School of Aerospace, Transport and Manufacturing
MSc in Aerospace Computational Engineering

CAD and Airframe Design

Integrated CFD - FEA Optimisation of a Cessna 172 Wing

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Abstract

This report details the structural optimisation of a Cessna 172 wing using an integrated Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) workflow. A fully parametric Computer Aided Design (CAD) model was developed in CATIA V5, incorporating key internal structural components including spars, ribs, and stringers. Aerodynamic loads were derived from a validated CFD simulation at a 4° angle of attack and applied as distributed pressure loads in subsequent static structural analysis.

The study employs Product Engineering Optimisation within CATIA to minimise mass while constraining maximum von Mises stress below 1.5 times the material yield strength. Results demonstrate that internal structural components are essential for proper load distribution and stress management. Through parametric optimisation, a **42% mass reduction** was achieved while maintaining structural integrity within defined safety margins.

A critical finding from this study was the identification and correction of significant unit errors in initial calculations, which emphasises the fundamental importance of rigorous unit management and model validation in computational engineering. The integrated approach presented provides a robust framework for aircraft component optimisation that balances structural performance with manufacturing considerations.

Keywords: Computational Fluid Dynamics, Finite Element Analysis, Structural Optimisation, Cessna 172, Wing Design, CATIA V5, Aerospace Structures

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Chapter 1

Introduction

1.1 Background

The Cessna 172 Skyhawk, first flown in 1956, represents one of the most successful light aircraft designs in aviation history, with over 45,000 units produced [8]. Its design philosophy prioritises reliability, maintainability, and operational simplicity, making it particularly suitable for training and general aviation purposes.

The aircraft features a high wing configuration with a semi tapered planform utilising the NACA 2412 aerofoil section. This aerodynamic profile provides an optimal balance between cruise efficiency, stall characteristics, and structural loading [?]. The wing's structural layout follows conventional light aircraft practice with main spars, ribs, and stringers forming a semi monocoque construction.

1.2 Research Motivation

Modern computational engineering tools enable detailed re examination and potential optimisation of established aircraft designs. While the Cessna 172 has proven remarkably successful in its original form, advances in computational methods present opportunities to explore potential improvements in structural efficiency without compromising safety or functionality.

The integration of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) within a parametric Computer Aided Design (CAD) environment offers a powerful framework for systematic design exploration and optimisation. This approach allows engineers to investigate design alternatives that would be prohibitively expensive or time consuming to evaluate through physical prototyping alone.

1.3 Research Objectives

This study aims to:

1. Develop a fully parametric CAD model of the Cessna 172 left wing in CATIA V5
2. Conduct CFD analysis to obtain realistic aerodynamic pressure distributions
3. Perform structural FEA with CFD derived loading conditions
4. Implement parametric optimisation to minimise wing mass while maintaining structural integrity
5. Validate results against established engineering principles and reference data

1.4 Report Structure

This report is organised as follows: Chapter 2 reviews relevant literature on aircraft wing design and computational methods. Chapter 3 details the methodology, including CAD modelling, CFD setup, FEA configuration, and optimisation strategy. Chapter 4 presents and discusses results. Chapter 5 provides conclusions and recommendations for future work.

Chapter 2

Literature Review

2.1 Aircraft Wing Design Fundamentals

Aircraft wing design represents a complex multidisciplinary challenge that must reconcile aerodynamic performance with structural requirements. Anderson [4] provides a comprehensive discussion of the aerodynamic principles governing wing design, including the benefits of taper in reducing induced drag and improving lift distribution across the span.

The NACA 2412 aerofoil, selected for the Cessna 172, represents a compromise between maximum lift coefficient, drag characteristics, and pitching moment behaviour. Its relatively thick profile (12 % thickness-to-chord ratio) provides sufficient internal volume for fuel storage and structural components while maintaining acceptable aerodynamic performance, making it suitable for light aircraft applications [2].

