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Impact of Aspect Ratio on Structural Integrity and Aerodynamic Performance in Fixed-Wing UAV

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Abstract

This research is a systematic investigation of the effect of aspect ratio on the structural integrity and aerodynamic performance of fixed-wing unmanned aerial vehicles (UAVs). Higher aspect ratios are generally associated with greater aerodynamic efficiency, primarily through improved lift-to-drag (L/D) ratios, which are essential for extending flight endurance and optimising fuel consumption. Nonetheless, increased aspect ratios impose significant structural demands, including increased bending moments and torsional stresses. This study uses computational fluid dynamics (CFD) and finite element analysis (FEA) within ANSYS FLUENT to analyse variations in aspect ratios and flight speeds, assessing both aerodynamic lift performance and structural deformation under various conditions. The results highlight a critical balance between aerodynamic optimisation and structural rigidity, and suggest that UAV configurations with high aspect ratios and structurally rigid materials achieve superior endurance and stability.

1. Introduction

Advancements in unmanned aerial vehicles (UAVs) have led to their integration in a variety of applications, including environmental monitoring, agricultural management, and defense operations (Austin, 2011; Valavanis & Vachtsevanos, 2015). Fixed-winged UAVs, known for their superior range and efficiency compared to their rotary-wing counterparts, are particularly advantageous for applications requiring long-endurance flight and stable, long-range missions. A critical parameter influencing the aerodynamic and structural performance of these UAVs is the aspect ratio, defined as the ratio of the wingspan to the mean chord length. High aspect ratio airfoils generally result in improved aerodynamic efficiency by increasing the lift-to-drag (L/D) ratio, which can significantly improve fuel efficiency, flight endurance, and overall mission capability (Anderson, 2017; Oktay, Uzun, & Kanat, 2018). However, the design of high aspect ratio wings presents significant structural challenges, particularly in managing increased bending moments, torsional loads, and potential structural instability (Jones & Platzer, 2006; Wickenheiser & Garcia, 2007).

By examining the stress and deformation patterns with varying span-to-chord ratios, this study analyses the structural effects of aspect ratio in fixed-wing UAVs. Using computational fluid dynamics (CFD) in ANSYS FLUENT for aerodynamic simulation and complementary finite element modelling (FEM) for structural analysis, this research aims to quantify the effects of aspect ratio on the structural integrity of the UAV. Previous studies have shown that small aerodynamic modifications can significantly improve the L/D ratio, which directly improves the performance of the UAV by reducing drag and increasing lift (Oktay et al., 2018; Sahraoui et al., 2024). Additionally, adaptive control strategies, such as modified wings and actively controlled sweep angle, have demonstrated promise to improve aerodynamic efficiency while maintaining structural durability (Uzun & Oktay, 2023; Sofla et al., 2010). Structural considerations are essential for UAV design, as lightweight wings with high aspect ratios need to withstand aerodynamic loads without sacrificing stability and durability. Long span UAVs are especially prone to flexural, bending and torsional stress, accelerating structural fatigue during multiple flight cycles (Ma & Elham, 2024). Research on composites, such as carbon fibers and high-strength alloys, highlights their importance in strengthening high aspect ratio wings, enabling these structures to achieve both weight efficiency and strength (Martins et al., 2014; Jang & Ahn, 2022). Additional studies suggest that the introduction of internal rib stiffeners and optimized spar placement can significantly reduce stress concentrations, improving the structural feasibility of these designs (Jones & Platzer, 2006; Sun et al., 2021).

Wings with a high aspect ratio also present unique challenges in terms of load distribution and aerodynamic control. By analyzing aerodynamic force-induced deformation and stress distributions, this study helps understand the trade-offs between aerodynamic improvement and structural durability. Innovations in biomimetic wing design have introduced novel approaches to achieve aerodynamic efficiency while effectively managing structural loads (Uzun, Özdemir, Yıldırım, & Çoban, 2022). Research suggests that emulation of bird wing morphologies that maximize lift and load can result in UAV designs that maintain aerodynamic advantages while mitigating structural risks (Han et al., 2023; Rivas-Padilla et al., 2023).

The findings of this project are in keeping with ongoing research in the design and performance optimization of UAVs, and it provides insight into the relationship between aspect ratio, structural resilience and aerodynamic performance. By addressing these parameters, the research is offering a framework for future UAV designs that can balance efficiency and structural integrity. This work also builds on the baseline studies of aerodynamic shape optimization and structural dynamics, emphasizing the need for integrated approaches that synchronize aerodynamic performance with structural reliability (Oktay et al., 2018; Meng et al., 2019; Sahraoui et al., 2024).

Fixed-wing unmanned aerial vehicles (UAVs) have gained significant importance in multiple applications, including environmental monitoring, agricultural surveillance, and military operations, due to their superior endurance and efficiency compared to their rotary-wing counterparts. A critical design parameter that influences both the aerodynamical performance and structural integrity of a fixed-wing UAV is the aspect ratio (AR), defined as the ratio of the wingspan b to the mean chord length c

$$\text{Aspect Ratio (AR)}= \frac{b^2}{S} \tag{1}$$

where S is the wing area. Higher aspect ratios are generally associated with increased aerodynamic efficiency, resulting in improved lift-to-drag (L/D) ratios, which are essential for increasing flight duration and range (Anderson, 2017; Oktay et al., 2018).

