



Structural analysis of the Wing of UCAV (Unmanned Cargo Aerial Vehicle) using finite element method

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ABSTRACT

This study analyzes and optimizes the wing structure design of an Unmanned Cargo Aerial Vehicle (UCAV) using the Finite Element Method (FEM). The initial structural assessment shows that the maximum stress of 566.83 MPa occurs at the wing root, resulting in a minimum safety factor of 0.67 which is well below the acceptable threshold of 1.8, as defined by the C.A.S.A Australia Subpart C standard. The maximum displacement amplitude was recorded at 3.81 mm, indicating potential structural failure under operational loads. To improve structural performance, modifications were implemented by increasing the thickness of ribs and spars in critical sections. The redesigned model reduced the maximum stress to 99.97 MPa, raised the minimum safety factor to 1.9, and decreased the maximum displacement amplitude to 0.672 mm. These findings confirm that the modified UCAV wing design achieves compliance with safety standards, enhances structural integrity, and demonstrates improved reliability under operational conditions.

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1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have become one of the most important innovations in the aviation sector, with rapid growth in both civil and military applications (Ghamari et al., 2022; Mohsan et al., 2023; Shakhathreh et al., 2019). Among them, the Unmanned Cargo Aerial Vehicle (UCAV) is designed as a dedicated platform for logistics distribution in areas that are difficult to access or unsafe for manned aircraft (Babetto et al., 2022; Mohsan et al., 2022; Poleshkina et al., 2021). At the Indonesian Defense University, a UCAV prototype has been developed to support military operations, particularly for delivering supplies to special forces in contested areas. Since the vehicle is unmanned and can be controlled remotely, the UCAV offers a practical solution for time-critical missions where conventional transport is limited or exposed to high risk (Hamilton & Ochmanek, 2020; Kunertova, 2019; Ljulj et al., 2024).

One of the most critical components that determines the reliability of a UCAV is its wing structure. The wing not only generates lift, but also transfers aerodynamic loads to the fuselage and ensures overall stability during flight. For this reason, the wing must be designed to meet acceptable standards of strength, stiffness, and safety factor (Belardo et al., 2021; Chinvorarat, 2021). Failure in the wing structure would directly result in mission failure and potential loss of the vehicle (Liou et al., 2019; Vries & Vos, 2023).

A commonly used approach to evaluate the strength of an aircraft wing is the Finite Element Method (FEM). FEM enables structural engineers to model complex geometries numerically by discretizing them into finite elements, so that stresses, strains, and displacements can be estimated with sufficient accuracy (Munjiza et al., 2020). With this method, ribs, spars, and skin can be analyzed individually as well as in their assembled configuration, giving insight into critical stress regions and possible design weaknesses.

This paper presents a structural analysis of a semi-span UCAV wing using FEM. The baseline wing geometry was adopted from a previous conceptual and preliminary design study (Adeloju et al., 2021; Nath et al., 2024). Simulations were carried out to evaluate the distribution of stresses, displacements, and safety factor under aerodynamic loads representative of operational conditions. To improve performance, modifications were introduced by increasing the thickness of ribs and spars in critical sections (Dao et al., 2024; Santo et al., 2019).

The objectives of this study are to assess the structural response of the baseline UCAV wing under aerodynamic loading conditions, to evaluate the effectiveness of structural modifications in reducing stress concentrations and improving the safety factor, and to determine whether the final design meets the safety requirements specified in C.A.S.A Australia Subpart C – Structure UA25.337

Through this study, the UCAV wing is expected to achieve a more reliable structural design suitable for operational use. The results also provide a reference for further development of UAV wings, especially for cargo and military logistics missions.

The novelty of this research lies in the application of Finite Element Method (FEM)-based structural analysis specifically to the wings of a prototype UCAV developed at the Indonesian Defense University, with a focus on military operational requirements for logistics missions in high-risk areas. Unlike previous studies, which generally emphasized only conceptual design or aerodynamics, this study emphasizes structural strength evaluation through semi-span wing modeling, testing of stress and displacement distribution under representative aerodynamic loads, and design improvements through modifications to the thickness of ribs and spars in critical areas. In addition, this research also integrates the analysis results with the Australian C.A.S.A Subpart C – Structure UA25.337 safety standards, thereby contributing to a new, more reliable, safer, and more applicable UCAV wing design for military logistics missions in Indonesia.

