

The Fabrication and Testing of Unmanned Aerial Vehicle (UAV) Wing Structure Using 3D Printing and Carbon Fibre Skinning Method

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Abstract

This study examines the efficacy of integrating 3D printing with carbon fibre skinning to construct wing structures for Unmanned Aerial Vehicles (UAVs). The primary objective is to enhance the structural integrity and material characteristics. The study performs static load tests, which demonstrate that wings reinforced with carbon fibre lamination can endure a substantially greater maximum stress of 29.43 N, in contrast to 14.391 N for wings produced only by 3D printing. The carbon fibre laminated wings have a greater load-bearing capability, as evidenced by the safety factor study. This analysis reveals that the permitted loads for carbon fibre laminated wings (19.61 N) are higher compared to 3D printed wings (9.594 N). The tensile testing of the specimens reveals that carbon fibre laminated wings demonstrate enhanced ductility, stiffness, and yield strength. Additionally, they withstand greater levels of maximum stress and strain, except for a slightly higher stiffness seen in 3D printed wings. This research highlights that carbon fibre laminated wings are typically more durable and versatile for many uses, although 3D printed wings may be favoured in situations when greater rigidity is necessary. In conclusion, the study effectively showcases the advantages of combining 3D printing with carbon fibre skinning in the construction of UAV wings. This research significantly contributes to the progress of UAV design and provides fresh insights in the fields of aeronautical engineering and materials science. It is particularly valuable for applications that require UAVs with exceptional performance, durability, and reliability.

1. Introduction

UAV, or Unmanned Aerial Vehicle, is an aircraft that can fly and remain in the air without the need for a human operator on board. Unmanned Aerial Vehicles (UAVs) can be operated from a distance by receiving control orders from a terrestrial base station (BS) via a remote control. The UAVs can execute control operations autonomously using autopilot and various sensors, such as the global positioning system (GPS) and inertial measurement units (IMU) [1]. These unmanned aircraft have acquired a great deal of popularity in recent years due to their adaptability, efficiency, and ability to access potentially inaccessible areas. UAVs are available in a range of sizes and configurations, from small consumer models to large, complex military-grade systems.

UAVs are becoming more common in a wide variety of industries and applications. One of the primary applications of UAVs is aerial photography and videography. Drones are now commonly used for obtaining video that was previously accomplished by costly helicopters and cranes [2]. The integration of UAVs has generated significant interest in the field of road traffic monitoring (RTM) systems. Unmanned Aerial Vehicles (UAVs) have the potential to fully automate the transportation industry in the Real-Time Monitoring (RTM) system [3].

A UAV wing serves multiple crucial functions. Its primary function is to generate lift, allowing the UAV to attain and sustain flight. As air flows over and under the wing, its air foil shape generates the necessary aerodynamic forces. This lift force counteracts the aircraft's weight and maintains flight. The surface area and the lift generated by the wing have a direct proportional relationship. The utilization of a long span wing results in an increased overall weight of the unmanned aerial vehicle (UAV) [4].

The wing is vital to the aircraft's stability, control, and maneuverability. Through wing-integrated control surfaces such as ailerons, flaps, and elevators, the pilot or autonomous system can regulate the UAV's movement. The roll is controlled by ailerons, the lift and drag by flaps, and the pitch by elevators.

2. Methodology

In this study, the UAV wing structure will be fabricated by using 3D print technology and carbon fibre skinned. Upon completing the wing structure printing, a comprehensive wing loading test will be conducted to determine the structural strength derived exclusively from the 3D printing process. The wing structure will be 3D printed again for the second phase of the project. In this phase, the wing structure will be laminated with carbon fibre. Following the laminating process, the structure's strength will be verified.

