Final Project Report on

Comparative Analysis of Tensile Strength of 3D printed Carbon Fiber Reinforced Onyx at various Fiber Orientations

(Experimental Track)

MEAM 5080: Materials and Machining for Mechanical Design

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1. Executive Summary

Composite materials have gained applications in the engineering domain for their excellent strength and low weight. This experimental research into carbon fiber-reinforced onyx is driven by the need to address the lack of reliable data about how the orientation of carbon fibers in the onyx matrix affects tensile strength. To analyze the effect of such reinforcement in the printed parts, samples were prepared keeping the number of carbon fiber layers the same but with different orientations. The analysis shows that the tensile strength of the specimen decreases as the carbon fiber layers orient away from the direction of the tensile force. The highest tensile strength was noticed when the fibers were orientated at 0° orientation. This pursuit of advanced materials, known for their superior strength-to-weight ratio and sustainability is vital for transforming various sectors.

Fig. 1: Markforged Mark Two printer nozzles while printing

2. Problem Definition

This experimental research is about performing a comparative analysis of the tensile strength of the 3D-printed composite material with Onyx as matrix and Carbon Fiber as reinforcement for various layer orientations of Carbon fiber filament.

The development of 3D printed composite materials marks a significant advancement in engineering, combining the benefits of 3D printing, such as rapid prototyping and design iteration, with the robust material properties needed for real-world engineering challenges. These composites offer high strength and stiffness and a favorable strength-to-weight ratio, making them ideal for industries like aerospace, healthcare, automotive, robotics, sports equipment, and consumer electronics, where both complex shapes and high-grade material properties are essential.

3D-printed parts can be reinforced with carbon fiber through the use of carbon fiber-filled filaments or continuous carbon fiber printing. Carbon fiber filaments incorporate tiny chopped pieces of carbon fiber in a thermoplastic printing filament providing moderate increases in material properties and can be used in a typical 3D printer if we change the extrusion tip material and temperature. An example of a carbon fiber-filled filament is Onyx by MarkForged which uses a Nylon-6 base with chopped carbon fiber. The process of continuous carbon fiber 3D printing directly integrates strands of carbon fiber into each layer of the material as it is being printed, providing the engineer acute control of the fiber location and orientation leading to much more robust parts that can exhibit similar strength properties to 6061-T6 aluminum. This production process is novel, becoming commercially available less than 10 years ago. As a result, there is a lack of reliable experimental data on the material properties of these 3D-printed composites.

As a result of the number of possibilities and impact the process of continuous carbon fiber printing has on the material we are interested in studying how an engineer can use these properties to optimize the strength of their parts. To further understand the performance of 3D-printed carbon fiber composites we will perform a comparative analysis of the tensile strength of the 3D-printed composite material with Onyx as matrix and Carbon Fiber as reinforcement for various layer orientations of Carbon fiber filament. Our analysis will aim to answer the following questions:

- How do the mechanical properties of the composite material vary with changes in carbon fiber orientation?

- Is there a particular layer orientation that maximizes the tensile strength of carbon fiber-reinforced Onyx?
- How does the orientation of carbon fiber layers in an Onyx matrix affect the tensile strength of the composite material?
- What implications do the findings have for the design and manufacturing of parts in industries such as aerospace, automotive, and robotics?

3. <u>Background</u>

The focus of this research lies at the intersection of material science and additive manufacturing, particularly exploring the tensile properties of onyx-reinforced carbon fiber composites. This study was conceived in response to the growing demand for materials that combine lightweight characteristics with high strength in various industrial applications, ranging from aerospace to automotive engineering. Historically, composite materials have been pivotal in various engineering applications due to their customizable properties. The advent of carbon fiber composites marked a significant advancement, offering unparalleled strength-to-weight ratios. However, the integration of these composites in practical applications often requires a fine balance between strength, flexibility, and other mechanical properties.

According to our literature survey, there was a research study focused on the mechanical strength of 3D-printed objects made from a composite material. This material comprised Onyx as the base, with glass and carbon fibers used as internal reinforcements. The research involved creating specimens with varying layers and arrangements of these reinforcements. The findings revealed that the tensile strength of the composite material increases with the number of reinforcement layers. This increase is attributed to the longitudinal effect of the fibers and a greater bonding area between the Onyx and the fibers. Additionally, the study found that distributing the reinforcements at regular intervals throughout the part resulted in higher tensile strength, compared to concentrating them in the center. This research provides valuable insights for future studies aiming to optimize the strength of fiber-reinforced composites in 3D printing.

I. Material Selection

Composite Material: A composite material is formed by combining two or more materials with differing physical and chemical properties. This amalgamation results in a material specifically tailored for a desired function, exhibiting enhanced strength, stiffness, lightness, or electrical resistance. Our chosen materials for creating this composite are as follows:

I. <u>*Onyx*</u>*:* Onyx, a specialized 3D printing material, consists of micro-chopped carbon fibers embedded in a nylon matrix. This integration bestows Onyx with exceptional strength and toughness, surpassing many standard 3D printing materials. It withstands high stress and is durable, making it suitable for challenging applications. Its resistance to various chemicals, including oils and industrial solvents, further extends its utility. Onyx's capabilities are further amplified when reinforced with continuous fibers like carbon fiber, fiberglass, or Kevlar during the printing process. This enhancement equips the material with properties akin to aluminum in terms of strength and stiffness. The resulting Onyx composite is not only robust but also maintains a low weight profile, making it ideal for sectors like aerospace and automotive where weight efficiency is crucial.

Fig. 2: Onyx material filaments

II. *<u>Carbon Fiber (CF)</u>:* Carbon Fiber is a material characterized by its composition of thin, crystalline carbon filaments, arranged in long chains. These chains are formed through the carbonization of organic precursors such as polyacrylonitrile (PAN) or pitch. CF stands out for its extraordinary stiffness and high strength-to-weight ratio, offering a lightweight yet potent solution. It is favored in high-performing sectors, such as aerospace, automotive, and sports equipment. Carbon Fiber's versatility is also evident in its common use in carbon fiber reinforced polymers (CFRPs), where it is blended with a polymer matrix, enhancing both strength and flexibility for various high-performance applications.

