

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

Salu Kumar Das¹, Sandipan Roy^{*1}

¹Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur.

*Corresponding author: sandipanroy.g@ktr.srmuniv.ac.in

Abstract. A wing is a structural component of aircraft which is used to produce lift during the flight. Wing is initially inclined at 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 (CFRP), Glass fiber reinforced polymer (GFRP) 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 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]

Table 1. Input parameters for wing design

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

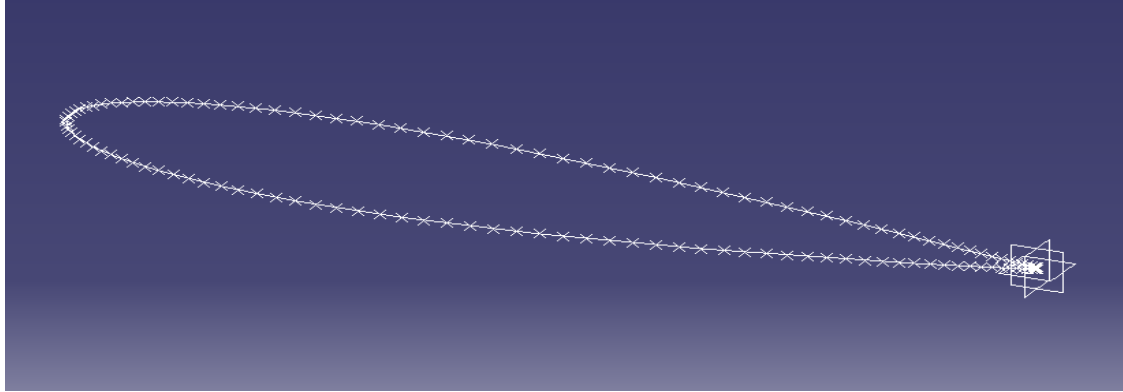


Figure 1. Airfoil Co-ordinates

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.