2.1 Development Tool

2.1.1 Fused Deposition Modelling Method (FDM)

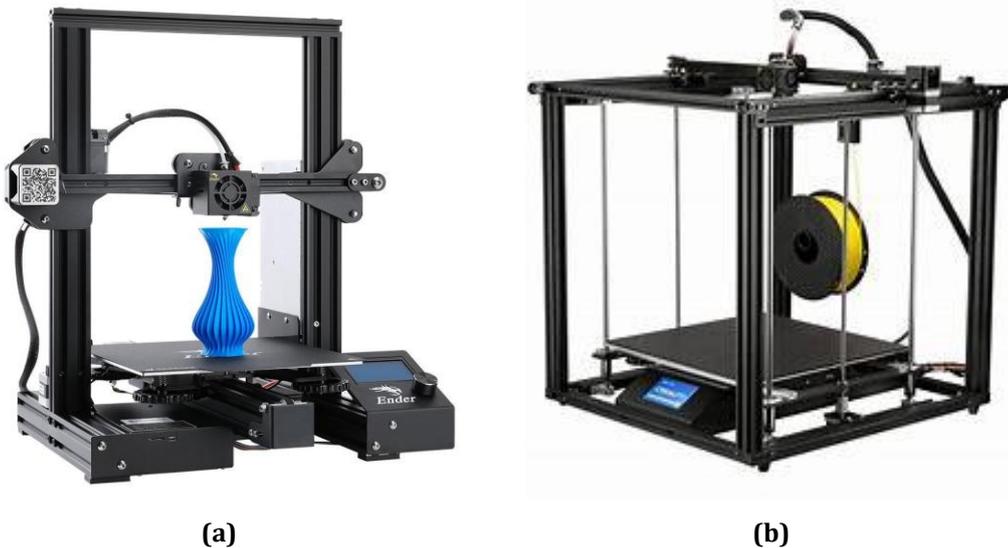


Fig. 1 Fused deposition modelling method (FDM) (a) Ender 3; (b) Ender 5 plus

2.1.2 Parameters

Before starting to print the wing structure, the parameters of the 3D printing needed to be decided to achieve good printing results. Configuration summary of the 3D printer is shown in Table 1.

Table 1 Configuration of the 3D printer

Parameter	Value
Filament material	PLA+
Am Process	Fused Deposition Modelling (FDM)
Infill Density (%)	5

Infill Pattern	Cubic subdivision
Speed (mm/s)	70 (Ender 3), 100 (Ender 5 Plus)
Nozzle temperature	215° C
Bed temperature	60° C

2.2 Static Load Test

There will be seven steps to conduct the static load test for the 3D printed UAV wing structure. The steps are:

1. 0.1kg of sand was inserted into the zip lock bag. Each bag will be taped with double sided tape to prevent the bag from sliding while doing the testing.
2. The wing structure was fabricated by using 3D printing technology. A total of six parts of wing structure was printed separately. After that, each part was glued together.
3. The glued wing structure was attached to the fuselage. The fuselage will act as the base to hold the wing while doing the testing.
4. The wing was divided into equal sections. The distance between the sections will be 0.1m.
5. One person will hold the fuselage to avoid the fuselage moving while putting the load on the wing structure.
6. The sandbags will be individually placed onto the wing structure. The time gap between each sandbag was three minutes. The purpose was to prevent errors throughout the testing process. The sandbags will be gradually added until the wing structure reaches its breaking point.
7. Record the result of the test.

The carbon fibre skinned wing structure will also go through the same process as the 3D printed only wing structure but only with one difference which is the wing going to be laminate with carbon fibre before it was attach to the fuselage.



Fig. 2 Preparation for static wing loading testing



Fig. 3 Static wing loading testing

2.3 Tensile Test

2.3.1 Specimen Preparation

The specimen is fabricated according to the ASTM D638 standard methodology [5], which outlines the specific geometry and dimensions required for conducting tensile and compression testing. As an example, Figure 9 displays the schematic diagram of the intended tensile and compression specimens while Figure 10 shows the Solidworks drawing of the specimen. These specimens will be constructed with varied parameters and will adhere to the specifications specified for the dog bone specimen ASTM D638.