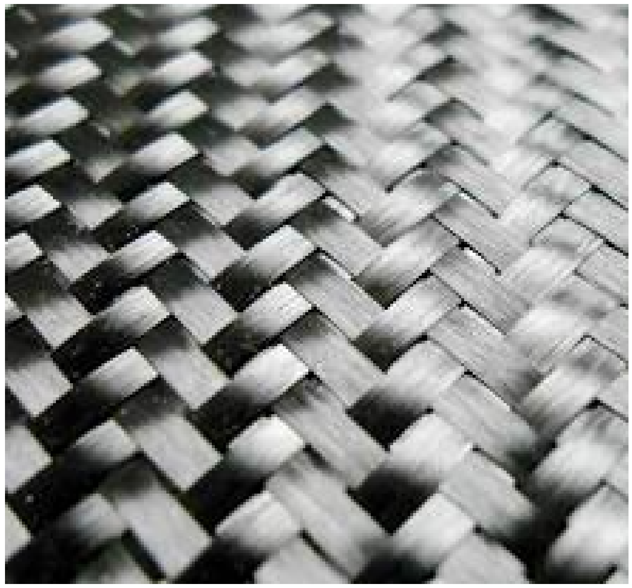


Fig. 3 Carbon fiber ply

Mechanical Properties	Onyx	Carbon Fiber (CF)
Tensile Strength (MPa)	30	800
Young's Modulus (GPa)	2.4	60
Poisson's ratio	0.35	0.33
Density (g/cm^3)	1.2	1.4
Tensile Strain at Break (%)	25	1.5

Table. 1: Mechanical properties of selected materials

III. *Onyx Reinforced with Carbon Fiber:* This composite material synergizes the strengths of Onyx and carbon fiber. It combines Onyx's high strength, toughness, and chemical resistance with the remarkable attributes of carbon fiber, particularly its stiffness, lightness, and strength-to-weight ratio. By reinforcing Onyx with carbon fiber strands, the material's mechanical properties are significantly bolstered, making it stronger and stiffer than Onyx alone while maintaining a lighter weight. This composite is highly valued in industries that require materials to withstand intense stress and strain without compromising structural integrity and efficiency. Onyx reinforced with carbon fiber emerges as a robust, versatile material, ideal for advanced applications in aerospace, automotive, and robotics, demanding durability, strength, and weight efficiency.

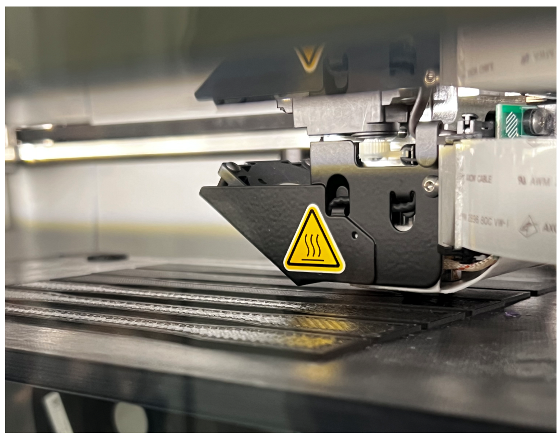


Fig. 4: 3D printing of Onyx with CF reinforcement

II. Additive Manufacturing

Additive manufacturing is a group of manufacturing techniques that construct objects by adding material, typically layer by layer, as opposed to subtractive manufacturing methodologies. This category includes various techniques like Fused Deposition Modeling (FDM), Selective laser sintering (SLS), Stereolithography (SLA), etc. Each technique uses different materials and processes to build up layers and create complex shapes and structures. This approach starkly contrasts with subtractive manufacturing, which involves removing material from a larger block through milling, machining, or other methods. Additive manufacturing excels in producing complex, customized, lightweight structures with high material efficiency and design flexibility, which is particularly advantageous in industries like aerospace, automotive, medical, and more.

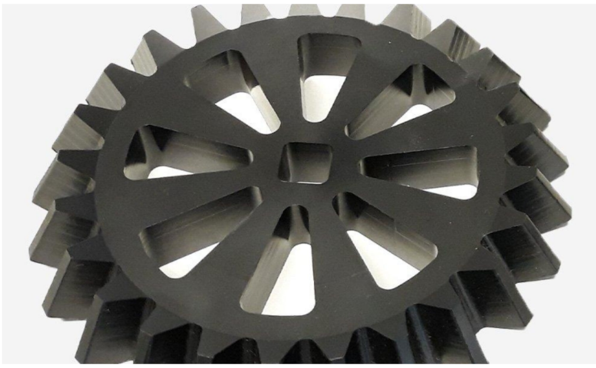


Fig. 5: 3D-printed gear

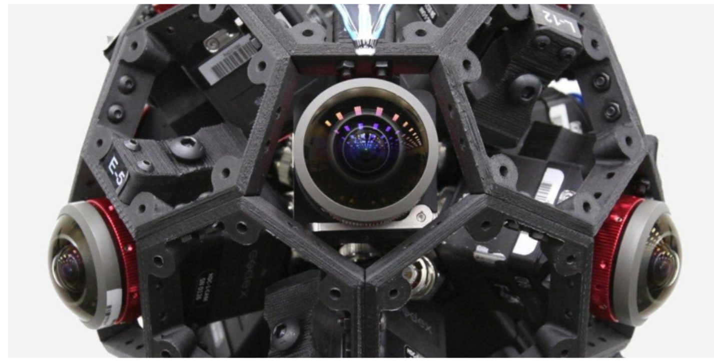


Fig. 6: 3D-printed robot

A. *Fused Deposition Modeling (FDM)*: Fused Deposition Modeling (FDM) is a known 3D printing technology that constructs objects layer by layer from thermoplastic filaments. The process involves designing a 3D model, which is then sliced into thin layers and fed into the printer through software. The printer heats the filament to a semi-liquid state and extrudes it through a nozzle, laying it down in a predetermined path. As the material is deposited, it cools and solidifies, forming the object from the bottom up. FDM is favored for its cost-effectiveness, user-friendliness, and material versatility, making it ideal for prototyping and educational purposes, although it generally lacks the precision and surface finish of more advanced 3D printing technologies like SLA or SLS. We will be adopting this 3D printing technique to manufacture our samples for this experimental research.

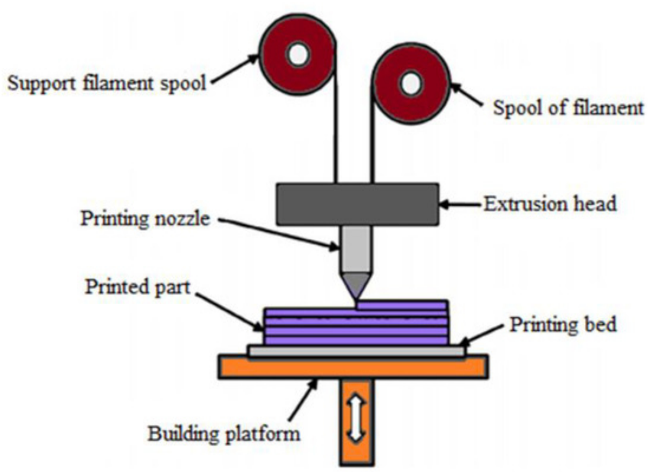


Fig. 7: FDM Schematic

4. <u>Experimental Approach</u>

Our experimental research was meticulously organized into four comprehensive stages:

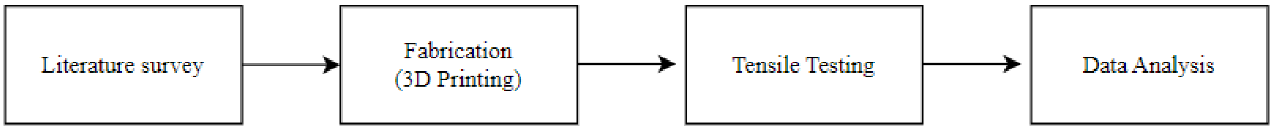


Fig. 8: Flow diagram of the experimental stages

A. Literature Survey

A rigorous literature survey was conducted to identify existing studies related to the tensile strength of onyx-reinforced carbon fiber. We focused on understanding how tensile strength varies with different levels of reinforcement. One pivotal research paper stood out, detailing the impact of changing carbon fiber volume percentages in 3D-printed composite materials. This study indicated a direct correlation between increased carbon fiber volume and enhanced load-bearing capacity, resulting in higher tensile strength but a concurrent decrease in material plasticity. However, there wasn't any study, noting the impact of changing carbon fiber orientation in the composite material on tensile strength.

