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Design of Leaf Spring Using Composite Material

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ABSTRACT

***Objective and scope of this project:** Development of An Analytical Formulation for The Composite Leaf Spring. Composite leaf spring in this project has been developed as a mono block construction with maximum thickness at the center. The thickness reduces towards the end in order to achieve the uniform strength construction. The cross-section is constant at any section along the spring length. This condition is imposed to accomodate the unidirectional fibers and to maintain the fiber continuity from one end to the other.*

A full-fledged finite element analysis will be carried out to find the stress distribution along the spring length. Due to the continuous variation of the geometry it is necessary to predict the stresses and strains more accurately and hence a finite element analysis is planned in this project work.

***Need for this project:** Composite leaf springs are being used in western countries for quite some time. However the exact design and related information is not much available. Since composite leaf springs offer potential benefits in terms of fuel efficiency, better ride characteristics, the work is undertaken in this project.*

1. INTRODUCTION

SPRINGS

A spring is an elastic body whose function is to distort when loaded and to recover its original shape when the load is removed. Though there are many types of springs, the following, according to their shape are important. The various applications of springs are:

- To cushion, absorb or control energy due to either shock or vibration, as in car springs, railway buffers, aircraft landing gears and vibration dampers.
- To apply forces, as in spring-loaded valves and spring balances.
- To control motion by maintaining contact between two elements as in cams and followers.
- To measure forces as in engine indicators and spring balances.
- To store energy as in watches and toys.

Applications

A leaf spring is a simple form of spring commonly used for the suspension in wheeled vehicles. 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. 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.

2. LITERATURE REVIEW

Shiva Shankar and Vijayarangan [2] manufactured a composite mono leaf spring with an integral eye and tested under static load conditions. Also fatigue life prediction was also done to ensure a reliable number of life cycles of a leaf spring. Niklas philipson and Modelan modeled [3] a leaf spring in conventional way and simulated for the kinematic and dynamic comparatives. Zhi'an Yang and et al. [4] studied the cyclic creep and cyclic deformation. Efforts were taken for Finite Element Analysis of multi leaf springs. These springs were simulated and analyzed by using ANSYS [5]. C.K. Clarke and G.E. Borowski [6] evaluated the failure of leaf spring at different static load conditions and J.J. Fuentes et al. [7] studied the effect of premature fracture in Automobile Leaf Springs. Mouleeswaran et al. [8] describes static and fatigue an alysis of steel leaf springs and composite multi leaf spring made up of glass fibre reinforced polymer using life data analysis.

The dimensions of existing conventional steel leaf springs of a light commercial vehicle are taken and are verified by design calculations. Static analysis of 2-D model of conventional leaf spring is also performed using ANSYS 7.1and compared with experimental results. H. A. Al-Qureshi [9] has described a single leaf, variable thickness spring of glass fiber reinforced plastic (GFRP) with similar mechanical and geometrical properties to the multi leaf steel spring, was designed, fabricated and tested. J.J.Fuentes et al. [10] in this work, the origin of premature failure analysis procedures, including examining the l eaf spring history, visual inspection of fractured specimens, characterization of various properties and simulation tests on real components, were used. Rajendran I, S. Vijayarangan [11] a formulation and solution technique using genetic algorithms (GA) for design optimization of composite leaf springs is presented here. J.P. Hou et al. [12] explained the design evolution process of a composite leaf spring for freight rail application. A.strzat and T.Paszek [13] performed a three dimensional contact analysis of the car leaf spring. They considered static three dimensional contact problem of the leaf car spring and the solution is obtained by finite element method performed in ADINA 7.5 professional system. The maximum displacement of car spring is chosen as reliability criterion. Different types of mathematical model were considered starting from the easiest beam model and ending on complicated three dimensional non-linear model which takes into consideration large displacements and contact effects between subsequent spring leaves. The static characteristics of the car spring was obtained for different models and later on, it is compared with one obtained from experimental investigations. Fu-Cheng Wang [14] performed a detailed study on leaf springs. Classical network theory is applied to analyze the behavior of a leaf spring in an active suspension system. I.Rajendran and S.Vijayarangan [15] performed a finite element analysis on a typical leaf spring of a passenger car. Finite element analysis has been carried out to determine natural frequencies and mode shapes of the leaf spring by considering a simple road surface model. Furthermore literatures are available on concepts and design of leaf springs [16-17]. The dimensions and the properties of the materials are taken from the spring manufacturing companies catalogues [18 - 19].

THEORETICAL BACKGROUND

3.1 SPRINGS

A spring is an elastic body whose function is to distort when loaded and to recover its original shape when the load is removed. Though there are many types of springs, the following, according to their shape are important. The various applications of springs are:

- To cushion, absorb or control energy due to either shock or vibration, as in car springs, railway buffers, aircraft landing gears and vibration dampers.
- To apply forces, as in spring-loaded valves and spring balances.
- To control motion by maintaining contact between two elements as in cams and followers.
- To measure forces as in engine indicators and spring balances.
- To store energy as in watches and toys.

