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Fabrication and Characterization of Carbon-Glass Fiber Hybrid Composite for Lightweight UAV Frame Application

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ABSTRACT—

A UAV frame should be light, stiff and able to take impact loads. In this work we made and tested a hybrid composite of carbon fiber and glass fiber in an epoxy matrix for UAV frames. We selected a four-layer [C/G/G/C] laminate with [0°/45°/−45°/90°] fiber orientations, having 25% carbon fiber, 25% glass fiber and 50% epoxy. The properties were first calculated using micromechanics formulas and the rule of mixtures (ROM). A tensile specimen of 250 × 25 × 3 mm was then analysed in ANSYS Workbench 2026 R1. The laminate was made by hand lay-up (roll-on method) with epoxy and hardener mixed in a 3:1 ratio, and specimens were tested for tensile (ASTM D3039), flexural (ASTM D790) and drop-weight impact (ASTM D7136) properties. ANSYS gave a maximum stress of 234.152 MPa, a maximum strain of 0.0032462, a deformation of 0.23165 mm and a Young's modulus of 72.44 GPa, while the ROM gave 77 GPa (5.92% difference). The average tensile strength of five specimens was 225.20 ± 17.3 MPa, which is 3.98% lower than the ANSYS value and 4.74% higher than the design value. The flexural strength was 24.3 ± 1.5 MPa, the flexural modulus was 1.55 ± 0.11 GPa and the plates absorbed 16.28 ± 1.02 J of impact energy from a drop height of 0.4 m. The laminate has a density of about 1.82 g/cm³ and a specific strength of about 124 MPa·cm³/g, which is close to aluminium 6061-T6. So this hybrid composite can be used for light UAV frame parts.

Keywords*— hybrid composite, carbon fiber, glass fiber, epoxy resin, UAV frame, hand lay-up, ANSYS, tensile test, flexural test, impact test*

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are used today for surveillance, agriculture, defence, environmental monitoring and aerial photography. The flight time and payload of a UAV depend a lot on the weight of its frame. Frames made of aluminium or steel are strong, but they are heavy, and this reduces flight time and payload [8]–[10]. For this reason, fiber reinforced polymer (FRP) composites are used more and more in UAVs, because they are light, strong for their weight and do not corrode [8], [15].

Carbon fiber composites are very stiff and strong, but they are costly and can break suddenly under impact. Glass fiber composites are cheaper and tougher, but not as stiff. When both fibers are used in the same laminate, we can get a good balance of stiffness, strength, toughness and cost [14]. Singh et al. [3] found that adding 6.56%, 13.79% and 21.07% carbon fiber to a glass/epoxy laminate increased its tensile strength by 34.18%, 55.44% and 85.40%, and their ABAQUS results were within 10% of the tests. Ra'eis et al. [2] showed that the stacking sequence changes the strength, stiffness and energy absorption of glass fiber laminates, and that balanced 0° and ±45° layers work best. Sabry et al. [4] found that carbon/epoxy is harder and wears less than glass/epoxy, and suggested carbon-glass hybrids for UAV and aircraft parts. Garre and Rohan [1] analysed a glass fiber sandwich panel in ANSYS and got results close to their experiments.

Based on these papers, we designed, analysed, fabricated and tested a simple carbon-glass/epoxy laminate that can be made by hand lay-up in a college lab. Our aims were: (i) to calculate the laminate properties using micromechanics and the ROM, (ii) to find its tensile behaviour in ANSYS Workbench, (iii) to make the laminate and test it in tension, bending and impact, and (iv) to compare the theory, simulation and test results and check if the material is suitable for UAV frames.

II. MATERIALS AND METHODS

A. Materials

We used woven carbon fiber fabric and woven glass fiber fabric as the reinforcements, and clear casting epoxy resin with its hardener as the matrix. The properties used in our calculations and in ANSYS are given in Table I. Carbon fiber has very different stiffness in different directions (230 GPa along the fiber and 23 GPa across it), while glass fiber and epoxy were taken as isotropic.

