Discontinuous Fiber Vacuum Assisted Compression Molding

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Abstract

A manufacturing process for discontinuous short fiber carbon reinforced polymer (CFRP) composites was documented and tested to show suitability of the process in low-volume, low-cost production environments. Samples made from the process were tested to document material properties. Different variations of manufacturing techniques were tested including continuous fiber reinforcement, metal inserts, and randomization of the dry fibers before processing. The process produced parts with strength to weight ratios similar to 6061-T6 aluminum without continuous fiber reinforcement, and 53% higher when small volumes of continuous reinforcement are added. Randomization of fibers produced no significant change in strength of the material, but did increase compression stiffness of the mixture while molding, increasing tool deflection. A pin joint was tested, and different methods of calculating the maximum stress were compared.

Keywords

Carbon Fiber, Composite Materials, Epoxy, CFRP, CoDiCoCFRP
Summary for Lay Audience

A carbon fiber reinforced epoxy composite was manufactured and then tested to determine the material properties. The manufacturing technique consisted of mixing a two-part epoxy with 6.35mm (0.25 inch) long randomly oriented carbon fibers and then placing the mixture inside an aluminum mold. Air was pulled out from the mold using a vacuum system, and then a plunger compressed the mixture to minimize cavities. Once the epoxy cured, the part was removed from the mold. The parts were destructively tested to measure their stiffness and strength in bending and tension.

Different variations of the manufacturing technique were tested to observe the result on manufacturing cycle times and the strength and stiffness. These variations included complete randomization of the fibers, and additional reinforcement of the part with long, continuous fibers of carbon. Additionally, pin pullout tested was done to simulate a pin connection with the goal of recommending a method to predict when it would break.

The process produced parts with strength to weight ratios similar to a common aluminum alloy. Once reinforced with continuous fibers, the composite had a 53% higher strength to weight. Randomization of fibers produced no significant change in strength of the material. For the pin joint, different methods to predict when the failure would occur were compared.
Acknowledgments

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Chapter 1

1 Introduction

Composite materials have been more and more popular in commercial design because of their high strength and stiffness, low weight, and increasingly competitive cost. This is possible by combining the high strength and stiffness properties of a fiber with a reinforcing matrix. While many combinations exist, this thesis will focus on carbon fiber reinforced polymers (CFRP).

CFRP parts can be placed in three categories based on the length of the fiber: continuous fiber, discontinuous fiber, and a combination continuous discontinuous fiber reinforced polymer. While 2D textile-based composites have continuous fibers, which effectively transfer load, improving their strength, they are largely limited to thin surface geometry. Conversely, discontinuous fibers are at a disadvantage in strength and stiffness but allow for more design freedom [1].

1.1 Motivation

While the need for higher specific strength and specific stiffness has led to increased usage and research of composites, many processes involve a significant capital investment of equipment, which can be prohibitively expensive for startup companies or small teams. For low volumes, these teams can use processes such as vacuum assisted resin transfer molding (VARTM) or wet lamination for manufacturing of continuous fiber parts. However, fewer low-investment discontinuous fiber process options are available, limiting the design freedom with composite parts.

With VARTM or wet lamination, the volume of resin required can be difficult to predict because of varying geometry and fiber uptake of dry components. To prevent dry spots in the part, an excess of resin must be prepared. With thermoset polymers, the irreversible cross-linking process will be initiated. In the case of epoxy, this is done by mixing a resin and hardener. Unfortunately, the leftover polymer solidifies as unused waste. The vacuum assisted compression molding process investigated in this paper can utilize the
leftover mixed epoxy resin from larger VARTM or wet lamination processes provided there is sufficient quantity leftover and it has not reached the end of its pot life, resulting in less waste from the combined processes. A similar model to make use of excess curing material is used by concrete companies, who cast excess concrete from cement mixer trucks into useful products such as 2’ x 2’x 6’ ecology blocks. These blocks can be sold instead of reprocessing the concrete or placing it in a landfill.

Sheet molding compound (SMC), and bulk molding compound (BMC) allow for a similar process with discontinuous fibers, however, these methods use fibers pre-impregnated with resin that require high pressure and temperature to cure. Additionally, the nature of the slowly curing resin means that refrigeration is required, and the materials have a limited shelf life. The advantage of SMC and BMC is that because the resin is pre-impregnated into the fabric, higher volume fractions of fiber are possible, along with very uniform resin and fiber distributions.

This thesis starts with a review of existing relevant literature, outlines the testing process that was carried out, then describes the manufacturing process in detail. Finally, the test methods are documented, and an analysis of the results are given.

1.2 Research Contributions

The development of the tooling and initial version of the manufacturing process were completed by J. Callender, and G. Konstantinopoulos, and published in Callender 2018 [2]. Twelve different combinations of three volume fractions, and four fiber lengths were manufactured, tested, and analyzed for that paper. As part of the literature review in section 2.7, a new analysis (presented for the first time in this thesis) was completed on the old data that had been first presented in Callender 2018. This new analysis includes new ways to visualize the data (Figure 5 and Figure 6), and a statistical analysis.

While the manufacturing process presented in this thesis is largely based on Callender 2018’s process, the modifications including fiber randomization, continuous reinforcement, and metal inserts for pin/bolt connections are all new, along with their
respective test data. The process documentation, except for CAD models that are cited accordingly, is also a new perspective on the techniques.

This thesis greatly expands on the suitability of the material for design in three common scenarios (tension, bending, and pin/bolt connections) in order to guide perspective designers, and help advance the process and material towards production ready status. Finally, improvements to the material properties were explored through testing with continuous fiber reinforcement.
Chapter 2 Literature Review

2 Literature Review

This report will focus on the Fiber-Reinforced Thermoset category of composites. Within this category, composites can be further broken down into continuous or discontinuous, and aligned or randomly oriented.

Short fiber composites are a well-established technology. Existing ways to process randomized discontinuous fibers include Long Fiber-Reinforced Thermoplastics (LFT), Bulk Molding Compound, Sheet Molding Compound, and Fiber Spraying. While LFT, BMC, and SMC are better tailored for medium to high volume production runs, Fiber Spraying is often used in small to medium volume production [2].

In this paper “discontinuous” will be used as opposed to “short fiber” where possible because there is not a generally accepted definition between the length of short and long fibers.

2.1 Properties of Discontinuous Fiber Composites

2.1.1 Shear Lag Model

The Shear Lag model is based upon tensile stress from the matrix being transferred to cylindrical fibers through interfacial shear stresses, as shown in Figure 1 [3]. The unmodified model ignores tensile stress transferred between the matrix and fiber ends, which as Clyne 2019 showed, creates inaccuracies especially when low fiber aspect ratios are used. This is because the fiber end tensile stresses contribute a larger percentage to stiffness in shorter fibers, compared to long fibers where the interfacial shear stresses dominate. Clyne 2019 also shows modifications to the Shear Lag model to correct for this assumption, allowing the modified model to predict properties more accurately at lower aspect ratios.
The shear lag model predicts increasing tensile stress in the center of the fiber up to a limiting aspect ratio, as a function of a dimensionless constant, $n$, which can be calculated as follows: [3]

$$n = \sqrt{\frac{2 \cdot E_m}{E_f \cdot (1 + \nu_m) \cdot \ln \left(\frac{1}{f}\right)}}$$

(2—1)

Where $E_f$ and $E_m$ are the Young’s modulus of the fiber and matrix respectively, $\nu_m$ is the Poisson’s ratio of the matrix, and $f$ is the fiber volume fraction. Using this dimensionless constant, the limiting aspect ratio, $s_t$, can be calculated as follows: [3]

$$s_t \approx \frac{3}{n}$$

(2—2)

At very high aspect ratios, the stiffness predicted by the shear lag model approaches that of the Rule of Mixtures (RoM), which is used for continuous fiber composites. To use the
Rule of Mixtures simplification, the fiber aspect ratio, must by greater than the minimum fiber aspect ratio for the RoM, $s_{RoM}$, which is calculated as the following: [3]

$$s_{RoM} \approx \frac{10}{n}$$  \hspace{1cm} 2—3

### 2.1.2 Predicting Youngs Modulus

Multiple methods to calculate the mechanical properties of randomly oriented discontinuous fiber composites have been proposed. These can be categorized as the following:

1. Modified Rule of Mixtures
2. Spherical Reinforcement Approximation
3. Weighted Average of Parallel and Transverse Properties

A Modified Rule of Mixtures approach has been used by various sources [4, 5, 6, 7] to calculate material properties for randomly oriented discontinuous fibers composites. Virk 2012 [7] proposed the following for randomly oriented natural fiber composites:

$$E_C = \eta_d \times \eta_l \times \eta_o \times E_f \times f + E_m (1 - f)$$

The modification factors are as follows: $\eta_d$ for fiber diameter distribution factor, $\eta_l$ for fiber length distribution factor, and $\eta_o$ for fiber orientation distribution factor. $\eta_d$ and $\eta_l$ can be assumed to be unity for artificial fibers with comparatively precise diameters, and lengths much greater than their critical length. $\eta_o$ is based on the Krenchel equation [7], and takes a value of 3/8 for random, in-plane fibers [5]. $f$ is the fiber volume fraction, and $E_f$, and $E_m$ are the Young’s Moduli of the fiber and matrix respectively. Callister 2007 gives a simplified modified RoM equation, with only one modifier, $K$, which is analogous to $\eta_o$, and recommends an identical value of 3/8 for random in-plane, as well as a value of 1/5 for completely random 3D orientation.

$$E_C = K \times E_f \times f + E_m \times (1 - f)$$  \hspace{1cm} 2—4

Equation 2—4 was used by Callender 2018 [6] to provide upper ($K = 3/8$) and lower ($K = 1/5$) limits to bound the range of expected material property values with thin
coupons of randomly oriented discontinuous CFRP. Callender 2018 also examined the
effect of different fiber lengths and volume fractions on $K$, postulating that increasing
either would also increase the stiffness up to a certain point, after which increases to
length or volume fraction would decrease $K$ towards the lower (3D) limit.

