Performance Evaluation and Optimization of Onyx Structures Fabricated via FDM for Drone Applications Using Statistical and Machine Learning Methods

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***Abstract*—Drones require lightweight yet structurally robust components to maximize flight efficiency and payload capacity. This study presents the design, additive manufacturing, and mechanical testing of a drone components fabricated using continuous fiber-reinforced composites. Using nylon-based Onyx reinforced with carbon fiber (CFRP) and glass fiber (GFRP), specimens were 3D printed with a constant 40% infill ratio and tested for tensile and flexural properties under ASTM D638 and D790 standards. The bracket, designed via CATIA and optimized using topology analysis, demonstrated that CFRP/Onyx with rectangular infill offers superior strength-to-weight performance suitable for drone frame and payload support systems. These findings indicate the potential for replacing conventional metallic brackets in drones with additively manufactured composites.**

***Index Terms*—Drone, 3D Printing, CFRP, GFRP, Onyx, Additive Manufacturing, Bracket, Lightweight Structures**

1. INTRODUCTION

Drones, or Unmanned Aerial Vehicles (UAVs), have experienced a transformative evolution across both civilian and defense sectors over the last decade. These flying platforms, ranging from small quadcopters to large-scale autonomous aircraft, are widely used for tasks such as aerial surveillance, package delivery, agricultural monitoring, mapping, and search and rescue missions. As drone applications diversify, there is a growing need for structural components that meet stringent demands of low weight, high strength, and reliability.

A crucial factor that determines drone performance is its payload-to-weight ratio. Reducing the structural mass of drone components while maintaining or enhancing their mechanical integrity allows for increased flight time, better maneuverability, and improved energy efficiency. Traditionally, drone brackets and support structures have been manufactured from metals such as aluminum due to their availability and favorable strength-to-weight ratio. However, metals are susceptible to corrosion, are relatively heavy, and have limited design flexibility for complex geometries. These constraints have led to the exploration of high-performance polymer composites as substitutes for metallic drone parts.

In particular, additive manufacturing (AM) has revolutionized the way drone components are designed and fabricated. Unlike subtractive manufacturing techniques, AM enables the creation of intricate and optimized designs with minimal material wastage. Among various AM methods, Fused Filament Fabrication (FFF) has emerged as one of the most accessible and versatile techniques for fabricating thermoplastic parts. FFF involves the layer-by-layer deposition of melted thermoplastic filaments according to a computer-generated toolpath. The adaptability of FFF has made it an ideal choice for prototyping and producing custom components for UAV applications.

Further, the integration of continuous fiber-reinforced thermoplastic composites into the FFF process has significantly expanded the functional capabilities of printed parts. Materials such as Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber

Reinforced Polymer (GFRP) are especially attractive for aerospace and UAV applications due to their high specific strength, stiffness, fatigue resistance, and thermal stability. When these fibers are embedded within a matrix such as Onyx—a nylon-based thermoplastic filled with chopped carbon fibers—they form a robust composite capable of withstanding demanding mechanical loads while retaining the lightweight advantage.

In the context of drone bracket design, these composite materials provide several key benefits. First, they enable the creation of parts that are not only lighter but also stronger than their metallic counterparts. Second, the use of AM allows for rapid iteration and customization of bracket geometry to meet specific performance requirements. Third, by incorporating topology optimization during the design phase, it is possible to minimize material usage without sacrificing strength, which further contributes to weight reduction.

The present study aims to capitalize on these benefits by designing, fabricating, and analyzing a structural bracket intended for drone applications using continuous fiber-reinforced thermoplastics. The research is structured around three primary objectives: (1) to explore the influence of different infill patterns on the mechanical behavior of CFRP- and GFRP-reinforced Onyx specimens; (2) to design a drone-specific bracket using CATIA V5 and optimize it through topology analysis; and (3) to validate the mechanical performance of the printed bracket using standard tensile and flexural tests.

To achieve these objectives, a Markforged Mark Two industrial-grade FFF printer was employed to fabricate the test specimens and bracket components. The printer's dual-extrusion capability allows for precise deposition of both Onyx base material and continuous fiber reinforcement. The mechanical testing followed ASTM D638 and D790 protocols to ensure the comparability and reliability of the experimental data. By bridging design innovation, advanced materials, and additive manufacturing, this study seeks to establish a viable alternative to traditional metal brackets in drone platforms. The results are expected to offer valuable insights into the optimal design configurations and material combinations that can significantly enhance the performance, efficiency, and longevity of UAV systems.

