Thermo-Mechanical Analysis of High-Strength High-Temperature Glass Fiber Reinforced 3D Printed Composites

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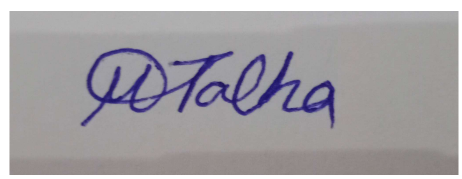

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DEDICATION

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS	**IX**
TABLE OF CONTENTS	**X**
LIST OF TABLES	**XI**
LIST OF FIGURES	**XII**
ABSTRACT	**XIII**
CHAPTER 1: INTRODUCTION	**1**
1.1 Aims and Objectives	**4**
CHAPTER 2: LITERATURE REVIEW	**5**
CHAPTER 3: MATERIALS AND METHODS	**10**
CHAPTER 4: RESULTS AND DISCUSSION	**19**
4.1. Flexural Test ASTM D-790	**19**
4.2. Stiffness	**28**
4.3. Center Deflection	**31**
4.4. Ansys Composite PrepPost (ACP)	**33**
CHAPTER 5: CONCLUSION	**39**
5.1 Future Recommendations	**40**
REFERENCES	**41**

LIST OF TABLES

Table 3.1: Markforged Mark Two Composite 3D Printer Properties 10
Table 3.2: Markforged Onyx and HSHT Fiber Glass Material Properties 11
Table 3.3: Fixed Print Parameters for 3-point bending test specimens. 12
Table 3.4: Number of Layers and Volume Fraction (Vf) for Flexural Test Specimens. 13
Table 3.5: Ansys Composite PrepPost (ACP) composite laminates design parameters............... 15
Table 3.6: Flexural Test Parameters. 15
Table 4.1: 3-Point Bend Test ASTM D-790 at 40°C Experimental Data. 19
Table 4.2: 3-Point Bend Test ASTM D-790 at 60°C Experimental Data. 20
Table 4.3: 3-Point Bend Test ASTM D-790 at 80°C Experimental Data. 21
Table 4.4: Percentage decrease in Flexural Strength with the increase in Temperature. 22
Table 4.5: Stress-Strain Graphs for 3-point bending test at 40°C, 60°C, and 80°C. 23
Table 4.6: Stress-Strain Graphs for 3-point bending test for Distributed vs. Concentrated Fiber.27
Table 4.7: Percentage Decrease in Flexural Strength from Equally Distributed to Center Concentrated HSHT FG layers at 40°C. 27
Table 4.8: Relationship of Stiffness with HSHT FG Vf and Temperature. 29
Table 4.9: Percentage Decrease in Stiffness from Equally Distributed to Center Concentrated HSHT FG layers at 40°C. 31
Table 4.10: Relationship of Deformation with HSHT FG Vf and Temperature. 32
Table 4.11: 3-Point Bend Test at 40°C Simulation Data. 35
Table 4.12: 3-Point Bend Test at 60°C Simulation Data 36
Table 4.13: 3-Point Bend Test at 80°C Simulation Data 36

LIST OF FIGURES

Figure 3.1: Markforged Mark Two Composite 3D Printer 10
Figure 3.2: ASTM D790 Flexural Test Specimen Drawing 13
Figure 3.3: 3D Printed Onyx and HSHT Glass fiber composite specimens. 14
Figure 3.4: Haida HD B607-S Universal Testing Machine with Thermal Chamber 16
Figure 3.5: Existing 3-point bending fixture 17
Figure 3.6: CAD Drawing of Supporting Jaws Extension Mounting for 3-point bending fixture. 17
Figure 3.7: 3-Point Bending Test fixture with Supporting Jaws Extension mounting. 18
Figure 3.8: Mitutoyo Digital Height gauge 18
Figure 4.1: Flexural Strength Vs. HSHT FG Volume Fraction (Vf) at 40℃, 60℃, and 80℃. ... 26
Figure 4.2: Composite test specimen after undergoing flexural test. 28
Figure 4.3: Stiffness Vs. HSHT FG Volume Fraction (Vf) at 40℃, 60℃, and 80℃. 30
Figure 4.4: Deformation Vs. HSHT FG Volume Fraction (Vf) at 40℃, 60℃, and 80℃. 33
Figure 4.5: Composite Laminate Model for Simulation 34
Figure 4.6: Mesh Geometry of Composite Laminate Model for Simulation 34
Figure 4.7: Maximum and Minimum Stress Concentrations in Simulation Results. 35
Figure 4.8: Experimental vs. Analytical Flexural Strength at 40℃. 37
Figure 4.9: Experimental vs. Analytical Flexural Strength at 60℃. 38
Figure 4.10: Experimental vs. Analytical Flexural Strength at 80℃. 38

ABSTRACT

3D printing has revolutionized the way products are designed and manufactured. Composite materials are considered the materials of the future because of their excellent material and mechanical properties and excellent strength-to-weight ratio. Composite 3D printing combines the best of both worlds. 3D-printed composite parts have excellent Mechanical and Material properties and design freedom at the same time. On the contrary, composite 3D printing is fairly a new technology and it is still under development. Research is being carried out; new materials are being developed to take the full potential of composite 3D printing. As we know Composite Materials are a replacement for our traditional metals, as they provide the same if not better performance and are lightweight at the same time. A research gap still exists, considering the performance of 3D-printed composite parts at elevated temperatures. This research focuses on Thermo-Mechanical Analysis of High-Strength High-Temperature glass-fiber reinforced 3D printing composites. Markforged Onyx served as the polymer matrix base and High-Strength High-Temperature Fiberglass was used as the fiber reinforcement for our composite design. This research explores the influence of High-Strength High-Temperature fiberglass (HSHT FG) volume fraction (Vf) and the temperature on the performance of composite test specimens, The 3-point bending test is carried out following ASTM D-790 standard at 40℃, 60℃, and 80℃. Ansys Composite PrepPost is used to model the composite laminates and Ansys Workbench is used for simulations. Both the experimental and simulation results indicate an increase in Flexural Strength and stiffness with the increase in HSHT FG volume fraction and a decrease in both with the increase in temperature. The results also indicate that the increase in HSHT Fiberglass volume fraction in 3D-printed composite specimens induces plastic behavior. Composite parts become less elastic and more elastic with the increase in HSHT FG volume fraction.

Key Words: *Thermo-mechanical analysis, 3D printing, High-Strength High-Temperature Fiberglass, Composite materials, Markforged Onyx, Fiber reinforcement, Volume fraction, Mechanical properties, Material properties, Temperature effects, 3-point bending test, Ansys Composite PrepPost.*

CHAPTER 1: INTRODUCTION

In recent times, composite materials have gained noteworthy interest from various industries, because of their exceptional mechanical, materials, chemical, and thermal properties. A high strength-to-weight ratio is also a deciding factor for choosing these materials over traditional metals [1]. Composite materials are made up of two different materials having different materials and mechanical properties, and they have distinct boundaries within the composite material construction [2]. Composite materials, because of their excellent material and mechanical properties, and high strength-to-weight ratios are used in a wide range of applications. The use of composite materials in aerospace industries is growing day by day. Primary structures like wings and fuselages use composite materials in their construction, and the use of composite materials in high-temperature applications is also on the rise [3]. The design capabilities of composite materials are unmatched, rendering them appropriate for a wide range of applications including spacecraft, dentistry, and pressure vessels.

3D printing, also known as additive manufacturing, involves the creation of three-dimensional objects from digital files. Additive Manufacturing as the name suggests builds parts layer by layer. 3D printing involves the use of additive processes to create objects. An object is formed through the process of adding successive layers of material until it is fully created. Every layer provides a glimpse into the object, like a delicate cross-section. However, there is one remarkable exception called volumetric 3D printing. Volumetric printing allows for the creation of entire structures in a single process, eliminating the need for gradual construction. It is important to mention that currently, volumetric technology is mainly being researched. 3D printing is a completely different process compared to subtractive manufacturing. Instead of removing material from a block, 3D printing builds objects layer by layer. 3D printing allows for the creation of intricate forms while minimizing material usage compared to conventional manufacturing techniques.

3D printing technology offers numerous benefits, including the potential for lighter parts, reduced lead times, and cost savings. This is all thanks to its main feature: a significantly improved design freedom, enabling the creation of parts with highly personalized and unique geometries. The numerous advantages of 3D printing are derived from this technology, resulting in various features like rapid prototyping, on-demand and just-in-time manufacturing, digital warehouses, reduced part count, shorter assembly times, and simplified maintenance. With its wide range of materials and design flexibility, 3D printing proves to be an incredibly versatile solution for industrial manufacturing. One of the primary drawbacks of Additive manufacturing is the relatively high cost of individual parts and the challenge of producing large volumes. The scope of 3D printing is limited to small runs and complex parts, as traditional manufacturing is sufficient for producing simple parts in large volumes.

Composite 3D printing is a relatively new technique in Additive Manufacturing (AM). It combines the design freedom of 3D printing technology and the high performance of composite material. Composite 3D printing improves the properties like strength, stiffness, and strength-to-weight ratio of plastics by reinforcing them with high-performance fiber tows [4]. 3D printing is proving to be an essential tool for the manufacturing of composite parts. It provides design flexibility, waste reduction, time and energy saving, rapid prototyping and the list goes on. Composite 3D printing helps to design strong and lightweight complex parts while minimizing waste material as well as saving energy [5]. Composite 3D printing has eliminated the need for traditional manufacturing processes like mold design, manual layup, and labor-intensive jobs. It has made manufacturing effortless, cost-effective, and time-saving. Continuous Fiber Reinforcement (CFR) 3D printing impregnates a polymer matrix base with fiber tows, as a result forming a composite, this process is completely automated [6]. Continuous Fiber Reinforcement (CFR) 3D printing has emerged as an automated manufacturing process for the design of polymer matrix composite. CFR 3D printing offers design freedom, cost-effectiveness, precision, and accuracy for the manufacturing of composite parts [7]. The utilization of 3D printing in structural applications has significantly enhanced the production of structures with exceptional precision in their dimensions [8]. CFR 3D printing technology has revolutionized the manufacturing industry. It has eliminated the need for molds to fabricate fiber-reinforced thermoplastics. Parts fabricated using CFR 3D printing exhibit enhanced mechanical properties like

Tensile and Flexural strengths as well as better thermal properties [9]. Although Composite 3D printing offers numerous advantages, it is still a relatively recent technology, and there are some concerns. Part quality is a major concern, and the room for newer materials is still huge. Some minor issues like void formation and nozzle clogging need to be addressed [10]. The utilization of 3D printing technology in research and development is progressively rising owing to its vast potential across various domains. However, its full potential is still untouched due to some limiting factors like lack of development in advanced materials, etc. The development of composite 3D printing technology has addressed this issue to some extent, with the use of this technology composite parts with desired physical and chemical properties can be fabricated. The use of 3D printable composites is expanding exponentially in applications like mechanical, biomedical, electrical, aerospace, thermal, and optical [11].

