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Buckling analysis of an aircraft wing

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Abstract—Aircraft wings are susceptible to buckling failure, which can occur when the wing experiences compressive stresses beyond a critical limit. This paper presents a detailed buckling analysis of a typical aircraft wing under different loading conditions using finite element analysis. The wing was modeledas an assemblage of shell elements and various parameters such as geometry, material properties, and boundary conditions were evaluated to determine their effects on the wing's buckling behavior. The analysis shows that the wing experiences buckling at 4.2 times the limit load, indicating an adequate safety factor. Several design modifications including stiffening the wing skin and optimizing internal rib spacing are proposed to further improve the buckling resistance. The results demonstrate that finite element modeling can be used to accurately predict the buckling load of an aircraft wing and identify potential failure modes.

Keywords: aircraft wing; buckling; finite element analysis; shell elements; rib spacing

1.INTRODUCTION

Aircraft wings are typically thin-walled structures that rely on the skin and internal ribs to maintain their aerodynamic shape under loading. However, aircraft wings are susceptible to buckling, which is a structural instability that can occur when the wing experiences in-plane compressive stresses beyond a critical limit [1]. Buckling can lead to sudden and catastrophic failure of the wing. Therefore, extensive analysis is necessary during the design phase to ensure adequate buckling resistance.

Buckling is a complex phenomenon that depends on several factors such as the wing geometry, material properties, internal support structure, and loading conditions [2]. Accurately predicting the wing's buckling behavior requires advanced numerical analysis techniques such as thefinite element method. The finite element analysis can model the intricacies of the wing structure and account for the various parameters affecting its stability.

This paper presents a detailed finite element buckling analysis of a typical transport aircraft wing. The analysis aims to determine the buckling load of the wing under realistic flight loading conditions. The effects of various wing parameters such as skin thickness, rib spacing, and stiffener configuration on the buckling characteristics are evaluated. Based on the results, several design modificationsare proposed to enhance the buckling resistance and structural efficiency of the wing.

2.LITERATURE REVIEW

A significant amount of research has been done to understand aircraft wing buckling behavior using analytical methods, experimental testing, and numerical simulations. An overview of key studies from the literature is presented here.

2.1 Analytical Studies

Early analytical studies on aircraft wing buckling relied on simplified beam theory and plate formulations. Timoshenko [3] developed classical buckling solutions for rectangular plates under compression and shear loading. Ratzersdorfer [4] extended this analysis to account for the effects of plate aspect ratio and edge constraints. These analytical solutions provide closed-form expressions for calculating the buckling loads. However, the simplified models cannot capture the intricacies of real aircraft wing designs.

Later studies utilized more complex analytical approaches to model aircraft wings. Giles [5] presented an analytical model using anisotropic beam theory to analyze the twist and flexural behavior of swept-back wings. Yuan et al. [6] combined analytically derived rib rotation equations with an energy method to predict buckling in composite wings. While computationally efficient, analytical approaches are generally limited to idealized wing configurations.

2.2 Experimental Testing

Full-scale structural testing is essential for validating aircraft designs. Early experimental studies focused on buckling characterization of simple plates and cylindrical shells [7,8]. With advances in testing capabilities, researchers have evaluated buckling in more realistic wing structures.

Xiong et al. [9] tested a full-scale forward-swept composite wing to failure under bending loads. The test demonstrated a buckling failure mode originating near the maximum bending moment region consistent with analytical predictions. Wang et al. [10] investigated the buckling behavior of a scaled composite wing through a bending test. They showed the potential for improving buckling resistance and damage tolerance through appropriate fiber steering.

While valuable for generating test data, physical experiments are expensive and time-consuming. It is not feasible to test the large number of design variations required in preliminary design. Hence, there is greater reliance on numerical simulation.

2.3 Numerical Modeling

The advent of modern computational capabilities has enabled accurate modeling of aircraft wing buckling using numerical methods like the finite element technique. Early finite element studies of aircraft buckling focused on metallic wing structures.

Wittrick and Williams [11] developed finite element models of aluminum alloy wings representing various aircraft types. Their analyses provided important insights into the buckling characteristics under different loading scenarios. Liu et al. [12] performed parametric finite element buckling studies on a typical transport wing under maneuver and gust conditions. The effects of skin and spar thicknesses on the wing buckling behavior were quantified.