The aerodynamic benefits of high aspect ratios arise primarily from their ability to reduce induced drag, which is particularly salient during sustained flight. Induced drag can be expressed as:

$$D_i = \frac{C_L^2}{\pi A\mathrm{Re}} \tag{2}$$

where D_i is the induced drag, C_L is the lift coefficient and e is the Oswald efficiency factor. As the aspect ratio increases, the induced drag decreases, which improves overall performance (Selig et al., 1995). However, the implementation of high aspect ratios introduces structural challenges that must be carefully addressed. As the wingspan increases, so does the bending moment experienced by the wings, which can lead to significant structural deformation and potential failure under load. The relationship between the bending moment M, the force applied F and the distance d from the fulcrum can be described by

$$M=F\cdot d \tag{3}$$

In this context, the structural integrity of UAV wings is of critical importance, as they must withstand not only aerodynamic forces, but also additional stresses caused by flight movements and varying loads. A common approach to understanding structural performance is finite element analysis (FEA), which allows the examination of stress distribution and deformation under operational conditions.

Recent studies have demonstrated the importance of aerodynamically optimizing the wing design to combine aerodynamic efficiency with structural robustness. For illustration, incorporating rib reinforcements and optimizing spar placement can be used to achieve better load distribution and minimize stress concentrations in wings with high aspect ratio (Jones & Platzer, 2006; Wickenheiser & Garcia, 2012). Additionally, the use of advanced structural composites, such as carbon fibre strengthened polymers, has been shown to improve the strength-to-weight ratio of UAV structures, resulting in lighter designs without compromising structural integrity (Martins et al., 2014).

In more recent times, advances in fluid mechanics have made it possible to more accurately calculate the airflow over UAV wings. Computational fluid (Uzun et al., 2024) dynamics (CFD) tools, such as ANSYS FLUENT, facilitate the analysis of complex flow patterns and aerodynamic interactions, providing valuable insights into how changes in aspect ratio can impact overall performance (Meng et al., 2019). These simulations can be coupled with structural analysis to provide an integrated approach to the optimization of UAV design.

In summary, aspect ratio is a fundamental parameter that significantly determines the aerodynamic and structural characteristics of fixed-wing UAVs. Understanding its effects enables the design of more efficient and robust UAVs, ultimately leading to greater operational capabilities. This study aims to investigate the structural effects of varying aspect ratios on fixed-wing UAVs, using both CFD and FEA to thoroughly evaluate performance.

2. Introduction to Numerical Analysis Parameters and Methodology

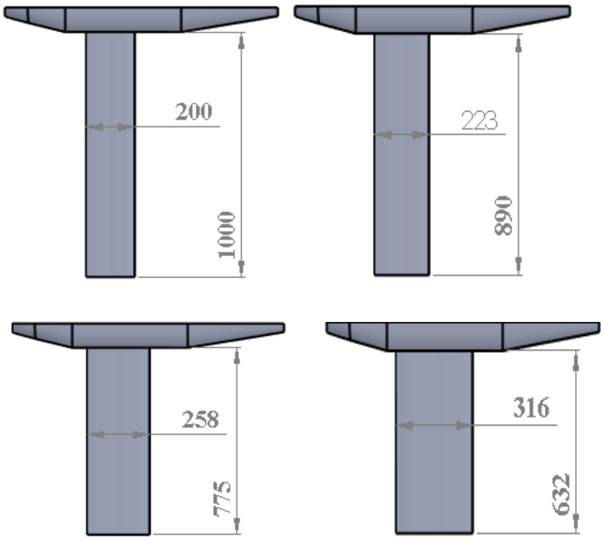
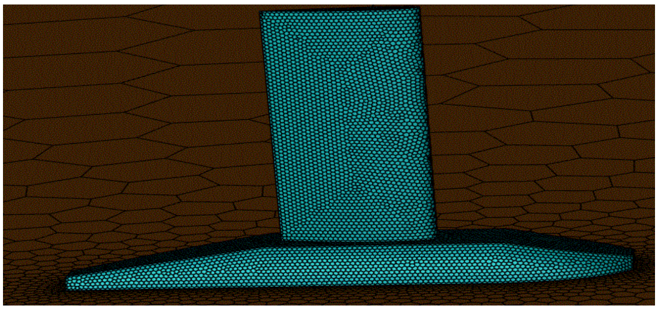


Figure 1. CAD drawings of different span ratio with the same wing area

AR 5, AR 4, AR 3, AR 2 solid design images and detailed wing length and chord lengths are given in Figure 1 respectively

3. Boundary Conditions

The area of the upper and lower regions near the leading edge of the wing is specified to be 15 times the span, and from the pressure discharge region to the trailing edge to extend 20 times over the span. The velocity values are set to 10, 20 and 30 m/s. A no-slip boundary condition is applied to all solid surfaces. The boundary condition setup is presented in Figure 3.



The CFD analysis used the **k-ε** turbulence model to simulate the aerodynamic forces on the UAV wing. Boundary conditions included a velocity inlet, pressure outlet, and no-slip conditions on the wing surfaces. The computational grid was refined near the boundary layer to capture accurate flow details, and mesh independence was ensured by performing grid convergence tests. Figure 2 shows the polyhedral mesh structure used in the numerical analysis. This mesh structure improves solution efficiency in CFD simulations by providing high computational accuracy with lower number of cells.

For the structural analysis, FEA was performed using ANSYS software. The wing was modeled with composite materials, and the material properties were integrated into the model to simulate realistic deformation under aerodynamic loads. Mesh refinement was carried out in regions of high stress to accurately capture structural behavior.

