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Structural and Fatigue Analysis of a UAV Wing

Metin Uzun[1*], Hasan Çınar[2], Abdullah Kocamer[3] and Sezer Çoban[4]

[1*]İskenderun Technical University, Department of Airframe and Powerplant Maintenance, 31200, İskenderun, Hatay, Türkiye. (metin.uzun@iste.edu.tr)
[2]Department of Aeronautical Engineering, Faculty of Aeronautics and Astronautics, Necmettin Erbakan University, Konya, Türkiye.(hasan.cinar@erbakan.edu.tr)
[3]İskenderun Technical University, Department of Airframe and Powerplant Maintenance, 31200, İskenderun, Hatay, Türkiye. (abdullah.kocamer@iste.edu.tr)
[4]İskenderun Technical University, Department of Airframe and Powerplant Maintenance, 31200, İskenderun, Hatay, Türkiye. (sezer.coban@iste.edu.tr)

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Corresponding Author: *Metin Uzun*

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Abstract

In this study, the structural and fatigue analyses of an unmanned aerial vehicle wing are investigated together. The spar, which is the main load carrier of the wing, and the ribs, which are the structural support parts that give the wing its aerodynamic shape, are analyzed using different numbers. Accordingly, 5 cases with different rip and spar numbers were examined with the finite element method. Additionally, aluminium and carbon epoxy materials were considered for the wing material in the simulations. The wall thickness for the wing is 0.5 mm and 1 mm, and the applied loads are 80 N, 150 N, and 250 N, respectively. As a result of these inputs, total deformation, maximum principal elastic strain, and fatigue analyses were performed.

1. Introduction

Structural and fatigue analysis of the aircraft wing is an important research topic in the aerospace industry. These analyses play a critical role in the safety, performance and durability of the aircraft. Aircraft wings have a particularly complex and delicate structure as they encounter aerodynamic effects and are subjected to large mechanical forces during flight (Kocamer et al, 2023).

Structural analysis is a detailed investigation process to evaluate the durability, strength, and overall performance of an aircraft wing. These analyses include factors such as material selection, geometry design, and manufacturing processes. Any structural weakness or defect in aircraft wings can seriously jeopardize the safety of the aircraft. Therefore, structural analyses are a critical stage in the design process. Fatigue analysis evaluates potential material fatigue under the repetitive loads and stresses to which the aircraft is subjected during its service life. This analysis plays an important role in determining the long-term durability and maintenance requirements of the aircraft. It also helps to identify in advance potential problems that may arise due to the use of the aircraft wing over time (Uzun et al, 2023).

The wing structure of the trainer aircraft, designed with Al-7075 and Kevlar, exhibits commendable stress and fatigue resistance, featuring a safety factor of 0.5 (Anil et al., 2017). CSIR_NAL's improved Fatigue Meter aids in the structural fatigue analysis of UAVs, reducing maintenance costs and prolonging service life (Nanda, 2013). Adjusting dynamic characteristics like natural frequencies, damping, and stiffness can enhance the fatigue life and damage tolerance of aerospace-grade composite materials (Anwar et al., 2017). Carbon fiber-reinforced polymer (CRFP) and glass fiber-reinforced polymer (GRFP) outperform Al alloy in aircraft wings, with GRFP showing superior fatigue life and noise reduction (Das & Roy, 2018). A study optimizing carrier-based UAV drawbar parameters through strain fatigue analysis reduces stress levels by 15.7% and increases drawbar life by 122% (Chen et al., 2021).

Conducting CFD analysis and employing structural optimization techniques to optimize a UAV wing structure results in significant weight reduction and an improved strength-to-weight ratio compared to the standard model (Sekar et al., 2020). The finite element model accurately simulates the structural performance of a composite wing for UAVs, featuring a tubercle design at the leading edge, and can predict failure modes at the seventh and eighth layers (Basri et al., 2021). The developed main wing for the HALE UAV reduces structural weight without compromising integrity, enhancing flight endurance without sacrificing safety (Park et al., 2018).

