Computer Aided Analysis for the Weight Optimization of Leaf Spring using Composite Material

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Abstract: Reducing the weight of the product while improving or keeping the same strength by using alternative design techniques is the world's biggest research subject. Composite materials are the one of the families which is attracting as solutions to this issue. Leaf springs are crucial suspension elements in automobile, necessary to minimize the vertical vibrations, impacts and bumps due to road irregularities. One of the main objectives of this project is to find out the best suited material for the leaf spring under the application of vibration loading. It will comprise of the study of leaf made with the composite material carbon fiber and comparing its strength and weight with the conventional steel leaf spring. Also vibration analysis will be carried out on the composite leaf spring and the natural frequencies will be compared to find out the feasibility of composite material for the leaf spring. The leaf spring is designed for TATA ACE mini truck suspension leaf spring using standard design procedures and the dimensions obtained are verified with the actual shackle used in the application. The designed leaf spring is analyzed using ANSYS 16.2 software for the maximum and minimum stress regions.Then analysis is carried out on the composite leaf spring made from carbon fiber. From the study, we notice that the weight of the conventional leaf spring is 5.53 and that of carbon fiber is 2.87,so the weight reduction is 48.16%

Index Terms - Leaf spring, ANSYS 16.2, stress.

I. INTRODUCTION

THE use of leaf spring can be traced back to the year 1804 when the inventor ― Obadiah Elliot first used the leaf spring on horse- drawn and later on railway rolling stock. Early designers of motor vehicle then took the advantage of this spring because it has the capacity of varying the leaves easier as well as obtaining the desired degree of resilience by varying the width and thickness of the leaves. In order to see natural resources and economize energy, weight reduction has been the main focus of automobile manufacturer in the present time. It is known that the failure nature of steel leaf springs is usually common. It is very important to reduce accidents and to replace steel leaf springs by gradually failing FRP (fiber reinforced polymer) composite material. Weight reduction can be achieved primarily by the introduction of Better Material, Design Optimization and Better Manufacturing Processes.

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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.

Leaf springs are general classified in to three types

1. Multiple leaf spring
2. Mono Leaf spring
3. Parabolic Single leaf spring
4. Fiber Composite Spring

Majority of the leaf spring function on dual capacity, one as a load carrying member and second as an axel control member. The spring is bolted tightly to the frame of the vehicle through the thick end, while the free end is attach to the axel through a bushing. Most of the trucks and light vehicles are equipped with leaf springs as shown figure1, either in the front or rear axle suspension systems in order to improve the ride comfort and to support heavy loads.

Fig.1. Truck equipped with leaf spring

They are interposed between the wheels and the body so that the body is partially isolated from the axle. This permit the axel can move autonomously from the body. When a vehicle rides over rough grounds, the wheels will rise when rolling over bump and will deflect the springs. The energy created due to this movement is momentarily stored in the spring; it is then release again, due to the elasticity of the spring material, and in expending this energy the spring will rebound. The spring will then oscillate at its natural frequency, causing the vehicle to bounce many times before equilibrium is restored. If the body were firmly joined to the axel, the kinetic energy produced by the bump would be imparted directly to the body, creating high impact stresses to the chassis and paneling and discomfort to the passengers.

Tomas W. Birch (1999) observed that as the spring absorbs load and deflects, the leaves change from a curve shape to a flat shape and then re-curve in the order direction. The length of the leaves is also change considerably as they flatten out and bend. However to take care of this changes most leaf springs uses shackle; while also there is a certain amount of sliding of the ends of one leaf over the next leaf, often know as interleaf friction.

A. COMPOSITE MATERIALS:

A composite material is defined as a material composed of two or more constituents combined on a macroscopic scale by mechanical and chemical bonds. Typical composite materials are composed of inclusions suspended in a matrix. The constituents retain their identities in the composite. Normally the components can be physically identified and there is an interface between them.

Many composite materials offer a combination of strength and modulus that are either comparable to or better than any traditional metallic materials. Because of their low specific gravities, the strength weight-ratio and modulus weight-ratios of these composite materials are markedly superior to those of metallic materials.