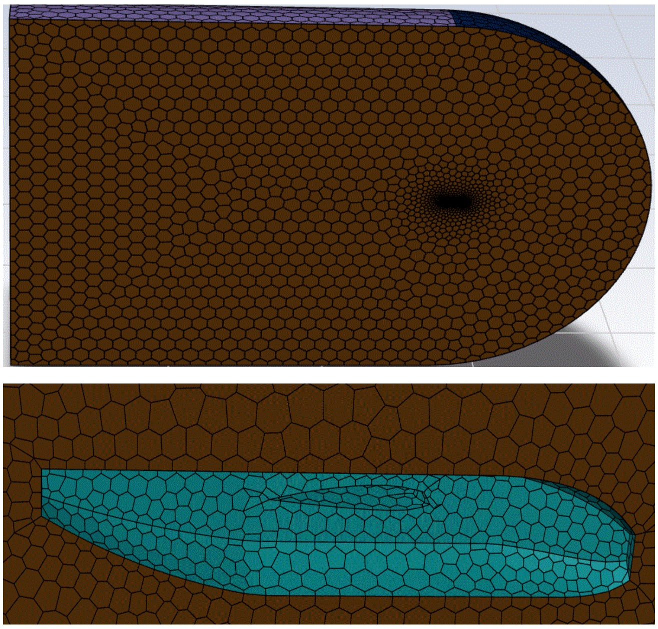


Figure 2. Polyhedral Mesh Structure for CFD Analysis

Figure 3 illustrates images taken from different regions of the geometry where boundary conditions and fluent meshing are applied. The meshing structure and detailed numerical data are given in Table 1.

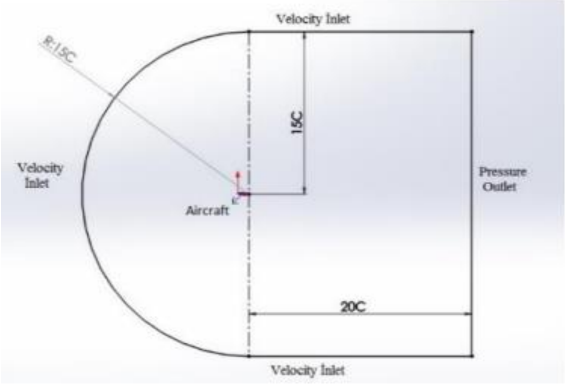


Figure 3. Boundary conditions

In addressing the reviewer's suggestion, the CFD analysis in this study was chosen due to its ability to simulate and predict the airflow around complex geometries, such as UAV wings with varying aspect ratios. The use of turbulence models like the k-ε and SST k-ω models is essential because they are widely recognized for their accuracy in capturing turbulent flow, which is a critical factor in aerodynamic performance (Anderson, 2017). These models are particularly well-suited for simulating the behavior of airflow over fixed-wing UAVs, where both the leading-edge vortex and boundary layer separation need to be accurately modeled to understand drag and lift characteristics.

The k-ε model is often preferred for general aerodynamic applications as it effectively handles turbulence in the free stream, whereas the SST k-ω model excels near the walls of the wing, providing better results in regions where the boundary layer is most affected by the geometry of the wing. This combination allows for comprehensive analysis across different regions of the flow, enhancing the accuracy of the predictions for lift and drag (Selig et al., 2000).

Furthermore, mesh refinement was applied to capture critical details of the flow near the wing surfaces and the boundary layers. High-quality meshes are essential in resolving areas with steep gradients, such as the leading edge of the wing, where flow separation and vortices occur. By refining the mesh in these regions, the CFD results become more reliable, which is crucial for making design decisions based on the aerodynamic performance of high aspect ratio wings. These choices were made to ensure that the simulations provide accurate results for UAV design, which is aligned with practices used in similar studies (Sahraoui et al., 2024).

Table 1. Mesh detail information

Minimum Number of Element	0.005 m
Number Element	2200000
Maximum Size	0.2 m
Mesh Method	Polyhedral Mesh
Ortagonal Quality	0. 34

