Design and Analsis of Composite Leaf Spring for Light Vehicles

K. Ramesh Nayak, G. Bheemanna, P. Sampath Rao

Abstract— **A leaf spring is a simple form of spring, commonly used for the suspension in wheeled vehicles. Leaf Springs are long and narrow plates attached to the frame of a trailer that rest above or below the trailer's axle. There are mono leaf springs, or single-leaf springs, that consist of simply one plate of spring steel. These are usually thick in the middle and taper out toward the end, and they don't typically offer too much strength and suspension for towed vehicles. Drivers looking to tow heavier loads typically use multi leaf springs, which consist of several leaf springs of varying length stacked on top of each other. The shorter the leaf spring, the closer to the bottom it will be, giving it the same semielliptical shape a single leaf spring gets from being thicker in the middle. Springs will fail from fatigue caused by the repeated flexing of the spring. The aim of the project is to design and model a leaf spring according to the loads applied. Presently used material for leaf spring is Mild steel. In this project we are going to design leaf spring for the materials Mild Steel, E-GLASS EPOXY AND ALUMINUM REINFORCED WITH BORON CARBIDE. For validating this design we are conducting FEA Structural Analysis is done on the leaf spring by using three materials. Modal Analysis is also done. The better material for leaf spring can be determined by this analysis. Pro/Engineer software is used for modeling and ANSYS is used for analysis. Modal analysis is also done on the leaf spring to determine the natural frequencies of the leaf spring.**

I. Introduction

Originally called laminated or carriage spring, a leaf spring is a simple form of spring, commonly used for the suspension in wheeled vehicles. It is also one of the oldest forms of springing, dating back to medieval times. The advantages of leaf spring over helical spring are that the end of the springs may be guided along a definite path. Sometimes referred to as a semi-elliptical spring or cart spring, it takes the form of a slender arc-shaped length of spring steel of rectangular cross-section. The center of the arc provides location for the axle, while tie holes are provided at either end for attaching to the vehicle body. For very heavy vehicles, a leaf spring can be made from several leaves stacked on top of each other in several layers, often with progressively shorter leaves. Leaf springs can serve locating and to some extent damping as well as springing functions. While the interleaf friction provides a damping action, it is not well controlled and results in stiction in the motion of the suspension. For this reason manufacturers have experimented with mono-leaf springs. A leaf spring can either be attached directly to the frame at both ends or attached directly at one end, usually the front, with the other end attached through a shackle, a short swinging arm. The shackle takes up the tendency of the leaf spring to elongate when compressed and thus makes for softer springiness. Some springs terminated in a concave end, called a spoon end (seldom used now), to carry a swiveling member. There were a variety of leaf springs, usually employing the word "elliptical". "Elliptical" or "full elliptical" leaf springs referred to two circular arcs linked at their tips. This was joined to the frame at the top center of the upper arc, the bottom center was joined to the "live" suspension components, such as a solid front axle. Additional suspension components, such as trailing arms, would be needed for this design, but not for "semi-elliptical" leaf springs as used in the Hotchkiss drive. That employed the lower arc, hence its name. "Quarter-elliptic" springs often had the thickest part of the stack of leaves stuck into the rear end of the side pieces of a short ladder frame, with the free end attached to the differential, as in the Austin Seven of the 1920s. As an example of non-elliptic leaf springs, the Ford Model T had multiple leaf springs over their differentials that were curved in the shape of a yoke. As a substitute for dampers (shock absorbers), some manufacturers laid non-metallic sheets in between the metal leaves, such as wood.

1.2 Composites: A composite material is described as a material composed of two or more distinct phases and the interfaces between them. At a macroscopic scale, the phases are indistinguishable, but at some microscopic scales, the phases are clearly separate, and each phase ex-hibits the characteristicsofthepurematerial.Thisspecialclassofcomposit esalwaysconsistsofareinforcingphaseandamatrixphase.Therei nforcingphase is typically a graphite, glass, ceramic, or polymer fiber, and the matrix is typically a polymer, but may also be ceramic or metal. The fibers provide strength and stiff-ness to the composite component, while the matrix serves to bind the reinforcements together, distribute mechani-cal loads through the part, provide a means to process the material into a net shape part, and provide the primary environmental resistance of the composite component. In Fig. 1, we can see the distinct cross section of graphite fibers in an epoxy matrix.