2. RESEARCH METHOD

UCAV Wing Design

This study focused on a semi-span wing of an Unmanned Cargo Aerial Vehicle (UCAV) designed for a payload of 60 kg. The geometric data was adopted from earlier conceptual and preliminary design work. The wing uses a rectangular planform with the SG 6043 airfoil, a span of 12.1 m, and a chord length of 0.605 m. The structural elements consist of ribs, spars, and skin. They were modeled individually in CAD software before being assembled into a complete wing configuration.

Table 1. UCAV Wing Specification and Flight Condition

Parameters	Symbols	Value
Maximum Take-Off Weight	MTOW	200 Kg
Payload	W_{pl}	60 Kg
UCAV Velocity	V	35 m/s
Lift Coefficient	C_l	1,6
Wing Airfoil	-	SG 6043
Wing Area	SW	7,135 m^2
Wing Chord	CW	0,605 m
Wing Span	bW	12,1 m
Wing Semi-Span	-	5,8 m
Wing Aspect Ratio	AR	20
Wing Taper Ratio	λ	1
Drag Coefficient	C_D	0,082

In its baseline form, the wing structure consists of 11 ribs, each 5 mm thick, two spars (front and rear) of 15 mm thickness, and a skin layer 2 mm thick as shown in Figure 1 and Figure 2. The front spar is positioned at 15% of the chord length from the leading edge, and the rear spar is positioned at 60%. This arrangement reflects a typical fixed-wing UAV layout.

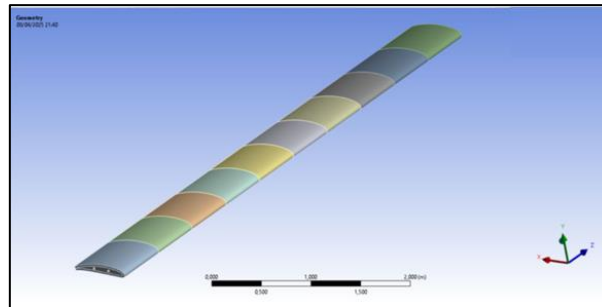


Figure 1. UCAV Wing 3D Design

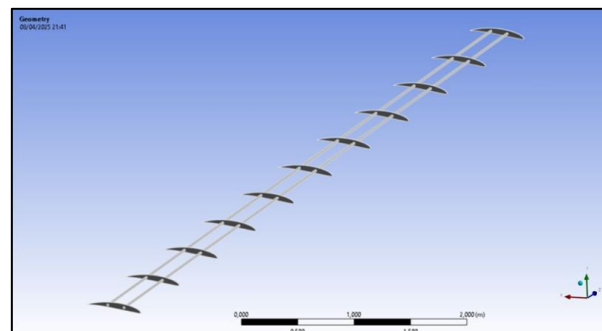


Figure 2. Spars and Ribs of UCAV Wing

Modified Wing Design

After the initial analysis of the baseline configuration, modifications needs to be introduced to improve load distribution and reduce stress concentrations. The ribs in sections 1 to 3 were thickened to 25 mm, ribs in sections 4 to 5 were thickened to 15 mm, while the remaining ribs were kept at 5 mm. The spars were also reinforced: 40 mm thickness in sections 1 to 3, 30 mm in sections 4 to 5, and 15 mm in sections 6 to 10. These adjustments were intended to achieve a minimum safety factor above 1.8, which is considered acceptable for structural reliability. The details about dimensions and sizing of the modified wing can be seen in Table 2 and Figure 3 and Figure 4.

