NATURAL FIBER COMPOSITE FOR UAV LANDING GEAR

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ABSTRACT

Sustainable composites with natural fiber reinforcement are getting more popular to replace traditional fibers for various engineering applications. One of these natural fibers, basalt fiber, is proposed as a reasonable alternative to carbon or glass fiber composite structures. These mineral fibers can replace carbon fibers for lower cost and glass fibers for higher strength. Basalt fiber is a high modulus substance that outperforms fiberglass in the aerospace industry allowing for improved performance and weight savings. In the aerospace industry, the weight of the main landing gear (MLG) structure becomes an important aspect, especially for unmanned aerial vehicles (UAV). Thus, it is essential to assess different types of composite fibers for MLG with the objective of reducing weight and cost. The aim of this work is to evaluate basalt fiber as a viable option for the MLG for a mid-size UAV in obtaining a lightweight bracket. Also, this research is to determine the geometry and performance of different fiber basis of MLG to make a comparison between commonly used composite fibers and basalt fiber composite.

For this purpose, a mid-size UAV landing gear was chosen from a list of attractive alternatives to be analyzed using analytical and FEA methods. Several MLG options of UAVs weighing 250kg were modeled to perform the comparison between the design options. Mechanical characteristics were obtained for the fibers and their laminates to compare the use for the MLG. Analytical modeling and Finite Element Analysis (FEA) were utilized to vary the geometry without the need to manufacture and test numerous design options. Thus, analytical and numerical studies were performed to improve the design. Also, alternate structural design options were investigated to enable minimizing the MLG weight and maximize its functionality. Finally, this work concluded the potential of using basalt fibers as a viable option for MLG manufacturing in the UAV industry.

1. INTRODUCTION

One of the challenging airframe designs for Unmanned Aerial Vehicles (UAVs) is related to the main landing gear (MLG). It is an essential component subjected to high stresses during the aircraft landing where the majority of structure failures occur [1]. Due to the importance of weight reduction in the aviation field, the strength to weight ratio of the MLG structure becomes a critical design target. The use of composite material in the landing gear design is favorable for weight saving but requires a balanced strength and flexibility for a successful landing impact and shock absorption. The integration of composite materials in the design of MLG is under continuous improvement by many researchers worldwide.

Several studies were conducted to evaluate the strength and behavior of various MLG shapes and sizes in order to obtain a lightweight bracket design, figure 1. Both analytical and numerical methods were used to study deflection and stresses for MLG structures [2-3]. For a simple geometry topology, the MLG deflections can be conducted analytically using, among others, Euler-Bernoulli beam theory [4], while finite element analysis (FEA) can be involved as a strong numerical analysis tool for complex structural and advanced material models. The results from FEA reproduce accurately experimental data of manufactured composite MLG structures [5]. The model of the landing gear can handle several parameters that control the design, such as the bracket cross-section and material configurations and properties used.

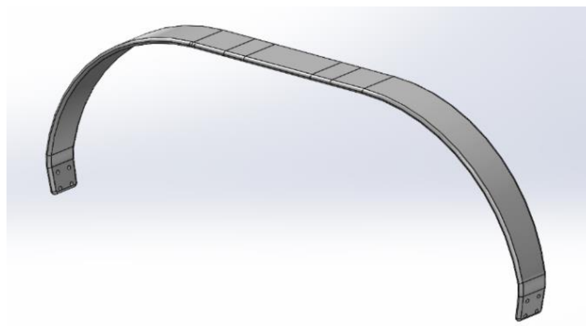

Figure 1: A Common MLG design

Composite materials are an excellent choice for mid-weight UAVs which weigh between 150Kg to 300kg [6]. Carbon Fiber Reinforced Polymer (CFRP) is considered a great candidate because of its high rigidity to weight ratio but has a high cost. The Glass Fiber Reinforced Polymers (GFRP) has a lower cost than CFRP making it a decent candidate that also has a higher deflection rate for a safe landing and impact load absorption [7]. Consequently, Glass fibered MLG would have a decent stiffness at a low cost but with heavier weight [8-9]. Hence, finding a suitable composite material is always a need for designing a lightweight MLG with optimized strength, stiffness, cost-effectiveness, and possibly a green footprint.