Manuscript received May 04, 2016

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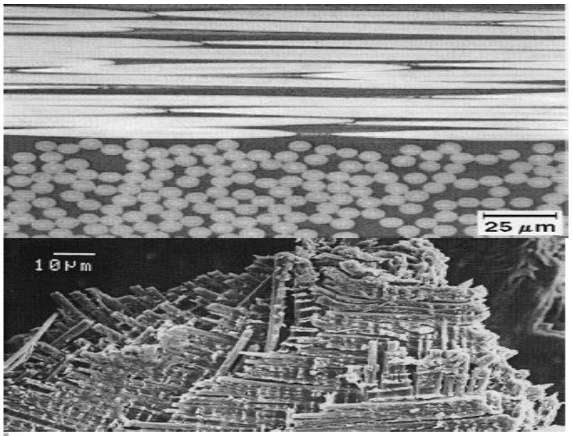


FIGURE 1 Cross section of a graphite fiber–reinforced epoxypolymer.

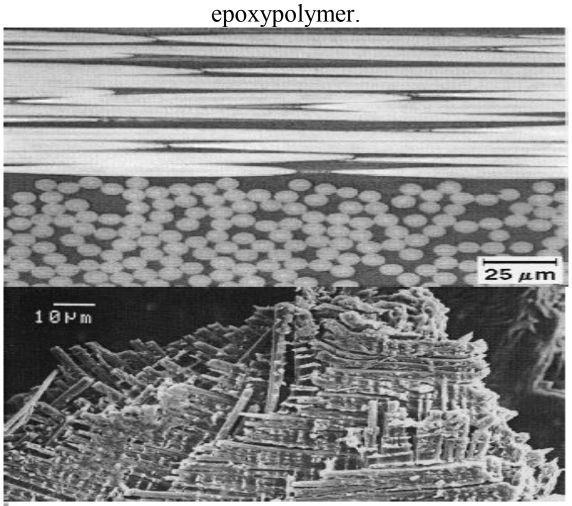


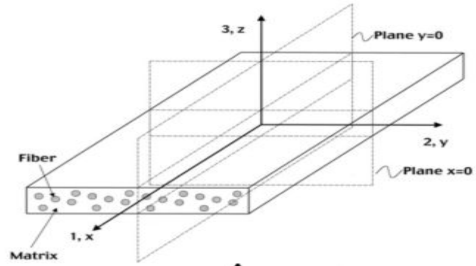
FIGURE 2 Scanning electron microscope (SEM) image of abessbeetle (Odontotaenius disjuncture) elytra fracture surface

2.1 Properties of Composites

In many of the applications in which composite materials are used, they can be considered to be constructed of several layers stacked on top of one another. These layers, or laminae, typically exhibit properties similar to those of orthotropic materials. Orthotropic materials have three mutually perpendicular planes of material property symmetry. Figure 3shows a lamina with its coordinate system and two of the planes of symmetry. We will first discuss the properties of the lamina and some factors that influence them. Next, the properties of laminates will be discussed. The lamina is made of one thickness of reinforcement embedded in the matrix. The elastic and strength proper-ties of the reinforcement and the elastic and strength properties of the matrix combine to give the lamina its properties. In addition to the properties of the constituents, the amount of reinforcement, the form of the reinforcement, and the orientation and distribution of the reinforcement all influence the properties of the laminate. The reinforcement provides the strength and stiffness of the composite. Increasing the amount of reinforcement increases the strength and stiffness of the composite in the direction parallel to the reinforcement. The effect of the form of the reinforcement is not as simple. However, some general observations can be made. Laminae reinforced by long, continuous, parallel fibers have greater strength and stiffness than laminae reinforced by short, randomly oriented fibers. Woven fiber reinforced laminate usually have greater strength perpendicular to the principal fiber direction than do unwoven fiber reinforced laminate. The strength and stiffness of laminae reinforced by unwoven continuous fibers decrease as the angle of loading changes from parallel to the fibers to perpendicular to the fibers. Table III shows typical values for some properties of composite materials made of unwoven continuous fiber reinforcements. The table shows the strength and elastic properties of a laminate made of several laminae stacked on top of one another with all the fibers aligned in the samedirection.