Materials with high-strength and high-temperature capabilities are highly important in industries like aerospace, manufacturing, mechanical, etc. These industries are highly dependent on materials that have high strength-to-weight ratios and are capable of withstanding higher operating temperatures such as polymer matrix composites and aluminum-lithium alloys [12]. These materials are of great importance in challenging applications like power plants and gas turbine engines [13]. On the contrary, these composite materials are still very expensive, inaccessible, and out of reach for most of the smaller industries. To get the full potential out of these materials, above mentioned issues need to be addressed. Mass production and cost-effective methods should be developed, to make composite materials accessible to everyone [14]. In a comprehensive study, Schneibel and Felderman (2004) explore the complex realm of high-strength, high-temperature materials and their potential applications in the aerospace industry. Their primary area of interest revolves around the investigation of Mo-Si-B alloys and their compatibility with specific aerospace uses [15].

Integrating high-temperature high-strength glass fiber reinforcement is crucial for significantly improving the mechanical properties of composites. It has been noted that the inclusion of metallic glass in metal matrix composites leads to a substantial enhancement in their mechanical properties [16]. Integrating high-temperature high-strength glass fiber reinforcement helps in reducing plastic deformation and retarding crack propagation. It significantly increases the compressive strength of glass fiber-reinforced polymer composites, particularly when combined with a matrix characterized by a low free volume and high material density [17]. One of the key abilities of High-Strength High-Temperature fiberglass is its ability to withstand challenging loading and thermal conditions at the same time without showing any permanent deformation [18]. The incorporation of glass fibers not only enhances the mechanical properties of biofiber-reinforced polyester composites but also improves the adhesion between the fibers and the matrix through surface modification of the biofibers.[19].

Prior research has primarily focused on analyzing the mechanical, thermal, and flame-retardant properties of 3D-printed composites. [20]. With the advancement in 3D printing composite technology, there is still a lack of research on the thermo-mechanical analysis of High-strength High-Temperature fiberglass reinforced 3D printed composite parts. It is necessary to close this research gap for further development in the field and to meet the industrial and engineering requirements for the need for high-performance lightweight materials [21].

1.1 Aims and Objectives

To determine the Mechanical and Material properties of 3D printed composites under various loading and thermal conditions, in order to use 3D printed composite parts in different working environments. This research would help us to understand the behavior of High-strength High-Temperature fiberglass reinforced 3D printed composites under varying mechanical and thermal loading conditions. In addition, this would also aid in the advancement of optimized printing parameters for these materials. In this research, we thoroughly investigated the impact of fiber volume fraction (Vf) and temperature on the strength of our composite test specimens. Our research is based on both analytical and experimental approaches.

CHAPTER 2: LITERATURE REVIEW

Day by day Fiber-reinforced polymer composites are gaining importance in a wide range of industries because of their exceptional mechanical, material, and chemical properties, like strength, stiffness, durability, high strength-to-weight ratio, and ability to withstand corrosion, wear, and high temperatures. These materials have found extensive applications in various industries such as aerospace, automotive, construction, sports, and biomedical. [22]. The aerospace industry is currently facing a critical need for advanced composite materials that exhibit exceptional strength and can withstand high temperatures. These materials have a wide range of uses in various applications such as nozzles, brake disks, and thermal protection systems [23]. Another significant area of interest involves the advancement of novel composites, such as bio-composites, green composites, and self-healing polymer composites [24].

Composites have a rich history that can be traced back to ancient civilizations. One fascinating example is the use of clay reinforced with wood and papier mâché, as documented by McMullen in 1984 [25]. The progression of composite materials throughout history has been characterized by significant turning points and technological innovations. The notion of composites has its origins in antiquity, as evidenced by the utilization of laminated metals by Japanese Samurai warriors and the incorporation of chopped straws into bricks by Jewish laborers [26]. In construction, however, significant advancements have been made in the field over the past few decades, specifically in the development of advanced polymer composites. Composites, which involve the combination of materials to improve their properties, have found growing application in the fields of civil and structural engineering because of their remarkable mechanical and in-service characteristics [27]. The progression of materials science has had a significant impact on the developments in the mechanics of continuous fiber composites [28]. The evolution of composites for aircraft primary structures can be traced back to the early days of using gelatin and starch reinforced with cellulose fibers. However, a significant breakthrough came with the invention of carbon fibers and their subsequent utilization as reinforcement for epoxy resins (McMullen, 1984) [25]. An extensive array of uses for composites is showcased, spanning from sports equipment to aerospace. The emphasis is placed on their exceptional strength, durability, and lightweight properties [29]. The use of composite materials in a wide range of applications like engineering, aerospace, biomedical, and so on is mentioned in this study, along with the promising future of composites in various fields and industries [30]. Composite materials have a bright future, as ongoing research and development endeavors strive to augment their properties and expand their range of applications.

The origins of 3D printing can be traced back to 1984 when Charles W. Hull introduced the world's inaugural 3D printer [31]. The introduction of 3D printing revolutionized the manufacturing industry, it helped us achieve, what could only be imagined in the past. Since then, there have been rapid advancements in technology, which have had a significant impact in various fields such as healthcare, manufacturing, and engineering. The advent of 3D printing has brought about a significant transformation in the area of product design and prototyping, as well as in the fields of arts and abstract concept visualization [32]. The layer-to-layer operation enables the creation of intricate structures and designs [33]. 3D printing, also referred to as additive manufacturing, is a technology that is constantly advancing and finding new uses. The significant impact of 3D printing in the construction and building industry by reducing the reliance on human resources and minimizing material wastage is highlighted in a study conducted by Y. W. D. Tay [34]. In a comprehensive study, Fang (2019) explores the growing utilization of this additive manufacturing technology in different sectors like footwear, jewelry, aerospace, and medical. The study emphasizes the revolutionary impact of this technology on traditional manufacturing methods [35]. The positive impact of 3D printing on the environment, including the reduction of raw material usage and the streamlining of supply chains is highlighted in a study conducted by S. Park [36]. It is expected that the rise of 3D printing will bring about a groundbreaking era of customized fabrication, rivaling the importance of traditional manufacturing methods.

3D printing technology has proven to be highly beneficial in the manufacturing of composite materials. A few of the key features of composite 3D printing technology are to create intricate shapes, economical production techniques, and improved mechanical, electrical, and thermal properties. [11]. With the development of composite 3D printing, there are several challenges associated with this technology at the same time, including the need to find a balance between in-plane and out-of-plane properties, difficulties in processing thick and compact 3D structures, and challenges in integrating with metal and 2D composites. Exciting advancements have emerged in composite 3D printing technology, with recent developments focusing on the utilization of nanocomposites and fiber-reinforced composites. These advancements provide advantages like conserving materials, offering design flexibility, and allowing for personalized prints [37]. Despite these advancements, technology is still in its early stages of development, leading to ongoing academic research to address its limitations and complexities [38].

Glass-matrix composites, when reinforced with high-temperature high-strength glass fibers like silicon carbide, offer significant mechanical advantages to composites. When these fibers like silicon carbide are impregnated into a glass matrix, this results in composite materials that exhibit exceptional flexural strength and fracture toughness over a broad spectrum of temperatures [39]. However, the effectiveness of these fibers reinforced composites may be compromised when they are subjected to high operating temperatures, leading to a decrease in strength, stiffness, and other mechanical properties. Furthermore, the composite's flexibility may be affected by the fibers' vulnerability to length degradation during melt processing [40]. Although there are still obstacles to overcome, the reinforcement of high-temperature glass fibers with exceptional strength into composites has the potential to greatly improve mechanical properties, rendering them well-suited for high-temperature applications.

A considerable amount of research has been devoted to exploring the thermomechanical properties of composite materials. Handy research on the thermal and mechanical properties of composites, employing different approaches - experimental and numerical methods, respectively had been carried out in the past. al. Research focusing on utilizing thermal emission measurements to identify and evaluate the extent of damage is carried out by M. Heller [41]. In contrast, R. R. Kumar, discovered that thermal stresses predominate in composite structures [42]. In 1996, Bailleul devised a technique for assessing the characteristics of temperature-dependent composites. This approach enables the assessment of thermophysical properties and curing rate. [43]. In a study conducted by Vergani (2013), the use of thermography was explored for the purpose of assessing fatigue behavior and investigating damage in composites [44]. The studies mentioned highlight the significance of considering thermal and mechanical factors in the analysis of composite materials.

Exciting advancements have been observed in the field of 3D-printed composites reinforced with high-temperature high-strength glass fibers, as per recent studies. Prajapati (2021) demonstrated the improved mechanical, thermal, and flame-retardant properties of these composites, particularly when a polymer composite filament was used as the matrix [20]. By incorporating UV-assisted 3D printing, Invernizzi (2016) further improved the aforementioned characteristics, including thermal stability and mechanical properties [45]. Nonetheless, there are still obstacles to overcome, as decreased fiber length can impact the stiffness of composites, thereby requiring post-treatment to optimize the interface between the fiber and matrix. Notwithstanding these obstacles, the capabilities of these composites are apparent, as demonstrated by Prewo (1980), who developed glass-matrix composites reinforced with silicon carbide fibers that exhibited exceptional flexural strength and fracture toughness [39].

Recent research has shown a growing interest in exploring the potential of 3D printing for manufacturing high-strength, high-temperature glass fiber reinforced composites. Handwerker (2021) and Monticeli (2021) offer comprehensive insights into the mechanical characteristics and optimization techniques for continuous fiber-reinforced thermoplastic components [46]. Handwerker highlights the comparable ultimate tensile strength of Kevlar and glass fiber-reinforced parts with commonly used aluminum alloys [47]. In their research, Faddoul (2023) delves deeper into the thermo-visco mechanical properties of glass fiber reinforced thermoplastic composites. They shed light on how these materials are affected by changes in temperature and strain rate [48]. In his review, Dickson (2020) explores the application of fused filament fabrication (FFF) 3D printing in the manufacturing of fiber-reinforced polymer composites, highlighting the exciting possibilities for improved mechanical performance [49]. These studies emphasize the potential of 3D printing in producing strong, heat-resistant composites reinforced with glass fibers. However, more research is needed in this field.

Although still a relatively new technology, composite 3D printing is increasingly being embraced by the manufacturing industry. It presents a quicker and highly automated method for manufacturing composite parts, which have traditionally been crafted by hand. Composite 3D printing offers a fresh perspective on material selection for specific applications, enabling manufacturers to substitute expensive metal with more affordable and durable plastic alternatives. Ultimately, it contributes to reducing the cost of manufacturing composite parts. Collectively, these advantages indicate that composite 3D printing is poised to expand and develop into a widely adopted technique in the composite manufacturing industry.

In recent years, quite a number of startups have made strides in developing systems for 3D printing composite materials. However, these approaches have shown notable drawbacks in comparison to machined aluminum, particularly focusing on industrial applications. As a result, these startups typically concentrate on either consumer 3D printing or solely offer geometric prototypes. One of the main challenges is the material feedstock. Markforged, the pioneer of carbon fiber 3D printing technology, stands out as the sole provider of a continuous fiber process in the industry. Their printer has revolutionized 3D printing, providing businesses and makers with enhanced performance for creating small prototypes. Nevertheless, studies have indicated that the filament exhibits significant voids and numerous resin-rich regions, leading to considerably reduced properties compared to what the rule of mixture predicts. In fact, the unidirectional coupons only marginally exceed the tensile strength of 6061 aluminum. In addition, the use of porosity and printing parallel layers instead of multiaxial printing can result in weakened shear and fatigue properties, which can lead to issues such as delamination and matrix cracking. Markforged has successfully catered their product to the consumer and prototyping market, providing a safer and more convenient alternative to CNC machining aluminum at home. However, the cost of their filament, which is priced at over $500 per pound, makes it hard to justify using this solution in settings other than home, workshop, or maker space.

