

Composite Material Manufacturing and Testing

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Abstract

This report discusses the manufacturing, testing, and analysis of flexural strength and modulus of five composite samples consisting of a neat epoxy-resin mixture, two continuous fiber samples of 9 layers of fiberglass fabrics sandwiched between epoxy-resin, and two samples of a mixture of epoxy-resin and finely chopped fiberglass fabric pieces. After curing, each of the samples was post-processed into a roughly uniform 9x9x50mm rectangular prism. Next, three-point bend testing was conducted on each of the samples where the force and displacement were measured to construct a full force-displacement curve for each sample. It was determined that the continuous fiber samples (2 and 3) had a higher average flexural strength of about 116 MPa than the strength values for the neat resin and the chopped fiber samples. Furthermore, the sample with the highest flexural modulus was the chopped fiber sample 4 with a modulus of 6.156 GPa. Overall, the results of the experiment coincided with expectations previously held that the layered and chopped fiberglass reinforced the samples and increased its strength and modulus compared to the neat resin sample. However, inconsistencies in strength and modulus values between the two continuous fiber samples (2 and 3) and the two chopped fiber samples (4 and 5) speak to the impact of having non-uniform samples on the results obtained.

1 Introduction

Composites consist of two constituent materials that act as a reinforcement and as a matrix. The matrix phase is typically a low-density material that acts as the continuous phase that distributes the load throughout the composite material whereas the reinforcement is a discrete phase that enhances stiffness and strength [1]. There are classes of matrix materials, such as metal matrix composites (MMCs) and polymer matrix composites (PMCs), since any material family can make up a matrix. On the other hand, reinforcements are characterized by their geometry, such as particle-reinforced, fiber-reinforced, and structural-reinforced [2].

Composites can be manufactured in different ways allowing for property combinations a single material could not achieve but are typically fabricated to increase strength and/or stiffness. Epoxy is a thermosetting polymer that is typically used as a matrix material because as it solidifies it creates covalent bonds along polymer chains and between chains creating crosslinks which lead to high stiffness and strength. However, because of how the epoxies are crosslinked they end up being brittle but with the benefit of high strength and improved thermal properties. The addition of materials or fillers like fiber reinforcement can help a brittle matrix materials better withstand failure modes such as bending.

Three-point bending is a test that can be used to assess the flexural properties of a sample by having a downward force applied to its center while its sides are supported. The force and positions are plotted from the collected data to get the ratio $F/\Delta x$,

$$\text{EQ 1} \quad \frac{F}{\Delta X} = \frac{48EI}{L^3}$$

which can then be used with the moment of inertia equation for a beam to get,

$$\text{EQ 2} \quad \frac{F}{\Delta X} = \frac{4bh^3E}{L^3}$$

which can be used to find the modulus, E. Additionally the bending strength,

$$\text{EQ 3} \quad \sigma_{bending} = \frac{3F_{max}L}{2bh^2}$$

can be determined using the sample dimensions and the span of the bend testing fixture.

2 Materials and Methods

A resin and hardener epoxy mixture was used to make composite beams with chopped glass fibers, woven fiberglass fabric strips, and without any fibers. After curing, the beams were measured and photographed and tested until failure using a load frame.

2.1 Materials

Materials Used:

Mold release (FibRelease 1153)

5 cavity mold

Cotton pads

Woven fiberglass fabric

Paper towels

Paper cup

Wooden stir stick

Resin (1000 laminating epoxy resin)

Hardener (1025 25 min epoxy cure)

Chopped glass fibers

Tools/Equipment:

Scissors

Digital scale

Gloves

Sanding wheel with 240 grit sandpaper

Load frame with bending fixture

Lab coat

Safety Glasses

2.2 Methods

To create the epoxy mixture, the resin and hardener were poured and weighed separately in different cups and then mixed together with a wooden stir stick. The epoxy mixture was then poured until the first mold cavity was $\frac{3}{4}$ full to create the neat resin sample. A thin layer of the mixture was then poured into the second and third cavities. 8 layers of fiberglass fabric strips were laid in the cavity before some additional epoxy was poured on top. The last two cavities were filled with a combination of the remaining mixture and chopped glass fibers. All five cavities were then smoothed out to ensure uniform thickness across all the samples as shown in Figure 1 below.



