STATIC ANALYSIS OF LEAF SPRING

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ABSTRACT

Leaf springs are special kind of springs used in automobile suspension systems. The advantage of leaf spring over helical spring is that the ends of the spring may be guided along a definite path as it deflects to act as a structural member in addition to energy absorbing device. The main function of leaf spring is not only to support vertical load but also to isolate road induced vibrations. It is subjected to millions of load cycles leading to fatigue failure. Static analysis determines the safe stress and corresponding pay load of the leaf spring and also to study the behavior of structures under practical conditions. The present work attempts to analyze the safe load of the leaf spring, which will indicate the speed at which a comfortable speed and safe drive is possible. A typical leaf spring configuration of TATA-407 light commercial vehicle is chosen for study. Finite element analysis has been carried out to determine the safe stresses and pay loads.

Keywords: Leaf spring, Geometric modeling, Static analysis.

1. INTRODUCTION

A spring is defined as an elastic body, whose function is to distort when loaded and to recover its original shape when the load is removed. 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 [1]. 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.

The spring is mounted on the axle of the vehicle. The entire vehicle load rests on the leaf spring. The front end of the spring is connected to the frame with a simple pin joint, while the rear end of the spring is connected with a shackle. Shackle is the flexible link which connects between leaf spring rear eye and frame. When the vehicle comes across a projection on the road surface, the wheel moves up, leading to deflection of the spring. This changes the length between the spring eyes. If both the ends are fixed, the spring will not be able to accommodate this change of length. So, to accommodate this change in length shackle is provided at one end, which gives a flexible connection. The front eye of the leaf spring is constrained in all the directions, where as rear eye is not constrained in X-direction. This rare eye is connected to the shackle. During loading the spring deflects and moves in the direction perpendicular to the load applied.

When the leaf spring deflects, the upper side of each leaf tips slides or rubs against the lower side of the leaf above it. This produces some damping which reduces spring vibrations, but since this available damping may change with time, it is preferred not to avail of the same. Moreover, it produces squeaking sound. Further if moisture is also present, such inter-leaf friction will cause fretting corrosion which decreases the fatigue

Strength of the spring, phosphate paint may reduce this problem fairly. The elements of leaf spring are shown in Figure 1. Where t is the thickness of the plate, b is the width of the plate and L is the length of plate or distance of the load W from the cantilever end.

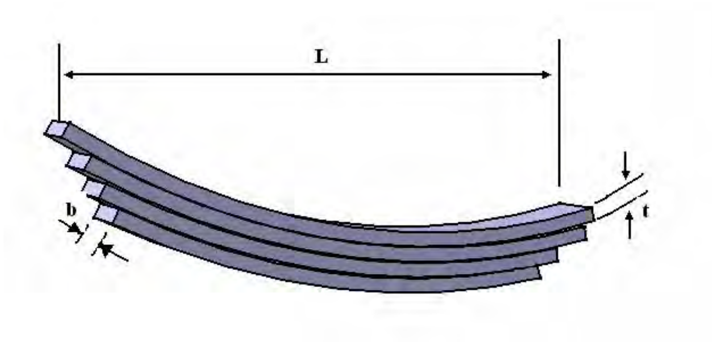

Fig. 1 Elements of Leaf Spring

Bending Stress of Leaf Spring

Leaf springs (also known as flat springs) are made out of flat plates. The advantage of leaf spring over helical spring is that the ends of the spring may be guided along a definite path as it deflects to act as a structural member in addition to energy absorbing device. Thus the leaf springs may carry lateral loads, brake torque, driving torque etc., in addition to shocks. Consider a single plate fixed at one end and loaded at the other end. This plate may be used as a flat spring.

Let t = thickness of plate
b = width of plate, and
L = length of plate or distance of the load W from the cantilever end, as shown in the Figure 1.