Natural fiber composites are becoming more popular in replacing traditional fibers. One of these natural materials is the basalt fiber which can be proposed as a valid substitute for synthetic composites. In fact, based on the mechanical characterization conducted in the references [10-12], mineral basalt fibers may possess the potential to replace carbon fibers for lower cost and replace glass fibers for higher strength. Basalt fibers composite can be an attractive alternative material for the MLG design offering almost the same stiffness as glass fibers [13]. Furthermore, the average density of both BFRP and GFRP are substantially similar as shown in table 1, allowing for weight reductions by making a thinner basalt based MLG carrying the same load [9,13].

Therefore, the aim of this work is to investigate and evaluate basalt fiber as a base material for the design of MLG for mid-size UAVs. The work also aims to determine the geometry and performance of the three different fiber materials. Comparisons between commonly used composite fibers and basalt fibers are conducted.

Table 1. Some properties, density, and cost of carbon, E-glass, and basalt fibers [8,9,13]:

Fiber	Tensile Strength (MPa)	Tensile Modulus (GPa)	Density (g/cm^3)	Approximate Price ($/kg)
Carbon	4500	270	1.8	35–50
E-glass	2500	70–80	2.55	1–2

2. MATERIAL AND METHODS:

2.1 Design Conditions

Tricycle-Type landing gear can be considered a stable configuration including one wheel in the front and two wheels at the back. It can be easily joined with the fuselage by only two mounting points. The aircraft can land in three different scenarios while touching the ground, figure2. The load can be distributed on three points for the first scenario (figure 2(*a*)). However, the load is applied on one single rear wheel. Design conditions and considerations must consider the three scenarios. Moreover, to suit the fuselage and runway, the landing gear span cannot be too large and wide. The height of the MLG is an important constraint where the deflected MLG should be tall enough to prevent the propeller from touching the ground at landing.

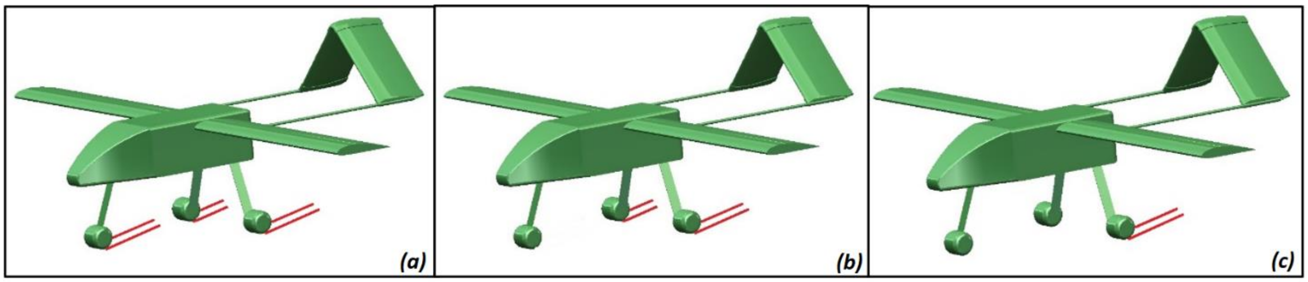

Figure 2: Different landing scenarios for landing gear

2.2 Loading

The balanced main wheel landing (figure 2(b)) is the scenario adopted in this work. The gross weight of the mid-size UAV is taken as 250kg. Both the wheels-ground friction forces and the tires' stiffness are not considered in this work. The vertical impact force is calculated based on the impulse-momentum equation (1) for a vertical landing speed of 4 m/s. The time of impact is considered as 0.5 seconds [14]. No glide angle is considered. The impact force will be doubled for a factor of safety of 2 in case of extreme landing. The force will be distributed equally between the two wheels. Considering all the parameters and assumptions, the impact force is evaluated to 2000N for each wheel.

$$F\,\Delta t = m\,V_f \qquad (1)$$

Where F is the Impact force, Δt is the impact time, m is the vehicle weight, and V_f is the final velocity at impact.

Table 2. Impact loads corresponding to different landing speeds:

Case	Velocity at impact (m/s)	Both wheel Force (N)	Each wheel force (N)
1 (Soft landing)	2	1000	500
2 (Normal landing)	4	2000	1000
3 (Hard landing)	6	4000	2000

2.3 Geometry

The MLG frame design is considered and modeled for this work as shown in figure 3, which is the most common shape in the UAV industry [15]. The design is made of a flat base surface with two smooth curved members. The design does not have angular edges to avoid high-stress concentration areas. This design is symmetric and only half of it will be considered in the analysis.