Table 2. Structural Dimensions of the Modified UCAV Wing

Components	Parameter	Nilai
Rib	Quantity	11
	Thickness (Section 1-3)	0,025 m
	Thickness (Section 4-5)	0,015 m
Spar	Thickness (Section 6-11)	0,005 m
	Chord Length	0,605 m
	Quantity	2

	Thickness (Section 1-3)	0,040 m
	Thickness (Section 4-5)	0,030 m
	Thickness (Section 6-11)	0,015 m
	Panjang	5,8 m
	Jumlah	1
Skin	Thickness	0,002 m
	Span Length	5,8 m

The target was not only to increase the strength of the wing but also to keep the safety factor below 2.5. This constraint was introduced to avoid unnecessary structural weight, since an excessively high safety factor typically indicates an overdesigned structure. By aiming for a safety factor within the range of 1.8 to 2.5, the modified design balances lightweight efficiency with structural safety, ensuring the wing is strong enough to withstand operational loads without compromising the payload capacity or aerodynamic performance of the UCAV.

Materials

Two materials were used in the simulation. The ribs and spars were modeled using Carbon Fiber Reinforced Polymer (CFRP), selected for its combination of high strength and low weight. The wing skin was modeled using polypropylene, a lightweight thermoplastic commonly applied for surface structures. The main properties of these materials are shown in Table 3 and Table 4 respectively.

Table 3. Structural Dimensions of the Modified UCAV Wing

Property	Value
Density	1900 Kg/M3
Young Modulus	90000 Mpa
Poisson's Ratio	0,3
Shear Modulus	3461,5 Mpa
Yield Strength	600 Mpa

Table 4. Structural Dimensions of the Modified UCAV Wing

Property	Value
Density	910 Kg/M3
Young Modulus	1100 Mpa
Poisson's Ratio	0,42
Shear Modulus	387,32 Mpa
Yield Strength	32 Mpa

CFRP was chosen because of its excellent stiffness-to-weight ratio, fatigue resistance, and ability to maintain structural integrity under high loads. These characteristics make it suitable for the primary load-bearing components of the wing, such as ribs and spars. Polypropylene, on the other hand, provides flexibility and corrosion resistance at a relatively low cost. Its use as the skin material ensures that the wing surface remains smooth and lightweight while still capable of transferring aerodynamic loads to the internal structure (Shaikh & Kubade, 2024). By combining CFRP for strength-critical parts and polypropylene for outer covering, the overall wing design achieves an optimal compromise between durability, performance, and manufacturability.

Loading and Boundary Conditions

The structural model was subjected to aerodynamic lift and drag loads representative of maneuvering flight. The lift distribution along the span was estimated using the Schrenk approximation, which combines elliptical and rectangular lift distributions to approximate real aerodynamic loading on finite wings (Sultan Nugraha et al., 2024). Drag was applied uniformly across the skin based on a simplified analytical expression. Schrenk approximation to calculate coefficient of lift is depicted by Equation 1 until Equation 4. The total aerodynamic load was calculated using a Maximum Take-Off Weight of 200 kg with a load factor of 3.8 to represent maneuvering flight.

$$C_{cl} = \frac{4s \sqrt{1 - \left(\frac{2y}{b}\right)^2}}{2 \cdot \pi \cdot b} + \frac{c}{2} \tag{1}$$

$$Cl_{max} = C_l \frac{C_{cl}}{c} \tag{2}$$

$$(C_{Cl_{max}} \Delta y)_n = \frac{Cl_{max(n)} + Cl_{max(n+1)}}{2} 2(y_{(n+1)} - y_{(n)}) \tag{3}$$

$$L_{new} = \frac{(C_{Cl_{max}} \Delta y)_n}{\Sigma(C_{Cl_{max}} \Delta y)_n} \times n \times \frac{w}{2} \times g \tag{4}$$

- C_l = Coefficient of Lift
- s = Wing Area (m^2)
- b = Wingspan (m)
- y = Distance between partitions (m)
- w = UCAV MTOW (kg)
- n = Load Factor (N)
- c = Chord Length (m)

