Self Project

FINITE ELEMENT ANALYSIS AND WEIGHT OPTIMIZATION OF SPAR OF AN AIRCRAFT WING

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Abstract. This research paper presents a comprehensive finite element analysis (FEA) of the spar structure in an aircraft wing, with a primary focus on weight optimization. The spar is a critical component in wing design, responsible for bearing aerodynamic loads and ensuring structural integrity. Our study combines advanced FEA techniques with optimization algorithms to enhance the spar's performance while reducing its weight. The analysis begins with the development of a detailed FEA model, considering material properties, loads, and boundary conditions. I explore various load cases, including maneuvers, turbulence, and landing stresses, to assess the spar's structural behavior. Through sensitivity analyses, I identify key design parameters affecting the spar's performance, such as material choice, cross-sectional geometry, and internal rib configurations To achieve weight reduction without compromising safety, a multi-objective optimization approach is employed. The study also explores the weight extraction of the material from the beam where stress is low in enhancing the spar's structural efficiency. The results demonstrate that weight reduction of the spar is achievable without compromising structural.integrity, leading to potential fuel savings and improved aircraft performance. This research contributes to the ongoing efforts in lightweight aircraft design, reducing environmental impact and operating costs.

Keywords: Cross-section, Moment of Inertia, Modulus of Elasticity, Deformation, Equivalent stress, Strength-to-weight ratio.

1 INTRODUCTION

One of the most practical forms of transportation in the modern world we live in is an airplane. An aircraft's performance is primarily determined by its wings—their strength, form, and composition of materials. A lot of effort is being made to design aircraft wings and choose materials that will maximize the aircraft's performance and fuel efficiency. The aim is to reduce the weight of aircraft and increase the strength of the wings. The wings of aircraft generally consist of loading carrying members with high strength, Spars, and the member used to impart aerodynamic shape to the wing, Ribs.

The most noticeable structural members of an aircraft are the spars, which are made of metal, wood, or composite materials and run parallel to the aircraft's lateral axis from the fuselage to the tip of the wing. Spars can be made of light material and must act as a strength stiffener; if stiffeners are not present, the material must have flanged holes to reduce weight without compromising strength. Spars are the most important part of an aircraft wing because they take up the majority of the stress when other members are placed under load.

The structure of an airframe is one of the best examples of strength-to-weight ratio in the discipline of Aeronautical Engineering. The goal of this project is to learn about the many types of aviation wing spar structures and to optimize an aircraft wing spar beam for a six-seater aircraft. Using a strength-of-material approach will result in an efficient design. The stresses created at each station for a given bending moment are to be estimated using the Finite Element Method (FEM). The design of the spar beam will be optimized over a series of iterations.[1]
The spar beam may be constructed to yield at the design limit load. The results from the conventional design approach and the optimized design are compared. Material saving and inexpensive design for operation, through the design The fuselage and wing are the two major components of an aircraft. Bending is the fundamental load-carrying ability required for an airplane wing. The design uses the standard aluminum alloy 6082-T6. The current study takes into account a four-seater airplane wing spar design. Wings are normally connected to the fuselage at the root of the wing. The wing spar beam now behaves nearly like a cantilever beam as a result of this. When designing wings, a minimum of two spars

are taken into account. In a conventional beam design approach one will end up in heavyweight for the spar of the wing. The spar is modeled as a beam with discrete loads at different stations in the current project. The design is based on the external bending moment at each station. A finite element technique is used to calculate the stresses generated at each station for a given bending moment. For the spar beam design optimization, several stress analysis iterations are performed. The linear static analysis is used to analyze stress. Design limit load is the point at which the spar beam is supposed to yield. By implementing lightning cutouts in the web region, the spar will be weight-optimized. I compare the outcomes of the optimized design versus the traditional design technique. Design optimization results in weight savings that are computed. Spar will be a built-up structure. A scale-down model of the spar will be fabricated using aluminum alloy 6082-T6 material. Static testing of the spar will be carried out to validate the design and stress analysis results. [2]

2 METHODOLOGY

The strength-to-weight ratio is a critical parameter in aircraft design, as it directly influences the structural efficiency, payload capacity, fuel consumption, and overall performance of an aircraft. Achieving a high strength-to-weight ratio is essential for both commercial and military aviation to meet stringent requirements for safety and performance. So, to deal with this problem first objective is to deal with the design and geometry. The study begins with the cross-section of the beam. The beam's cross-section carries out an important role in the stress and deformation of the body.