Figure 1: Composite beams in the mold prior to curing.

After the samples had cured and hardened, they were removed from the mold and sanded down using a polishing wheel. The samples were then measured, photographed, and labeled according to their composition. The samples were then placed onto the bend testing fixture and preloaded to 20N. The samples were then tested until failure and the data was recorded as shown in Figure 2 below.

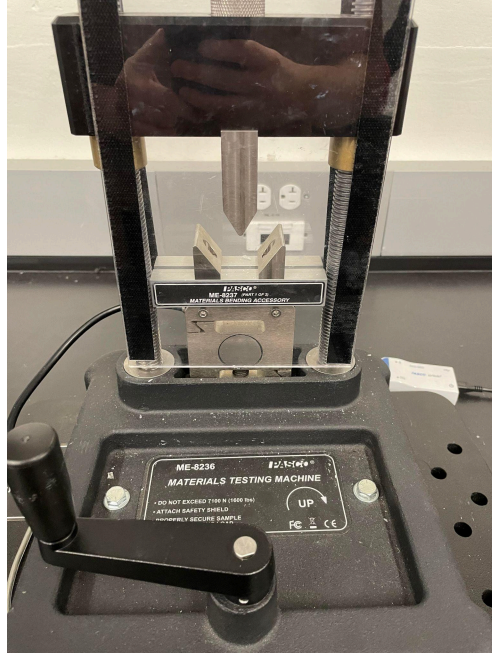


Figure 2: Bend testing fixture on load frame.

Lastly, photographs were taken of the failed samples to examine their failure mode which are shown in Figures 3a and 3b.

3 Results

Data Table 1 organizes all calculations and details for each separate composition trial. Flexural strength and flexural modulus are presented in their respective units (MPa and GPa). The table also includes physical dimensions and sample ID numbers.

Table 1: Summary of composite sample properties.

Sample ID	Composition	b [mm]	h [mm]
1	Neat resin	9.625	6.2
2	Resin + 8 layers woven glass fiber (continuous)	9.725	10.15
3	Resin + 8 layers woven glass fiber (continuous)	9.825	9
4	Resin + Chopped glass fiber	9.925	9.3
5	Resin + Chopped glass fiber	9.575	11.2

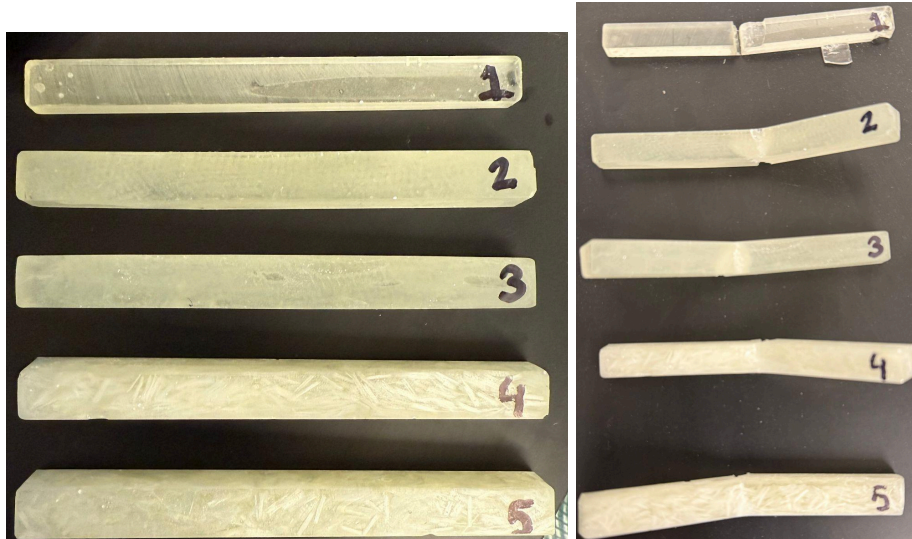


Figure 3a-3b: Composite samples pre and post-testing.