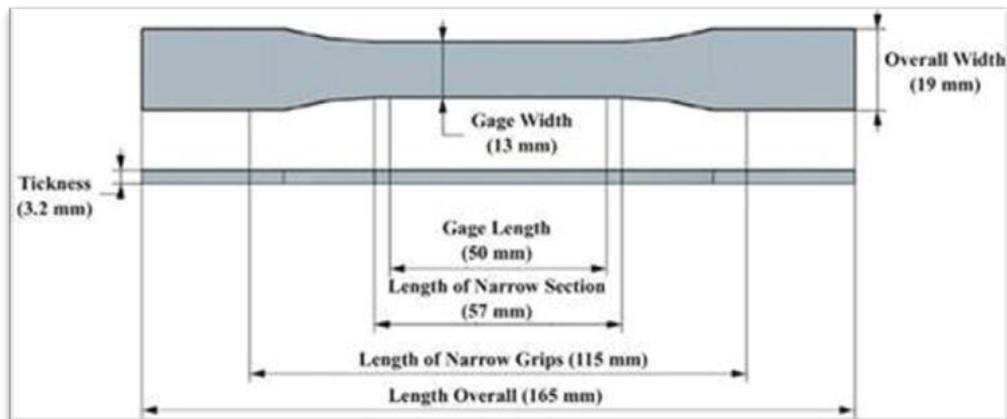


Fig.4 Schematic diagram D638 specimen

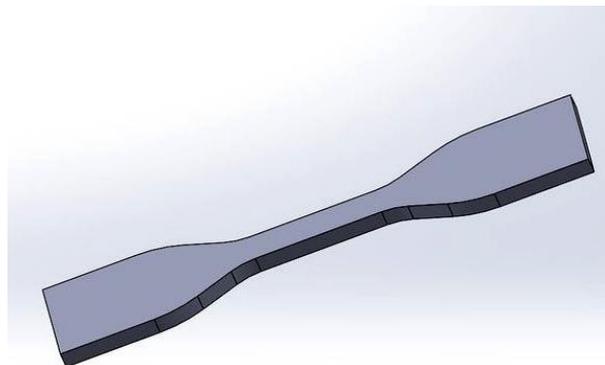


Fig.5 SolidWorks drawing of D638 specimen

The specimen was drawn by using Solidworks which follows the standard dimensions of ASTM D638. Then, the drawing will be exported into Standard Tessellation Language (STL) file which then later will be configured in UltiMaker Cura for slicing.

There will be two different thickness of specimens that will be fabricated which are 1 mm and 8 mm. The thickness for 1 mm and 8mm were chosen because the minimum thickness of a specimen for the UTM was 1 mm while the maximum thickness of a specimen was 8 mm. For specimens with 1 mm of thickness, there will be five for each 3D printed only and carbon fibre laminated type of dog bone, Meanwhile, the specimens with 8 mm of thickness, there will only be three specimens for each 3D printed and also carbon fibre laminated dog bones.

2.3.2 Universal Testing Machine

The procedure for conducting the tensile test using the Universal Testing Machine are as below:

1. Mark on the end of the specimen to indicate where the gripper should grip.
2. Turn on the computer of the machine.
3. The readings of the data need to be reset. Insert the new data of the specimen that is going to be tested.
4. The specimen will be placed between the two grippers.

5. Lower the upper gripper until it reaches the mark on the specimen.
6. Tighten the upper and lower gripper.
7. 'Zero' the machine by pressing the button zero on the machine.
8. When the machine is 'Zero', start the test.
9. After the test is completed, record the data from the computer.

3. Discussion

3.1 Comparison of Fabricated Wing Structures

Table 2 shows mass of both 3D printed, and carbon fibre laminated wing structure. The difference between the masses is 0.234 g which is equivalent to 26.90%.