B. Fabrication (3D Printing)

For sample fabrication, we leveraged the advanced capabilities of 3D printing, a pivotal technology in additive manufacturing renowned for its proficiency in rapid prototyping and production of complex geometries. Our experiments utilized the Markforged Mark Two printer, situated in Addlabs, Towne building. This phase involved printing multiple samples, each with varying carbon fiber orientations. These orientations were meticulously planned to assess their impact on the material properties. The printing process, fiber alignment, and other technical details of the fabrication phase are elaborated further in subsequent sections of this report.

C. Tensile Testing

To evaluate the mechanical properties of our specimens, tensile testing was chosen as the primary analytical method as composite materials show good mechanical behavior in strength. The Universal Testing Machine (MTS machine) in the Towne building served as our testing apparatus. Each specimen was subjected to a controlled tensile force, and we meticulously recorded their responses. Key metrics such as peak load, peak stress, strain at break, and Young's modulus were gathered for each specimen. This data provided insights into the mechanical robustness and elasticity of the different fiber orientations under tensile stress.

D. Data Analysis

The final stage involved a thorough analysis of the data obtained from the tensile tests. Stress vs. Strain plots were generated for each specimen, offering a visual representation of how variations in fiber orientation impacted the tensile strength of the composite materials. Additionally, we documented the physical appearance of the specimens before and after testing to identify any macroscopic changes. A critical examination of the fracture surfaces was also conducted to discern the failure mechanisms at play. This analysis was instrumental in understanding the structural integrity and fracture patterns of the specimens under stress.

5. Methods

1. 3D Printing Process

The process used is called Continuous Fiber Reinforcement (CFR). We used the *Markforged* Flagship Continuous Fiber Composite 3D Printer for manufacturing the samples for the tensile test (Fig. 1). Parts are printed by extruding a thin filament of *Onyx* (micro carbon fiber filled nylon material) to create successive layers ranging from 0.1 mm (0.004″) to 0.2 mm (0.008″) thick. The Carbon Fiber filament was used as inlaid fiber reinforcement at the selected layers. The printer is located in the AddLabs in the Towne building. The software used for this printer was *Eiger Cloud*.

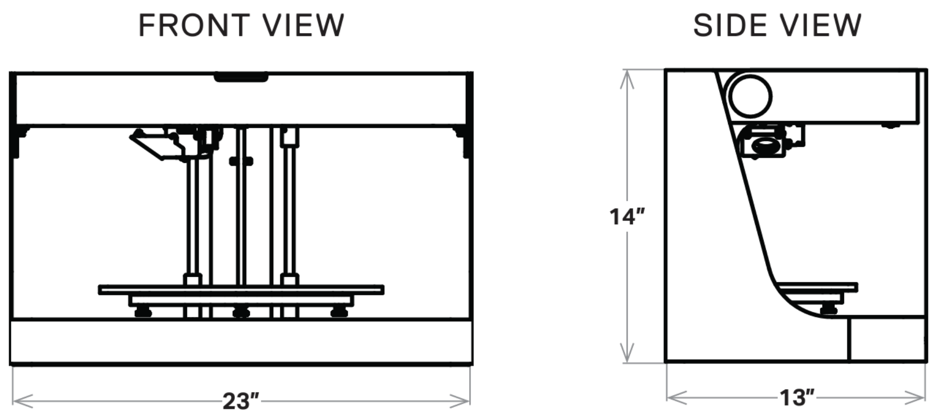


Fig. 9: Markforged Mark Two 3D Printer Schematic

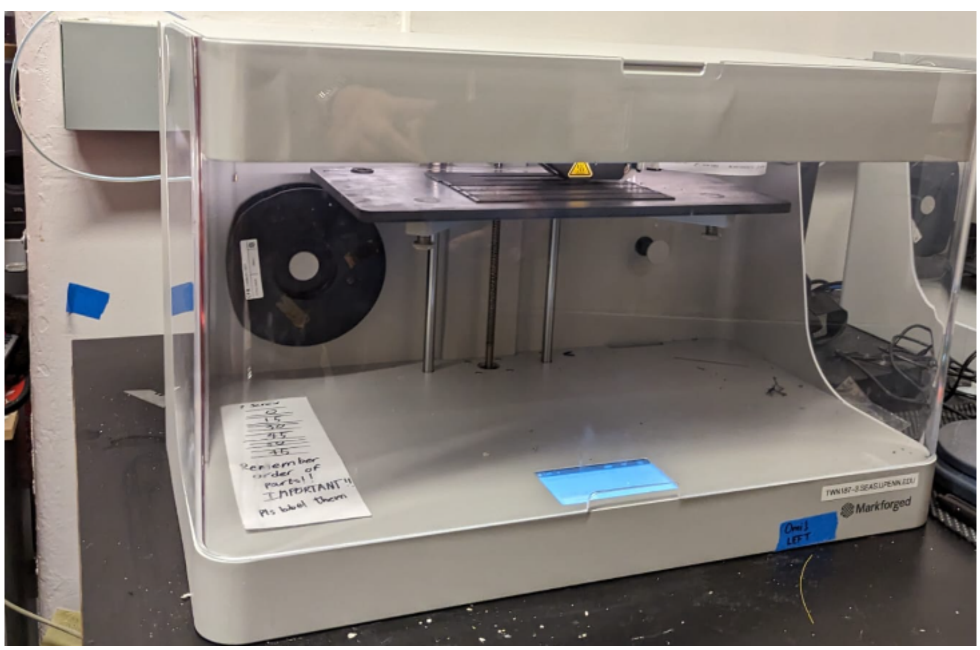
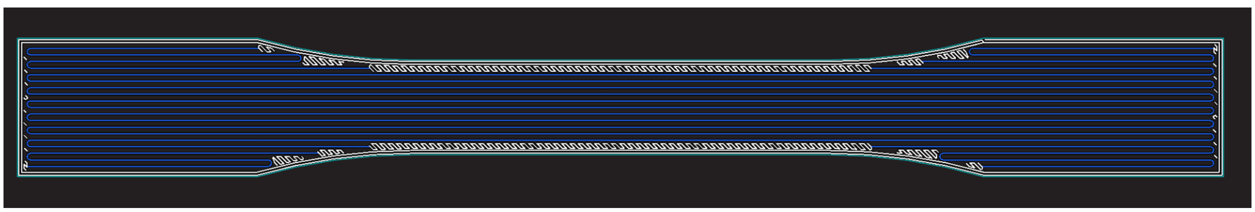


