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Numerical Analysis on Fatigue Strength of Composite Materials

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Abstract: The interest and development of composite materials is growing now days, as aluminium does not have a very long life, and needs timely maintenance. The aim of this project is to suggest an alternative for the existing aluminium skin.

Carbon fiber is one of the widely used materials accounted for its strength and stiffness. We aim at testing the fatigue life of carbon fiber and making it alternative to the present day aluminium skins.

Our approach begins with the study of fatigue in metals, fractures which are the resultant of fatigue. Mechanical components can fail at stresses well below the tensile strength of the material if subjected to alternating loads. Failure of ductile materials under alternating loads occurs in a quasi-brittle manner, i.e. by crack propagation, in vast metals.

In this paper we have chosen an aluminium alloy that is used as a fuselage skin in many aircrafts, commonly called aluminium 2024. For the composite material analysis, carbon fiber was checked for fatigue life. Analysis has been done with the help of Ansys software. Experimental work was carried out both on carbon fiber and aluminium skin. Fatigue life of both aluminium and carbon fiber material has been compared and the suitable result was obtained.

1. INTRODUCTION

Metal fatigue is the relatively slow growth of cracks through metal structures or objects. For this fatigue to occur the object must be subjected to a tensile, cyclic load. In other words, there must be some force tending to pull the object apart and the force must vary over time. These conditions occur with rotating or vibrating machinery .Fatigue cracks are very slow to develop initially but their rate of growth increases dramatically as the crack grows. The initiation of fatigue cracks is promoted by the presence of defects in the original material and by sharp notches in the object

Some materials have a fatigue limit. For example, mild steel will not normally admit fatigue crack growth if the applied stresses are below about 10% of the strength of the material. Other materials like Aluminium alloys do not have such limits. If a cyclic load is applied, Aluminium alloys will always fatigue. As a consequence, Aluminium alloys cannot be used for shafts where an infinite fatigue life is specified.

It is possible to calculate the crack by fatigue in any particular situation. This allows us to use nondestructive methods. The interval period should not be large enough for crack to become large and produce failure in metals. Some materials (e.g., some steel and titanium alloys) exhibit a theoretical fatigue limit below which continued loading does not lead to structural failure.

2. PREVIOUS RESEARCH

In recent years, researchers (see, for example, the work of Bathias, Murakami, and Stanzl-Tschegg) have found that failures occur below the theoretical fatigue limit at very high fatigue lives (10^9 to 10^{10} cycles). An ultrasonic resonance technique is used in these experiments with frequencies around 10–20 kHz.

High cycle fatigue strength (about 10^3 to 10^8 cycles) can be described by stress-based parameters. A load-controlled servo-hydraulic test rig is commonly used in these tests, with frequencies of around 20–50 Hz. Other sorts of machines like resonant magnetic machines can also be used, achieving frequencies up to 250 Hz

3. FATIGUE IN ALUMINIUM ALLOY

Aluminium alloy 2024 is an Aluminium alloy, with copper as the primary alloying element. It is used in applications requiring high strength to weight ratio, as well as good fatigue resistance. Example of fatigue crack in Aluminium is shown in fig 1.

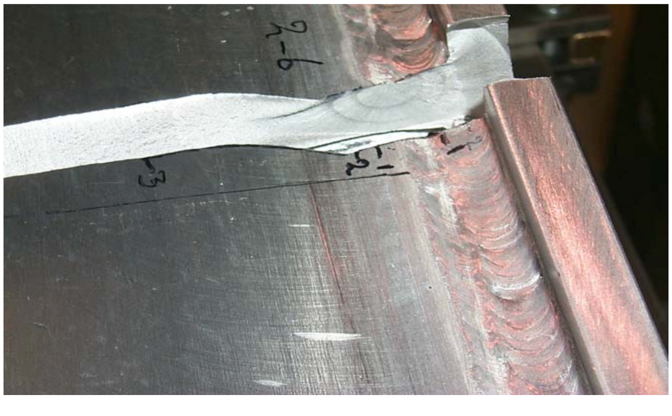


Figure 1 Fatigue Crack in Aluminium

4. COMPOSITES

There is a problem in determining the resistance of fiber reinforced plastics by engineers. Composite materials have complex failure mechanisms fatigue loading because of anisotropic characteristics in their strength and stiffness. Fatigue causes extensive damage to whole volume which leads to failure from a single crack. Predominant single crack is the most common failure mechanism brittle materials such as metals. There are four basic failure mechanisms for composite materials because of fatigue:

- Matrix cracking
- Delamination
- Fiber breakage
- Interfacial deboning

The failure modes combined with the inherent isotropies complex stress fields and overall non-linear behavior of composites limits our ability to understand the true nature of fatigue.