The data logged from the load cell was then exported from the PASCO software to a csv file. Using the data logs, the full and linear regions of the force-displacement curves were plotted for each material as shown in Figures 4-7.

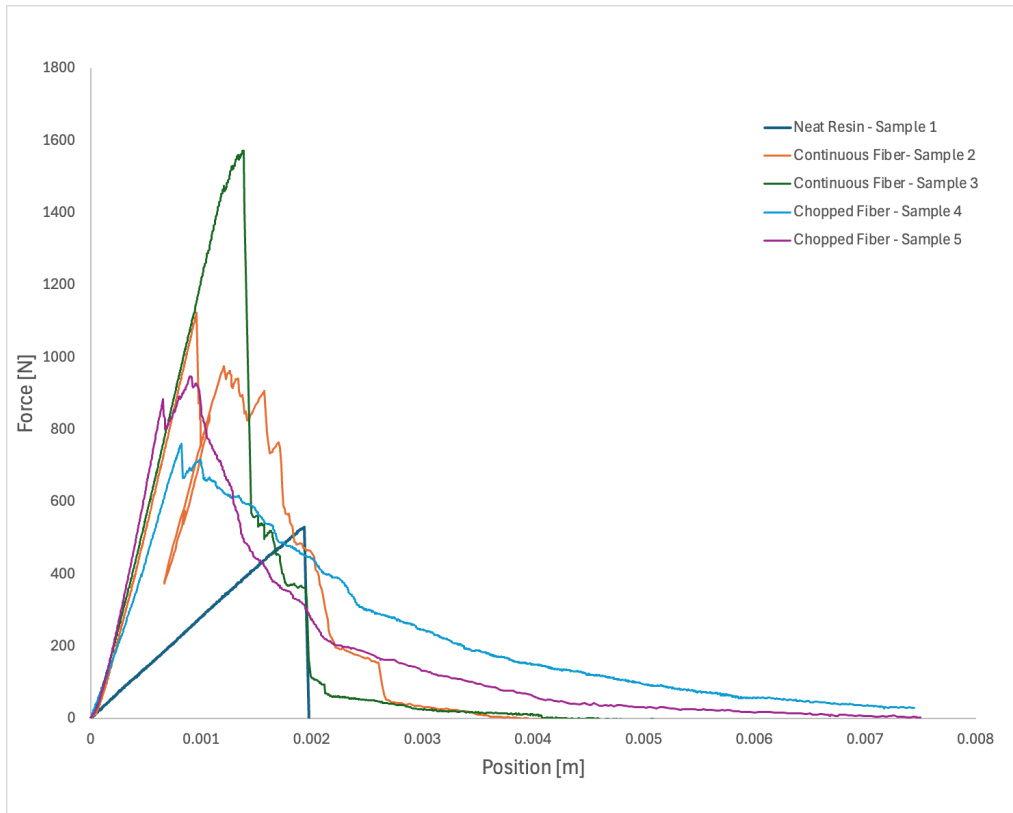


Figure 4: Combined plot of the full force-displacement curve for all composite samples.

