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STATIC, DYNAMIC AND FATIGUE ANALYSIS OF COMPOSITE LEAF SPRING FOR LIGHT WEIGHT VEHICLE

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Abstract: To describe design and experimental analysis of composite leaf spring made of glass fiber reinforced polymer or other material base on light weight vehicle. The objective is to compare the load carrying capacity, stiffness and weight savings of composite leaf spring with that of steel leaf spring. The design constraints are stresses and deflections. The dimensions of an existing conventional steel leaf spring of a light commercial vehicle are taken. Same dimensions of conventional leaf spring are used to fabricate a composite multi leaf spring using Glass/Epoxy unidirectional laminates. Modeling of leaf spring is done in Solid Works 2011. Static analysis of 2-D model of conventional leaf spring is also performed using ANSYS. Finite element analysis with full load on 3-D model of composite multi leaf spring is done using ANSYS by taking two different material structural steel and E-Glass/Epoxy. Also done dynamic analysis of multi leaf spring for frequency analyses in different modal form of leaf spring. Compare both result of von misses stress, total shear stress and total deflection in static condition for both material.

Keywords: Composite leaf spring, Weight, Stress, Deflection, Stiffness, Solid Works.

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INTRODUCTION

In order to conserve natural resources and economize energy, weight reduction has been the main focus of automobile manufacturers 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 automobiles as it accounts for 10% - 20% of the unstrung weight. This achieves the vehicle with more fuel efficiency and improved riding qualities. The introduction of composite materials was made it possible to reduce the weight of leaf spring without any reduction on load carrying capacity and stiffness. Since, the composite materials have more elastic strain energy storage capacity and high strength to weight ratio as compared with those of steel, multi-leaf steel springs are being replaced by mono-leaf composite springs. The composite material offer opportunities for substantial weight saving but not always are cost-effective overtheir steel counter parts.

The leaf spring should absorb the vertical vibrations and impacts due to road irregularities by means of variations in the spring deflection so that the potential Energy is stored in spring as strain energy and then released slowly. So, increasing the energy storage capability of a leaf spring ensures a more compliant suspension system. According to the studies made a material with maximum strength and minimum modulus of elasticity in the longitudinal direction is the most suitable material for a leaf spring. Fortunately, composites have these characteristics. Fatigue failure is the predominant mode of in-service failure of many automobile components. This is due to the fact that the automobile components are subjected to variety of fatigue loads like shocks caused due to road irregularities traced by the road wheels, the sudden loads due to the wheel traveling over the bumps etc. The leaf springs are more affected due to fatigue loads, as they are apart of the unstrung mass of the automobile.

The fatigue behavior of Glass Fiber Reinforced Plastic (GFRP) epoxy composite materials has been studied in the past. Theoretical equation for predicting fatigue life is formulated using fatigue modulus and its degrading rate. This relation is simplified by strain failure criterion for practical application. A prediction method for the fatigue strength of composite structures at an arbitrary combination of frequency, stress ratio and temperature has been presented. These studies are limited to mono-leaf springs only.

In the present work, a seven-leaf steel spring used in passenger cars is replaced with a composite multi leaf spring made of glass/epoxy composites. The dimensions and the number of leaves for both steel leaf spring and composite leaf springs are considered to be the same. The primary objective is to compare their load carrying capacity, stiffness and weight savings of composite leaf spring. Finally, fatigue life of steel and composite leaf spring is also predicted using life data.

[1] ANALYTICAL CALCULATION AND CAD MODELLING OFCOMPOSITE LEAF SPRING

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 3.1. 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.

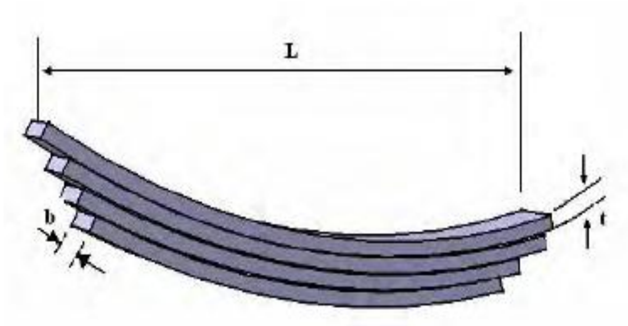


Fig. 1 Elements of Leaf Spring

[2] 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 = I/y

Where I = (b.t3 / 12) and Y = t/2

So Z = b.t2 / 6

The bending stress in such a spring,

$f = M / Z = (6W.L) / b.t^2$------------------- (i)

