Finite element analysis of aircraft wing using carbon fiber reinforced polymer and glass fiber reinforced polymer.

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Abstract. A wing is a structural component of aircraft which is used to produce lift during the flight. Wing is initially inclined at a certain angle of attack. When the flow passes over it, due to the pressure difference at top and bottom surface of the wing lift force is generated. The aim of this present study is to analyze the wing of an aircraft using Carbon fiber reinforced polymer (CRFP), Glass fiber reinforced polymer (GRFP) and compare with Al alloy to find suitable material for wing. The wing is designed in solid modeling software CATIA V5 R20 and analysis is done using finite element method by using ANSYS. Static structural analysis of the wing is done to find deformation, stress, and strain induced in the wing structure. Modal analysis is done to find the natural frequency of the wing to reduce the noise and avoid vibration. Finally fatigue life analysis is carried out to find out the damage, life and factor of safety of the wing due to applied pressure loads. In this study, the trainer aircraft wing structure with skin, 2 spars and 15 ribs is considered for the analysis. The ribs are running from leading edge to trailing edge and 2 spars running longitudinally along the length of wing. Front spar is made “I” section and rear spar having “C” section according to design.

Keywords. Finite element analysis, Modal analysis, Aircraft Wing, CFRP, GFRP

1. Introduction

The wing is a primary structural component of aircrafts (air breathing engines) which is used to produce lift force during flight. When the engine is started air is sucked into the compressor through the inlet increasing pressure ratio at the exit of the compressor. Then air and fuel is mixed inside combustion chamber and burnt. When high pressure, high temperature gases is accelerated through the nozzle, thrust force is produced which propels the aircraft in forward motion. Due to this forward motion, air flows over the wing which is aerodynamic in shape. Due to the aerodynamic shape of the wing along with Bernoulli’s principle the velocity of flow is less at bottom of the wing and high at top of wing. Due to this pressure difference creation is created between top and bottom surface of wing and thus lift is generated [1]. Wing must have high strength to weight ratio, high fatigue life since it is subjected to alternate repeated loadings during flight. The main aim of this research is to find the suitable material for the wing like composite to replace the conventional Aluminum 2024 T3 (Al-2024
T3) by which skin of the wing is made with. The cross section of wing is called airfoil which is made aerodynamic in shape to reduce drag [3]. The aerodynamic efficiency of wing is expressed in terms of lift/drag ratio. Fuselage and empennage are other structural components of aircraft. Fuselage houses passengers, crew, and cargo etc. while as empennage provides stability to the aircraft during flight. Aluminum is widely used material for aircraft structure. About 80% of the structure is made up aluminum and aluminum alloys [5]. Composite material is made of two materials one is matrix which surrounds and binds the reinforcement material and another is reinforcement material [6]. In this analysis epoxy is used as matrix material and fiber as reinforcement materials. Fibers can be glass fiber, carbon fiber etc. A composite laminate is an assembly of layers of fibrous material like carbon fibers, glass fibers; aramids lay in the matrix material which can be joined to provide required specific and desired properties [9]. A laminate is formed by stacking number of individual lamina one above another in desired orientation. A fiber which is embedded in the lamina in different orientation carries the load. The matrix material provides support to the fibers and protects fibers from damage [12]. The main function of the matrix is to transfer load to the fiber and keep the fiber in predefined position and orientation.

2. Materials and Methods

In this study, trainer aircraft wing structure with skin, spars and ribs is considered for the detailed analysis. The wing structure consists of 15 ribs and two spars with skin. Front spar having “I” section and rear spar having “C” section [11]

| Parameters         | Dimensions       |
|--------------------|------------------|
| Root chord         | 2400mm           |
| Tip chord          | 700 mm           |
| Semi span length   | 5500mm           |
| Exposed Length of wing | 4750mm       |
| Airfoil (Root)     | NACA-64A215      |
| Airfoil (Tip)      | NACA-64A210      |
| Front Spar         | 18-25% of chord  |
| Rear spar          | 62-70% of chord  |
The airfoil co-ordinate is taken from NASA website and exported to Microsoft Excel. From the help of macros the airfoil shape is generated in Catia. The airfoil is divided in 15 sections at an equal distance from reference plane with thickness of 100mm [13]. Front spar, rear spar and holes are created as per the assumptions. The complete design of the wing structure is formed. Before importing the CAT file to the ansys workbench, the file has been converted into IGS format.