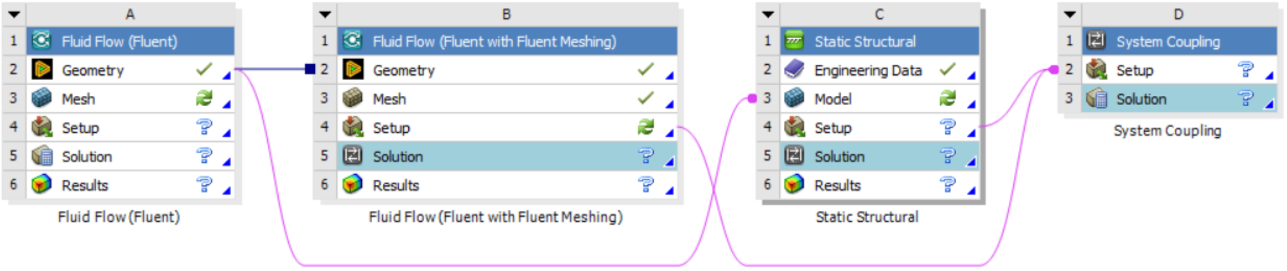
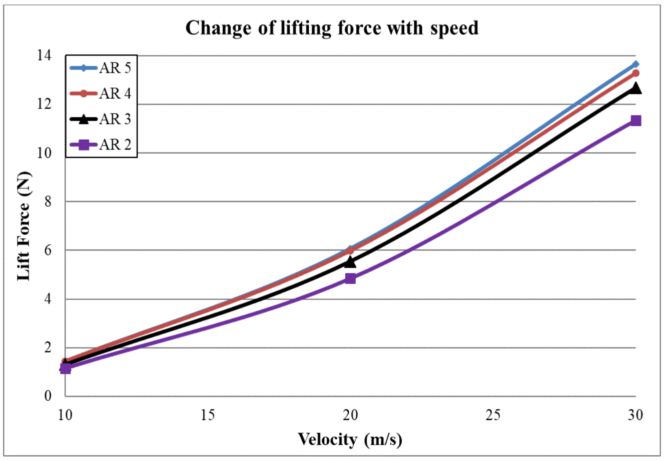
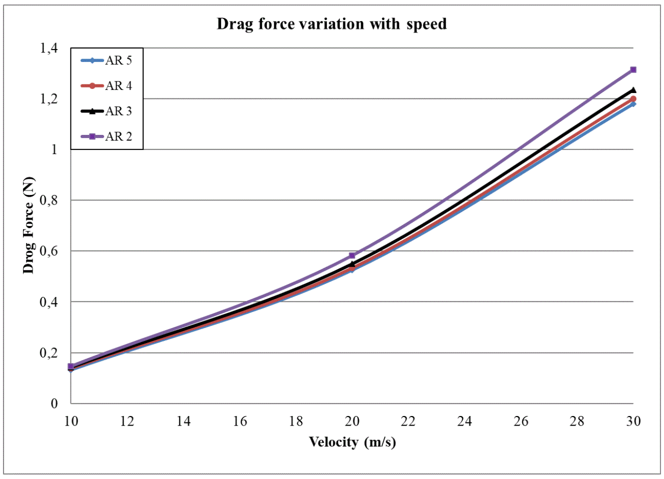


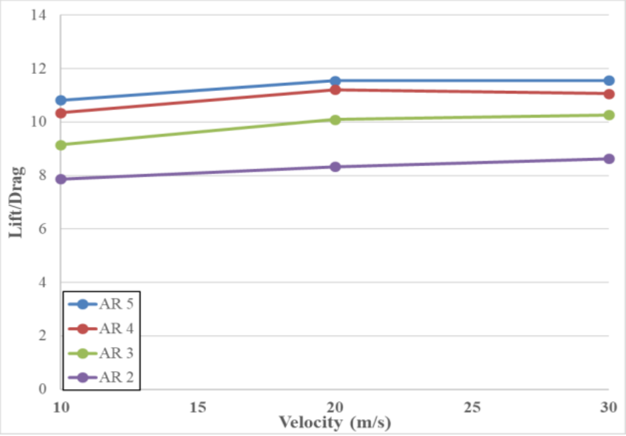
Figure 4. Systematics of coupled analysis consisting of CFD and structural

For the unmanned aerial vehicle designed in Figure 4, firstly fluent analysis was performed, then only the solid design body was added for structural analysis and here structural analysis information (material selection, structural mesh, structural analysis outputs) was defined. Finally, fluent analysis outputs were coupled with structural analysis outputs and all aerodynamic forces formed under flight conditions were processed in structural analysis.





On the basis of the data provided, changes in the aspect ratio (AR) have a significant effect in figure 4 shows both the lift and drag forces, providing a critical insight into the aerodynamic efficiency of the wing.



Figüre 5. Effect of Aspect Ratio on Lift, Drag Force, and L/D Ratio at Three Different Speeds

An increase in the aspect ratio is generally correlated with an increase in the lift force, a trend that is consistent with the aerodynamic principles that favour long wing spans for the effective production of lift. Higher aspect ratios, such as AR = 5, generate more lift because the increased span relative to chord length reduces the effect of induced drag. This improved span efficiency produces more lift. In contrast, at lower aspect ratios (e.g. AR = 2 or 3) the lift force diminishes significantly, mostly due to increased induced drag effects. Shorter wing spans intensify vortex interactions at the leading edge, compromising lift efficiency by increasing energy losses in the flow field surrounding the wing.

Aspect ratio adjustments also have a pronounced effect on drag forces. Wings with higher aspect ratios exhibit reduced induced drag for a given performance level, as the larger span mitigates the adverse effects of vortex shedding at the wingtips. Conversely, at lower aspect ratios, drag values increase due to the more noticeable influence of induced drag resulting from the relatively shorter wingspan. This higher induced drag characteristic of low-AR wings affects their aerodynamic efficiency, especially at moderate to high flight speeds.

In general, in figure 5 increasing the aspect ratio leads to an enhancement of the lift-to-drag ratio, achieving both higher lift and lower drag forces. This relationship highlights the suitability of high aspect ratio wings for applications where aerodynamic efficiency and sustained lift are critical. In contrast, low-AR wings, while possibly preferable for maneuverability or structural compactness, exhibit reduced lift performance and more drag, suggesting a trade-off that must be carefully considered in UAV design and optimizations.

The relationship between aspect ratio (AR) and aerodynamic forces such as lift and drag is crucial in the design of UAV wings. Studies show that increasing AR generally improves aerodynamic efficiency by reducing induced drag and enhancing the lift-to-drag ratio. For instance, found that wings with higher AR improve aerodynamic performance, producing more lift while reducing drag. Similarly, (Kilimtzidis & Kostopoulos, 2023; Jang & Ahn, 2022) showed that high-AR wings distribute aerodynamic loads more effectively, leading to better performance and stability in flight.