Composite materials are superior to all other known structure materials in specific strength and stiffness, high temperature strength, fatigue strength and other properties. The desired combination of properties can be tailored in advance and realized in the manufacture of a particular material. Moreover, the material can be shaped in this process as close as possible to the form of final products or even structural units.

The first major structural application of composite is the corvette rear leaf spring in Commercial. Other structural chassis components, such as drive shafts and road wheels, have been successfully tested in the laboratories and are currently being developed for future cars and vans. The metal matrix composites containing either continuous or discontinuous fiber reinforcements, the latter being in the form of whiskers that are approximately 0.1-0.5 μm in diameter and have a length to diameter ratio up to 200. Particulate-reinforced metal matrix composites containing either particles or platelet that ranges in size from 0.5 to 100 μm. Dispersion-strengthened metal matrix composites containing particles that are less than 0.1 μm in diameter and metal matrix composites are such as directionally solidified eutectic alloys.

II. LITERATURE REVIEW

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[1].

Finite Element analysis tools offer the tremendous advantage of enabling design teams to consider virtually any molding option without incurring the expense associated with manufacturing and machine time. The Ability to try new designs or concepts on the computer gives the opportunity to eliminate problems before beginning production. Additionally, designers can quickly and easily determine the sensitivity of specific molding Parameters on the quality and production of the final part. The leaf spring model is created by modeling software like pro-E , Catia and it is imported in to the analysis software and the loading, boundary conditions are given to the imported model and result are evaluated by post processor. [2]

Traditional leaf springs used in vehicles are made of mild steel, which is heavy in weight. A leaf spring of reduced weight, without compromising stiffness can increase the efficiency of vehicle. Hence, composites can be used as an alternative to traditional engineering materials for leaf spring the introduction of fibre reinforced plastics (FRP) made. It is possible to reduce the weight of a machine element without any reduction of the load carrying capacity. Because of FRP materials high elastic strain energy storage capacity and high strength to-weight ratio compared with those of steel, multi-leaf steel springs are being replaced by GFRP leaf springs. Composite leaf spring in the early 60 failed to yield the production facility because of inconsistent fatigue performance and absence of strong need for mass reduction. Particularly the automobile manufacturers and parts makers have been attempting to reduce the weight of the vehicles in recent years. Studies are made to demonstrate viability and potential of FRP in automotive structural application[3].

Composite materials consist of two or more physically dissimilar and instinctively separable components called reinforcement and matrix. These two components can be mixed in a restricted way to achieve optimum properties, which are superior to the properties of each individual component. Composite materials have been widely used in automobile industry because of its high strength and modulus to weight ratio, low cost and flexibility in material and structure design. 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. Since the strain energy in the spring is inversely proportional to density and young’s modulus of the material, it is always suggested that the material for leaf spring must have low density and modulus of elasticity. Many researches have been carried out in the direction to replace conventional steel leaf spring by composites[4].

In the present scenario, weight reduction has been the main focus of automobile manufactures. The suspension leaf spring is one of the potential items for weight reduction in automobiles as it accounts for ten to twenty percent of the unsprung weight, which is considered to be the mass not supported by the leaf spring. The introduction of composite materials made it possible to reduce the weight of the leaf spring without any reduction on the load carrying capacity and stiffness. Studies were conducted on the application of composite structures for automobile suspension system. A double tapered beam for automotive suspension leaf spring has been designed and optimized. Composite mono leaf spring has also been analyzed and optimized.

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[5].

Many industrial visits, past recorded data shows that steel leaf springs are manufactured by EN45, EN45A, 60Si7, EN47, 50Cr4V2, 55SiCr7 and 50CrMoCV4 etc. These materials are widely used for production of the parabolic leaf springs and conventional multi 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. Many suspension systems work on the same principle including conventional leaf springs. However, for the same load and shock absorbing performance, conventional (steel) leaf springs use excess of material making them considerably heavy. This can be improved by introducing composite materials in place of steel in the conventional spring[6].