In order to conserve natural resources and economize energy, weight reduction has been the main focus of automobile manufacturer in the present scenario.

Weight reduction can be achieved primarily by the introduction of better material, design optimization and better manufacturing processes. The suspension leaf spring is one of the potential items for weight reduction in automobile as it accounts for ten to twenty percent of the unsprung weight. This helps in achieving the vehicle with improved riding qualities. It is well known that springs, are designed to absorb and store energy and then release it. Hence, the strain energy of the material becomes a major factor in designing the springs. The relationship of the specific strain energy can be expressed as

$$U = \frac{\sigma^2}{\rho E},$$

Where σ is the strength, ρ the density and E the Young's modulus of the spring material. It can be easily observed that material having lower modulus and density will have a greater specific strain energy capacity. The introduction of composite materials was made it possible to reduce the weight of the leaf spring without any reduction on load carrying capacity and stiffness. Since; the composite materials have more elastic strain energy storage capacity [1] and high strength-to-weight ratio as compared to those of steel.

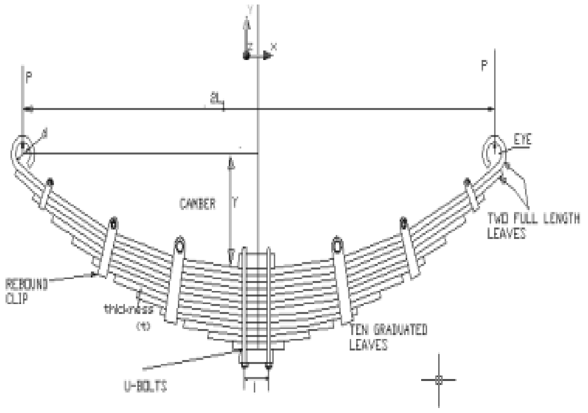

Figure 3.1: Various components of Leaf Spring

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.

3.1.1 SPRINGS FOR AUTOMOTIVE SUSPENSION SYSTEM

The automotive suspension system connects the road wheels to the frame or body of the vehicle. The primary function of the suspension system is to support the weight of the vehicle and to isolate the vehicle body and the passengers within from the road shocks and vibration caused due to the unevenness of the road surface. Secondly, the suspension system has to perform this function without impairing the stability and road holding of the vehicle. The primary requirement of road shock isolation is achieved by the use of springs and shock absorbers (dampers) while the vehicle stability is taken care of by the use of stabilizer or anti-roll bar.

The anti-roll bar reduces the effect of vehicle body rolling and pitching (vertical movement tendency) which the vehicle experiences during a severe turn.

Figure shows the representation of an automobile suspension system. The suspension connects the vehicle's sprung weight to the unsprung weight as shown in the sketch. In a Vehicle, the sprung weight is the weight of all elements supported by the suspension spring while the unsprung weight is the weight of all elements between the spring and road. When the vehicle passes over a bump or ditch, the road wheels experience a sudden load, which can induce severe vibration and set up high stresses in the mechanism, if the road wheels are rigidly connected to the vehicle chassis. The springs in conjugation with the shock absorbers serve to isolate the vehicle body from the shock loads and vibration by absorbing the same. The spring and the shock absorber act in a complimentary fashion in reducing the transmission of road vibration into the vehicle body. When the spring is deflected by the action of shocks loads, it continues to rise and fall and makes the carriage unit to bounce accordingly until the oscillation set up in the spring dies down on its own.

The shock absorber along with the spring element dampens the spring oscillation after the spring's initial deflection. Shock absorbers have two functions. Firstly, they are used for reducing the tendency of the carriage unit to continue to bounce up and down on its springs after the disturbance that caused the initial deflection has ceased. Secondly, they prevent the high excitation due to resonance when the natural frequency of vibration of the spring coincides with the induced frequency of vibration. The damping in a shock absorber is achieved by forcing the hydraulic fluid at high velocities through small holes by means of a piston. The shock absorber applies force in the direction opposite to that of the instantaneous motion of the spring. The energy absorbed by the fluid is converted into heat and the heat is dissipated to the surrounding air.

The leaf spring used in an automotive suspension system is either a cantilever or a simply supported beam. It absorbs shock by bending. The conventional steel leaf spring is an assembly of number of steel strips of constant width and varying length mounted together so as to form a steel beam thickest at the center and the thinnest at the ends.