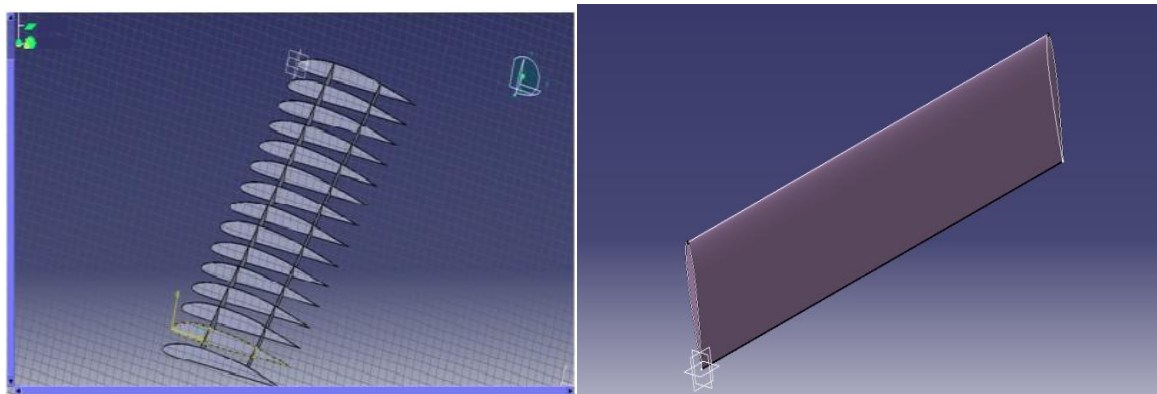


Figure 2. Wing Structure

2.1 Material Characteristics:

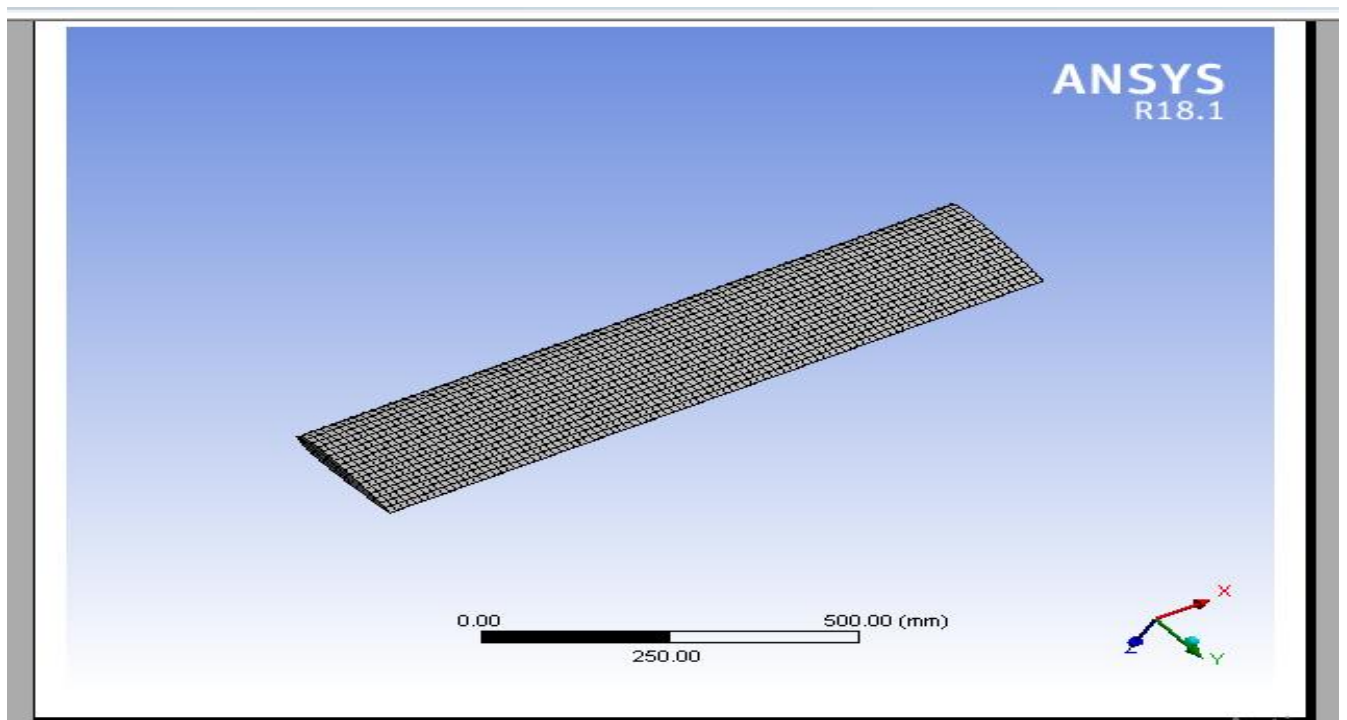
E_x , E_y and E_z are Young's modulus along X, Y and Z directions respectively. $\mu(xy)$, $\mu(yz)$, $\mu(zx)$ are Poison's ratio in xy, yz, and zx plane respectively. G_{xy} , G_{yz} and G_{zx} are modulus of rigidity in xy, yz and zx plane respectively. The material properties are taken from different 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	
$\mu(xy)$	0.27	0.04	0.3	0.3	
$\mu(yz)$	0.4	0.3	0.4	0.4	0.33
$\mu(zx)$	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	
$\rho(\text{kg/m}^3)$	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