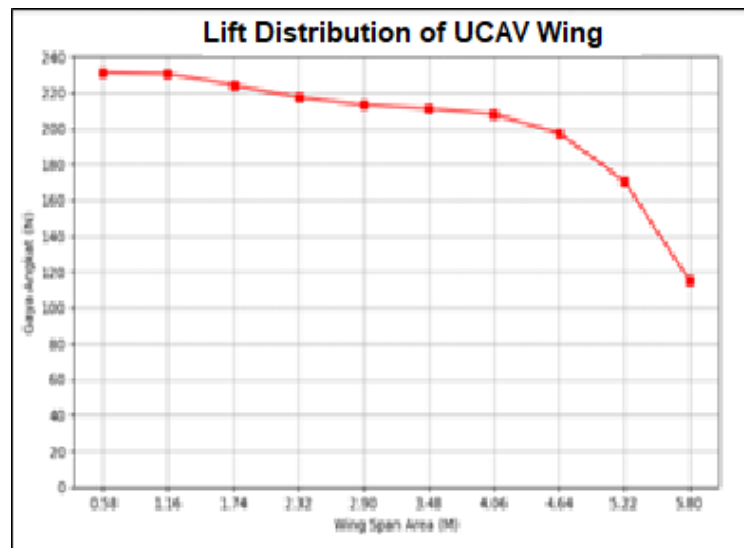


Figure 3. Lift Distribution of UCAV Wing

Boundary conditions were applied at the wing root, where the structure was fixed to represent a cantilever attachment to the fuselage. Contact conditions were defined between ribs, spars, and skin to ensure realistic load transfer during simulation. This approach allows the model to replicate how forces are transmitted from the aerodynamic surfaces into the primary load-bearing components of the aircraft. By constraining the wing root as a fixed support, the simulation captures the worst-case bending and shear effects experienced in actual flight. This setup provides a reliable representation of the operational environment, ensuring that the analysis results can be used with

confidence for structural evaluation and design optimization. Figure 4 provides description of the UCAV loading and boundary condition setup for the finite element analysis.

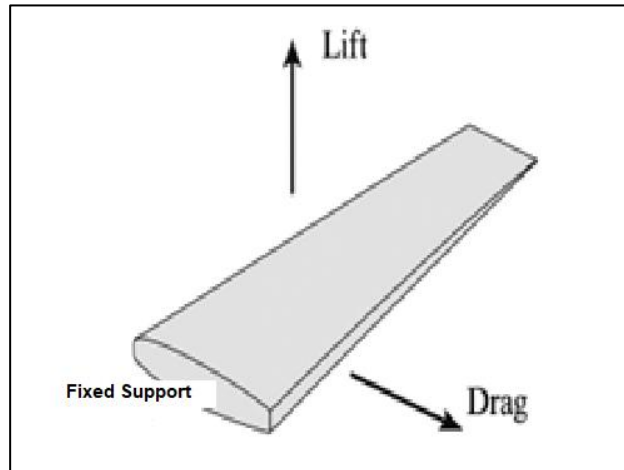


Figure 4. Free Body Diagram of UCAV Wing

3. RESULTS AND DISCUSSIONS

Baseline Wing Analysis

The initial finite element analysis of the baseline UCAV wing revealed significant stress concentrations near the wing root. The maximum von Mises stress was recorded at 566.83 MPa, occurring at the first rib, which bears the highest portion of the lift load. In contrast, the wing tip experienced a minimum stress value close to zero. The distribution pattern confirmed that the wing root carries the critical load, while stresses diminish progressively toward the tip.