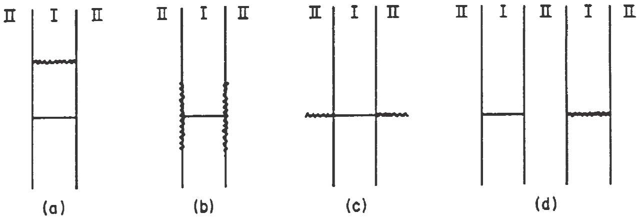


Figure 2 Types of Failure in Composite Material

5. FRACTURE IN COMPOSITE MATERIALS

Composite materials are developed to reduce the weight in structural application and also to increase the mechanical and thermal properties of the materials. It is a combination of matrix and reinforced materials.

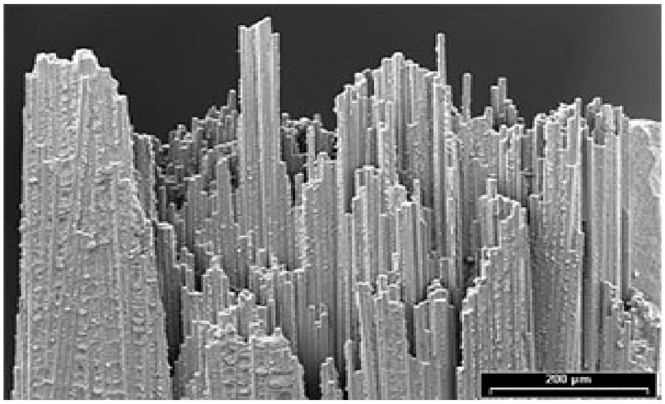


Figure 3 Carbon Fiber Fracture Surface

Mechanisms that control this behavior is

- Crack trapped in particulate reinforce composites
- Crack bridging in fiber reinforced composites

6. PROBLEM IDENTIFICATION

Although Aluminium is now used most of the aircraft fuselage skin it experiences loads caused by global impact of bending moment, torque, intersecting forces well as the surplus internal pressure. It contains rather big cutouts. Mazier said the metal fails below the tensile strength of the material if subjected to alternating loads and in ductile metal it occurs in a quasi-brittle manner, i.e. by crack propagation. Failure is preceded by characteristic changes in the material microstructure.

The use of Aluminium increases the maintenance cost and time consumption and then also it could not be told easily weather it could withstand for long time. Fatigue is a major problem for all the kind of failure occurring in the metal skin. It does not give prior indication of the failure. It creates small cracks and after threshold load it explodes making the material to fail. There is also a problem with carbon fiber that although from earlier test it has good fatigue strength, corrosion proof but they have rather low shear and contortion properties. They are also highly sensitive to the impact load. Since we are going to compare the fatigue life of Aluminium and carbon fiber in fuselage we need to design fuselage as per the need of future, which leads us to a point that tomorrow fuselage should have 30% mass reduction, 40% manufacturing cost, passenger's safety, corrosion resistance, fire safety etc. Keeping in mind all this points if the material has long life then other it automatically compensates the other costs. Thus fatigue life study of that metal will tell about the life of that material.