CHAPTER 3: MATERIALS AND METHODS

In this current study, a Markforged Mark Two composite 3D printer is used to print composite test specimens of Onyx and High-Strength High-Temperature Fiber Glass (HSHT FG) for the evaluation of the part's strength under varying temperatures and fiber volume fractions (Vf).

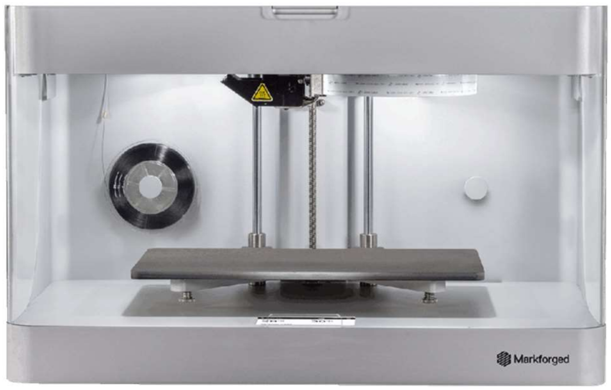


Figure 3.1: Markforged Mark Two Composite 3D Printer

Table 3.1: Markforged Mark Two Composite 3D Printer Properties

Printer Properties	Process	Fused filament fabrication, Continuous Filament Fabrication
	Build Volume	320 x 132 x 154 mm
	Weight	16 kg
	Machine Footprint	584 x 330 x 355 mm (23 x 13 x 14 in)
	Print Bed	Kinematic coupling — flat to within 160 µm
	Extrusion System	Second-generation extruder, out-of-plastic detection

Onyx is a type of nylon that is filled with micro-carbon fiber. It possesses a strength and stiffness that is 1.4 times greater than ABS and can be strengthened with any type of continuous fiber. Onyx establishes the standard for surface smoothness, resistance to chemicals, and ability to withstand high temperatures. High-strength High-temperature Fiberglass (HSHT FG) demonstrates exceptional strength similar to that of aluminum and possesses a remarkable ability to withstand high temperatures. With a strength five times greater and a stiffness seven times greater than Onyx, this material is most suitable for components subjected to elevated operating temperatures.

Table 3.2: Markforged Onyx and HSHT Fiber Glass Material Properties

Properties	**Onyx**	**HSHT FG**	**Units**
Density	1200	1500	kg/m^3
Melting Temperature	215	1700	℃
Young's Modulus	2.4	21	GPa
Tensile Stress at Break	37	600	MPa
Flexural Strength	71	420	MPa
Heat Deflection Temperature	145	150	℃

Markforged Mark Two composite 3D printer accuracy is generally within +/- 250um or 0.25% for the X and Y axes, and +/- 100um or 0.15% for the Z axis. The test specimens were fabricated by keeping the nozzle temperature constant at 290℃, with 100 percent infill, and 0.1 mm layer height. The test specimens were 3D printed following the dimensions given in the Markforged Composite material data sheet i.e. 114.3mm×10.16 mm×3.048mm (L×W×H). HSHT Fiberglass volume fraction (Vf) depends on the number of layers of HSHT FG. Initially, four layers of HSHT fiberglass were introduced around the neutral axis and the number of layers of HSHT FG gradually increased. The test specimens were printed at six different HSHT Fiber Glass volume fractions (Vf) i.e. 13%, 20%, 27%, 33%, 40%, and 47%. (4, 6, 8, 10, 12, and 14 layers of HSHT fiberglass).

Table 3.3: Fixed Print Parameters for 3-point bending test specimens.

Print Parameters	**Description**
Printer	Markforged Mark Two
Materials	Onyx/ HSHT FG
Infill Density	100%
Layer Height	0.10 mm
Raster angle	0°
Print Orientation	0° (flat on bed)
Support Structure	-
Extruder Temperature	290 °C
Printing Bed Temperature	120 °C

Markforged 3D printers come with their own slicing software, known as Markforged Eiger. Slicing of the geometry, printing parameters selection/adjustment, and preparation of the 3D printable model was done using the Markforged Eiger software.

Table 3.4: Number of Layers and Volume Fraction (Vf) for Flexural Test Specimens**.**

Sample	**Onyx**		**HSHT FG**	
	Number of Layers	**Volume Fraction (Vf)**	**Number of Layers**	**Volume Fraction (Vf)**
Sample 1	26	87%	4	13%
Sample 2	24	80%	6	20%
Sample 3	22	73%	8	27%
Sample 4	20	67%	10	33%
Sample 5	18	60%	12	40%
Sample 6	16	53%	14	47%
Sample 7	16	53%	14	47%

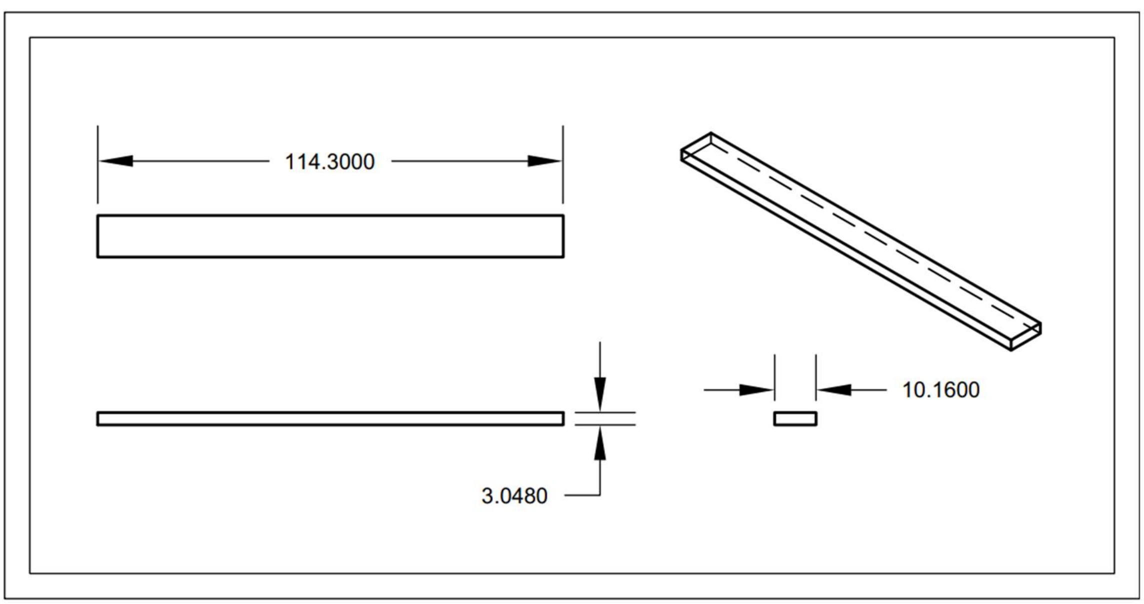


Figure 3.2: ASTM D790 Flexural Test Specimen Drawing

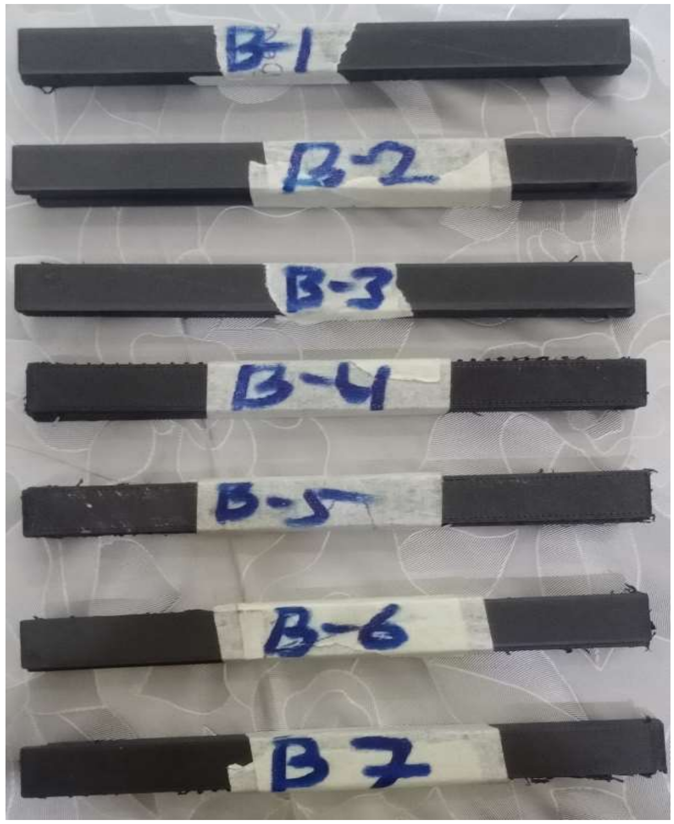


Figure 3.3: 3D Printed Onyx and HSHT Glass fiber composite specimens.

The experimental simulations were conducted using Ansys Workbench. The modeling of composite laminates was done using Ansys Composite PrepPost (ACP). The edge sizing for meshing was set to 1mm by applying a mesh convergence study. The ply thickness and angle for Onyx and HSHT Fiber Glass were both set to 0.1016 mm and 0º, respectively. The glass-fiber volume percentage (Vf) was adjusted by altering the number of plies of HSHT Fiber Glass. The data from the composite laminate model was then transferred to Ansys Steady State thermal and Steady State Mechanical modules simultaneously for Thermo-Mechanical analysis. Temperatures, loading, and boundary conditions for thermo-mechanical analysis were varied according to our experimental setup.

Table 3.5: Ansys Composite PrepPost (ACP) composite laminates design parameters.

Parameters	Samples						
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**
Onyx Plies (No.)	26	24	22	20	18	16	16
HSHT FG Plies (No.)	4	6	8	10	12	14	14
Ply Thickness	0.1016 mm	0.1016 mm	0.1016 mm	0.1016 mm	0.1016 mm	0.1016 mm	0.1016 mm
Ply Angle	0º	0º	0º	0º	0º	0º	0º
Edge Sizing (Mesh)	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm

The Flexural Test (3-point bending test) followed the ASTM D790 standard. Haida HD B607-S Universal Testing Machine and the Thermal chamber (Environmental Chamber) were used for the 3-point bending test. Three-point bending tests were conducted using a test fixture with a 3 mm radius of the loading nose and radii of the support noses. Bending measurements were taken by applying a strain rate of 2 mm/min and a 10kN load cell at three different temperatures i.e. 40°C, 60°C, and 80°C.

Table 3.6: Flexural Test Parameters.

Parameters	**Description**
Testing Standard	ASTM D790
Testing Machine	Haida HD B607-S with Thermal Chamber
Testing Temperature	40°C, 60°C, 80°C
Testing Speed	2 mm/min

Load Cell Capacity	10 KN

Figure 3.4: Haida HD B607-S Universal Testing Machine with Thermal Chamber.

Unfortunately, we did not have the required mounting/fixture for the Haida HD B607-S Universal Testing Machine to perform 3-point bending test using a Thermal Chamber, as supporting jaws for 3-point bending test fixtures were not long enough, so we had to modify the existing 3-point bending test fixture.

Figure 3.5: Existing 3-point bending fixture.

