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Static Structural and Modal Analysis for Leaf Spring with Composite Material

Manohar Allada
M.Tech. Research Scholar,
Department of Mechanical Engineering,
Jawaharlal Nehru Technological University Kakinada
University College of Engineering
Vizianagaram, (O.R.) [INDIA]
Email: manoharallada123@gmail.com

K. Srinivasa Prasad
Assistant Professor
Department of Mechanical Engineering,
Jawaharlal Nehru Technological University Kakinada
University College of Engineering
Vizianagaram, (O.R) [India].
Email: ksprasad.me@jntukucev.ac.in

ABSTRACT

Automobiles play important role in day to day life which requires better mechanical characteristics and long life. Suspension system is one of the basic components in every class automobile which is used to avoid vibrations due to uneven road conditions and wheel shimming. Suspension system consists of leaf springs. Leaf springs are generally elliptically laminated plates installed in automobile suspension system to support the weight of vehicle. Leaf spring of the vehicle is one of best option to increase strength, fatigue life and vibration control and also to reduce the weight by replacing of steel by composite material. The objective of this present work is to estimate the deflection, stress and mode frequency induced in the leaf spring of variable thickness. Modelling is done using PTC CREO parametric and Analysis is carried out by using ANSYS 18.1 software to determine various stresses, Deformation, fatigue life and mode frequency.

Keywords: *ANSYS, Composites, Leaf spring, Modal analysis, PTC CREO.*

I. INTRODUCTION

Increasing competition and innovations in automobile sector tends to modify the existing products or replacing old products by new and advanced material products. A suspension system of vehicle is also an area where these innovations are carried out regularly. More efforts are taken in order to Increase the comfort of user. Appropriate balance of comfort riding qualities and economy in manufacturing of leaf spring becomes an obvious necessity. To improve the suspension system many modification have taken place over the time. Use of composite materials for these springs is some of these latest modifications in suspension systems. This paper is mainly focused on the implementation of composite materials by replacing steel in conventional leaf springs of a suspension system.

Automobile-sector is showing an increased interest in the area of composite material-leaf springs due to their high strength to weight ratio. Therefore analysis of composite material leaf springs has become essential in showing the comparative results with conventional leaf springs. Advantages of leaf spring over helical spring are that the ends of the leaf springs are guided along a definite path so as to act as a structural member in addition to shock absorbing device. This is the reason why leaf springs are still used widely in a variety of automobiles to carry axial loads and lateral loads in the suspension system.

II. SPECIFICATIONS OF LEAF SPRING

The material used for present leaf spring analysis is made up of 50Cr1V23.The composition of material is 0.45%C, 0.1-0.3%Si, 0.6-0.9%Mn and 0.9-1.2%Cr. The properties of 50Cr1V23 material [7] are provided in Table 1.

Table 1: Properties of 50Cr1V23

Parameter	Values
Material selected	50Cr1V23
Young's Modulus	200000MPa
Poisson' Ratio	0.3
Ultimate tensile strength	2000MPa
Density	7800Kg/m^3

The design parameters of leaf spring are tabulated in table 2.

Table 2: Parameters of Leaf Spring

Parameters	Value
Length of the spring (Eye to Eye)	1250mm
Ineffective length	110mm
No. of full length leaves (n_f)	02
No. of graduated leaves (n_g)	04
Diameter of the eye (d)	30mm
Thickness of leaf (t)	7mm
Width of leaf	60mm
Load on the leaf spring(2W)	7125N

2.1 Selection of composite material

As mentioned earlier, the ability to absorb and store more amount of energy ensures the comfortable operation of a suspension system. However, the problem of heavy weight of spring is still persistent. This can be remedied by introducing composite material, in place of steel in the conventional leaf spring. Research has indicated that the results of e-Glass, carbon and graphite were found with good characteristics. So, the solid modeling of leaf spring is done in PTC CREO parametric. Model is imported to ANSYS and then composite materials are assigned to the model. These results can be used for comparison with the conventional steel leaf spring.

The material properties for the selected composites are given in table 3 which are studied [7].

Table 3: Material Properties of Composites

Sr. No.	Properties	E-glass epoxy	Carbon epoxy	Graphite epoxy
1	Tensile modulus along X-direction E_x(MPa)	73000	177000	294000
2	Tensile modulus along Y-direction E_y(MPa)	6500	10600	6400
3	Tensile modulus along Z-direction E_z(MPa)	6500	10600	6400
4	Poisson ratio along XY-direction PR_{xy}	0.27	0.27	0.23
5	Poisson ratio along YZ-direction PR_{yz}	0.06	0.02	0.01
6	Poisson ratio along ZX-direction PR_{zx}	0.06	0.02	0.01
7	Shear modulus along XY-direction G_{xy}(MPa)	4500	7600	4900
8	Shear modulus along YZ-direction G_{yz}(MPa)	2500	2500	3000
9	Shear modulus along ZX-direction G_{zx}(MPa)	2500	2500	3000
10	Mass density of the material ρ(Kg/m^3)	2000	1680	1590
11	Tensile strength of the materiall σ_{ut} (MPa)	900	600	2301

III. THEORETICAL CALCULATIONS

Bending stress generated in the leaf spring is as under:

$$\sigma_b = \frac{6*W*L}{n*b*t^2}$$

$$\sigma_b = \frac{6*3562.5*570}{6*60*7^2}$$

$$\sigma_b = 690.68 N/mm^2$$

Deflection generated in the assembly of leaf spring is

$$Y = \frac{6*W*L^3}{n*E*b*t^3}$$

$$Y = \frac{6*3562.5*570^3}{6*2*10^5*60*7^3}$$

$$Y = 160.289 mm$$

Fatigue life:

For prediction of fatigue life, adopted the analysis model of Hwang and Han and it is proved that the analytical formula predicts the fatigue life of component composite material, using

Hwang and Han relation:

$$N = (B*(1-r))^{\frac{1}{C}}$$

Where, N is the number of cycles to failure, B = 10.33, C =0.14012 and

r = (maximum stress/ultimate tensile stress) = Applied stress level.

Stress (σ) on the E-glass epoxy leaf spring is 238.53MPa.

$$r = \frac{\sigma}{\sigma_{ut}}$$

$$r = \frac{238.51}{900}$$

$$r = 0.265$$

Therefore number of cycles for failure is

$$N = (B*(1-r))^{\frac{1}{C}}$$

$$N = (10.33(1-0.265))^{\frac{1}{0.14102}}$$

$$N = 6.44^{7.0911}$$

$$N = 590800.69 \approx 590800$$

$$N = 5.9e5 \text{ cycles}$$

Modal analysis:

For a cantilever beam subjected to free vibration, and the system is considered as continuous system in which the beam mass is considered as distributed along with the equation of motion can be written as

$$\frac{d^2}{dx^2}\left\{EI(x)\frac{d^2Y(x)}{dx^2}\right\} = \omega^2 m(x)Y(x)$$

Where E is the modulus of rigidity of beam material I is the moment of inertia of the beam cross-section Y(x) is displacement in y direction at distance x from fixed end, ω is the circular natural frequency m is the mass per unit length, $m = \rho A(x)$, ρ is the material density, x is the distance measured from the fixed end.

