AERO2357 – Design Analysis of an Aircraft Wing Structure

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ABSTRACT: The Lockheed U-2 reconnaissance aircraft, known as the "Dragon Lady," has played a significant role in intelligence gathering since the 1950s. To enhance its performance and efficiency, this study employs Finite Element (FE) analysis to optimize the wing design of the aircraft. Two airfoil types and four different load cases are analysed to determine the most weight-efficient wing configuration. Design parameters must be adhered too. This includes a 14m wing length, 3m chord, and the ability to support various loads while maintaining a safety factor of 2. The analysis employs Abaqus CAE 2020 software and two materials: Aluminium-2024 (Al-2024) and epoxy/carbon fibre (ECF) composite. The results reveal that the carbon fibre composite can meet all design requirement with ultra-lightweight capabilities. However the cost effectiveness of this solution will be problematic. This study provides valuable insights into the structural design of the U-2 reconnaissance aircraft's wings, offering potential improvements in performance and efficiency that were unheard of in the 1950s.

KEY WORDS: *FE Analysis, Airfoil, U-2, Aircraft, Mass, Aerodynamics, Optimisation.*

Introduction

The Lockheed U-2 is a single-jet engine spyplane that was built to revolutionise reconnaissance aircrafts in the 1950s.

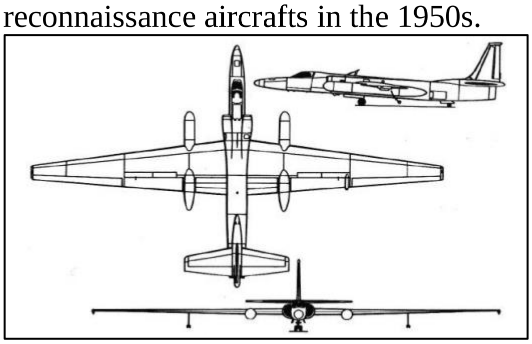


FIGURE A: 3-view Schematic of the Lockheed U-2 Reconnaissance Aircraft.

Developed by the Kelly Johnson and the 'Skunkworks' engineering team, it was nicknamed the "Dragon Lady" and provided day and night intelligence for the US government at an altitude of 21,300 meters [1]. The secretive nature of the aircraft reflected the specific mission requirements that was intended. The large wingspan allowed the spyplane to travel at much higher altitudes.

The U-2 aircraft uses a hybrid airfoil. At the wing root it uses a NACA64A409 and at the wing tip, it uses a NACA64A406 [1]. Its' first flight was on the 1st of August 1955, and can be controlled by one pilot [2]. Figure A displays the 3-view schematic of the aircraft that is being analysed [1].

To decrease weight of the wing, Finite Element (FE) analysis must be conducted. The aim is to conduct a better job at designing the wings for the U-2 to maximise efficiency of the aircraft. This will be done by analysing two airfoil types with four different Load Cases (LC) as detailed in Table A.

TABLE A: 3-view Schematic of the Lockheed U-2 Reconnaissance Aircraft.

Load Case	Analysis Type	Considerations
(a)	Static	Fuel, wing
(b)	Static	Fuel, wing, lift
(c)	Dynamic	Fuel
(d)	Dynamic	No Fuel

The analysis involves solving the maximum vertical deflection and von Mises stress for LC (a) and (b), and the first three natural frequencies for LC (c) and (d). Plotting the fundamental mode shape for load cases (c) and (d) must also be conducted. These FE analysis methods will help determine the most weight efficient wing.

Wing Design Requirements

The length of the wing must be 14m long with a 3m cord. The total mass of fuel is 10,887kg which is split evenly amongst the two wings exactly 4m from the root. They must be able to support the mass of the wing itself, max fuel load, fuselage, tail (dry weight), and lift load. The dry weight is a total of 7,257kg and the tip of the wing must not displace more than 1m. Finally, the fundamental natural frequency must be at a minimum of 20% away from 1200 rpm (20Hz). This accounts for the engine idling for an empty and fully fuelled aircraft.

Because only one side is being examined, it is important to consider half of all masses that the singular wing must carry. The wing must also be designed with a Factor of Safety (FoS) of 2 against the yield strength of the decided material.

TABLE B: Summary of Design Requirement

Design Requirement
- 14m length and 3m chord.
- Fixed wing root.
- Total fuel mass is 10,887kg (halved) located 4m from the wing root.
- Wing supports dry, wing and fuel weight.
- Wing supports lift load.
- Design with a FoS of 2
- Total dry weight is 7,257kg (halved).
- Wing tip displacement < 1m
- First mode natural frequency < 20% of 20Hz

Some assumptions that must be considered are as follows. The wing has no taper. The root of the wing is fully fixed to the fuselage. The mass of the spars, strings and ribs are disregarded. And finally, the shape of the airfoil does not affect any other specifications like drag generation.