The wing structure of the newly configured UAV meets design requirements and is optimized for weight and stress analysis, paving the way for integrated aero-structural optimization and design (Shi, 2008). A study showcasing the effectiveness of ABAQUS in analyzing static strength and modal behavior of composite UAV wings underscores the importance of evaluating structural integrity and engineering feasibility (Liang-zhong, 2012). Recent research extensively explores structural and fatigue analysis of UAV wings. Johnson et al. (2018) comprehensively studied the impact of varying aerodynamic loads on UAV wing structural integrity, emphasizing the importance of understanding these loads for long-term durability. Smith and Brown (2019) conducted a detailed investigation into material aspects of UAV wing construction, stressing proper material selection for enhanced structural robustness. In the study Chinvorarat, S. (2021). in which Ansys software was used for analysis, it is stated that a light and cost-effective composite wing was created by balancing the amount and orientation of carbon fiber and glass fiber ply patterns. As a result of experimental tests, it has been shown that the optimal wing design is made to withstand maximum loads (positive and negative loads) and can carry these loads without structural collapse. It is stated that the experimental structural deformation and elastic stress are compatible with the finite element model and within an acceptable error range. In a study examining the strength and rigidity properties of the wing of an ultralight unmanned aerial vehicle Sullivan et al. (2009), the wing consists of foam core sandwich skins and various spars with varying laminate layer patterns. A non-geometric finite element model was developed and the static response of the wing under simulated whiffletree loading conditions was obtained by carefully matching the boundary conditions with the experimental setup. Stress and bending predictions obtained from finite element simulations were found to be in good agreement with experimental observations. Peruru et al. (2017) where the material to be used in this study was examined under a different condition and Ansys program was used for analysis, it was determined that carbon epoxy material had lower stress values than s2 glass and aluminium alloy 6061-T8 in static analyses. Additionally, Thompson et al. (2020) provided insights into advanced fatigue analysis techniques for UAV wings, highlighting the necessity of predicting and mitigating potential fatigue failures over the operational life cycle. These studies collectively deepen our understanding of UAV wing structural and fatigue analysis, offering valuable perspectives to enhance the reliability and performance of unmanned aerial systems.

2. Material and Methods

This study aims to examine the total deformation, Maximum principal elastic strain, and fatigue behaviors of a UAV wing (NACA2414) with different rib and spar numbers under different load conditions. In this context, simulation studies were carried out using the ANSYS Structural module. Figure 1 shows the working principle of the structural analysis format in the Ansys analysis program.
The unmanned aerial vehicle wing design has been obtained in a solid design with rib, spar and surface coating in order to prepare it to be strong enough to meet the mechanical loads that may occur during flight.

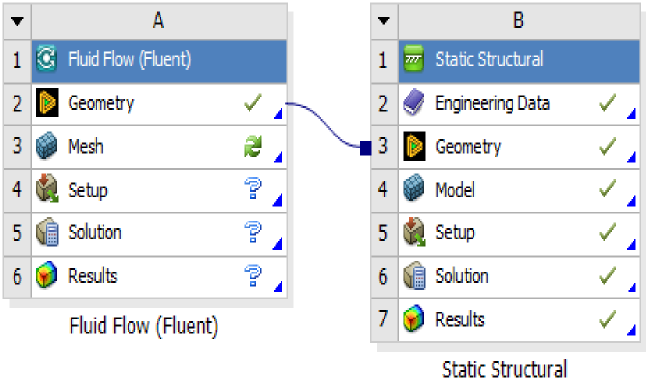


Figure 1. Ansys Static Structural

Mechanical loads acting on the aircraft, deformation in the wing structure, shear stress, compressive stress, as well as the number of ribs and spars to be selected, material preference, and material dimensions affect the life of the structural design. Since the number, material type and dimensions of the structural support parts used in the mechanical design will also affect the take-off weight of the aircraft, choosing the optimum values for the structural design in this study will help in the optimization study. For this reason, it will provide information about the material type, the number of ribs and spars, and the range in which the surface coating thickness can change under loads that may affect the aircraft throughout the flight. Figure 2 shows the mesh work images of the structurally designed wing design before it is sent to structural analysis. To prepare the wing solid design for static analysis, the smallest number of mesh elements was selected as 2 mm, the number of mesh elements was 347318 and the maximum value of mesh skewness was obtained as 0.6677.