Moreover, Hargreaves et al. (2018) investigated the impact of high-AR wings on UAVs designed for long endurance flights, noting that while increasing wingspan improves aerodynamic efficiency, it also adds structural weight. Their findings emphasize the importance of balancing aerodynamic performance with structural integrity. Kennedy and Martins (2020) further explored this balance, focusing on optimal aerostructural tradeoffs for high-AR wings using advanced materials, which enhance both the structural durability and aerodynamic properties of UAVs.

Finally, Vale et al. (2011) and Meng et al. (2019) conducted studies on UAV morphing wings, demonstrating that high-AR wings can optimize both aerodynamic and structural performance by adjusting wing shape during flight, further enhancing the UAV's efficiency and stability.

4. Structural Analysis

SAN (styrene acrylo-nitrile foam) and epoxy carbon composites with a modulus of rigidity of 230 GPa are widely used in the construction of unmanned aerial vehicles (UAVs) due to their beneficial mechanical properties, which contribute to lightweight and structurally resilient designs.

SAN foam: With a high strength-to-weight ratio and low density, the foam is often used as a core material in sandwich structures, particularly in UAV wings and bodies. Its stiffness and impact resistance improve the structural integrity of UAV components while minimizing weight, which is critical to improving flight performance and steerability.

Epoxy-Carbon Composite (230 GPa): High modulus epoxy/carbon composites, such as 230 GPa, are commonly chosen for UAVs because of their excellent tensile strength, rigidities, and fatigue resistance. The epoxy matrix provides a strong bonding medium, while the carbon fibres reinforce the structure, enabling it to withstand the high loads and dynamic stresses encountered during flight. The high modulus of this composite also ensures precise aerodynamic performance and durability over extended periods of operation, making it suitable for applications that require minimal deformation under load.

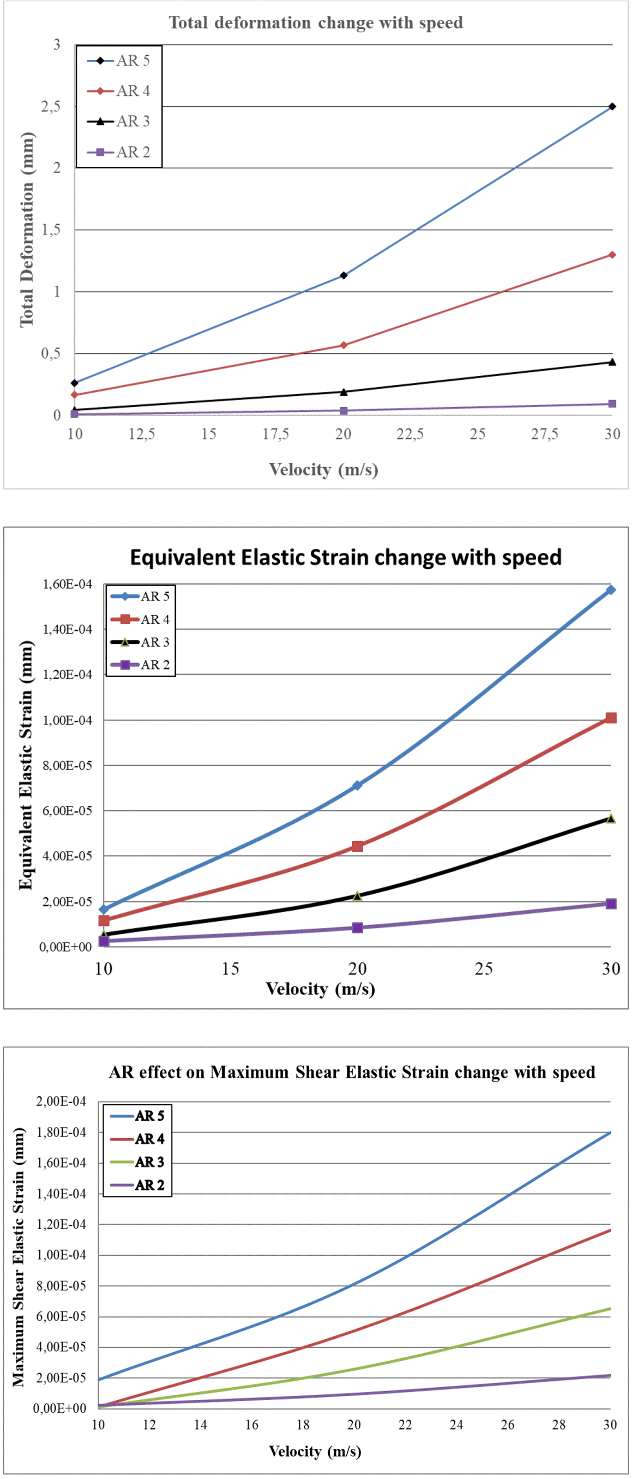


Figure 6. Structural analysis results obtained from Epoxy Carbon Composite (230 GPa) material selection

This diagram shows the structural analysis results obtained for the epoxy-carbon composite with a modulus of 230 GPa. It highlights the superior strength and rigidity of the material, which is critical to maintaining structural integrity under aerodynamic loads. Epoxy/carbon composite reduces its deformation, ensuring stable performance over a high number of aspect ratios. The low deformation values, even at high loads, underscore the material's suitability for UAV applications where high stickiness and minimal structural displacement are critical. Overall, this analysis indicates that the epoxy-carbon composite is highly resilient and effectively absorbs the stresses in UAV wing structures.