Methodology and Analysis

Abaqus CAE 2020 will be used to analyse two airfoils with four different load cases. As detailed in table A, the four load cases help determine if the wing will meet the mandatory design requirements, with fuel, weight and lift taken into consideration.

During the testing phase, troubleshooting Abaqus was difficult to manage. The process began by drawing the FE representation of the structure in 3D space using a wire. Following this, an appropriate metal alloy was assigned in the materials module.

This analysis will study two materials. Aluminium-2024 (Al-2024) [3] and an epoxy/carbon fibre (ECF) composite [4]. Table C details the properties for these two materials.

TABLE C: Material Properties for Aluminium-2024 and Epoxy/Carbon Fibre Composites [3, 4].

Property	Al-2024	ECF
Density	2.78 g/cc	1.41 g/cc
Tensile Yield Strength	324 MPa	1230 MPa
Elasticity Modulus	73.1 GPa	99.9 GPa
Poisson Ratio	0.33	0.29

Al-2024 is made of the following elements. Al, Cr, Cu, Fe, Mg, Mn, Si, Ti, and Zn. It is often used in aircraft structures due to its high strength and fatigue resistance. It is also relatively light weight hence a great material for aircraft wings [3]. ECF is an extremely strong and light weight composite. The manufacturing costs are high, hence is not practical to use for all components. However, it will be perfect for the U-2s wings due to its high strength to weight ratio [4].

These materials are created in Abaqus, and the specific properties are applied to the application. It is important to keep units consistent with each other as Abaqus does not specify when inputting the data. Throughout the analysis, SI units will be used which are as follows: pascals (Pa), kilograms (kg), meters (m), newtons (N), and seconds (s).

A beam section is created using a beam profile which is then assigned a beam orientation. This profile is created using the arbitrary module.

The arbitrary beam section is a useful tool to model an airfoil. An airfoil plotter index is used to select an appropriate cross-section and provides exact coordinates in a CSV file format. The NACA64A410 and NACA0012 airfoil cross-sections will be analysed. The units in the CSV file are converted to meters, and the skin thickness is adjusted according to the specific design parameters.

After an optimal thickness is determined for each material and airfoil, the weight of the wing can be calculated by Abaqus. This is found in the 'Tools' module in the 'Query' tab. Selecting 'mass properties will display the mass of the wing in the message window.

The lift load must be calculated next using the equation displayed below.

$$Lift\ Load = \frac{1}{2} dry\ weight\ excluding\ wing + \frac{1}{2} total\ fuel\ mass + wing\ weight \qquad (1)$$

It is important to note that lift load is a distributed line load, and that the units must be in N/m. Hence to convert a force in kg, the value must be multiplied by gravity (9.81m/s) to generate the newton force, and then divided by the length of the airfoil (14m). This process must also be done when converting the mass of the wing according to the material properties from a concentrated force to a line load in N/m.

Now, using the load module in Abaqus, the mass of the wing, fuel and lift load can be applied to the wing profile, and the boundary conditions can be set. Figure B shows how the beam analysis should approximately appear.

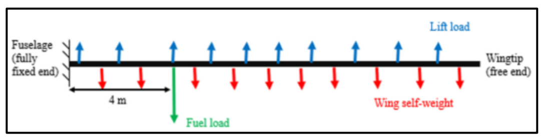


FIGURE B: Beam Model of Wing with Loads Applied.

Most of the computer aided programming is set, and the analysis process is slowly piecing together. The analysis steps must be implemented. An effective way to do this involved creating three main steps. The 'initial' step loaded the boundary conditions. Following this a 'LoadCaseAB' step was programmed. This step aided in the analysis of LC(a) and LC(b). The final step was labelled 'LoadCaseCD' Similarly, this step aided in the vibrational analysis of LC(c) and LC(d). An additional process required to allow the third step to process correctly involved adding a special 'pointmass /

inertia' within the property module. This allowed for fuel to be a consideration when undergoing vibrational analysis.

Abaqus allows for specific modules to be supressed. This tool helped when conducting separate jobs for each load case. To analyse LC(a) the third step, lift load, and point mass were all supressed. To analyse LC(b), lift load was unsuppressed. To analyse LC(c), the third step and pointmass was unsuppressed. Finally, to analyse LC(d), point mass was supressed once again. These suppression account for the special considerations as detailed in table A. It is important to note that when switching between materials for each airfoil, one must always be supressed to not confuse Abaqus when producing results.

The final step was to submit each job for each load case, for each airfoil, and for each material. The results are as follows.