Boundary conditions for a cantilever beam,

$$at: x=0, y(x)=0, \frac{dY(x)}{dx}=0$$

$$at: x=l, \frac{d^2Y(x)}{dx^2}=0, \frac{d^3Y(x)}{dx^3}=0$$

For a uniform beam under free vibration from equation 3.5,

$$\frac{d^4Y(x)}{dx^4} - \beta^4 Y(x) = 0$$

$$\beta^4 = \frac{\omega^2 m}{EI}$$

The natural frequency ω_n, from above equation of motion and boundary conditions can be

$$\omega_n = \beta_n^2 \sqrt{\frac{EI}{\rho AL^4}}$$

Where β_n = 4.694, 7.885, 10.996.

The natural frequency of both the steel leaf spring and composite leaf spring is calculated analytically by Euler's Beam Theory for Continuous System.

The Euler's Equation for natural frequency is given as

$$F = \frac{1}{2\pi}(\beta_n{}^2)\sqrt{\frac{EI}{\rho AL^4}}$$

Where,

$\beta_n{}^2$= constant depending on end conditions

I = Moment of inertia of system (mm^4)

ρ = Density of Material (Kg/m^3)

A = Area of cross section (mm^2)

L = Length of spring (mm)

The end conditions for system are same as that of suspension connected to vehicle body.

The values of different parameters for Steel leaf spring are

$(\beta_n)^2$ = 22.4., 61.7, 121.
E = $200*10^3$ N/mm^2
I = 1715 mm^4

ρ = $7.85*10^{-7}$ Kg/mm^3

A = 420 mm^2

l = 1250 mm

By substituting these values in above equation we get natural frequencies for steel leaf spring as :

- The first natural frequency equals 60.91 Hz
- The second natural frequency equals 167.72 Hz
- The third natural frequency equals 328.92 Hz

IV. Design and Analysis

The leaf spring is modeled PTC CREO parametric. For the finite element analysis, ANSYS 18.1 is selected due to its simplicity and quick results. The static structural and modal analysis is performed for both the leaf springs.

The boundary conditions used for analysis are as follow, rotation about z axis at left eye and translation about x axis at right eye.

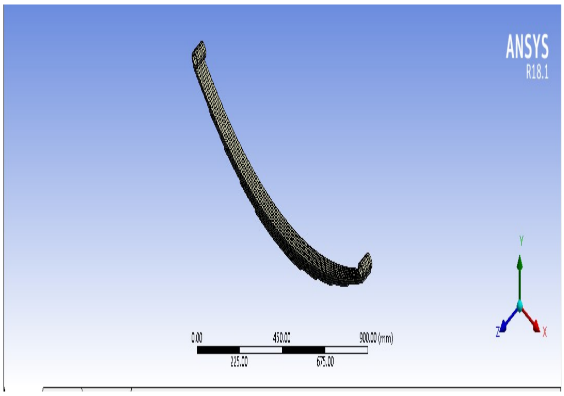

Figure 1: Meshed Model of Leaf Spring

Number of elements and nodes are 5264 & 35214.

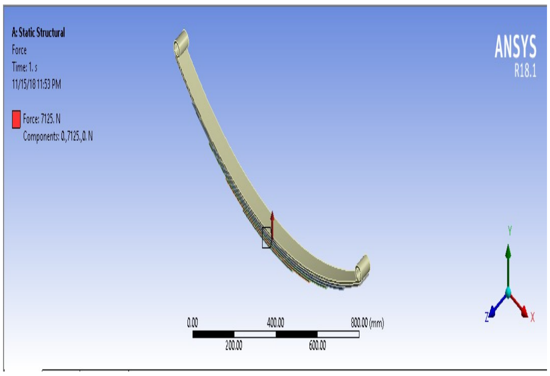

Figure 2: Load acting on Leaf Spring

The meshed model and the load applied on the leaf spring are depicted in figure 1 and figure 2 respectively.

V. Results and Discussion

The static analysis is carried out for the leaf spring. The analysis of leaf spring under varying thickness is shown from figure. 3 to 32.

5.1 Analysis of leaf spring for 7mm thickness:

5.1.1 50Cr1V23 leaf spring Analysis:

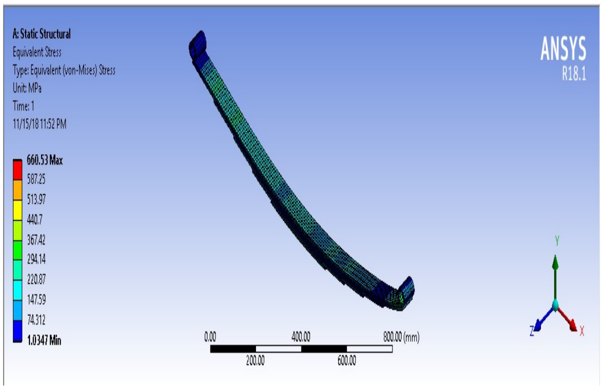

Figure 3: Von-Misses Stress on Steel Leaf Spring is 660.53MPa.

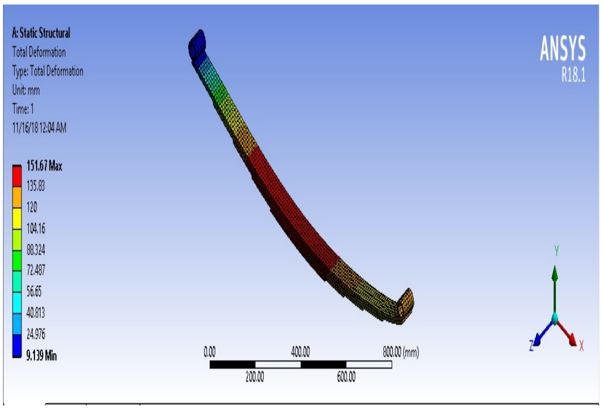

Figure 4: Deflection on Steel Leaf Spring 151.67mm

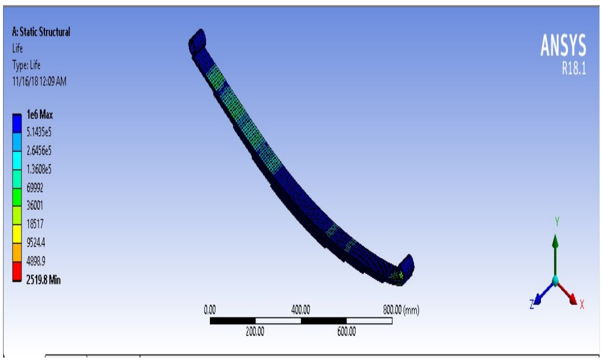

Figure 5: Fatigue Life of Steel Leaf Spring is 1e6 Cycles.

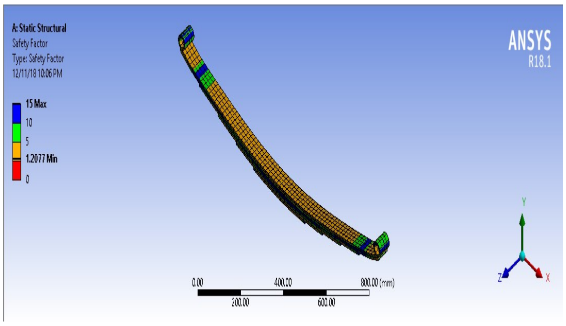

Figure 6: Safety Factor of Steel Leaf Spring is 1.2

The analysis with material steel for leaf spring are shown in figure 3 to figure 6.