In the analysis, every cross-sectional shape was designed using Catia. The initial phase involved the design of closed sections, specifically circular and rectangular cross-sections. The I-section was designed with the same length and width as the rectangular cross-section. Once the design of each beam was completed, static structural analysis was conducted for each beam using Ansys software. A point load of 100,000N was applied to the free end of each beam to determine their maximum stress and deformation.

In the subsequent step, Ixx was maintained as a constant value for all four cross-sectional shapes, and their dimensions were calculated. After designing in Catia, the same process for analysis was executed for all the beams.

After comparing the results, the I section was selected for further analysis. The I section was tapered using a taper ratio of a Boeing 747-400. Also, holes were made in areas where the beam experienced minimum stress, in order to reduce weight without compromising the strength of the beam.

3 MATERIAL SELECTION

In the Aircraft industry, most of the structural components are manufactured using aluminum alloy due to its high strength-to-weight ratio. The spar of the beam is mostly made up of an aluminum sheet, in most of the places aluminum alloy 6082-T6 is been taken in the reference. So, I chose aluminum 6082-T6 for our further study and computational analysis.

Material Properties :- Density = 2700 kg/ m^3 , Modulus of elasticity = 70 GPa, Poisons ratio = 0.33

4 DIMENSIONS

We have taken the reference of Boeing 747-400, the length of the beam is taken as per the length of the wing of the Boeing aircraft i.e. L = 1268inch. The cross-section of the beam is selected on the basis of the study. I have chosen three cross-sections, two sections are closed sections(Rectangular and Circular), and one open section (I-section).

The deflection of the cantilever Beam is

$$\delta = \frac{Pl^2}{3EI}$$

As in the above equation of the deflection of the cantilever beam, Deflection of the beam δ = f (load, length of beam, modulus of elasticity, and moment of inertia), From these four variables, two are geometrical properties first is length of the beam and another is moment of inertia Ixx. Further, as the beam length is the same to took keep Ixx the same I have taken Ixx of the I-section and then calculated the dimensions of the cantilever beam.

5 CALCULATIONS OF THE DIMENSIONS OF THE CROSS-SECTION OF THE BEAM

The Moment Of Inertia (I_{XX}) of all the cross-sections (I-section, Circular Section, Rectangular Section, Square Section) is taken the same

Due to this, the Deflection in all sections are same.

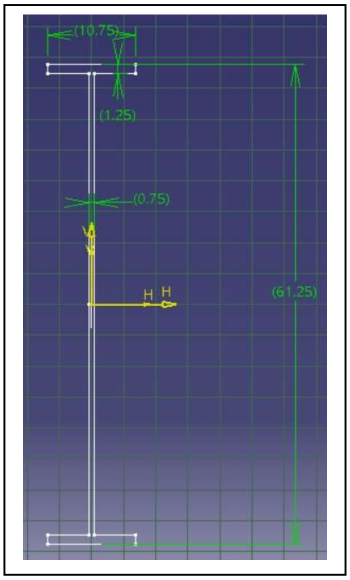


Fig. 1. I-section

So, Taking the Moment of Inertia same for Every Cross Section for the Value of $I_{XX} = 36864.7$ inch^4

$$I_{XX} = \frac{b_1 d_1^3}{12} + A_1(Y - y_1) + \frac{b_2 d_2^3}{12} + A_2(Y - y_2) + \frac{b_3 d_3^3}{12} + A_3(Y - y_3)$$

$I_{XX} = 36864.7$ inch^4

- For Circular Cross Section,

  $$I_{XX} = \frac{PiD^4}{64}$$

  D = 29.438 inch by taking $I_{XX} = 36864.7$ inch^4

- For Rectangular Section,

  $$I_{XX} = \frac{b_1 d_1^3}{12}$$

  Assumed breadth (b) = 10.75 inch and find depth by using I_{XX} value.