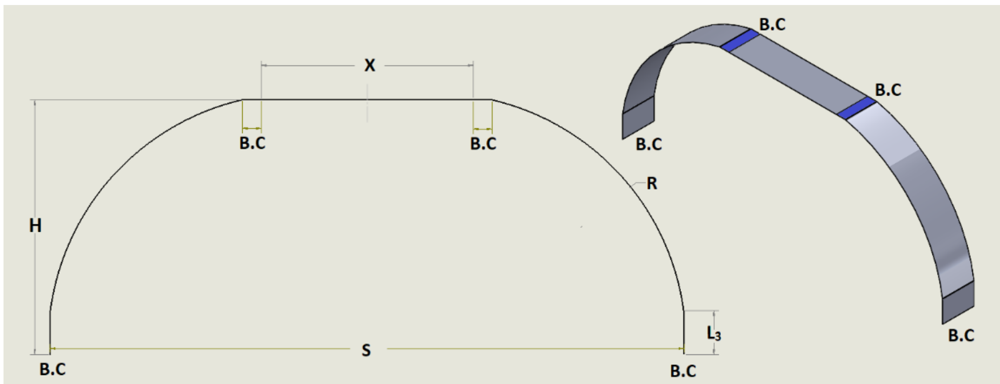

Figure 3: The actual configuration of the landing gear

Meanwhile, the frame design can be idealized to enable the optimization of beam analytical solutions to optimize the spring stiffness of the MLG. The design can be represented as five members frame, figure 4, made of flat surfaces with no smooth connections between the members. That would facilitate the analytical solution using the Euler-Bernoulli beam theory. Symmetry still applies to this design reducing the total number of members to three.

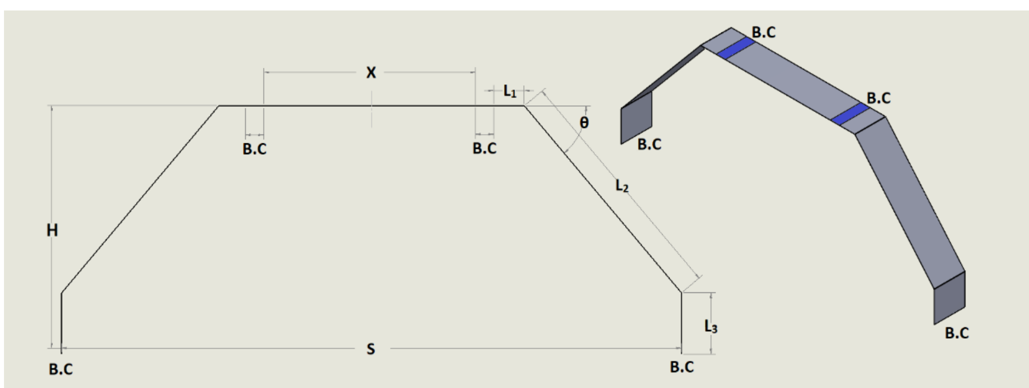

Figure 4: The Idealized configuration of the landing gear

2.4 Material

All three fiber types are chosen as reinforced by epoxy resin polymer. The mechanical properties of composite laminate were taken from several references [8,16,17]. The material properties that were used in the design are illustrated in table 3.

Table 3: The composite material properties:

Material	Carbon /Epoxy [8,16]	E-Glass/Epoxy [8,16,17]	Basalt/Epoxy [17]
Density (g.cm^3)	1.53	2.08	2.10
Fiber volume ratio	0.6	0.6	0.6
Tensile Properties			
Longitudinal Tensile Modulus (GPa)	134	45	44.3
Transverse Tensile Modulus (GPa)	7	12	11.9
Shear Modulus (GPa)	4.2	4.5	3.73
Longitudinal Tensile Strength (MPa)	1270	1250	1310
Transverse Tensile Strength (MPa)	42	35	49.8
Ultimate Shear Strength (MPa)	80	90	50.5
Longitudinal Tensile Strain (%)	1.67	2.95	3.1
Transverse Tensile Strain (%)	0.6	0.5	0.47
Ultimate Shear Strain (%)	0.06	0.016	0.05
Major Poisson's Ratio	0.25	0.3	0.27
Compressive Properties			
Longitudinal Compressive Modulus (GPa)	38.3	41.2	46.2
Transverse Compressive Modulus (GPa)	12.3	14	15.2
Longitudinal Compressive Strength (MPa)	1130	600	776
Transverse Compressive Strength (MPa)	141	141	135
Longitudinal Compressive Strain (%)	- 1. 08	-1.5	- 1.7
Transverse Compressive Strain (%)	-1.72	-1.2	- 1.6