2. MATERIALS AND METHODS

2.1 Materials

The selection of suitable materials is critical for developing high-performance structural components in drone systems. In this study, three distinct material systems were selected and evaluated based on their compatibility with additive manufacturing, mechanical strength, thermal properties, and lightweight nature. All materials used were compatible with the Markforged Mark Two 3D printer, which supports dual-material printing including continuous fiber reinforcement.

CFRP/Onyx: This composite consists of a nylon-based thermoplastic matrix (Onyx) reinforced with continuous carbon fibers. Carbon fibers are known for their exceptionally high tensile strength, stiffness, and low density. When embedded in the Onyx matrix, they provide superior structural reinforcement, making CFRP/Onyx one of the strongest composite materials available for 3D printing. The continuous fibers are laid down strategically within the part during the FFF process to align with the principal stress directions, significantly enhancing the load-bearing capacity of the printed components. This material system is especially suitable for applications that demand high strength-to-weight ratios, such as drone arms, payload brackets, and other critical structural elements.

GFRP/Onyx: This material is a hybrid composite combining the Onyx matrix with continuous glass fiber reinforcement. Glass fibers, while less stiff and strong compared to carbon fibers, offer better flexibility and cost-effectiveness. They are also non-conductive, making them suitable for applications where electrical insulation is required. GFRP/Onyx is ideal for structural components that experience moderate loads and require impact resistance and durability. Its mechanical performance is robust enough for use in secondary drone structures, gimbal supports, or protective housings where weight reduction is still essential.

Onyx: Onyx is a proprietary nylon-based thermoplastic material developed by Markforged. It is infused with chopped carbon fibers, providing enhanced stiffness, dimensional stability, and surface finish over conventional nylon filaments. While it does not contain continuous fibers, Onyx alone exhibits superior performance compared to many other standard FFF thermoplastics like ABS or PLA.

It serves as the foundational matrix for both CFRP and GFRP composites and can be printed independently to fabricate less demanding drone components such as covers, fixtures, and mounts. Its strength, ease of printing, and professional surface quality make it a preferred material for prototyping and producing functional end-use parts.

Each of these material systems was selected to provide a comprehensive understanding of the mechanical performance benefits that continuous fiber reinforcement offers when applied to polymer matrices. Their individual and comparative performances under tensile and flexural loading form a key part of the experimental evaluation conducted in this study.

2.2 3D Printing Parameters

A Markforged Mark Two industrial-grade FFF 3D printer was utilized for all manufacturing tasks in this study. This printer features a dual-extrusion system capable of printing both Onyx (a nylon-based matrix with chopped carbon fibers) and continuous fiber reinforcements (carbon and glass fibers). The build platform has a heated bed that supports dimensional stability and layer adhesion during the printing process.

The following parameters were consistently applied throughout the fabrication of both mechanical test specimens and the drone bracket prototype:

- Infill Density**:** A constant 40% infill was selected based on preliminary studies indicating a good balance between strength and material usage. This density level also provides sufficient internal support while keeping the weight low, which is ideal for UAV components.
- Infill Patterns**:** Three infill geometries—rectangular, triangular, and hexagonal—were investigated. These patterns significantly influence mechanical behavior under stress. Rectangular infill generally promotes uniform stress distribution; triangular infill provides higher rigidity; and hexagonal infill mimics natural cellular structures with potential for improved load transfer.
- Layer Thickness: A fine resolution of 0.125 mm layer height was used to enhance surface finish, part strength, and layer-to-layer adhesion. Thinner layers contribute to better mechanical integration and reduce void formation.
- Nozzle Temperature**:** 270°C was maintained to ensure proper melting and flow of the Onyx filament, facilitating strong bonding between layers and continuous fibers.
- Bed Temperature: Set to 60°C to reduce warping and maintain part flatness during print cooling.

These controlled parameters helped ensure that all fabricated parts were dimensionally accurate, mechanically consistent, and suitable for comparative mechanical testing.

2.4 Mechanical Testing

2.4.1 Mechanical Performance Validation

Validating the mechanical performance of the proposed composite a critical phase in determining its viability as a substitute for traditional metal components. To this end, two widely accepted standardized tests—tensile and flexural testing—were performed in accordance with ASTM protocols to characterize the strength and stiffness of the fiber-reinforced composite materials under different loading conditions.