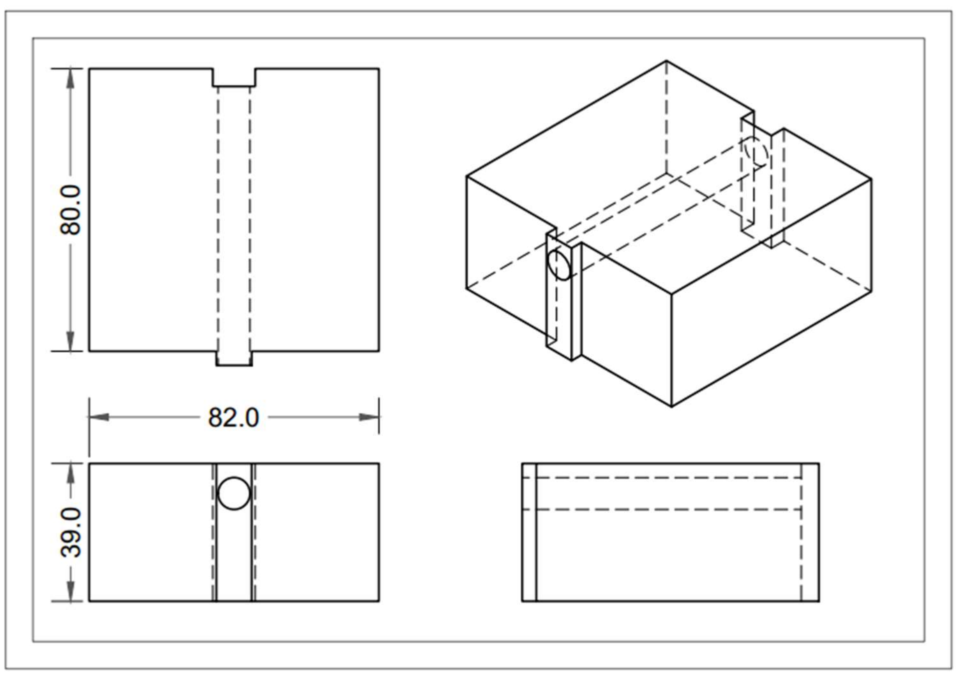


Figure 3.6: CAD Drawing of Supporting Jaws Extension Mounting for 3-point bending fixture.

For the 3-point bending test fixture, we designed a Supporting Jaws extension mounting. With the help of this mounting, we were able to extend the jaw's length by 80 mm.

Aluminum alloy T6-6061 was used to fabricate this extension mounting. Aluminum T6-6061 was used because of its ability to withstand high temperatures without deformation.

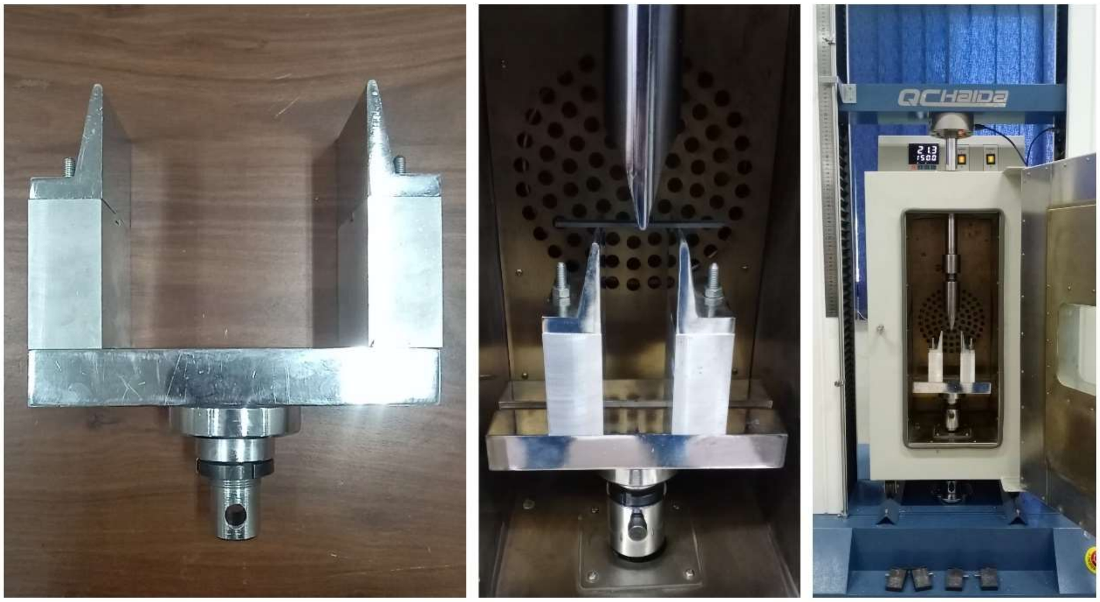


Figure 3.7: 3-Point Bending Test fixture with Supporting Jaws Extension mounting.

The center deflection/ permanent deformation of the test specimens was measured using the Mitutoyo Digital Height gaug e.

Figure 3.8: Mitutoyo Digital Height gauge.

CHAPTER 4: RESULTS AND DISCUSSION

4.1.Flexural Test ASTM D-790

3-Point Bend Test at elevated temperatures serves as a valuable tool for Thermo-Mechanical Analysis of composite test specimens. It enables us to evaluate the mechanical properties of composites like strength, stiffness, deformation, etc. The 3-Point Bend Test at elevated temperatures also helps us to investigate the effect of an increase in temperature on the Mechanical and Material properties of our composite test specimens. The table provided below provides valuable information on the Mechanical properties of Onyx and High-Strength High-Temperature Fiberglass (HSHT FG) composites with 100% infill density, at variable HSHT Fiberglass volume fractions (Vf) i.e. 13%, 20%, 27%, 33%, 40%, and 47%. (4, 6, 8, 10, 12, and 14 layers of HSHT fiberglass) and three different temperatures i.e. 40℃,60℃ and 80℃ respectively. Results demonstrate that at higher temperatures there is a considerable decline in mechanical properties like strength, stiffness, etc. It is also demonstrated by these results that with the increase in High-Strength High-Temperature Fiberglass (HSHT FG) volume fractions (Vf), there is a noticeable amount of improvement in the Mechanical properties of composite test specimens. Composite test specimens with higher volume percentages of HSHT Fiberglass were able to handle mechanical loading at higher temperatures much better.

Table 4.1: 3-Point Bend Test ASTM D-790 at 40℃ Experimental Data.

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)	Strain (%)
Sample 1A	87%	13%	56.8	45.18	9.44
Sample 2A	80%	20%	74.4	59.13	8.02
Sample 3A	73%	27%	82.8	65.76	9.39

Sample 4A	67%	33%	94.4	74.95	5.62
Sample 5A	60%	40%	114.6	91.02	5.57
Sample 6A	53%	47%	114.8	91.21	5.44
Sample 7A	53%	47%	61.4	48.75	12.95

From Table 4.1, it can be seen that Sample 6 and Sample 7 both have the same Volume Fractions for Onyx (53%) as well as HSHT GF (47%), but still, there is a huge difference in their overall strength. This difference is because of the HSHT FG overall distribution in the composite test specimen. For Sample 6 HSHT GF layers are well distributed throughout the sample. This distribution in HSHT GF layers distributes the stress as well, stress is not concentrated on a single point, thus sample 6 can take more load for the same volume fractions of Onyx and HSHT FG. In the case of sample 7, all the layers of HSHT FG are concentrated around the center/ neutral axis of the sample, because of this there is no stress distribution, and stress is concentrated on a single point. Thus, for the same Volume fraction of Onyx and HSHT FG, sample 7 has a much lower strength as compared to sample 6. In the case of distributed Fiberglass throughout the sample, we have much better mechanical properties.

Table 4.2: 3-Point Bend Test ASTM D-790 at 60℃ Experimental Data.

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)	Strain (%)
Sample 1B	87%	13%	51.8	41.20	5.79
Sample 2B	80%	20%	62.4	49.50	7.50
Sample 3B	73%	27%	49	38.88	7.41

Sample 4B	67%	33%	72.8	57.82	7.04
Sample 5B	60%	40%	89.2	70.87	7.31
Sample 6B	53%	47%	96.2	76.38	6.92

Table 4.3: 3-Point Bend Test ASTM D-790 at 80°C Experimental Data.

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)	Strain (%)
Sample 1C	87%	13%	44.2	35.05	11.62
Sample 2C	80%	20%	45	35.83	9.67
Sample 3C	73%	27%	55.4	44.02	8.86
Sample 4C	67%	33%	61.4	48.86	8.36
Sample 5C	60%	40%	72.4	57.56	8.83
Sample 6C	53%	47%	-	-	-

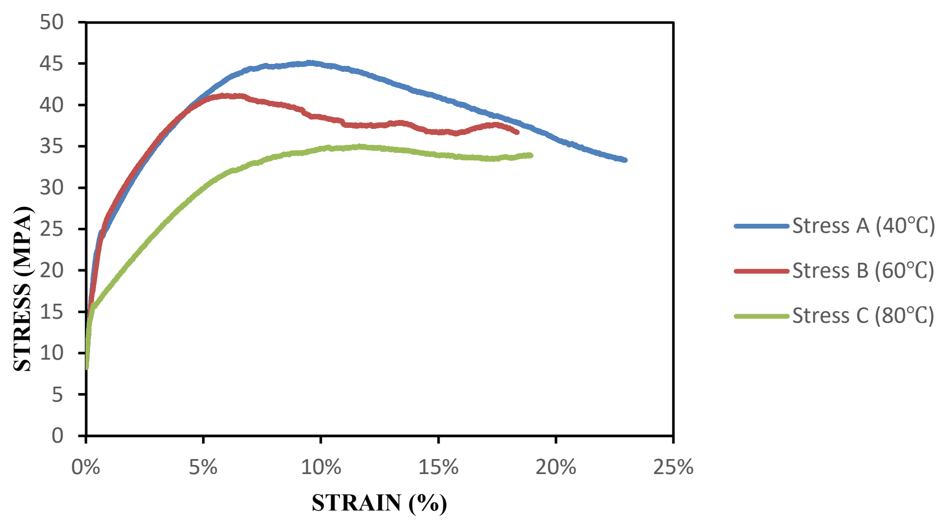
It is clearly demonstrated from the above two tables that with the increase in temperature there is a considerable drop in the Mechanical properties of our 3D-printed composite test specimens. Maximum Flexural Strength of **91.21 MPa** for Sample 7A can be observed at 40°C when the Volume fraction (Vf) of Onyx is 53% and HSHT FG is 47% respectively, and HSHT FG layers are distributed throughout the sample construction. The percentage decrease in Flexural Strength with the increase in temperature is demonstrated in the table below.

Table 4.4: Percentage decrease in Flexural Strength with the increase in Temperature.