2.5 Analyses

2.5.1 Analytical Methods

The analytical solution was conducted for the idealized design to determine the initial geometry for the MLG corresponding to an acceptable stiffness. The design was made as a fixed frame with three members as shown in figure 5 (a).

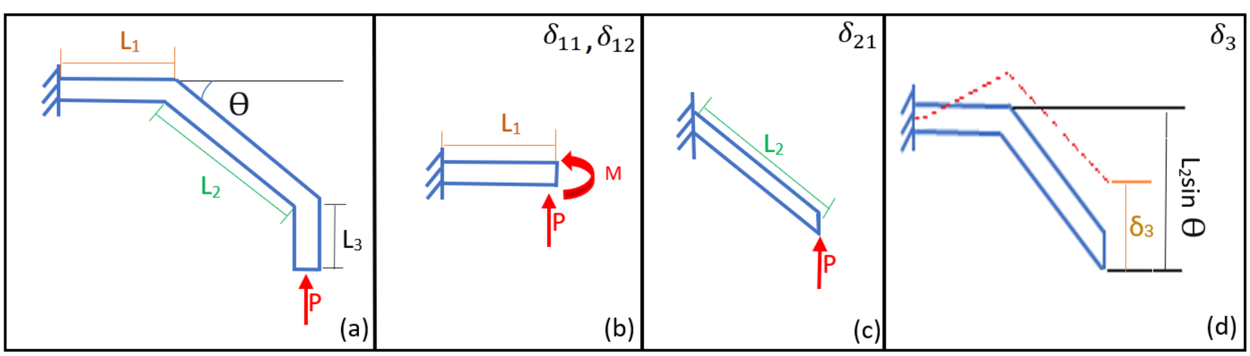

Figure 5: MLG analytical deflections analysis using the superposition method (Half model-symmetry)

The total deflection of the MLG structure (Figure 5 (a)) is calculated by superposing the deflection of each member (Figure 5 (b-d)). The large stiffness and elastic behavior of the composite materials are thought to satisfy the linear behavior required by the superposition method. The total displacement of the MLG (δ_T) is reduced to the summation of the four displacements calculated by the following equations:

$$\delta_{11} = PL_1^3/3EI \tag{2}$$
$$\delta_{12} = PL_1^2L_2\,cos\,\theta/2EI \tag{3}$$
$$\delta_{21} = PL_2^3\,cos^2\,\theta/3EI \tag{4}$$
$$\delta_3 = L_2(\sin\theta - sin(\theta - \theta_{11} - \theta_{12}) \tag{5}$$
$$\theta_{11} = PL_1^2/2EI \tag{6}$$
$$\theta_{12} = PL_1L_2\,cos\,\theta/EI \tag{7}$$
$$\delta_T = \delta_{11} + \delta_{12} + \delta_{21} + \delta_3 \tag{8}$$
$$k = P/\delta_T \tag{9}$$

Where $\delta_{11}$the first-member deflection from the load applied on the first member, δ_{12} is first-member deflection from the moment counted there, δ_{21} is the deflection from the load applied on the second member, δ_3 is the deformation from the first superposition rotation conducted from the slops θ_{11} and θ_{12} (rigid body rotation displacement), δ_T directional displacement, and k is the spring stiffness on the whole frame. From the equations above, the effect of the frame lengths and the angle between them on the design (L1, L2, and Θ) can be noticed that they are controlling the deflection. The analytical solution is used to determine the initial thickness for the CFRP needed for the desired deflection not to exceed 10% of the MLG height (H). All calculations were performed in the EES solver (Engineering Equation Solver) [18].