Fig. 10: Markforged Mark Two 3D Printer at Addlab

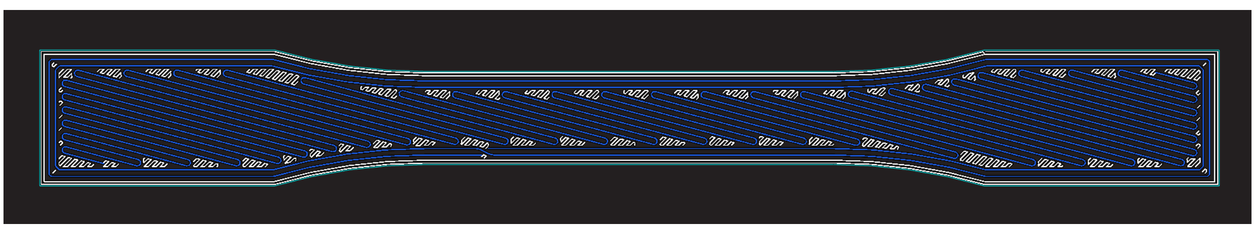
Specifications of 3D printed sample

The samples are made of an Onyx matrix with Carbon fiber filament reinforcement. The top, bottom, and side layers consist of the Onyx matrix, while the central layers are composed of Carbon fiber filament, maintaining the overall thickness across all specimens. The layer orientation of CF was changed by keeping the same layer orientation of Onyx (45°) to compare the strength due to the change in CF orientation only. 3 Samples of each orientation were 3D- printed i.e. 0, 15, 30 and 45°. The 3D Printing process needs the outer layer to be of Onyx, thus it was decided to keep the core of Carbon Fibers and outer layers of Onyx. The number of Carbon Fiber layers was determined based on the volume fraction of CF required in the sample. The following figures show the layer of carbon fiber and the fiber orientation as seen in the *Eiger Cloud* Environment.

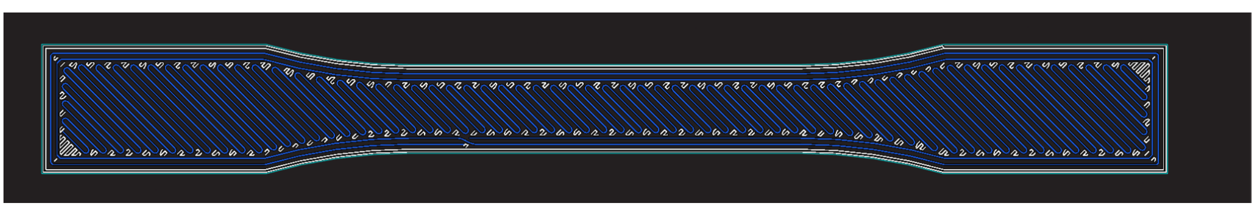
Fibers at 0°:



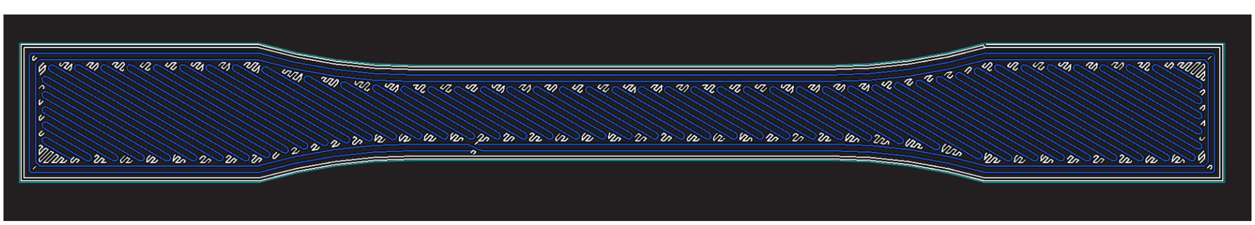
Fibers at 15°:



Fibers at 30°:



Fibers at 45°:



3D Printing Parameter	Onyx	Carbon Fiber
Layer height	0.125 mm	0.125 mm
No. of layers	16 layers	10 layers
Layers orientation	45 degrees	0, 15, 30, 45 degrees
Infill percentage	100%	100%

Table. 2: 3D printing parameters for the tensile test specimens

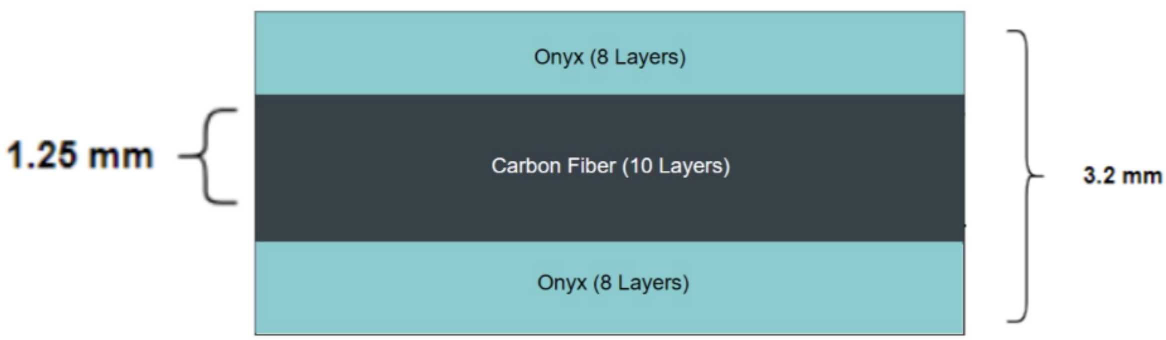


Fig. 11: Layer arrangement in the 3D-printed tensile test specimen

The volume fraction of Fibers in the sample can be calculated as (neglecting the voids between the adjacent fibers): **Vf = (1.25/3.2) *100 = 39.06 %**

2. Tensile Testing

Tensile testing, also known as tension testing, is a fundamental materials science and engineering test in which a sample is subjected to controlled tension until failure. Properties that are directly measured via a tensile test are ultimate tensile strength, breaking strength, maximum elongation, and reduction in area.

Tensile test performed for this project

Tensile testing for the specimens was carried out on the MTS Tensile Machine (*MTS Criterion - Model 43*) in the Towne building, test settings were set the same for all the specimens. The software used for data collection was *MTS TestWorks 4*. We tested three specimens for each CF orientation and two samples of Onyx material without CF printed at 45 degrees orientation.