Coil springs absorb the road shocks by compression. These springs are made from steel rods. The spring takes the shear as well as bending stresses. Torsion bars are simply a rod acting in torsion and taking shear stresses only. The amount of energy stored per unit weight of material is nearly the same as for coil springs. Rubber springs used are compression spring and compression shear spring. These have excellent vibration damping properties.

3.2 LEAF SPRINGS

The automobile in the late 1890's was still a crude machine in terms of road handling and ride comfort, as these factors were overlooked in the search for more power and better efficiency. Its suspension system was basically the rubber that the tyres were composed of and the axles. The first real development in suspension was at the turn of the 18th century when leaf springs were introduced. The leaf spring started out as two strips of curved metal supported at each end with the load at the centre. The design evolved through many stages as more demands were placed on suspension. By the mid 1930's the design had changed to a beam simply supported at each end which effectively halved the weight. The design contributed to a greater fuel economy and was also relatively cheap to manufacture. The success of this design was so great that it was still used in the 1980's on heavy-duty vehicles and some American cars.

Figure 3.2: Leaf Spring

Because it was already used in the horse drawn carriages, the leaf spring has a heavy usage in the automobile suspensions. The original C-shaped spring was strengthened by the addition of steel strips. At first, the elliptical leaf spring was employed. It was made of two long, curved leaves or blades pivoted together at their end to form an ellipse. They were strengthened at their mid-point by additional leaves whose lengths decreased, as they were located farther from the main blade. This arrangement was designed to provide the maximum strength with adequate deflection for given loads. As the loads increased, the elliptic spring was replaced by the semi-elliptic, smaller and stronger than the first one. It had its ends secured to the chassis and its centre to the axle a new problem appeared: as the spring was flattened, its length increased which was not compatible with a strong contact with the chassis. To overcome this, one end was bolted to the chassis while the other was allowed to slide on the frame or pivoted to a shackle.

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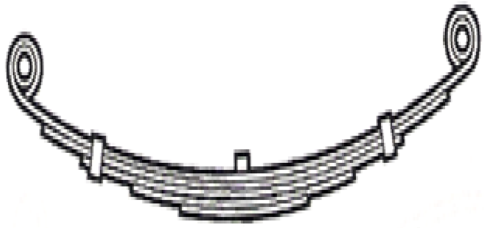
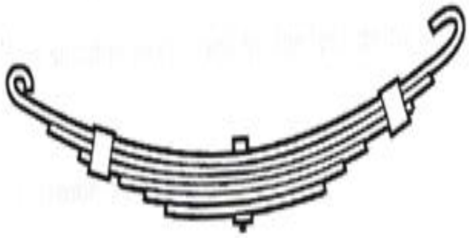
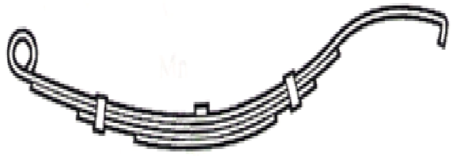


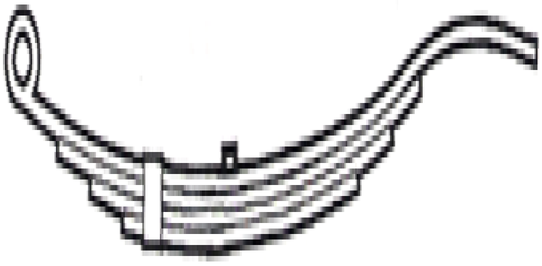
Double eye springs



Open eye slipper springs



Hook end slipper springs



Radius end slipper springs
Figure 3.3. TYPES OF SEMI

ELLIPTICAL LEAF SPRINGS

Leaf springs absorb the vehicle vibrations, shocks and bump loads (induced due to road irregularities) by means of spring deflections, so that the potential energy is stored in the leaf spring and then relieved slowly. Ability to store and absorb more amount of strain energy ensures the comfortable suspension system. Semi-elliptic leaf springs are almost universally used for suspension in light and heavy commercial vehicles. For cars also, these are widely used in rear suspension. The spring consists of a number of leaves called blades.

The blades are varying in length. The blades are us usually given an initial curvature or cambered so that they will tend to straighten under the load. The leaf spring is based upon the theory of a beam of uniform strength. The lengthiest blade has eyes on its ends. This blade is called main or master leaf, the remaining blades are called graduated leaves. All the blades are bound together by means of steel straps.