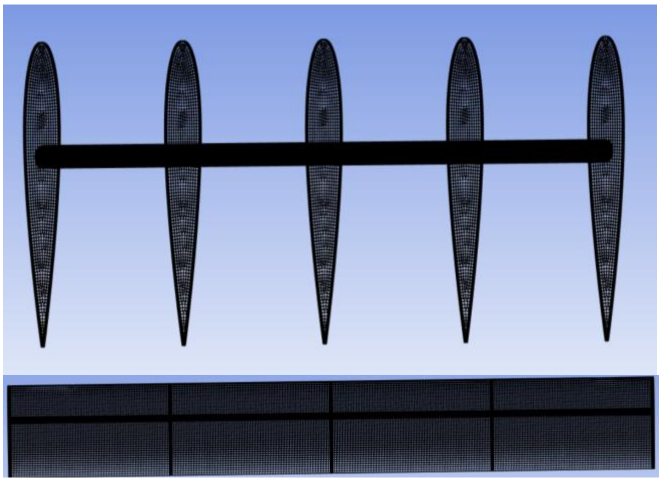


Figure 2. Mesh image of wing structural design

In this study, data is presented in table 1 to examine the static analyzes that will occur as a result of using different numbers of wing support equipment. Here, first of all, a total of 5 ribs and 1 spar, including the wing root and tip, were used for case 1. In Case 2, 3 ribs and 1 spar were used in the wing tip, wing root and wing mid-range. In Case 3, a total of 2 ribs and 1 spar were used at the wing root and wing tip. In Case 4, only 2 ribs were used at the wing root and wing tip, without the use of spar. Finally, in case 5, only 1 rib was used at the wing root.

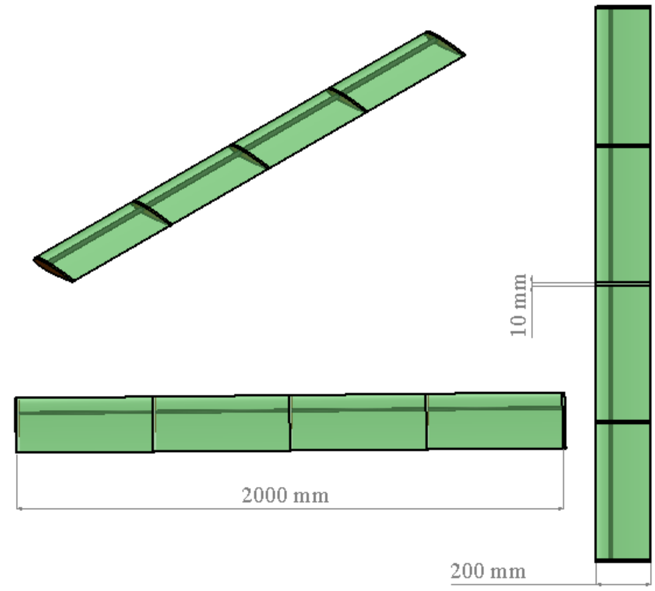


Figure 3. Geometric dimensions of the wing.

In the figure, 3D images of the analysis, structural support parts and dimensions of the wing geometry are given.

Table 1. Cases examined according to the number of ribs and spars.

	Number of ribs	Number of spars
Case 1	5	1
Case 2	3	1
Case 3	2	1
Case 4	2	-
Case 5	1	-

To evaluate the structural analysis of the wing, studies were carried out with different numbers of support equipment used, the support elements were made of aluminum and carbon materials, and the surface coating was made of only aluminum material. Another variable used in this study is the wall thickness of the surface coating material, which was analyzed at two different values: 0.5 mm and 1 mm. In this study, the static forces that will occur as a result of applying three different forces as 80N, 150N and 250N to our aircraft carrying force-producing wing designed with wing surface coating and support equipment are calculated.

3. Result and Discussion

Simulation results of total deformation, maximum principal elastic strain, and fatigue on the UAV wing are given in Tables 2-6 for cases 1-5, respectively. These simulations were performed for wing thicknesses of 0.5 mm and 1 mm and loads of 80 N, 150 N, and 250 N. In addition, aluminum and carbon were examined as wing materials. The yield strength for aluminum and carbon epoxy materials is 240 MPA and 300 MPA, respectively (Rumayshah et. Al (2018); Frulla and Cestino (2008)). Simulation results on the wing are given in Figures 2,3 and 4. In all cases, the wings that have carbon epoxy material have higher total deformation than aluminum material. In addition to the given tables, the maximum principal elastic strain, total deformation, and fatigue results for all cases are given in Figures 5, 6, and 7 respectively.