2.5.2 Finite Element Method

The actual geometry would be migrated from the initial idealized geometry developed by using the analytical method. Therefore, FEA became the appropriate tool to deal with this actual geometry. Simulations of the layered composite are performed using static structural analysis using ANSYS Mechanical and ANSYS Composite Pre-Post (ACP) software. The simulation is conducted to study the deflection and principal stresses of the whole laminate and for each ply. The idealized model is modeled as a reference with a stacking sequence of $[90_{n1}/0°_{n1}/\pm45°_{n2}]_s$. The CFRP is presented as a nominal design selection to compare its results with GFRP and BFRP. The actual curved design will be using almost the same stacking sequence as the idealized design. The displacement of the actual curved design will be calculated using the FEA tool.

3. Results and Discussion:

3.1 Analytical Results:

From the iterative solution of the analytical equations using EES, at 2000N load, the preliminary design values of the MLG bracket were 50mm, 400mm, and 50mm for L_1, L_2, and L_3 respectively. The preliminary bracket thicknesses were 9.42mm, 16.32mm, and 16.42 mm for CFRP, GFRP, and BFRP respectively. All these results were conducted by controlling the vertical deflection as 9% of the bracket height to possess an acceptable spring stiffness at 0.07252 N/m. All three thicknesses are applicable for Euler Bernoulli beam theory assumptions compared with the deflection [16]. The height of the deflected bracket was 328.82mm.

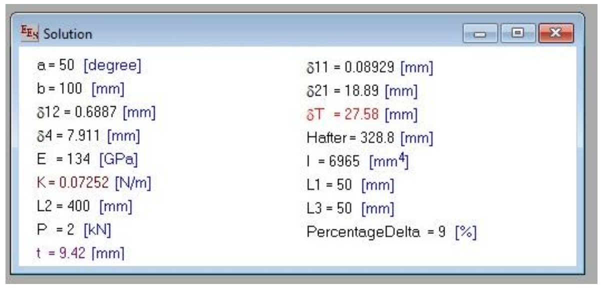

Figure 6: EES solver results for estimating CFRP thickness for 2000N load

3.2 Numerical Solutions

The first process in every simulation is to generate a good quality mesh to obtain accurate results with keeping the computational time reliable. To ensure that, mesh convergence was conducted for the MLG model for both maximum deflection and maximum stress as shown in figure 7. Fairly after the 2000 element number, the results of the analyses are not largely affected by changing the number of the elements. The element type was chosen as a shell element and the number of elements was 2420 which is within the range of the convergence.

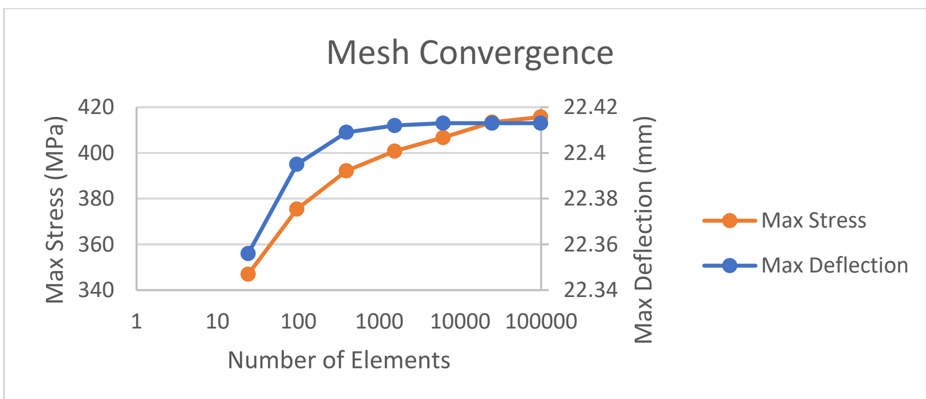

Figure 7: Mesh Convergence for the MLG

Subsequently, the simulation started with three CFRP models (FEA-actual, FEA-idealized, and EES-idealized) to verify and compare the deflection results between the FEA and the analytical solution. All models have the same thickness at 9.5mm. As you can see in figure 8 (a and c), the deflection was almost the same between the FEA and EES idealized models at 26mm. That deflection is comparable with the FEA-actual model, figure 8 (b), at 22.41 mm, even though it is slightly lower by almost 3.6mm to the actual model. That is because of the curved frame is marginally increasing spring stiffness [19].