2.4.2 Tensile Testing

Tensile tests were conducted following the ASTM D638 standard, which is specifically designed for evaluating the tensile properties of plastic materials. Type I dog-bone specimens, measuring 165 mm in length, 13 mm in width, and 3 mm in thickness, were fabricated using additive manufacturing with consistent print orientation and infill parameters to ensure reproducibility. The specimens were subjected to uniaxial tensile loads until failure using a computer-controlled 30 kN Universal Testing Machine (UTM). The machine was equipped with precision-calibrated wedge grips to minimize slippage and alignment errors. Real-time stress-strain data were collected using an extensometer attached within the gauge section of the specimen. Key tensile properties obtained from the test included the Ultimate Tensile Strength (UTS), the Young's Modulus (modulus of elasticity), and the elongation at break. These metrics

provided insight into the material's load-bearing capacity and ductility under tensile forces.

Tensile Performance

Sample	Sample Type	CS Area (mm^2)	Peak Load (N)	% Elongation	UTS [N/mm^2]
1	CFRP/ONYX Hexagonal	39.000	2713.142	3.870	69.573
2	CFRP/ONYX Rectangular	39.000	2587.319	2.220	66.345
3	GFRP/ONYX Hexagonal	39.000	2717.988	6.840	69.690
4	GFRP/ONYX Rectangular	39.000	2718.861	7.650	69.710
5	CFRP/ONYX Triangle	39.000	2537.023	2.330	65.050
6	GFRP/ONYX Triangle	39.000	2714.613	10.780	69.602

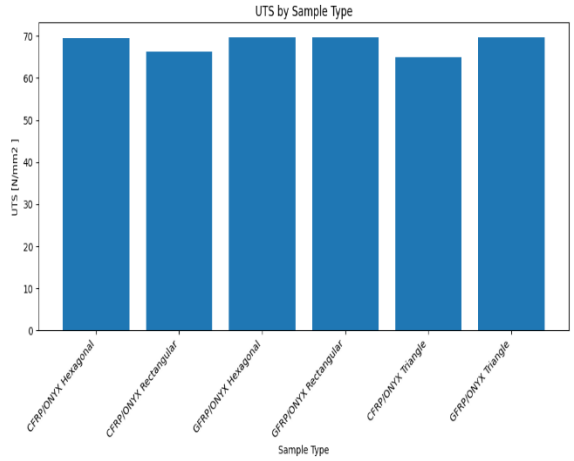

Figure 1. Ultimate Tensile Strength

2.4.3 Flexural Testing

Flexural behavior was evaluated using the ASTM D790 standard, which governs the testing of plastic materials under bending loads. Rectangular bar specimens of 125 mm × 13 mm × 3 mm were used in a three-point bending configuration. The specimens were supported at both ends with a span length set according to standard guidelines, while a centrally applied load was introduced at a constant crosshead speed of 2 mm/min until the specimen either fractured or underwent significant deformation. This test enabled the assessment of the flexural strength and flexural modulus, which are critical for understanding the material's behavior under out-of-plane loading—an important consideration for structural aerospace components subjected to complex stress distributions.

Flexural Performance

Trail	Sample Name	Cross-Section Area (mm^2)	Peak Load (N)	Flexural Strength (MPa)	Flexural Modulus (GPa)
1	CFRP/ONYX Hexagonal	39.000	191.678	122.871	3143.786
2	CFRP/ONYX Rectangle	39.000	203.479	130.435	3175.481
3	GFRP/ONYX Hexagonal	39.000	151.437	97.075	3212.251
4	GFRP/ONYX Rectangle	39.000	131.650	84.391	2907.496
5	CFRP/ONYX Triangle	39.000	117.307	75.235	1060.897
6	GFRP/ONYX Triangle	39.000	103.476	66.331	805.288

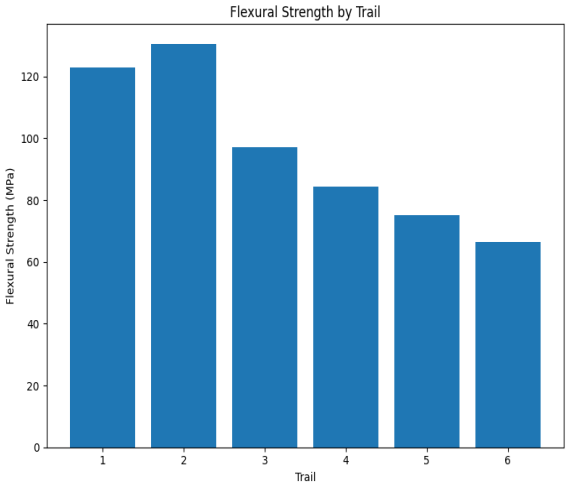

Figure 2. Flexural Strength

3. RESULTS AND DISCUSSION

This section discusses the mechanical behavior of CFRP/Onyx and GFRP/Onyx composites printed with different infill patterns—hexagonal, rectangular, and triangular—under tensile and flexural loading conditions. The data provides insights into how fiber type and infill geometry influence the structural performance of drone components fabricated via FDM.