5.1.2 E-glass epoxy analysis:

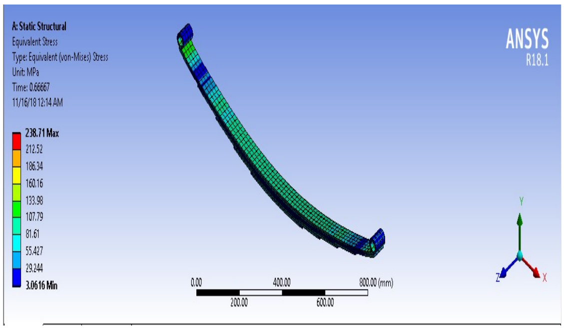

Figure7: Von-Misses Stress on E-glass Epoxy Leaf Spring 238.71MPa.

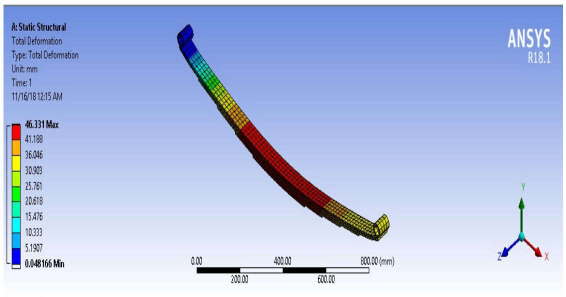

Figure 8: Deflection on E-glass Epoxy Leaf Spring 46.311mm.

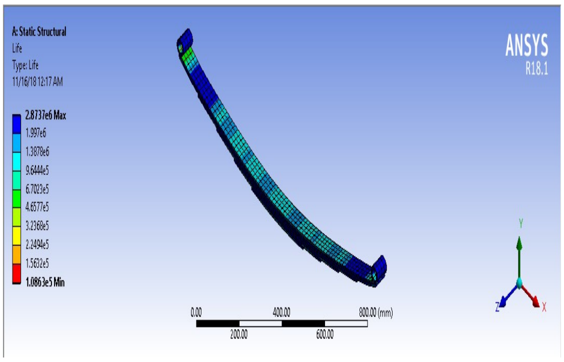

Figure 9: Fatigue life of E-glass Epoxy Leaf Spring is 2.87e6 Cycles.

The analysis with material E-glass epoxy for leaf spring are shown in figure 7 to figure 9.

5.1.3 Graphite epoxy analysis:

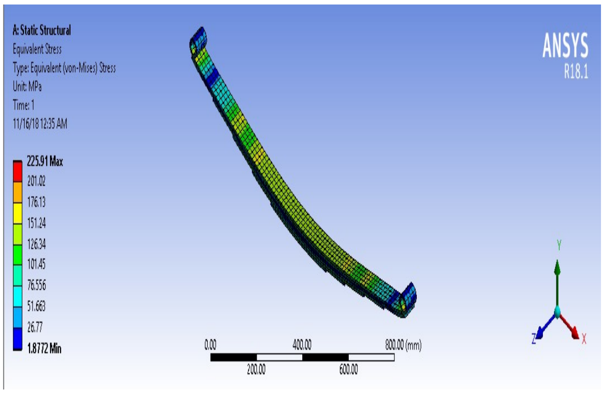

Figure 10: Von-misses Stress on Graphite Epoxy Leaf Spring is 225.91MPa.

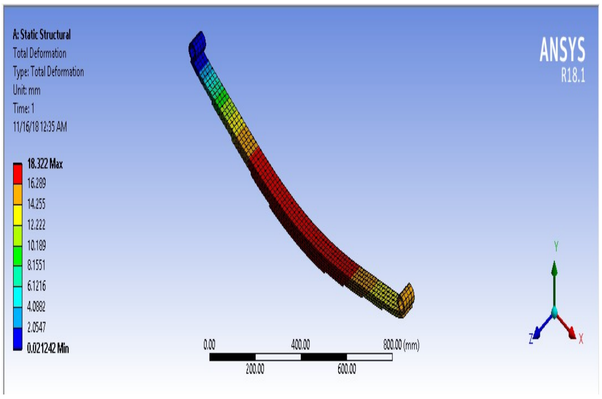

Figure 11: Deflection on Graphite epoxy Leaf Spring 18.322mm

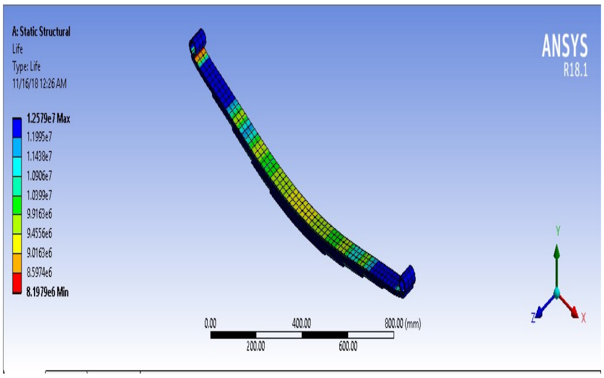

Figure 12: Fatigue life of Graphite Epoxy Leaf Spring 1.25e7 Cycles.

The analysis with material Graphite epoxy for leaf spring are shown in figure 10 to figure 12.

5.1.4 Carbon epoxy analysis:

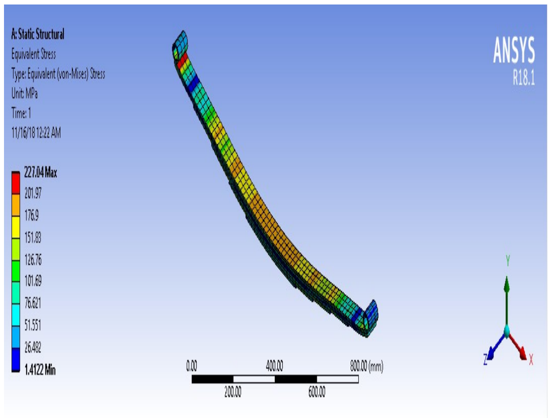

Figure 13: Von-misses Stress on Carbon Epoxy Leaf Spring 227.04MPa.

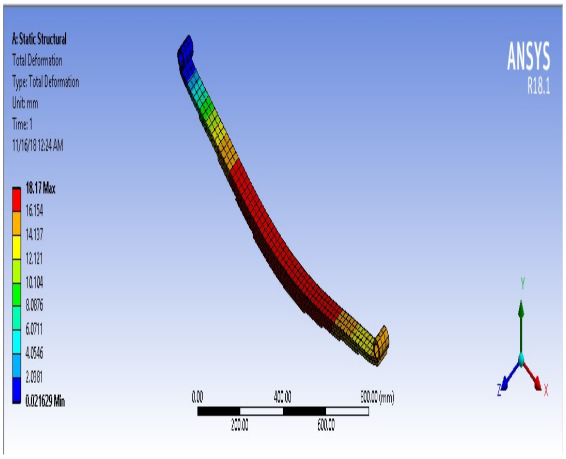

Figure 14: Deflection on Carbon Epoxy Leaf Spring 18.77mm

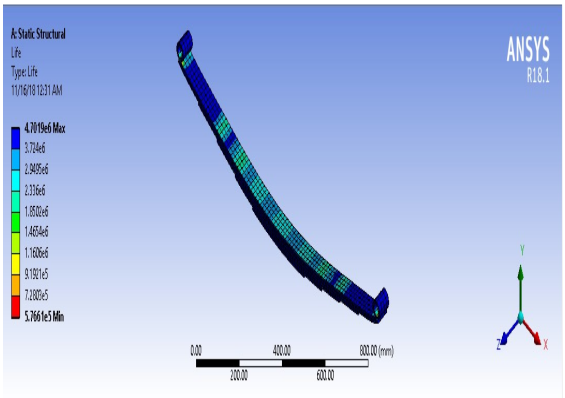

Figure 15: Fatigue life of Carbon Epoxy Leaf Spring 4.7e6 Cycles.