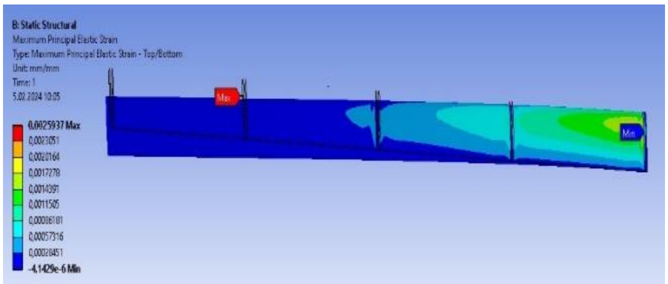


Figure 4. Maximum principal elastic strain on the wing

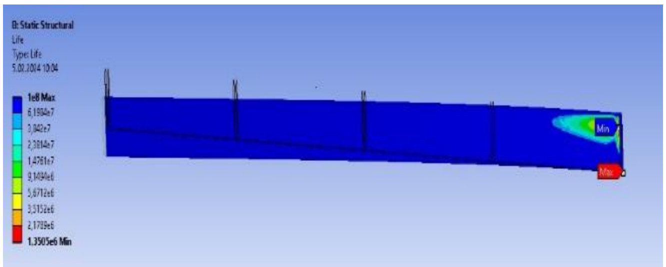


Figure 5. Fatigue on the wing

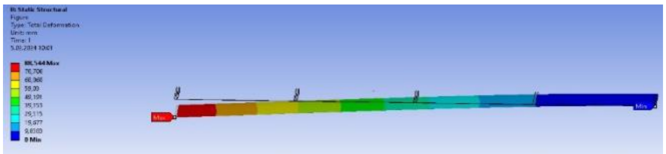


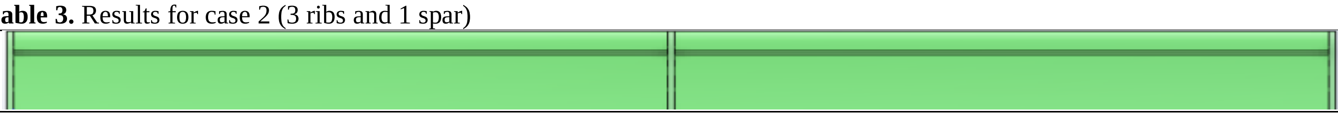
Figure 6. Total deformation on the wing

In table 2, static analysis results are given for the wing structure called case 1, where 5 ribs and 1 spar are used. Here, the different material information used for rib and spar is given in column 1, the thickness of the surface coating in column 2, and the values in N of the different forces applied to the wing surface in column 3. For 3 different input values, total deformation in the wing structure, Max. Principal elastic strain and fatigue values are given as output. When aluminum material is preferred instead of carbon material for rib and spar, which are wing support parts, total deformation and Max. It was observed that the principal elastic strain decreased, but the fatigue values increased in general, although not for every force value. The surface coating material was aluminum for the entire work. When the surface coating material thickness was preferred as 1 mm instead of 0.5 mm, the total wing weight increased, the total deformation decreased, and the value of the change in deformation increased as the applied force value increased. For example, in the case of 250 N applied force with 0.5 mm surface coating, the total deformation was 139 mm, while when the surface coating was selected as 1 mm, it decreased by 50% and was measured as 71 mm. The change in surface thickness also affected the fatigue value, increasing from 2.95E+05 cycle to 8.51E+07.

Table 2. Results for case 1 (5 ribs and 1 spar)

	Thickness (mm)	Load (N)	Total deformation (mm)	Max. principal elastic strain (mm)	Fatigue (cycle)
Carbon	0.5 mm	80	44.531	0.0047072	1.00E+08
		150	83.495	0.0088259	3.13E+07
		250	139.16	0.01471	2.95E+05
	1 mm	80	22.822	2.42E-03	1.00E+08
		150	42.791	4.54E-03	1.00E+08
		250	71.318	7.56E-03	8.51E+07
Aluminum	0.5 mm	80	38.664	3.75E-03	1.00E+08
		150	72.496	7.04E-03	6.52E+07
		250	120.83	1.17E-02	5.28E+05
	1 mm	80	21.147	1.75E-03	1.00E+08
		150	39.651	3.28E-03	1.00E+08
		250	66.084	5.46E-03	1.00E+08