Table 2 Mass of 3D printed, and carbon fibre laminated wing

Type of wing	Mass
3D printed only	0.318 g
Carbon fibre laminated	0.552 g

3.2 Static Wing Loading Testing

3.2.1 3D Printed Static Wing Loading Testing

Table 3 shows the number of tests that had been done and the loadings for each test. Test 1 and Test 3 had the highest loadings which were 1500 g while Test 2 had the lowest loadings which was 1400 g. The average loading was 1467 g. Therefore, the average loading that the wing structure can hold was 1467 g which is also equivalent to 14.391 N.

Table 3 Static wing loading test result for 3D printed wing structure

Test	Loading
Test 1	1500 g
Test 2	1400 g
Test 3	1500 g
Average	1467 g

3.2.2 Carbon Fibre Skinned Wing Loading Testing

Table 4 shows the result of static wing loading testing carbon fibre laminated wing structure. The maximum loading that it can withstand was 3000 g which also equivalent to 29.43 N. Thus, the carbon fibre laminated wing structure can withstand 29.43 N of force.

Table 4 Static wing loading result carbon fibre skinned wing structure

Test	Loading
Test 1	3000 g
Test 2	3000 g
Average	3000 g

3.3 Factor of Safety

$$FOS = \frac{F_{fail}}{F_{allow}} \quad (1)$$

F_{allow} : Allowable load
 F_{fail} : Failure load

By choosing the factor of safety 1.5 as suggested by the Federal Aviation Administration (FAA) regulations that require a safety factor of 1.5 to be employed in the structural design of passenger aircraft [6], the allowable load can be determined as below:

$$\begin{aligned}
 F &= mg \\
 F_{fail} &= 1.467(9.81) \\
 F_{fail} &= 14.391 \text{ N} \\
 F_{allow} &= \frac{14.391}{1.5} \\
 F_{allow} &= 9.594 \text{ N}
 \end{aligned} \tag{2}$$

Therefore, by having the factor of safety, 1.5, the allowable load for the wing structure without the lamination of carbon fibre is 9.594 N.

$$\begin{aligned}
 F &= mg \\
 F_{fail} &= 3(9.81) \\
 F_{fail} &= 29.43 \text{ N} \\
 F_{allow} &= \frac{29.43}{1.5} \\
 F_{allow} &= 19.61 \text{ N}
 \end{aligned} \tag{3}$$

Therefore, by having the factor of safety 1.5, the allowable load for the wing structure laminated with carbon fibre is 19.61 N.

Table 5 Result of the allowable load

Material	Allowable Load (N)
Without carbon fibre lamination	9.54
With carbon fibre lamination	19.61

3.4 Tensile Test

3.4.1 3D Printed (1mm)

Based on the average values from Table 6, the material would possess moderate durability and strength. The 3D printed wing structure will be suitable for use in applications that involve moderate loads and require a certain level of flexibility. The average yield strength shows that the material possesses an average ability to withstand persistent deformation. The material's strength, as determined by its maximum stress, indicates that it may not be able to withstand high loading.