The analysis with material Carbon epoxy for leaf spring are shown in figure 13 to figure 15.

Table 4: Comparison of Static Structural Analysis Result for Steel and Composite Leaf Spring

Materi-als	Stress (MPa)	Deflec-tion (mm)	Fatigue life (cycles)	Weight (Kg)
Steel	660.63	151.54	1e6	18.5
E-glass epoxy	238.51	46.311	2.87e6	4.72
Graphite epoxy	225.9	18.636	1.25e7	3.71
Carbon epoxy	227.1	18.322	4.7e6	3.75

5.2 Analysis of leaf spring for 8mm thickness:

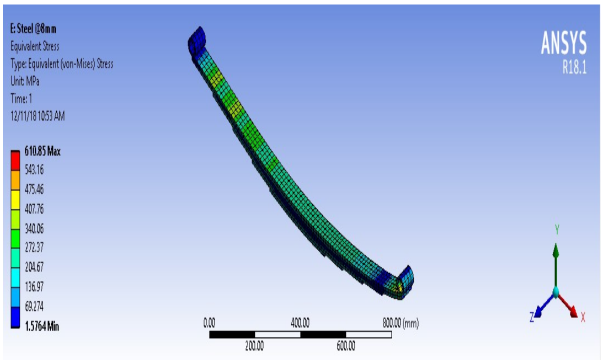

Figure 16: Von-misses Stress Contour is 610.85MPa

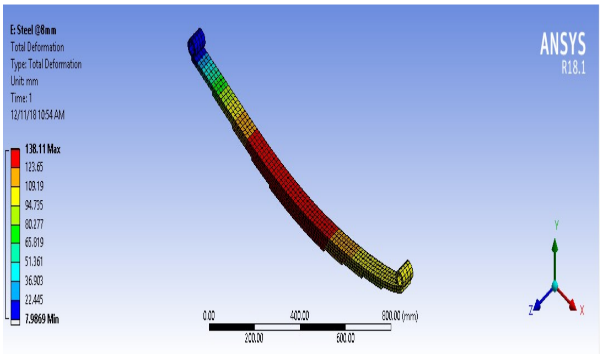

Figure 17: Deflection Contour is 138.11mm

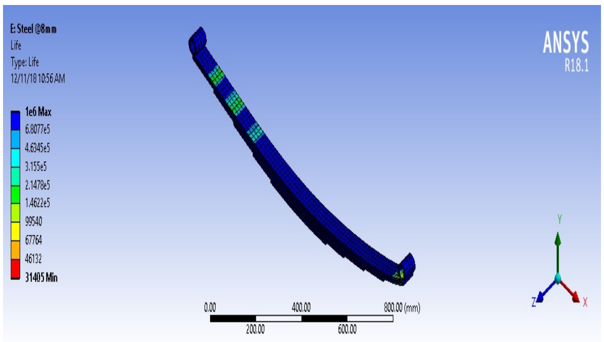

Figure 18: Fatigue Life is 1e6 Cycles.

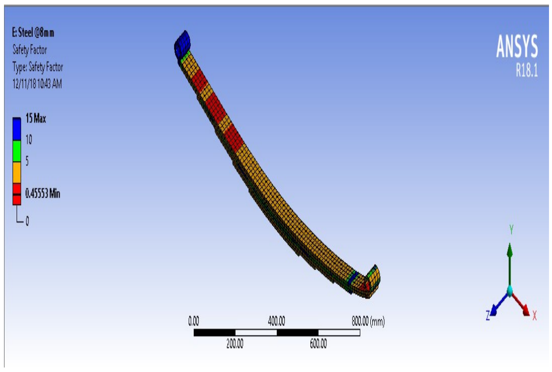

Figure 19: Safety Factor of Steel Leaf Spring is 0.4553

Though the stress and deflection for leaf spring of thickness 8mm is slightly less compared to leaf spring of thickness 7mm, considering the factor of safety the design is not safe. So, the analysis is stopped and further analysis is done for the leaf spring of thickness 6mm.

5.3 Analysis of leaf spring for 6mm thickness

5.3.1 50Cr1V23 Steel leaf spring Analysis:

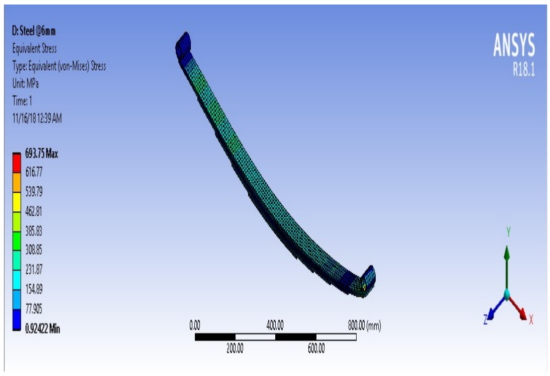

Figure 20: Von-misses stress on Steel Leaf Spring is 693.35MPa.

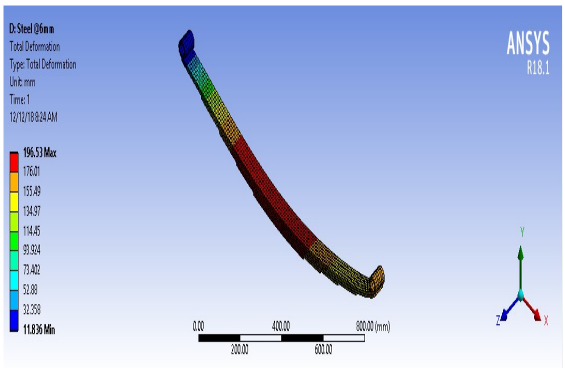

Figure 21: Deflection on Steel Leaf Spring is 196.53mm.

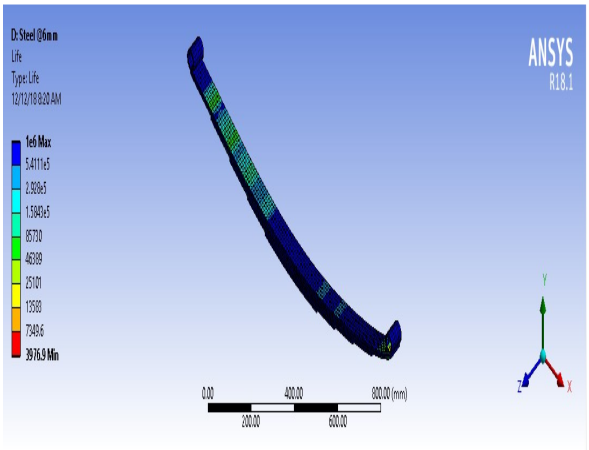

Figure 22: Fatigue Life of Steel Leaf Spring is 1e6 Cycles.