TABLE I

Properties of the Materials Used

Property	**Carbon fiber**	**Glass fiber**	**Epoxy**
Density (kg/m³)	1800	2550	1150
E_x (GPa)	230	72	3
$E_y = E_z$ (GPa)	23.0	72	3
G_{xy} (GPa)	9.0	29.91	1.1
G_{yz} (GPa)	8.2143	29.91	1.1
ν_{xy}	0.20	0.22	0.35
ν_{yz}	0.40	0.22	0.35

B. Laminate Design

We chose a four-layer laminate with the stacking sequence [C/G/G/C] and fiber angles [0°/45°/−45°/90°]. The two carbon layers are on the outside because the outer layers take the highest stress in bending, and the two glass layers are in the middle to make the laminate tougher and cheaper. Each layer is 0.75 mm thick, so the laminate is 3 mm thick. The volume fractions are $V_c = 0.25$, $V_g = 0.25$ and $V_m = 0.50$. For a 200 × 400 × 3 mm plate (volume 0.00024 m³), which is similar to a small UAV panel, the average density of 1816.67 kg/m³ gives a mass of only about 0.436 kg.

C. Theoretical Calculation

We used the following micromechanics formulas [15], [16] to find the fiber volume fraction and the moduli along and across the fibers:

$$V_f = \rho_m W_f / (\rho_m W_f + \rho_f W_m) \quad (1)$$

$$E_1 = E_f V_f + E_m V_m \quad (2)$$

$$E_2 = E_f E_m / (E_f V_m + E_m V_f) \quad (3)$$

To check these formulas, we first used the E-glass/polyester data of Ra'eis et al. [2]. From their fiber and matrix weights, Eq. (1) gave $V_f = 0.6257$ (the paper reports 0.6562), and Eq. (2) gave E_1 between 45.8 and 51.1 GPa for E_f = 72 to 76 GPa. This is close to the 49.4 GPa measured for their best (S9) laminate. We then found the modulus of our laminate using the ROM for three materials [3]:

$$E = V_c E_c + V_g E_g + V_m E_m \quad (4)$$

With E_c = 230 GPa, E_g = 72 GPa and E_m = 3 GPa, Eq. (4) gives E = 0.25(230) + 0.25(72) + 0.50(3) = 77 GPa. We also calculated the load at which the tensile specimen should break using F = σA. Taking an expected tensile strength of 215 MPa and a cross-section of 25 × 3 = 75 mm², the expected failure load is 16.125 kN.

D. ANSYS Analysis

We did a static structural analysis of the 250 × 25 × 3 mm tensile specimen in ANSYS Workbench 2026 R1. The properties from Table I were entered in Engineering Data, the four layers were defined in the [C/G/G/C] order, and the model was meshed along its length. One end of the specimen was fixed, like the bottom grip of the UTM, and the tensile load was applied at the other end. We then found the equivalent (von Mises) stress, the equivalent elastic strain and the total deformation.

E. Fabrication

The laminate was made by hand lay-up using the roll-on method (Fig. 1). The epoxy resin and hardener were mixed in a 3:1 ratio. We placed the first carbon layer on a plastic sheet coated with resin, spread resin over it and used a roller to soak the fabric. The glass, glass and carbon layers were then placed one by one, with resin and rolling after each layer. Rolling pressed the layers together and pushed out trapped air and extra resin. The laminate was left to cure at room temperature as per the resin manufacturer's instructions (Fig. 2), and the uneven edges were trimmed off.



Fig. 1. Placing the carbon and glass fiber layers during hand lay-up.



Fig. 2. Carbon-glass fiber/epoxy laminate after curing.