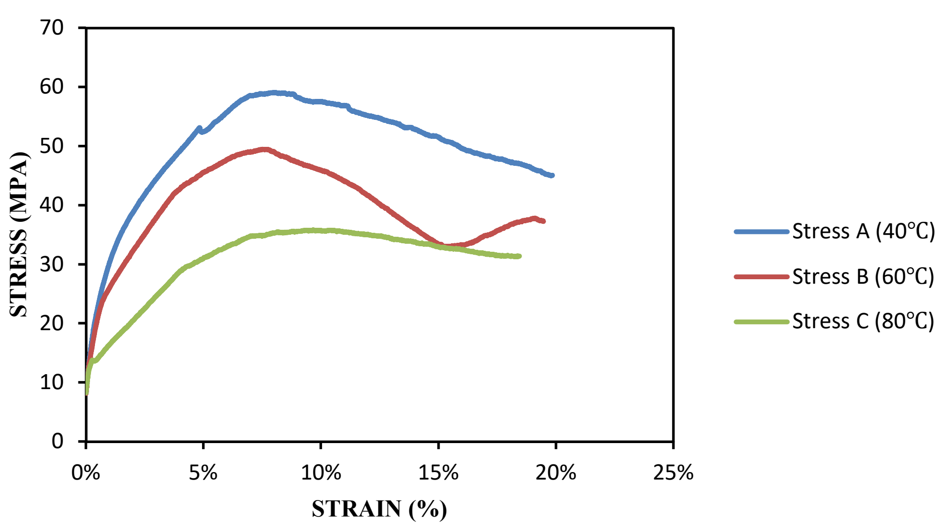
Sample	Volume Fraction (Vf)		Flexural Strength			Percentage Decrease in Flexural Strength	
	Onyx	HSHT FG	40°C	60°C	80°C	% Decrease 40°C to 60°C	% Decrease 40°C to 80°C
Sample1	87%	13%	45.18	41.20	35.05	9%	22%
Sample2	80%	20%	59.13	49.50	35.83	16%	39%
Sample3	73%	27%	65.76	38.88	44.02	41%	33%
Sample4	67%	33%	74.95	57.82	48.86	23%	35%
Sample5	60%	40%	91.02	70.87	57.56	22%	37%
Sample6	53%	47%	91.21	76.38	-	16%	-

Table 4.5: Stress-Strain Graphs for 3-point bending test at 40°C, 60°C, and 80°C.

<table>
<tr><th>Volume Fraction (Vf)</th><th>Temperature (°C)</th></tr>
<tr><td>Onyx 87%

HSHT FG 13%</td><td>


</td></tr>
<tr><td>Onyx 80%

HSHT FG 20%</td><td>


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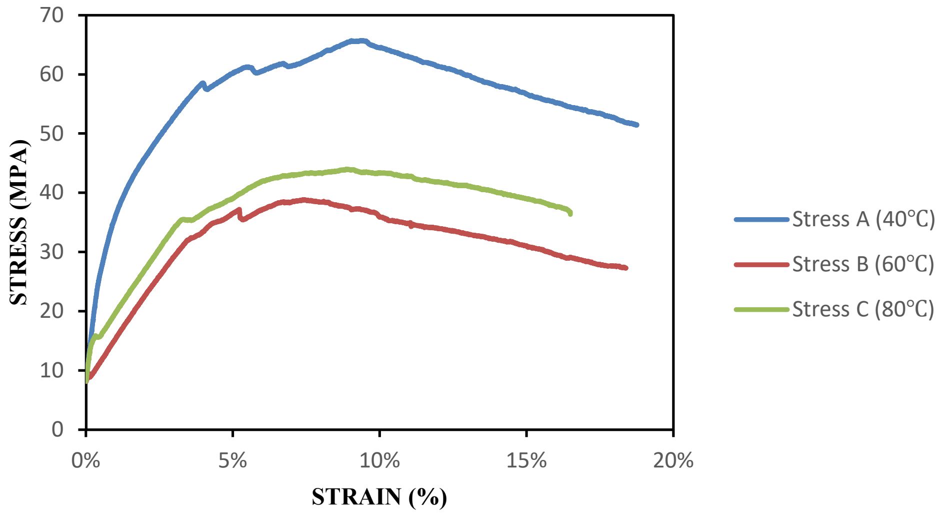
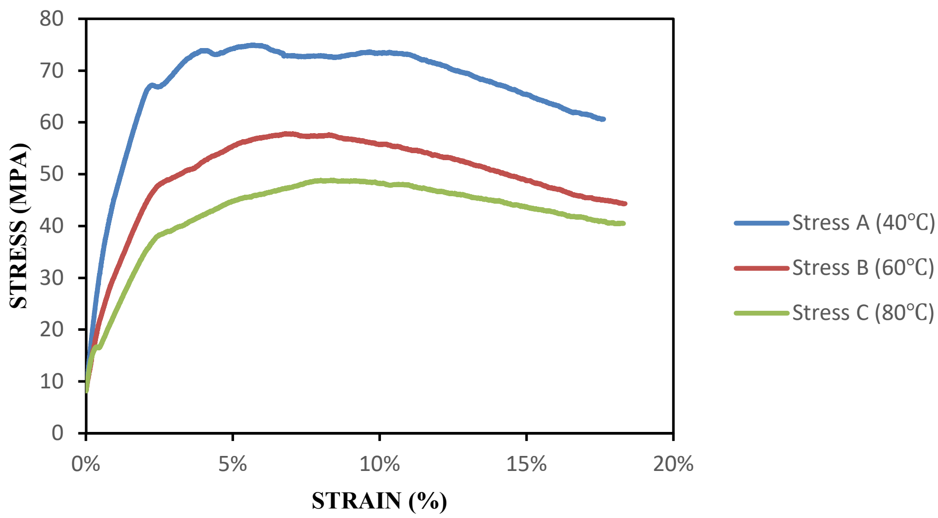
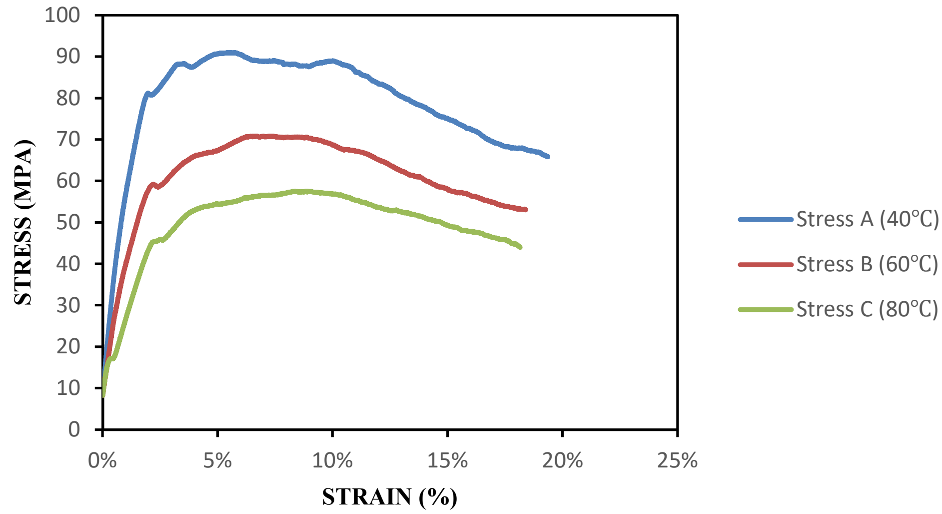
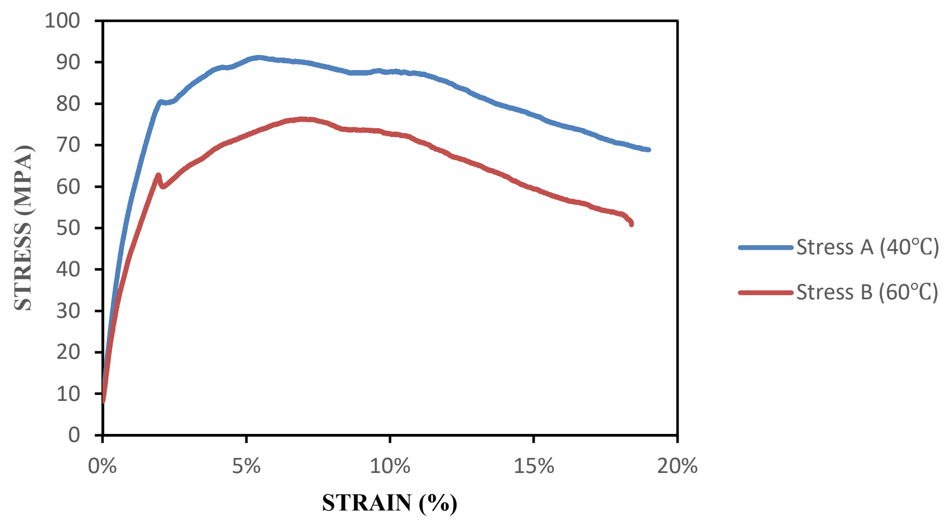
Onyx 73% HSHT FG 27%	
Onyx 67% HSHT FG 33%	

Onyx 60% HSHT FG 40%	
Onyx 53% HSHT FG 47%	

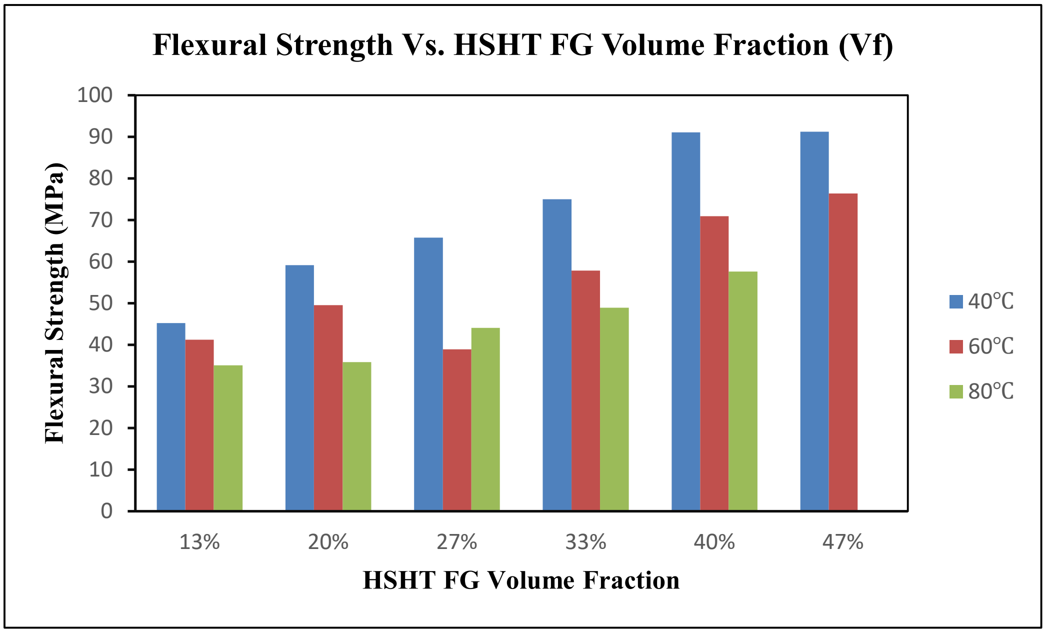


Figure 4.1: Flexural Strength Vs. HSHT FG Volume Fraction (Vf) at 40°C, 60°C, and 80°C.

Figure 4.1 demonstrates the relationship between Flexural Strength, Temperature, and HSHT Fiberglass Volume Fraction (Vf). With the increase in HSHT FG Vf, the flexural strength of our composite test specimen significantly increases. On the contrary with the increase in temperature, the flexural strength of our composite test specimens remarkably decreases. Thus, fiber volume fraction as well as the temperature at which the composite has to be used are two crucial factors and should be considered before designing a composite. For higher operating temperatures high-volume fractions of fiber should be used, and mechanical loading conditions should also be considered to use an adequate amount of fiber reinforcement in a composite.