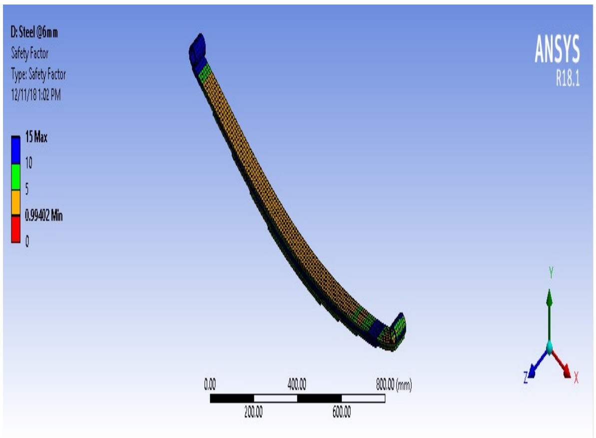

Figure 23: Safety Factor of Steel Leaf Spring is 0.994.

The analysis with material Steel for leaf spring are shown in figure 20 to figure 23

5.3.2 E-glass epoxy analysis:

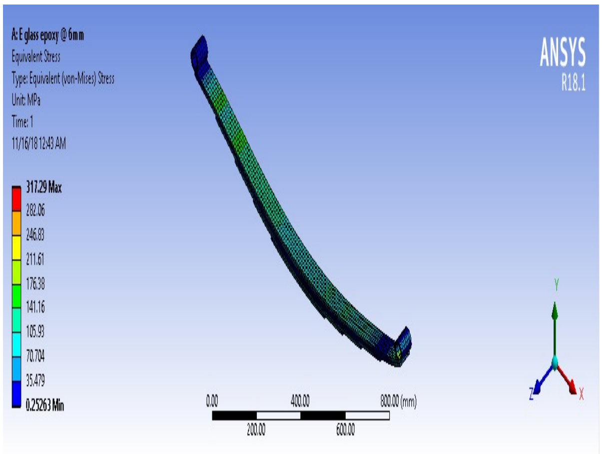

Figure 24: Von-misses Stress on E-glass Epoxy Leaf Spring is 317.29MPa.

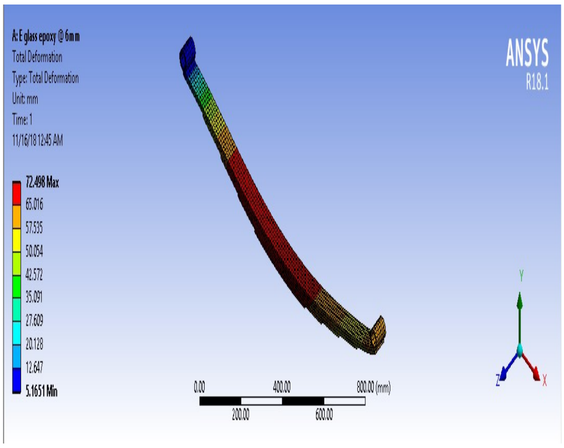

Figure 25: Deflection on E-glass Epoxy Leaf Spring is 72.498mm.

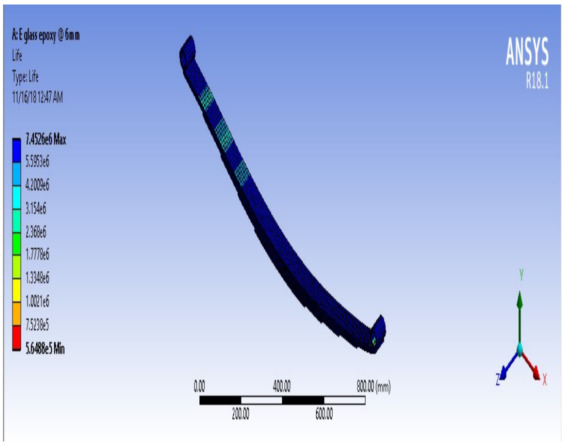

Figure 26: Fatigue Life of E-glass Epoxy Leaf Spring is 7.42e6 Cycles

The analysis with material E-glass epoxy for leaf spring are shown in figure 24 to figure 26.

5.3.3 Graphite epoxy analysis:

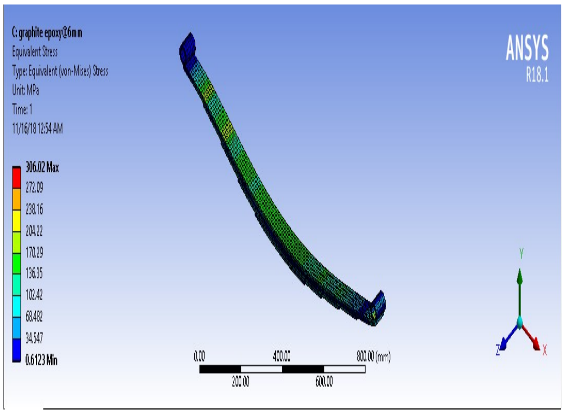

Figure 27: Von-misses Stress on Graphite Epoxy Leaf Spring is 306.02MPa.

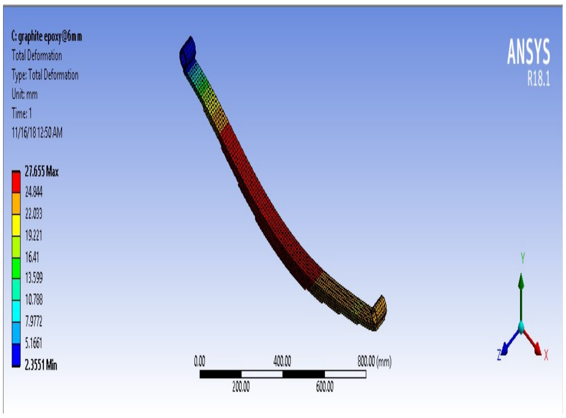

Figure 28: Deflection on Graphite Epoxy Leaf Spring is 27.655mm

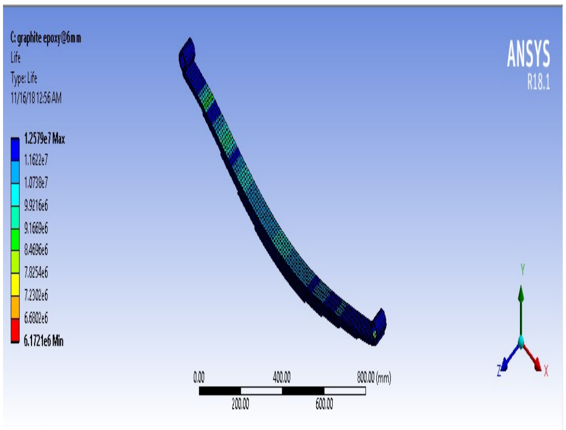

Figure 29: Fatigue Life of Graphite Epoxy Leaf Spring is 1.25e7 Cycles.