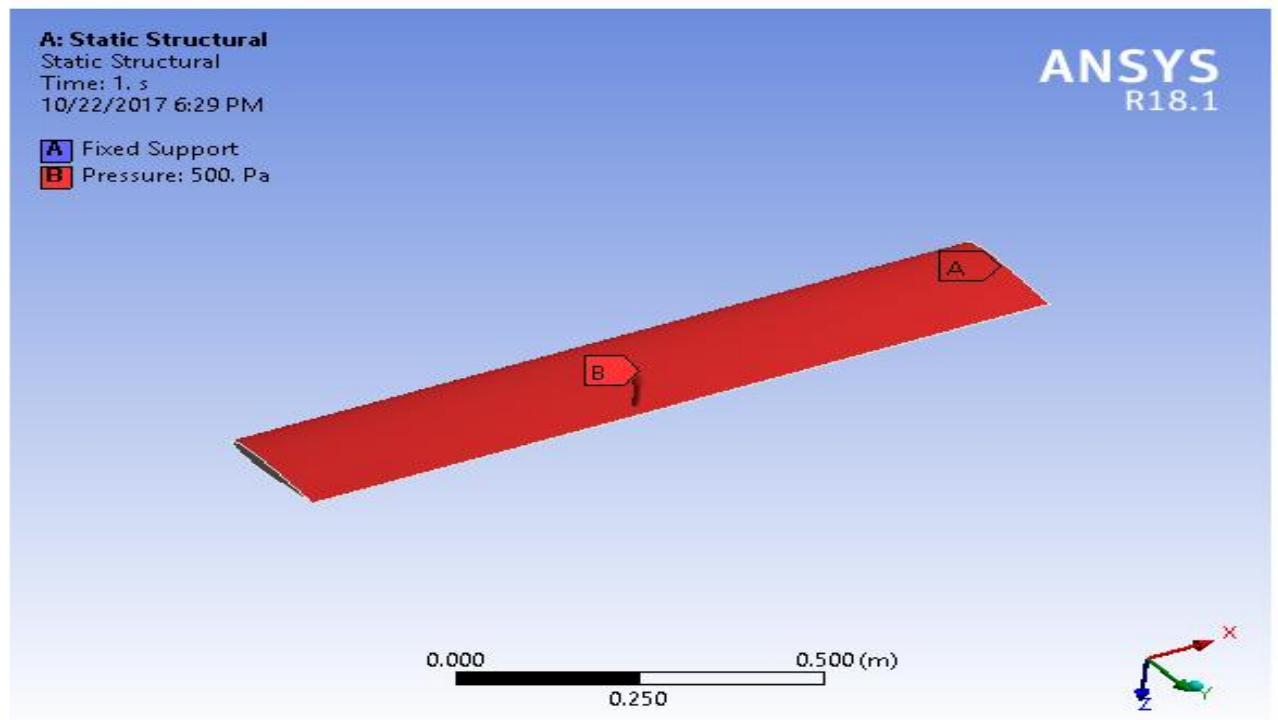


Figure 4. Boundary Condition

3. Static structural analysis results

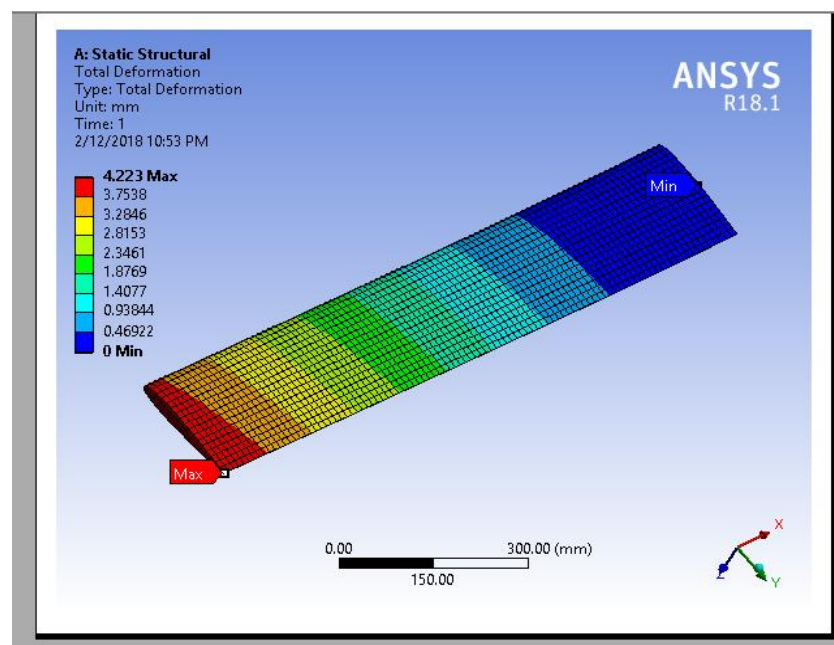
Table 3. Static Structural Analysis Results