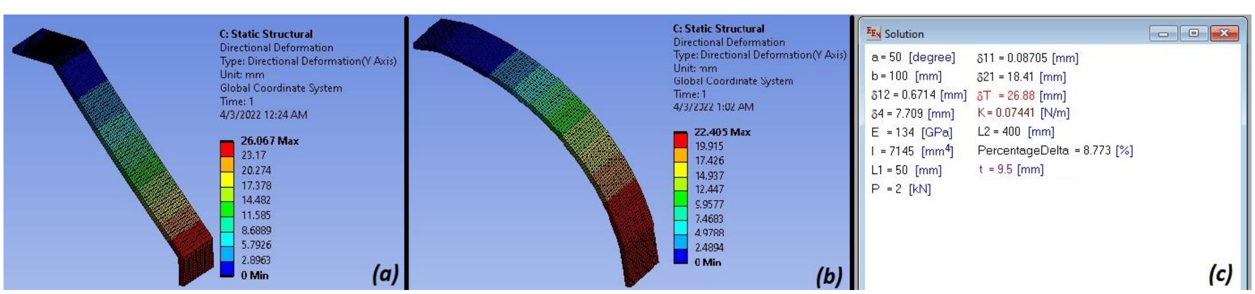

Figure 8: The deflection results for 0° direction CFRP models at t= 9.5mm, (a) is the idealized configuration-FEA, (b) is the actual configuration-FEA, (c) is the EES idealized configuration-

Accordingly, three design attempts in the actual geometry for the three different fibers (CFRP, GFRP, BFRP) were conducted to identify the desired thicknesses. Mainly, a similar percentage of the stacking sequence of the total number of layers was controlled for all designs to provide a valid comparison at nearly $[90_{16\%}/0°_{16\%}/\pm45°_{68\%}]s$ [20]. The angular layers (90°, ±45°) were added to prevent MLG failure due to any unsymmetrical landing scenario. The maximum-stress criteria were used to identify possible failures and compare the three designs. The failures percentage ranges from zero to one where one is when the failure accrues. Thus, the FEA models were conducted to guarantee the failure of maximum stress is less than one. The one-ply thickness was considered as 0.19mm. All the results of the three designs are in table 4 and figure 9.

Table 4: Some FEA results for the actual configuration for CFRP, GFRP, and BFRP:

Composite model	CFRP	GFRP	BFRP
Stacking Sequence	$[90°_6/\pm45°_6/0°_{24}]_s$	$[90°_{10}/\pm45°_{10}/0°_{42}]_s$	$[90°_8/\pm45°_8/0°_{35}]_s$
Number of Layers	72	124	102
Percentage of 90°, ±45°,0°	16.6%,16.6%,66.7%	16.1%,16.1%,67.7%	15.7%,15.7%,68.6%
Thickness (mm)	13.68	23.56	19.38
Vertical Deflection (mm)	26.813	8.3563	14.429
Max Stress (MPa)	78.225	40.244	58.887 MPa
Failure Max Stress Percentage	0.62635	0.98112	0.98304
Full MLG Weight (Kg)	3.08	7.57	6.26

From the table, it can be noticed that all three vertical deflections were lower than the preliminary controlled deflection which was at 27.58mm. Considering the thickness of the additional angular layers presented, GFRP and BFRP deflections are still reasonable. However, the bracket of CFRP was enhanced by more 0° layers to reduce the vertical deflection to an acceptable range at 26.82mm. Even though the failure percentage was the lowest in the CFRP bracket, it still has the lowest number of layers at 72 plies. Both GFRP and BFRP brackets were designed at nearly below one for the failure percentage.

Based on these designs, geometry, and thickness, the full MLG weights were found to be 3.08 Kg, 7.57 Kg, and 6.26 Kg for CFRP, GFRP, and BFRP respectively. All weights were calculated for the full actual frame. The weight of the CFRP bracket is very low, which makes it the best choice for the MLG in weight wise. While the weight of BFRP is actually much less than GFRP by 17% as expected. The BFRP bracket had a larger deflection than the GFRP bracket due to the lower thickness which is in an acceptable range. Basalt MLG is a very combative and applicable design option for the MLG.

