Results of Test Simulation and Prediction

A display of Von Mises stress distribution in the RVE is shown in Figures 7c and 7d, with and without the matrix displayed. As expected, the x-direction tows are stressed along the loading direction, while the y-direction tows, pultruded rods, and the matrix demonstrate much less stress. Also as expected, the stress is uniform along the x-direction tows, with only localized areas that indicate stress concentration, which could be an artifact from meshing or boundary conditions.

![Figure 7](image)

Figure 7. Digimat Images of Composite RVE. 7a: unloaded meshed RVE (yellow matrix). 7b: unloaded RVE with matrix hidden. 7c: uniaxially loaded Von Mises Stress in RVE. 7d: uniaxially loaded Von Mises Stress in RVE with matrix phase hidden.

Figure 8 shows the simulated uniaxial X-direction tension curve plotted against experimental stress strain curves used to calculate the average value of 570 MPa shown in Table 1. The solid
line is the simulation while the dashed lines show several specimens tested in the lab. As predicted, the behavior is linear elastic with the simulated stress-strain curve within the range of experimental data scatter. The modulus calculated from the simulation was 41 GPa, also the average value of the experimental tensile modulus; and the simulated curve exhibits strain levels equivalent to the experimental data (average 1.4 %) at the average failure stress of 570 MPa.

The stress-strain curves in Figure 8 reflect mechanical behavior in uniaxial tension along the x-direction. The model was next used to compute the homogenized bulk properties of the composite, including elastic modulus (E), shear modulus (G), and Poisson’s ratio (v) in each direction. Due to the orthotropic nature of the material, the simplified homogenized properties can be represented by the data shown in Table 3. The value for E agrees with available experimental data. The data in Table 3 is intended to be compared with experimental data and to be used in homogenization FEA modeling of parts, assemblies, or systems in which the details of the microstructure are captured in the homogenized properties.

![Figure 8. Simulated stress versus strain curve plotted against experimental data (dashed lines). Uniaxial tension in x-direction.](image)

<table>
<thead>
<tr>
<th>E_{xx}=E_{yy}=E_{zz} (GPa)</th>
<th>G_{12}=G_{23}=G_{13} (GPa)</th>
<th>v (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>2.2</td>
<td>0.10</td>
</tr>
</tbody>
</table>

In addition to the elastic tensile response, the model was used to predict the stress distribution in both the matrix and tow phases. The stresses can be used to identify critical areas in the RVE or composite and serve as inputs into the damage or failure models. The stress distributions are shown instead of peak values since there can be isolated stress concentrations that are artifacts of meshing or boundary conditions.
Figure 9a shows the Von Mises stress distribution in the composite matrix for a range of applied strain loads (0.25 % - 1.50 %) in the X-direction, at the different strain levels given in the figure caption. This graph plots the cumulative fraction of the matrix volume corresponding to the indicated stress level, similarly to a cumulative distribution function in statistics. As the applied strain is increased, the stress distribution in the matrix increases, and the shape of the curve changes slightly with increasing loading. The magnitude of the highest Von Mises stress reaches the reported tensile strength of the matrix (40 MPa) at loadings above 1 % tensile strain. Figure 9b shows the Von Mises stress in the x-direction fiber tows at each of the applied strain loads in the X-direction. As expected, the fibers, being stiffer than the matrix, are taking most of the stress. In general, at all loading conditions, the Von Mises stress levels are lower than the 4.4 GPa tensile strength reported for AS-4 6k fibers. Figure 9c shows the hydrostatic cumulative stress distribution in the matrix. Similarly to the Von Mises stress, the magnitude of hydrostatic stress in the matrix reaches the 40 MPa reported tensile strength of the matrix at strain loadings above 1 %. Figure 9d shows the hydrostatic stress distribution in the X-direction tows at each of the applied strain loads. Similarly to the Von Mises stress, the fibers are taking most of the stress, and at levels lower than the fiber tensile strength.

Figure 9. Von Mises cumulative stress distribution in the matrix (9a) and in the x-direction tows (9b). Hydrostatic cumulative stress distribution in the matrix (9c) and in the x-direction tows (9d). Applied X-direction strain of 0.25 %, 0.50 %, 0.75 %, 1.00 %, 1.25 %, and 1.50 %.
4. CONCLUSIONS

4.1 Materials and Properties

The developed 3D PMC composite system provides a unique design of un-crimped 3D fiber reinforcement, producing fiber tows with no significant waviness, which is not possible with typical composite manufacturing equipment and processes. The block construction was intended to meet property requirements that cannot be achieved with traditional 2D or 3D crimped carbon epoxy materials, namely material thickness and the same properties through-thickness as in-plane. The architectural construction characterized in this investigation represents a balanced fiber volume by direction and thus balanced properties between the X, Y, and Z fiber reinforcement directions. The material is considered “iso”-orthotropic in this regard, more balanced than other orthotropic composites. The described material represents only one point on the design scale of fiber reinforcement architectures achievable with the developed processes. The composite can be tailored to different fiber volumes by direction with broad constraints without modification to the equipment. Design variables that may be changed to refine the composite system to specific applications including fiber type, tow spacing, fiber volume by direction, and resin selection.

Balanced weave PMC preforms were densified to meet density, porosity, and microstructure requirements. Challenges in the manufacturing process that needed to be addressed were resin selection, pultruded rod quality, resin shrinkage, and microcracking. Thermal and structural material properties were measured and reported. Within testing variation, balanced properties in-plane versus through-thickness were exhibited.

4.2 FEA Microstructural Modeling

A 3D FEA model was developed in order to simulate the composite material system. First, the effects of resin, fiber, and tow properties on the homogenized properties were simulated and compared with available experimental data, with acceptable agreement found. The predicted stress versus strain curve was directly compared with experimental data from the same loading direction where the prediction was found to be within experimental scatter. The model confirms the experimental results that the non-crimp orthotropic fiber reinforcement creates a unique bulk composite that has balanced strength and modulus in the 3 orthogonal directions, in comparison to traditional 2D composites that have limitations with out-of-plane properties.

Next, the stress distributions in the matrix and tows as a function of uniaxial tension loading was simulated. As expected, the fibers aligned in the loading direction experienced much greater stresses than the matrix pockets. Models will be extended to incorporate the failure criteria in order to compare with experimental data for tension, compression, shear, and multiaxial loading conditions. Future work will focus on alternative versions of the multi-D PMC material, as well as application-specific component design and performance modeling.

5. REFERENCES