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

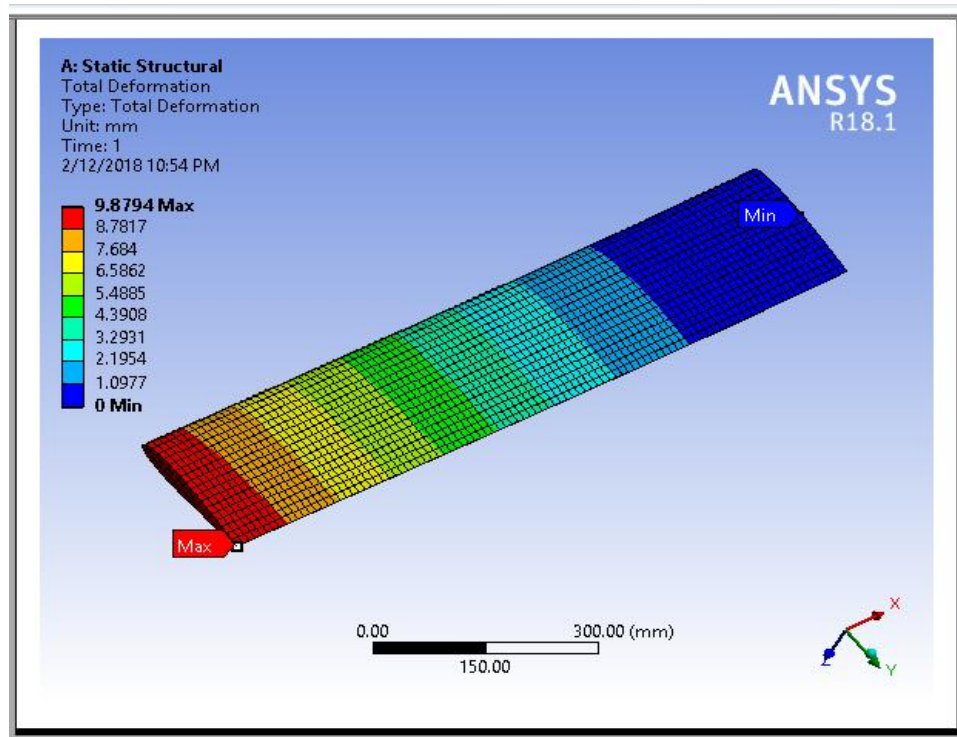
Table 4. Static Structural Analysis under different Speeds

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

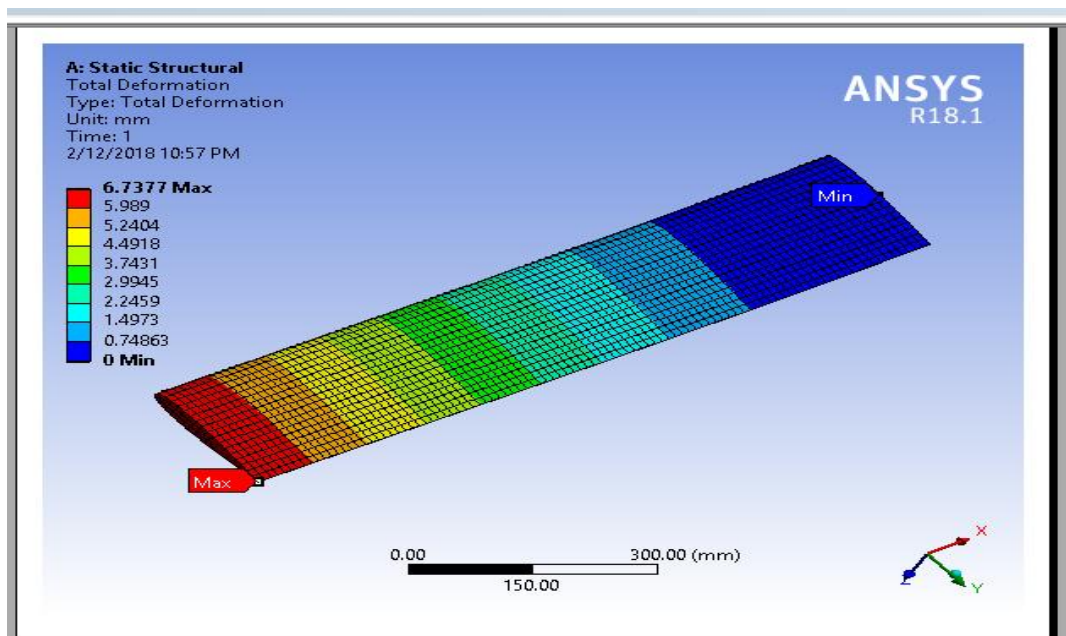
Epoxy-carbon UD	600	4.1501	102.69	0.00010383
	800	4.2540	179.16	0.00181151
	1000	4.4651	277.62	0.00280721
Epoxy S-glass UD	200	9.7966	20.068	0.00049880
	400	9.8664	62.051	0.00153883
	600	10.086	133.82	0.00331862
	800	10.597	234.77	0.00582183
	1000	11.611	364.71	0.00904401
Aluminum 2024 T3	200	6.6401	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