Table 3. Results for case 2 (3 ribs and 1 spar)



	Thickness (mm)	Load (N)	Total deformation (mm)	Max. principal elastic strain (mm)	Fatigue (cycle)
Carbon	0.5 mm	80	45.303	2.94E-03	1.00E+08
		150	84.943	5.51E-03	2.84E+07
		250	141.57	9.19E-03	2.74E+05
	1 mm	80	2.30E+01	1.39E-03	1.00E+08
		150	43.156	2.61E-03	1.00E+08
		250	71.927	4.35E-03	8.31E+07
Aluminum	0.5 mm	80	40.439	1.88E-03	1.00E+08
		150	75.823	3.52E-03	5.39E+07
		250	126.37	5.87E-03	4.41E+05
	1 mm	80	21.63	9.24E-04	1.00E+08
		150	40.556	1.73E-03	1.00E+08
		250	67.593	2.89E-03	1.00E+08

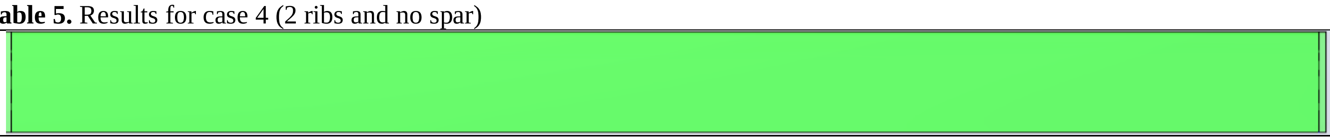
In table 3, static analysis values are given for the wing geometry, which we call case 2, consisting of the wing root, wing tip and 3 ribs and 1 spar located at the wing center. In the transition from case 1 to case 2 design for wing geometry, there is an increase in the total deformation value for all cases, although fatigue values are not affected for the entire study, there is a general decrease, Max. Principal elastic strain values showed differences. For example, when rib and spar carbon material and 250 N force was applied, the total deformation was 139 mm for case 1, while it was 141.57 mm for case 2. For the same input values, the fatigue value decreased from 2.95E+05 to 2.74E+05. It is clearly seen in Table 3 that decreasing the number of ribs in the wing design increases the deformation, albeit slightly, and reduces the fatigue value.

Table 4. Results for case 3 (2 ribs and 1 spar)

	Thickness (mm)	Load (N)	Total deformation (mm)	Max. principal elastic strain (mm)	Fatigue (cycle)
Carbon	0.5 mm	80	45.60746524	0.002855105	100000000
		150	85.51400257	0.005353322	27334157.93
		250	142.5233351	0.008922204	266719.7363
	1 mm	80	23.08689743	0.001243775	100000000
		150	43.28793053	0.002332079	100000000
		250	72.1465547	0.003886798	82198005.26
Aluminum	0.5 mm	80	41.10578463	0.001819731	100000000
		150	77.07334713	0.003411996	49114697.07
		250	128.455576	0.00568666	411815.5266
	1 mm	80	21.80096711	0.000776571	100000000
		150	40.87681357	0.001456071	100000000
		250	68.1280239	0.002426784	100000000

Table 4 shows the static analysis results for different input values for the geometry consisting of 2 ribs at the wing root and wing tip and 1 spar in wing design. Unlike case 2, 1 more rib located in the center of the wing was removed and the results were evaluated. The static analysis results that occurred when moving from case1 to case 2 were similar to those when moving from case2 to case3. When Table 3 is examined, the number of ribs was reduced by keeping the input values constant, and a partial increase in total deformation was observed for each analysis, along with a partial decrease in fatigue values.