2.1 Material Characteristics:

Ex, Ey and Ez are Young’s modulus along X, Y and Z directions respectively. μ(xy), μ(yz), μ(zx) are Poison’s ratio in xy, yz, and zx plane respectively. Gxy, Gyz and Gzx are modulus of rigidity in xy, yz and zx plane respectively. The material properties are taken from different research papers [4, 7, 8, 10, 14, and 17] and matched with Ansys library.
Table 2. Material Properties

| Materials          | Epoxy-Carbon UD | Epoxy-Carbon Woven | Epoxy E-Glass | Epoxy S-Glass | Al-2024 T3 |
|--------------------|-----------------|--------------------|---------------|---------------|------------|
| Ex(Gpa)            | 121             | 61.34              | 45            | 50            |            |
| Ey(Gpa)            | 8.6             | 61.34              | 10            | 8             | 73.1       |
| Ez(Gpa)            | 8.6             | 6.9                | 10            | 8             |            |
| μ(xy)              | 0.27            | 0.04               | 0.3           | 0.3           |            |
| μ(yz)              | 0.4             | 0.3                | 0.4           | 0.4           | 0.33       |
| μ(zx)              | 0.27            | 0.3                | 0.3           | 0.3           |            |
| Gxy(Gpa)           | 4.7             | 19.5               | 5.0           | 5.0           |            |
| Gyz(Gpa)           | 3.1             | 2.7                | 3.846         | 3.486         | 26.6       |
| Gzx(Gpa)           | 4.7             | 2.7                | 5.0           | 5.0           |            |
| ρ(kg/m³)           | 1490            | 1420               | 2000          | 2000          | 2770       |

2.2 Boundary Condition:

The loads and boundary conditions along with finite element model are shown in figure 3 below. One end of the wing is fixed because it is embedded inside the fuselage and other end is left free with 6 degree of freedom. Pressure force of 500Pa is applied at the bottom surface of the wing at center of pressure [16]. Center of pressure is a point at which total pressure is assumed to be act [2].

![Figure 3. Mesh](image-url)
3. Static structural analysis results

Table 3. Static Structural Analysis Results

| Materials          | Total deformation (mm) | Equivalent stress (Mpa) | Equivalent strain       |
|--------------------|------------------------|-------------------------|-------------------------|
| Epoxy-carbon UD    | 4.223                  | 16.225                  | 0.00016508              |
| Epoxy S-glass UD   | 9.8794                 | 16.145                  | 0.00040288              |
| Aluminum 2024 T3   | 6.7377                 | 16.034                  | 0.00022722              |
| Epoxy-carbon Woven | 7.9845                 | 15.709                  | 0.00030371              |
| Epoxy E-glass      | 10.943                 | 15.943                  | 0.00044117              |

Table 4. Static Structural Analysis under different Speeds

| Materials     | Speed (km/hr) | Total deformation (mm) | Equivalent stress (Mpa) | Equivalent strain |
|---------------|---------------|------------------------|-------------------------|-------------------|
|               | 200           | 4.1013                 | 17.382                  | 0.00018043        |
|               | 400           | 4.1106                 | 48.259                  | 0.00048840        |
|                  |   |   |   |   |
|------------------|---|---|---|---|
| **Epoxy-carbon UD** | 600 | 4.1501 | 102.69 | 0.00010383 |
|                  | 800 | 4.2540 | 179.16 | 0.00181151 |
|                  | 1000 | 4.4651 | 277.62 | 0.00280721 |
| **Epoxy S-glass UD** | 200 | 9.7966 | 20.068 | 0.00049880 |
|                  | 400 | 9.8664 | 62.051 | 0.00153883 |
|                  | 600 | 10.086 | 133.82 | 0.00331862 |
|                  | 800 | 10.597 | 234.77 | 0.00582183 |
|                  | 1000 | 11.611 | 364.71 | 0.00904401 |
| **Aluminum 2024 T3** | 200 | 6.6401 | 25.051 | 0.00035280 |
|                  | 400 | 6.7384 | 84.141 | 0.00118511 |
|                  | 600 | 7.0510 | 183.79 | 0.00258862 |
|                  | 800 | 124.94 | 321.76 | 0.00453193 |
|                  | 1000 | 462.41 | 502.04 | 0.00707101 |
| **Epoxy-carbon Woven** | 200 | 8.2013 | 17.080 | 0.00033361 |
|                  | 400 | 8.2590 | 46.266 | 0.00089541 |
|                  | 600 | 8.3816 | 98.275 | 0.00190540 |
|                  | 800 | 8.6483 | 171.33 | 0.00331470 |
|                  | 1000 | 9.1602 | 265.43 | 0.00513490 |
| **Epoxy E-glass** | 200 | 10.847 | 20.066 | 0.00054441 |
|                  | 400 | 10.927 | 62.048 | 0.00168010 |
|                  | 600 | 11.175 | 133.82 | 0.00362340 |
|                  | 800 | 11.749 | 234.77 | 0.00635650 |
|                  | 1000 | 12.886 | 364.70 | 0.00987450 |

(a) Total deformation using Epoxy-Carbon UD
(b) Total Deformation using Epoxy S-Glass

(c) Total Deformation Using Aluminum 2024 T3
(d) Total Deformation using Epoxy-Carbon Woven

(e) Total Deformation using Epoxy E-Glass

Figure 5 (a)(b)(c)(d)(e) Total deformation contour plots
Figure 6. Deformation versus Speed curve for different materials

Figure 7. Stress versus Speed curve for different materials
4. Modal Analysis Results

Modal analysis is a study of dynamic properties of vibrating structures. It is used to determine the natural frequency of continuous structural members. Lowest frequency mode is desired because vibration will be less as compared to higher frequency modes. From the Modal Analysis result it can be seen that Epoxy-carbon UD has relatively high natural frequency than other materials. At high natural frequency resonance can be delayed.