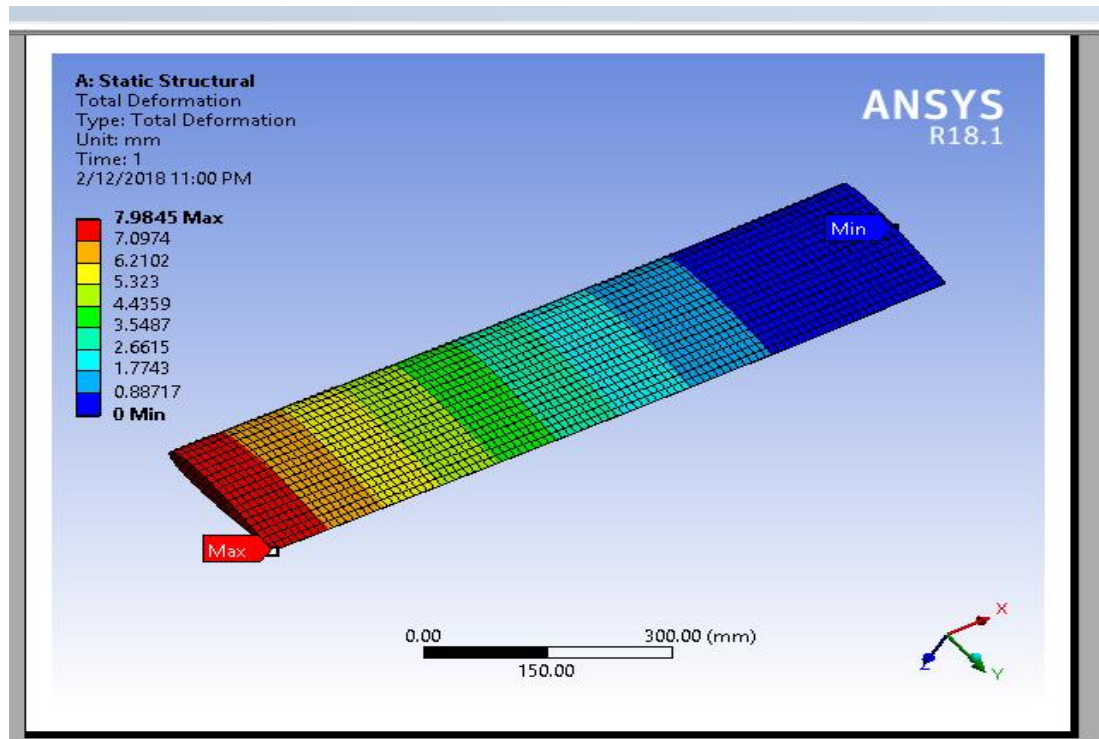
(a) Total deformation using Epoxy-Carbon UD



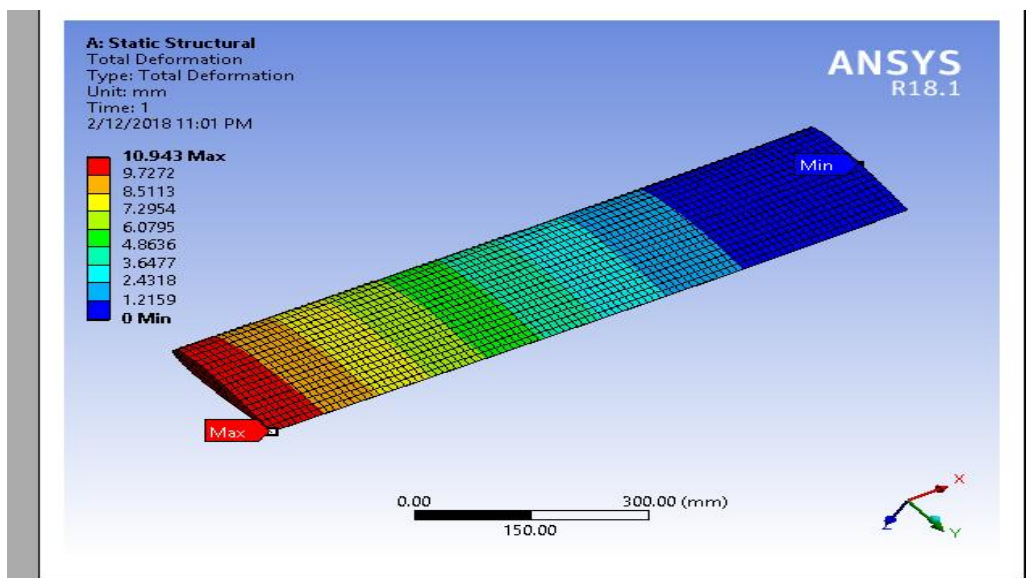
(b) Total Deformation using Epoxy S-Glass