Fig. 12: MTS machine in Towne Building

Test Parameters for Tensile Test as input parameters in the software:

Calculation Inputs:

Name	Value	Units
Break Marker Drop	50.0	%
Break Marker Elongation	2.540	mm
Grip Separation	41.350	mm
Slack Pre-Load	4.448	N
Slope Segment Length	20.000	%
Yield Offset	0.002	mm/mm
Yield Segment Length	2.0	%

Test Inputs:

Name	Value	Units
Break Sensitivity	90	%
Break Threshold	8.896	N
Data Acq. Rate	100.0	Hz
Test Speed	20.000	mm/min

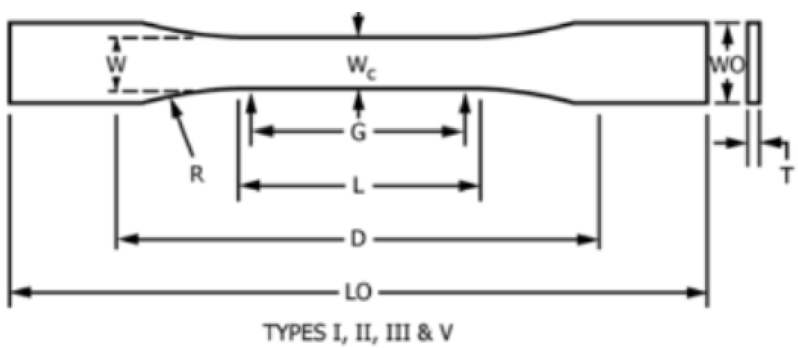
Table. 3: Tensile test input parameters for the MTS software

Specifications of Tensile Test Sample:

The preparation of test specimens depends on the purposes of testing and the governing test methods or specifications. A tensile specimen usually has a standardized sample cross-section. It has two shoulders and a gauge (section) in between. The shoulders and grip section are generally larger than the gauge section by 33% so that they can be easily gripped. The gauge section's smaller diameter also allows deformation and failure to occur in this area.

Following are the specifications of the specimen:

- We used the Standard test method for tensile properties of plastics i.e. ASTM D638-14
- For reinforced composite, a Type I specimen is used. The specimen is flat and of 3.2 mm thickness (T).



Dimensions (see drawings)	Type I
W—Width of narrow section[E,F]	13 (0.50)
L—Length of narrow section	57 (2.25)
WO—Width overall, min[G]	19 (0.75)
WO—Width overall, min[G]	...
LO—Length overall, min[H]	165 (6.5)
G—Gage length[I]	50 (2.00)
G—Gage length[I]	...
D—Distance between grips	115 (4.5)
R—Radius of fillet	76 (3.00)
RO—Outer radius (Type IV)	...

Fig. 13: Tensile test sample dimensions (in mm)

The following values were noted from the experiment:

a. Peak Load

b. Peak Stress

c. Strain at Break

d. Modulus

3D Printed Tensile Test Specimen:

From left to right: Onyx, Fibers at 0°, 15°, 30° and 45° respectively:

Fig. 14: 3D-Printed Tensile test specimens.

Procedure for carrying out the tensile test

1. The specimen should be vertical during the tensile test to ensure that the load is applied along the correct axis.
2. Tight the jaws just enough for the friction to overcome the tensile load.
3. Make sure that the distance between the grips is as mentioned in the figure.
4. After the tensile test there should be no slip marks on the grip to ensure that the specimen did not slip during the test.
5. Unload the specimen after the test by carefully removing the engaging pins.
6. The specimens were tested following the above considerations and the results have been analyzed in the following section.

6. Analysis

For different orientations, observations were made and the data was compared for all the orientations to conclude. Visual observations were made too to conclude. Following were the observations made:

1. 0° Orientation Specimen

Specimen #	Peak Load (N)	Peak Stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
1	12278.715	295.2	0.090	5386.194
2	12020.587	289.0	0.104	3541.470
3	10901.913	262.1	0.087	3917.347
Average	**11733.738**	**282.1**	**0.093**	**4281.670**

Table. 4: 0° Orientation Specimen Tensile properties

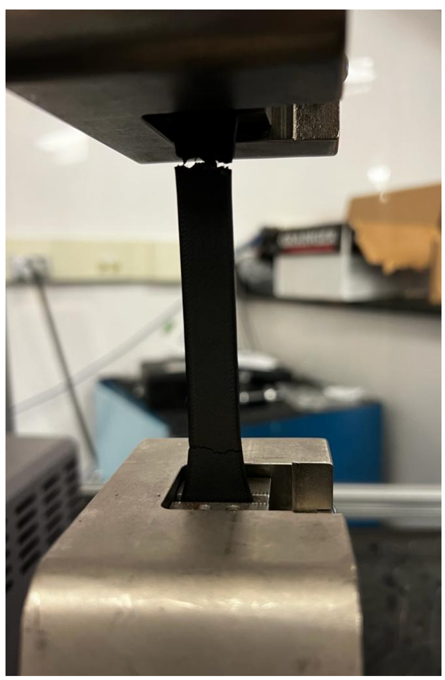


Fig. 15: 0° Orientation tested specimen

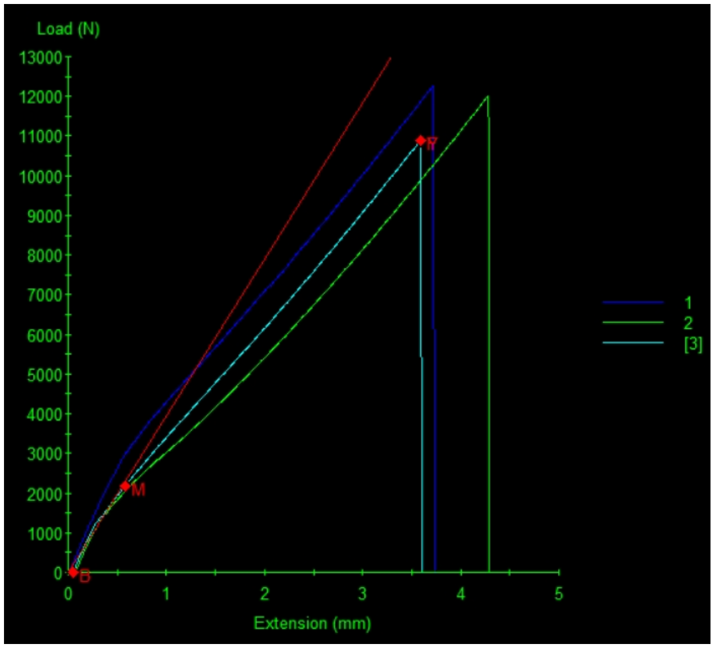


Fig. 16: 0° Orientation Specimen Stress Vs Strain graph

2. 15° Orientation Specimen

Specimen #	Peak Load (N)	Peak Stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
1	7543.516	181.3	0.079	3745.021
2	7136.827	171.6	0.070	4010.851
3	7801.588	187.5	0.086	2652.234
Average	**7493.977**	**180.1**	**0.078**	**3469.368**