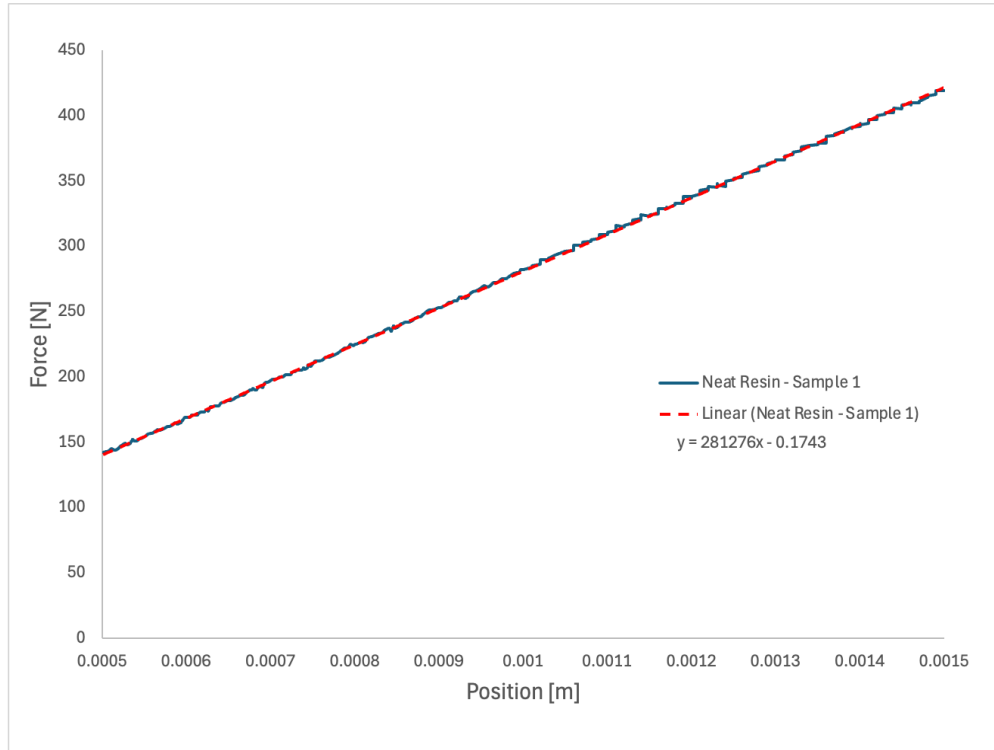


Figure 5: Linear region of the force-displacement curve of neat resin sample with linear trendline.