NACA 64A410

The NACA64A410 was the first airfoil examined. The cross section is displayed in figure C [5].

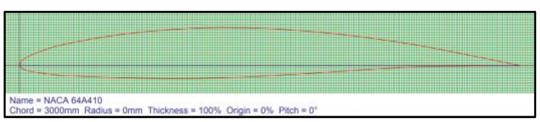


FIGURE C: NACA64A410 Airfoil [5].

This airfoil was historically used for heavy bomber aircrafts, however, will be repurposed for this design project [6].

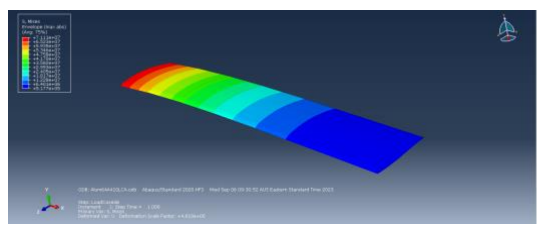
Aluminium-2024

Following the steps detailed in the methodology and analysis section, the NACA64A410 was able to be optimised to meet each specific design requirement as detailed in table D. It was found that a skin thickness of 0.015m fulfilled these standards.

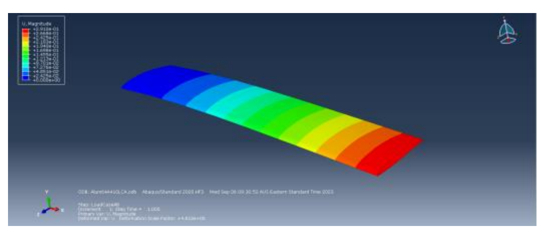
TABLE D: Design Requirements for NACA64A410 Al-2024 with skin thickness = 0.015m

Design Requirement	Fulfilled
14m length and 3m chord.	✓
Fixed wing root.	✓
Total fuel mass is 10,887kg (halved) located 4m from the wing root.	✓
Wing supports dry, wing and fuel weight.	✓
Wing supports lift load.	✓
Design with a FoS of 2	✓
Total dry weight is 7,257kg (halved).	✓
Wing tip displacement < 1m	✓
Natural frequency < 20% of 20Hz	✓

LC(a) is displayed in figure D. To keep track of each analysis, a key was created for organisational purposes. Each title is represented by the following key: *Criteria_LoadCase_Airfoil_Material_Thickness(m)*
For example *U_LCF_0012_Fe_t=0.2*
Where the criteria are represented by
S= stress, U=displacement, Freq1=mode1
The example above means the image is displaying displacement, for load case F, with the airfoil 0012, made of Iron with a thickness of 0.2m. This key will be used throughout the analysis process.



S_LCA_64A410_Al_t=0.015

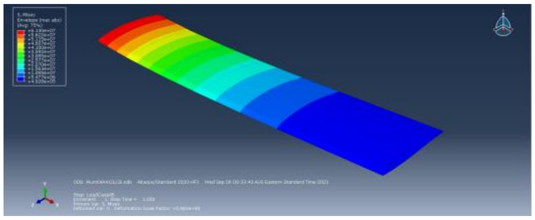


U_LCA_64A410_Al_t=0.015

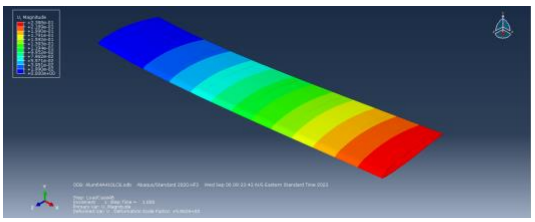
FIGURE D:LC(a) for NACA64A410.

The maximum von Mises Stress is 7.111e07Pa and the maximum vertical displacement is 2.910e-01m for LC(a)

LC(b) is displayed in figure E.



S_LCB_64A410_Al_t=0.015

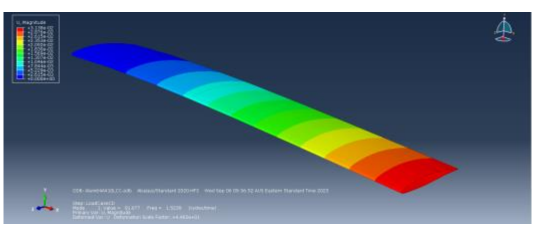


U_LCB_64A410_Al_t=0.015

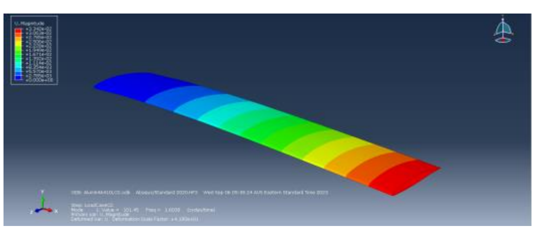
FIGURE E:LC(b) for NACA64A410.