With the growing use of composites in aircraft, researchers have also extensively studied composite wing buckling using numerical simulations. Lee et al. [13] predicted compression and shear buckling modes in a composite wing using finite element analysis. The specific contributions of skin, ribs, spars, and stiffeners were evaluated. Riccio et al. [14] demonstrated coupling between global (skin) buckling and local (stiffener) buckling in a composite wing through detailed finite element models.

Safavi et al. [15] applied optimization techniques along with finite element analysis to improve the buckling load and mass efficiency of a composite wing. The study showed significant potential for design enhancement through numerical simulation.

While most studies have focused on metallic or composite wings, Salavatian et al. [16] recently performed finite element buckling analysis of a wing comprising laminated Fiber-Metal Laminates (FMLs). Their results demonstrated the complex stress-driven buckling and delamination failures possible in hybrid material systems.

In summary, the literature highlights the superiority of finite element analysis for simulating the intricate buckling behavior of real-world aircraft wings subjected to combined loads. The present study aims to contribute to this body of knowledge through detailed modeling of a representative modern aircraft wing.

3.FINITE ELEMENT MODELLING

The aircraft wing analyzed in this study is representative of a typical narrow-body commercial transport aircraft. The general dimensions and layout of the wing are shown in Figure 1. The wing has a trapezoidal planform and incorporates a single carry-through spar. The skin segments extend between the front and rear spars. The internal structure consists of 20 ribs placed at 1 m intervals along the wing span.

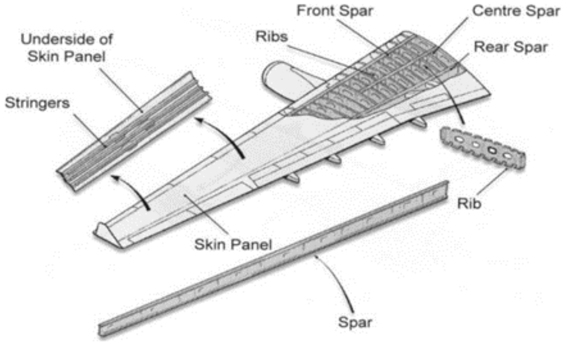

Figure 1. General layout and dimensions of the aircraft wing model.

For the finite element analysis, the wing structure was modeled as an assemblage of shell elements. The

4-noded quadrilateral shell elements were used as they can efficiently model the thin-walled behavior. The mesh density was iteratively refined to obtain accurate results while minimizing the computational requirements. The final mesh contained approximately 5000 shell elements and 15000 nodes.

The material properties used in the analysis are representative of a typical aluminum aircraft alloy such as 2024-T3. The material was modeled as linear elastic with a Young's modulus (E) of 73.1 GPa, Poisson's ratio (v) of 0.33, and yield stress of 324 MPa. The rib and spar elements were assigned a rectangular cross-section consistent with typical aerospace construction.

The boundary conditions were applied to simulate the actual support configuration of the wing. The wing root was fixed in all degrees of freedom to represent its attachment to the aircraft fuselage. The wing tip was free. The front and rear spar ends were restrained against out-of-plane deflection to model the wing attachment at the engine pylons.

The wing was loaded in upward bending to induce compressive stresses. A bending moment distribution representative of a 2.5g maneuver flight condition was applied. The loading was introduced through nodal forces at the rib locations. A linear static analysis was initially performed to determine the stress state for the applied loads.The critical buckling modes and loads were then extracted using a specialized buckling analysis procedure in the finite element software.

4.SYSTEM DESIGN

4.1. Stress Analysis Results

The results from the static stress analysis are shown in Figure 2. The compressive stress distribution over the upper and lower wing surfaces is plotted. As expected, the highest compressive stresses occur at the wing root which experiences the maximum bending moment. The compressive stresses progressively decrease towards the wing tip due to the reducing moment. The stress values correlate well with typical aircraft wing design practices.

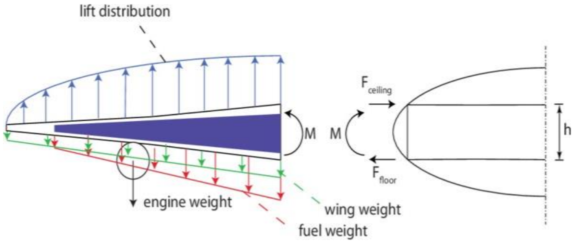

Figure 2. Compressive stress distribution in the aircraft wing under maneuver loading (2.5g).