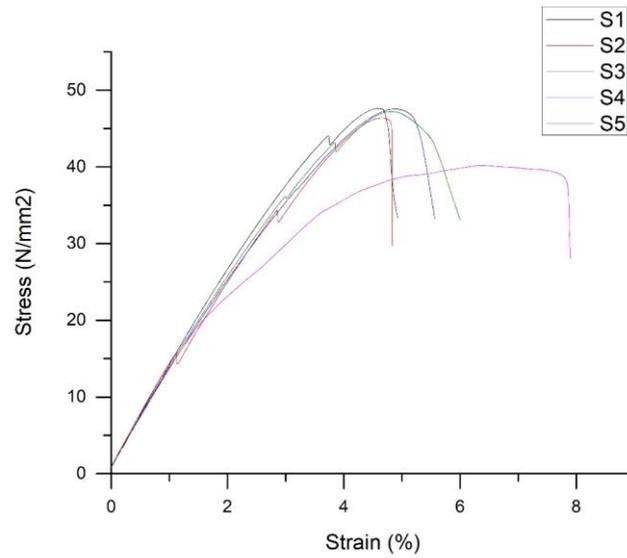


Fig. 6 Stress strain diagram for S1 to S5

Table 6 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
1	0.60	2.29	1258.62	39880.212	47.61	4587
2	0.58	2.32	1040.35	43031.196	46.36	4.650
3	0.59	2.44	1161.51	37207.142	47.51	4.877
4	0.50	3.19	1084.64	24388.223	40.17	6.372
5	0.59	2.40	1180.95	37921.526	47.20	4.806
Average	0.572	2.528	1145.214	31608.015	45.77	5.058

3.4.2 Carbon Fibre Laminated (1mm)

From Table 7, the carbon fibre laminated dog bone result shows strong, stiff, and durable qualities with a moderate to high ductility, making it well-suited for high strength, high stiffness, and the capacity to sustain large loads without permanent deformation or imminent failure are required.

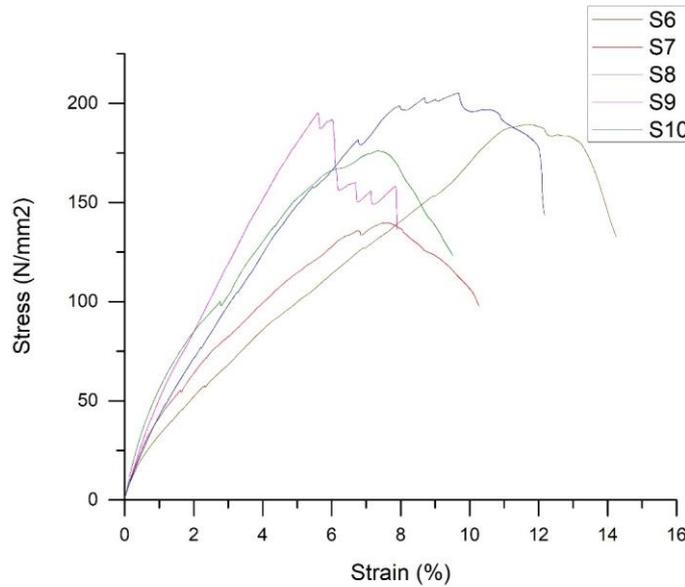


Fig. 7 Stress strain diagram for S6 to S10

Table 7 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
1	2.56	6.65	1593.17	119.798.482	189.33	11.666
2	1.88	4.28	2225.95	83700.056	139.58	7.501
3	2.77	5.51	2679.80	156382.574	205.20	9.662
4	2.64	3.19	3322.21	186514.502	195.27	5.604
5	2.37	4.19	2870.06	100250.767	175.89	7.345
Average	2.444	4.764	2538.238	129329.276	181.054	8.356

3.4.3 Comparison for 1mm specimens

Table 8 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
3D Print	0.572	2.528	1145.214	31608.015	45.77	5.058
Carbon Fibre Laminated	2.444	4.764	2538.238	129329.276	181054	8.356

The carbon fibre laminated specimen exceeds those in the 3D printed specimen in the following aspects which are greater load-bearing capacity, greater ductility, increased stiffness, higher yield strength, and enhanced ability to tolerate stress and strain. These indicate that carbon fibre laminated specimens are better suited for applications that need high strength, adaptability, and durability.