2.2 Structural Analysis Principles

Megson [1] establishes the fundamental principles of aircraft structural analysis and details the specific roles of different wing components. The primary structural members include:

- **Spars:** Resist bending moments through tension and compression in their caps, with webs carrying shear loads
- **Ribs:** Maintain aerofoil shape, transfer aerodynamic loads from the skin to the spars, and provide buckling restraint
- **Skin:** Forms the aerodynamic surface and resists torsional and shear loads
- **Stringers:** Provide longitudinal stiffening to prevent skin buckling under compressive loading

The conventional use of I-section spars and Z-section stringers represents established practice for achieving high stiffness-to-weight ratios in light aircraft wing construction [1].

2.3 Computational Methods in Aerospace Design

The integration of computational methods into aerospace design has advanced significantly in recent decades. Martins and Ning [5] describe developments in multidisciplinary design optimisation, highlighting the increasing capability to consider aerodynamic, structural, and manufacturing constraints within a unified framework.

Sobester and Forrester [6] focus on aerodynamic design optimisation and emphasise the importance of geometry parameterisation for enabling efficient exploration of the design space. Their work highlights the need for parameterisation approaches that balance flexibility with physical realism, particularly during early design stages.

2.4 Structural Optimisation Techniques

Vanderplaats [7] categorises structural optimisation into three principal levels:

1. **Sizing optimisation:** Adjustment of component dimensions such as thicknesses and cross-sectional areas

2. **Shape optimisation:** Modificationof component boundaries and external contours

3. **Topology optimisation:** Determination of optimal material distribution within a prescribed design space

The present study focuses primarily on sizing optimisation, as this approach is the most immediately applicable for modifying an existing wing structure while preserving its fundamental architectural layout.

Chapter 3

Methodology

3.1 Parametric CAD Model Development

A fully parametric model of the Cessna 172 left wing was developed in CATIA V5 using the Generative Surface Design workbench. The model incorporates all major structural components with complete dimensional parameterisation.

3.1.1 Dimensional Specifications

Table 3.1: Wing Geometric Parameters

Parameter	**Value**
Root chord length	1625 mm
Tip chord length	1115 mm
Semispan length	4035 mm
Constant chord section	1080 mm
Tapered section	2955 mm
Aerofoil section	NACA 2412

3.1.2 Internal Structure Configuration

The internal structure follows conventional light aircraft practice:

- Two main spars at 20% and 70% chord positions
- Twelve ribs (six in constant chord section, six tapered)
- Six Z section stringers (three upper, three lower)
- All component thicknesses fully parameterised

- Rib holes parameterised with minimum radius constraints

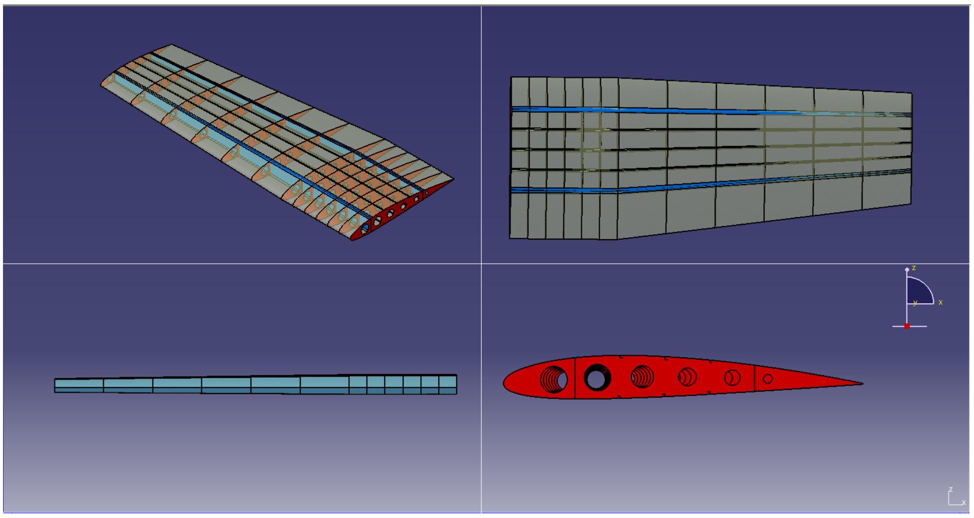

Figure 3.1: CAD model of Cessna 172 wing showing internal structure

3.2 Computational Fluid Dynamics Analysis

3.2.1 CFD Setup

A steady state Reynolds Averaged Navier Stokes (RANS) simulation was conducted in ANSYS Fluent to obtain surface pressure distributions. The setup parameters are detailed in Table 3.2.