(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

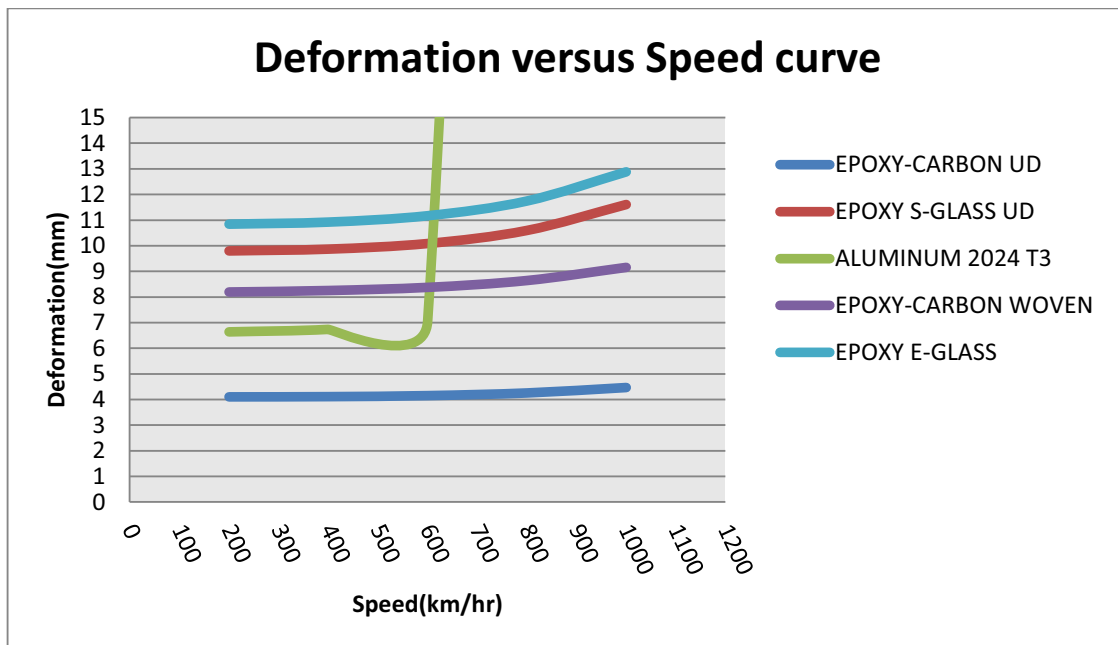


Figure 6. Deformation versus Speed curve for different materials

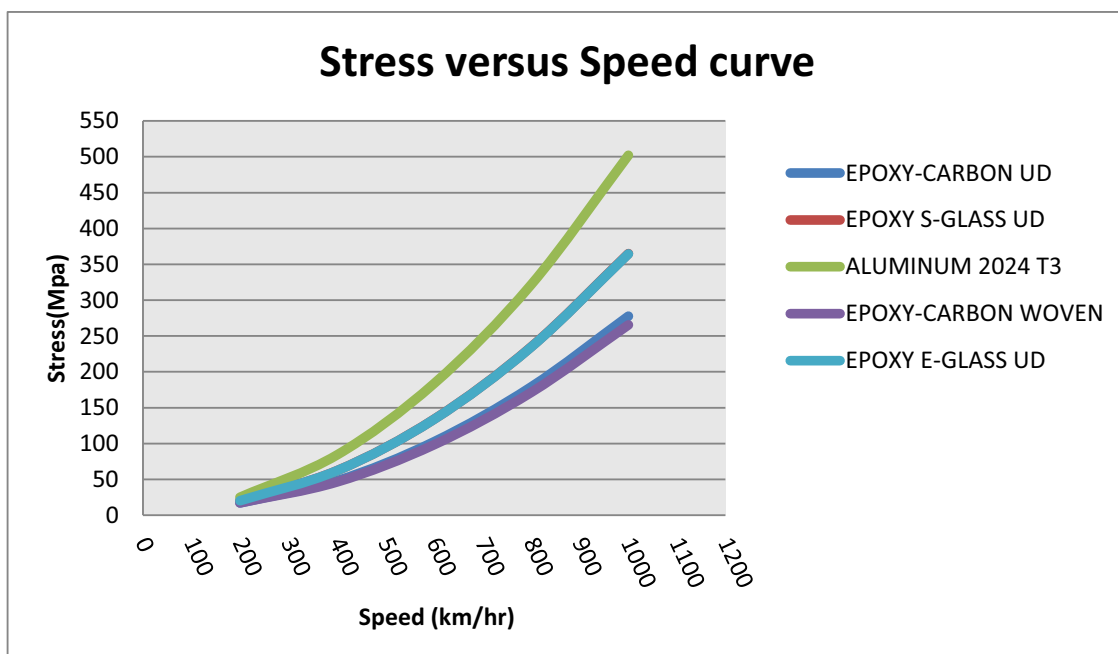


Figure 7. Stress versus Speed curve for different materials

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.

8. References

- [1] A M H Abdul Jalil, W Kuntjoro and J Mahmud 2012 Wing structure static analysis using super Element, *Procedia Engineering*. **41**, 1600 – 1606
- [2] T V Baughn and P F Packman 1986 Finite element analysis of an ultra-light aircraft, *Journal of Aircraft*. **23**, 82-86
- [3] Yuvraj S R and Subramanyam P 2015 Design and analysis of Wing of an ultra-light Aircraft *International journal of innovative research in science, engineering and technology*. **4**,78-85
- [4] John D Anderson *Introduction to flight*, 6th Edition
- [5] Kuntjoro W 2008 *An Introduction to The Finite Element Method*, Mc Graw-Hill
- [6] Fiorina A, Seman B, Castanie K M, Ali C, Schwob and L. Mezeix 2017 Spring-in prediction for carbon/epoxy aerospace composite structure, *Composite Structures*. **168**,739–745.
- [7] K Sommerwerk, B Michels, K Lindhorst, M C Haupt and P Horst 2016 Application of efficient surrogate modeling to aero elastic analyses of an aircraft wing, *Aerospace Science and Technology*. **55**, 314–323
- [8] J Splichal, A Pistek and J Hlinka 2015 Dynamic tests of composite panels of aircraft wing, *Progress in Aerospace Sciences*.**78**, 50–61