3.4.4 3D Printed (8mm)

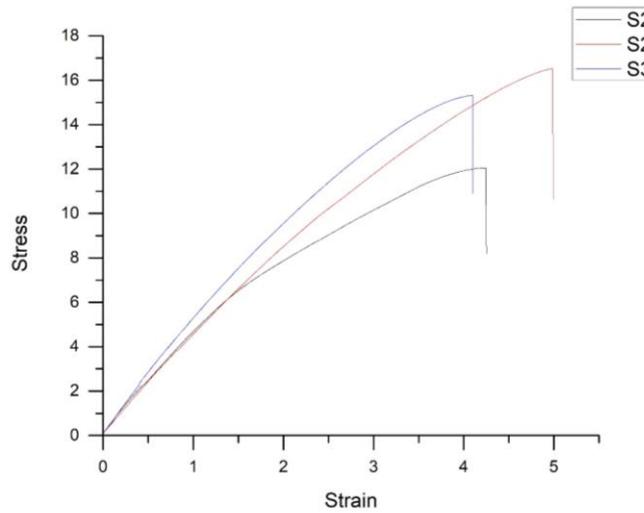


Fig. 8 Stress Strain diagram for S1 to S3

Table 9 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
1	1.20	2.11	402.59	7877.762	12.04	4.217
2	1.65	2.49	393.94	12100.010	16.51	4.976
3	1.65	2.31	452.75	12186.904	15.31	4.087
Average	1.50	2.31	416.427	10721.559	14.62	4.427

The average yield strength shows that the material can endure substantial loads without experiencing permanent deformation, while the average maximum stress reveals its average resistance to tension-induced fracture. The material's moderate Young's modulus and strain values indicate a balanced rigidity and malleability.

3.4.5 Carbon Fibre Laminated (8mm)

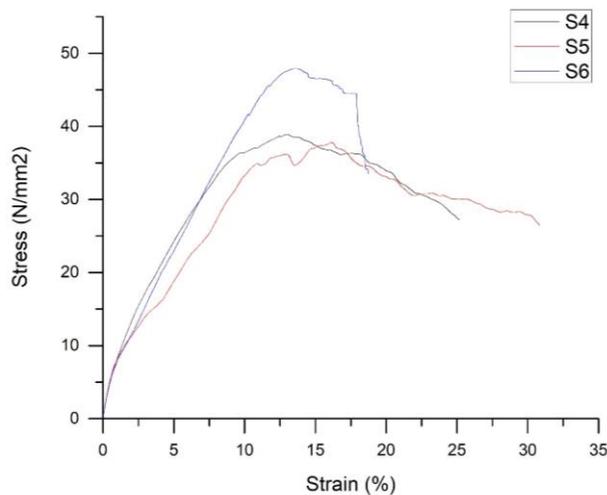


Fig.9 Stress Strain diagram for S4 to S6

Table 10 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
1	4.20	7.40	396.68	25158.127	38.85	12.976
2	4.08	9.18	251.36	35681.122	37.78	16.109
3	5.17	7.79	378.69	30555.422	47.86	13.673
Average	4.483	8.123	342.243	30464.89	41.497	14.253

The results show good resistance to stretching, a moderate to significant ability to be stretched without breaking, and a reduced rigidity, resulting in a harmonious equilibrium between power and adaptability. These materials are ideal for applications that demand resistance to both static and dynamic stresses, together with the capacity to endure significant deformation before breaking.

3.4.6 Comparison for 8mm specimens

Table 11 Result of tensile test for 1mm 3D printed dog bone

Name	Max Load (kN)	Max Elongation (mm)	Young Modulus (MPa)	Yield Strength (kN/m ²)	Max Stress (MPa)	Max Strain (%)
3D Print	1.5	2.31	416.427	10721.559	14.62	4.427
Carbon Fibre Laminated	4.483	8.123	342.243	30464.89	41.497	14.253

The carbon fibre laminated specimen is typically better in several aspects which are stronger load-bearing capacity, more flexibility, increased yield strength, and enhanced ability to tolerate stress and strain. The 3D printed specimen only has better stiffness, proven by a small gap of better Young's Modulus.

3.4.7 Summary

From the results that were gained from the tests, wing structure that was laminated with carbon will have higher durability and therefore can withstand higher loading compared to the non-laminated 3D printed wing structure. From the result of tensile test for both 1 mm and 8 mm thickness specimen, it was proven that when the 3D printed structure laminated with carbon fibre, it will have better ductility and strength. The result shows that the carbon fibre laminated specimen can withstand higher load compared to the 3D printed specimen.