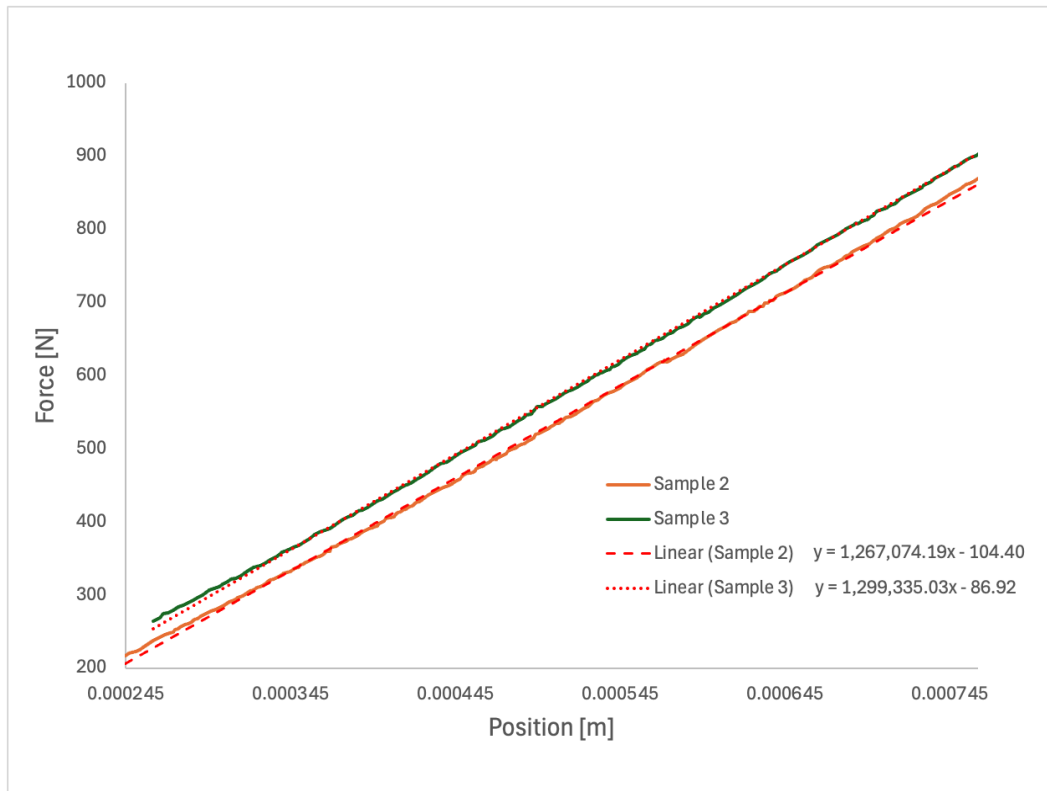


Figure 6: Linear region of the force-displacement curve of continuous fiber samples (2 and 3) with linear trendlines.

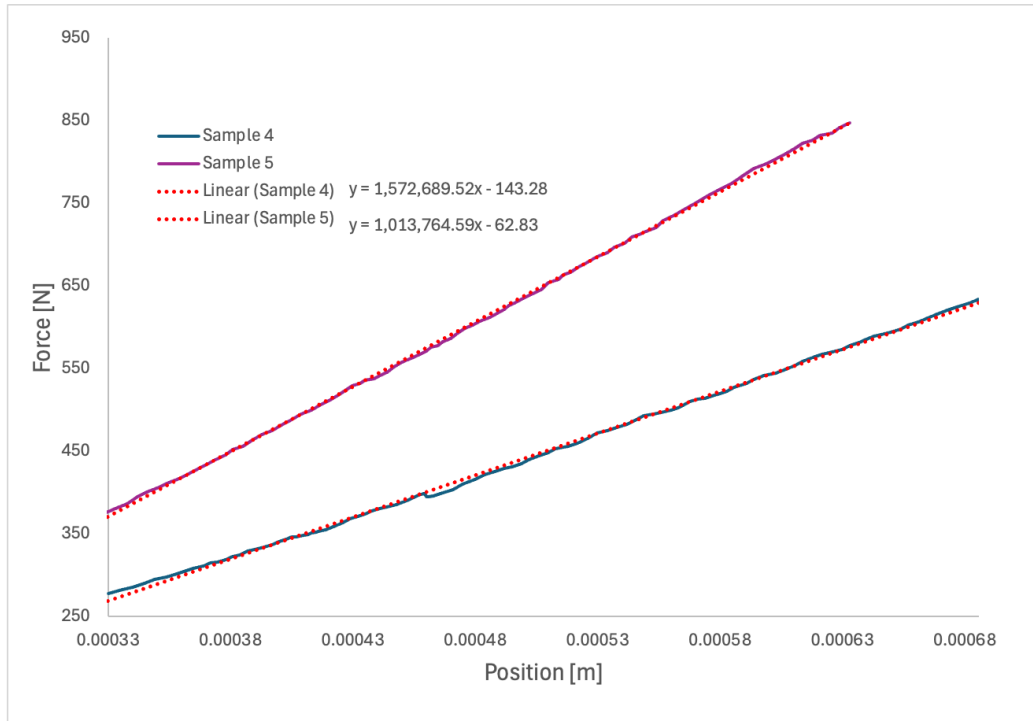


Figure 7: Linear region of the force-displacement curve of chopped fiber samples (4 and 5) with linear trendlines.

Using the slopes calculated from the linear regions of the force-displacement curves of each sample and Equation 2, the flexural modulus E of each sample was calculated. The flexural strength $\sigma_{bending}$ was solved using Equation 2 given that F_{max} was the maximum force logged by the load cell during testing. See Table 2 below for the flexural strength and modulus for each sample.

Table 2: Calculated flexural strength and modulus for each composite sample.