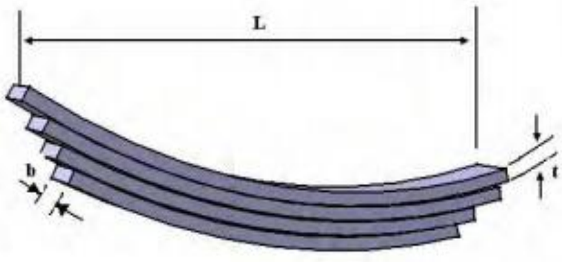
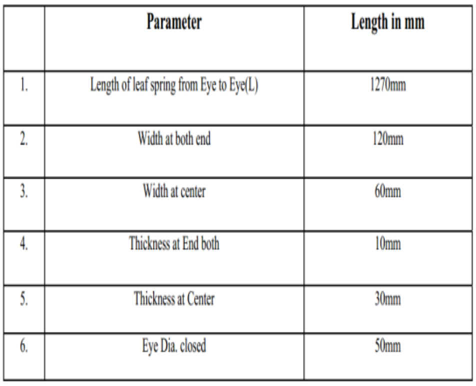


Figure 3.4: Elements of Leaf Spring

MODELING AND CALCULATIONS

4.1 Design Considerations

The suspension leaf spring behaves like a simply supported beam and hence the flexural analysis is done considering it as simply supported curved beam. The concentrated load at the center produces bending stress and transverse shear stress in the beam. The main stresses are tension on one side of the neutral axis and compression on the other side. The flexural rigidity is an important parameter in the leaf spring design and it should increase from the end to the center, the maximum bending stress occurs at the center.



	Parameter	Length in mm
1.	Length of leaf spring from Eye to Eye(L)	1270mm
2.	Width at both end	120mm
3.	Width at center	60mm
4.	Thickness at End both	10mm
5.	Thickness at Center	30mm
6.	Eye Dia. closed	50mm

Table 4.1: The design Parameters of Leaf spring

Procedure for modeling in CATIA:

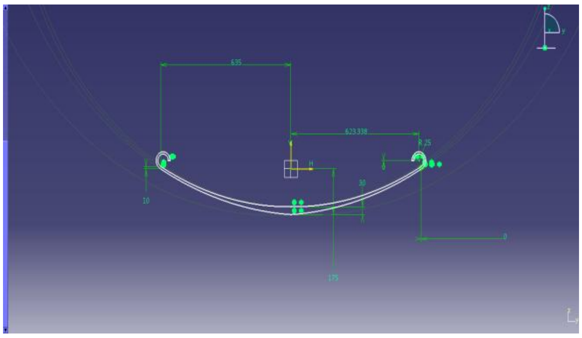


Figure 4.1: Sketch Of The Leaf Spring

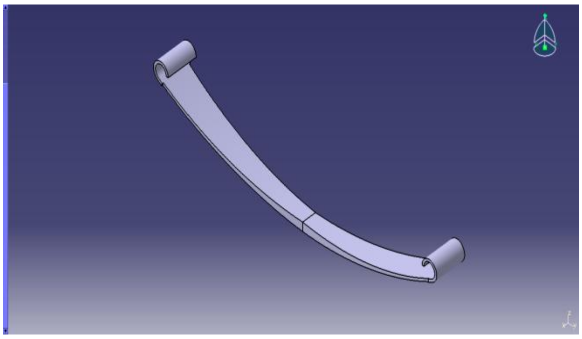


Figure 4.2: Model of Leaf Spring in CATIA

4.2 Theoretical Calculations

To have an idea of working principle of a leaf spring, let us think of the diving board in a swimming pool. The diving board is a cantilever with a load, the diver, at its free end. The diver initiates a to and fro swing of the board at the free end and utilizes the spring action of the board for jumping. The diving board basically is a leaf spring.

The leaf springs are widely used in suspension system of railway carriages and automobiles. But the form in which it is normally seen is laminated leaf spring. A simple cantilever type leaf spring is shown in the below figure.

In the cantilever beam type leaf spring, for the same leaf thickness, h, leaf of uniform width, b(case 1) and, leaf of width, which is uniformly reducing from b(case 2) is considered. From the basic equations of bending stress and deflection, the maximum stress, σmax and tip deflection δmax can be derived.

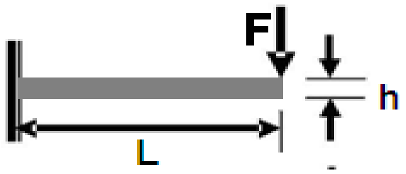


Figure 4.2: For Case 1(Uniform Width)

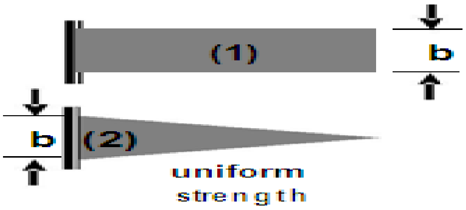


Figure 4.3: For Case 2 (Non Uniform Width)

For case 1(uniform width)

$$\sigma_{max} = 6FL/bh^2$$

$$\delta_{max} = 4FL^3/Ebh^3$$

Where, E is the Elastic modulus of the spring material.