We know that the maximum bending moment at the cantilever end

$$M = W.L$$

And section modulus,

$$Z = \frac{I}{y} \quad \text{where } I = (b.t^3 / 12) \text{ and } Y = t/2$$

So $Z = b.t^2 / 6$

The bending stress in such a spring,

$$f = M / Z = (6W.L) / b.t^2 \quad \ldots\ldots \text{(i)}$$

We know that the maximum deflection for a cantilever with concentrated load at free end is given by

$$\partial = W.L^3 / 3.E.I = 2f.L^2 / \ 3.E.t \quad \ldots\ldots \text{(ii)}$$

It may be noted that due to bending moment, top fibers will be in tension and bottom fibers are in compression, but the shear stress is zero at the extreme fibers and the maximum at centre, hence for analysis, both stresses need not to be taken into account simultaneously. We shall consider bending stress only.

If the spring is not of cantilever type but it is like a simply supported beam, with length 2L and load 2W in the centre

Maximum bending moment in the centre,

$$M = W.L$$

Section modulus

$$Z = b.t^2 / 6$$

Bending stress

$$f = 6W.L / b.t^2$$

We know that maximum deflection of a simply supported beam loaded in the centre is given by

$$\partial = W.L^3 / 3.E.I$$

From above we see that a spring such as automobile spring (semi-elliptical spring) with length 2L and load in the centre by a load 2W may be treated as double cantilever. If the plate of cantilever is cut into a series of n strips of width b and these are placed as shown in Figure 1, then equations (i) and (ii) may be written as

$$f = 6W.L / n.b.t^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{(iii)}$$

$$\partial = 4.W.L^3 / n.E.b.t^3 = 2.f.L^2 / 3.E.t \ \ldots\ldots\ldots\ldots\ldots \text{(iv)}$$

The above relation gives the bending stress of a leaf spring of uniform cross- section and is given in Table 1 at various loads. The stress at such a spring is maximum at support.

Table 1 variation of Bending Stress with load

Load (Newton)	**Bending Stress N/mm^2**
1000	145.507
2000	291.015
3000	436.522
4000	582.0302
5000	727.540
6000	873.045
7000	1018.550
8000	1164.060
9000	1309.570
10000	1455.076
11000	1600.583
12000	1746.091
13000	1891.598
14000	2037.106
15000	2182.613

Length of Leaf Spring Leaves

The length of the leave springs are calculated by using the formulas given below

$$\text{Length of smallest leaf} = \frac{\text{Effective length}}{n-1} \times 1 + \text{Ineffective length}$$

$$\text{Length of next leaf} = \frac{\text{Effective length}}{n-1} \times 2 + \text{Ineffective length}$$

Similarly,

$$\text{Length of (n-1)}^{\text{th}} \text{ leaf} = \frac{\text{Effective length}}{n-1} \times (n-1) + \text{Ineffective length}$$

$$\text{Length of master leaf} = 2L_1 + 2\prod(d + t)$$

Where $2L_1$ = Length of span or overall length of the spring,
l=distance between centers of U-bolts (ineffective length (I.L) of the leaf spring),
n_F = Number of full length leaves,
n_G = Number of graduated leaves,
n = Total number of leaves = $n_F + n_G$,
E.L = Effective length of the spring = $2L_1 - (2/3)l$,
d = Inside diameter of eye and
t = Thickness of master leaf.

Geometric Properties of leaf spring

Camber = 80 mm, Span = 1220 mm, Thickness = 7 mm, Width = 70 mm, Number of full length leaves $n_F = 2$, Number of graduated leaves $n_G = 8$ and Total Number of leaves n = 10

2. LITERATURE SURVEY

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 analysis 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 leaf 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. Further more 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].

The present work attempts to find the maximum pay load of the vehicle by performing static analysis using ANSYS software and the obtained results are compared with the mathematical calculations and the maximum bending stress and the corresponding pay load is determined by considering the factor of safety.

3. MODELING & ANALYSIS OF LEAF SPRING

In computer-aided design, geometric modeling is concerned with the computer compatible mathematical description of the geometry of an object. The mathematical description allows the model of the object to be displayed and manipulated on a graphics terminal through signals from the CPU of the CAD system. The software that provides geometric modeling capabilities must be designed for efficient use both by the computer and the human designer.