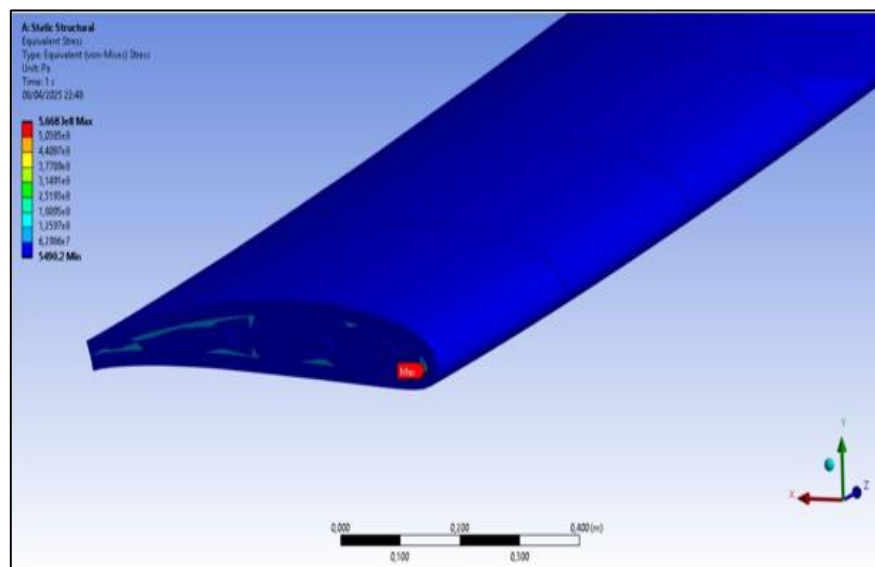


Figure 5. Maximum Von Mises Stress of Baseline UCAV Wing

The maximum displacement amplitude of the baseline design was 3.81 mm. Although this value appears moderate, it reflects the limited structural stiffness of the thin ribs and spars. More critically, the safety factor reached a minimum of only 0.67665, far below the acceptable threshold of

1.8. This indicates that under maneuvering flight conditions, the baseline design would fail to meet the required standards of structural integrity.

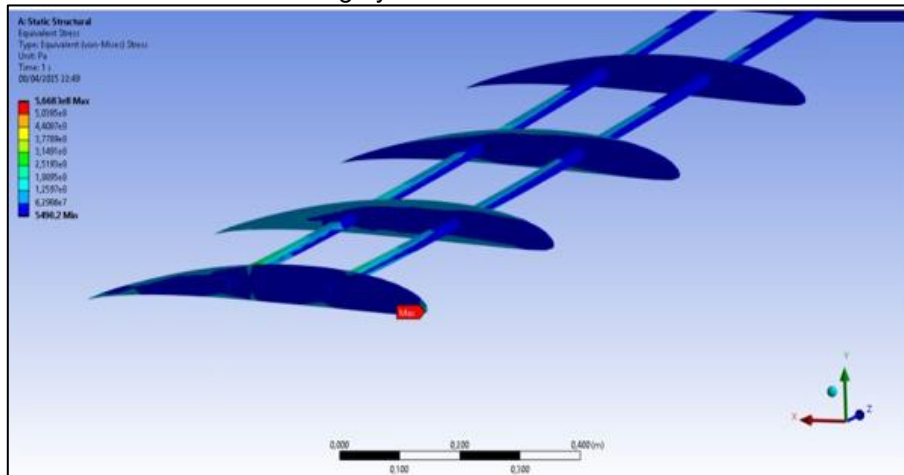


Figure 6. Maximum Deformation of Baseline UCAV Wing

Modified Wing Analysis

The modified wing design, featuring thicker ribs and spars in the root and mid-span sections, demonstrated a substantial improvement in load distribution compared to the baseline. The maximum von Mises stress decreased from 566.83 MPa to 99.97 MPa, representing an almost sixfold reduction. Stress contours showed that the critical stress concentrations previously observed at the wing root were successfully redistributed, resulting in a more uniform load path along the structure. Unlike the baseline case, no critical “hot spots” appeared in the reinforced ribs or spars, indicating that the modifications effectively addressed the weaknesses of the original configuration.

In terms of displacement, the maximum amplitude was reduced from 3.81 mm to 0.672 mm as shown in Figure 7 and Figure 8. This improvement highlights the significant gain in stiffness due to rib and spar reinforcement. A lower displacement value implies that the modified wing is less prone to excessive bending or oscillation during maneuvering conditions, which is essential not only for structural safety but also for maintaining aerodynamic efficiency. Excessive deformation of the wing can alter the airflow over the surface, reducing lift and increasing drag; the modified design minimizes this risk.