7. ANALYSIS SPECIFICATION

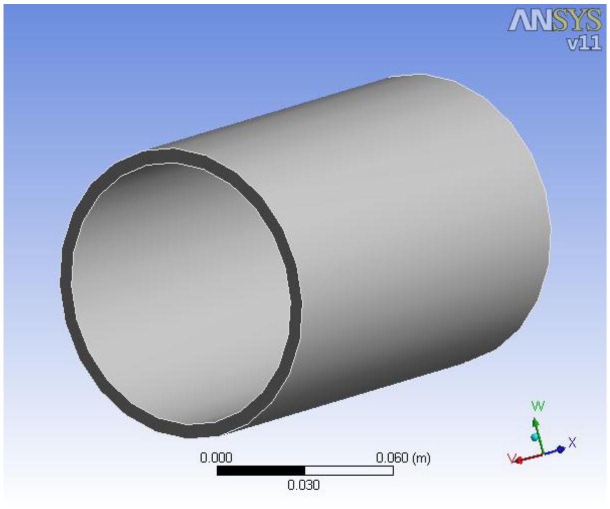


Figure 4 Work Bench Model of Aluminium 2024 Fuselage

We have analyzed the fatigue life of the Aluminium and carbon fiber using Ansys work bench. We have given pressure to the Aluminium and carbon fiber. We also have neglected the aerodynamic forces and thermal force; we have concentrated on the structural properties for both.

Parameters for the fuselage design

Diameter:	100 mm
Volume:	2.2384 x 10^4 mm^3
Thickness:	5 mm
Mass:	1.7571 Kg
Length:	150 mm

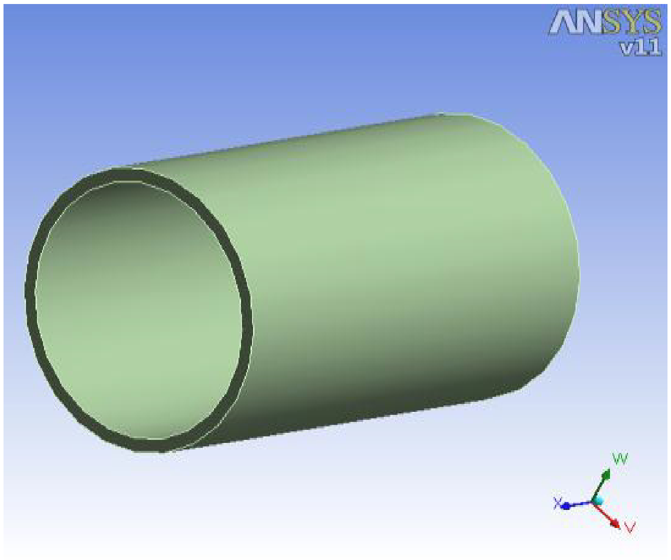


Figure 5 Work Bench Model of Carbon Fiber fuselage

Ansys Simulation of Aluminium at 0.5 bar:

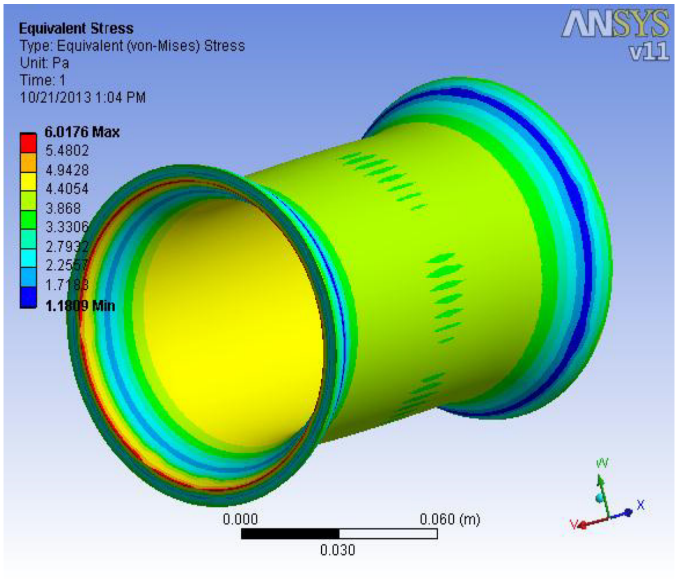


Figure 6 Equivalent Stress in Aluminium 2024

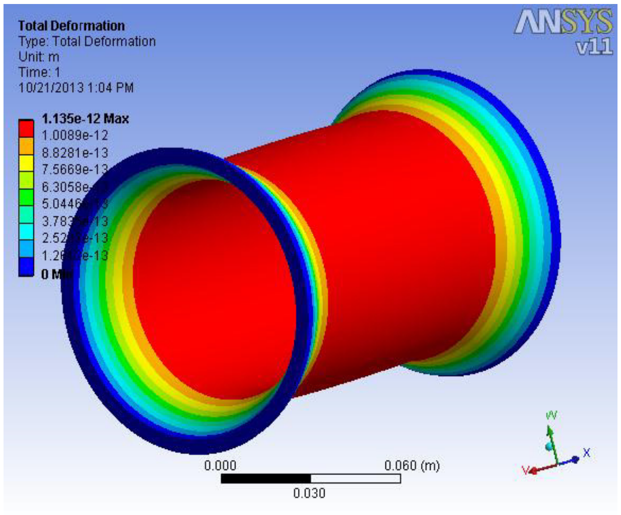
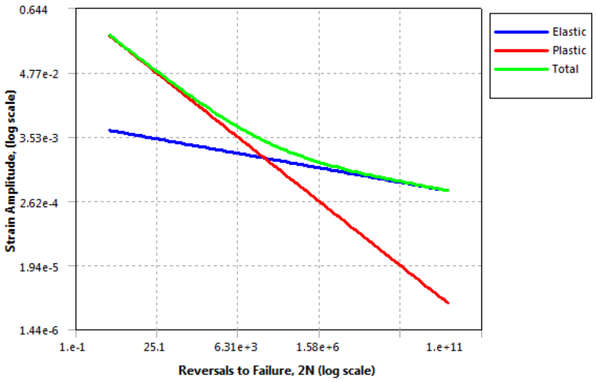


Figure 7 Total Deformation in Aluminium 2024



Graph 1 Strain Life Parameter of Aluminium 2024

Ansys Simulation of Carbon Fiber at 0.5 bar:

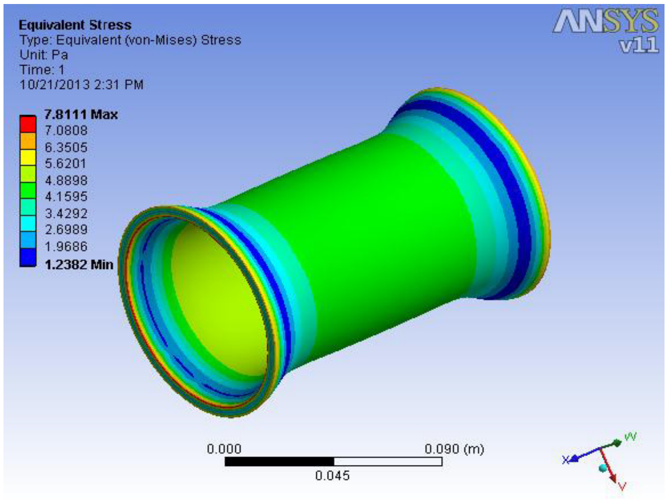


Figure 8 Equivalent Stress in Carbon Fiber

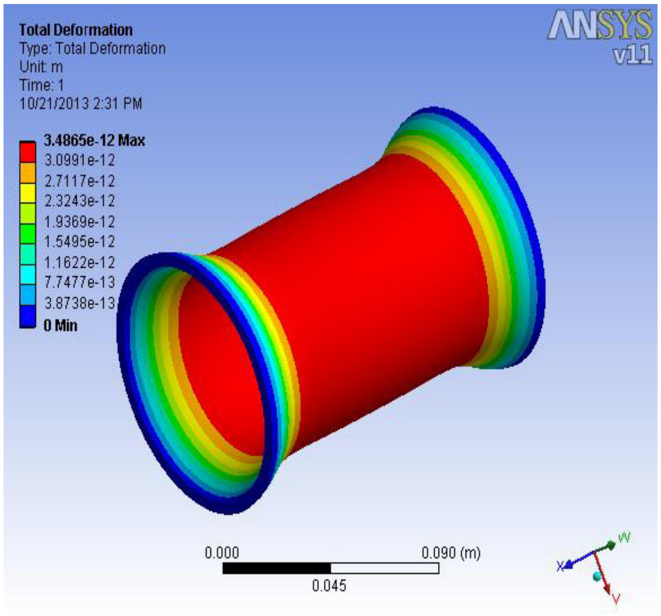
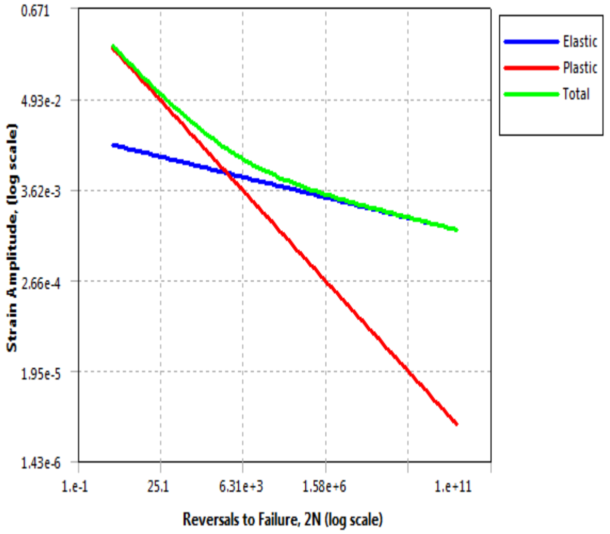


Figure 9 Total Deformation in Carbon Fiber



Graph 2 Strain Life Parameter of Carbon Fiber

8. COMPARISON OF ALUMINIUM AND CARBON FIBER USING ANSYS DATA

Here we have compared the strain value for both Aluminium and carbon fiber. Generally the material with less elongation is better for the aircraft skin. From the above report we can tell that carbon fiber holds less strain value than that of the Aluminium. We have also compared the stress value for both the material and we have obtained the result such that carbon fiber withstands high stress at high pressure hence it is better than the Aluminium.

Table 1 Comparison of Aluminium and Carbon Fiber

Pressure: 0.5 bar	Aluminium (Max Value)	Carbon Fiber (Max Value)
Equivalent Elastic strain	5.025×10^5	4.066×10^5
Equivalent Stress	6.0176 pa	5.8111 pa
Total Deformation	6.9736×10^6 m	2.142×10^5 m

The total deformation gives the result of damage; from the above table we conclude that the carbon fiber has less deformation then the Aluminium.

Carbon Fiber Properties:

Young's Modulus:	241*109 Pa
Poisson's Ratio:	0.1
Density:	1.8 g/cm^3
Thermal Expansion:	1.3e+005 1/°C
Tensile Ultimate Strength:	6.e+008 Pa
Compressive Ultimate Strength:	5.7e+008 Pa
Thermal Conductivity:	60.5 W/m·°C
Specific Heat	434 J/kg·°C
Resistivity:	1.7e-007 Ohm·m

Table 2 Fatigue Life of Aluminium and Carbon Fiber

Pressure	Fatigue life (1Cycle= 10 Cycles)		Safe factor	
Bar	**Aluminium**	**Carbon fiber**	**Aluminium**	**Carbon fiber**
0.2	1*e6	1*e7	5.7321	7.2327
0.5	0.78*e5	1.5*e6	2.526	3.6163
1	0.256*e5	1*e6	0.8531	2.4109

From the Ansys software we have found the fatigue life of the carbon fiber and aluminum and here one cycle is equal to 10 cycles. From the result obtained we got that the cycles between aluminum and carbon fiber is 10 cycles Thus from the above Table 2 carbon fiber has more number of cycles before it gets crack initiation and then breaking of the material then the aluminum and also its safe factor is better than that of the aluminum hence the carbon fiber is a good replacement for the aluminum.