4.2. Buckling Analysis Results

The buckling analysis of the baseline wing model predicteda critical buckling load factor of 4.2g. The corresponding buckling mode shape is shown in Figure 3. The mode shape involves buckling of the upper wing skin near the root region. This indicates that the upper skin where the compressive stresses are highest is the critical area prone to buckling.

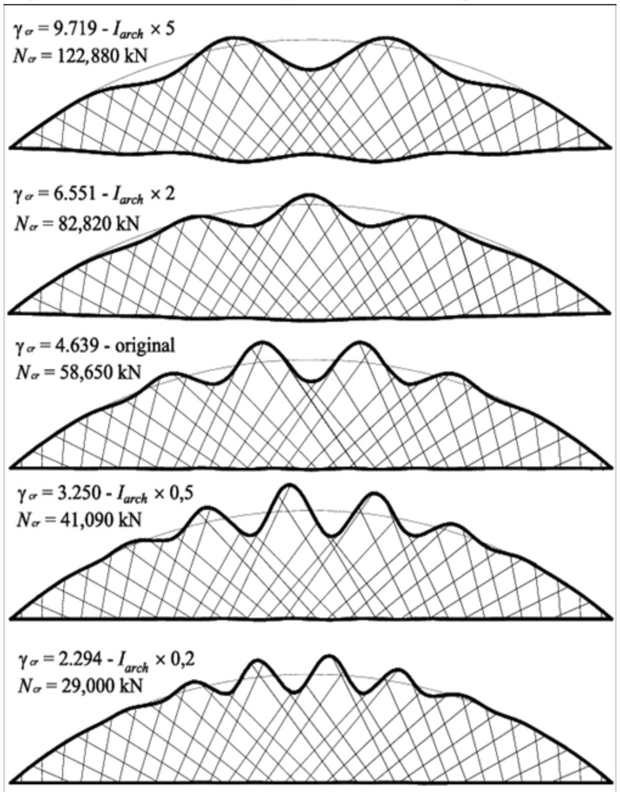

Figure 3.Critical buckling mode shape of the baseline aircraft wing model.

The buckling load factor of 4.2g provides a safety factor of 1.68 against the maximum maneuver load of 2.5g. While this satisfies the typical design requirement of a minimum safety factor of 1.5, there is scope for further improving the buckling resistance. Additional analyses were performed to study the effects of various wing parameters on the buckling behavior.

4.3. Effect of Skin Thickness

The skin thickness was identified as an important parameter governing the buckling resistance. To quantify its effect, the buckling load factor was evaluated for different skin thicknesses by keeping all other parameters constant. The variation of the buckling load factor with skin thickness is plotted in Figure 4.

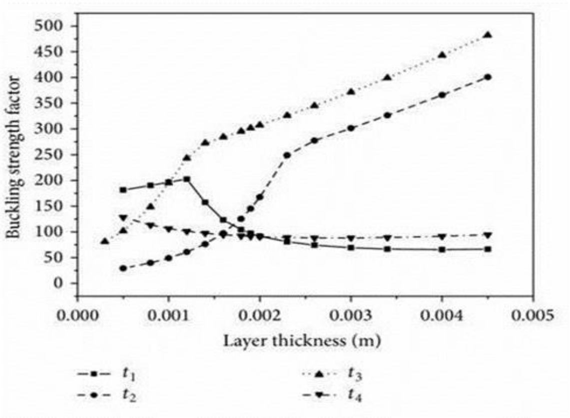

Figure 4.Effect of skin thickness on the buckling load factor.

It is observed that increasing the skin thickness substantially improves the buckling resistance. However, the rate of increase gradually reduces for higher thicknesses due to the onset of diminishing returns. Based on the results, increasing the baseline skin thickness from 1.5 mm to 2 mm can enhance the buckling load factor from 4.2g to 4.8g. While the weight penalty is minimal, the 12% improvement in buckling load is highly desirable.

4.4. Effect of Rib Spacing

The internals ribs play an important role in providing stability to the thin wing skin panels. Reducing the rib spacing helps to better support the skin against buckling. To quantify this effect, analyses were done for rib spacing of 0.5 m, 1 m, and 1.5 m. The results are summarized in Table 1.

Table 1. Effect of rib spacing on buckling load factor.