F. Specimen Preparation and Testing

The specimens cut from the laminate are listed in Table II. The tensile test was done as per ASTM D3039 [18] on a Universal Testing Machine (UTM) using straight 250 × 25 × 3 mm strips (Fig. 3). The flexural test was a three-point bending test as per ASTM D790 [19] with a 100 mm span. The impact test was a drop-weight test as per ASTM D7136 [20] on 150 × 100 × 3 mm plates in a vertical drop tower, with a drop height of 0.4 m. The machine recorded the energy absorbed and the peak load.

TABLE II

Tests Conducted

Test	**Standard**	**Specimen (mm)**	**No.**
Tensile	ASTM D3039	250 × 25 × 3	5
Flexural (3-point)	ASTM D790	100 × 25 × 3	4
Drop-weight impact	ASTM D7136	150 × 100 × 3	4



Fig. 3. Tensile test specimens.

III. RESULTS AND DISCUSSION

A. ANSYS Results

The ANSYS results are given in Table III and Figs. 4 to 6. The stress is almost the same along the length of the specimen, which is what we expect in a tensile test, and the maximum stress of 234.152 MPa is near the loaded end (Fig. 4). The maximum strain is 0.0032462 (0.32%), so the laminate is stiff and stays elastic. The deformation increases steadily from zero at the fixed end to 0.23165 mm at the loaded end (Fig. 5). We plotted the stress and strain values from the ANSYS colour legends to get Fig. 6; the curve is nearly straight at first and becomes flatter above about 180 MPa.

TABLE III

ANSYS Results of the Tensile Specimen

Result	**Minimum**	**Maximum**
Equivalent stress (MPa)	12.576	234.152
Equivalent elastic strain	0.00022402	0.0032462
Total deformation (mm)	0	0.23165

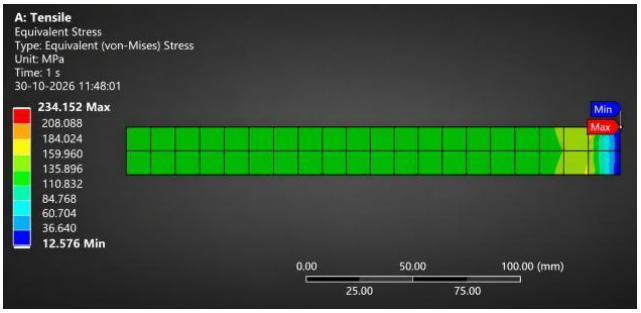


Fig. 4. Equivalent (von Mises) stress in the tensile specimen.

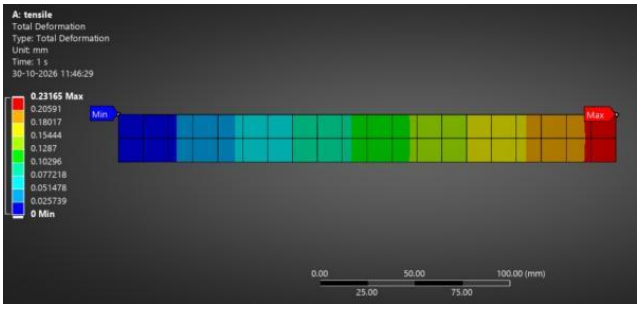


Fig. 5. Total deformation of the tensile specimen.

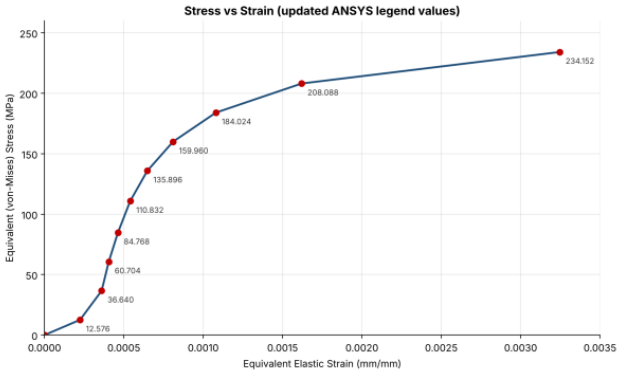


Fig. 6. Stress-strain curve from the ANSYS results.