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

$\delta = W.L^3 / 3.E.I = 2f.L^2 / 3.E.t$---------------- (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 load2W 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

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

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

$f = 6W.L / n.b.t^2$---------------- (iii)

$\delta = 4.W.L^3 / n.E.b.t^3 = 2.f.L^2 / 3.E.t$---------------- (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 and Deflection with load

Sr. No.	Load (W) in N	Bending Stress (f) in N/mm^2	Deflection (δ) in mm
1	1000	187	31.0
2	2000	373	61.9
3	3000	560	92.9
4	4000	747	123.9
5	5000	933	154.9

6	6000	1120	185.8
7	7000	1307	216.8
8	8000	1493	247.8
9	9000	1680	278.8
10	10000	1867	309.7

[3] Length of Leaf Spring Leaves

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

Length of smallest leaf = Effective length * 1/ (n-1) + Ineffective length

Length of next leaf = Effective length * 2 / (n-1) + Ineffective length

Similarly,

Length of $(n-1)^{th}$ leaf = Effective length * (n-1) / (n-1) + Ineffective length

Length of master leaf = $2L_1 + 2\,\Pi\,(d + t)$

Where 2L1 = 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.

[4] Specifications of Steel Leaf Spring

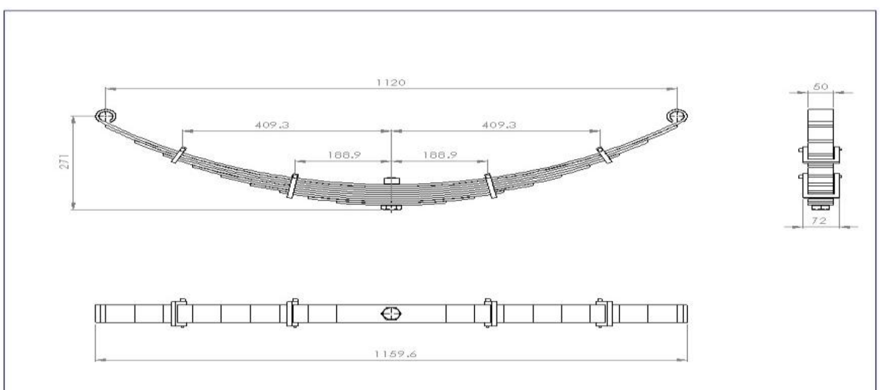
Table 2 Specification of Steel Leaf Spring

Sr. No.	Specifications	
1	Total Length of the spring (Eye to Eye)	1120mm
2	Free Camber (At no load condition)	180mm
3	No. of full length leaves	2

4	No. of graduated leaves	8
5	Thickness of leaf	6mm
6	Width of leaf spring	50mm
7	Maximum Load given on spring	6685N
8	Young's Modulus of the steel	210000 (MPa)
9	Weight of the leaf spring	17.78 kg
10	Poisson's ratio	0.3

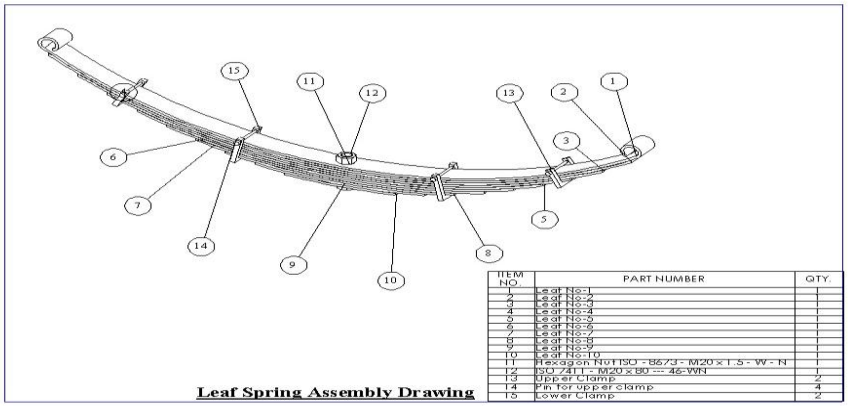
[5] Solid Modeling

In multi-leaf steel spring and mono-composite leaf spring are modeled. For modeling the steel spring, the dimensions of a conventional leaf spring of a light weight commercial vehicle are chosen. Since the leaf spring is symmetrical about the neutral axis only half of the leaf spring is modeled by considering it as a cantilever beam and a uniformly distributed load is applied over the ineffective length of the leaf spring in the upward direction.