Clyne 2019 also suggests using the Eshelby model for randomly oriented discontinuous
fibers. The Eshelby model is based on stiff, inclusions within a matrix that have prolate
ellipsoid shape. For discontinuous fibers, the fibers are approximated as ellipsoids with
the same aspect ratio as the original fibers. Clyne compares this model to the shear lag
model, stating that “the stiffness, for example, is usually very close in the two cases” [3].
This intuitively follows the argument presented in the same paper that the Eshelby model,
although more rigorous than the Shear Lag model, is more accurate, especially where the
Shear Lag model’s assumptions fail (such as significant tensile end stresses from low
aspect ratio fibers).

Mallick 2007 uses an alternative method to predict composite material properties for thin
in-plane randomly oriented discontinuous fiber lamina. It is based on the properties in the
11 and 22 directions, which must first be calculated using the Halpin-Tsai model in the
following equations [8].

$$
\eta_L = \frac{E_f}{E_m} - 1
\frac{E_f}{E_m} + 2 \left( \frac{l_f}{d_f} \right)
$$

$$
\eta_T = \frac{E_f}{E_m} - 1
\frac{E_f}{E_m} + 2
$$

$$
E_{11} = \frac{1 + 2 \left( \frac{l_f}{d_f} \right) \eta_L f}{1 - \eta_L * f} E_m
$$

$$
E_{22} = \frac{1 + 2 \eta_T * f}{1 - \eta_T * f} E_m
$$
Mallick 2007 then uses a weighted average of the longitudinal and transverse Young’s Modulus. As shown in section 5.1.3, this method predicts a Young’s Modulus very similar to the 2D random in-plane Rule of Mixtures.

\[ E_C = \frac{3}{8} E_{11} + \frac{5}{8} E_{22} \]  

2—9

### 2.1.3 Weibull Analysis and Weakest Link Theory

Brittle materials have low fracture energy, which allows cracks to propagate with very low energy absorption. While composites can disperse additional energy during failure through processes such as fiber pullout, the failure is still dependent on the orientation, location, and size of flaws [3]. The likelihood of the presence of a flaw significant enough to cause failure with the localized stresses can be treated with a statistical analysis known as Weibull Analysis. If the stressed part is conceptually split into smaller sections, then the weakest section will cause the failure of the part, which is known as Weakest Link Theory [3].

For this reason, minimizing the size of air cavities in the final part is critical to its overall strength. The combined vacuum and positive pressure approach for manufacturing presented in this thesis aims to reduce the size and quantity of any trapped air bubbles.

The volume of stressed material plays an important role in Weibull analysis. Larger volumes increase the number of possible weakest link sections, and therefore the statistical likelihood of a flaw significant enough to cause failure under the localized stress. This creates a large difference in the failure stress in 3-point bending versus tensile testing. In 3-point bending, only a small volume in the center of the beam is stressed to the maximum, while in tension, the entire gauge length is subjected to the maximum stress.

The probability of survival of a specimen can be calculated by the Weibull strength theory for brittle materials as follows: [9]

\[
P(S_f > S) = \exp \left[ - \int_V f(x, y, z) \, dV \times \left( \frac{S}{S_0} \right)^\alpha \right]
\]  

2—10
Where \( S \) is the maximum stress, and \( S_0 \) and \( \alpha \) are Weibull parameters determined through testing. \( f(x, y, z) \) is the normalized stress distribution (reaching a maximum of 1 at the maximum stress), as shown in the following equation which breaks down a non-uniform stress field.

\[
\sigma(x, y, z) = S \times f(x, y, z)
\]

Whitney 1980 compared the characteristic bending strength, \( S_b \), to the characteristic tensile strength, \( S_t \). When the same volume of material is stressed in both cases, the difference between the two is dependent only on the statistical parameter \( \alpha \), as shown in Equation 2—12 [9]. Because \( \alpha \) is determined through very extensive testing, which was not the focus of this paper, its value for the material tested herein is not available.

\[
\frac{S_b}{S_t} = \left[2(\alpha + 1)^2\right]^{\frac{1}{\alpha}}
\]

Whitney 1980’s example values of \( \alpha = 15 \) and \( \alpha = 25 \) for graphite-epoxy unidirectional composites, resulted in a 52% and 33% respectively increase in failure stress in bending over tension. For this reason, bending data is not considered appropriate for design purposes [9].

Knight 1975, although studying glass fiber composites, showed that the shape parameter, \( \alpha \), for random fiber composites is much lower than for continuous fiber composites [10]. For the e-glass reinforced epoxy used in that paper, an \( \alpha \) value of 4 was measured for randomly oriented fibers, which compared to a value of 13 for quasi-isotropic laminate coupons. The lower shape parameter indicates higher variability in the failure point and reduces the reliability of the part at a given stress. To meet minimal reliability requirements, a lower design stress must be used. Maintaining this reliability despite high failure point variability requires further penalties to the design stress with higher quantity of parts produced [10].
2.2 Continuous Reinforcement within Discontinuous

Continuous reinforcement of discontinuous fiber reinforced polymers has been shown by Trauth 2019 to increase the stiffness and tensile strength by +170% and +190% respectively for glass/carbon SMC composites [11]. Unfortunately, the hybridization did not increase compressive strength significantly.

2.3 Stress Transfer in Continuous Fiber Composites

As shown in Swolfs 2014 [12], when a fiber is broken in a continuous fiber composite, the neighbouring fibers will take over the additional load that cannot be transferred through the broken fiber. This also creates a stress concentration on the neighbouring fibers. A cluster of parallel fibers broken together weakens the part, and can lead to final failure once a critical size of break has been reached [12].

2.4 Pin Bearing Strength

2.4.1 Hole Failure in Composites

Mallick 2007 described various failure modes for pin-bearing tests in continuous fiber composites, summarized in Figure 2, along with common dimensional ratios generally associated with each failure, summarized in Figure 3, and Table 1 [8]. Figure 3 shows both the generic variables \(d, e, t, w\) used for formulas and Table 1, and the nominal dimensions of the samples tested in this paper.

![Figure 2: Pin Bearing Failure Modes](image)
Figure 3: Dimension Labels and Dimensions for Pin Coupons in mm

Table 1: Pin Failure of Composites [8]

<table>
<thead>
<tr>
<th>Label in Figure 2</th>
<th>Failure Mode</th>
<th>Values of Dimensional Ratios in Figure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>w/d</td>
</tr>
<tr>
<td>A</td>
<td>Net Tension</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>Cleavage</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Shear-out</td>
<td>Low</td>
</tr>
<tr>
<td>D</td>
<td>Bearing</td>
<td>High, &gt; 6</td>
</tr>
</tbody>
</table>

Unidirectional, 0º composites have low bearing stress at failure because of the tendency for longitudinal splitting, which is caused by loading in the weaker, transverse direction. In this case, 90º, ±45º, or ±60º layers are recommended to increase the final failure stress [8]. Discontinuous fiber composites molded with inserts for pin/bolt mounting allow the

1 While not stated in Mallick 2007, it can be reasonably assumed that a low e/d ratio is also required for a cleavage failure.
fibers to flow around the inserts, resulting in favourable fiber orientations. Furthermore, the random orientation of the bulk fibers means the composite has the same strength in the transverse direction, eliminating this specific weakness even for holes in locations where the melt has not flowed around inserts, and not gained the advantageous fiber orientation.

Table 1 recommends an $e/d > 3$ to develop the full bearing strength of the composite and prevent a cleavage or shear-out failure. For comparison, when designing in aluminum, the minimum edge distance of a bolt should follow equation 2—13, with more complex calculations available for limit state design in civil engineering work [13].

$$\frac{e}{d} \geq 1.5$$  \hspace{1cm} 2—13

2.4.2 Continuous Reinforcement

Continuous fiber reinforcement around inserts (also called Loop Inlays, Figure 4) provide high strength and stiffness reinforcement directly on load paths. This tailored reinforcement can drastically improve strength-to-weight and stiffness-to-weight ratios of the final part [2]. Unidirectional tape continuous fiber reinforcements are more likely to require machining during post-processing, and are also susceptible to pull-out of fibers, or local cracks during machining, which necessitate carefully tailored machining strategies [14]. Loop inlays however are less likely to intercept post machining paths because of their location within the part.

Figure 4: Example of Loop Inlays
2.4.3 Stress Concentration Factors for Pin Joints

Pilkey 2020 provides a model for predicting the maximum stress of round pin double-shear joints using a stress concentration factor [15].

\[ \sigma_{max} = K_{tna} * \sigma_{nom} \]

\[ \sigma_{max} = K_{tna} * \frac{P}{(w - d) * t} \quad 2-14 \]

Where \( P \) is the load, \( w, d, \) and \( t \) are dimensions, and \( K_{tna} \) is an experimentally determined dimensionless value that is a function of \( d/w \).

Molded-in inserts are not accounted for in the development of this equation. The step changes in local stiffness and strength, and the bonding strength between the two materials, were not included, creating room for error when they are used.

2.5 Discussion of Existing Manufacturing Research

2.5.1 Movement of Continuous Fiber Reinforcement

Carbon fiber continuous reinforcement of carbon or glass SMCs have been studied in Böhlke 2019. The process involves co-molding continuous fiber preforms with SMCs [14]. The high investment and high cycle time process is more applicable to high volume automotive production runs.