The maximum von Mises Stress is 6.130e07Pa and the maximum vertical displacement is 2.388e-01m for LC(b)

The first mode natural frequency for LC(c) and LC(d) are plotted in figure F.



Freq1_LCC_64A410_Al_t=0.015



Freq1_LCD_64A410_Al_t=0.015

FIGURE F:LC(c) and LC(d) for NACA64A410.

The first mode natural frequency for load case (c) and (d) is 1.52Hz and 1.60Hz respectively.

Table E summarises the findings from each analysis for Al-2024.

TABLE E: Results Summary

Findings	**Value**
Airfoil Type	NACA64A410
Thickness	0.015m
Material	Aluminium-2024
Weight	3549.63 kg
Lift Load	8844.156 N/m
LCA Displacement	291mm
LCA Stress	71.11 MPa
LCB Displacement	238.8mm
LCB Stress	61.3 MPa
LCC Freq 1	1.5239 Hz
LCC Freq 2	5.5734 Hz
LCC Freq 3	11.387 Hz
LCD Freq 1	1.6030 Hz
LCD Freq 2	9.2715 Hz
LCD Freq 3	12.155 Hz

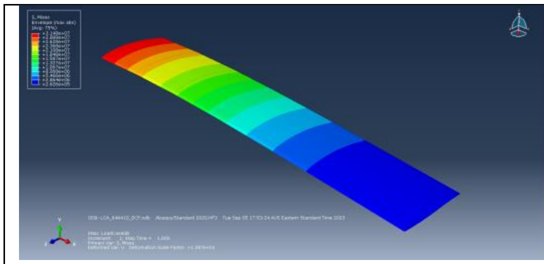
Epoxy/Carbon Fibre

By analysing the airfoil using ECF, it was found that the skin thickness was most optimal at t=0.008. With this thickness, each design requirement was fulfilled as detailed in table F.

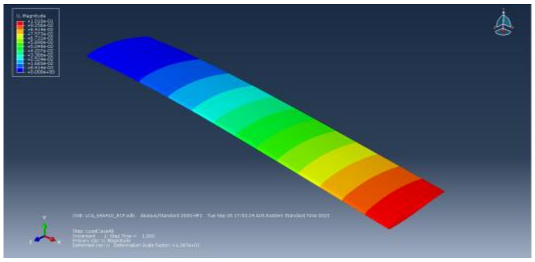
TABLE F: Design Requirements for NACA64A410 ECF with skin thickness = 0.008m

Design Requirement	**Fulfilled**
14m length and 3m chord.	✓
Fixed wing root.	✓
Total fuel mass is 10,887kg (halved) located 4m from the wing root.	✓
Wing supports dry, wing and fuel weight.	✓
Wing supports lift load.	✓
Design with a FoS of 2	✓
Total dry weight is 7,257kg (halved).	✓
Wing tip displacement < 1m	✓
Natural frequency < 20% of 20Hz	✓

Now that all of the design requirements are met, the airfoil can be analysed. LC(a) is displayed in figure G.



S_LCA_64A410_ECF_t=0.008

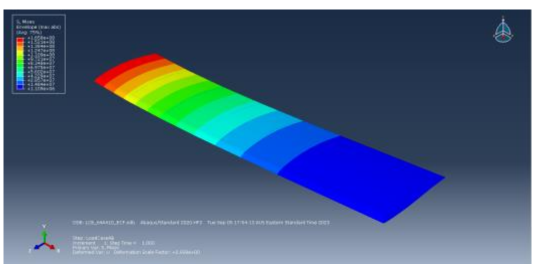


U_LCA_64A410_ECF_t=0.008

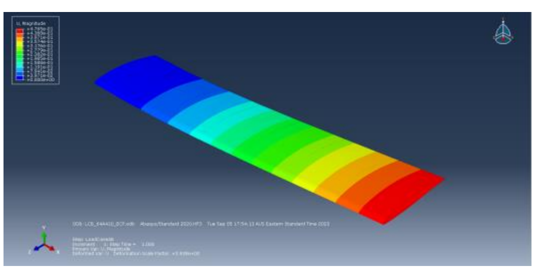
FIGURE G:LC(a) for NACA64A410

The maximum von Mises Stress is 3.148e07Pa and the maximum vertical displacement is 1.010e-01m for LC(a)

LC(b) is displayed in figure H.