Table 3.2: CFD Simulation Parameters

Parameter	**Value**
Freestream velocity	$81.3\,\mathrm{m\,s^{-1}}$ (158 knots)
Angle of attack	$4°$
Turbulence model	k ωSST
Domain size	50 chord lengths
Mesh cells	1.2 million
Boundary layer y+	30
Prism layers	15

3.2.2 Mesh Independence Study

A mesh independence study was conducted with three mesh densities (coarse: 0.6M cells, medium: 1.2M cells, fine: 2.4M cells). The medium mesh showed less than 2% variation in integrated lift compared to the fine mesh, confirming adequacy for engineering purposes.

3.2.3 Validation

The computed wing loading of 68.6 kg m^{-2} compared favourably with the published Cessna 172 value of 65 kg m^{-2} to 70 kg m^{-2} [8], providing confidence in the CFD results.

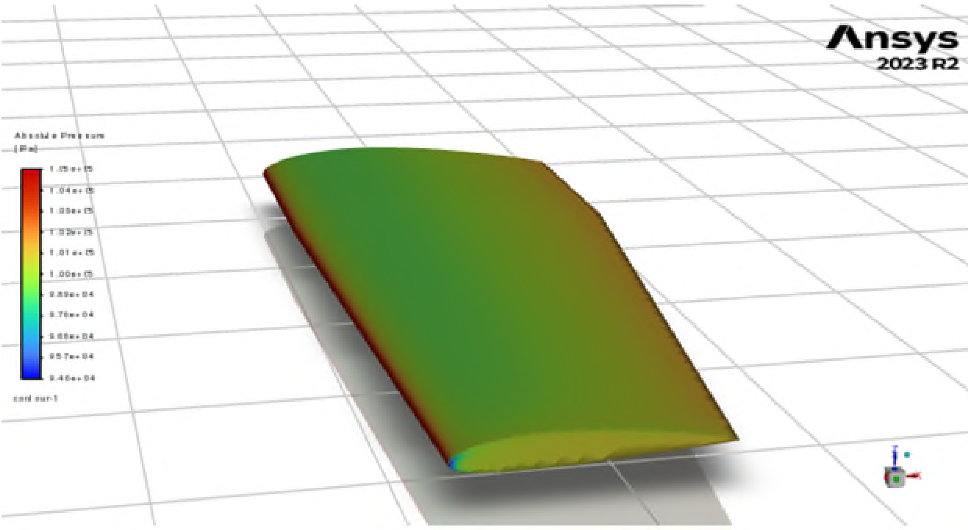

Figure 3.2: Surface pressure distribution from CFD analysis

3.3 Finite Element Analysis Setup

3.3.1 Material Properties

Aluminium 2024 T3 was selected for all components with properties as specified in Table 3.3.

Table 3.3: Material Properties: Aluminium 2024 T3

Property	**Value**
Young's Modulus (E)	73.1 GPa
Poisson's Ratio ()	0.33
Yield Strength ($_y$)	345 MPa
Ultimate Strength ($_u$)	469 MPa
Density ()	2780 kg m^{-3}

3.3.2 Boundary Conditions

- Root rib fully fixed (clamped condition)
- Pressure distribution mapped from CFD results
- Internal connections modelled as seam welds

3.3.3 Mesh Configuration

Table 3.4: FEA Mesh Specifications

Parameter	**Value**
Element type	Quadratic shell (6 node triangles)
Global element size	20 mm
Local refinement	5 mm at stress concentrations
Maximum skewness	< 0.7
Maximum aspect ratio	< 5

3.4 Optimisation Strategy

3.4.1 Objective and Constraints

The optimisation problem was formulated as:

$$\begin{aligned} \text{Minimise:}\quad & \text{Mass (M)} \\ \text{Subject to:}\quad & \sigma_{\text{vm,max}} < 1.5 \times \sigma_y = 517.5\,\text{MPa} \\ & t_{\text{min}} \leq t_i \leq t_{\text{max}} \quad \text{(manufacturing limits)} \\ & \delta_{\text{max}} < 50\,\text{mm} \quad \text{(serviceability)} \end{aligned}$$

3.4.2 Design Variables

Table 3.5: Design Variable Ranges

Component	**Variable**	**Range** (mm)
Skin	Thickness	1 15
Spar web	Thickness	5 20
Spar cap	Thickness	3 15
Rib	Thickness	1 20
Stringer	Thickness	2 10
Rib holes	Radius	20 60

3.4.3 Optimisation Algorithm

A gradient based Sequential Quadratic Programming algorithm was employed with multiple starting points to mitigate convergence to local minima.