Table 5. Results for case 4 (2 ribs and no spar)



	Thickness (mm)	**Load (N)**	**Total deformation (mm)**	**Max. principal elastic strain (mm)**	**Fatigue (cycle)**
Carbon	0.5 mm	80	46.16313289	0.002890485	100000000
		150	86.55587226	0.005419659	24490549.89
		250	144.2597846	0.009032764	245863.0446
	1 mm	80	23.22830823	0.001251567	100000000
		150	43.55307865	0.002346688	100000000
		250	72.58846441	0.003911146	79182346.31
Aluminum	0.5 mm	80	45.1608937	0.001997619	100000000
		150	84.67667616	0.003745535	21151120.64
		250	141.1277961	0.006242558	220547.8036
	1 mm	80	22.89032986	0.00081514	100000000
		150	42.91936968	0.001528387	100000000
		250	71.53228153	0.002547311	76089377.54

Table 5 shows the static analysis results for different input values for the geometry consisting of only 2 ribs at the wing root and wing tip. After the static analysis in Table 4, the spar, which is the longitudinal support piece, was also removed and its static effect was examined in this table. After the spar was removed, the total deformation created more difference as the case 4 study, spar was removed in this study and a decrease in fatigue value was observed for the first time for an aluminum material with 2 mm wall thickness. Therefore, it is clearly seen that spar is an important factor for structural support. applied force value increased. Especially when 250 N force was applied using carbon material with a wall thickness of 0.5 mm, approximately 2.5 mm more deformation was observed. Fatigue values remained constant at 80 N force application, but a decrease was observed in fatigue values at 150 and 250 N force applications. While spar was used in all studies until the

Table 6. Results for case 5 (1 ribs and no spar)

	Thickness (mm)	Load (N)	Total deformation (mm)	Max. principal elastic strain (mm)	Fatigue (cycle)
Carbon	0.5 mm	80	46.838563	0.001086038	100000000
		150	87.82230706	0.002036321	23475428
		250	146.3705041	0.003393868	238268.0057
	1 mm	80	23.31540189	0.000704117	100000000
		150	43.71637664	0.00132022	100000000
		250	72.860629	0.002200367	78361312.19
Aluminum	0.5 mm	80	46.42790796	0.001110006	100000000
		150	87.05232791	0.002081261	18841497.41
		250	145.0872157	0.003468769	202432.2108
	1 mm	80	23.09100956	0.000580818	100000000
		150	43.29564149	0.001089034	100000000
		250	72.15940249	0.001815056	73900939.52

In this study, there is only 1 structural rib at the wing root, which we call case 5 in table 6. After removing 1 rib at the wing tip, there was a decrease in the total deformation for the study, but no serious change was observed. However, when we look at the fatigue values, the structural strength decreased significantly, especially when 250 N force was applied.