For case 2(non uniform width)

$$\sigma_{max} = 6FL/bh^2$$

$$\delta_{max} = 4FL^3/Ebh^3$$

In the second case it is observed that instead of uniform width leaf, if a leaf of varying width (triangular one as shown in the figure 2) is used, the bending stress at any cross section is same and equal to σ_{max}. This is called as leaf of a uniform strength. Moreover, the tip deflection being more, comparatively, it has greater resilience than its uniform width counterpart. Resilience, as we know, is the capacity to absorb potential energy during deformation.

However one should keep in mind that in order to withstand the shear force the tip has to have some width. This is shown as a red zone in the below figure. In one way non uniform width leaf is a better design than a uniform width leaf.

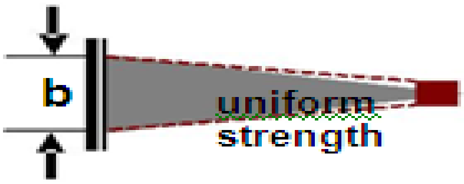


Figure 4.4

RESULTS AND DISCUSSIONS

This leaf spring is modeled in CATIA and analysis has been performed on the leaf spring i.e., static, fatigue and modal analysis. For performing the analysis three materials have been considered steel, carbon epoxy and E-glass epoxy. The material properties for these three materials are given in the table below.

Sl. no.	Properties	Units	Steel	Carbon Epoxy	E-Glass Epoxy
1	Young's Modulus E11	N / m^2	$2.068*10^{11}$	$1.34*10^{11}$	$50*10^9$
2	Young's Modulus E22	N / m^2	$2.068*10^{11}$	$7*10^9$	$12*10^9$
3	Density	kg / m^3	7830	1600	2000
4	Poisson Ratio	-	0.3	0.3	0.3
5	Shear Modulus	N / m^2	-	$5.8*10^9$	$5.6*10^9$

Table 5.1: Material Properties of the Three Materials

ANALYSIS IN ANSYS WORKBENCH:

For steel material:

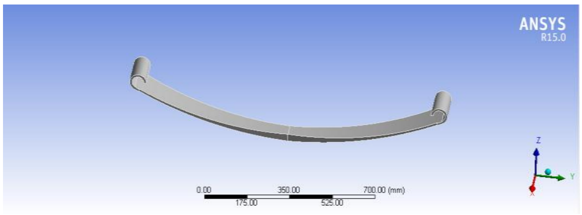


Figure 5.1: The above shown figure shows the model of the leaf spring drawn in CATIA and imported in ANSYS.

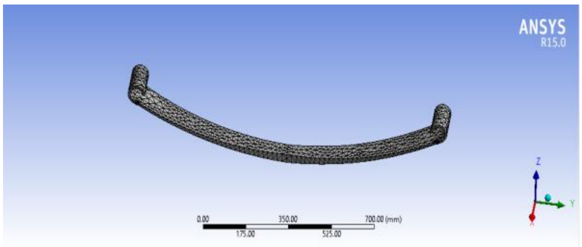


Figure 5.2: The above shown figure shows the meshed model of the leaf spring model in ANSYS.

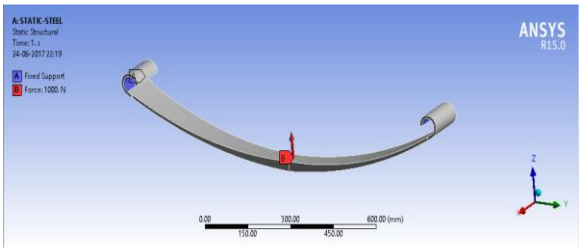


Figure 5.3: The above shown figure shows the boundary condition of the leaf spring and the load is applied on the leaf spring.

Case 1: static analysis

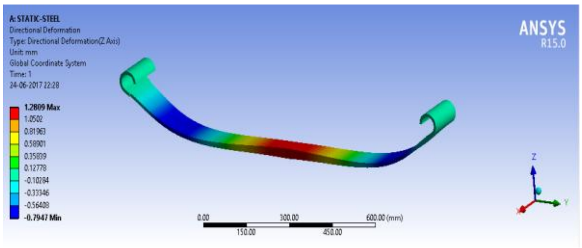


Figure 5.4: The above shown figure shows the deformation in leaf spring model when the load is applied on the leaf spring and the maximum deformation observed in Z-axis is 1.2797 mm

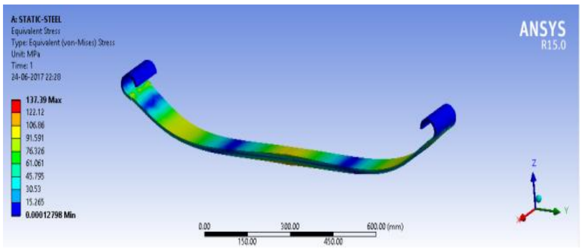


Figure 5.5: The above shown figure shows the von-mises stresses in the leaf spring when the load is applied on the leaf spring and the maximum stress obtained is 137.39 MPa.