**Table 5.** Natural frequency (Hz) for different materials

| Mode shape | Epoxy-Carbon UD | Epoxy S-Glass | Aluminum 2024 T3 | Epoxy-Carbon Woven | Epoxy E-Glass |
|------------|----------------|--------------|------------------|--------------------|---------------|
| 1          | 20.136         | 11.205       | 11.446           | 14.698             | 10.636        |
| 2          | 95.864         | 69.375       | 71.416           | 91.124             | 65.959        |
| 3          | 124.56         | 83.381       | 91.407           | 118.07             | 83.099        |
| 4          | 149.56         | 87.626       | 159.48           | 177.87             | 83.444        |
| 5          | 295.95         | 191.28       | 198.73           | 250.95             | 182.07        |
| 6          | 339.32         | 253.22       | 385.80           | 480.17             | 252.29        |

**Table 6.** Maximum amplitude (mm) of vibration

| Mode shape | Epoxy-Carbon UD | Epoxy S-Glass | Aluminum 2024 T3 | Epoxy-Carbon Woven | Epoxy E-Glass |
|------------|----------------|--------------|------------------|--------------------|---------------|
| 1          | 0.84036        | 0.7176       | 0.60774          | 0.84665            | 0.7172        |
| 2          | 1.38780        | 0.8117       | 0.61325          | 0.85416            | 0.7855        |
| 3          | 1.10660        | 1.3689       | 0.60580          | 0.84461            | 1.3456        |
| 4          | 0.79319        | 0.7027       | 1.08580          | 1.50790            | 0.7043        |
| 5          | 1.63000        | 0.7843       | 0.62033          | 0.85557            | 0.7491        |
| 6          | 1.61390        | 1.4494       | 0.63568          | 0.90700            | 1.4152        |
5. Fatigue Life Analysis Results:

Table 7. Fatigue life analysis data

| Materials           | Life | Damage | Factor Of Safety |
|---------------------|------|--------|------------------|
| Epoxy-Carbon UD     | 1e8  | 10     | 5.1696           |
| Epoxy-Carbon Woven  | 1e8  | 10     | 5.2869           |
| Aluminum 2024-T3    | 1e8  | 10     | 5.2344           |
| Epoxy S-Glass       | 1e6  | 1000   | 5.4533           |
| Epoxy E-Glass       | 1e6  | 1000   | 5.4533           |

6. Results

As per the calculated design requirement, the modeling of wing of a trainer aircraft with 15 ribs and 2 spars was done with the help of designing software CATIA V5R20 and finite element analysis was carried out to find deformation, stress, strain, frequency and life of wing. The structural analysis of the wing section was carried out for materials such as Epoxy-Carbon UD, Epoxy-Carbon Woven, Epoxy S-Glass, Epoxy E-Glass and Aluminum 2024-T3 with the help of ANSYS Static Structural. The modal analysis was carried out to find the frequency and maximum amplitude of vibration of wing for same materials. From the above analysis it can be concluded that epoxy-carbon gives better strength, low weight and minimum deformation than aluminum 2024-T3. It can be seen from the above graph.1 that the deformation and stress value is increasing with increasing rotational speed. But for aluminum 2024-T3 the deformation curve abruptly increases beyond 600rad/sec. Epoxy-carbon material offers less stress an aircraft wing than aluminum alloy. 6 mode shapes have been created from the modal analysis for the different materials to find the natural frequency and maximum amplitude of vibration. Lowest frequency mode is desirable for any structure (wing) because it has less amplitude of vibration. These results hold true for trainer aircraft wing with 15 ribs and 2 spars as designed. And results may vary accordingly with different aircraft wing and design.

7. Conclusion

From the comparisons of results it can be seen that Epoxy-Carbon UD has better structural characteristics than other materials. It has less deformation, high strength, light weight as compared to Aluminum 2024 T3 and other materials. So it is concluded that Epoxy- Carbon UD is suitable material for making aircraft wing.

As future enhancement, different materials can be tested with different boundary conditions to find more suitable materials with good aerodynamic and structural characteristics, number of main load carrying members can be changed and analysis can be performed.
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