Table 4.6: Stress-Strain Graphs for 3-point bending test for Distributed vs. Concentrated Fiber.

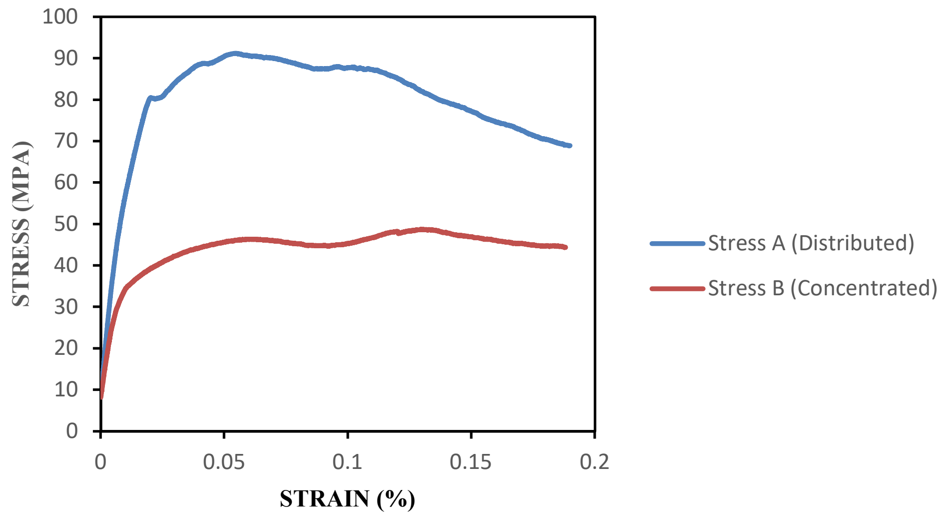
<table>
<tr>
<td>Onyx 53%
HSHT FG 47%</td>
<td>
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Table 4.6 compares Stress-Strain graphs of Distributed HSHT FG layers vs. Concentrated HSHT FG layers around the neutral axis at 40. In the case of Distributed HSHT FG Flexural Strength is much higher than the one with concentrated HSHT FG. The percentage decrease in Flexural Strength for this given scenario is illustrated in the table given below.

Table 4.7: Percentage Decrease in Flexural Strength from Equally Distributed to Center Concentrated HSHT FG layers at 40°C.

Flexural Strength (MPa)	**Volume Fraction (Vf)**	**Fiber Orientation**		**Percentage Decrease in Strength**
		Equally Distributed	**Center Concentrated**	
	Onyx 53 HSHT FG 47%	91.21	48.75	**47%**

Figure 4.2: Composite test specimen after undergoing flexural test.

4.2.Stiffness

Stiffness is another important material property to consider before designing a composite. Stiffness is the ability of a body to resist permanent deformation under an applied force. The stiffer the material, the harder it will be to deform, and it would take a much larger force to deform it. From the data obtained from the Flexural Test, we calculated the stiffness for each composite test specimen. With the increase in Volume Fraction (Vf) of HSHT Fiberglass, the stiffness of our composite test specimens significantly increased. The stiffness went from **4.41 N/mm** to the maximum **15.43 N/mm** for the samples test at 40°C. This trend also followed the other testing temperatures of 40°C and 80°C. If we look at the effect of temperature on stiffness, the stiffness of our composite test specimen noticeably decreased with the increase in temperature and this happened for each volume fraction of HSHT FG, for a composite test specimen with a minimum 13% Vf of HSHT GF at 40°C we obtained a stiffness value of 4.41 N/mm and for the same Vf of HSHT GF at 80°C, the stiffness decreased to 2.78 N/mm. Similarly, if look at the composite test specimen with a maximum of 47% Vf of HSHT GF at 40°C, we obtained a stiffness value of 15.43 N/mm, and this dropped to 6 N/mm at 80°C. So, we can say that temperature has an adverse effect on the stiffness of composites. Table 4.8 illustrates the relationship between stiffness and HSHT FG Vf as well as temperature.

Table 4.8: Relationship of Stiffness with HSHT FG Vf and Temperature.

Sample	Volume Fraction (Vf)		Stiffness (N/mm)			Percentage Decrease in Stiffness	
	Onyx	HSHT FG	40°C	60°C	80°C	% Decrease 40°C to 60°C	% Decrease 40°C to 80°C
Sample1	87%	13%	4.41	5.22	2.78	19%	37%
Sample2	80%	20%	6.78	6.07	3.41	10%	50%
Sample3	73%	27%	6.90	4.83	4.57	30%	34%
Sample4	67%	33%	12.26	7.56	5.38	38%	56%
Sample5	60%	40%	15.04	8.93	6.00	41%	60%
Sample6	53%	47%	15.43	10.16	-	34%	-

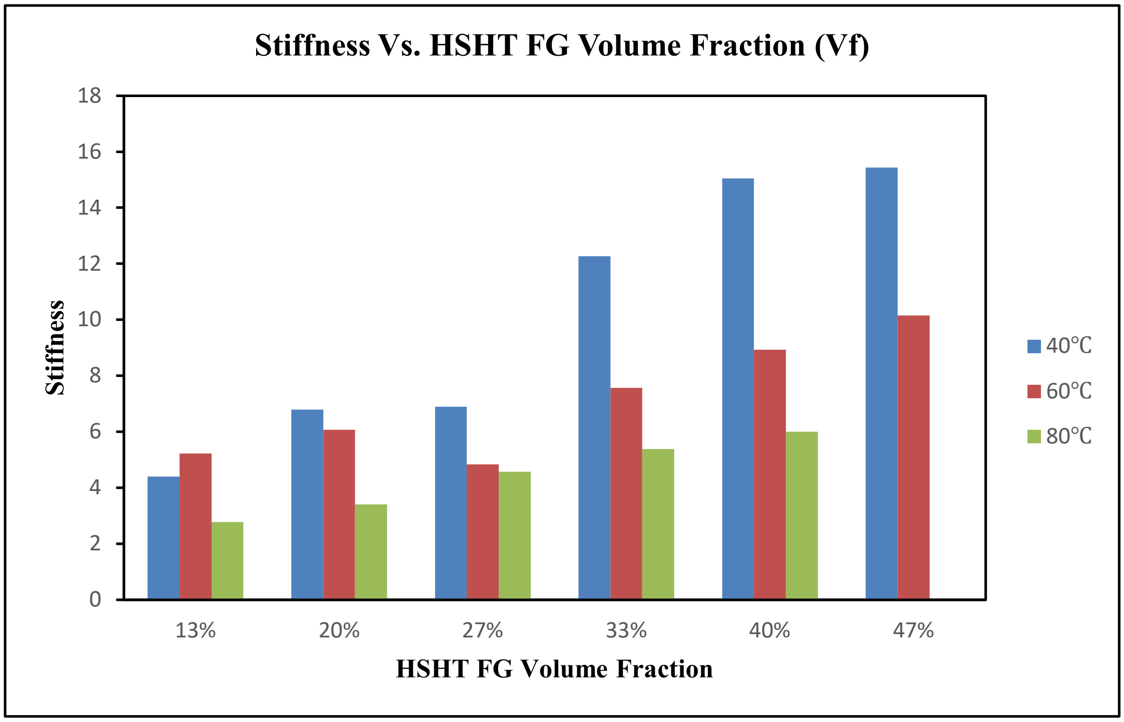

Figure 4.3: Stiffness Vs. HSHT FG Volume Fraction (Vf) at 40°C, 60°C, and 80°C.

It was observed that for the same Volume Fractions of HSHT GF but different fiber orientations, there was a huge difference in the overall stiffness of the composites test specimen. For samples 6 and 7 we had 53% of Onyx and 47% of HSHT FG volume fractions respectively. In the case of sample 6, HSHT fiberglass was equally distributed throughout the sample but in the case of sample 7, all the layers of HSHT fiberglass were concentrated in the center. The sample with distributed fiber layers showed much higher stiffness than the one with layers concentrated in the center, this is because of the overall stress distribution and load-taking capability of these samples, similar to what was observed in the case of flexural strength.

Table 4.9: Percentage Decrease in Stiffness from Equally Distributed to Center Concentrated HSHT FG layers at 40°C.

Stiffness (N/mm)	Volume Fraction (Vf)	Fiber Orientation		Percentage Decrease in Strength
		Equally Distributed	**Center Concentrated**	
	Onyx 53 HSHT FG 47%	15.43	3.47	**78%**

There is a huge difference of 78% in the stiffness of both composite test samples having the same amount of fiber percentage as shown in the table above.

4.3.Center Deflection

The Center Deflection/ permanent deformation of our composite test specimen was measured using a Mitutoyo digital height gauge. The composite test specimens were laid on a flat surface and then center deflection was measured. It was noted that when composite test specimens were allowed to cool down after 3-point bending tests at higher temperatures, they regained their shapes to some extent. The composite test specimen showed elastic behavior to some extent. It was also noted that composite test specimens with higher stiffness values took a much larger force to deform, but once deformed they showed less elastic behavior as compared to the ones having smaller stiffness values. The composite test specimen having less percentage of HSHT FG had lower stiffness values, and when they were allowed to cool down after the flexural test at elevated temperature they showed elastic behavior to a much larger extent, as compared to the ones with higher percentages of HSHT FG and higher values of stiffness. This trend was followed for nearly every test sample. When we take a look at the effect of temperature on the deformation of composite test samples, the results were as expected, with the increase in testing temperature the center deflection/ permanent deformation of our composite test specimens also increased. Table 4.10 illustrates the trend in permanent deformation of our composite test specimens with the increase in testing temperature as well as HSHT FG volume percentage.

Table 4.10: Relationship of Deformation with HSHT FG Vf and Temperature.

Sample	Volume Fraction (Vf)		Deformation (mm)		
	Onyx	HSHT FG	40°C	60°C	80°C
Sample1	87%	13%	7.69	9.90	10.66
Sample2	80%	20%	7.97	10.02	10.93
Sample3	73%	27%	8.35	11.10	11.77
Sample4	67%	33%	9.77	12.06	12.68
Sample5	60%	40%	10.83	12.55	13.59
Sample6	53%	47%	11.18	13.62	-

From above table 4.10, it can concluded that the higher the stiffness of a composite test specimen, the harder it will be to deform it and it will take a much larger force to deform it, but once deformed it will stay deformed, and it is likely to show less elastic behavior and upon unloading and letting it cool down would have the minimum effect on its permanent deformation/ center deflection, as compared to the samples with lower stiffness values, which shows elastic behavior to a much visible extent and upon unloading and letting it cool down has a much apparent effect on its permanent deformation/ center deflection.