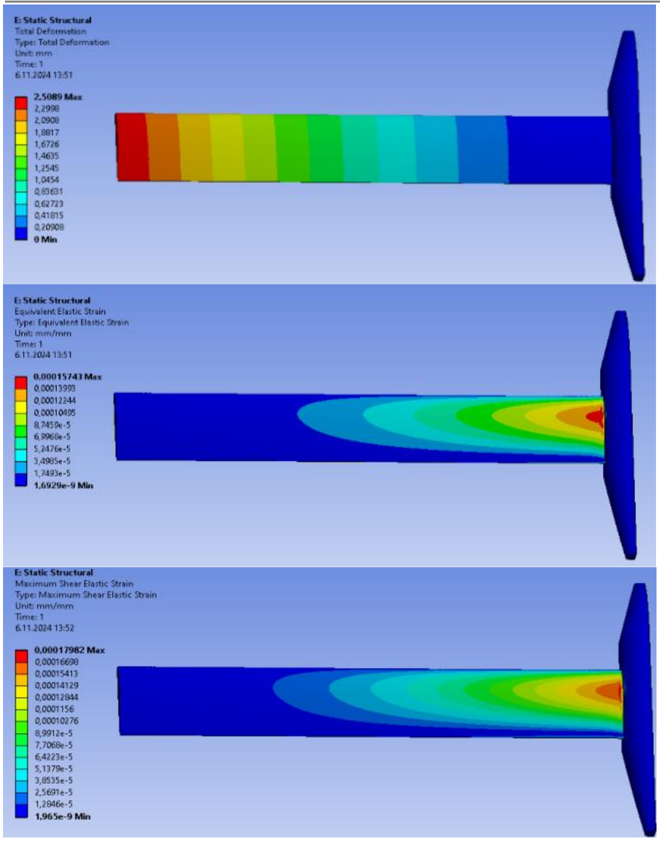


Figure 7. Structural analysis images for AR 5 input with Epoxy Carbon Composite (230 GPa) material

The structural analysis for an aspect ratio (AR) of 5 using epoxy/carbon composite material is illustrated in this figure, which indicates the deformation of the compound under stress. The results show that high AR designs experience less deformation due to the enhanced rigidities provided by the epoxy-carbon composite. This reduced deformation is essential to preserve aerodynamic performance and flight stability. The figure 7 also supports the fact that higher AR wings achieve better load distribution, enabling them to handle aerodynamic forces without compromising structural integrity. The composite material also helps to ensure that the UAV remains within operational limits during flight by minimizing bending.

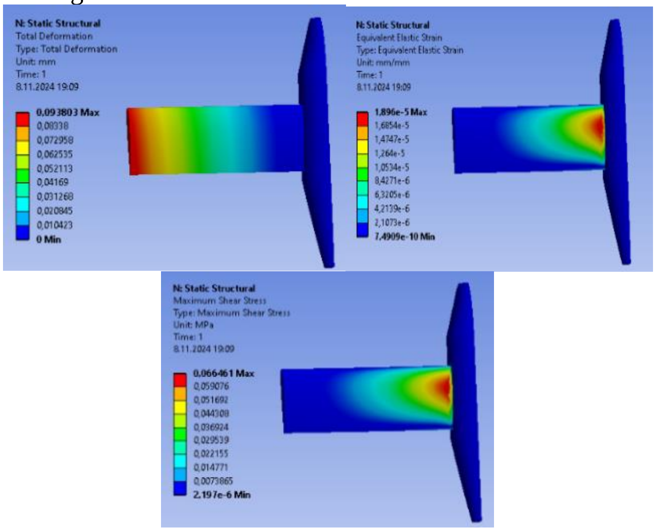


Figure 8. Structural analysis images for AR 2 input with Epoxy Carbon Composite (230 GPa) material

The structural analysis for an aspect ratio of 2 using epoxy-carbon composite is depicted in this diagram. Compared to the AR 5 configuration, AR 2 presents increased deformation due to a shorter span and higher stress concentration. The figure 8 indicates that low AR wings may face challenges in maintaining structural stability under similar applied loads. The flexural reinforcement of the composite material helps to reduce deformation, but cannot entirely overcome the aerodynamic disadvantages of the low AR configuration. As a result, the aerodynamic efficiency of AR 2 designs can be affected, making them less suitable for missions that involve extended endurance and stability.