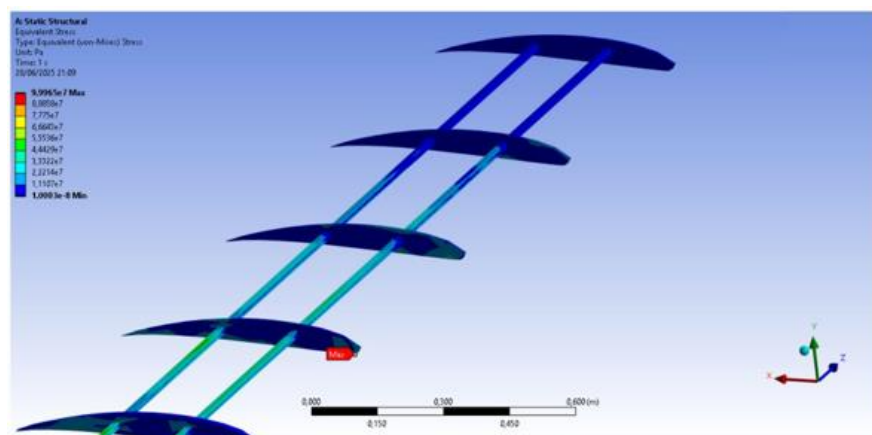


Figure 7. Maximum Von Mises Stress of Modified UCAV Wing

The most important result was the improvement in the minimum safety factor, which increased from 0.67665 in the baseline configuration to 1.9 in the modified wing. By surpassing the lower limit of 1.8 specified in the C.A.S.A Australia Subpart C – Structure UA25.337 standard, the modified design ensures compliance with safety requirements. At the same time, keeping the safety factor below 2.5 prevents unnecessary structural weight, achieving a balance between lightweight efficiency and structural strength. This balance is especially important for unmanned aerial vehicles, where payload capacity and endurance are strongly influenced by structural mass.

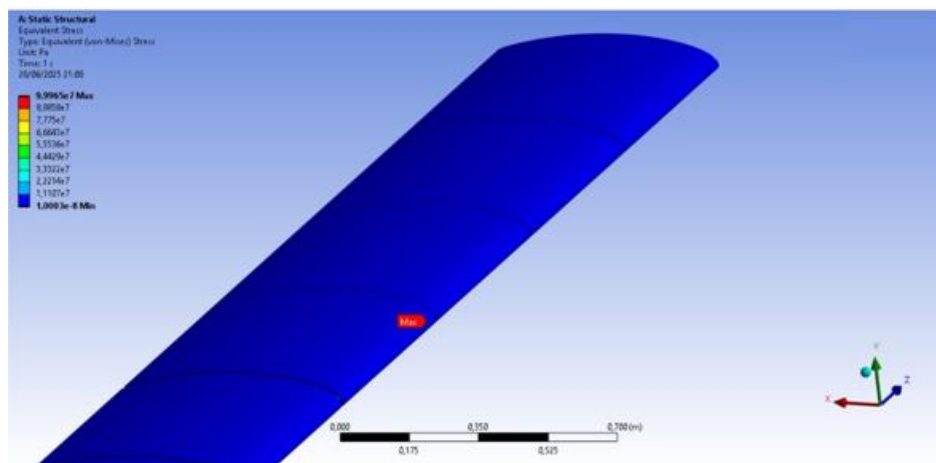


Figure 6. Maximum Deformation of Modified UCAV Wing

Overall, the modified wing analysis demonstrates that targeted reinforcement of ribs and spars is an effective and relatively simple method to enhance structural integrity. Instead of redesigning the entire wing or adopting more exotic materials, incremental changes in thickness in critical areas proved sufficient to ensure safety and reliability. These results suggest that future optimization efforts could explore alternative reinforcement strategies, such as tapering rib thickness along the span or integrating hybrid composite materials, to further reduce weight while maintaining or even improving safety margins.