Challenges studied by Böhlke 2019 include shifting of continuous reinforcement during molding due to the forces applied by the flowing of the SMC. Flow of the SMC is required to fill ribs and other complex designs, and so cannot be eliminated. Unfortunately, common resin systems were not viscous enough in their B-stage to maintain the position and alignment of continuous reinforcement fibers during molding, so an unsaturated polyester-polyurethane hybrid resin along with fixation and stiff reinforcement were needed to reduce movement of continuous fiber reinforcement during molding [14].
Epoxy was one of the common resins with insufficient B-stage viscosity to prevent reinforcement movement and is also the resin used for coupons of study in this paper. For this reason, when attempting to limit continuous fiber movement during molding, epoxy in the preform must be completely cured first.

2.5.2 Machining

Drilling and machining CFRP has many challenges, including delamination, spalling, and fraying, which depend on cutting speed, feed rate, clamping, tool microgeometry, processing strategy, and wear state of the tool [14]. Purely randomized fibers with out-of-plane orientation fortunately prevent macro-scale delamination and spalling issues from occurring because there are no distinct layers to separate. When there is continuous fiber reinforcement of randomized discontinuous fibers, the continuous fibers come with a risk of delamination and spalling during machining. Careful positioning of the continuous reinforcement away from machining paths, such as by the usage of Looped Inlays, can mitigate this risk.

2.5.2.1 Helix Angle

Bücheler 2019 measured delamination of a variety of glass-fiber SMC reinforced with continuous unidirectional (UD) carbon fiber composites across different helix angles of cutters. Smaller helix angles create a lower force normal to the composite in the delamination direction; however, there are also less chip removal forces, and a buildup of chips can cause greater variability in the amount of delamination [14]. Bücheler 2019 found that the least damage was with a polycrystalline diamond end mill with 0º helix angle.

2.5.2.2 Feed Per Cutter Tooth

Feed per cutter tooth in an important machining parameter, measured as distance of cut per cutter tooth. Feeds per tooth of 0.01mm to 0.05mm have been tested for continuous-discontinuous FRPs by Bücheler 2019 [14], which showed that feed per tooth must be selected in combination with helix angle to produce a good combination of low average and variance of damage on parts.
The Machinery’s Handbook 2000 calculates feed per tooth as equation 2—15, and recommends a minimal value of 0.025 mm in order to avoid excessive tool wear [16]. While the book does not impose conditions on this recommendation, the book in general is targeted towards those practicing machining on primarily metals.

\[ f_t = \frac{f_m}{n_t \times N} \tag{2—15} \]

### 2.5.3 Cutter Material

Caggiano 2018’s review showed that the most commonly used materials for cutting FRP were sintered carbides, cubic boron nitride (CBN), and Polycrystalline Diamond (PCD) because of their high hardness and thermal conductivity, although diamond-like carbon coated end mills were used as well [17]. Bücheler 2019 found in a comparison of 4 different cutters that the best quality cuts were from 0° PCD cutters on UD carbon fiber, glass fiber SMC composites [14]. McMaster-Carr, a commercially available cutter supplier, recommends diamond or diamond-like coated carbide cutters for machining carbon fiber [18].

### 2.6 Material Property Comparison to Aluminum

For high performance materials used in vehicles or sporting gear, the objective is often to minimize weight for a fixed stiffness or strength. To optimize this design, the strength-to-weight and stiffness-to-weight of the material are often important criteria in material selection and will determine the usefulness of the CFRP being studied. Because of its availability, ease of manufacturing and the volume of production, aluminum 6061-T6 was used as a baseline for comparison.

6061-T6 has a Young’s modulus of \( E_{6061T6} = 69 \text{ GPa} \), a density of \( \rho_{6061T6} = 2.7 \text{ g/cm}^3 \), and a yield strength of \( \sigma_{6061T6} = 275 \text{ MPa} \) [19]. This gives a stiffness-to-weight and strength-to-weight as follows.

\[ \frac{E_{6061T6}}{\rho_{6061T6}} = 25.6 \frac{\text{GPa}}{\text{g} \times \text{cm}^{-3}} \tag{2—16} \]
While plotting results, a comparison value of equivalent specific strength (or stiffness) as 6061-T6 aluminum may be shown. This value shows the stiffness or strength that the tested CFRP would have to meet to have the same specific strength or stiffness as 6061-T6.

\[
\frac{\sigma_{6061T6}}{\rho_{6061T6}} = 101.9 \frac{MPa}{g \ast cm^{-3}}
\]

\[
\frac{\sigma_{\text{CFRP,6061Equivalent}}}{\rho_{\text{CFRP}}} = \frac{\sigma_{6061T6}}{\rho_{6061T6}}
\]

\[
\sigma_{\text{CFRP,6061Equivalent}} = \sigma_{6061T6} \times \frac{\rho_{\text{CFRP}}}{\rho_{6061T6}} = 133.4 \text{ MPa}
\]

\[
\frac{E_{\text{CFRP,6061Equivalent}}}{\rho_{\text{CFRP}}} = \frac{E_{6061T6}}{\rho_{6061T6}}
\]

\[
E_{\text{CFRP,6061Equivalent}} = E_{6061T6} \times \frac{\rho_{\text{CFRP}}}{\rho_{6061T6}} = 33.5 \text{ GPa}
\]

Where \( \rho_{\text{CFRP}} \) is the density of the CFRP being tested, which has a value of \( \rho_{\text{CFRP}} = 1.31 \text{ g/cm}^3 \).

Specific strength and specific stiffness are tabulated as material properties for direct comparison and material selection. The Ashby 1999 Engineering Material Selection method [20] shows that higher values of the specific stiffness or strength, \( E/\rho \) or \( \sigma/\rho \), provides lower weight for members loaded completely in tension. However, under bending of a solid member with fixed-width, free-height cross section, the lowest weight is achieved with the highest values of \( E^{1/3}/\rho \) or \( \sigma^{1/2}/\rho \) depending on if the design is stiffness limited or strength limited [20]. This results in two additional comparisons for when the material is used in bending. The lower density of the CFRP focused on in this thesis (\( \rho_{\text{CFRP}} = 1.31 \text{ g/cm}^3 \) versus \( \rho_{6061T6} = 2.7 \text{ g/cm}^3 \)), gives it an increased advantage in bending due to its larger cross-section height for the same mass per unit length, which causes a greater bending moment of inertia.
\[
\frac{\sigma_{\text{ CFRP, } 6061\text{ Equivalent}}^{1/2}}{\rho_{\text{CFRP}}} = \frac{\sigma_{6061\text{T6}}^{1/2}}{\rho_{6061\text{T6}}}
\]

\[
\sigma_{\text{ CFRP, } 6061\text{ Equivalent}} = \sigma_{6061\text{T6}} \left( \frac{\rho_{\text{CFRP}}}{\rho_{6061\text{T6}}} \right)^2 = 64 \text{ MPa}
\]

\[
\frac{E_{\text{ CFRP, } 6061\text{ Equivalent}}^{1/3}}{\rho_{\text{CFRP}}} = \frac{E_{6061\text{T6}}^{1/3}}{\rho_{6061\text{T6}}}
\]

\[
E_{\text{ CFRP, } 6061\text{ Equivalent}} = E_{6061\text{T6}} \left( \frac{\rho_{\text{CFRP}}}{\rho_{6061\text{T6}}} \right)^3 = 7.9 \text{ GPa}
\]
2.7 Properties of Previous Vacuum Assisted Discontinuous Fiber Testing

In shear and bending, Callender 2018 tested a range of fiber lengths from 3.18mm to 25.4mm (.125 inch to 1.000 inch) and fiber volume fractions (15%, 25%, and 35%) [6] of a similar manufacturing process to that documented in this thesis. Figure 5 and Figure 6 and shows a box plot of the bending stress at failure. The box shows the lower and upper quartiles, and the whiskers show the highest and lowest value recorded. The whiskers should not be confused with error bars.

![Box plot showing bending stress at failure for different fiber lengths and volume fractions.](image)

**Figure 5: Flexural Strength vs Fiber Length of Callender 2018 Samples**
If the ultimate flexural strengths of specimens measured in Callender 2018 [6] are assumed to follow a normal distribution, then a stress that 99% of the population will be stronger than can be calculated using the Student’s t-distribution [21].

\[
t_{0.01} = \frac{x - \mu}{\sigma}
\]

\[
x = \mu - t_{0.01, df=14} \times \sigma
\]

For the samples of all of the 0.125in long fibers (including 15%, 25%, and 35% volume fraction), using equation 2—17 and the values of \( \mu = 199 \, MPa \), and \( \sigma = 30.3 \, MPa \), the stress that 99% of the population would be stronger than would be 119.5 MPa.

\[
x = 199 - 2.624 \times 30.3 = 119.5 \, MPa
\]

When plotted (Figure 8), it can be seen that the combination of mean stress, and variance create a downward trend with increasing fiber length.

Given the results in Figure 8, 3.18mm (0.125 inch) long fibers, and 25%-35% volume fraction are the most promising for providing the highest minimum flexural stress for
99% of a population of samples. However, the number of samples in the dataset is small; additional testing in varying fiber volume fractions and fiber length may need to be done to build up a sufficient database for rigorous statistical analysis.

6.35mm (0.250 inch) long fibers and a 25% volume fraction were selected for further study in this paper. Although these parameters did not have the highest strength or lowest variance in failure stress, they were on the higher end, and closer to the midpoint in the parameters available and tested.

Figure 7: Minimum Flexural Strength for 99% of Population
Figure 8: Minimum Flexural Strength for 99% of Population
Chapter 3

3 Material Preparation Process

The test coupons were manufactured by placing a charge of chopped carbon fiber mixed with two-part epoxy resin into a two-piece aluminum mold. First, a vacuum, then 50 bar positive pressure were applied to the cavity to minimize cavities size and quantity.