3.1 Tensile Performance Analysis

Tensile testing revealed that all specimens reinforced with continuous fibers (CFRP or GFRP) outperformed plain Onyx (not tested here) in terms of Ultimate Tensile Strength (UTS). Among the configurations, GFRP/Onyx with rectangular infill exhibited the highest elongation at break (7.65%), suggesting superior ductility and energy absorption under tensile loads. Interestingly, CFRP/Onyx with hexagonal infill achieved the highest UTS (69.573 MPa), closely followed by all GFRP/Onyx variants, indicating that both fiber types, when properly aligned, contribute substantially to tensile strength.

The triangular infill pattern yielded the lowest UTS for both CFRP (65.050 MPa) and GFRP (69.602 MPa) samples. This is attributed to the less uniform stress distribution and possible stress concentrations induced by the sharp angular transitions in triangular structures. The hexagonal infill, known for mimicking efficient natural honeycomb structures, provided a balance between strength and elongation, making it a viable candidate for applications where tensile resilience and weight optimization are critical.

3.2 Flexural Performance Analysis

Flexural testing provided a more nuanced understanding of how infill pattern affects bending behavior—a critical factor for components like drone brackets that experience out-of-plane loads. The CFRP/Onyx rectangular infill sample outperformed all others, recording a flexural strength of 130.435 MPa and a modulus of 3175.481 MPa, thereby establishing it as the most robust configuration under bending loads.

Notably, while GFRP/Onyx hexagonal infill achieved a moderate flexural strength (97.075 MPa), it also exhibited the highest flexural modulus (3212.251 MPa) among the GFRP variants, highlighting its rigidity and stiffness. Conversely, triangular infill patterns consistently underperformed in both CFRP and GFRP composites, reflecting their inefficiency in distributing bending stresses.

The mechanical superiority of CFRP over GFRP across all tests is consistent with the intrinsic material properties—carbon fibers have higher stiffness and tensile strength compared to glass fibers. However, the relatively small performance gap, especially in tensile testing, suggests that GFRP remains a cost-effective and sufficiently strong alternative for less critical structural components.

3.3 Comparative Assessment for Drone Applications

The combination of CFRP/Onyx with rectangular infill pattern emerged as the optimal material-infill configuration, particularly suitable for drone bracket applications where both tensile and flexural strengths are paramount. GFRP/Onyx with hexagonal infill is recommended for secondary structural components that require rigidity with some cost savings.

These results validate the feasibility of replacing metal components in UAVs with continuous fiber-reinforced polymer composites. The ability to fine-tune mechanical performance via infill geometry provides designers with significant flexibility to meet specific loading requirements while minimizing weight.

4. CONCLUSION

This study presents a systematic evaluation of the mechanical behavior of 3D-printed Onyx composites reinforced with continuous carbon and glass fibers for UAV structural applications. Through tensile and flexural testing, the influence of infill pattern and fiber type on mechanical performance was quantitatively

assessed. The key conclusions drawn from the investigation are: CFRP/Onyx composites demonstrated superior mechanical strength, with the rectangular infill configuration delivering the highest flexural strength and stiffness, ideal for high-load-bearing drone structures such as brackets. GFRP/Onyx offered competitive tensile performance with greater ductility, especially in hexagonal and rectangular infill forms, making it suitable for secondary components that may require higher impact resistance and flexibility. Infill geometry significantly affects performance: Rectangular patterns promote uniform stress distribution and high mechanical integrity, while hexagonal patterns offer a good balance between strength and weight. Triangular patterns, however, underperformed and are not recommended for critical structural parts. The use of additive manufacturing with fiber reinforcement provides a lightweight, customizable alternative to traditional metal parts, aligning well with the demands of drone applications.

The integration of fiber-reinforced composites and design optimization in AM can revolutionize the fabrication of UAV components, enabling enhanced flight performance, extended mission range, and reduced energy consumption. Future research may focus on fatigue testing, environmental degradation studies, and dynamic loading analysis to further establish the operational reliability of these composite structures in real-world drone applications.

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