The analysis with material Graphite epoxy for leaf spring are shown in figure 27 to figure 29.

5.3.4 Carbon epoxy analysis:

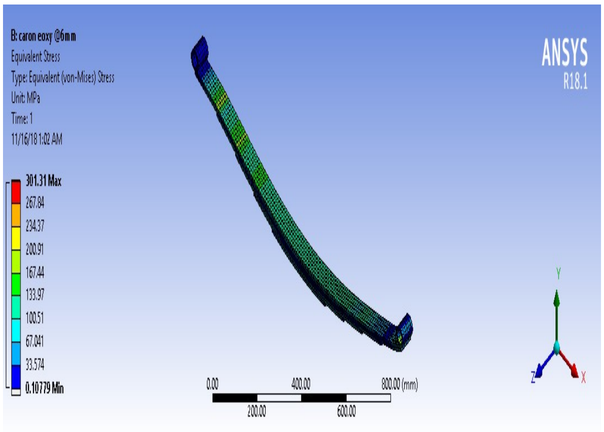

Figure 30: Von-misses Stress on Carbon Epoxy Leaf Spring 301.31MPa.

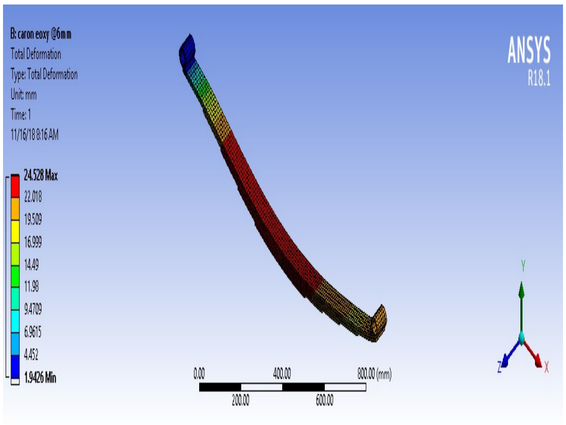

Figure 31: Deflection on Carbon epoxy leaf spring is 24.528mm.

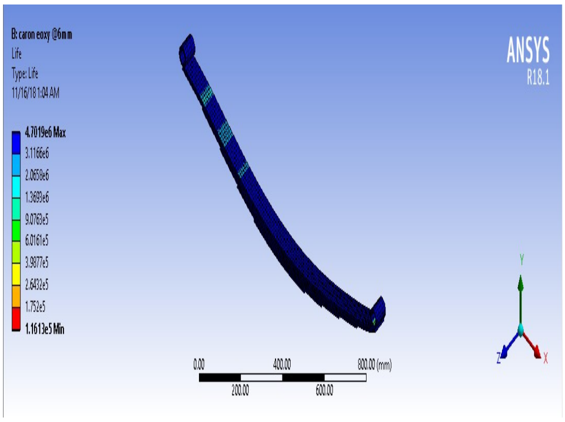

Figure 32: Fatigue life of Carbon epoxy leaf spring is 4.0e6 cycles.

The analysis with material Carbon epoxy for leaf spring are shown in figure 30 to figure 32.

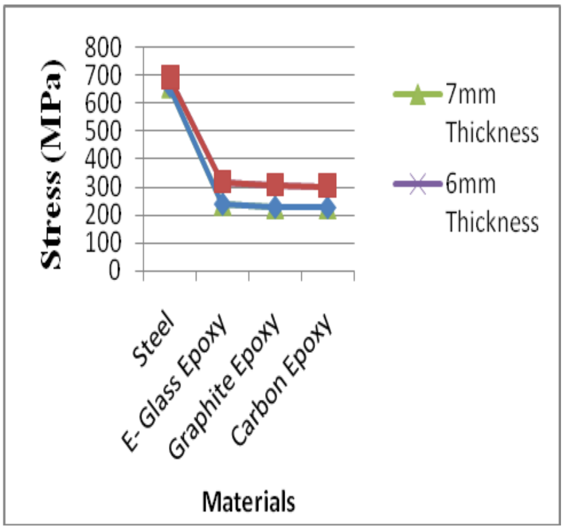

Figure 33 : Stress Vs material

This figure 33 shows the stresses for steel and composites for 7mm and 6mm thickness of leaf spring

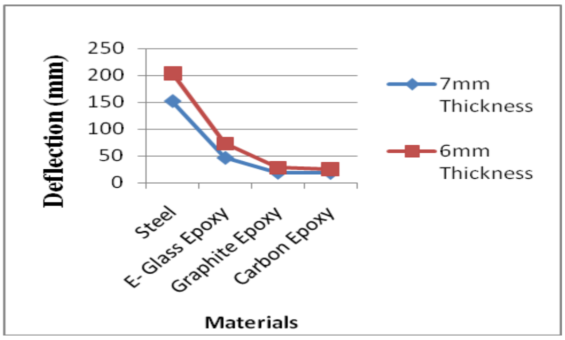

Figure 34: Stress Vs Deflection

This Figure 34 represents the relation between deflection and materials for different materials. Leaf spring of 6mm thickness with steel material has high deflection where as leaf spring of 7mm thickness with graphite epoxy material has the lowest deflection.

Table 5: Comparison of Leaf Spring for Thickness of 7mm and 6mm with 50Cr1V23 Steel and Composites.

Thick-ness	Prop-erty	Materials			
		Steel	E-glass epoxy	Carbon epoxy	Graph-ite epoxy
7mm	Stress (MPa)	660.6	238.5	227.1	225.9
	Deflec-tion (mm)	151.5	46.169	18.636	18.322
	Weight (Kg)	18.6	4.72	3.71	3.75
	Fatigue Life (cycles)	1e6	2.87e6	4.7e6	1.25e7
6mm	Stress (MPa)	693.7	317.2	306	301.7
	Deflec-tion (mm)	204.5	72.498	27.655	24.528
	Weight (Kg)	18.56	4.43	3.63	3.65
	Fatigue Life (Cycle s)	1e6	7.42e6	4e6	1.25e7

The results comparison of leaf spring for thickness of 6mm & 7mm are shown in table 5.

5.4 Modal analysis of leaf spring:

5.4.1 Mode shapes of 50Cr1V23 steel leaf spring:

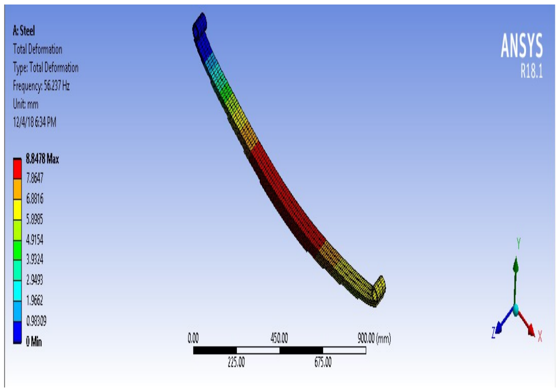

Figure 35: Natural Frequency of Steel Leaf Spring at 1st Mode Shape is 56.237Hz.