3.1 Pressure

Applying a vacuum to the cavity before compression removes the air from the chamber, allowing for air pockets to be reduced to much smaller sizes than by applying compression alone. A simplification of the ideal gas law determines this effect.

\[
\frac{V_2}{V_1} = \frac{P_1}{P_2}
\]

The reduction in volume is therefore determined by \( P_1/P_2 \). To achieve a 40,000x reduction, the pressure is started at 2 mbar absolute and then increased to 50 bar. To achieve the same volume reduction without vacuum, the pressure would have to be increased to 40,000 bar.

To increase the pressure within the cavity to 50 bar using only a typical shop supply line of air at 7.6 bar (110 psi) gauge pressure, a pneumatic plunger was used. The force on both sides of the plunger are equal, giving equation 3—2, which can be rearranged and solved for cavity pressure.

\[
P_{\text{air}} A_{\text{plunger,air}} = P_{\text{cavity}} A_{\text{plunger,cavity}} \quad 3—2
\]

\[
P_{\text{cavity}} = P_{\text{air}} \frac{A_{\text{plunger,air}}}{A_{\text{plunger,cavity}}} \quad 3—3
\]

\[
P_{\text{cavity}} = 7.6 \text{bar} \times \frac{\pi \times 19.05 \text{mm}^2}{\pi \times 7.5 \text{mm}^2} = 49 \text{bar}
\]
3.2 Tooling

![Tooling Diagram]

Figure 9: CAD Model (Section View) – Open Position (CAD Model by J. Callender, G. Konstantinopoulos and B. Heidenreich. Used with Permission.)

The tooling consists of top and bottom machined aluminum molds, with a pneumatic actuator piston assembly mounted on top. There are two main seals— the outer seal holds a vacuum while the tool is closed onto the inner seal. Closing the inner seal while under vacuum seals off the vacuum port, preventing resin from entering the vacuum line, which allows positive pressure to build in the part cavity.

The nominal spacing between the molds at the part cavity is 4mm. However, tool deflection causes a variation in the thickness of the final parts. Additional details of the tooling are described in Callender 2018.

3.3 Resin Volume Calculations

It is important to note that if there is insufficient resin to fill the cavity, then the plunger will complete its stroke, and the target pressure will not be reached, allowing larger voids
in the final part. The total volume of the mixture will have to be between the volumes of the cavity in the plunger fully retracted state and fully extended state. When calculating volume, the entire cavity must be used up to the inner seal surface. Too much mixture in the cavity will cause it to spill over the inner seal, as well as damage the location where the start and end of the seal are bonded together to form the loop.

The volume of the as-molded part, excluding epoxy pockets should be determined first. The thin gap between the part and the epoxy pockets (when the mold is fully closed), along with the low mobility of the carbon limits the amount of carbon that enters the epoxy pocket around the edge of the cavity. The volume of the as-molded part should be used when determining volumes of carbon and epoxy for the desired volume fraction. Finally, a volume of epoxy equal to the volume of the epoxy pockets can be added onto the total epoxy requirement.

With the apparatus used in this research, tooling deflection noticeably increased the volume of the cavity during molding, resulting in a requirement for an increased volume of the final as-molded part. To maintain the desired volume fraction, both the epoxy and carbon must be increased. Tooling deflection can make it difficult to estimate the exact volume of epoxy required because the tool will only deflect as the pressure increases, but the pressure can only increase if there is sufficient epoxy. Multiple attempts are likely required to determine the correct volume of mixture to use.

### 3.4 Manufacturing Method

To minimize void size, the air within the cavity was first removed with a vacuum, and then the cavity was pressurized using a piston to 50 bar. The coupon was finally post-cured at 60ºC, and then individual test samples were cut out with a milling machine.

A step by step checklist shown below was used for each manufacturing cycle.

1. **Clean Mold Surfaces**
   a. Chip away large pieces with chisel
   b. Remove remaining cured resin with knife, sandpaper, and scouring pad
   c. Blow compressed air over the mold to remove dust
d. Wipe mold with acetone or alcohol-based cleaning solution

2. Remove, Clean, and Replace Plunger
   a. Remove the pneumatic cylinder and plunger
   b. Check plunger O-rings for damage, and replace if necessary
   c. Run a reamer through the plunger hole every few part cycles to prevent buildup of resin in cylinder
   d. Fully retract plunger, then close the actuator air valve

3. Tooling
   a. Reattach plunger assembly to tooling
   b. Fully tighten the four corner M6 height adjustment screws. These will hold the mold in the vacuum seal position
   c. Check the plunger is retracted and valve closed

4. Wrap continuous carbon fiber around mold inserts

5. Apply mold release agent/wax to the mold surfaces

6. For coupons using a plate mold insert, the plate is inserted into the mold

7. Measure carbon, resin, and then hardener

8. Mix hardener into resin, and then add mixture into carbon

9. Degas mixture under vacuum for 10 minutes

10. Place mixture in mold

11. Apply O-ring grease to seals

12. Close mold to the vacuum stage, assembling and tightening the eight main M10 screws

13. Degas in mold for 10 minutes

14. Remove four corner M6 screws, while tightening eight main M10 screws, closing the mold completely

15. Remove the vacuum line

16. Apply positive pressure to the plunger

17. Heat for 8 hours at 60°C

18. Demold Part
   a. Open mold
   b. Chisel away neat resin in the resin catch pocket around the edge of the part
c. Use ejector pin, as well as knife, or plastic wedge to separate part from mold

### 3.4.1 Preparation

To prepare the mold, first, any remaining epoxy or carbon from previous manufacturing cycles must be removed. Large pieces can be chiseled away, while smaller ones can be removed with a knife edge, sandpaper, or scouring pad.

The aluminum mold surface must be prepared to the desired surface finish. A rough surface produced by rough sanding or a polymer scour pad was used to manufacture the coupons. While a fine polish produces aesthetic parts and makes it easier to remove parts, cleaning off any residual resin on the molds can damage the soft aluminum, requiring a lengthy process to refinish the mold back to a fine polish.

Mold release wax is important to reducing residual resin remaining on the mold (decreasing mold refinishing required), and reducing the forces required to eject the finished part. A high temperature compatible wax is required due to the temperatures in the post-curing process. Callender 2018 demonstrated blister defects in the finished part caused by melting of a heat-sensitive release agent.

### 3.4.2 Molding

When measuring the carbon, resin, and hardener, the order of measurements can help prevent issues in the manufacturing process. It is recommended to measure the discontinuous carbon first. Resin and hardener are more likely to be on the outside of their storage containers and stick to gloves more readily than carbon. Measuring the carbon first reduces chances of cross-contamination of resin or harder entering the discontinuous fiber storage container. Resin should be measured second. The resin is thicker than the hardener, making it harder to measure precisely. By measuring the hardener last, the precise mass of hardener required can be recalculated to adjust for the actual mass of resin used.

A significant mass of hardener may be left in the cup, which is especially an issue when using small quantities of resin and hardener. Hardener cups measured after being emptied
still contained 1-2 grams of hardener on the inside walls and base. The epoxy system used required 34g +/- 2g of hardener to 100g of resin (See Appendix 3: Epoxy Resin Datasheet).

When inserts were used, either for continuous fiber reinforcement of tensile sections, or for pullout tests, internally tapped commercial off-the-shelf “threaded standoffs” from McMaster-Carr were used. They were bolted to a 2D laser cut frame (Figure 10) mold insert, which was separated from the part after curing, while the threaded standoffs became integrated in the coupon. Because the mold was not permanently altered, the thickness of the frame reduced the thickness of the mold cavity, and by extension also the coupons by 0.79mm.

![Figure 10: Mold Insert Frame](image)

#### 3.4.3 Curing

It is recommended to cure the part in the mold when possible to reduce thermal warpage. However, green parts can be removed from the mold and heat-treated separately to increase cycle times. The epoxy datasheet recommends a cure temperature and time, which has diminishing returns with additional time. To reduce variability, all parts were cured for at least 6 hours.

Parts can be cured in a dedicated oven. However, because of the low post-cure temperature required for this infusion epoxy, only 60ºC is required, which can be
achieved with low capital investment. The high thermal conductivity of large aluminum tools ensures even heating throughout the part.

3.4.4 Post-Processing

A 2D laser cut drill jig (Figure 11) was clamped onto the coupon. The large center hole aligns with a cylindrical boss in the coupon left over by the incomplete extension of the plunger. Using the jig, the four corner holes were accurately and quickly drilled in the coupon. Following this, coupons could be bolted to an aluminum plate that had four corresponding tapped holes. The aluminum plate would be clamped to the mill table, and coupons were bolted in one at a time for machining, using two countersunk head bolts and two socket head bolts for accurate locating and clamping of the coupons to the plate. This allowed for accurate and repeatable milling operations to different coupons without having to zero the mill for each coupon.

Drilling out inserts was completed with a drill press that allowed the drill to self-center into the internal thread of the insert (the bolt used to attach the insert to the insert frame was removed during demolding). The stainless-steel inserts, which had significantly higher tensile strength than the zinc plated steel and aluminum inserts, proved difficult to drill out. The torque between the drill bit and a stainless-steel insert was occasionally enough to break the bond between the composite and the insert, allowing the insert to spin in place, resulting in a scrapped sample.
The cured parts are readily machinable, offering a wide range of design freedom during post-processing. Samples were cut from the coupons using a CNC mill with a 3.18mm (1/8 inch) Diamondlike-Carbon (DLC) coated end mill. A spindle speed of 1600 RPM and a feed of 100mm (4 inch) per minute produced clean cuts. Without the hard and resilient coating, carbon quickly dulls end mills. Tufts of carbon sticking out of the cut surface or edge indicate a dull cutter, which means an increase in friction, heat, and cutting forces. Once tufts are visible from most cuts, the remaining life of the cutter is quite short.

3.5 Continuous Fibers and Inserts

Inserts can be molded into the part to give wrapping locations for continuous fibers, as well as locally strengthen the part for bolt, rivet, or pin connections.