9. FATIGUE LIFE PREDICTION BY THEORETICAL METHOD

The relationship between polymer kinetics and mechanical behavior was developed more than five decades ago by

Zhurkov and Coleman in parallel efforts. Zhurkov used experimental observations to show that the conceiving of strength in terms of molecular kinetics was well-founded. Most importantly, Zhurkov showed that the bond rupture rate determines the fracture strength of a polymer and the time to failure under a creep load, where the bond rupture rate K_b under a tensile load σ has the form.

$$\boldsymbol{K_b = v_0 exp\left(-\frac{U-\gamma\sigma}{kT}\right)} \text{ Equation} \qquad 1$$

In Equation (1), U is an activation energy that is closely related to bond energy, γ is an activation volume, and k is the Boltzmann constant. Approaching the problem from a statistical mechanics approach, Coleman developed a similar equation and noted that it could also be used to predict polymer fatigue life. The value v_0 is the oscillation frequency of the atom, which should be proportional to kT/h, where h is Planck's constant; at room temperature $kT/h = 6.105\times1012\text{s}^{-1}$. Zhurkov reports a value of 1013s^{-1} for this term, while Coleman reports a value of $1.84\times1012\text{s}^{-1}$. As a first-order approximation, we simply use kT/h, such that Equation (1) becomes,

$$\boldsymbol{K_b = \frac{kT}{h} exp\left(-\frac{U-\gamma\sigma}{kT}\right)} \text{Equation} \qquad 2$$

Hansen and Baker-Jarvis combined these earlier works to develop a rate-dependent kinetic theory of fracture for polymers, which successfully predicted the strength of polymers subjected to a wide range of stress rates. In their formulation, they introduced a differential equation for the evolution of a damage variable n with time t, where the evolution of the damage variable is directly related to the bond rupture rate as,

$$\boldsymbol{\frac{dn}{dt} = (n - n_0)K_b} \text{Equation} \qquad 3$$

$$Where, n_0 = \frac{e}{e-1}$$

Where, the damage variable, which represents the fraction of micro crack density required for fracture, is zero initially (n (t=0) = 0) and unity at failure (n (t=t_f) = 1). Combining Equations (2) and (3) gives the starting equation for determining the fatigue life of a polymer.

$$\frac{dn}{dt} = (n_0 - n)\frac{kT}{h} exp\left(-\frac{U-\gamma\sigma(t)}{kT}\right), \quad n(0) = 0$$

For the work reported here, we derived the equation for fatigue life cycles to failure assuming a saw tooth-shaped load history with frequency f, maximum stress σ_{max}, and minimum stress σ_{min}. As a first-order approximation, we assume that the stiffness properties do not degrade with increasing n, as has been observed in some experimental work on composites. Using these assumptions and solving Equation (4) gives the number of cycles to failure N_f.

$$N_f = \frac{fh\gamma(\sigma_{max}-\sigma_{min})}{(kT)^2} exp\left(\frac{U}{kT}\right)\left[exp\left(\frac{\gamma\sigma_{max}}{kT}\right) - exp\left(\frac{\gamma\sigma_{min}}{kT}\right)\right]^{-1}$$

Fatigue Life Prediction:

Aluminium 2024:

$$= \frac{[2500 \times 6.626 \times 10^{-32} \times 9(427 — 269)]}{\{(1.3806 \times 10^{-23} \times 642)^2\}} exp^{\left(\frac{115}{8.863\times10^{-21}}\right)}\left\{exp^{\left[\frac{9\times427}{1.3806\times10^{-23}\times273}\right]} - exp^{\left[\frac{9\times-269}{1.3806\times10^{-23}\times273}\right]}\right\}^{-1}$$

$$= \frac{1.03763 \times 10^{-24}}{7.856 \times 10^{-41}} \text{exp}(1.2975 \times 10^{22})[exp(1.019 \times 10^{24}) - exp(-6.642 \times 10^{23})]^{-1}$$

$$= (1.3208 \times 10^{16}) \times 3.527 \times 10^{22}[(2.9952 \times 10^{24}) — (1.745136 \times 10^{24})]^{-1}$$

$$= 4.6584 \times 10^{38}[2.109555 \times 10^{-25}]$$

$$Number\ of\ cycles\ to\ failure = 9.82715 \times 10^{13}$$

Carbon Fiber

$$= \frac{\{2500\times(6.626\times10^{-32})\times1.312[260.49—430.715]\}}{7.856\times10^{-41}} exp\left(\frac{110}{8.863\times10^{-21}}\right)\left[exp\left\{\frac{1.312\times260.49}{8.863\times10^{-21}}\right\} - exp\left\{\frac{1.312\times-430.715}{8.863\times10^{-21}}\right\}\right]^{-1}$$