Case 2: fatigue analysis

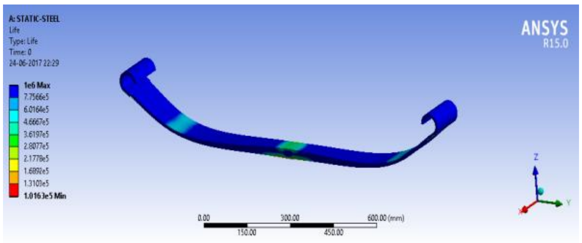


Figure 5.6: The above shown figure shows the fatigue life of the leaf spring when the leaf spring is loaded with fatigue load.

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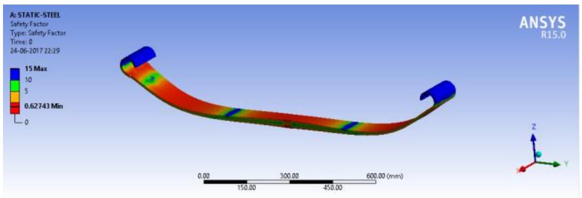


Figure 5.7: The above shown figure shows the safety factor of the leaf spring when the leaf spring is loaded with fatigue load and the maximum safety factor observed is 15.

Case 3: Modal Analysis

MODE NO.	NATURAL FREQUENCY (HZ)
1	92.016
2	202.12
3	203.19
4	359.71
5	472.17
6	613.57

Table 5.2: The table above shows the natural frequency obtained when modal analysis has been performed on the leaf spring

For carbon epoxy material:

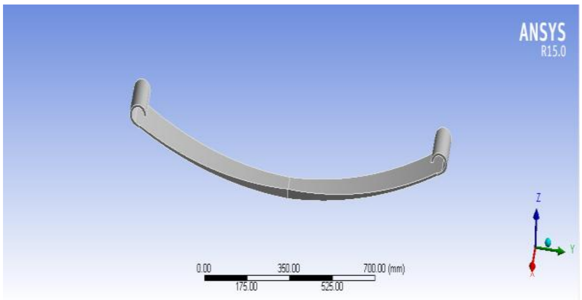


Figure 5.8: The above shown figure shows the model of the leaf spring drawn in catia and imported in Ansys.

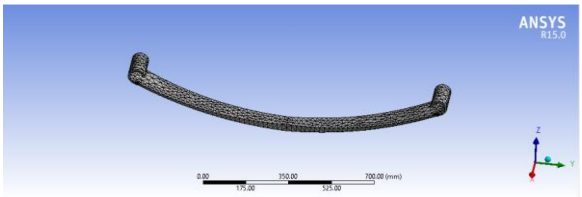


Figure 5.9: The above shown figure shows the meshed model of the leaf spring model in ansys.

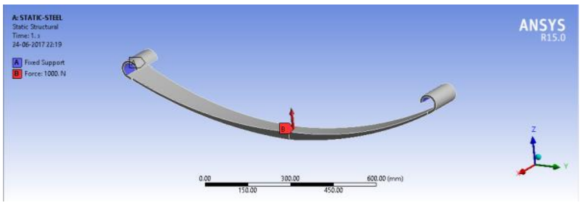


Figure 5.10: The above shown figure shows the boundary condition of the leaf spring and the load is applied on the leaf spring.

Case 1: static analysis

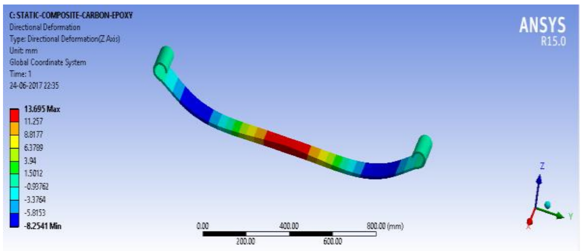


Figure 5.11: The above shown figure shows the deformation in leaf spring model when the load is applied on the leaf spring and the maximum deformation observed in Z-axis is 13.689 mm

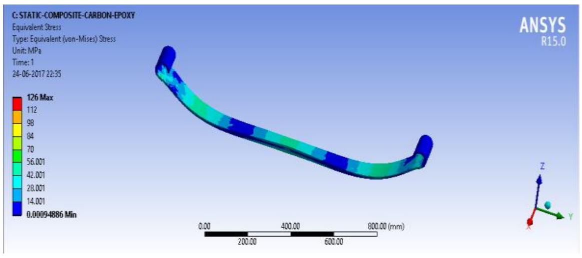


Figure 5.12: The above shown figure shows the von-mises stresses in the leaf spring when the load is applied on the leaf spring and the maximum stress obtained is 126.01 MPa.