Leaf Spring Drawing

Fig 2 Leaf Spring Drawing



ITEM NO.	PART NUMBER	QTY.
1	Leaf No-1	1
2	Leaf No-2	1
3	Leaf No-3	1
4	Leaf No-4	1
5	Leaf No-5	1
6	Leaf No-6	1
7	Leaf No-7	1
8	Leaf No-8	1
9	Leaf No-9	1
10	Leaf No-10	1
11	Hexagon Nut ISO - 8673 - M20 x 1.5 - W - N	1
12	ISO 7411 - M20 x 80 --- 46-WN	1
13	Upper Clamp	2
14	Pin for upper clamp	4
15	Lower Clamp	2

Fig 3 Leaf Spring Assembly Drawing

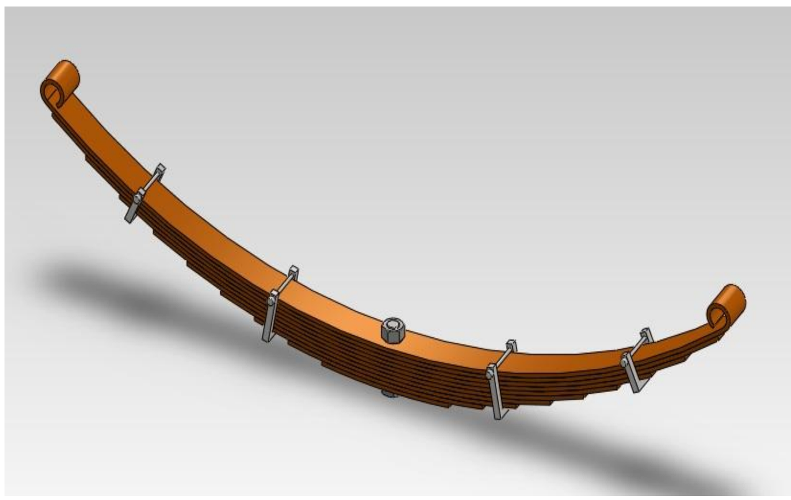


Fig 4 Solid model of steel leaf spring created in Solid Work 2011 and imported it's for analysis in ANSYS

[6] Assumptions

- All non-linear effects are excluded.
- The stress-strain relationship for composite material is linear and elastic; hence Hooke's law is applicable for composite materials
- The leaf spring is assumed to be in vacuum.
- The load is distributed uniformly at the middle of the leaf spring.
- The leaf spring has a uniform, rectangular cross section.

[7] Selection of Cross Section

The following cross-sections of mono-leaf spring for manufacturing easiness are considered.

- Constant thickness, varying width design
- Varying width, varying thickness design.
- Constant thickness, constant width design

In the present work, only constant cross-section design method is selected due to the following reasons: due to its capability for mass production and accommodation of continuous reinforcement of fibers. Since the cross-section area is constant throughout the leaf spring, same quantity of reinforcement fiber and resin can be fed continuously during manufacturing.

[8] Materials for Leaf Spring

The material used for leaf springs is usually a plain carbon steel having 0.90 to 1.0% carbon. The leaves are heat treated after the forming process. The heat treatment of spring steel products greater strength and therefore greater load capacity, greater range of deflection and better fatigue properties.

Material Properties:

Name : Mild steel

Yield strength: 5.5e+008N/m^2

Tensile strength: 3e+007 N/m^2

Elastic modulus: 2.6e+011 N/m^2

Poisson's ratio: 0.266

Density : 7860kg/m3

Shear modulus: 30189e+008N/m^2

Chemical Composition: EN 45 Materials

Table 3 Chemical Composition of EN 45 Materials

%C	%Si	% Mn	%S	%P
0.50/0.60	1.50/2.00	0.70/1.00	0.050	0.050

Carbon/Graphite fibers: Their advantages include high specific strength and modulus, low coefficient of thermal expansion and high fatigue strength. Graphite, when used alone has low impact resistance. Its drawbacks include high cost, low impact resistance and high electrical conductivity.