  Depth (d) = 34.524 inch

6 CROSS-SECTION SELECTION

After Performing the analysis on all the cross-sections which were having the same Ixx as the I-section, the strength-to-weight ratio of the I-section was higher than the closed section.

7 TAPER I-CROSS SECTION

In order to construct the beam as per the wing use, I have taper, the spar beam which also has reduced the weight of the beam. Tapering has been performed by taking the reference of the wing root cord and the tip cord of the transport aircraft Boeing 747-400.

- BY TAKING THE REQUIRED RATIOS THE TIP CROSS SECTION HAS BEEN CALCULATED.
- THE WEB AND FLANGE VALUES HAVE BEEN CALCULATED.

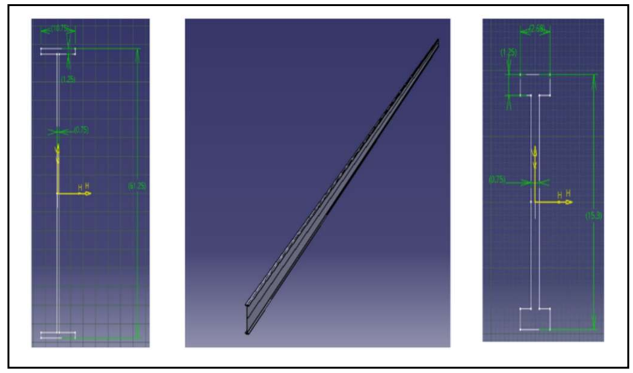


Fig. 2. Root cord section and Tip Cord Cross section

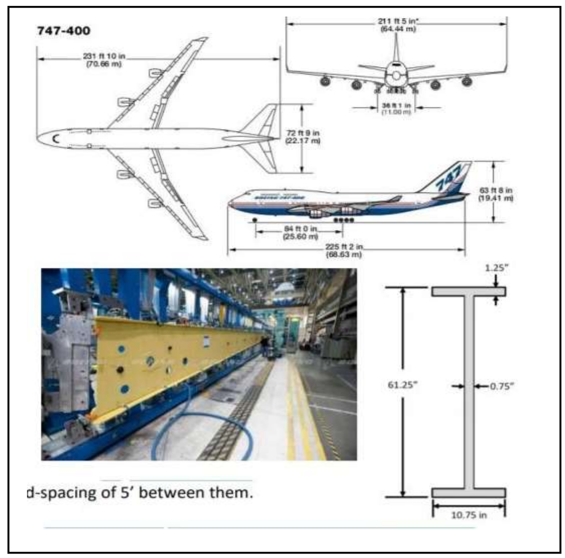


Fig. 3. Boeing 747-400 dimension

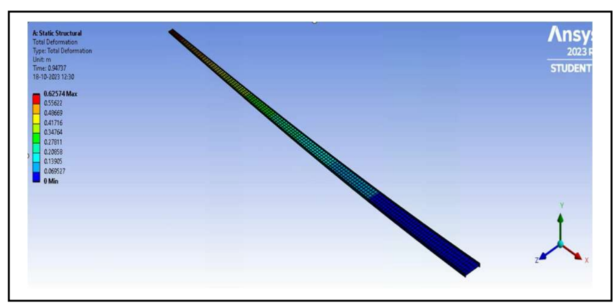


Fig. 4. Deflection of the Taper I – section beam

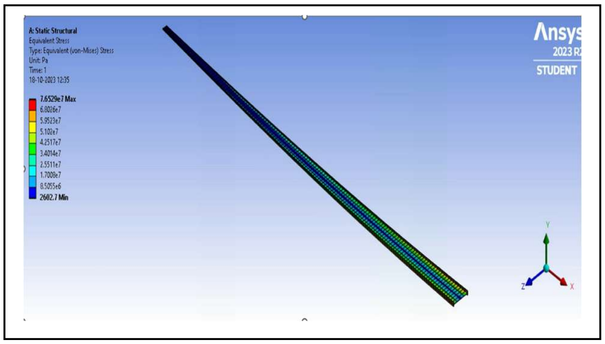
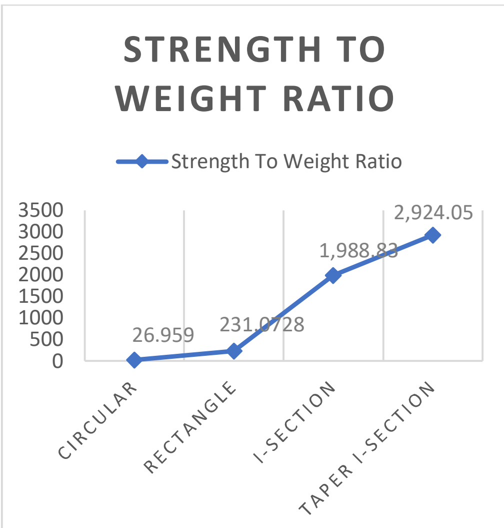


Fig. 5. Equivalent stress on the Taper I – section beam



Graph 1. Strength to weight ratio v/s Cross-Section

8 Extraction of the Material

From the Taper I-section beam the extraction of the circular disc was performed where stress concentration of the beam is low.