To use geometric modeling, the designer constructs the graphical model of the object on the CRT screen of the ICG system by inputting three types of commands to the computer. The first type of command generates basic geometric elements such as points, lines, and circles. The second type command is used to accomplish scaling, rotation, or other transformations of these elements. The third type of command causes the various elements to be joined into the desired shape of the object being created on the ICG system. During this geometric process, the computer converts the commands into a mathematical model, stores it in the computer data files, and displays it as an image on the CRT screen. The model can subsequently be called from the data files for review, analysis, or alteration. The most advanced method of geometric modeling is solid modeling in three dimensions.

Modeling Procedure for Leaf Spring

1. First create the key point 100 at origin, i.e. x ,y, z = (0, 0, 0).
2. Create another key point 200 at some arbitrary distance in Z-direction, say x, y, z = (0, 0, 200).
3. Join the above two key points 100 and 200 to get the reference axis.
4. By using data from mathematical analysis Create the key point1 with a distance of radius of curvature R_1 in vertically down-ward direction, i.e. x, y, z = (0, $-R_1$, 0).
5. Similarly key points 2 and 3 correspond to R_2, i.e. x, y, z = (0, $-R_2$, 0) and key points 4 and 5 corresponds to R_3, i.e. x, y, z = (0, $-R_3$, 0).
6. Key point 20 corresponds to R_{11}. i.e. x, y, z = (0, -R11, 0).
7. Join the pair of key points sequentially as follows Key points 1 and 2, 2 and 3, 3 and 4...and 19 and 20.
8. Then line1 formed by the key points 1 and 2, line2 formed by the key points 2 and 3 and line10 formed by the key points 19 and 20.
9. Extrude the above lines with respect to reference axis stated in step3 as follows:
   Extrude line1 with an angle Φ_1, will get area1
   Extrude line2 with an angle Φ_2, will get area2,………and
   Extrude line10 with an angle Φ_{10}, will get area10.
10. After extruding all the lines, the semi area of the spring without eye will form on XY- plane with significant degeneracy.
11. To avoid degeneracy, extend the right side line of smallest area i.e. area 10 to some extent such that it cross the top most area i.e. area1.Now divide area by line. For this, select the areas left to extended line1 and divide with that line. Similarly, extend the right side line of second smallest area i.e. area9 to some extent such that it cross the top most area i.e. area1. Again divide area by line.
    For this select the areas left to extended line2 and divide with that line.
12. The above process is to be done up to extension of line of area9 and divide area area by extension line9.
13. Now perfect half area of leaf spring without eye will form.
14. Eye construction:
    Extend the right side line of top most area i.e. area1 to the length equal to the radius of eye. Delete lines only, so that key point of that line will remain. Shift the origin to that key point. Create another key point say some key point300 in Z-direction. Join the above two key points to get reference axis to rotate the right side line of area1. Extrude the line with respect to reference axis to an angle 275^0 to 280^0. Delete all reference lines. So half area of leaf spring with eye is formed.
15. To get the full area of the leaf spring. Shift the origin to the top left most area key point i.e. key point1. Reflect the entire area with respect to YZ – plane.
16. To get the solid model of the leaf spring, extrude the area by Z-offset to a length equal to the width of the leaf spring.
17. To make a cylindrical hole at centre of the leaf spring to provide bolting for all the leaves, so that all the leaves are in perfect alignment: Create centre key point of the leaf spring on the top view i.e. XY-plane, by using key points between key points' command. Shift the origin to that key point. Choose the proper work plane by using work plane Create a cylinder along Z-axis in vertically downward direction.
    Subtract the cylinder from the solid leaf spring. So that leaf spring with hole to provide bolt will obtain.
    The models are presented in the Figure 2 and Figure 3.