S_LCB_64A410_ECF_t=0.008

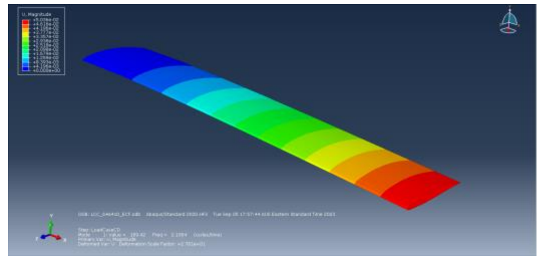


U_LCB_64A410_ECF_t=0.008

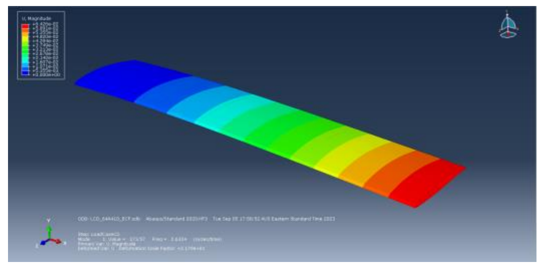
FIGURE H:LC(b) for NACA64A410

The maximum von Mises Stress is 1.648e08Pa and the maximum vertical displacement is 4.765e-01m for LC(b)

The first mode natural frequency for LC(c) and LC(d) are plotted in figure I.



Freq1_LCC_64A410_ECF_t=0.008



Freq1_LCD_64A410_ECF_t=0.008

FIGURE I:LC(c) and LC(d) for NACA64A410

It was found that the fundamental (first mode) natural frequency with fuel was 1.52Hz and without fuel is 1.60Hz.

Table G summarises the findings from each analysis for ECF.

TABLE G: Results Summary

Findings	**Value**
Airfoil Type	NACA64A410
Thickness	0.008m
Material	Epoxy/Carbon Fibre
Weight	960.19kg
Lift Load	7029.699 N/m
LCA Displacement	101mm
LCA Stress	31.48MPa
LCB Displacement	476.5mm
LCB Stress	165.8MPa
LCC Freq 1	2.1904 Hz
LCC Freq 2	6.0920 Hz
LCC Freq 3	15.997 Hz
LCD Freq 1	2.6324 Hz
LCD Freq 2	15.285 Hz
LCD Freq 3	20.010 Hz

NACA 0012

The NACA0012 was the next airfoil examined. The cross section is displayed in figure J [5].

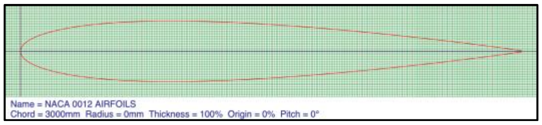


FIGURE J: NACA0012 Airfoil [5].

The NACA0012 is a symmetrical airfoil and is one of the most widely used cross-section in the aerospace industry. This is due to its high lift to drag ratio, relative to its low drag coefficient [7].

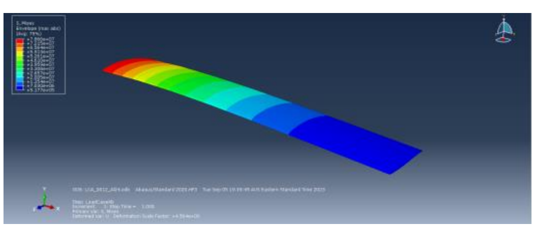
Aluminium-2024

By analysing the airfoil using Al-2024, it was found that the skin thickness was most optimal at t=0.012.

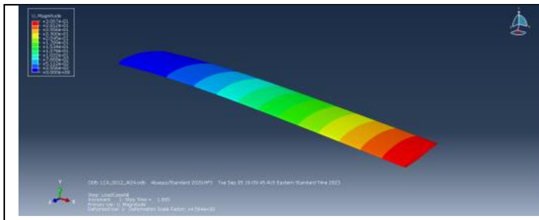
TABLE H: Design Requirements for NACA0012 Al-2024 with skin thickness = 0.012m

Design Requirement	Fulfilled
14m length and 3m chord.	✓
Fixed wing root.	✓
Total fuel mass is 10,887kg (halved) located 4m from the wing root.	✓
Wing supports dry, wing and fuel weight.	✓
Wing supports lift load.	✓
Design with a FoS of 2	✓
Total dry weight is 7,257kg (halved).	✓
Wing tip displacement < 1m	✓
Natural frequency < 20% of 20Hz	✓

All design requirements have been fulfilled and the load cases can now be investigated. LC(a) is displayed in figure K.