Sample ID	Composition	Flexural Strength [Mpa]	Flexural Modulus [Gpa]
1	Neat epoxy resin	107.437	3.832
2	Resin + 8 layers of woven glass fiber (continuous)	84.066	3.894
3	Resin + 8 layers of woven glass fiber (continuous)	148.148	5.669
4	Resin+chopped glass fiber	66.489	6.156
5	Resin+chopped glass fiber	59.134	2.355

4 Discussion

The experiment evaluated and characterized the mechanical behavior of polymer matrix composites, with a specific focus on comparing continuous and chopped glass fiber reinforcements. A neat resin sample was also molded as the control for the experiment. Five samples were manufactured and analyzed; one neat resin, two reinforced with woven continuous glass fibers, and two containing chopped glass fibers. The samples were subject to a bending test to failure, during which data was collected and analyzed to determine the mechanical properties of the material such as the flexural modulus and bending strength. These results facilitated a comparison between the two different polymer matrices and the neat resin control.

Fibers are valued for their high strength-to-weight ratio. Under tension, fibers demonstrate reliability and maintain their strength, unlike in shear or compression, where their performance is not as effective. As a result, fibers are used in a variety of applications where weight and tensile strength are critical. Chopped fibers, do not fully capitalize on the continuous strength of fibers under tension. While they theoretically should be stronger than the control (neat resin) in this experiment, their structural integrity depends on the surrounding material holding the bonds together [3]. In contrast, continuous fiber reinforcement utilizes the tensile strength of the fibers more effectively by forming a continuous load path, enabling better stress transfer between the fibers and the matrix material. A comparison between the chopped and continuous woven composition is shown below in Figure 8.



Figure 8: A comparison of the continuous fiber sample (2) and the chopped fiber sample (5).

Note: The random orientation of the chopped fibers and the semi-transparent nature of the continuous woven fibers.

The maximum bending stress is indicated by peak points on the full force-displacement curve for all the composite samples (Figure 4). Sample 3, the continuous woven fiber, generated the highest bending stress of 148.148 MPa. Interestingly enough the next highest recorded value was 107.437 MPa for the neat resin epoxy (Sample 1). The chopped fiber indicated the lowest bending stress at its greatest value of 66.489 MPa (Sample 4). Thus, the sample size for our data is too small to indicate any real trends. One sample for the continuous fiber far outperformed the

neat resin and chopped fibers in terms of bending stress but the neat resin outperformed one sample of continuous fibers (Sample 2) and both chopped fiber samples. The trends should highlight the reinforcing effect of glass fibers in improving strength, especially in the continuous fiber architecture. While this is true for one sample the other sample of continuous fiber only outperformed the chopped fiber samples and not the neat epoxy resin.

The flexural modulus, calculated from the slopes of the linear elastic region in the force-displacement curves (Figures 5-7), revealed improvements with fiber reinforcement except for one chopped fiber sample (Sample 5). The chopped sample resin (Sample 4), indicated the highest modulus of 6.156 GPa, followed by Sample 3 (continuous fiber reinforcement) at 5.669 GPa, both outperforming the neat resin's 3.832 GPa. This aligns with the expectations, as the addition of glass fibers should enhance the stiffness and load-bearing capabilities and capacities in the composites. That being said, there are outliers thus a complete trend can not be highlighted. Sample 2 (continuous) and Sample 5 (chopped) were outliers in the data. Sample 2 indicated only a slight increase of 1.6% from the neat resin. Sample 5 indicated a decrease in flexural modulus by 47.7%.

For both the flexural modulus and bending stress, the composite data does not consistently align with expectations. While some samples performed as anticipated, others deviated significantly. This inconsistency can be attributed to manufacturing and fabrication defects, such as air pockets in the resin, uneven fiber distribution, or poor resin spreading, which are common in hand-fabricated composites. These defects reduce the effective load-bearing capacity of the composites and introduce unwanted stress concentrations, weakening the material, especially in the chopped fiber samples [4]. By having a weaker fiber matrix, effective stress transfer is prevented. In continuous fiber samples, uneven fiber distribution disrupts the load path, while in chopped fiber samples irregular fiber distribution creates localized inconsistencies, leaving some areas stronger or weaker than others [5]. Another significant factor that can contribute to poor performance is interfacial bonding issues, where insufficient adhesion between the fiber and matrix prevents effective load transfer. Without proper stress transfer from the matrix to the fibers, the fibers cannot provide the intended reinforcement, leading to premature failure or fiber pull-out [6]. Chopped fibers are particularly dependent on proper orientation and distribution, and if these factors are not well-controlled, they may act as stress concentrators rather than reinforcements, further weakening the composite. These factors emphasize the importance of precise fabrication and material consistency in achieving reliable composite performance.