TABLE III Typical Properties of Composite Materials: Laminates Reinforced With Unidirectional Continuous Fibers

Property	Unit	E-glass epoxy	Aramid epoxy	Graphite epoxy	Boron epoxy
Parallel to the fibers					
Tensile strength σ_x^T	MPa	1100	1380	1240	1296
Tensile modulus E_x^T	GPa	39.3	75.8	131	207
Poisson's ratio ν_{xy}	—	0.25	0.34	0.25	0.21
Total strain ε^T	%	2.2	1.8	1.21	0.66
Compressive strength σ_x^C	MPa	586	276	1100	2426
Compressive modulus E_x^C	GPa	39.3	75.8	131	221
Shear strength τ_{xy}	MPa	62.0	44.1	62.0	132
Shear modulus G_{xy}	GPa	3.45	2.07	4.83	6.2
Transverse to the fibers					
Tensile strength σ_y^T	MPa	34.5	27.6	41.4	62.7
Tensile modulus E_y^T	GPa	8.96	5.5	6.2	18.6
Compressive strength σ_y^C	MPa	138	138	138	310
Compressive modulus E_y^C	GPa	8.96	5.5	6.2	24.1
Specific gravity	—	2.08	1.38	1.52	2.01
Fiber volume V_f	%	~50	~60	~62	~50



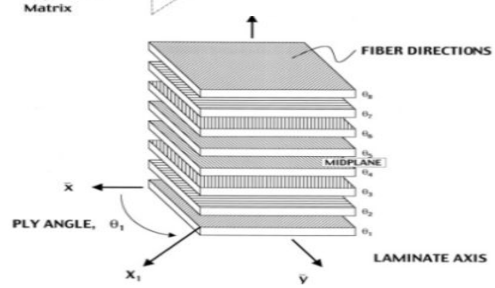


FIGURE 4 Orientation and location of laminae in a laminate.

Calculations for Radius and Lengths of Leaves

When n=9, Rear suspension

Overall length of the spring = $2L_1$ = 1620mm

Width of leaves = 90mm

Number of full length leaves = 2 = n_f

Number of graduated leaves = 7 = Ng
Number of springs = 9 (Ng+N_f)
Center load = 2W =15 tones = 15000kg

$$2W = \frac{total\ load}{no\ of\ springs} = 15000/6 = 2500kg$$

W = 2500/2 = 1250kg
W =1250×9.81 = 12262.5N
W = 12262.5N

3.1 Material used for leaf spring - mild steel

Bending stress σ_b = 21600 psi = 149 N/mm^2
Spring is simply supported beam
Width length = 2L
Central load =2W
Bending moment = M =W$\times L = 9932625$ Nmm
Section modulus Z = bt^2/6
b= width of leaves
t = thickness of leaves = 8Dt^2/6

$$\text{bending stress} = \sigma = \frac{M}{Z} = \frac{6wL}{nbt^2}$$

n = no of full length leaves &graduated leaves
2L = 2$L_1 - l$; L = 660mm;(l =300mm)
σ = 149 N/mm^2
n = 9

$$\sigma = \frac{6wL}{nbt^2}$$

$$149 = \frac{6 \times 12262.5 \times 660}{9 \times 90t^2}$$

$$t^2 = \frac{6 \times 12262.5 \times 660}{9 \times 90 \times 149} = 402.348; t = 20.05 = 20 \text{ mm}$$