- [9] H Hu and H Kao 2009 Model Validation of an ultralight aircraft using experimental modal analysis *Journal of aeronautics, astronautics and aviation, series A*. **41**,271-282
- [10] J Schijve 2004 *Fatigue of Structures and Materials*, Kluwer Academic Publishers.
- [11] J Schijve 2009 Fatigue Damage in Aircraft Structures Not Wanted but Tolerated, *International Journal of Fatigue* .**31**,998-1011
- [12] F.H.Darwish, G.M.Atmeh, Z. F. Hasan 2012 Analysis and Modelling of a General Aviation Aircraft, *Jordan Journal of Mechanical & Industrial Engineering* .**6**, 183–191
- [13] G. R. Benini, E. M. Belo and F. D. Marques 2004 Numerical Model for the Simulation of Fixed Wings Aeroelastic Response, *Journal of the Brazil Society of Mechanical Science and Engineering*. **XXVI**, 129-136
- [14] Michael C and Y. Niu, 1989 'Airframe structural design', Conmilit press Ltd.,
- [15] F Al-Mawahra and O Zaza 2009 Structural Analysis of an Aircraft Wing, Thesis submitted to the faculty of engineering, Jordan University of Science and Technology
- [16] A Ramesh Kumar 2013 Design of an Aircraft Wing Structure for Static Analysis and Fatigue Life Prediction, *International Journal for Engineering Research & Technology*. **2**,129-135
- [17] F H Darwish, G M Atmeh, Z F Hasan Design 2012 Analysis and Modeling of a General Aviation Aircraft, *Jordan Journal of Mechanical & Industrial Engineering*.**6**, 183-191.