Table. 5: 15° Orientation Specimen Tensile properties

Fig. 17: 15° Orientation tested specimen

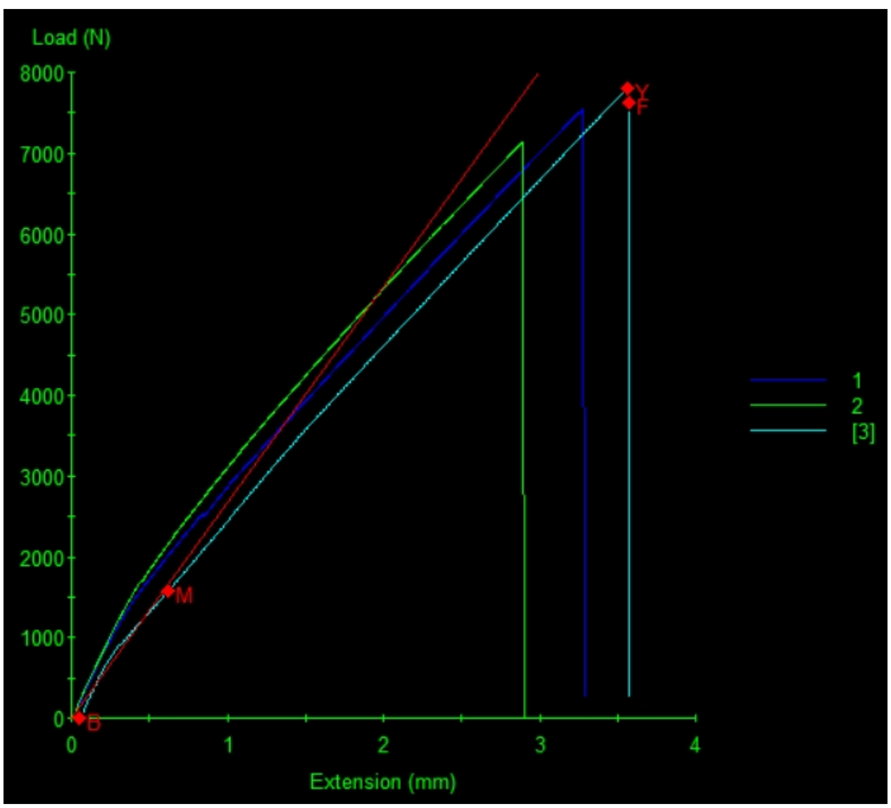


Fig. 18: 15° Orientation Specimen Stress Vs Strain graph

3. 30° Orientation Specimen

Specimen #	Peak Load (N)	Peak Stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
1	6068.534	145.9	0.075	2809.350
2	6231.325	149.8	0.067	3323.506
3	5598.561	134.6	0.070	2577.769
Average	**5966.14**	**143.4**	**0.070**	**2903.541**

Table. 6: 30° Orientation Specimen Tensile properties

Fig. 19: 30° Orientation tested specimen

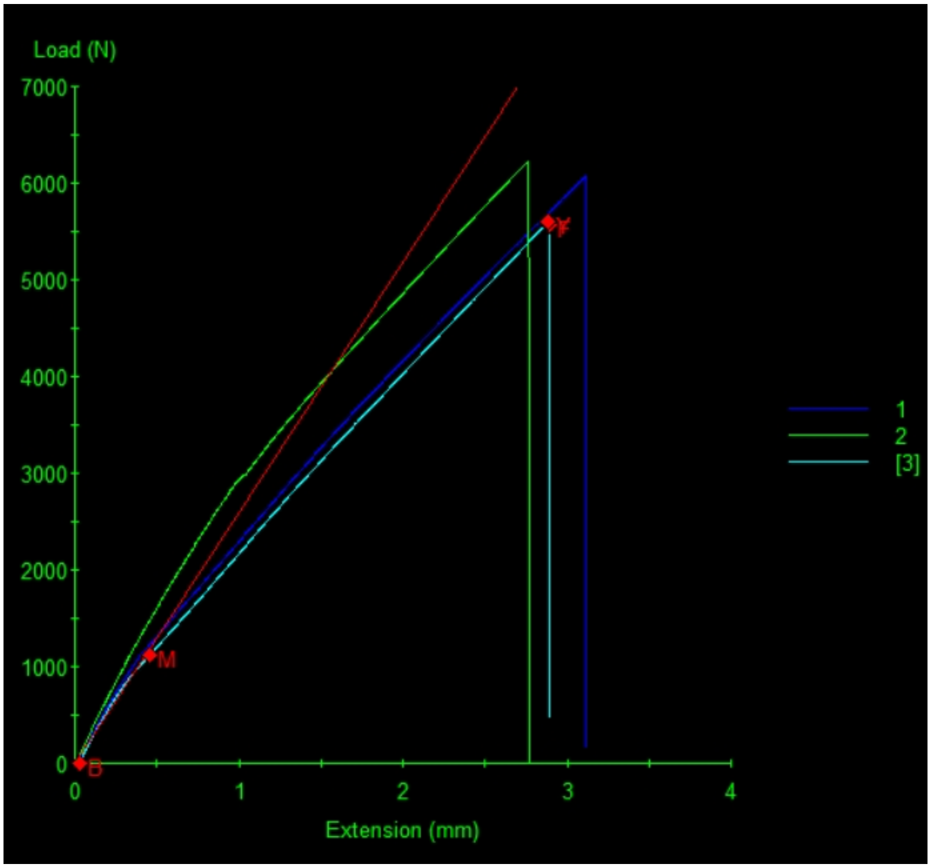


Fig. 20: 30° Orientation Specimen Stress Vs Strain graph

4. 45° Orientation Specimen

Specimen #	Peak Load (N)	Peak Stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
1	5486.886	131.9	0.065	2830.707
2	5657.938	136.0	0.073	2802.986
3	5321.633	127.9	0.070	2851.405
Average	**5488.819**	**131.9**	**0.069**	**2828.366**

Table. 7: 45° Orientation Specimen Tensile properties

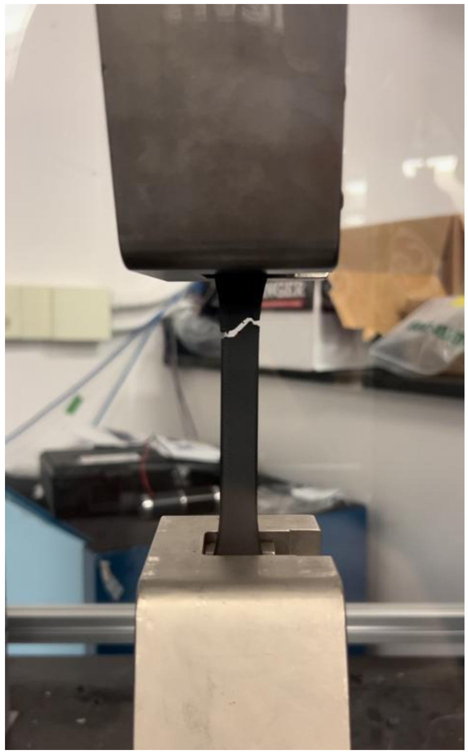


Fig. 21: 45° Orientation tested specimen

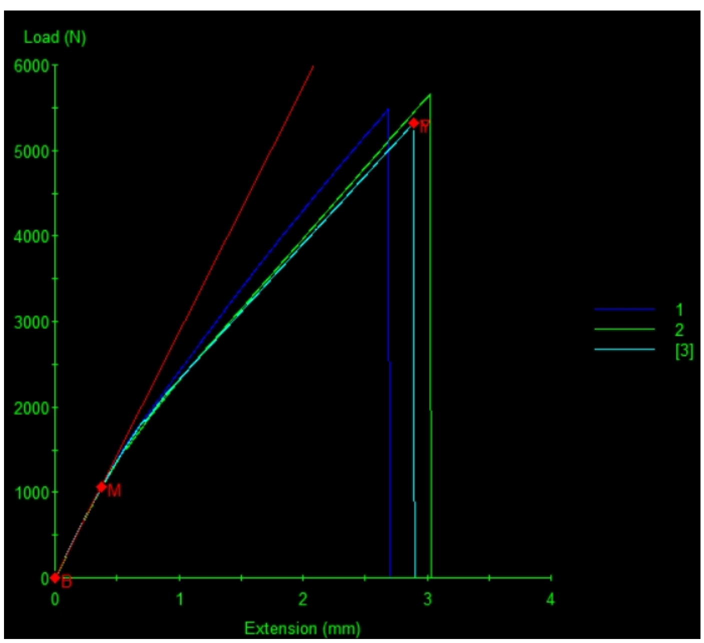


Fig. 22: 45° Orientation Specimen Stress Vs Strain graph

5. 45° Orientation Specimen - Onyx (no CF)