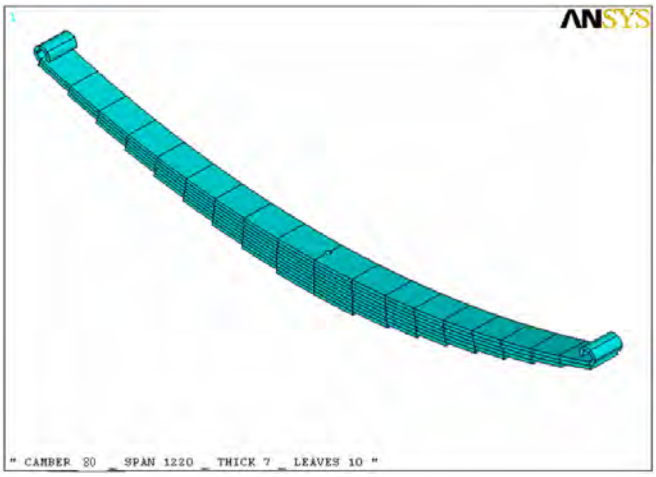

Fig. 2 Full model of leaf spring

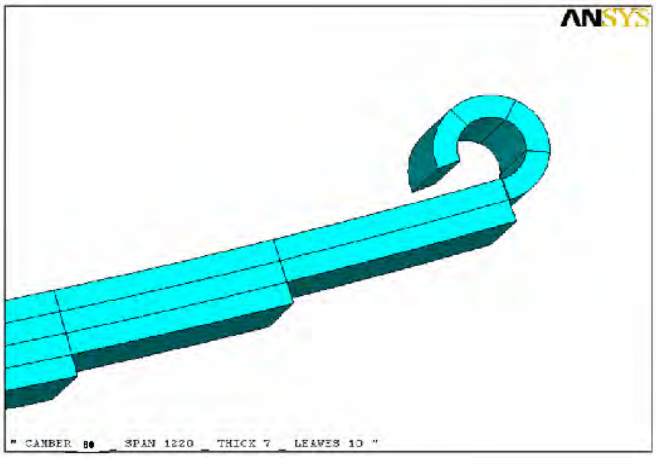

Fig. 3 Enlarged view of leaf spring

STATIC ANALYSIS

For the above given specification of the leaf spring, the static analysis is performed using ANSYS to find the maximum safe stress and the corresponding pay load. After geometric modeling of the leaf spring with given specifications it is subjected to analysis. The Analysis involves the following discritization called meshing, boundary conditions and loading. However modal analysis does not need loading.

Meshing

Meshing involves division of the entire of model into small pieces called elements. This is done by meshing. It is convenient to select the free mesh because the leaf spring has sharp curves, so that shape of the object will not alter. To mesh the leaf spring the element type must be decided first. Here, the element type is solid 72. The element edge length is taken as 15 and is refined the area of centre bolt to 2. Fig 7.2 shows the meshed model of the leaf spring.

The following are the material properties of the given leaf spring.
Material = Manganese Silicon Steel, Young's Modulus E = 2.1E5 N/mm^2, Density ρ = 7.86E-6 kg/mm^3, Poisson's ratio = 0.3 and Yield stress = 1680 N/mm^2.

Boundary Conditions

The leaf spring is mounted on the axle of the automobile; the frame of the vehicle is connected to the ends of the leaf spring. The ends of the leaf spring are formed in the shape of an eye. The front eye of the leaf spring is coupled directly with a pin to the frame so that the eye can rotate freely about the pin but no translation is occurred. The rear eye of the spring is connected to the shackle which is a flexible link; the other end of the shackle is connected to the frame of the vehicle. The rear eyes of the leaf spring have the flexibility to slide along the X-direction when load applied on the spring and also it can rotate about the pin. The link oscillates during load applied and removed. Therefore the nodes of rear eye of the leaf spring are constrained in all translational degrees of freedom, and constrained the two rotational degrees of freedom. So the front eye is constrained as UX, UY, UZ, ROTX, ROTY and the nodes of the rear eye are constrained as UY, UZ, ROTX, ROTY. Figure 4 shows the boundary conditions of the leaf spring.