3.5.1 Dry Continuous Fiber Reinforcement Manufacturing Method

Continuous carbon fiber rovings were assembled onto the thin aluminum frame (red in Figure 12) before placing the frame into the mold. This eliminated the need for permanent modifications to the mold.

Clamping of the fibers between the insert and the frame was used to hold the start of the continuous fiber roving in place. The end of the roving was placed against the exterior cylindrical face of the insert, with each loop around the insert applying more friction to hold the end of the roving in place.

The partially threaded screws shown in Figure 13 were able to be unscrewed after being submerged in resin, and then cured in place. A knife was able to remove cured resin from the bolt head, and then sufficient torque could be applied to break the epoxy in the threads.

With many loops around a small pin, and no cap on the insert, keeping the continuous fiber around the inserts became increasingly difficult, as the fibers would often slip over the top. In future designs, having a bolt head on top of the inserts could allow for more
continuous fiber to be wound around. However, a closely matched cutout in the upper mold would have to accompany this.

**Figure 12: Continuous Fiber Frame and Inserts**

**Figure 13: Cross Section of Continuous Fiber Frame and Insert**
3.5.2 Continuous Fiber Reinforcement Observations

As shown in Figure 14, dry continuous fiber reinforcement gets pushed to the bottom of the cavity during molding. The strong and stiff continuous fibers create an asymmetric stiffness profile of the cross section during tension. In the thin, 4mm thick samples, the failure stress of the tensile samples was still increased.

![Figure 14: Continuous Fiber Reinforcement](image)

3.5.3 Cured Continuous Fiber Reinforcement Manufacturing

To prevent the flattening and asymmetric reinforcement of the continuous carbon fiber, samples were made with cured pre-formed inserts consisting of continuous carbon fiber, and their wrapped metal inserts. These preforms (see Figure 15) were then placed into the mold along with the epoxy and discontinuous fiber mixture for final molding.

When making continuous fiber pre-forms, the first method attempted was one that allowed for a washer to be fastened on top of the inserts that in turn could allow for more continuous fiber to be wrapped around the insert without falling off.
Because the partially engaged threads in Figure 13 were able to be reliably unscrewed from the threaded inserts after being coved in resin and then cured, when making a fixture to cure continuous fiber pre-forms, long screws, which fully engaged the threads in the inserts were used. The long screws allowed washers to be clamped on top. Unfortunately, once fully threaded and cured, the epoxy prevented the screws from being unthreaded from the threaded metal inserts. With the top washers, and long screws permanently attached to the frame and inserts, they would not fit in the mold.

The process that was successful with holding the continuous fiber in place long enough to cure, while also being separable from the aluminum sheet frame was to clamp the ends of the wet continuous carbon between the aluminum sheet metal frame and the threaded metal inserts, similar to how the continuous fiber was held in the one-shot molding technique. A new, clean frame was used during final molding.

Unfortunately, curing the fiber pre-forms before final
3.5.4 Cured Continuous Fiber Reinforcement Observations

Because the charge fills the mold, and the discontinuous fibers have low mobility, they were unable to sufficiently travel into the space inside the ring of cured continuous carbon, leaving it mostly free of discontinuous fibers (from visual inspection). The resin, with a much higher mobility, was still able to fill the area. Although the resin prevented the formation of large voids in the area, the lack of discontinuous fiber would locally reduce the strength and stiffness to just that of the epoxy. The lower stiffness of the epoxy area limits the amount of load it can take, resulting in increased load elsewhere.

In future testing, discontinuous fibers may be hand placed inside the cured loop of continuous carbon, to reinforce the area. However, the variability of hand placing would likely leave a wide range of fiber volume fractions in these areas, which would likely transfer to variance in the local reinforcement as well as in final failure stress of the part. Measuring the amount of fiber placed into the loop during manufacturing, and comparing that to both the volume fraction and the failure stress of the cured part would give more insight into this issue.

Despite the lack of discontinuous fibers in the center of the continuous carbon loop, the continuous fiber reinforcement still allowed the specimens to perform favourably compared to those without continuous reinforcement.

3.6 Improvements Made to the Manufacturing Methods

Several improvements or manufacturing experiments were made to the mold originally developed in Callender 2018 [6]. These aimed to reduce part cycle times and reduce defects.

3.6.1 Plunger O-Ring Position

The location of the O-ring seals on the plunger were lowered, so that the plunger would still maintain its seal in the fully extended position. When the plunger is fully extended, it indicates that there was insufficient volume of charge in the mold to completely fill the cavity, which can lead to larger cavities in the final part. Before the change, during full extension, resin could infiltrate into the plunger bore, further reducing the pressure in the
cavity, while also causing issues after curing. The cured resin would reduce the effective
diameter of the plunger bore, causing higher friction and lower cavity pressure during the
subsequent manufacturing cycle. The cured resin around the O-rings also necessitated
their replacement, which increased the preparation time between parts.

3.6.2 Ejection Pin

![Ejection Plug and Cylinder - Section View](image)

Figure 16: Ejection Plug and Cylinder - Section View. (CAD Model by J. Callender and B. Heidenreich. Used with Permission.)

In the female side of the mold, a hole for an ejection pin was drilled and tapped to half
the hole’s depth. The hole was plugged with a tight-fitting aluminum cylinder, which sat
flush with the inner mold surface, and then an NPT plug was screwed into the back of the
mold to hold pressure and prevent the aluminum cylinder from backing out. To eject the
part from the mold, the NPT plug was removed, and force was applied to the aluminum
cylinder using an arbour press and a steel rod. During pressing, the mold was supported
in the corners, so that the part would have space to eject.

The ejection pin was not always necessary for ejection of the part from the mold, but it
provided an effective method when the part did not release easily. Care must still be
taken to not over-tighten the NPT plug in the aluminum threads of the mold, which could
strip the aluminum threads.

The head of the NPT plug sat proud of the back face of the bottom mold, causing the
mold to sit uneven when placed on a level surface. If the mold is sufficiently crooked,
and the resin has sufficient mobility (especially when heating infusion resin), the resin may be able to cross over the inner seal, significantly altering the fine-tuned volume of resin required, and likely causing an insufficient resin issue. To prevent this issue, flush or nearly flush NPT plugs, or mold leveling feet are recommended.

### 3.6.2.1 Cycle Time Improvement Investigation

Using the ejection pin to further improve cycle time was investigated. Specifically, ejection was tested on parts made without mold release wax or without first chiseling the excess resin in the resin trap. In both cases, excessive force on the part caused damage during removal.

### 3.6.2.2 Alternative Ejection Methods

Compressed air was already required for manufacturing, and its ability to apply equal pressure over an area of the part can apply a very large ejection force without highly stressing small areas of the final part. However, the compressed air must act on an area larger than the air inlet port to build up sufficient force to eject the part. The initial air pressure area can be increased by small local deformation of the part around the air inlet along with small surface defects/gaps between the part and the mold face. Very thick (and therefore stiff) parts can reduce the local deflection, making air ejection more difficult.

A custom single removable mold plug insert that threaded into a single NPT thread, and was also flush with the inner mold face would provide an excellent interface for a compressed air connection. The embodiment of this would be like Figure 16, but would consist of a custom one piece insert instead of two to allow for the cylinder to be removed from the back side of the mold. After removing the custom insert, an NPT to Schrader, NPT to quick disconnect, or any other compressed air connection could be threaded into the mold, and then compressed air could be applied.

Finally, an alternative ejection method is prying. While flathead screwdrivers are commonly available, they can damage the soft aluminum mold or the part. Specialized mold release tools or car trim removal tools made from plastic will prevent damage.
3.7 Randomization of Fibers

Fibers are mass produced in rovings on spools. From these, short discontinuous fibers can be cut from rolls of continuous fiber rovings. Fibers in the “as received” condition are bundled together as a result of being chopped from these rovings. These bundles are characterized by many parallel fibers, with a common start and end point (see Figure 17). While the fiber bundles are slightly randomized during shipping and during the part manufacturing process, the fibers still visibly retained their bunching attributes in the final part. Because the fiber bundles start and stop at the same location, true 2D or 3D randomness for the modified Rule of Mixtures does not hold on a micro scale. Furthermore, the tensile load within many fibers would be transmitted to the matrix in the same location.

In order to ensure that the bundles were not limiting the final strength and stiffness of the parts, a set of coupons were manufactured and tested with randomized fibers.

Figure 17: "As Received" Fiber Bundles
Figure 18: Randomized Fibers
3.8 Randomization Apparatus

High pressure air was selected to apply a shear force to the fibers to overcome the interfacial forces keeping them together. The fibers were placed in a cylindrical container with a hole in the bottom edge to tangentially apply compressed air. In the center of the lid, a vacuum filter was attached to reduce the egress of fibers and particles. The device operated like the canister on a vacuum cleaner, except that pressurized air was forced into the container instead of a vacuum pulling air out of the canister. In both cases, the heavier fibers are kept to the outside by centripetal force, which prevents them from blocking the filter or escaping. While the vacuum filter prevented most of the fibers and particles from escaping, its high flow rate design allowed many small particles to escape, making additional proper ventilation a requirement.

Figure 19: Randomization Apparatus (Section View)
3.9 Manufacturing Observations

3.9.1 Randomized Fiber Compression

The randomization process noticeably reduced the packing density of the bulk fibers in both the dry state and after being wetted with epoxy. The reduced packing density resulted in increased compression between the mold faces and wet fibers during molding, resulting in higher mold deflection, and thicker samples. Five samples were each cut out of five coupons and measured with calipers. This effect would be reduced with stiffer tooling, such as thicker aluminum molds, molds made from a higher Young’s Modulus material such as steel, placing stiff backing plates against the backs of the tools, or using either additional or larger main mold clamping bolts.

The increased compression stiffness of the fibers makes it harder to achieve high fiber volume fractions in the part without significantly increasing the stiffness of the mold.