The Young's modulus from ANSYS was 72.44 GPa and the ROM value from Eq. (4) was 77 GPa. The difference is $|77 - 72.444| / 77 \times 100 = 5.92\%$. The ROM value is higher because it assumes perfect bonding and all fibers lined up with the load, while in our laminate the 45°, −45° and 90° layers carry less of the axial load, and ANSYS takes this into account. A difference of less than 10% is usually accepted [3].

B. Tensile Test Results

Table IV gives the tensile test results. All specimens have a cross-section of 75 mm², so the tensile strength is the maximum load divided by 75 mm². The maximum load was between 15.20 and 18.20 kN (average 16.89 kN), which is close to our calculated 16.125 kN. The tensile strength was between 202.667 and 242.667 MPa, with an average of 225.20 MPa and a standard deviation of 17.3 MPa (7.7%). Some scatter is normal for hand lay-up, because each specimen can have slightly different resin content, voids and fiber alignment. In Fig. 7, the curves are almost straight up to the peak and then drop suddenly, which shows brittle failure of the fibers.

TABLE IV

Tensile Test Results (250 × 25 × 3 mm)

Specimen	**Max. load (kN)**	**Tensile strength (MPa)**
SP2	16.15	215.333
SP3	18.15	242.000
SP4	16.75	223.333
SP5	15.20	202.667
SP6	18.20	242.667
Mean ± SD	16.89 ± 1.30	225.20 ± 17.3

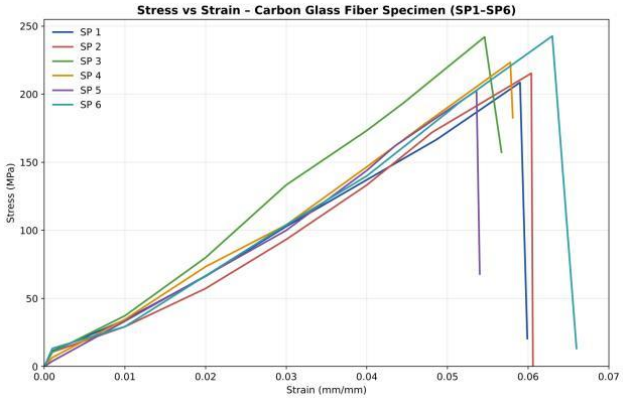


Fig. 7. Stress-strain curves from the tensile tests.

C. Flexural Test Results

Table V gives the three-point bending results. The average peak load was 36.5 N, which gives a maximum flexural stress of 24.3 MPa at a strain of 1.57% and a deflection of 8.72 mm. After the peak, the specimens did not break at once. They kept bending up to about 20 mm deflection and a strain of 3.60%

at break, so the failure was gradual (matrix cracking and layers separating). The results of the three specimens were close to each other. However, the flexural strength and modulus are much lower than the tensile values. We think this is because the specimen is thin compared to the span (span-to-thickness ratio of about 33), because hand lay-up leaves resin-rich areas and weaker bonding between layers, and because the ±45° and 90° layers are near the middle. This needs to be checked further with thicker specimens and better curing.

TABLE V

Flexural Test Results (100 mm span)

Property	**M2**	**M3**	**M4**	**Mean ± SD**
Peak load (N)	36.9	38.5	34.0	36.5 ± 2.3
Max. stress (MPa)	24.6	25.6	22.7	24.3 ± 1.5
Strain at peak	0.0156	0.0157	0.0159	0.0157 ± 0.0002
Deflection at peak (mm)	8.64	8.71	8.82	8.72 ± 0.09
Total deformation (mm)	22.18	19.06	18.86	20.0 ± 1.9
Strain at break	0.0399	0.0343	0.0339	0.0360 ± 0.0034
Flexural modulus (GPa)	1.58	1.64	1.43	1.55 ± 0.11

The 100 × 25 × 3 mm specimens also gave absorbed energies of 7.968, 7.463, 8.161 and 7.798 J (average 7.85 J), and the peak load for specimens M2 to M4 was about 3,420 N.