S_LCA_0012_Al_t=0.012

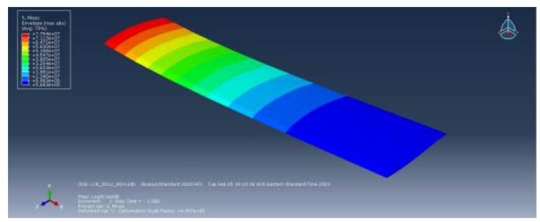


U_LCA_0012_Al_t=0.012

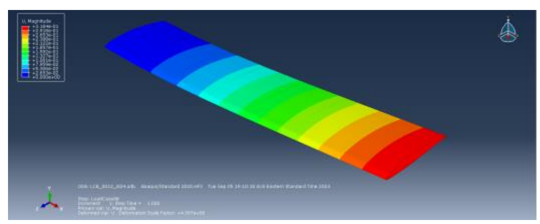
FIGURE K:LC(a) for NACA0012

The maximum von Mises Stress is 7.866e07Pa and the maximum vertical displacement is 3.067e-01m for LC(a)

LC(b) is displayed in figure L.



S_LCB_0012_Al_t=0.012

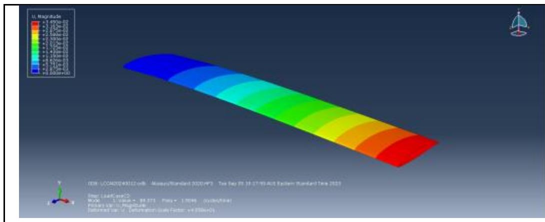


U_LCB_0012_Al_t=0.012

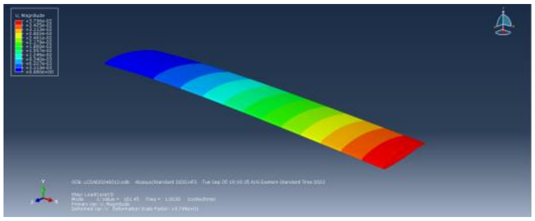
FIGURE L:LC(b) for NACA0012

The maximum von Mises Stress is 7.754e07Pa and the maximum vertical displacement is 3.184e-01m for LC(b)

The first mode natural frequency for LC(c) and LC(d) are plotted in figure M.



Freq1_LCC_64A410_Al_t=0.012



U_LCD_64A410_Al_t=0.012

FIGURE M:LC(c) and LC(d) for NACA0012

It was found that the fundamental natural frequency (first mode) for LC(c) and LC(d) was 1.50Hz and 1.60Hz respectively.

Table I summarises the findings from each analysis for Aluminium-2024.

TABLE I: Results Summary

Findings	**Value**
Airfoil Type	NACA0012
Thickness	0.012m
Material	Epoxy/Carbon Fibre
Weight	2839.7kg
Lift Load	8346.698 N/m
LCA Displacement	306.7mm
LCA Stress	78.66 MPa
LCB Displacement	318.4mm
LCB Stress	77.53MPa
LCC Freq 1	1.5046 Hz
LCC Freq 2	5.1961 Hz
LCC Freq 3	11.214 Hz
LCD Freq 1	1.6030 Hz
LCD Freq 2	9.2715 Hz
LCD Freq 3	12.155 Hz

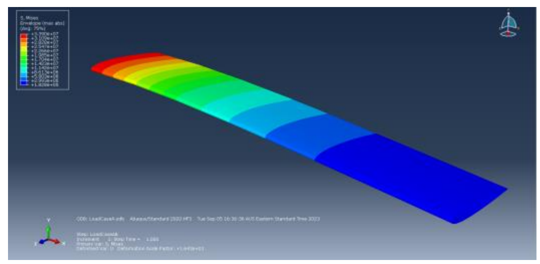
Epoxy/Carbon Fibre

To meet design requirement and make the airfoil design as optimal as possible, it this airfoil was tested with a skin thickness of t=0.006m. Table J displays the checks that were conducted with this thickness.

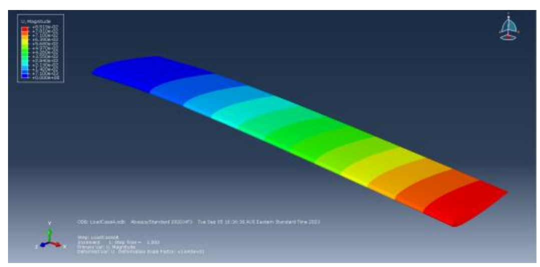
TABLE J: Design Requirements for NACA0012 ECF with skin thickness = 0.006m

Design Requirement	**Fulfilled**
14m length and 3m chord.	✔
Fixed wing root.	✔
Total fuel mass is 10,887kg (halved) located 4m from the wing root.	✔
Wing supports dry, wing and fuel weight.	✔
Wing supports lift load.	✔
Design with a FoS of 2	✔
Total dry weight is 7,257kg (halved).	✔
Wing tip displacement < 1m	✔
Natural frequency < 20% of 20Hz	✔

All specific design requirements have been fulfilled and the analysis can begin. LC(a) is displayed in figure N.