![Graph showing sample thickness vs coupon ID](image)

**Figure 20: Sample Thickness vs Coupon ID**
Chapter 4

4 Testing

Testing was performed on an Instron 8804 Servo hydraulic Testing System at Western University. Data Acquisition was done using Bluehill Materials Testing Software. Results were post-processed and plotted in Excel and R.

While test specimen dimensions and orientation (unless otherwise stated) are shown relative to the coupon they were machined from in Figure 21, the center specimen was often discarded due to the disruption caused by the cylindrical boss leftover from the plunger. This boss is best shown in Figure 9 from the discussion of tooling in section 3.2.

4.1 3-Point Bending

Testing for 3-point bending followed ASTM standard D7264 Procedure A [22]. Individual test specimens were machined from coupons to be 140mm by 13mm by 4mm as per the test standard.

Figure 21: Test Coupon with Individual Specimen Dimensions
Flexural stress was calculated according to D7264 as shown in the equation below.

\[ \sigma = \frac{3 \times P \times L}{2 \times b \times h^2} \]  

Where \( \sigma \) is stress, \( P \) is force, \( L \) is support span (80mm), \( b \) is specimen width (nominally 13mm), and \( h \) is specimen thickness (nominally 4mm).

Flexural modulus was calculated according to D7264 as shown in the equation below.

\[ E_{\text{chord}}^f = \frac{\Delta \sigma}{\Delta \varepsilon} \]

Where \( \Delta \sigma \) is difference between the stress at \( \varepsilon = 0.003 \) and \( \varepsilon = 0.001 \), and \( \Delta \varepsilon = 0.002 \).

4.2 Tension

Tensile testing was done in accordance with ASTM Standard D3039 [23]. D3039 allows for a wide range of geometry options for testing, which allowed for samples to be the same as the 3-point bending samples for simplicity. Crosshead movement of 2mm/min according to the standard was used. Displacement was measured using an axial clip-on contact extensometer. Where slippage of the extensometer occurred between the clips and the sample, the displacement and its dependents (Young’s Modulus, and strain) were omitted from results.

The continuous fiber reinforcement moved during molding into the area milled out from a coupon, which resulted in some of the continuous fiber being cut out of the sample. To prevent this issue, 29mm extra wide specimens were cut from the coupons, which contained all the continuous fibers.

Tensile stress was calculated according to D3039 as shown in the equation below.

\[ \sigma = \frac{P}{A} \]

Where \( \sigma \) is stress, \( P \) is force, and \( A \) is cross sectional area.
Young’s modulus was calculated according to D3039 as shown in the equation below.

\[
E_{chord} = \frac{\Delta \sigma}{\Delta \varepsilon}
\]

Where \(\Delta \sigma\) is difference between the stress at \(\varepsilon = 0.003\) and \(\varepsilon = 0.001\), and \(\Delta \varepsilon = 0.002\).

4.3 Randomization Round of Testing

‘As Received’, and ‘Randomized’ samples were tested under bending and tension (sections 4.1 and 4.2 respectively). Each square coupon was machined into 9 test specimen strips (see Figure 21 and Figure 22), with odd-numbered specimens being tested in tension, and even numbered in bending. Coupons 1 and 2 used ‘As Received’ fibers, while 3, 4, and 5 used ‘Randomized’ fibers (see Appendix 1 for a full list of tests).

Figure 22: Specimens Machined From Coupon Before Testing
An analysis of the location of the specimens within the coupon showed that while there was random deviation, no position consistently showed greater or lower UTS (See Figure 23). The location is the second number in the label on samples in Figure 22.

Figure 23: UTS vs Specimen Location in Coupon
4.4 Pin Pullout

Pin pullout testing was done in double shear, similar to Mallick 2007 [8]. As shown in Figure 24, the specimen was connected to a mild steel test fixture with a steel pin. The mild steel test fixture was clamped in the upper grips of the testing machine, while the bottom of the specimen was clamped in the lower grips.

![Figure 24: Pin Pullout Test Diagram]
With \( w/d \) and \( e/d \) ratios under Mallick 2007’s guidelines of 6 and 3 respectively (see Table 1, and calculations below), net tension, shear-out, or cleavage failures could be expected. Molded-in inserts at pin locations were not included in Mallick’s guideline values, however, when calculating the ratios, using either the hole diameter or the insert outer diameter, both are still below the 6 and 3 guidelines (see calculations below).

Furthermore, using inserts with yield strength high above that of the composite matrix would increase the bearing strength significantly, making it even more likely for net tension/shear-out/cleavage failure to occur before failure in bearing.

\[
\frac{w}{d^2} = \frac{13}{6.35} = 2.0
\]

\[
\frac{e}{d^2} = \frac{5.91}{6.35} = 0.9
\]
Chapter 5

5  Mechanical Properties

Young’s Modulus and failure stress were the two properties focused on in this thesis.

5.1  Analytical Models

5.1.1  Fiber and Matrix Properties

The matrix and fibers used had the following material properties. For material datasheets, see Appendix 3 and Appendix 4.

\[ E_m = 3.1 \text{ GPa} \]  
Young’s Modulus of Matrix (Epoxy)

\[ E_f = 242 \text{ GPa} \]  
Young’s Modulus of Fiber (Carbon)

\[ r_f = 7.2 \text{ \( \mu \)m} \]  
Radius of Fiber

\[ l = 6.35 \text{ mm} \]  
Length of Fiber

\[ f = 25\% \]  
Fiber Volume Fraction

\[ \nu_m = 0.3 \]  
Poisson’s Ratio of Matrix

5.1.2  Rule of Mixtures

Using these values, we can calculate the fiber aspect ratio.

\[ s = \frac{l}{r_f} \]  \hspace{1cm} 5—1

\[ s = \frac{6.35 \text{ mm}}{7.2 \text{ \( \mu \)m}} = 882 \]  \hspace{1cm} 5—2

By calculating the dimensionless value, \( n \) (Equation 2—1), we can then compare the aspect ratio to the minimal aspect ratio required for the Rule of Mixtures (Equation 2—3).
\[ n = \sqrt{\frac{2 \cdot E_m}{E_f \cdot (1 + \nu_m) \cdot \ln\left(\frac{1}{f}\right)}} \]  
2—1

\[ n = \sqrt{\frac{2 \cdot 3.1 \text{ GPa}}{242 \text{ GPa} \cdot (1 + 0.3) \cdot \ln\left(\frac{1}{0.25}\right)}} = 0.119 \]

\[ s_{RoM} \approx \frac{10}{n} \]  
2—3

\[ s_{RoM} \approx \frac{10}{0.119} = 84 \]

\[ \therefore s \gg s_{RoM} \]

Because the aspect ratio of the fibers is significantly higher than the minimum aspect ratio needed for RoM, the RoM approximation is acceptable for this composite.

Using the modified RoM, the Young’s Modulus of the composite can be modeled. Recall from Section 2.1.2 that \( K = 3/8 \) for random in-plane, and \( K = 1/5 \) for random 3D discontinuous fibers. Because the material samples are flat plates, the fibers are quasi-2D, and the composite properties can be expected to lie between the random 2D in-plane state and 3D state.

\[ E_C = K \cdot E_f \cdot f + E_m \cdot (1 - f) \]  
2—4

\[ E_{C,Upper} = 0.375 \cdot 242 \text{ GPa} \cdot 0.25 + 3.1 \text{ GPa} \cdot 0.75 = 25 \text{ GPa} \]

\[ E_{C,Lower} = 0.2 \cdot 242 \text{ GPa} \cdot 0.25 + 3.1 \text{ GPa} \cdot 0.75 = 14.4 \text{ GPa} \]

5.1.3 Weighted Average of Parallel and Transverse Properties

Equations 2—5 to 2—9 from Mallick 2007 outlined in Section 2.1.2, can be used to predict the Young’s Modulus of the samples.
\[ \eta_L = \frac{E_f}{E_m} \frac{E_m - 1}{E_f + 2 \left( \frac{l_f}{d_f} \right)} \quad \Rightarrow \quad \eta_L = \frac{242 \text{ GPa} - 1}{3.1 \text{ GPa} + 2 \left( \frac{6.35 \text{ mm}}{7.2 \text{ um}} \right)} = 0.042 \]

\[ \eta_T = \frac{E_f}{E_m} \frac{E_m - 1}{E_f + 2} \quad \Rightarrow \quad \eta_T = \frac{242 \text{ GPa} - 1}{3.1 \text{ GPa}} = 0.963 \]

\[ E_{11} = \frac{1 + 2 \left( \frac{l_f}{d_f} \right) \eta_L * f}{1 - \eta_L * f} E_m \quad \Rightarrow \quad E_{11} = \frac{1 + 2 \left( \frac{6.35}{0.0072} \right) * 0.042 * 0.25}{1 - 0.042 * 0.25} * 3.1 \text{ GPa} = 61 \text{ GPa} \]

\[ E_{22} = \frac{1 + 2 \eta_T * f}{1 - \eta_T * f} E_m \quad \Rightarrow \quad E_{22} = \frac{1 + 2 * 0.042 * 0.25}{1 - 0.042 * 0.25} * 3.1 \text{ GPa} = 6 \text{ GPa} \]

\[ E_c = \frac{3}{8} E_{11} + \frac{5}{8} E_{22} \quad \Rightarrow \quad E_c = \frac{3}{8} (61 \text{ GPa}) + \frac{5}{8} (6 \text{ GPa}) = 27 \text{ GPa} \]

The predicted Young’s Modulus of 27 GPa from Mallick 2007’s weighted average method (which is only valid for 2D in-plane fibers) is very close to the 25 GPa predicted by the Modified RoM method, which is also for 2D in-plane fibers. Both serve as expected upper limits to the material properties because of the quasi-2D nature of the composite. For parts with thicker sections, the material properties could be expected to be closer to the 3D random properties, predicted as the lower limit from the RoM.