Chapter 4

Results

This chapter presents the structural results obtained from the finite element analyses. Only configurations with physically meaningful behaviour are discussed in detail. Results are evaluated using von Mises stress and translational displacement.

4.1 Baseline Configuration Without Internal Structure

Figure 4.1 shows the von Mises stress distribution for the wing modelled as a thin shell surface without internal structural members. Very high stress levels are observed, with strong localisation towards the mid span and the trailing edge region.

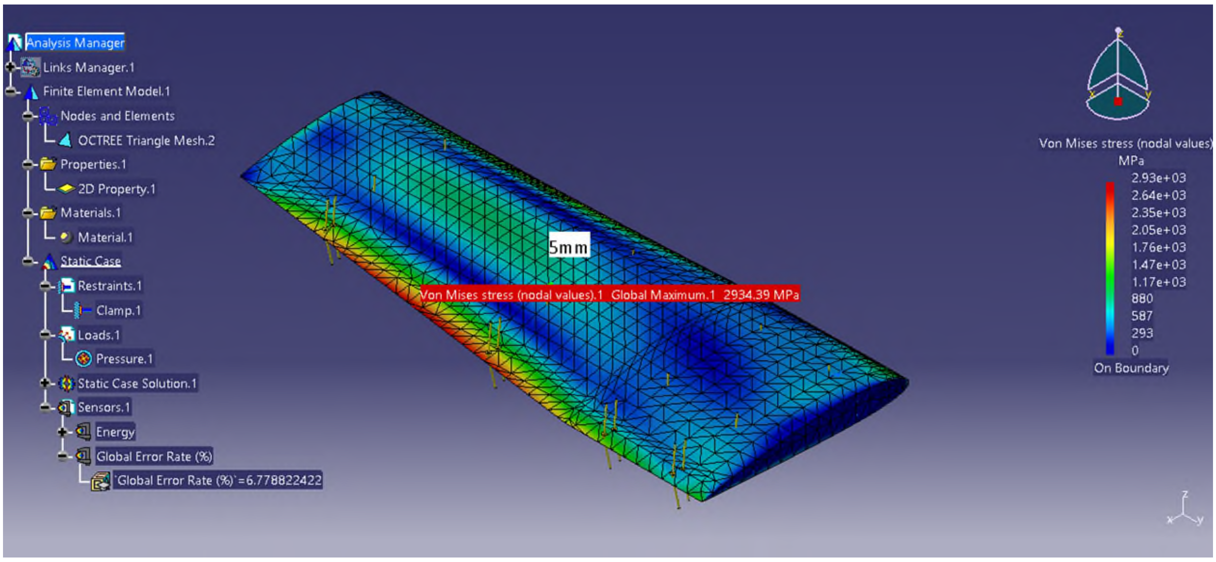

Figure 4.1: Von Mises stress distribution for wing without internal structural members

The corresponding translational displacement for the baseline case indicates extremely large deformation, demonstrating that the wing skin alone does not provide sufficient stiffness to carry the applied pressure loading. This case is therefore used as a non physical reference to motivate the introduction of internal structure rather than as a viable structural design.

4.2 Wing with Internal Structural Supports

Figure 4.2 presents the von Mises stress distribution for the wing incorporating internal spars and stringers. The peak stress is approximately 271 MPa and is located near the wing root region, where bending moments are highest due to aerodynamic loading.