Case 2: fatigue analysis

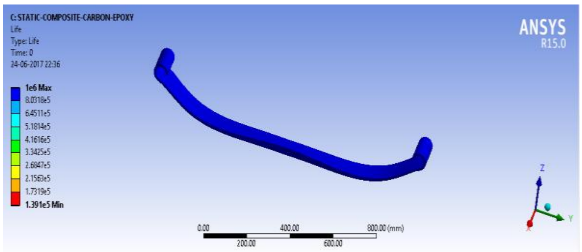


Figure 5.13: The above shown figure shows the fatigue life of the leaf spring when the leaf spring is loaded with fatigue load.

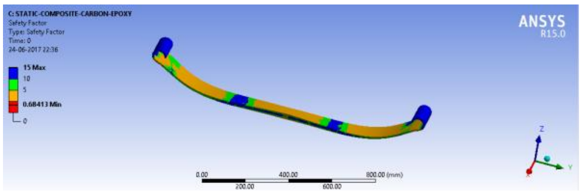


Figure 5.14: The above shown figure shows the safety factor of the leaf spring when the leaf spring is loaded with fatigue load and the maximum safety factor observed is 15.

Case 3: Modal Analysis

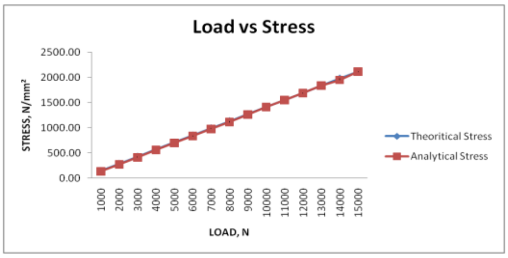
MODE NO.	NATURAL FREQUENCY(HZ)
1	0
2	67.691
3	99.284
4	141.22
5	206.52
6	282.67

Table 5.3: The table above shows the natural frequency obtained when modal analysis has been performed on the leaf spring

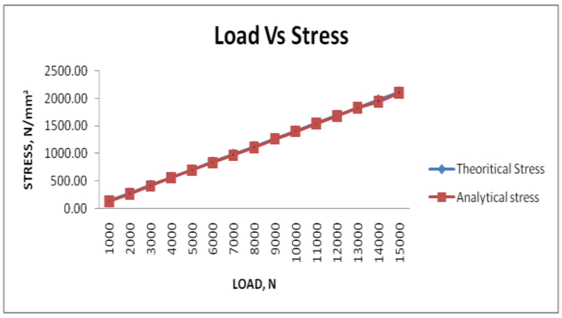
RESULTS OBTAINED

FORCE N	THEORITICAL STRESS Mpa	ANALYTICAL STRESS Mpa	DEFORMATION mm
1000	141.11	137.39	1.2797
2000	282.22	274.79	2.5594
3000	423.33	417.67	3.8903
4000	564.44	560.56	5.2212
5000	705.56	703.45	6.5521
6000	846.67	835.35	7.7806
7000	987.78	978.24	9.1115
8000	1128.89	1110.1	10.34
9000	1270.00	1264	11.773
10000	1411.11	1406.9	13.104
11000	1552.22	1549.8	14.435
12000	1693.33	1681.7	15.664
13000	1834.44	1830.1	17.046
14000	1975.56	1945.5	18.121
15000	2116.67	2110.4	19.656

Table 5.5: The table above shows the stress values and deformation values obtained at different loads for the material steel



Graph 5.1: The graph above shows the stress values calculated theoretically and analytically for the steel material



Graph 5.2: The graph above shows the stress values calculated theoretically and analytically for carbon epoxy material

FORCE N	THEORITICAL STRESS Mpa	ANALYTICAL STRESS Mpa	DEFORMATION mm
1000	141.11	126.01	13.689
2000	282.22	262.53	28.518
3000	423.33	409.55	44.489
4000	564.44	556.56	60.459
5000	705.56	693.08	75.288
6000	846.67	829.60	90.118
7000	987.78	966.11	104.950
8000	1128.89	1102.60	119.780
9000	1270.00	1260.10	136.890
10000	1411.11	1396.70	151.720
11000	1552.22	1543.70	167.690
12000	1693.33	1680.20	182.520
13000	1834.44	1827.20	198.490
14000	1975.56	1932.20	209.890
15000	2116.67	2100.20	228.150

Table 5.6: The table above shows the stress values and deformation values obtained at different loads for the material carbon epoxy