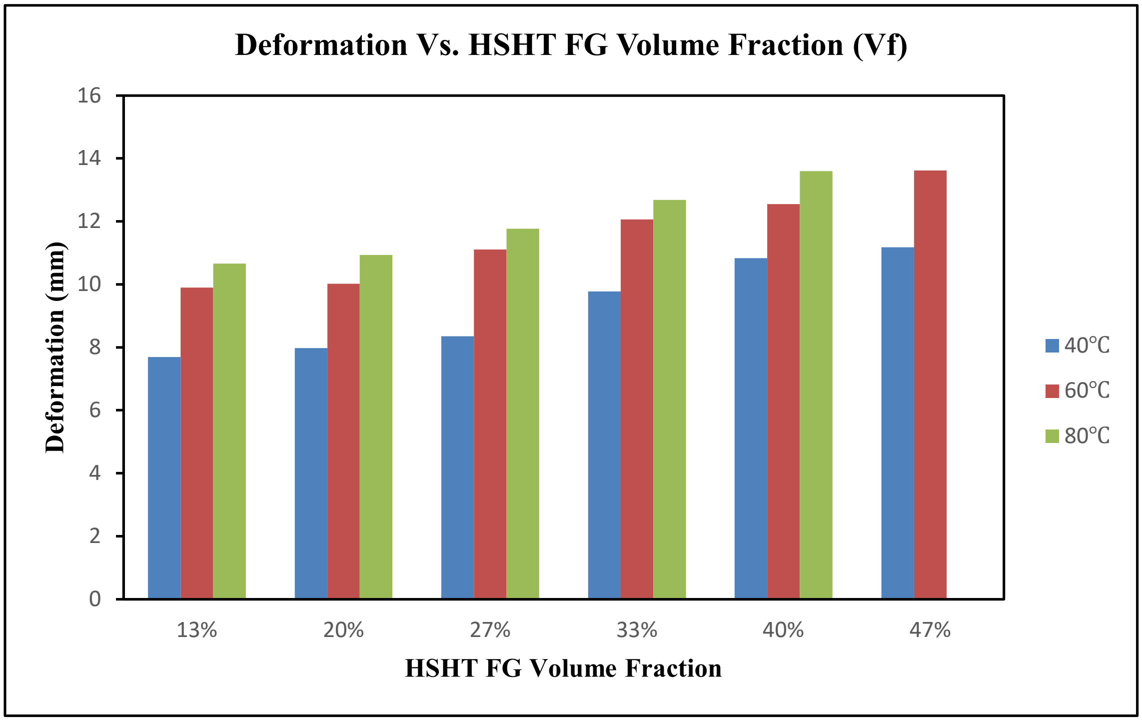

Figure 4.4: Deformation Vs. HSHT FG Volume Fraction (Vf) at 40°C, 60°C, and 80°C.

Sample 7 had a sample Volume fraction of 47% of HSHT as compared to sample 6 but had all the fiber layers concentrated at the center as compared to sample 6 where fiber layers were distributed, which showed the worst performance. It has a value of **13.97 mm** for center deflection as compared to sample 6 which had much higher stiffness and had a value of **11,18 mm** for center deflection.

4.4.Ansys Composite PrepPost (ACP)

Ansys Composite PrepPost (ACP) is a very handy tool when it comes to composite laminate modeling. Composite laminate model data was then transferred to Ansys Workbench Steady-State Thermal and Static Structural modules for Thermo-Mechanical Analysis. The simulations were carried out considering the experimental setup and conditions of our ASTM D-790 3-point bending test. Loading and thermal conditions were also kept similar to our experimental setup. Ansys Workbench is quite useful when it comes to simulating real-life experimental setups. The results we got for the Thermo-Mechanical Analysis of High-Strength High-Temperature Glass-fiber reinforced 3D printed composite test specimen from Ansys Workbench were fairly comparable with the ones we got from our 3-point bending tests and the simulation results follow in pursuit to the experimental results.

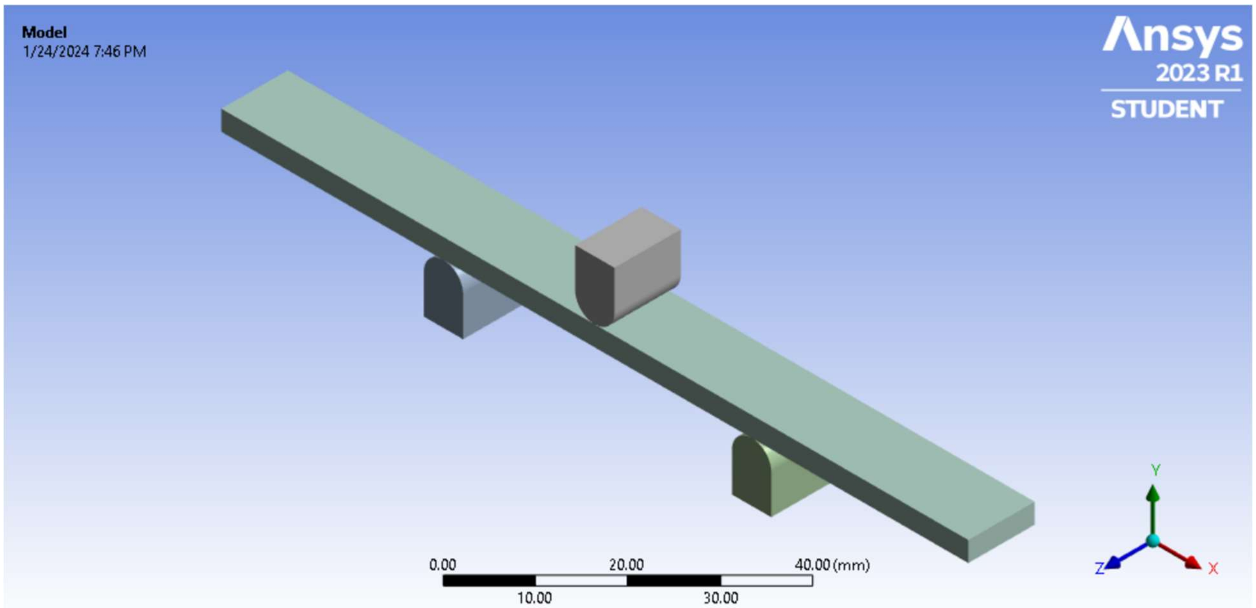

Figure 4.5: Composite Laminate Model for Simulation

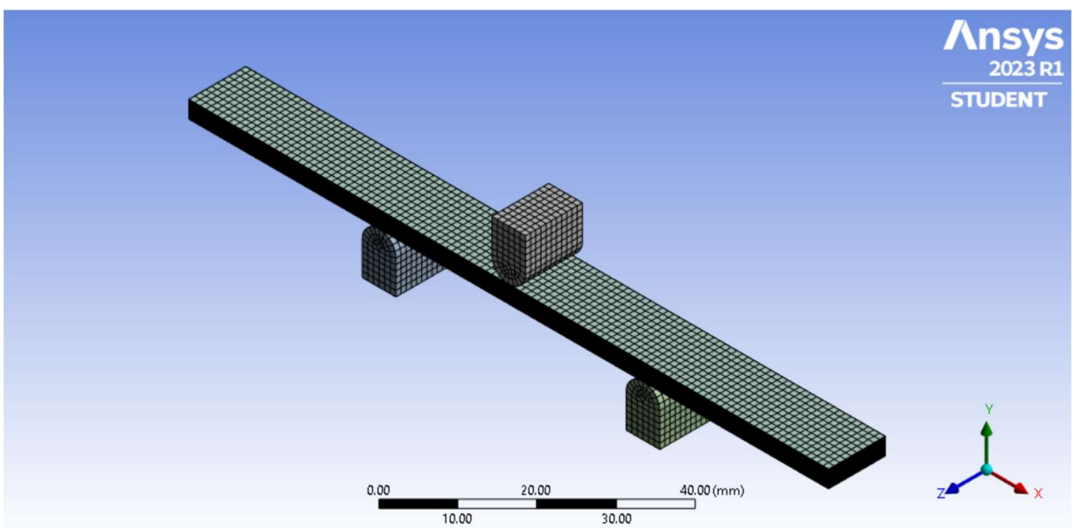

Figure 4.6: Mesh Geometry of Composite Laminate Model for Simulation

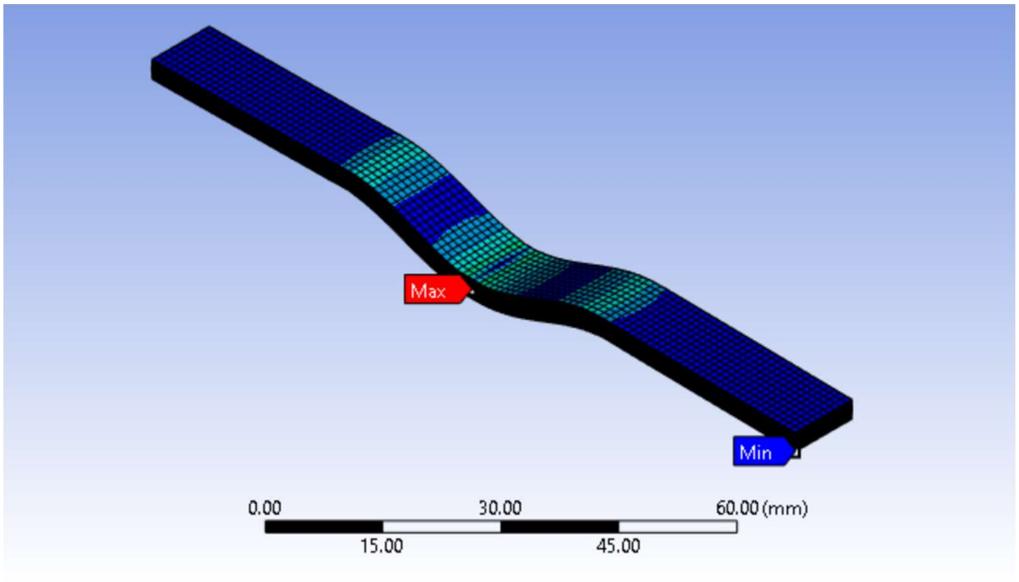

Figure 4.7: Maximum and Minimum Stress Concentrations in Simulation Results.

Table 4.11: 3-Point Bend Test at 40°C Simulation Data.

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)
Sample 1A	87%	13%	56.8	32.34
Sample 2A	80%	20%	74.4	60.73
Sample 3A	73%	27%	82.8	76.46
Sample 4A	67%	33%	94.4	84.94
Sample 5A	60%	40%	114.6	92.38
Sample 6A	53%	47%	114.8	80.01
Sample 7A	53%	47%	61.4	71.80

Table 4.12: 3-Point Bend Test at 60°C Simulation Data

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)
Sample 1B	87%	13%	51.8	32.24
Sample 2B	80%	20%	62.4	53.78
Sample 3B	73%	27%	49	48.63
Sample 4B	67%	33%	72.8	68.50
Sample 5B	60%	40%	89.2	70.16
Sample 6B	53%	47%	96.2	70.04

Table 4.13: 3-Point Bend Test at 80°C Simulation Data

Sample	Onyx (Vf)	HSHT FG (Vf)	F max (N)	Stress (MPa)
Sample 1C	87%	13%	44.2	30.789
Sample 2C	80%	20%	45	42.606
Sample 3C	73%	27%	55.4	50.093
Sample 4C	67%	33%	61.4	53.39
Sample 5C	60%	40%	72.4	56.944
Sample 6C	53%	47%	-	-

Simulation results give us similar insight as did the experimental results. With the increase in High-Strength High-Temperature Fiberglass (HSHT FG) Volume fraction (Vf), the performance of composite test specimens distinctly improved. The flexural strength of composite test specimens had a huge leap with the increase in HSHT FG Vf. Similarly with the increase in test temperatures performance of composite test specimens significantly dropped. We can say that the flexural strength is inversely proportional to the temperature. Similarly, the sample with the distributed fiberglass layers gave way better results than the one with center concentrated fiberglass layers at the center.