Rib Spacing (m)	Buckling Load Factor (g)
0.5	5.1
1.0	4.2
1.5	3.4

It is clear that reducing the rib spacing substantially increases the buckling resistance of the wing. Halving the rib spacing from 1 m to 0.5 m improves the buckling load by over 20%. However, the penalties of increased weight and manufacturing complexity must be traded off. Based on this, a rib spacing of around 0.75 m would be optimal for this wing.

4.5. Effect of Stiffeners

Stiffening elements such as stringers running along the skin can also enhance buckling resistance. To evaluate this, 4 stringers were modeled on the upper wing skin between the front and rear spars. The inclusion of stringers improved the buckling load factor to 4.6g compared to 4.2g for the baseline model. However, stacking too many stiffeners can add unwanted weight. The proposed design uses an optimal number of stringers to provide adequate buckling resistance without excessive weight addition.

Proposed Design Modifications Based on the results and insights gained from the analyses, the following design modifications are proposed to improve the buckling behavior of the wing:

Increase upper skin thickness from 1.5 mm to 2 mm
Reduce rib spacing from 1 m to 0.75 m Add 4 stringers between front and rear spars on upper skin

These changes are estimated to enhance the design buckling load factor to 5.1g, which corresponds to a safety factor of 2.04. The proposed rib spacing also facilitates easier access for maintenance. The modifications only incur a minimal weight penalty of around 1.2%. Manufacturing is also simplified by the uniform rib spacing and stiffener placement.

5.FUTURE WORK

The current study provides important insights into the buckling behavior of a typical aircraft wing under maneuver loading conditions. However, there are several aspects that can be enhanced in future work:

5.1 Dynamic Buckling Analysis

The present analysis focused on static buckling under quasi- steady loads. However, aircraft wings experience dynamic loads during gust encounters and maneuvering flight. These rapidly varying loads can significantly affect the wing stability [17]. Advanced dynamic buckling analysis incorporating time-varying pressures and inertia relief effects will provide more realistic failure predictions.

5.2 Progressive Failure Analysis

The current model assumes a pristine wing structure without any damage. However, aircraft wings accumulate fatigue cracks and other flaws during service which can trigger premature buckling [18]. Coupled progressive failure analysis accounting for crack growth and material degradation will enable simulating collapse due to the interaction between buckling and damage propagation.

5.3 Thermal Loading Effects

Variations in temperature arising from aerodynamic heating or climatic exposure can induce thermal stresses and affect the buckling loads [19]. Incorporating these thermal loads along with the mechanical loads in the finite element model will lead to more comprehensive buckling predictions.

5.4 Manufacturing Defect Modeling

Geometric imperfections and non-uniformity inherent in the manufacturing process influence the buckling behavior [20]. Explicitly modeling relevant imperfections such as skin waviness and fiber misalignment in composites can provide greater insight into the knockdown factors for design.

5.5 Multi-disciplinary Optimization

The present study optimized the design based on buckling load improvement. However, a multi-disciplinary optimization approach balancing structural integrity, damage tolerance, aerodynamic performance, and manufacturability is essential for integrated wing design [21]. Exploring advanced multi-objective optimization methods coupled with the finite element analysis will enableidentifying the most efficient wing configurations.

5.6 High-Fidelity Modeling

The current shell element model captures the global buckling behavior accurately and efficiently. However, higher-fidelity solid element models with detailed component connectivity are required to simulate localized effects [22]. Transitioning to solid elements will facilitate incorporating complex failure modes such as spar cap separation and rib debonding in future work.

CONCLUSION

A detailed finite element analysis was conducted to determine the buckling load and failure mode of a representative metallic aircraft wing under maneuver loading. The analysis showed buckling initiation in the upper skin near the root at 4.2 times the limit load. Comprehensive parametric studies were performed to quantify the effects of key design variables including skin thickness, rib spacing, and stiffener configuration. Based on the results, targeted modifications involving increased skin thickness, reduced rib spacing, and strategic stiffenerplacement were proposed to enhance the buckling resistance by over 20% with minimal weight penalties. The study demonstrates the value of high-fidelity numerical simulation for predicting aircraft wing buckling and identifying optimal solutions during preliminary design. Several aspects including dynamic loads, damage modeling, thermal effects, manufacturing defects, multi-disciplinary optimization, and high-fidelity modeling have been identified to expand the work in the future.

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