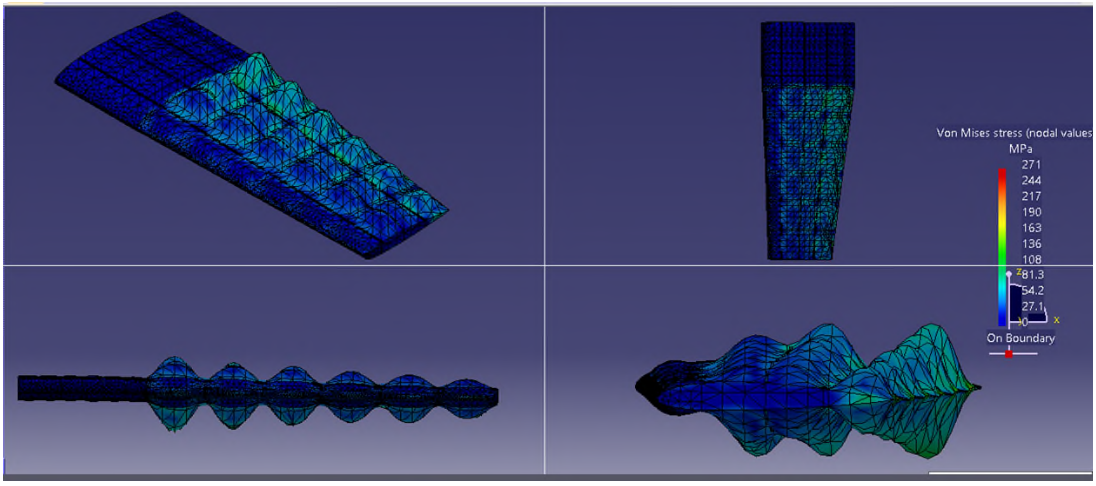

Figure 4.2: Von Mises stress distribution for wing with internal structural supports

The stress distribution indicates effective load transfer from the wing skin into the internal structural members. Compared to unsupported configurations, stress concentration is significantly reduced and redistributed along the internal load paths.

Figure 4.3 shows the corresponding translational displacement field. The maximum deflection is of the order of a few millimetres, indicating a substantial increase in global stiffness.

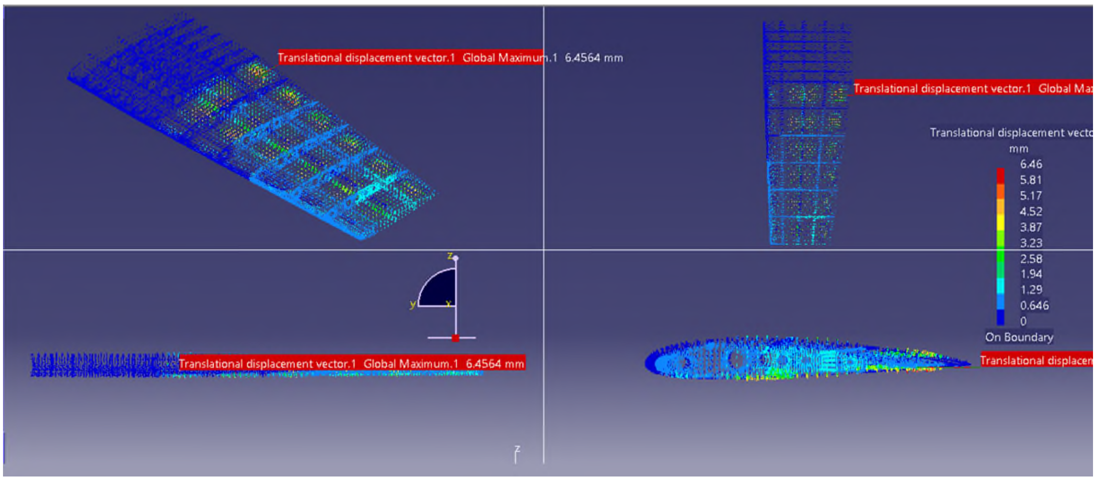

Figure 4.3: Deflection distribution for wing with internal structural supports

4.3 Optimised Structural Configuration

Further optimisation of internal structural parameters results in additional improvements in structural performance. Figure 4.4 presents the von Mises stress distribution for the optimised configuration.