S_LCA_0012_ECF_t=0.006

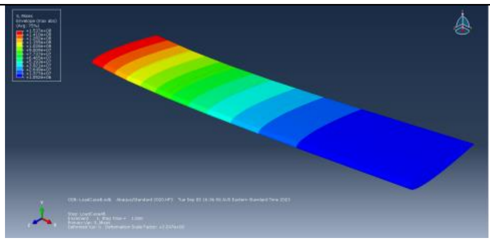


U_LCA_0012_ECF_t=0.006

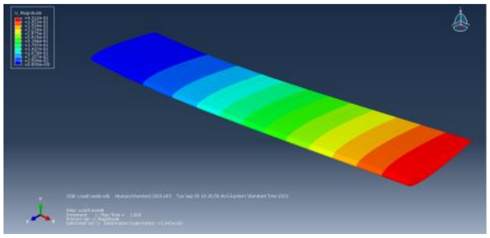
FIGURE N:LC(a) for NACA0012

The maximum von Mises Stress is 3.390e07Pa and the maximum vertical displacement is 8.519e-01m for LC(a)

LC(b) is displayed in figure O.



S_LCB_0012_ECF_t=0.006

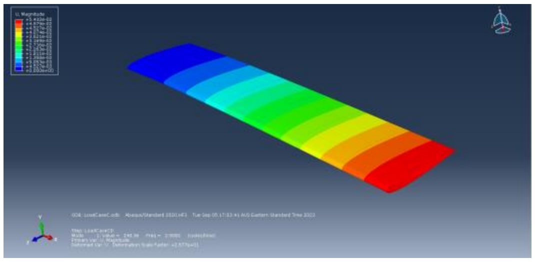


U_LCB_0012_ECF_t=0.006

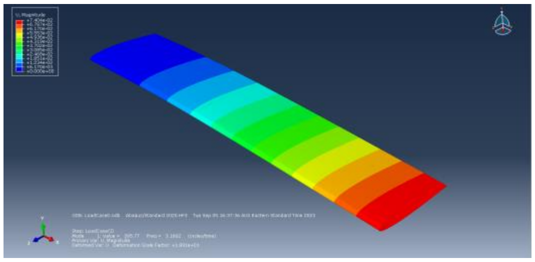
FIGURE O:LC(b) for NACA0012

The maximum von Mises Stress was 1.537e08Pa and the maximum vertical displacement was 4.312e-01m for LC(b)

The first mode natural frequency for LC(c) and LC(d) were plotted in figure P.



Freq1_LCC_64A410_ECF_t=0.006



Freq1_LCD_64A410_ECF_t=0.006

FIGURE P:LC(c) and LC(d) for NACA0012

It was found that the fundamental (first mode) natural frequency for LC(c) and LC(d) was 2.51Hz and 3.17Hz respectively.

Table K summarises the findings from each analysis for ECF.

TABLE K: Results Summary

Findings	**Value**
Airfoil Type	NACA0012
Thickness	0.006m
Material	Epoxy/Carbon Fibre
Weight	725.45kg
Lift Load	6865.212 N/m
LCA Displacement	85.1mm
LCA Stress	33.9MPa
LCB Displacement	431.2mm
LCB Stress	153.7MPa
LCC Freq 1	2.5082
LCC Freq 2	6.9799
LCC Freq 3	15.447
LCD Freq 1	3.1662
LCD Freq 2	18.828
LCD Freq 3	20.602

Discussion

This work on optimising the wing design of the Lockheed U-2 reconnaissance aircraft holds immense relevance in the field of engineering design analysis. It exemplifies the critical role of FE analysis in evaluating structural integrity and performance under various load conditions. Additionally, the study underscores the significance of material selection, safety factors, and iterative design processes, all fundamental aspects of engineering design analysis. Furthermore, the research demonstrates how this interdisciplinary approach can be applied not only to aerospace engineering but also to other engineering domains where optimising design for improved efficiency, safety, and reliability is paramount. Ultimately, this work serves as a valuable case study highlighting the importance of rigorous engineering analysis in achieving design excellence and enhancing the capabilities of complex engineering systems.

An issue that occurred involved the airfoils skin thickness. Through trial and error, airfoils met each design requirement. Figure Q displays the first trial using a NACA64A410 airfoil for LC(a).