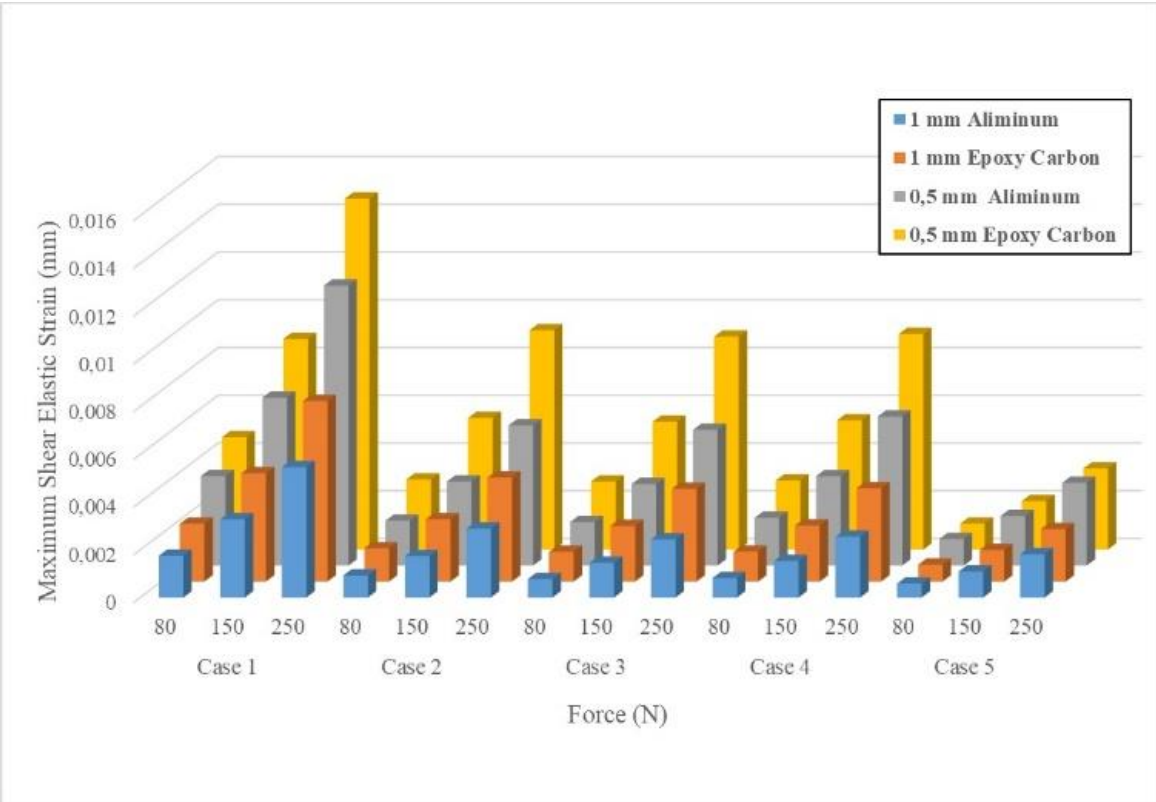


Figure 7. The results of the maximum principal elastic strain

In figure 7, the maximum shear elastic strain values for different input values are given graphically as a summary of all studies. In this chart, the horizontal axis shows the structural designs and applied force values we mentioned in Table 1, and the vertical axis shows the maximum shear elastic strain values for these input values.

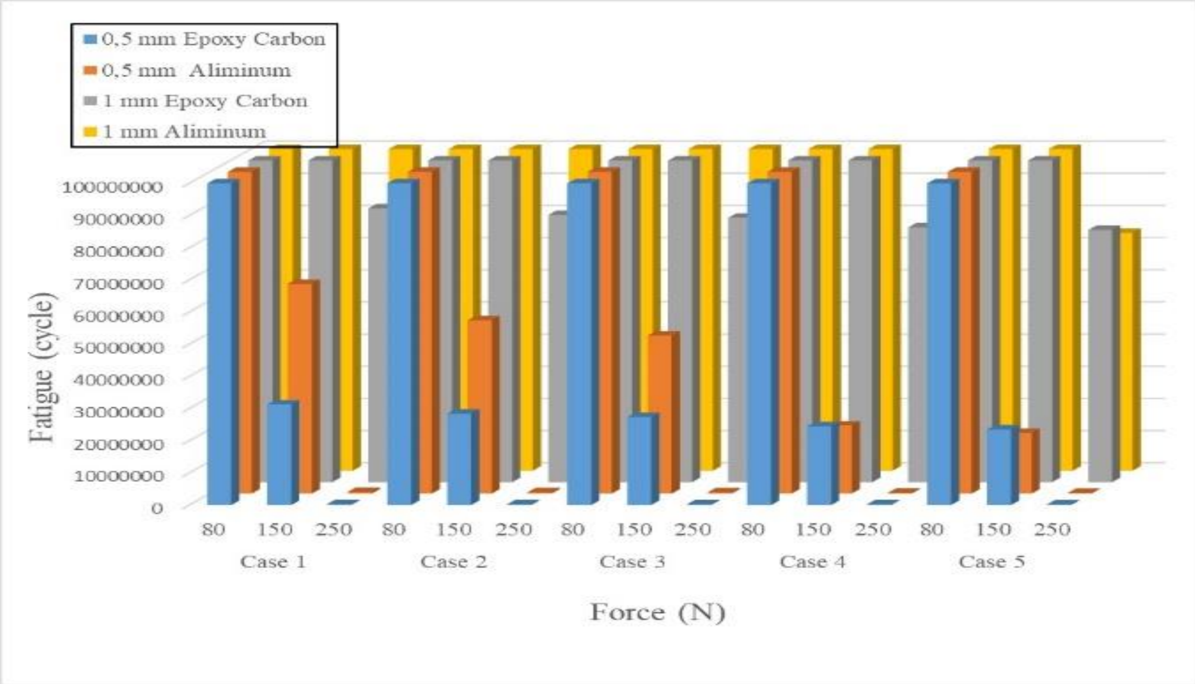


Figure 8. The results of fatigue

In figure 7, the fatigue values for different input values are given graphically as a summary of all studies. In this chart, the horizontal axis shows the structural designs and applied force values we mentioned in Table 1, and the vertical axis shows the fatigue values for these input values.