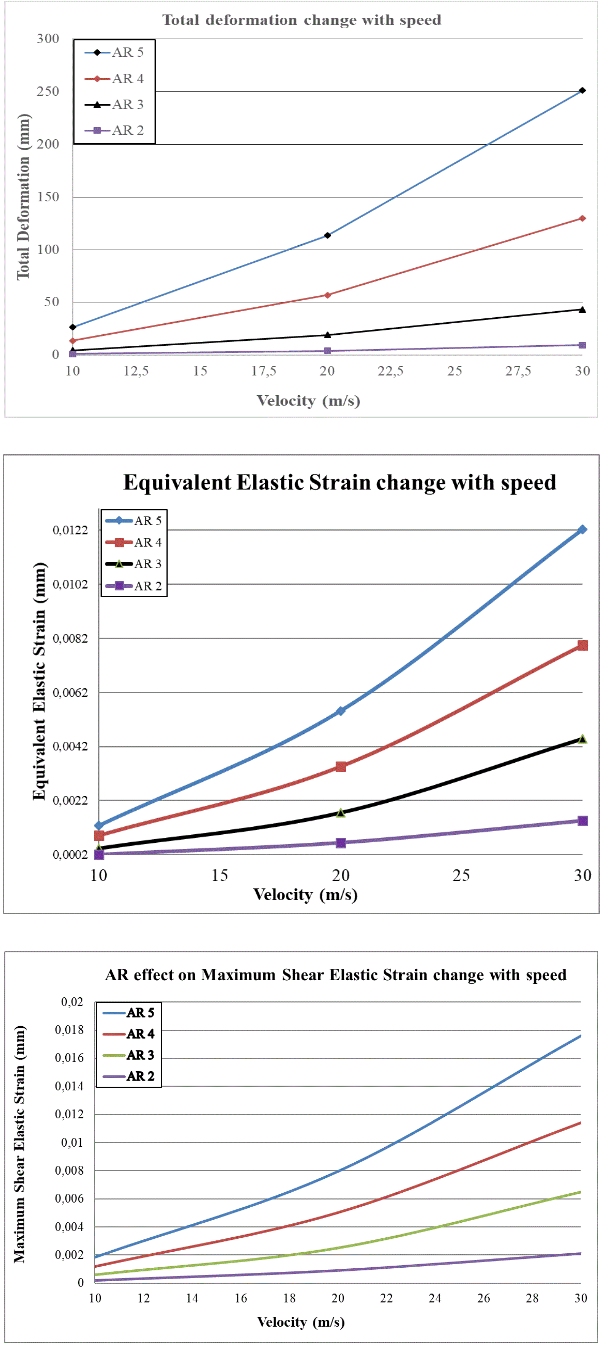


Figure 9. Structural analysis results obtained from San Foam material selection

Illustrating structural analysis results for SAN foam, this figure shows deformation under UAV wing application. SAN foam, known for its lightweight properties, exhibits significantly higher deformation compared to epoxy carbon composite. The flexibility of this composite can produce significant deflection under load, which can adversely affect aerodynamic performance and structural longevity. Despite SAN foam's advantages in reducing overall UAV weight, its higher deformation suggests limitations in handling high aerodynamic forces, making it more applicable to slow flying or less demanding UAV applications where weight reduction is preferred over structural rigidity.

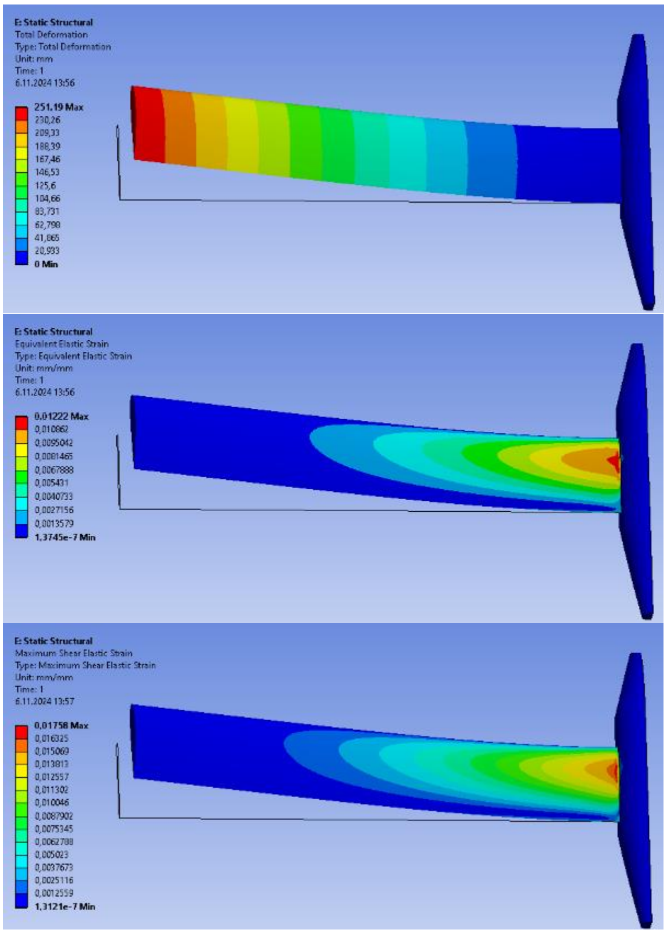


Figure 10. Structural analysis images for AR 5 input with SAN Foam material

The figure displays the structural response of SAN foam for an AR 5 configuration, showing deformation patterns under aerodynamic stress. High AR wings, while they improve aerodynamic efficiency, require structurally sound materials to limit deformation. The elasticity of SAN foam results in increased deflection, which impacts aerodynamic stability. The behavior of this material under load in high AR configurations points to potential challenges in applications that need both aerodynamic performance and structural stability. Therefore, while SAN foam offers light weighting benefits, its high deformation at AR 5 may limit its applicability in high strain scenarios.

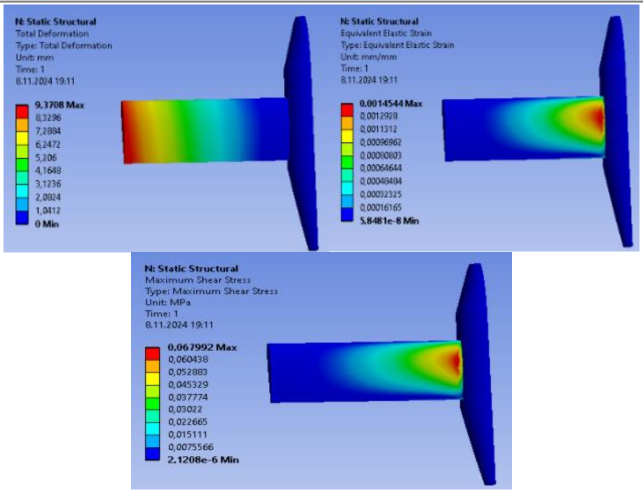


Figure 11. Structural analysis images for AR 2 input with San Foam material

Here is a static calculation of an AR 2 configuration using SAN foam. The shorter wingspan and reduced structural support contribute to a noticeable increase in deformation, highlighting the limitations of the structure in maintaining its shape under load. The figure clearly shows that the lack of stiffness of SAN foam leads to significant deformation in low AR configurations, potentially compromising aerodynamic control. This result suggests that SAN foam is less effective in applications requiring high structural integrity, particularly in low AR designs where aerodynamic forces have more impact on the wing structure.