D. Impact Test Results

The four 150 × 100 × 3 mm plates absorbed 16.14, 17.2, 14.9 and 16.87 J, which gives an average of 16.28 ± 1.02 J, and the average peak load was 5,840 ± 220 N (Table VI). The plates absorbed about twice the energy of the smaller specimens, because a bigger plate has more material that can bend, crack and separate before it fails. The glass layers in the middle help to absorb energy and stop sudden breaking, which is useful for a UAV frame during hard landings or small crashes.

TABLE VI

Impact Test Results (drop height 0.4 m)

Specimen	**Energy absorbed (J)**
1	16.14
2	17.20
3	14.90
4	16.87
Mean ± SD	16.28 ± 1.02
Peak impact load (N)	5,840 ± 220

E. Comparison of Results

Table VII compares the theory, ANSYS and test results. The tested tensile strength (225.20 MPa) is between the design value (215 MPa) and the ANSYS value (234.152 MPa). The difference between ANSYS and the test is (234.152 − 225.20) / 225.20 × 100 = 3.98%, and the difference between the test and the design value is (225.20 − 215) / 215 × 100 = 4.74%. These small differences come from air bubbles, uneven resin and small fiber misalignment during hand lay-up, from differences in curing and bonding, and from the ideal material properties and boundary conditions used in ANSYS.

TABLE VII

Comparison of Results

Property	**Theory**	**ANSYS**	**Test**
Young's modulus (GPa)	77	72.44	–
Tensile strength (MPa)	215*	234.152	225.20
Failure load (kN)	16.125	–	15.20–18.20
Difference	5.92% (E)	3.98% (σ)	4.74% (σ)

Expected tensile strength taken for the load calculation

For a UAV frame, strength and stiffness per unit weight matter more than the actual values. With a density of 1.817 g/cm³, our laminate has a specific strength of about 124 MPa·cm³/g and a specific modulus of about 40 GPa·cm³/g. For aluminium 6061-T6, using typical handbook values (310 MPa, 69 GPa, 2.70 g/cm³), these are about 115 MPa·cm³/g and 26 GPa·cm³/g. So our laminate is about 33% lighter than aluminium, has a similar specific strength and a higher specific modulus, and it does not corrode.

IV. CONCLUSIONS

We designed, analysed, made and tested a [C/G/G/C] carbon-glass fiber/epoxy laminate with 25% carbon, 25% glass and 50% epoxy. From this work we conclude that:

(1) The ROM gave a Young's modulus of 77 GPa and ANSYS Workbench gave 72.44 GPa, a difference of 5.92%. ANSYS also gave a maximum stress of 234.152 MPa, a strain of 0.32% and a deformation of 0.23165 mm for the 250 × 25 × 3 mm specimen.

(2) The average tensile strength from the tests was 225.20 ± 17.3 MPa. This is within 3.98% of the ANSYS value and 4.74% of the design value, and the failure loads (15.20 to 18.20 kN) were close to our calculated 16.125 kN.

(3) In bending, the laminate failed gradually, with a flexural strength of 24.3 ± 1.5 MPa and a flexural modulus of 1.55 ± 0.11 GPa. In the impact test, the plates absorbed 16.28 ± 1.02 J from a height of 0.4 m.

(4) The laminate has a density of about 1.82 g/cm³, a specific strength similar to aluminium 6061-T6 and a higher specific modulus, so it is a good low-cost material for UAV arms, panels and mounting plates.

In future, we plan to use vacuum bagging or resin infusion to reduce voids, measure the tensile modulus directly using an extensometer or strain gauges, study the low flexural stiffness with thicker specimens, and test other stacking sequences and fiber volume fractions.

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