Specimen #	Peak Load (N)	Peak Stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
1	1704.903	41.0	0.727	720.785
2	1713.472	41.2	0.717	731.626
Average	**1709.187**	**41.1**	**0.722**	**726.205**

Table. 8: 45° Orientation Specimen Tensile properties with no CF reinforcement

Fig. 23: 45° Orientation tested specimen with no CF reinforcement

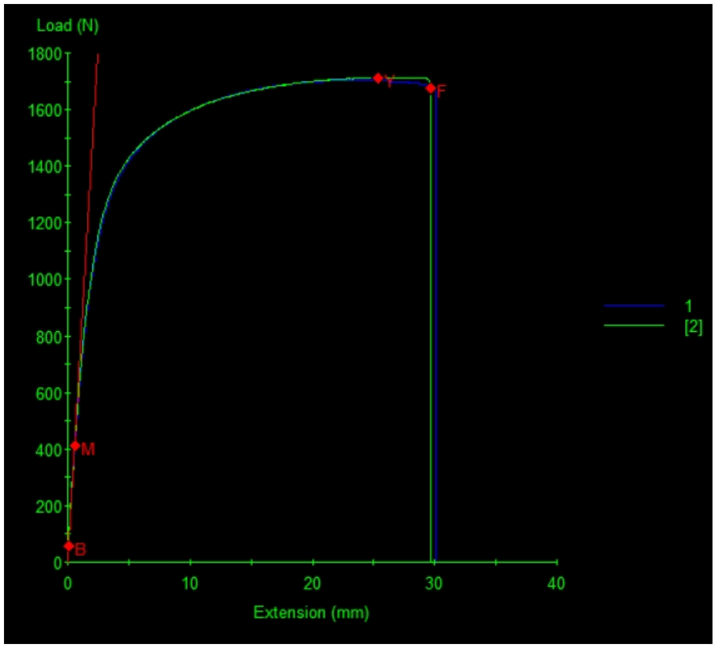


Fig. 24: 45° Orientation Specimen Stress Vs Strain graph with no CF reinforcement

6. Tested tensile test samples

Samples with blue tape are the ones printed at 45° of Onyx material with no carbon fiber reinforcement. The ones with the yellow tape have reinforced carbon fiber and the numbers on them represent the layer angle orientation.

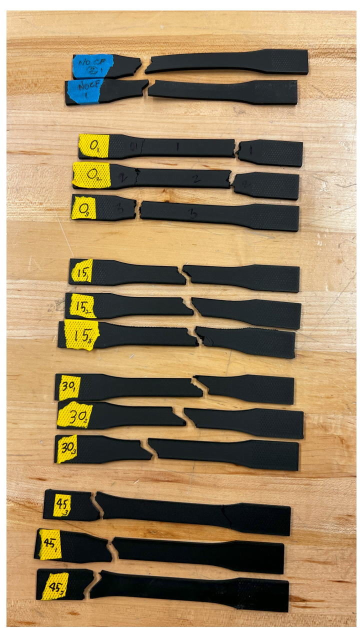


Fig. 25: Tested samples of CF-reinforced Onyx

7. Results and Discussions

The following is the comparison of the mechanical properties between different layer orientations:

Orientation of the Carbon Fibers	Avg. Peak Load (N)	Avg. Peak Stress (MPa)	Avg. Strain at Break (mm/mm)	Avg. Modulus (MPa)
0° Degrees	**11733.7**	**282.1**	0.094	**4281.6**
15° Degrees	7494.0	180.1	0.078	3469.4
30° Degrees	5966.1	143.4	0.071	2903.5
45° Degrees	5488.8	131.9	0.069	2828.4
Onyx (no CF)	1709.0	41.1	**0.722**	726.2

Table. 9: Comparison of tensile properties between different layer orientations

1. As seen in Table 9, the Modulus, peak load, and peak stress decrease as the angle of orientation with respect to axial loading increases. This indicates the tensile strength of the sample with 0° Degrees orientation is the highest and the Onyx material 3D-printed at 45° Degrees with no CF reinforcement has the lowest.
2. The strain at break and elongation for just the onyx material was the highest showing CF reinforcement decreases its plasticity.

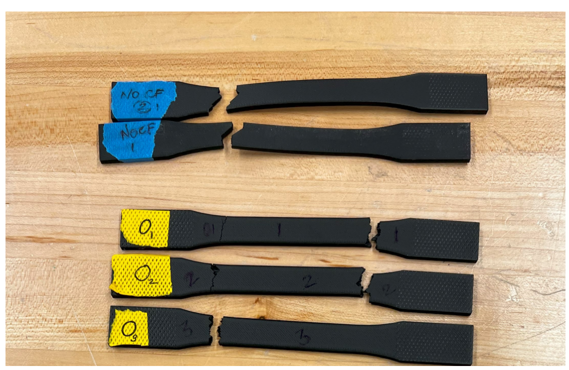
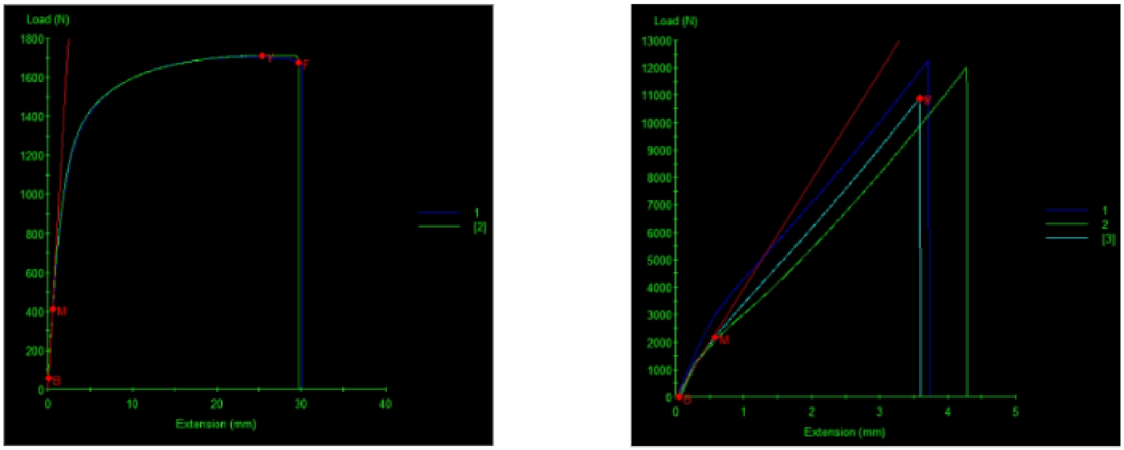


Fig. 26: Comparison between the lengths of the tested 0° and 45° with no CF samples

3. The stress vs. strain plots of Onyx samples with no CF show a high plastic nature whereas the plots for composite material show more initial plastic nature and a brittle nature before failure. The brittle nature comes from the CF reinforcement.