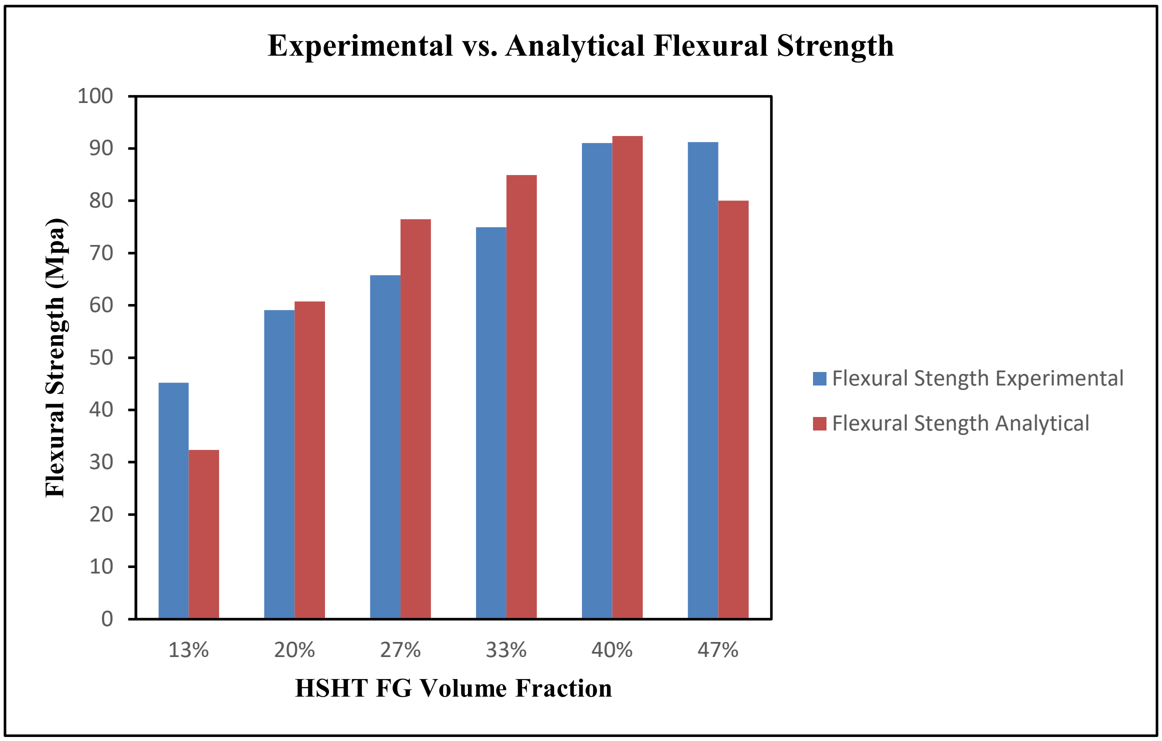

Figure 4.8: Experimental vs. Analytical Flexural Strength at 40°C.

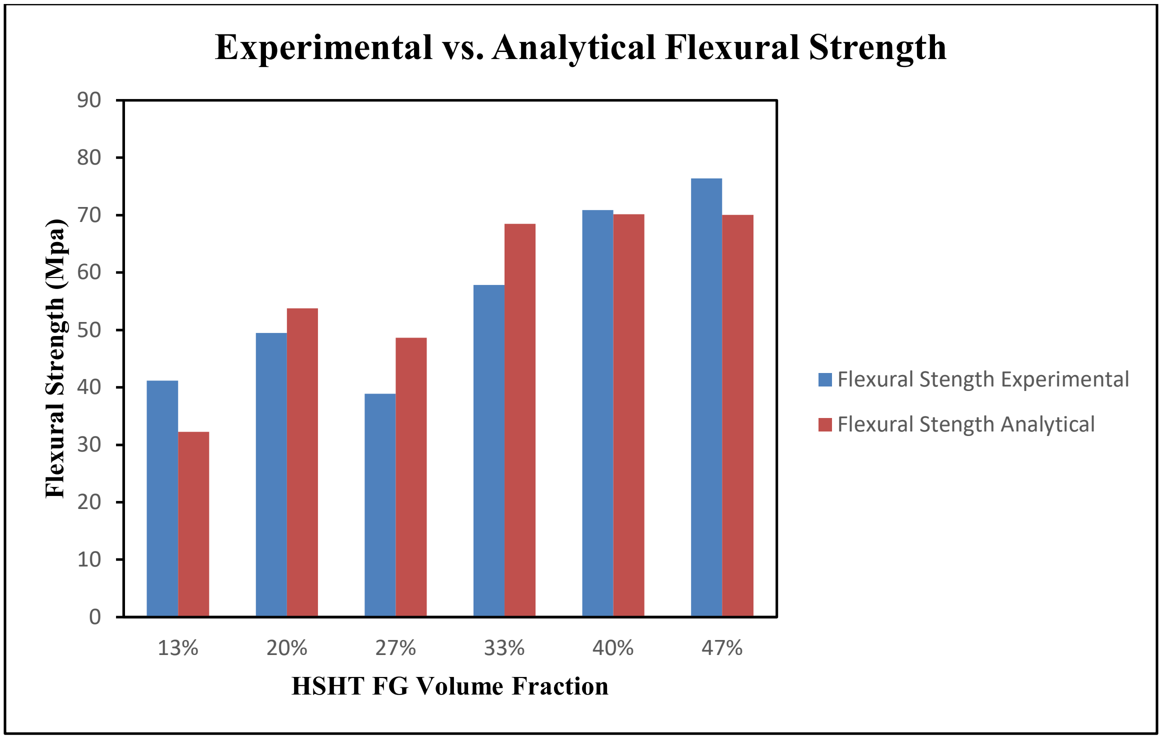

Figure 4.9: Experimental vs. Analytical Flexural Strength at 60°C.

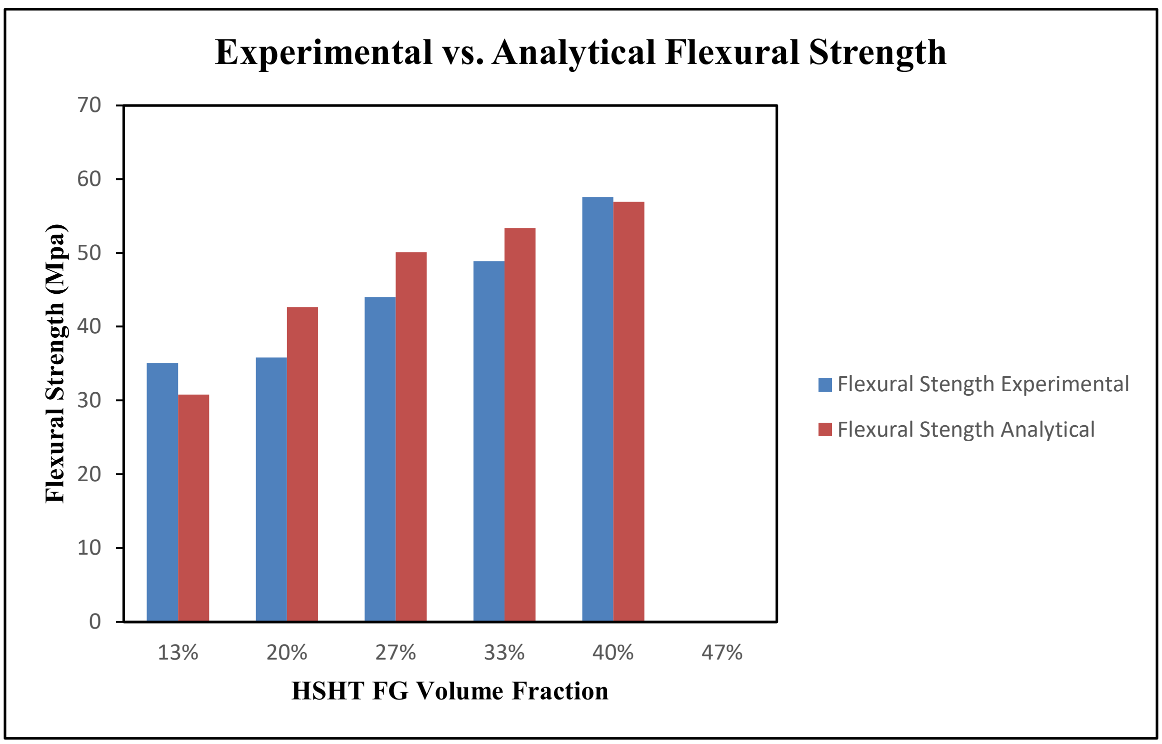

Figure 4.10: Experimental vs. Analytical Flexural Strength at 80°C.

CHAPTER 5: CONCLUSION

Thermo-mechanical analysis of High-Strength High-Temperature Fiberglass reinforced 3D-printed composites test specimens has been carried out in this research. Markforged Onyx served as the polymer matrix base and High-Strength High-Temperature Fiberglass was used as the fiber reinforcement for our composite design. High-strength High-Temperature Fiberglass (HSHT FG) volume fraction (Vf) and temperature were the two ruling parameters of our research and their impact on the performance and design of our composite test specimens was investigated. Both the experimental and simulation results of the 3-point bending test at three different testing temperatures indicate that the composite samples printed with higher volume fractions of High-strength High-Temperature Fiberglass exhibit superior Mechanical and Material properties at higher temperatures. The composite test samples with higher volume fractions of HSHT FG indicate higher flexural strength and stiffness at high testing temperatures. On the contrary, the composite test samples with higher volume fractions of High-strength High-Temperature Fiberglass showed more permanent deformation upon the removal of Mechanical and Thermal Loads. Although higher volume fractions of HSHT fiberglass promote higher stiffness and flexural strength, at the same time it induces plastic behavior in the composite test samples. The composite test samples with lower volume fractions of HSHT fiberglass showed an elastic behavior to some extent, upon the removal of Thermal and Mechanical loads. Orientation of the fiber reinforcement layers is also paramount to the mechanical and material properties of composite test specimens. The composite test sample with fiber layers equally distributed throughout the sample construction showed a lot better results as compared to the composite test sample with fiber layers concentrated in the center around the neutral axis. It can be concluded that composite part strength, stiffness, deformation, fiber reinforcement volume fraction, and the part operating temperatures all are interrelated, and all of these factors should be considered preliminary to composite part design.

5.1 Future Recommendations

In our current study composite test specimens were printed on 0º Raster angle and fiber orientation was either equally distributed or center concentrated around the neutral axis, for future it is recommended to print composite parts with different fiber orientations and raster angles, to find out the impact of these factors on the performance of composite test parts. In our research composite test specimen were tested on a maximum of 80℃ temperature, and only flexural tests were performed to analyze flexural strength and stiffness at elevated temperatures. Tensile tests and heat deflection tests at higher temperatures should also be performed to analyze composite test specimen performance. Flexural tests at temperatures higher than 80℃ should be performed to analyze composite test specimen mechanical and material properties at higher temperatures. Furthermore, X-ray imaging or radio imaging of deformed composite test specimens should also be performed to analyze internal fracture mechanics.

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