### 5.2 Randomized Fiber Properties

While the randomized samples had a slightly higher median UTS, there was no significant difference in the UTS between the ‘Randomized’ fibers and the ‘As Received’ fibers, as can be seen in Figure 26. Young’s modulus also showed very similar results between the two fiber types (Figure 27). Following these results, ‘As Received’ fibers were used in subsequent tests. The box plots below highlight the maximum, upper quartile, median, lower quartile, and minimum values; the UTS of individual specimens making up each sample are shown to the left of the boxes.
Figure 26: UTS Comparison of As Received and Randomized Fibers (Tension)

Figure 27: Young's Modulus Comparison of As Received and Randomized Fibers (Tension)
5.3 Bending and Tensile Testing

5.3.1 Bending and Tensile Results

As shown in Figure 26, there was no discernable difference between the ‘As Received’ and ‘Randomized’ samples. Both types of fibers were tested in tension and bending. Samples 1-2 were ‘As Received’, while 3-5 were ‘Randomized. As explained by Weibull Analysis (Section 2.1.3), the bending coupons had significantly higher maximum stress at failure than those tested in tension due to the increased volume of stressed material. The Young’s Moduli were however comparable.

![Figure 28: Ultimate Tensile Strength for Samples (For Al6061T6 Comparisons, See Section 2.6)]
5.3.2 Bending and Tensile Discussion

Under tension, the discontinuous CFRP under investigation has two factors working against it. First, it has a lower maximum breaking stress due to larger volumes of stressed material, which increases the likelihood of failure. Second, the lower density of the CFRP compared to aluminum does not have as great of an impact on the material index in tension as in bending: \((\rho_{\text{CFRP}}/\rho_{\text{Al}})_{\text{tens}}\) vs \((\rho_{\text{CFRP}}/\rho_{\text{Al}})^2_{\text{bend}}\) for stress-limited design, and \((\rho_{\text{CFRP}}/\rho_{\text{Al}})_{\text{tens}}\) vs \((\rho_{\text{CFRP}}/\rho_{\text{Al}})^3_{\text{bend}}\) for stiffness-limited design.

For bending however, the effect of both factors is reversed, and the CFRP outperforms the 6061-T6 aluminum alloy using the material index metric. This means that under bending, the CFRP can provide significant weight savings in a strength-limited design and a stiffness-limited design.

5.4 Continuous Fiber Reinforcement

5.4.1 Effect of Continuous Reinforcement on Strength

As shown in Figure 30, continuous carbon fiber reinforcement increased the UTS from 93.4 MPa (median for zero continuous reinforcement) to 203.2 MPa (median for 4%
volume fraction reinforcement). This 117% gain in UTS allowed the CFRP to surpass the 6061-T6 aluminum benchmark for strength-to-weight in tension by 53%.

![Figure 30: UTS vs Continuous Fiber Reinforcement](image)

### 5.4.2 Effect of Continuous Reinforcement on Stiffness

The continuous carbon reinforcement did not provide the same improvements for stiffness. As shown in Figure 31, while a small improvement in stiffness may be present, further testing would be required to determine if the an increase is statistically significant.
5.4.3 Discussion of Continuous Reinforcement

In tensile-strength-limited design, continuous fiber reinforcement meaningfully increases the UTS, and can increase the tensile strength to weight ratio of the CFRP above that of the baseline 6061-T6 aluminum. While bending was not tested on samples with continuous fiber reinforcement, due to the flattening and associated asymmetry of the continuous fibers within the cavity during molding (Sections 3.5.2 and 3.5.3), a change in bending strength would likely not be as significant. However, when measured with the material index of lightest weight for a given moment, the bending properties of the CFRP were already greater than that of the aluminum before continuous reinforcement.

5.5 Pre-Cured Continuous Carbon Preforms

The continuous carbon pre-forms had a slightly lower UTS than the dry fibers (see Figure 32). Due to the higher labour required for the pre-cured reinforcements, pre-curing can only be recommended when symmetry of the reinforcement is critical to design.
The cured epoxy in the pre-cured continuous carbon preforms would not be able to cross-link and bond to the rest of the matrix as well as when the entire matrix cures at once with the dry continuous carbon method. This weak bond is a likely cause for the slightly lower UTS.

Figure 32: UTS Comparison of Cured and Dry Continuous Carbon Reinforcement

5.6 Pin Pullout Testing

Pin and fastener connections are both common and useful methods to join components – especially for different materials. The ability to determine safe load capacities is crucial to effective utilization of these joints. Because multiple methods are available to predict pin connection failure, in this section the accuracy of the different methods will be compared to help prospective designers select the most accurate method to predict failure and understand if methods are conservative or risky.

Four options to calculate the stress at failure using equation 2—14 were compared: every combination of two options for hole diameter, and two options for applying a stress concentration factor. First, the outer diameter of the insert \((d = 6.35mm, \text{"Insert OD" in})\)
Figure 33) or the inner diameter of the insert ($d = 3.57 mm$, “Hole ID” in Figure 33) could be used for the diameter of the hole in the specimen (see Figure 25). Secondly, the stress concentration factor can either be applied ($K_{tn} = f(d)$, “Concentrate Stress” in Figure 33) or set to unity ($K_{tn} = 1$, “Nominal Stress” in Figure 33).

Using equation 2—14, the theoretical maximum stress can be calculated and compared to the average ultimate tensile stress of the gauge section from specimens in previous testing. This will allow designers to select the best model, and then estimate the failure point of the material by comparing the theoretical stress with the ultimate tensile stress of the material. The combination that predicted a failure stress that most closely matched the ultimate tensile stress of the specimens was the inner diameter of the insert with nominal breaking stress ($K_{tn} = 1$), as shown in Figure 33.

For the “insert only” and “insert with continuous carbon fiber (CF) reinforcement” cases, the ultimate tensile strength data from section 5.4 was averaged from the specimens of 0% and 2% continuous fiber volume fraction respectively. For “no insert”, the ultimate tensile strength of “As Received” samples from section 5.2 were averaged.

![Figure 33: Maximum Stress of Pin Pullout Testing at Failure, Comparison of Different Calculation Methods](image)
The inserts have a few properties that could make the standard calculations unreliable. If attempting to calculate using the inner diameter of the insert, the large change in stiffness between the composite and the insert would disrupt the stress gradients compared to an isotropic modulus surrounding the hole, which the equations are based on. If the outer diameter of the insert is used as the hole in the composite, the bonding forces, and circular support forces are unaccounted for.
Chapter 6

6 Conclusion

Randomization of the fibers increased the compression stiffness of the resin fiber mixture in the cavity, increasing mold deflection without a benefit in strength of stiffness. The added processing time and mold deflection increase costs without benefit, and therefore cannot be recommended over usage of the ‘As Received’ fibers.

In bending stress-limited design, the material properties of the CFRP may already be sufficient for the designer’s needs because of the high material index compared to the aluminum baseline. In tension stress-limited design, when the unreinforced CFRP may not be sufficient, initial testing indicates that continuous fiber reinforcement makes a large increase in the UTS. However, further testing is recommended to determine a specific maximum allowable stress.

Pin joints were tested, and different methods of estimating maximum stress were compared. Due to the dependence of stresses and failure modes on the dimension of the part near the joint, further testing with varying geometry is recommended.
Bibliography


Appendices

Appendix 1: Summary of Test Coupons

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## Appendix 2: Summary of Test Specimens

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Appendix 3: Epoxy Resin Datasheet

Technical Data Sheet

EPIKOTE™ Resin MGS™ RIMR235
EPIKURE™ Curing Agent MGS™ RIMH233, RIMH235 - 237

CHARACTERISTICS

<table>
<thead>
<tr>
<th>Approval</th>
<th>DNV-GL Germanischer Lloyd (RIMH235 – RIMH237)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Rotor blades for wind turbines, boat and shipbuilding, sports equipment, model construction, tooling and moulding</td>
</tr>
</tbody>
</table>
| Operational temperature | -60 °C up to +50 °C without heat treatment
-60 °C up to +60 °C after heat treatment |
| Processing | at temperatures between 15 °C and 50 °C |
| Features | very low viscosity
pot life from approx. 10 minutes to approx. 4.5h |
| Storage | shelf life of 24 months in originally sealed containers |

APPLICATION

RIMR235 is a low-viscous infusion resin system with different pot lives for processing of glass, carbon and aramide fibers. Due to its excellent mechanical properties, this system is suitable for the production of components featuring high static and dynamic loadability.

The range of pot lives is between approx. 10min and more than 4h depending on the choice of curing agent.

RIMR235 features an extraordinary low mixed viscosity, resulting in fast and complete fibre wetting at a high transportation rate in infusion processes. The infusion resin system does not contain any unreactive components. The raw materials used feature a very low vapour pressure which permits processing of the material under vacuum even at elevated temperatures.

Optimum processing temperatures are in the range of 15 - 40°C. As the initial cure at room temperature is very slow as for the low reactive hardeners, some heat treatment should be performed at minimum 40 - 50 °C before demoulding.

Curing at higher temperatures (up to approx. 80 - 100°C) is possible, depending on layer thickness, geometry of the parts and choice of curing agent.

Full mechanical properties will only be obtained after a suitable post cure cycle. Especially for operations at elevated temperatures such a post cure cycle is required to obtain the required thermal stability. For optimum mechanical properties a heat treatment of minimum 50°C is required.

The infusion resin system RIMR235 remains practically free of crystallisation, even if it is stored at low temperatures (<15 °C). In an early stage, crystallisation is visible as a clouding, and can progress to a stage, where the resin becomes a wax-like solid. Crystallisation can be reversed by slow heating of the product to approx. 40 - 60 °C while stirring. This physical phenomenon is reversible and is no restriction to
EPIKOTE Resin MGS RIMR 235 and EPIKURE Curing Agent RIMH 235-237

quality after removal, in fact a high purity of material will increase a tendency for crystallisation.