Loads Applied

The load is distributed equally by all the nodes associated with the center bolt. The load is applied along Fy direction as shown in Figure 4. To apply load, it is necessary to select the circumference of the bolt hole and consequently the nodes associated with it. It is necessary to observe the number of nodes associated with the circumference of the bolt hole, because the applied load need to divide with the number of nodes associated with the circumference of the center bolt.

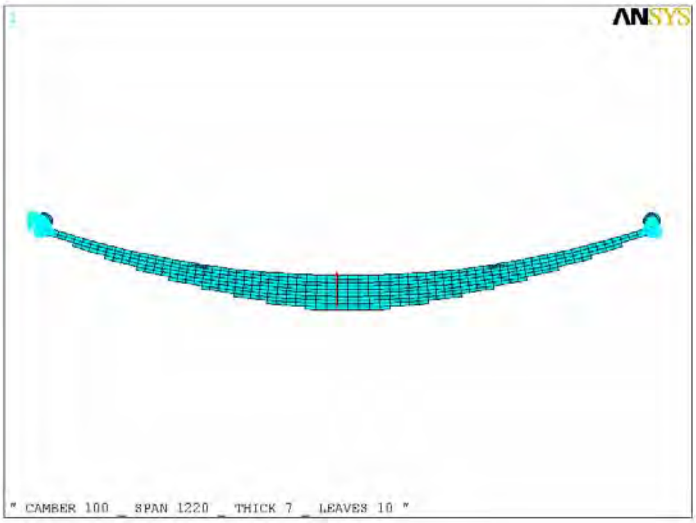

Fig. 4 Meshing boundary conditions and loading of leaf spring

For this problem the load is 9000 N, and the number of associated nodes is 12. So the load on each node is 750 N.

5. RESULTS AND DISCUSSIONS

The deformed and undeformed shape of the leaf spring is shown in Figure 5 and the Table 2 gives the Von-Mises stress at various loads.

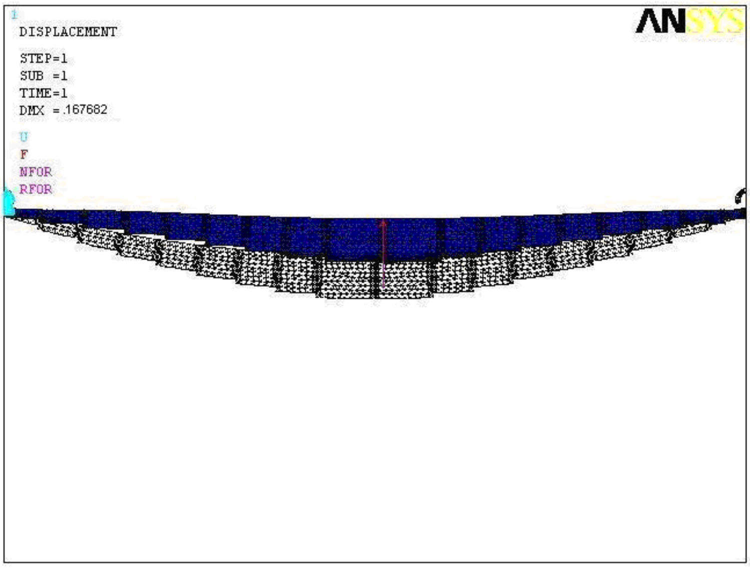

Fig. 5 Deformed and undeformed shape of leaf spring

Table 2 variation of Von-mises stress with load

Load N	Von-mises Stress N/mm^2
1000	139.628
2000	282.615
3000	426.152
4000	568.83
5000	712.642
6000	852.345
7000	993.515
8000	1136.106
9000	1277.672
10000	1420.076
11000	1458.076
12000	1602.463
13000	1746.091
14000	1891.599
15000	2037.106

Static analysis is performed to find the Von-Mises stress by using ansys software and these results are compared with bending stresses calculated in mathematical analysis at various loads and is shown in Table 3.