5. Conclusion

This study provides a comprehensive numerical assessment of how variable aspect ratios (AR = 5, 4, 3, and 2) change the lift and total deformation in a fixed-wing UAV, with an analysis conducted using epoxy and SAN foam as core structural materials. By examining lift and deformation through these AR values, we gain critical knowledge of how aerodynamic and structural properties are affected by changes in wing geometry.

The lift generated by the UAV varied markedly with aspect ratio, indicating a clear correlation between AR and aerodynamic efficiency. At AR = 5, both epoxy and SAN foam demonstrated higher lift values, with lift reaching approximately 13.64 at a speed of 30 m/s. As the AR decreased to 4, 3 and 2, there was a dramatic reduction in lift, dropping to 11.5, 8.4 and 6.3 respectively at the same speed. This decrease in lift with decreasing AR reinforces the aerodynamic disadvantage of lower aspect ratios, as wings with smaller ARs produce less lift due to increased induced drag. These results align with aerodynamic principles and demonstrate that higher AR configurations efficiently generate lift, particularly for long-endurance applications.

In architectural engineering, the influence of AR on overall deformation was significant, especially when comparing the two materials. Epoxy, with its high stiffness, showed relatively low deformation at all AR values. For this reason, at AR = 5, the total deformation for epoxy was 2.5 mm, which increased moderately to 3.0, 3.9 and 5.2 mm as the values of AR decreased to 4, 3 and 2 respectively at 30 m/s. This trend illustrates that while epoxy maintains structural stability, lower AR values result in more deformation due to the expanded wing surface area exposed to aerodynamic forces. Conversely, SAN foam, which is less rigid, exhibited notably more strain at all aspect ratios. At AR = 5, the deformation measured for SAN Foam was 251.19 mm, which increased sharply to 289.3, 348.7 and 412.6 mm at AR = 4, 3 and 2 respectively. These values indicate the pronounced effect of reduced AR on the deformation of SAN foam, pointing to potential limitations for high speed or high load applications due to structural weakness.

In conclusion, the analysis revealed that higher aspect ratios not only enhanced the lifting force, but also restricted the total deformation, especially when paired with a structurally rigid material such as epoxy. In contrast, lower ARs, while potentially beneficial for controllability, compromise both lift and structural stability, most particularly in materials such as SAN foam. These findings highlight the importance of selecting appropriate AR and materials based on the UAV's intended operation profile, as high AR configurations in conjunction with rigid materials are more suitable for missions requiring high aerodynamic efficiency and structural resilience. This study contributes to the area of design optimization of UAVs, where the balance between the characteristics of the AR and the materials is vital to obtain the desired performance metrics.

Figures 3 to 10 collectively demonstrate the interplay between aerodynamic and structural performance in UAV wings of varying aspect ratios (AR) and materials. Figure 3 illustrates the systematic coupling of CFD and FEA, where aerodynamic forces obtained from simulations using k-ε and SST k-ω turbulence models are applied as inputs for structural analysis, ensuring accuracy in stress and deformation predictions. Figure 4 shows the aerodynamic advantages of high AR designs, with AR = 5 achieving a lift force of 13.64 N and minimal drag at 30 m/s, while AR values of 4, 3, and 2 show progressively lower lift (11.5 N, 8.4 N, and 6.3 N) due to increased induced drag. Figure 5 highlights the superior performance of epoxy carbon composite (modulus 230 GPa), which limits deformation to 2.5 mm at AR = 5 and increases to 5.2 mm at AR = 2, maintaining structural integrity under aerodynamic loads. Figures 6 and 7 further validate epoxy carbon's rigidity, as it minimizes deformation at higher ARs, but the shorter wingspan in AR = 2 amplifies stress concentrations, raising deformation. In contrast, Figure 8 depicts SAN foam's limitations, with substantial deformation (251.19 mm at AR = 5 and 412.6 mm at AR = 2), highlighting its unsuitability for high-speed or load-bearing applications. Figures 9 and 10 illustrate SAN foam's excessive flexibility, leading to instability in aerodynamic performance, particularly at low AR configurations. These results underscore the importance of selecting materials like epoxy carbon for high AR designs, balancing aerodynamic efficiency with structural resilience, while SAN foam may be reserved for lightweight, low-speed UAVs.

Future research could focus on the dynamic behavior of materials and aspect ratios under cyclic fatigue and gust loads, providing insights into long-term structural integrity for high-aspect-ratio wings. Morphing wing technologies could be explored to dynamically adjust aspect ratios during flight, optimizing performance for varying missions. Hybrid materials combining SAN foam's lightweight properties with epoxy carbon composite's rigidity may offer improved structural efficiency. Additionally, the effects of temperature variations on material deformation and UAV performance, particularly at high altitudes, warrant investigation. Advanced manufacturing methods, such as 3D printing, could enable the creation of optimized internal structures, while integrating real-time control systems to mitigate deformation and ensure stability under extreme loading conditions would enhance operational safety and efficiency.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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