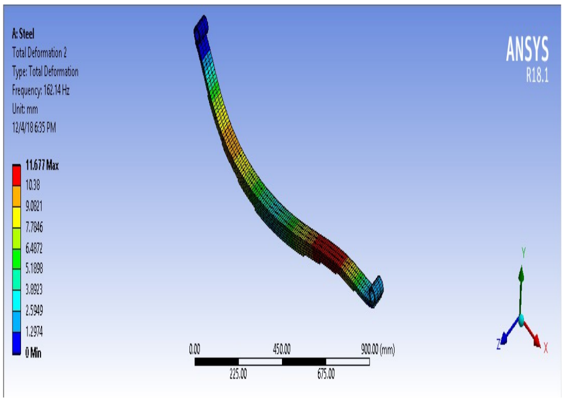

Figure 36: Natural Frequency of Steel Leaf Spring at 2nd Mode Shape is 162.14Hz.

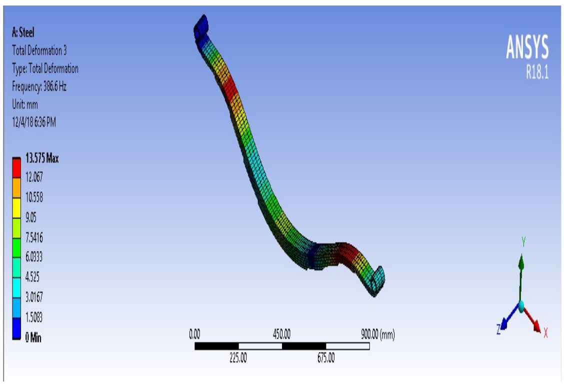

Figure 38: Natural Frequency of Steel Leaf Spring at 3rd Mode Shape is 386.6Hz.

Modes shapes for leaf spring with 50Cr1V23 material are shown in figure 34 to figure 36.

5.4.2 Mode shapes of E-Glass epoxy leaf spring:

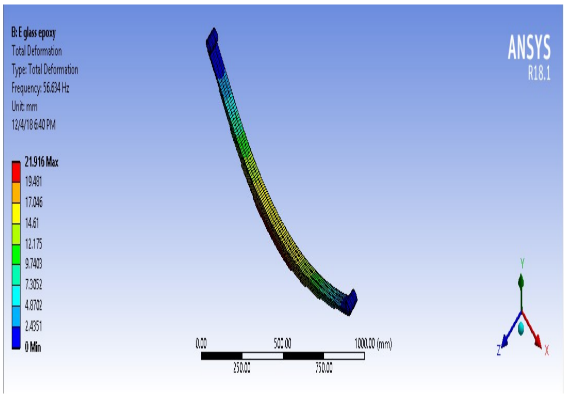

Figure 39: Natural Frequency of E-glass Epoxy Leaf Spring at 1st Mode Shape 56.634Hz.

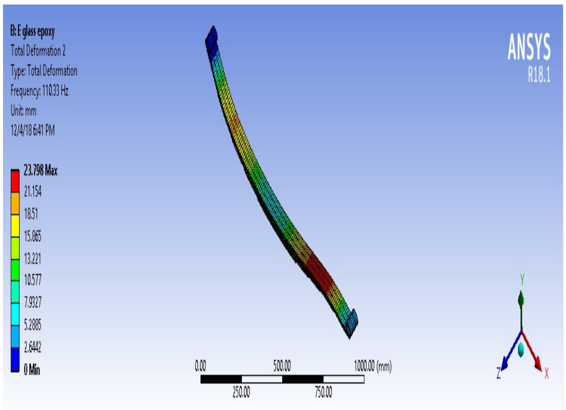

Figure 40: Natural Frequency of E-glass Epoxy Leaf Spring at 2nd Mode Shape is 110.33Hz.

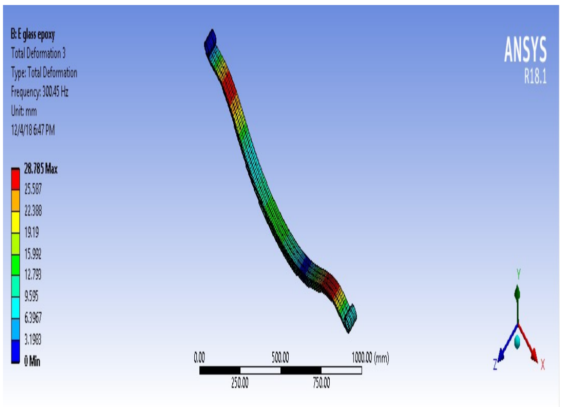

Figure 41: Natural Frequency of E-glass Epoxy Leaf Spring at 3rd Mode Shape is 300.45Hz.

Modes shapes for leaf spring with E-glass epoxy material are shown in figure 39 to figure 41.

5.4.4 Mode shapes of Carbon epoxy leaf spring

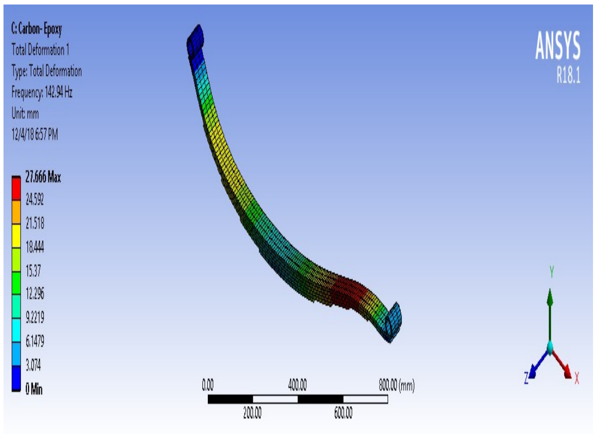

Figure 42: Natural Frequency of Carbon Epoxy Leaf Spring 1st Mode Shape is 142.94Hz

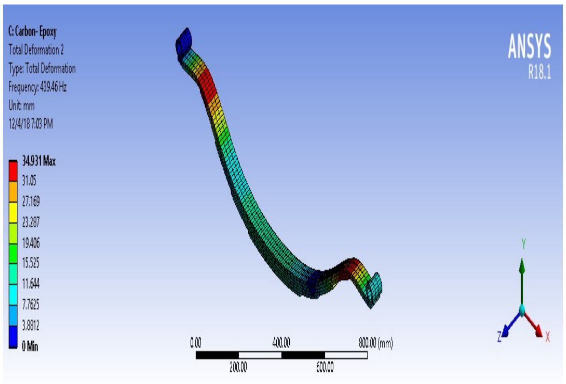

Figure 43: Natural Frequency of Carbon Epoxy Leaf Spring 2nd Mode Shape is 439.46Hz

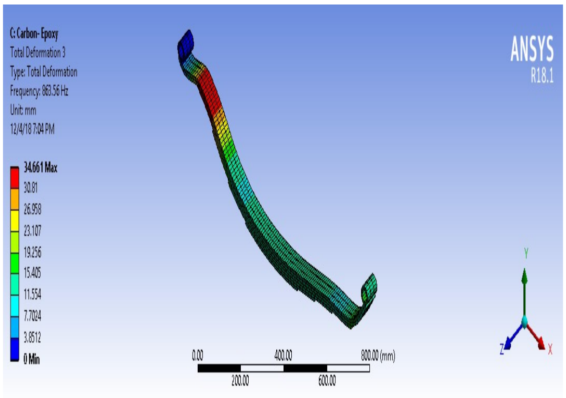

Figure 44: Natural Frequency of Carbon Epoxy Leaf Spring 3rd Mode Shape is 863.56Hz.