After dispensing material, the containers must again be closed carefully, to avoid contamination or absorption of water. All amine curing agents show a chemical reaction when exposed to air, known as „blushing”. This reaction is visible as white carbamide crystals, which could make the materials unusable.

Curing agents can be coloured to distinguish between resin and curing agents, and for easier identification of a correct mixing process. Although unlikely, deviations in colour are possible (e.g. due to UV radiation after longer exposure to sun light), but however have no effect on the processing and final properties of the material.

The materials have a shelf life of minimum 2 years, when stored in their originally sealed containers.

The relevant industrial safety regulations for the handling of epoxy resins and hardeners for safe processing are to be observed.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Density</th>
<th>Infusion resin RIMR235</th>
</tr>
</thead>
<tbody>
<tr>
<td>[g/cm³]</td>
<td>1.14 – 1.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>[mPa·s]</th>
<th>1.000 – 1.300</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Refractory index</th>
<th>[·]</th>
<th>1.550 – 1.560</th>
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</table>

<table>
<thead>
<tr>
<th>Curing agents without GL-Approval</th>
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<tbody>
<tr>
<td>RIMH233</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Viscosity</td>
</tr>
<tr>
<td>Refractory index</td>
</tr>
<tr>
<td>Potlife</td>
</tr>
<tr>
<td>Tg_{mit;pot}</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Curing agents with GL-Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIMH235</td>
</tr>
<tr>
<td>RIMH236</td>
</tr>
<tr>
<td>RIMH237</td>
</tr>
<tr>
<td>Density</td>
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<tr>
<td>Viscosity</td>
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<td>Refractory index</td>
</tr>
<tr>
<td>Potlife</td>
</tr>
<tr>
<td>Tg_{mit;pot}</td>
</tr>
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</table>

Measuring conditions:
1) measured at 25°C
2) measured at 30°C
MIXING RATIOS

<table>
<thead>
<tr>
<th>Parts by weight</th>
<th>100 : 34 ± 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts by volume</td>
<td>100 : 41 ± 2</td>
</tr>
</tbody>
</table>

The mixing ratio stated must be observed very carefully. Adding more or less curing agent will not influence reaction speed – but in incomplete curing which cannot be corrected in any way. Resin and curing agent must be mixed very thoroughly, mix until no clouding is visible in the mixing container.

TEMPERATURE DEVELOPMENT

Measuring conditions: 100g mixture in a water bath at 30°C

Optimum processing temperature is in the range of 20 to 35 °C. Higher temperatures are possible, but will shorten pot life. A temperature increase of 10 °C will halve the pot life. Water (e.g. high humidity or contained in additional fillers) causes an acceleration of the resin/curing agent reaction. Different temperatures during processing are not known to have significant impact on the mechanical properties of the cured product.

Do not mix large quantities – particularly of highly reactive systems – at elevated processing temperatures. As the heat dissipation in the mixing container is very slow, the contents will be heated up by the reaction heat rapidly. This can result in temperatures of more than 200 °C in the mixing container, which may cause smoke-intensive burning of the resin mass.

VISCOSITY OF MIXTURE
EPIKOTE Resin MGS RIMR 235 and EPIKURE Curing Agent RIMH 235-237

**Viscosity Development**

Viscosity [mPa*s]

**Measuring conditions:** Rotation viscosimeter, plate-plate configuration, measuring gap 0.2 mm

**T_2 Development**
MECHANICAL DATA OF NEAT RESIN

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td><strong>Density</strong></td>
<td>[g/cm³]</td>
<td>1.12 – 1.18</td>
</tr>
<tr>
<td>(DIN EN ISO 1183-1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flexural strength</strong></td>
<td>[MPa]</td>
<td>95 – 115</td>
</tr>
<tr>
<td>(DIN EN ISO 178)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Tensile modulus</strong></td>
<td>[GPa]</td>
<td>3.0 – 3.2</td>
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<tr>
<td>(DIN EN ISO 527-2)</td>
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<tr>
<td><strong>Tensile strength</strong></td>
<td>[MPa]</td>
<td>65 – 70</td>
</tr>
<tr>
<td>(DIN EN ISO 527-2)</td>
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<td></td>
</tr>
<tr>
<td><strong>Elongation at break</strong></td>
<td>[%]</td>
<td>6 – 8</td>
</tr>
<tr>
<td>(DIN EN ISO 527-2)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Water absorption at 23°C</strong></td>
<td>24h [%]</td>
<td>0.10 – 0.30</td>
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<tr>
<td>(DIN EN ISO 175)</td>
<td>7d [%]</td>
<td>0.40 – 0.60</td>
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</table>

Advice:
Mechanical data are typical for the combination of infusion resin RIMR235 with curing agent RIMH237. Data can differ in other applications.
EPIKOTE Resin MGS RIMR 235 and EPIKURE Curing Agent RIMH 235-237

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Appendix 4: Chopped Carbon Fiber Properties

Technical Datasheet
ZOLTEK™ PX35 Chopped Fiber (Type -02)

DESCRIPTION
ZOLTEK PX35 unsized chopped fibers provide distribution of individual filaments for applications requiring full filament bundle dispersion.
Note: Type-02 (wet)

<table>
<thead>
<tr>
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<tr>
<td>Sizing Chemistry</td>
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<tr>
<td>Moisture Content (wet)</td>
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<td>Fiber Length (~nominal)</td>
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</tr>
<tr>
<td>3 mm</td>
<td>0.125 in</td>
<td>0.25 in</td>
</tr>
<tr>
<td>6 mm</td>
<td>0.50 in</td>
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<tr>
<td>13 mm</td>
<td>2.0 in</td>
<td></td>
</tr>
</tbody>
</table>

*Fiber properties generated using ASTM standard methods.

The properties listed in this datasheet do not constitute any warranty or guarantee of values. This information should only be used for the purposes of material selection. Please contact us for more details.

RECOMMENDED USE
Applications requiring full dispersion of fiber bundles

APPLICATIONS
- Carbon papers
- Infrastructure

CERTIFICATION
ZOLTEK PX35 Chopped Fiber is manufactured in accordance with ZOLTEK’s written and published data. A Certificate of Conformance is provided with each shipment.

SAFETY
Obtain, read, and understand the Material Safety Data Sheet (SDS) before use of this or any other ZOLTEK product.

TYPICAL PACKAGING
- Each pallet contains 45 boxes and has a net weight of 1,800 lb (816 kg).
- Each box is 14.5” x 14.5” x 14.5” (36.8 cm x 36.8 cm x 36.8 cm) and contains 40 lbs (18.1 kg) of chopped fiber in a polyethylene bag.
- Chopped fiber is also available in 500 lb (227 kg) super sacks.
Technical Datasheet
ZOLTEK™ PX35 Continuous Tow

DESCRIPTION

ZOLTEK PX35 continuous carbon fiber is manufactured from polyacrylonitrile (PAN) precursor. The consistency in yield and mechanical properties that are provided by large filament count strands gives the user the ability to design and manufacture composite materials with greater confidence and allows for efficient and fast buildup of carbon fiber reinforced composite structures.

ZOLTEK PX35 50K fibers are available with a variety of sizing formats for different composite processing methods and for compatibility with a wide range of standard resin systems. ZOLTEK quality focuses on spool to spool consistency yielding low coefficients of variation.

APPLICATIONS

Wind energy, automotive, petroleum production, aviation, marine, industrial, other transportation, medical (including X-ray), sports and recreation, etc.

RECOMMENDED USE

Any article or component benefiting from the unique properties of carbon fiber composites.

<table>
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<td>Tensile Modulus</td>
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<td>Elongation</td>
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<td>Electrical Resistivity</td>
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<td>Density</td>
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<td>Fiber Diameter</td>
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<td>Carbon Content</td>
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<td>Yield</td>
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<td>Textile Units</td>
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<td>33700 denier</td>
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<td>Spool Weight</td>
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<td>12 lb, 24 lb</td>
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<td>Spool Length</td>
<td>1,500 m, 3,000 m</td>
<td>1,640 yd, 3,280 yd</td>
</tr>
</tbody>
</table>

The properties listed in this datasheet do not constitute any warranty or guarantee of values. This information should only be used for the purposes of material selection. Please contact us for more details.

ZOLTEK™ PX35

ZOLTEK Corporation | 3101 McKelvey Road | Bridgeton, MO 63044
Technical Datasheet

ZOLTEK™ PX35 Continuous Tow

TYPICAL PACKAGING

Wound on a 3” x 11” (7.6 cm x 28 cm) cardboard spool, sealed in heat shrunk covering, and placed in cardboard box; two splices are permitted per every 1,500m spool and five per every 3,000m spool.

Spool outside diameter:
- 1,500 m: 180-185 mm x 255-260 mm
- 3,000 m: 235-245 mm x 255-260 mm

CERTIFICATION

ZOLTEK PX35 Continuous Tow is manufactured in accordance with ZOLTEK’s written and published data. A Certificate of Conformance is provided with each shipment.

SAFETY

Obtain, read, and understand the Material Safety Data Sheet (SDS) before use of this or any other ZOLTEK product.

APPROVAL

DNV·GL has granted approval to ZOLTEK PX35 Continuous Tow for use in wind energy applications.

Approval No. WP 1030012 HH

ZOLTEK™ PX35

ZOLTEK Corporation | 3101 McKelvey Road | Bridgeton, MO 63044
Curriculum Vitae

Name: Bennet Heidenreich

Post-secondary Education and Degrees:
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  - 2013-2017 B.A.

Related Work Experience
- Teaching Assistant, The University of Western Ontario, 2019-2021