Deflection for both full length and graduated leaves

$$\delta = \frac{4WL^3}{n\epsilon bt^3} = \frac{4 \times 12262.5 \times 660^3}{9 \times 210 \times 10^3 \times 90 \times 20^3} = \frac{1.41016788 * 10^{13}}{1.3608 * 10^{12}} = 10.3627 \text{ mm}$$

Deflection for graduated leafs

$$\delta_G = \frac{6WL^3}{N_G \epsilon bt^3} = \frac{6 \times 12262.5 \times 660^3}{2 \times 210 \times 10^3 \times 90 \times 20^3} = \frac{2.11525182 * 10^{13}}{3.024 * 10^{11}} = 69.948mm$$

For same deflection in stress in uniform x- section leaves

$$\sigma_f = \frac{3}{2}\sigma_G$$

Load for graduated leavers $W_G = \left(\frac{2n_G}{3n_F + 2n_G}\right)W$

W = total load on the spring

W_G = load taken up by graduated leaves

W_F = load taken up by full length leaves

$$w_G = \left(\frac{2 \times 2}{3 \times 7 + 2 \times 2}\right)12262.5 = \frac{4}{25} \times 12262.5$$

$w_G = 1962$ N
W = $W_G + W_F$
W_F = 10300.5 N

3.2 Bending stress for full length leaves

$$\sigma_F = \frac{18WL}{bt^2(2n_G + 3n_F)} = \frac{18 \times 12262.5 \times 660}{90 \times 20^2 \times (2 \times 2 + 3 \times 7)} = \frac{145678500}{900000} = 161.865 \text{ N/mm}^2$$

$$\sigma_G = \frac{12wL}{bt^2(2n_G + 3n_F)} = \frac{12 \times 12262.5 \times 660}{90 \times 20^2 \times 25} = \frac{97119000}{900000} - 107.91 \text{ N/mm}^2$$

δ_F = Deflection of full length leaves

$$\delta_F = \frac{12wL^3}{\epsilon bt^3(2n_G+3n_F)} = \frac{12 \times 12262.5 \times 660^3}{210 \times 10^3 \times 90 \times 20^3 \times 25} = \frac{4.23050364 * 10^{13}}{3.78 * 10^{12}} = 11.191 \text{ mm}$$

Equalized stress in spring leaves (nipping)
C = nip
C = $\delta_G - \delta_F = 69.948 - 11.191 = 58.757$ mm

C = $\frac{2wL^3}{n\epsilon bt^3}$; $\delta_F \frac{4L^3}{n_F \epsilon bt^3} \times \frac{Wb}{2}$; $\delta_G = \frac{6L^3}{n_G \epsilon bt^3} \times \frac{Wb}{2}$

Load on clip bolts (W_b) required to close the gap is determined by fact that gap is equal to initial deflection.
C = $\delta_G - \delta_F$

$$W_b = \frac{2n_F \times n_G \times W}{n(2n_G + 3n_F)} = \frac{2 \times 2 \times 7 \times 12262.5}{9 \times 25} = \frac{343350}{225} = 1526 \text{ N/mm}^2$$

3.3 Length of Leaf Springs

$2L_1$ = overall length of spring
Ineffective length l = width of band/distance between centers of u-tubes
n_F = no of full length leaves
n_G = no of graduated leaves
Effective lengths 2L = 2$L_1 - \frac{2}{3}l$ (when u bolts are used)
$2L_1 = 1620$ mm
ineffective length l = 300 mm (assume)
2L = 1620 - $\frac{2}{3} \times 300 = 1420$ mm

It may be noted that when there is only one full length leaf (master leaf only) then the no. of leaves to be cut will be n and when there are two full length leaves (including one master leaf) then the no of leaves to be cut will be (n-1) if a leaf spring has two full length leaves then the length of leaves is obtained as follows

Length of smallest leaf = $\frac{effective\ length}{n-1}$ + ineffective length
n= 9

$$= \frac{1420}{8} + 300$$

= 477.5mm

Length of next leaf = $\frac{effective\ length}{n-1} \times 2 + ineffective\ length$