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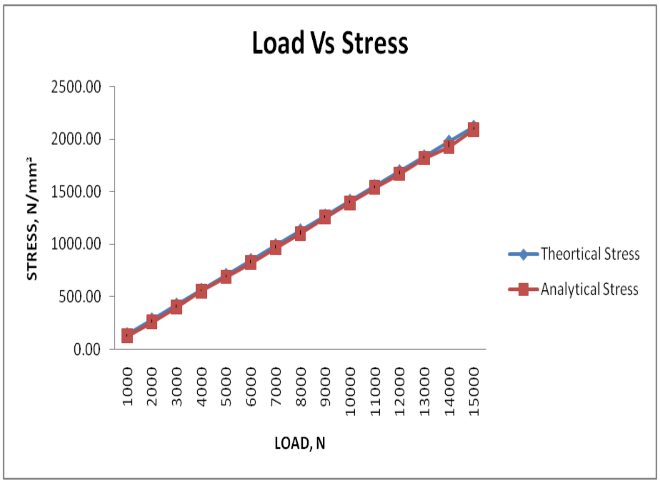
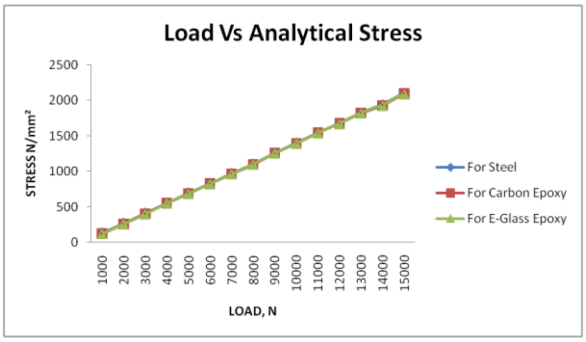
FORCE N	THEORITICAL STRESS Mpa	ANALYTICAL STRESS Mpa	DEFOMATION mm
1000	141.11	123.40	28.258
2000	282.22	258.55	59.207
3000	423.33	399.58	91.502
4000	564.44	552.37	126.490
5000	705.56	687.52	157.440
6000	846.67	822.67	188.390
7000	987.78	963.70	220.680
8000	1128.89	1098.90	251.630
9000	1270.00	1257.50	287.960
10000	1411.11	1392.70	318.910
11000	1552.22	1539.60	352.550
12000	1693.33	1668.90	382.150
13000	1834.44	1821.60	417.140
14000	1975.56	1927.40	441.360
15000	2116.67	2091.90	479.040

Table 5.7: The table above shows the stress values and deformation values obtained at different loads for the material e-glass epoxy

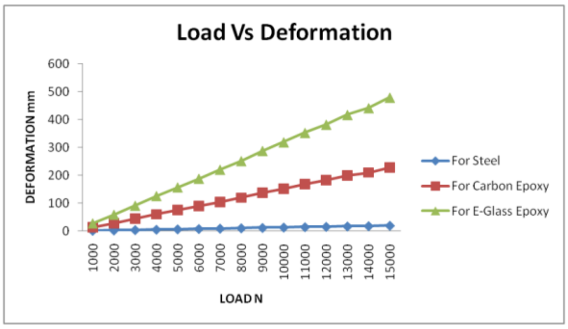


Graph 5.3: The graph above shows the stress values calculated theoretically and analytically for e-glass epoxy material

NATURAL FREQ			
S.NO.	STEEL	Carbon Epoxy	E-Glass Epoxy
1	92.016	0	32.496
2	202.12	67.691	40.065
3	203.19	99.284	68.718
4	359.71	141.22	110.93
5	472.17	206.52	117.13
6	613.57	282.67	127.17



Graph 5.4: The graph above shows the analytical stress values of all the three materials at different loads



Graph 5.5: The graph above shows the deformation at different loads for all the three materials

CONCLUSION

The following are the conclusions obtained:

- A procedure to design a composite leaf spring has been established.
- Leaf spring made up of E-Glass/Epoxy Single layered composites has been designed.
- FRP and steel models are created in CATIA V5 .
- The Finite Element Modeling presented in the analysis is able to predict the stress distribution.

- When maximum load is applied on the steel leaf spring, the maximum stress is greater than that of FRP leaf spring.
- Even under the maximum load, the maximum stress in the FRP is within the allowable limit.
- The weight reduction has greater influence in noise and vibration characteristics.
- Glass fibers are for manufacturing instead of carbon due to low cost.
- The results are encouraging and suggest that ANSYS can be used effectively and efficiently in other complex and realistic designs often encountered in engineering applications, where experimental is not possible due to shortage of time and other constraints.

As outlined above, the FRP (glass fiber) leaf spring we developed has achieved a great reduction. The problem remaining to be solved is manufacturing the FRP leaf springs, their environmental resistance, long term practical endurance, productivity etc. The cost of carbon fiber, at present, is also a great factor preventing practical use of carbon fiber reinforced plastic leaf spring.

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