Modes shapes for leaf spring with Carbon epoxy material are shown in figure 42 to figure 43.

5.4.3 Mode shapes of Graphite epoxy leaf spring

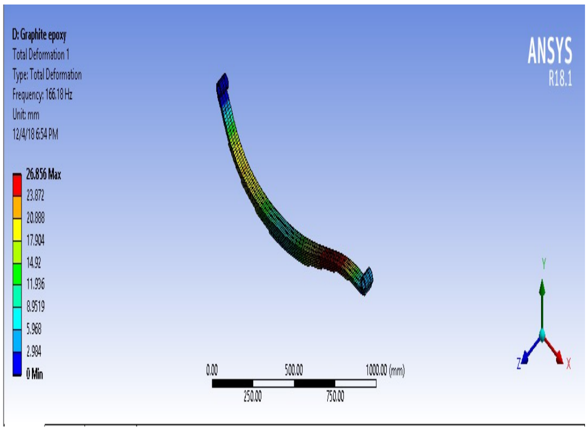

Figure 45: Natural Frequency of Graphite Epoxy Leaf Spring 1st Mode Shape is 166.18Hz.

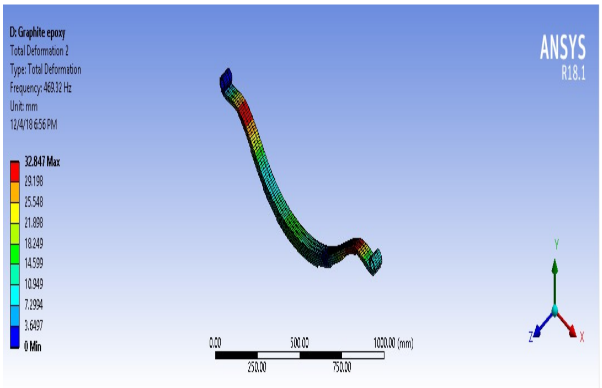

Figure 46: Natural Frequency of Graphite Epoxy Leaf Spring 2nd Mode Shape is 469.32Hz.

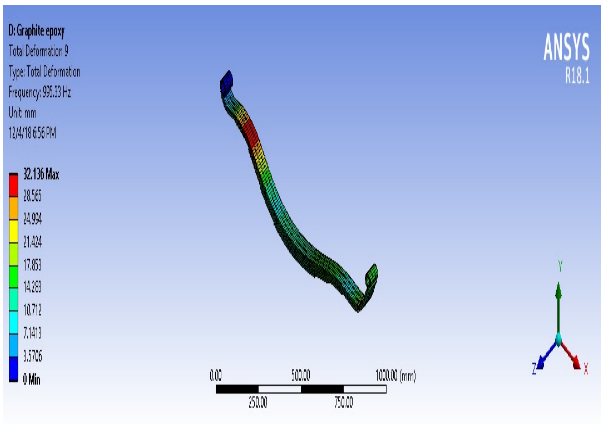

Figure 47: Natural Frequency of Graphite Epoxy Leaf Spring 3rd Mode Shape is 995.33Hz.

Modes shapes for leaf spring with Graphite epoxy material are shown in figure 42 to figure 44.

Table 6: Theoretical Results for Modal Analysis of Leaf Spring.

Mode shapes	Frequency(Hz)			
	Steel	E-glass epoxy	Carbon epoxy	Graph-ite epoxy
1	60.91	56.93	149.65	168.25
2	167.32	128.43	412.20	509
3	328.92	311.66	793.41	1070.9 2

Table 7: ANSYS Results for Modal Analysis of Leaf Spring.

Mod e shap es	Frequency(Hz)			
	Steel	E-glass epoxy	Carbon epoxy	Graph-ite ep-oxy
1	50.237	56.63	142.94	166.18
2	162.14	110.33	439.46	469.32
3	328.92	300.42	863.56	995.33

Theoretical and Analyses results for modal analysis of leaf spring are shown in table 6 & 7.

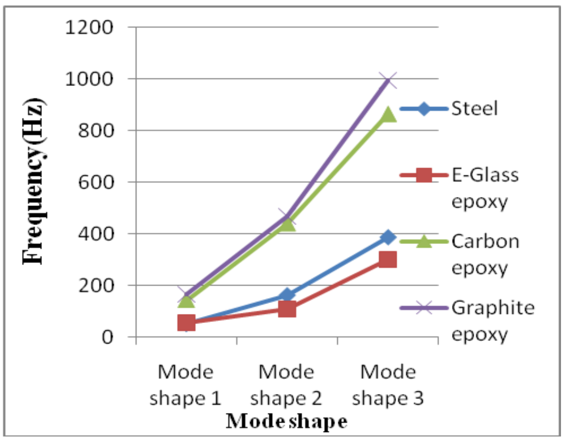

Figure 48: Frequency Vs Mode Shape

This Figure 48 represents the relation between the frequency and mode shapes for Steel, E-glass epoxy, Carbon epoxy and Graphite epoxy which show that Graphite epoxy have the high natural frequency.

VII. CONCLUSIONS

The design, static structural and modal analysis of steel leaf spring and composite leaf spring has been carried out. Comparison has been made between composite leaf spring with steel leaf spring having same design and same load carrying capacity.

- From the static analysis results, the von-misses stress with 50Cr1V23 and composites (E-glass, Graphite and Carbon epoxy) for a leaf spring of 7mm thickness are 660.63MPa, 238.51MPa, 225.9MPa and 227.1MPa. For a leaf spring of 6mm thickness are 693.7MPa 317.2MPa, 306.02MPa and 301.7MPa respectively.
- The maximum displacement with 50Cr1V23 and composites (E-glass, Graphite and Carbon epoxy) for a leaf spring of 7mm thickness are 151.54 mm, 44.169 mm, 18.636 mm and 18.322 mm. For a leaf spring of 6mm thickness are204.56 mm, 72.498 mm, 27.655 mm and 24.528 mm.
- The fatigue life of with 50Cr1V23 and composites (E-glass, Graphite and Carbon epoxy) for a leaf spring of 7mm thickness are 1e6, 2.87e6, 1.25e7 and 4.7e6. For a leaf spring of 6mm thickness are 1e6, 7.42e6, 1.27e7 and 4e6 cycles.
- Form the modal analysis the natural frequencies at 3mode shapes for steel are 56.237Hz, 162.14Hz and 386.6Hz.
- The natural frequencies at 3mode shapes for E-glass epoxy are 56.634Hz, 110.33Hz and 300.45Hz.
- The natural frequencies at 3mode shapes for Carbon epoxy are 142.94Hz, 439.46Hz and 863.56Hz
- The natural frequencies at 3mode shapes for Graphite epoxy are 166.18Hz, 469.32Hz and 995.33Hz
- The leaf springs with composites have low stresses and displacements than that of existing steel leaf spring. In this Graphite have the less bending stress compared to all the materials.
- Composites reduce the weight of leaf spring by 74.54% for E-glass/epoxy, 80.66% for Carbon epoxy and 79.77% for Graphite epoxy over steel leaf spring.

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