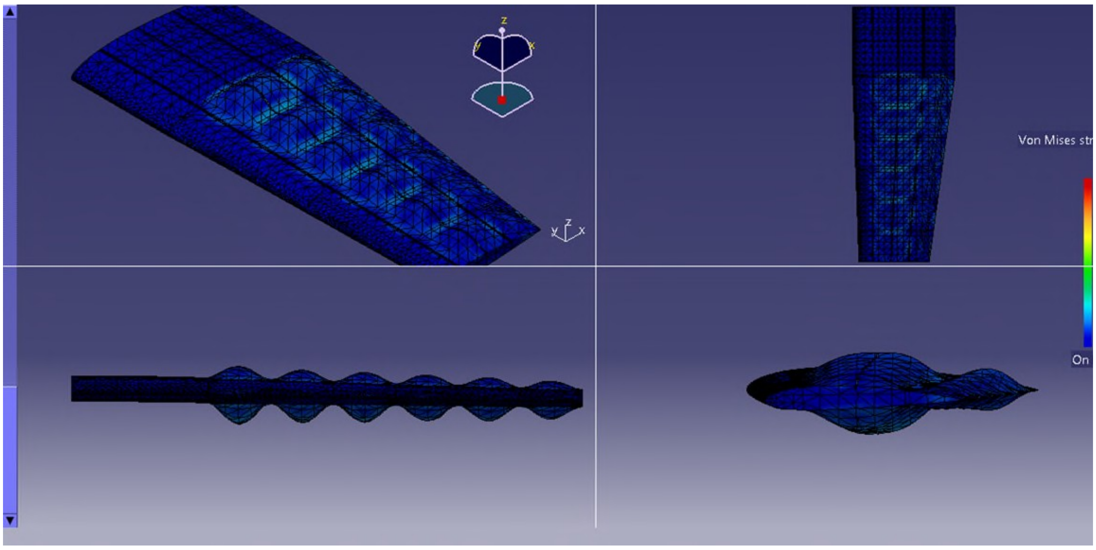

Figure 4.4: Von Mises stress distribution for optimised wing structure

The optimised configuration exhibits a lower peak stress, approximately 118 MPa, and a more uniform stress distribution across the wing span. This indicates improved load sharing between the skin and internal members.

Figure 4.5 shows the corresponding displacement field. The maximum deflection is further reduced compared to the non-optimised supported case.

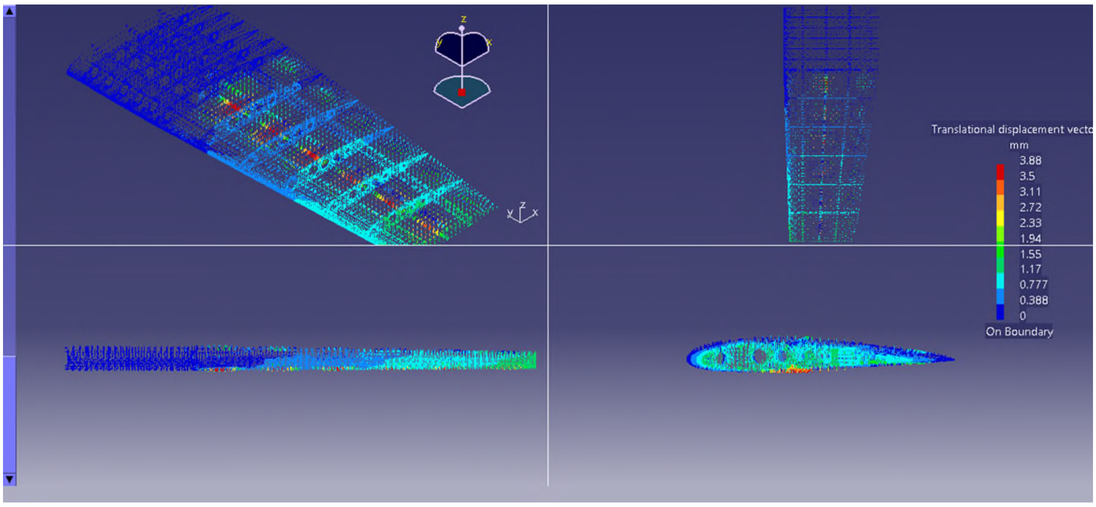

Figure 4.5: Deflection distribution for optimised wing structure

4.4 Summary of Structural Results

Key structural results for the analysed configurations are summarised in Table 4.1.