$$= \frac{2.1733 \times 10^{-28} \times 691.205}{7.856 \times 10^{-41}} exp(1.24 \times 10^{22})[exp(3.856 \times 10^{22}) - exp(-3.386 \times 10^{22})]^{-1}$$

$$= 1.312 \times 10^{16} \times 3.3706 \times 10^{22}[1.048 \times 10^{23} + 1.733 \times 10^{23}]^{-1}$$

$$= 1.094 \times 10^{33} \times 5.080 \times 10^{-24}$$

$$Number\ of\ cycles\ to\ failure = 5.557 \times 10^{14}$$

$$\%\ of cycles\ to\ failure = \frac{(5.557\times10^{14})-(9.82715\times10^{13})}{5.557\times10^{14}} \times 100$$

From the calculation of Fatigue Life Prediction, the number of cycles to failure for Aluminum Alloy 2024 is 9.82715×10^{13} and the number of cycles to failure for CFRP is 5.557×10^{14}. Tacitly, we conclude that Carbon Fiber Achieves **82.31%** more than Aluminum Alloy 2024

10. FATIGUE LIFE PREDICTION BY EXPERIMENTAL METHOD

The experimental approach to the comparison of metal and composite give more accurate result. Firstly for that a specimen has to be made for each of the aluminum and composite materials. Aluminum can be found in any of the company which makes aluminum. For the composite material we took carbon fiber to compare it with aluminum. Carbon fiber has been bought in a sheet form and then by using a hand layup it has to be made into a strip. This strip has to be cured for two days which makes it stronger the by using ASM standard the strip has to be made so that it could fit into the machine. The machine which is shown in the figure is the fatigue testing machine. In this machine the strip has to be fixed at both end and then stress obtained from universal testing machine is also to be entered in it and repeated load is given

Figure 10 Design of a specimen Tested

Table 3 Experimental Fatigue Life

S.NO	**APPLIED STRESS (MPa)**	**EXPERIMENTAL FATIGUE LIFE(cycles)**	
		ALUMINUM	**CARBON FIBER**
1	180	5*106	7.7*107
2	200	4.28*105	5.8*106
3	250	2.086*105	3.89*106

11. CONCLUSION

In this paper we have compared the fatigue life of aluminum and carbon fiber both in Ansys software, theoretical approach and experimental method. In the Ansys workbench parameters regarding these materials, needed for analysis like young's modulus, Poisson's ratio, weight and stiffness are collected from many reference papers. With the help of these parameters, analyzing was started and we compared the result obtained from the analysis and found a satisfactory result.

From the result of analysis it is revealed that the carbon fiber skin experiences less amount of stress, strain and total deformation than aluminum 2024 alloy for the same load applied at same points. It also has more number of cycles for the same particular stress and has a high fatigue life then aluminum.

Figure 11 Fatigue Testing Machine

Theoretical calculation was also performed for aluminum 2024 and carbon fiber and we got that the carbon fiber has a percentage life cycles of failure of 82.31%. From experimental approach we fabricated same length of aluminum and carbon fiber and tested in UTM and fatigue testing machine and found out that the experimental fatigue life of carbon fiber is 10 cycles greater than that of aluminum in most of the applied stress and because of its valuable benefits like less weight, high stress withstanding capability and greater life time carbon fiber is very suitable for replacement of aluminum as a skin in aircraft So we conclude that based upon the analysis and the theoretical calculation carried on both the material carbon fiber seems to be a better material for the replacement of aluminum

12. FUTURE WORK

- Analysis can be done using *Ansys APDL* for more accurate results. And also it can be carried out in *"NASTRAN"* for precise results.
- Fatigue life could be analyzed for other composites materials and then compared.
- For the fuselage section carbon fiber with different orientation could be made and then analyzed, later on fabrication could be done. And also improved fabricating tool could be found to increase the fatigue life.

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