Lastly, as mentioned above, the mode of loading plays a critical role in determining how the material behaves. In tension, fibers perform exceptionally well, but under shear, compression, or bending, their performance can be less effective. Randomly oriented chopped fibers excel in multi-axial stress conditions, where fibers are aligned with tensile or compressive stresses, but in bending, they are less effective due to the inconsistent stress distribution across the fibers.

Continuous fibers, on the other hand, should perform well in bending due to their ability to sustain tensile loads along their alignment [2]. However, any misalignment or issues with fiber consistency can lead to premature failure. Additionally, continuous longitudinal fibers are not well-suited to handling stress transverse to their alignment, making them less effective under multi-axial loading conditions.

In this experiment, we expected the continuous fibers to outperform the chopped fibers, which was observed. However, we also anticipated the continuous fibers to outperform the neat resin, which did not consistently occur. These discrepancies highlight the complexities introduced by interfacial properties, loading modes, fiber orientation, and potential manufacturing inconsistencies.

As shown in Figure 3b, the neat resin exhibited a sudden brittle fracture, characterized by an abrupt failure with minimal deformation. In contrast, the continuous fiber sample exhibited a ductile fracture where the sample had significant plastic deformation and gradual failure. This behavior was more pronounced in the continuous fiber sample than in the chopped fiber sample due to its reinforcement architecture of long, longitudinal fiber strips. While the chopped fiber strands also exhibited a ductile fracture with gradual failure, it was not to the same extent as the 8-layer continuous woven fiber composite. This is further exhibited in the force-displacement curve (Figure 4) where the neat resin sample reaches a peak stress followed by a sudden drop, whereas the chopped and continuous samples indicate a prolonged failure. After reaching peak stress, they exhibit a gradual decline, indicating structural stability beyond the peak force. The glass fibers successfully minimize a major failure by maintaining the structure's integrity under load for a prolonged time.

5 Conclusion

The purpose of this lab was to manufacture, test, and explore the mechanical behaviors of fiber-reinforced polymer composites. The focus was on observing the differences in bending strength and stiffness and by performing applied load capacity tests using the bend testing fixture on the load frame. The primary objective was to determine the influence of chopped and continuous fiber matrices and see how they can enhance the strength of a material. In this case, a neat epoxy resin acted as the control material while two samples of chopped fiber and continuous fiber reinforcement molds were tested. The data was captured using the capstone software and images were taken at every milestone.

The results did not highlight any significant trends in the mechanical properties of the materials, Due to the variations and possible mistakes when hand-fabricating the samples. These variations and variables completely outweighed the ability to get reliable data. Thus, more testing is required to come up with accurate conclusions. Theoretically, it can be understood that chopped and continuous fiber samples should increase material bending stress and its flexural modulus. We did see signs of this in the data. Sample 3 (continuous fiber reinforcement) was the

only fiber-reinforced sample that exceeded the control material's flexural strength. While all but Sample 5 exceeded the stiffness of the neat resin control.

Conclusions regarding the stiffness of the material can be drawn. The fibers increased the stiffness of the composite, allowing it to resist deformation more effectively. However, the bending stress did not behave as expected. This discrepancy occurred because the fibers are strong and stiff in tension along their axis, but they performed poorly when subjected to stresses perpendicular to their axis. If the fabrication process had been improved, the results might have been different. The real-world applications of composite materials have led to significant progress in the industry. A lighter, more efficient material is sought after in many industries and has been applied in the automotive, aerospace, and medical fields. To improve our experiment, a more reliable fabrication method is necessary to mitigate the variability in this process. More samples and testing are also needed to extract valuable data trends that can characterize the material and provide a more comprehensive understanding.

References

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