Table 3 Comparison between Theoretical and ANSYS for Von-mises Stress

	Von-mises stress N/mm^2	
Load N	**THEORITICAL**	**ANSYS**
1000	145.507	139.628
2000	291.015	282.615
3000	436.522	426.152
4000	582.030	568.830
5000	727.540	712.642
6000	873.045	852.345
7000	1018.550	993.515
8000	1164.060	1136.106
9000	1309.570	1277.672
10000	1455.076	1420.076
11000	1600.583	1558.076
12000	1746.091	1702.463
13000	1891.598	1846.091
14000	2031.106	1991.599
15000	2182.613	2137.106

It is seen that at load 12000 N, it crosses the yield stress (yield stress is 1680 N/mm^2). By considering the factor of safety 1.5 to 2, it is obvious that the allowable design stress is 840 to 1120 N/mm^2. So the corresponding loads are 6000 to 8000 N. Therefore it is concluded that the maximum safe pay load for the given specification of the leaf spring is 7700N.

Table 4 Near corresponding safe loads

	Von-mises stress N/mm^2	
Load N	**THEORITICAL**	**ANSYS**
7500	1091.310	1072.133
7600	1105.857	1084.372
7700	1120.408	1097.681

From the Theoretical and the ANSYS, the allowable design stress is found between the corresponding loads 6000 to 8000N. Therefore the near corresponding safe loads are given in Table 4.

A graph is plotted as shown in Figure 6 between Load versus Von-mises stress with Load on the X-Axis and Von-mises stress on the Y-Axis.

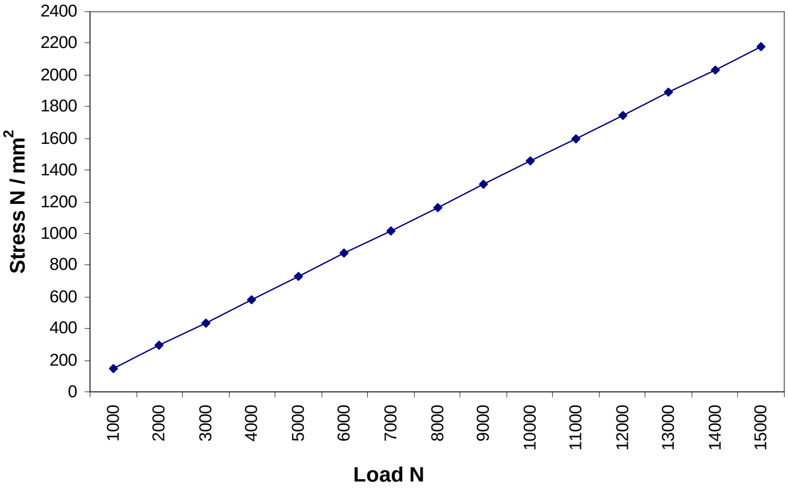

Fig. 6 Variation of Von-mises stress with load

It is seen that from the above graph that when load increases the bending stress increases linearly. So load-stress graph gives the straight line relationship. At lower loads both theoretical and **ANSYS** results are very close, but when load increases the ANSYS results are uniformly reduced compared to theoretical results.

From Figure 7 and Figure 8, it is obvious that maximum stress developed is at inner side of the eye sections i.e. the red color indicates maximum stress, because the constraints applied at the interior of the eyes. Since eyes are subjected to maximum stress, care must be taken in eye design and fabrication and material selection. The material must have good ductility, resilience and toughness to avoid sudden fracture.