Bakhtawar Sehar et al. [7], discussed the impact of laminations on the mechanical strength of carbon fibre composites for prosthetic foot fabrication. From the research, the result showed that the linear segments of these graphs demonstrate that as the load on the laminates grows, the strain rate also increases, causing deformation of the fibres in the sample and ultimately leading to the failure of the carbon-fibre laminates being tested.

4. Conclusion

In summary, the project has not only accomplished its original aims but also proven the effectiveness of the techniques used for the fabrication and strengthening of UAV wings. The first objective of creating a UAV wing structure using a combination of 3D printing and carbon fibre skinning was successfully achieved.

The second objective is to determine the most effective approach to apply carbon fibre skinning onto the 3D printed wing. An ideal application technique was determined after thorough trial and improvement. This procedure ensured that the carbon fibre skin was applied in a way that optimized the structural advantages of both materials. The practicality of this method was not just theoretical but shown in the wing's durability and reliability.

Importantly, the third and fourth objectives, which included static load and tensile testing, provided actual findings confirming the accuracy of the applied procedures. The loading which was the sandbags were put on the top side of the wing structure. The total load that the wing structure can handle was recorded. The static load test model provided statistical proof on the wing's ability to endure different stress levels, confirming its

practicality. Moreover, the tensile tests conducted on the wing structure, which was fabricated using 3D printing and reinforced with carbon fibre layer, showed its significant strength and structural integrity.

These tests were crucial, not only to evaluating the wing's performance, but also for validating the accuracy and effectiveness of what was done throughout the 3D printing and carbon fibre skinning procedures. The results showed a clear correlation between the applied fabrication techniques and the wing's enhanced performance characteristics. This validation provides evidence of the careful and precise setup and execution of the project.

The project validates the practicality and efficiency of combining 3D printing with carbon fibre skinning in the manufacturing of UAV wings and also the steps taken to laminate the wing structure with carbon fibre. This achievement sets an example for future progress in UAV technology, offering wings that are not only more durable and dependable but also creatively engineered to satisfy the changing requirements of UAV applications.

5. Recommendations

Based on the results of the study on 3D printed UAV wing structures strengthened using carbon fibre lamination, multiple ideas may be proposed to enhance future developments. Optimizing the lay-up process of the carbon fibre material has the potential to greatly improve the strength-to-weight ratio.

To enhance structural integrity in certain areas, it is recommended to investigate various weave patterns or utilize unidirectional carbon fibres that are aligned with the principal stress methods. In addition, including finite element analysis (FEA) into the design process can provide a more precise prediction of stress distribution and allow for customized reinforcing.

Furthermore, exploring other composite materials like Kevlar or fiberglass for lamination might provide advantages in terms of impact resistance or cost-effectiveness. These materials can be evaluated against carbon fibre to determine whether they are suitable for different UAV applications.

Furthermore, it is essential to enhance the interaction between the 3D printed PLA material and the carbon fibre skin. Applying adhesion boosters or surface treatments can enhance the bond strength, hence minimizing the possibility of delamination occurring under applied stress. Investigations on nanomaterials or hybrid composites that improve interfacial bonding have the potential to result in notable progress in this field.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Muhammad Ariff Nazrin Mohd Kamarulnizam, Mohd Fauzi Yaakub; **data collection:** Muhammad Ariff Nazrin Mohd Kamarulnizam, Mohd Fauzi Yaakub; **analysis and interpretation of results:** Muhammad Ariff Nazrin Mohd Kamarulnizam, Mohd Fauzi Yaakub; **draft manuscript preparation:** Muhammad Ariff Nazrin Mohd Kamarulnizam, Mohd Fauzi Yaakub. All authors reviewed the results and approved the final version of the manuscript.*

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