$= \frac{1420}{8} \times 2 + 300 = 655$ mm

Length of 3rd leaf = $\frac{1420}{8} \times 3 + 300 = 832.5$ mm

Length of 4th leaf = $\frac{1420}{8} \times 4 + 300 = 1010$ mm

Length of 5th leaf = $\frac{1420}{8} \times 5 + 300 = 1187.5$ mm

Length of 6th leaf = $\frac{1420}{8} \times 6 + 300 = 1365$

Length of 7th leaf = $\frac{1420}{8} \times 7 + 300 =$ 1542.5

Length of 8th leaf = $\frac{1420}{8} \times 8 + 300 = 1720$ mm

The nth leaf will be the master leaf and it is of full length since the master leaf has eyes on both sides therefore

Length of master leaf = 2 $L_1 + \pi(d+t) \times 2$

d = Inside diameter of eye

t = thickness of master leaf = 20mm

d =22mm

Length of master leaf = 1620 +π(22+20) $\times 2$ = 1883.76mm

3.4 Radius of curvature

The approximate relation between the radius of curvature (R) and camber (Y) of spring is given by R = $\frac{L_1^2}{2y}$

$L_1 = half\ span\ of\ spring$

Y = δ (the maximum deflection of spring is equal to camber(y) of spring)

$$L_1 = \frac{1620}{2} = 810mm\ ;\ \delta = 11.191mm$$

R = $\frac{810^2}{2 \times 11.191} = \frac{656100}{22.382} = 29313.734$ mm

3.4 RADIUS VALUES OF LEAVES

= 29313.734 mm

= 29293.734 mm

= 29273.734 mm

= 29253.734 mm

= 29233.734 mm

= 29213.734 mm

= 29193.734 mm

= 29173.734 mm

= 29153.734 mm

Analysis of leaf spring

Mild steel

Structural analysis

Imported Model from Pro/Engineer

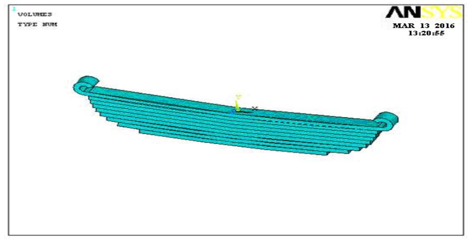
Element Type: Solid 20 node 95

Material Properties: Young's Modulus (EX) : 205000N/mm^2

Poisson's Ratio (PRXY) : 0.29

Density : 0.000007850 kg/mm^3

Meshed Model:



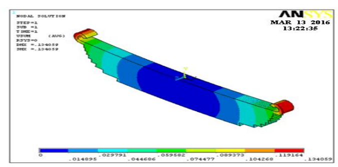
Loads

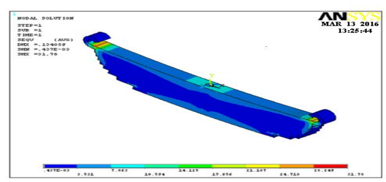
Pressure – 2.408580 N/mm^2

Solution

Solution – Solve – Current LS – ok

Displacement Vector Sum





Von Mises Stress

Modal analysis

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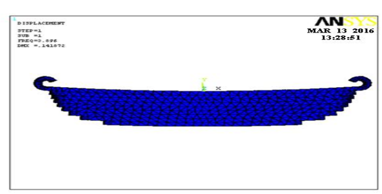
Main menu>Preprocessor>Loads>Analysis Type> Analysis Options> No. Of Modes to Extract: 5



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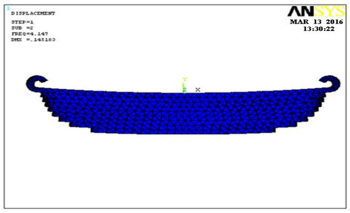