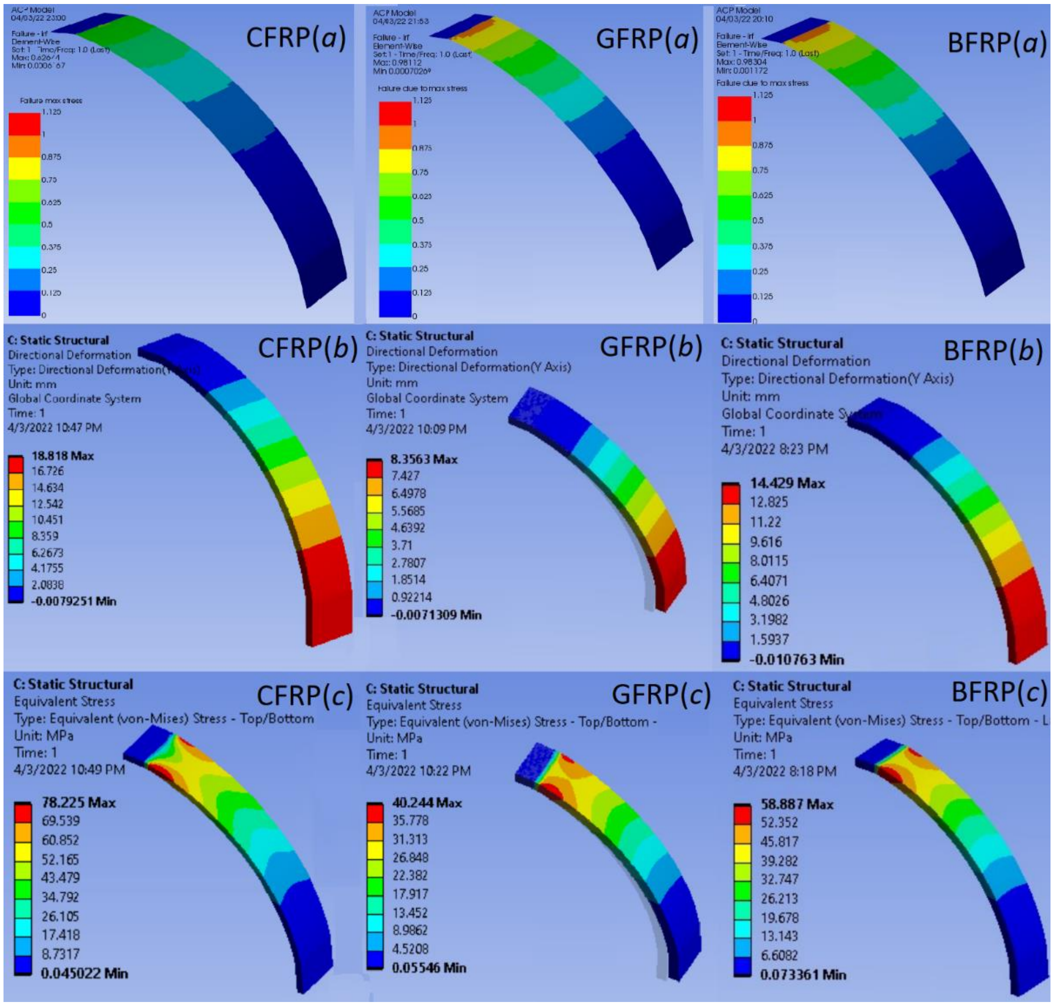

Figure 9: Some FEA results for the actual configuration for CFRP, GFRP, and BFRP. (a) is the failure percentage, (b) is the directional deflection, and (c) is the maximum stress.

4. Conclusions

This work investigated three different options of composite fibers for the objective of designing the main landing gear of mid-size UAVs. Both analytical and numerical studies were conducted to perform a comparison between the design options which are Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP), and Basalt Fiber Reinforced Polymers (BFRP). This work showed that the basalt MLG is an intermediate option between carbon and glass in terms of strength. Meanwhile, the BFRP bracket had less weight than the GFRP bracket by 17%, and the deflection of the basalt MLG had a similar behavior to the glass MLG. Therefore, basalt fibers can be used in aerospace applications with the advantage of competitive strength, weight, and cost. Moreover, being a natural fiber provides an extra advantage when considering the environment.

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