No CF in Onyx

With CF reinforcement

Fig.27: Comparison b/w the nature of stress-strain plots with and without CF reinforcement

4. 0° orientation CF specimens failed at both ends of the sample at the end of the gauge length. This indicates there was stress concentration near the radius of the samples and the material was strong in the gauge length.

Fig. 28: 0° orientation Tensile test samples after test

5. 45° orientation CF specimens failed at the neck outside the gauge length.

Fig. 29: 45° orientation Tensile test samples after test

Fig. 30: Cross-section of the failed tensile test sample with 45° CF layer orientation

6. For composite materials, there was no necking and the fracture shows the brittle nature.
7. Due to its brittle nature, we cannot predict the direction of the crack propagation. This can be seen in Fig. 25 though most of the cracks are S-shaped.
8. The following graphs show how the loading bearing capacity and strength of the composite material change concerning fiber orientation.

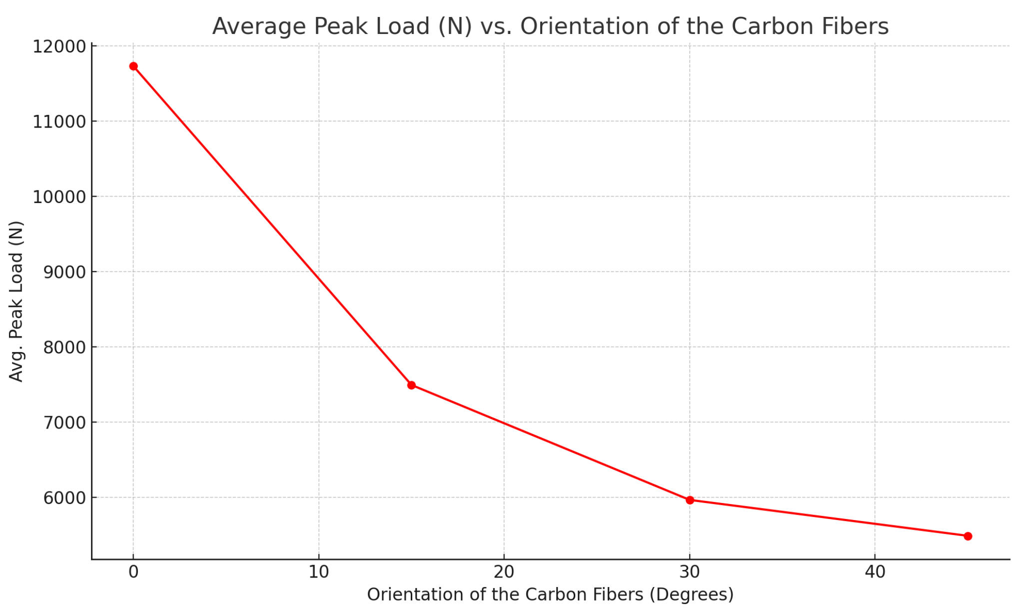


Fig. 31: Plot between Avg. Peak load and Orientation of Carbon Fiber Layers

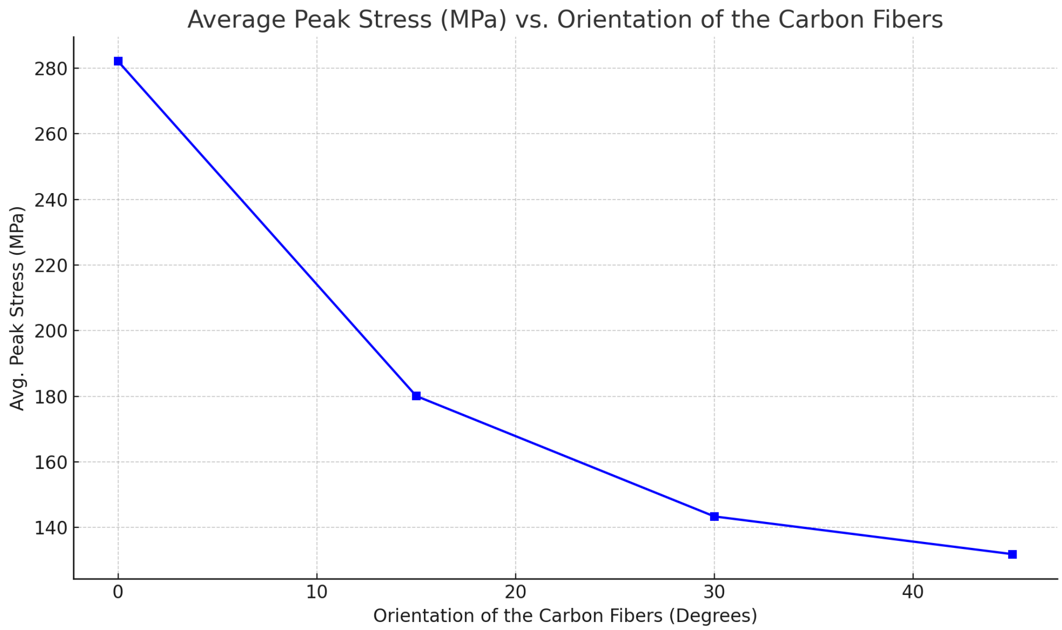


Fig. 32: Plot between Avg. Peak stress and Orientation of Carbon Fiber Layers

8. **Conclusion**

- The graphs indicate that the tensile loading capacity and strength of a material increase when its fibers are aligned to the direction of the applied force. Specifically, fibers oriented at 0° relative to the direction of force exhibit the highest tensile strength.

- The crucial role of fiber alignment is evident in enhancing the material's ability to withstand tensile stress, highlighting its importance in material design and engineering.

- The Carbon fiber reinforcement increases the tensile strength of the Onyx material.

- The Carbon fiber reinforcement makes the material brittle.

9. **Future work**

- Three-point bending test to determine the flexural strength of the material.
- Comparison of the tensile properties by varying the volume fraction of onyx and carbon fiber reinforcement.
- Comparison of the tensile properties by alternating the layers of onyx and carbon fibers.
- Impact test to determine the toughness of the composite material.
- Effect of printing speed on the properties of the part.
- Effect of change in sample size on the results of tensile strength.
- Performing extensive tensile tests to validate the failure mechanism of the specimen that broke outside the gauge length.

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