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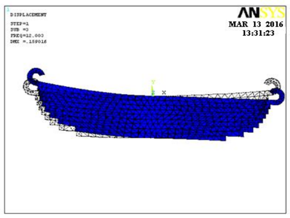

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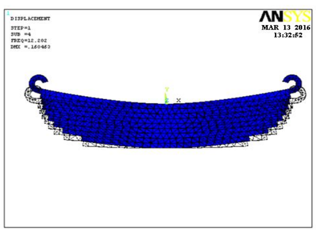

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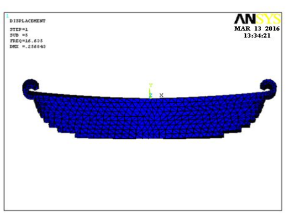


Mode 5

E GLASS EPOXY

STRUCTURAL ANALYSIS

Element Type: Solid 20 node 95

Material Properties: Young's Modulus (EX) : 72400 N/mm^2

Poisson's Ratio (PRXY) : 0.2

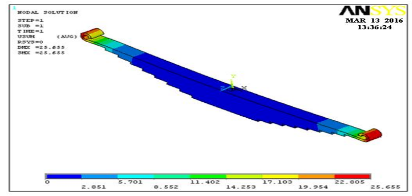
Density : 0.0000019 kg/mm^3

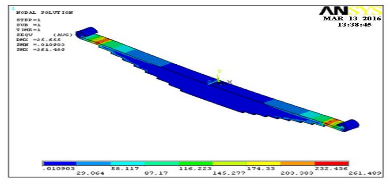
Loads

Pressure – 2.408580 N/mm^2

Solution

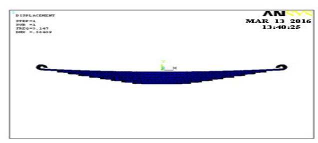
Solution – Solve – Current LS – ok Displacement Vector Sum

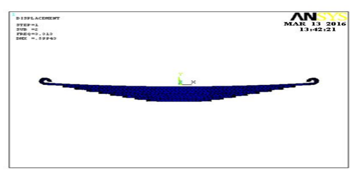




Von Misses Stress

MODAL ANALYSIS RESULTS
Mode 1





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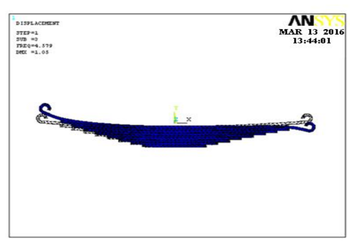

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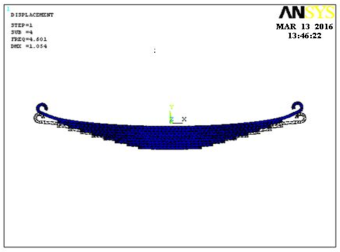

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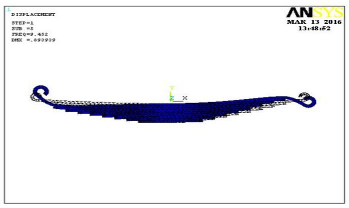