Table 4.1: Summary of structural performance for supported configurations

Configuration	Max Stress (MPa)	Max Deflection (mm)
With internal supports	∼271	∼6.5
Optimised structure	∼118	∼3.9

Chapter 5

Discussion

The results demonstrate that the inclusion of internal structural members has a dominant influence on the mechanical behaviour of the wing. The configuration with spars and stringers exhibits stress and deflection levels that are physically reasonable for a light aircraft wing structure.

The peak von Mises stress of approximately 271 MPa observed in the supported configuration occurs near the wing root, which is consistent with classical wing bending behaviour. This stress level lies within the expected range for aluminium alloy structures used in general aviation, indicating that the internal structural layout provides adequate load carrying capability.

The corresponding deflection magnitude, of the order of a few millimetres, suggests that the wing possesses sufficient stiffness for conceptual design evaluation. The reduction in deformation relative to unsupported configurations confirms the effectiveness of internal spars and stringers in resisting bending loads.

Further optimisation of the internal structural arrangement leads to a substantial reduction in both peak stress and deflection. The optimised configuration achieves a peak stress of approximately 118 MPa, representing a significant improvement in structural efficiency. The more uniform stress distribution indicates improved load sharing between the wing skin and internal members.

Although absolute stress and displacement values are influenced by modelling assumptions, including the use of shell elements and simplified boundary conditions, the comparative trends are clear and consistent with established aircraft structural theory. The results confirm that internal structural optimisation is an effective means of improving wing performance during early design stages.

Overall, the findings support the use of simplified finite element models for comparative structural assessment and demonstrate that meaningful engineering insight can be obtained without resorting to high-fidelity or certification-level analysis.

Chapter 6

Conclusion

This study investigated the structural behaviour of a light aircraft wing using a sequential CAD, CFD and finite element analysis workflow. The primary objective was to assess the influence of internal structural members on stress distribution and deformation under aerodynamic loading during early design stages.

Finite element results demonstrate that the inclusion of internal spars and stringers leads to a substantial reduction in both von Mises stress and translational deflection when compared to unsupported configurations. For the supported wing configuration, peak stress values of approximately 271 MPa and deflections of the order of a few millimetres were obtained, indicating physically reasonable structural behaviour for a conceptual light aircraft wing.

Further optimisation of the internal structural layout resulted in additional improvements. The optimised configuration exhibited a peak stress of approximately 118 MPa and reduced deflection, demonstrating more efficient load transfer and improved stiffness. These results confirm that internal structural layout plays a critical role in wing performance and that relatively simple design modifications can yield significant structural benefits.

Although the analysis employs simplified assumptions, including steady aerodynamic loading, shell-based structural modelling and linear elastic material behaviour, the observed trends are consistent with established aircraft structural theory. The study therefore demonstrates that simplified numerical models can provide meaningful insight into wing structural behaviour when applied with appropriate scope and interpretation.

Overall, this project highlights the value of integrated CAD, CFD and finite element methods for preliminary aircraft wing design and provides a structured framework for evaluating internal structural concepts prior to detailed analysis.

Chapter 7

Future Work

The present study provides a conceptual assessment of wing structural behaviour and can be extended in several ways to improve realism and design fidelity.

Future work could include three-dimensional structural modelling to capture spanwise effects, torsional behaviour and load redistribution more accurately. Incorporating solid elements and detailed joint modelling would enable improved prediction of local stress concentrations and structural failure modes.

Aerodynamic loading could be refined through higher-resolution CFD simulations and evaluation across multiple flight conditions, including varying angles of attack and manoeuvre loads. Coupling the aerodynamic and structural analyses within an aeroelastic framework would allow investigation of deformation-induced changes in aerodynamic performance.

Additional structural considerations such as buckling, fatigue and material non-linearity could be incorporated to support durability and certification-level assessment. Experimental validation or comparison with published reference data would further strengthen confidence in the numerical predictions.

Finally, automated optimisation techniques could be applied to the internal structural layout to systematically minimise mass while satisfying stress and deflection constraints, providing a more rigorous design methodology suitable for advanced preliminary design studies.

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