Glass fibers: The main advantage of Glass fiber over others is its low cost. It has high strength, high chemical resistance and good insulating properties. The disadvantages are low elastic modulus poor adhesion to polymers, low fatigue strength and high density, which increase leaf spring weight and size. Also crack detection becomes difficult.

[9] E-Glass/Epoxy:

Table 4 Material properties of E-Glass/Epoxy

Sr. No.	Properties	Value
1	Tensile modulus along X-direction (Ex), MPa	34000
2	Tensile modulus along Y-direction (Ey), MPa	6530
3	Tensile modulus along Z-direction (Ez), MPa	6530
4	Tensile strength of the material, MPa	900
5	Compressive strength of the material, MPa	450
6	Shear modulus along XY-direction (Gxy), MPa	2433
7	Shear modulus along YZ-direction (Gyz), MPa	1698
8	Shear modulus along ZX-direction (Gzx), MPa	2433
9	Poisson ratio along XY-direction (NUxy)	0.217
10	Poisson ratio along YZ-direction (NUyz)	0.366
11	Poisson ratio along ZX-direction (NUzx)	0.217
12	Mass density of the material (ρ), kg/mm^3	2.6e-6
13	Flexural modulus of the material, MPa	40000
14	Flexural strength of the material, MPa	1200

[10] Specific Design Data

Here Weight and initial measurements of Mahindra “Model - commander 650 di” light vehicle are taken

Gross vehicle weight = 2150 kg

Unspring weight = 240 kg

Total sprung weight = 1910 kg

Taking factor of safety (FS) = 1.4

Acceleration due to gravity (g) = 10 m/s²

There for; Total Weight (W) = 1910*10*1.4 = 26740 N

Since the vehicle is 4-wheeler, a single leaf spring corresponding to one of the wheels takes up one fourth of the total weight.

F = 26740/4 = 6685 N

[11] Design Parameters of Steel Leaf Spring

Table 5 Design Parameter of Steel Leaf Spring

Leaf no.	Full leaf length (mm) 2L	Half leaf length(mm) L	Radius of curvature R (mm)
1	1120	560	961.11
2	1120	560	967.11
3	1007	503.5	973.11
4	894	447	979.11
5	780	390	985.11
6	667	333.5	991.11
7	554	277	997.11
8	440	220	1003.11
9	327	163.5	1009.11
10	214	107	1015.11

Since the leaf spring is fixed with the axle at its center, only half of it is considered for analysis purpose with half load.

[12] Static Analysis

Table 6 Comparison of Static Analysis Result

Material	Von-mises stress (MPa)	Max. Shear Stress (MPa)	Total Deflection (mm)
Structural Steel(EN45)	126.44	21.96	37621
E-Glass/Epoxy	126.99	23.07	22128

[13] DYNAMic Analysis

The table show modal analysis of Leaf Spring which having material EN 45 containing different six mode of defamation.

Mode	Frequency Hz
1	71.612
2	138.94
3	305.44
4	307.44
5	631.4
6	648.69

The table show modal analysis of Leaf Spring which having material E-PROXY containing different six mode of defamation.

Mode	Frequency Hz
1	83.037
2	151.9
3	338.14
4	350.3
5	670.15

6	713.65

[14] FAtiGUE Analysis

Table 7 Comparison of Fatigue Analysis Result

Sr. No.	Material	Life $1X10^9$ (Minimum)	Damage Life $1X10^9$ (Maximum)	Safety Factor (Minimum)	Fatigue Sensitivity (Nos. of Fill Point)
1	Structural Steel	20.797 Cycles	4.8085×10^7	0.031015	50-150% (25)
2	E Glass/Epoxy	1.3521 X 105 Cycle	7395.7	0.6788	50-150% (25)

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CONCLUSION

In this study, the response of Composite Leaf Spring is determined input parameter identified. Basic design calculation of multi leaf spring includes different parameter of Composite Leaf Spring identified and calculation represent basic component‘s parameter geometric constraint form.

The analysis performed in this research is based on some assumptions and restrictions. However, complete literature review and input parameter of Composite Leaf Spring identification, thus, understanding of behavior of Composite Leaf Spring is attained taking every possible detail into account.

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