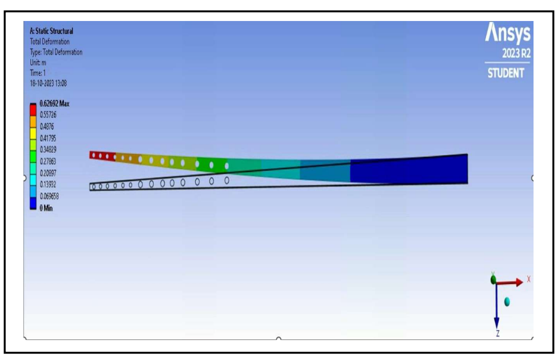


Fig. 6. Deflection of the Taper I – section beam with holes

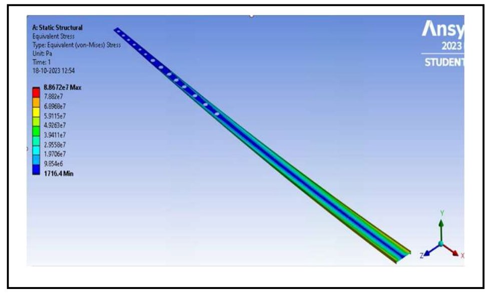


Fig. 7. Equivalent stress on the Taper I – section beam with Holes

Table 1. Comparison of different cross-sections of Beam

Cross Section of Beam	Weight	Maximum Deformation	Maximum Stress	Strength To Weight Ratio
Circle	1,624,357.57 N	0.47204	43,791,000 Pa	26.959
Rectangle	222,618.114 N	0.47216	51,441,000 Pa	231.0728
I-Section	42,548.5795 N	0.43871	84,622,000 Pa	1,988.8326
Taper I-Section	26,163.27 N	0.454	76,529,000 Pa	2,924.0459
Taper I-Section with extraction of circular disk	25,613.91 N	0.53713	88,672,000 Pa	3,461.869

Conclusion

- For the same values of Moment of Inertia, I get the same deflection for different cross sections as per the above results.
- However, for I cross-section and tapered I cross-section the strength-to-weight ratio is maximum
- For tapered I cross-section in order to reduce weight, material from areas where the stress concentration is negligible, was removed.
- This resulted in weight reduction without compromising the strength of the spar
- Hence, increasing the strength-to-weight ratio of Spar

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