Mode 5

ALUMINUM REINFORCED WITH BORON CARBIDE

STRUCTURAL ANALYSIS

Element Type: Solid 20 node 95

Material Properties: Young's Modulus (EX) :20000/mm^2

Poisson's Ratio (PRXY) : 0.394

Density : 0.0000010206 kg/mm^3

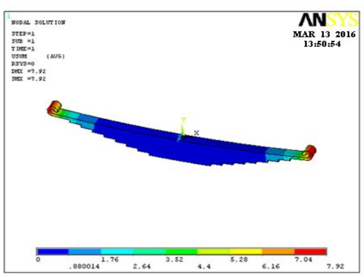
Loads

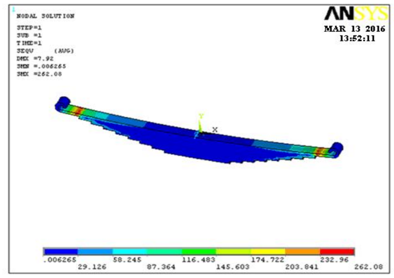
Pressure – 2.408580 N/mm^2

Solution

Solution – Solve – Current LS – ok

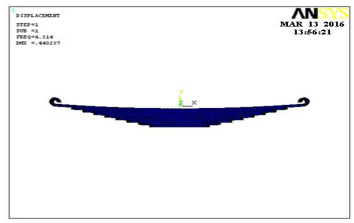
Displacement Vector Sum





Von Misses Stress

MODAL ANALYSIS RESULTS



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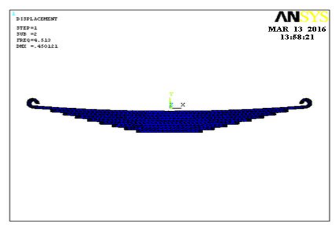

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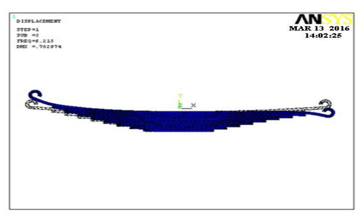

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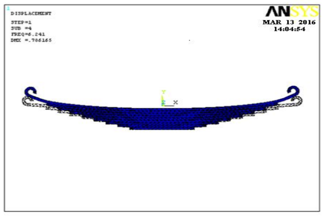

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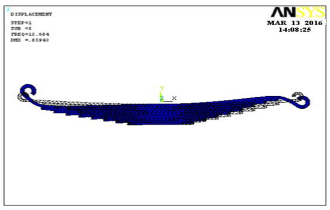

Mode 5

RESULTS AND DISCUSSIONS

STRUCTURAL AND MODAL ANALYSIS RESULTS OF LEAF

		MILD STEEL	E GLASS	ALUMINUM REINFORCED WITH BORON CARBIDE
STRUCTURAL	DISPLACEMENT(mm)	0.134059	25.655	7.92
	STRESS (N/mm^2)	3.78	261.489	262.08
MODE 1	DEFLECTION (mm)	0.141872	0.58409	0.440237
	FREQUENCY (Hz)	3.896	3.147	4.314
MODE 2	DEFLECTION (mm)	0.145183	0.59943	0.450121
	FREQUENCY (Hz)	4.147	3.313	4.513
MODE 3	DEFLECTION (mm)	0.159016	1.05	0.782974
	FREQUENCY (Hz)	12.003	4.579	6.215
MODE 4	DEFLECTION (mm)	0.160463	1.054	0.786165
	FREQUENCY (Hz)	12.202	4.601	6.241
MODE 5	DEFLECTION (mm)	0.256843	0.893939	0.65943
	FREQUENCY (Hz)	16.635	9.452	12.864

SPRING

	MILD STEEL	E GLASS	ALUMINUM REINFORCED WITH BORON CARBIDE
WEIGHT (Kg)	294.5	48.454	27.5

CONCLUSION

- In this thesis a leaf spring is designed and modeled in 3D modeling software Pro/Engineer. Present used material for leaf spring is Steel. In this project, the material is replaced with composites since they are less dense than steel and have good strength The composites used are E Glass Epoxy and Aluminum Reinforced with Boron Carbide.
- Modeling is done in Pro/Engineer. By replacing the material with composites, the weight of the leaf spring is reduced the weight is reduced almost by 267kgs when Aluminum Reinforced with Boron Carbide is used and almost by 246kgs when E Glass is used. The strength of the composites is more when compared to that of Mild Steel. Strength validation is done using structural analysis in Ansys.
- By observing the analysis results, the stress values are less than their respective yield stress values for every material, so using composites for leaf spring is safe under given load condition.
- Modal analysis is done to determine the frequencies. By observing the modal analysis results, the vibrations produced are less for composites than mild steel since their frequencies are less
- By comparing the results for 3 materials, using Aluminum Reinforced with Boron Carbide is better since its weight is less and also stresses values and frequencies analyzed are less than E Glass.

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