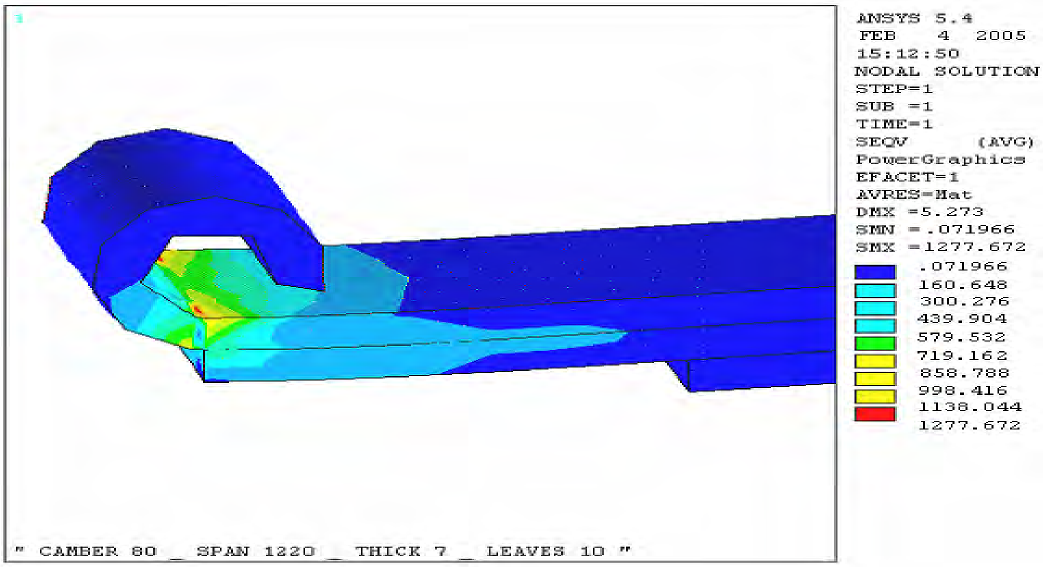

Fig. 7 Von-mises Stress contour plot of Front eye of leaf spring

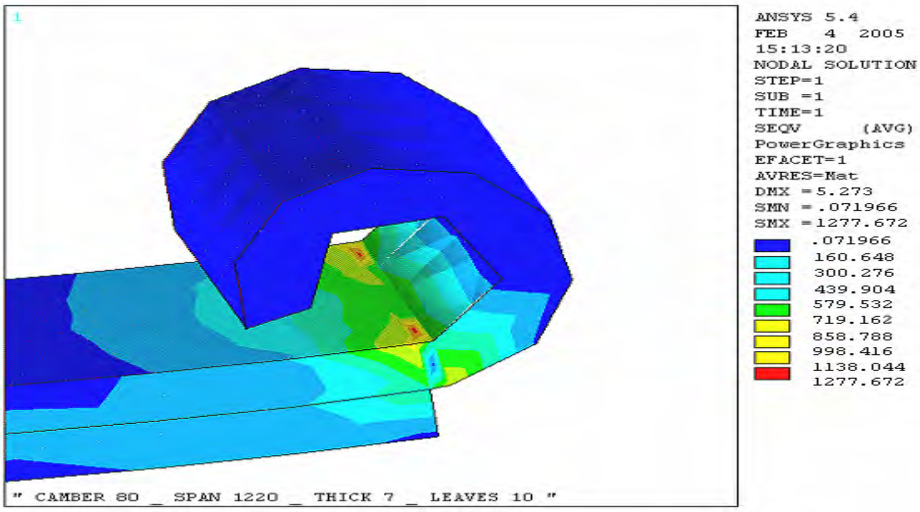

Fig. 8 Von-mises Stress contour plot of Rear eye of leaf spring

6. CONCLUSIONS

The automobile chassis is mounted on the axles, not direct but with some form of springs. This is done to isolate the vehicle body from the road shocks which may be in the form of bounce, pitch, roll or sway. These tendencies give rise to an uncomfortable ride and also cause additional stress in the automobile frame and body. All the part which performs the function of isolating the automobile from the road shocks are collectively called a suspension system. Leaf spring is a device which is used in suspension system to safeguard the vehicle and the occupants. For safe and comfortable riding i.e, to prevent the road shocks from being transmitted to the vehicle components and to safeguard the occupants from road shocks it is necessary to determine the maximum safe load of a leaf spring. Therefore in the present work, leaf spring is modeled and static analysis is carried out by using ANSYS software and it is concluded that for the given specifications of the leaf spring, the maximum safe load is 7700N. It is observed that the maximum stress is developed at the inner side of the eye sections, so care must be taken in eye design and fabrication and material selection. The selected material must have good ductility, resilience and toughness to avoid sudden fracture for providing safety and comfort to the occupants.

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