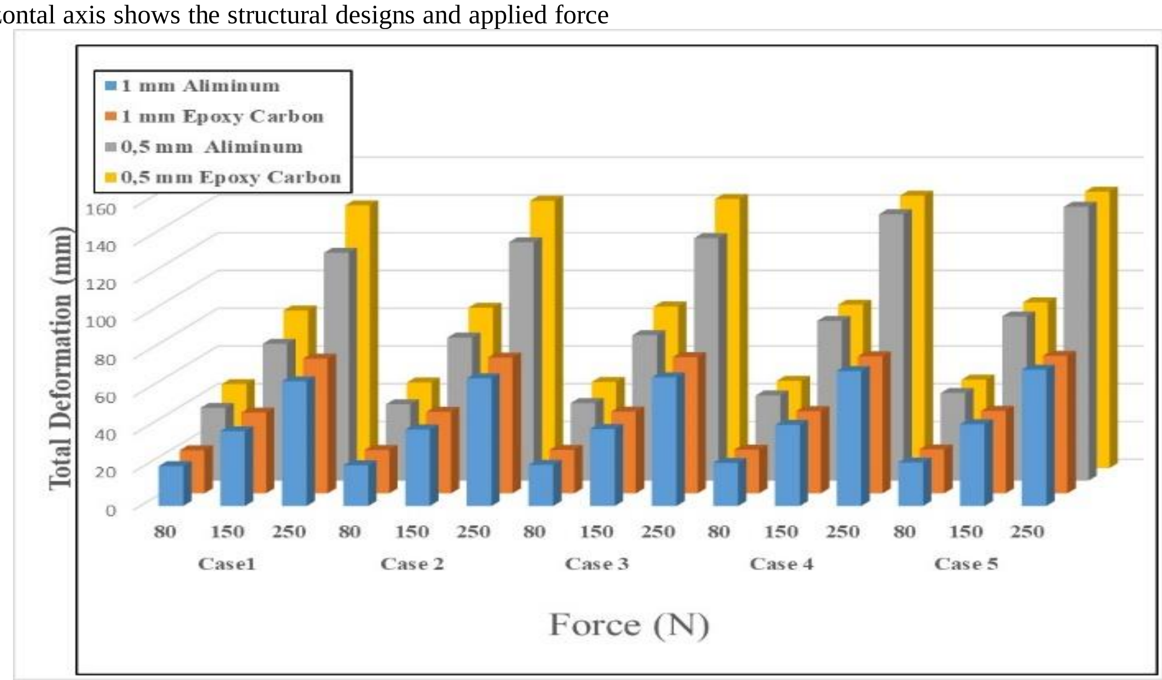


Figure 9. The results of total deformation

In figure 7, the total deformation values for different input values are given graphically as a summary of all studies. In this chart, the horizontal axis shows the structural designs and applied force values we mentioned in Table 1, and the vertical axis shows the total deformation values for these input values.

4. Conclusion

In this study, the structural behavior of a UAV wing with NACA 2414 airfoil was examined in 5 different cases depending on the number of ribs and spars. As wing materials, were considered carbon and aluminum, and simulation studies were conducted with the help of the ANSYS program under 80, 150, and 250 N loads and with 0.5 mm and 1 mm wing thickness. As a result, for these 5 cases, the total deformation, Maximum principal elastic strain and fatigue results are summarized in Table 2-6. According to these results, the maximum elastic strain among all cases was in case 1 for Epoxy carbon material with 0.5 mm wing thickness. The largest total deformation was for epoxy carbon material of 0.5 mm blade thickness in case 5 (for 250 N). In general, the life behavior of the aluminum material was better than that of the epoxy carbon material for all cases. In addition, it was observed that the total deformation and maximum principal elastic strain values decreased with increasing material thickness. This indicates that the structural strength increases with increasing material thickness and the material is subjected to less deformation. Another finding is that the deformation and elastic strain values of the material increase with increasing load. This shows that the material deforms more under higher loads and pushes its elastic limits more. As a result, it was determined that carbon and aluminium materials exhibit different behaviours under different thicknesses and loads. These findings should be taken into account in material selection and design processes in structural engineering applications. It is also recommended that future research should investigate and analyze these factors in more detail. In future work, the authors plan to carry out geometric optimization studies of the variable thickness wing for case 5 of this study.

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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