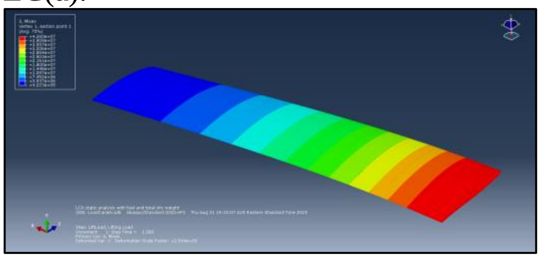


FIGURE Q: 64A410 Von-Mises Stresses Trial with 10mm Skin Thickness.

The first trial used a thickness of 10mm and met every specific design parameter. However, upon closer inspection, the maximum Von-Mises stress was 4.26e7 kg/m^2. This value is technically viable according to the ultimate tensile strength of 469MPa (4.78e7kg/m^2), however the wing must be designed with a FoS of 2. Hence with a tensile yield strength of 324MPa (3.30e7kg/m^2), this Von-Mises stress did not meet the required parameters. It is important to note that the units inputted were not consistent during this first trial, hence kg/m^2 was the resultant output. The second trial is displayed in figure R.

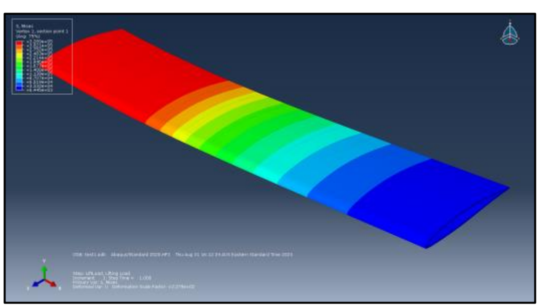


FIGURE R: 64A410 Von-Mises Stresses Trial with 50mm Skin Thickness.

The second trial used a skin thickness of 50mm for LC(b). This produced a maximum Von-Mises stress of 3.289e5kg/m^2, which is considerably lower than the maximum tensile strength. However, this is too low and is not optimised for the design requirements. The airfoil can be designed more effectively which was shown in further investigation. These trials were crucial for the analysis process, as it provided perspective on how mistakes are easily made using Abaqus CAE 2020. Forthgoing, every aspect was carefully examined to ensure minimal mistakes were made due to human error.

ECF in aircraft design, is renowned for their remarkable strength-to-weight ratio and durability. Utilising it often encounters practical limitations primarily driven by cost considerations. This advanced material come with a high price tag, mainly due to the high cost of raw materials, manufacturing processes, and rigorous quality control requirements, needed for production. Furthermore, the limited number of manufacturers capable of producing high-quality carbon fibre components reduces competition, potentially inflating costs. Additionally, the environmental impact of production and stringent environmental regulations can further amplify the overall cost. While carbon fibre composites offer undeniable advantages, their high cost poses a substantial challenge in striking a balance between performance benefits and financial feasibility in aerospace applications. In scenarios where cost-efficiency takes precedence, alternative materials like Al24 often emerge as more practical choices.

In the context of this study, assumptions play a crucial role in shaping the analysis outcomes and potential errors. The study relies on several key assumptions, such as the neglect of wing taper, fixed wing root, and disregarding the mass of specific structural components like spars, strings, and ribs. These assumptions simplify the analysis but introduce a degree of uncertainty, as real-world aircraft designs may not always adhere to these simplifications. Additionally, the choice of material properties, while based on established data, can introduce errors if the real-world materials deviate from the specified properties. Furthermore, errors might arise from modelling simplifications and the use of finite element analysis software itself, as demonstrated by the need for iterative adjustments in skin thickness to meet design criteria. These potential sources of errors emphasise the importance of validating the analysis results through physical testing and verification, a standard practice in engineering design to ensure that the design meets performance, safety, and reliability requirements in real-world applications.

Conclusion

In conclusion, this study has yielded several key findings that are instrumental in the pursuit of optimising the wing design of the Lockheed U-2 reconnaissance aircraft. Through FE analysis, it was determined that two materials, Aluminium-2024 and epoxy/carbon fibre composite, can meet the stringent design requirements while offering varying trade-offs in terms of weight, stress distribution, and displacement. It was found that ECF was the best material to minimise the total weight of the skin. However the practicality of using ECF for the entire wing is low due to the cost of the material. The optimisation process revealed the critical importance of skin thickness in achieving the desired structural performance, as evident in the trials. Additionally, the study emphasised the role of safety factors, material properties, and rigorous engineering design analysis in ensuring the reliability and efficiency of the aircraft's wings. These findings provide valuable insights into the intricate balance between design criteria and materials selection, offering a roadmap for enhancing the performance and capabilities of complex engineering systems like the U-2 aircraft.

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