Comparison and Discussion

A direct comparison between the baseline and modified UCAV wing designs highlights the effectiveness of targeted structural reinforcement. The baseline wing, while geometrically complete and suitable in concept, revealed severe limitations when subjected to aerodynamic loads. With a maximum stress of 566.83 MPa and a safety factor below 1.0, the structure was clearly unable to withstand operational conditions. In practical terms, this meant that the wing would likely fail prematurely during maneuvering or high-load operations, long before meeting the endurance requirements of an unmanned cargo mission. The modified wing addressed these shortcomings through selective reinforcement of ribs and spars in the root and mid-span sections. This strategy is effective because the root region experiences the highest bending moments, making it the most critical area in terms of structural strength. By thickening ribs and spars in these locations, stress concentrations were significantly reduced and redistributed more evenly along the span. The resulting decrease in maximum stress to 99.97 MPa and increase in safety factor to 1.9 show that the structural integrity of the wing is now sufficient to meet the prescribed safety standards.

Another important aspect of the comparison lies in the displacement behavior. The baseline wing showed a maximum displacement of 3.81 mm, which may lead to aerodynamic penalties such as reduced lift-to-drag ratio or even instabilities at high deflection levels. The modified wing, with a reduced displacement of 0.672 mm, exhibited greater stiffness and stability, which translates into more predictable aerodynamic performance. In unmanned aerial vehicles, where stability and endurance are crucial, such structural improvements directly contribute to operational reliability.

The discussion also underscores the balance between safety and weight. A safety factor that is too low indicates risk of failure, while a safety factor that is excessively high often reflects overdesign and unnecessary weight penalties. By maintaining the safety factor within the range of 1.8 to 2.5, the modified design achieves a balance between robustness and efficiency. This is particularly important for cargo UAVs, where payload capacity, range, and endurance are sensitive to structural weight. In this sense, the modified design not only resolves the structural weakness of the baseline but also aligns with the design philosophy of lightweight efficiency.

From a broader perspective, the results highlight a general principle in wing design: small, localized modifications can lead to significant improvements in structural performance. Rather than replacing materials or drastically altering geometry, the study shows that carefully chosen reinforcements in high-stress regions are often sufficient to bring a design into compliance with safety standards. This approach is practical and cost-effective, especially in early development stages where rapid iteration is required.

In future work, the lessons learned here could be applied to more advanced optimization strategies. For instance, instead of uniform reinforcement, gradual tapering of rib and spar thicknesses could be explored to further reduce weight. Similarly, hybrid material systems for example combining CFRP with other composites or lightweight alloys could be tested for additional performance gains. Such developments would build on the foundation established in this study, where a simple but effective modification transformed a non-compliant baseline design into a structurally reliable wing suitable for operational use.

4. CONCLUSION

This study evaluated the structural performance of a semi-span UCAV wing using the Finite Element Method. The baseline design was found to be inadequate, with a maximum stress of 566.83 MPa, a displacement of 3.81 mm, and a minimum safety factor of 0.67665, all of which indicated potential structural failure under operational loads. To address these shortcomings, the ribs and spars in critical regions were reinforced. The modified design demonstrated substantial improvements. Maximum stress was reduced to 99.97 MPa, displacement decreased to 0.672 mm, and the minimum safety factor increased to 1.9. These results confirm that the wing is structurally sound, compliant with airworthiness requirements, and capable of carrying out operational loads safely. Importantly, the safety factor was kept within the range of 1.8 to 2.5, ensuring that the structure is both strong and lightweight without unnecessary overdesign. The findings highlight the effectiveness of targeted reinforcement as a practical approach to UAV wing design. Rather than relying on wholesale redesign or exotic materials, relatively simple modifications to rib and spar thickness produced a wing structure that meets safety standards while preserving efficiency. This balance is critical for unmanned cargo missions, where both reliability and payload capacity must be optimized. Looking ahead, further optimization could include exploring tapered rib and spar geometries, advanced composite materials, or dynamic loading conditions to refine the design. Nonetheless, the results of this study already provide a strong foundation for the continued development of UCAV platforms capable of supporting modern military and logistics operations. Future research development can focus on optimizing rib and spar geometry with tapered designs for more efficient load distribution. In addition, the use of advanced composite materials can be explored to increase strength while reducing structural weight. Further studies also need to consider dynamic loads and extreme operating conditions so that UCAV wing designs are more reliable for military and logistics missions.

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