The suspension system is to isolate the vehicle body from road shocks and vibrations. It must also keep the tires in contact with the road, regardless of road surface. A basic suspension system consists of springs, axles, shock absorbers, arms, rods, and ball joints. The spring is the flexible component of the suspension. Basic types are leaf springs, coil springs, and torsion bars. 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. Leaf springs are known as flat springs or laminated springs. Their lengths are generally reduced from first plate to last plate and all the plates are held together to act as a single spring by means of central to band, containing two U clips bolted at the centre. The centre of the arc provides location for the axle, while tie holes are provided at either end for attaching to the heavy vehicle body. Thus the leaf spring acts as a linkage for holding the axle in position and thus separate linkage are not necessary. It makes the construction simple and strong. The development of a light flex suspension leaf spring is first achieved. Based on consideration of chipping resistance base part resistance and fatigue resistance, a carbon glass fiber hybrid laminated spring is constructed. A general discussion on analysis and design of constant width, variable thickness, and composite leaf spring is presented. The fundamental characteristics of the double tapered FRP beam are evaluated for leaf spring application. Recent developments have been achieved in the field of materials improvement and quality assured for composite leaf springs based on microstructure mechanism [8].

III. PROBLEM STATEMENT AND OBJECTIVE

In automobiles, weights of the components play an important role in defining the efficiency of the vehicle. In this study we will optimize the weight of the leaf spring suspension while maintaining the strength and other mechanical properties. The leaf spring is designed for TATA ACE mini truck suspension using standard design procedures and the dimensions obtained are verified with the actual leaf spring used in the application. The designed leaf spring will be analyzed using ANSYS 16.2 software for the maximum and minimum stress regions. Then the leaf spring made of carbon fiber will be analysed and the reduction in the weight will be compared.

IV. THEORETICAL ANALYSIS

In this chapter we will calculate the dimensions required for the conventional steel and composite material carbon fiber leaf spring.

The gross vehicle weight of TATA ACE is 2250 kg from the manual. Therefore, we can say that on dividing the load on 4 wheels, each wheel carries a load of 562.5 kg.

The force acting on the wheel is 5625 N. Thus the leaf spring carries the load of 5625 N.

$$F = 5625\ N$$

A. Design of Conventional Leaf Spring:

The material for leaf spring is selected as 55Si2Mn90.

SUT = 1962 Mpa
SYT = 1470 Mpa
E = 200000 Mpa
Max. Deflection = 120 mm
Assuming Factor of Safety (FOS) = 2.25

Therefore allowable stress for bending,

$$\sigma allowable = \frac{Syt}{2.25}$$

$$\sigma allowable = 653\ MPa$$

From the bending equation for beam we get the following,

$$\sigma = \frac{6WL}{nb\,t^2}$$

Due to the packing constraints, we have to limit the width b, of the leaf spring to 60 mm and the number of leafs as 3. For the deflection of the leaf spring, we have the following equation.

$$\delta = \frac{WL^3}{EI}$$

Using the above equations, a DOE sheet is prepared as below.

TABLE I
DESIGN OF EXPERIMETNS FOR STEEL LEAF SPRING

Sr no	Width (b) mm	Thickness (t) mm	Number of leaves (n)	Load (W) N	Sigma (N/mm^2)	E (N/mm^2)	Maximum Delta (mm)	Length mm	Moment of Inertia (I)	Defelction (Delta) mm
1	60	1.5	3	5625	653	200000	120	313.44	27000	10.69
2	60	2.0	3	5625	653	200000	120	417.92	36000	19.01
3	60	2.5	3	5625	653	200000	120	522.40	45000	29.70
4	60	3.0	3	5625	653	200000	120	626.88	54000	42.77
5	60	3.5	3	5625	653	200000	120	731.36	63000	58.21
6	60	4.0	3	5625	653	200000	120	835.84	72000	76.03
7	60	4.5	3	5625	653	200000	120	940.32	81000	96.23
8	60	5.0	3	5625	653	200000	120	1044.80	90000	118.80
9	60	5.5	3	5625	653	200000	120	1149.28	99000	143.75
10	60	6.0	3	5625	653	200000	120	1253.76	108000	171.08

From the above Design of Experiments (DOE) table, we select the deflection closest to the maximum deflection. Therefore the thickness of the leaf spring is obtained as 5 mm and length of the spring is obtained as 1045 mm.

B. Design of Composite Spring:

For designing the mono composite material carbon fiber leaf spring, the same equations mentioned above for designing conventional leaf spring are used. In this case, the width of the leaf will be assumed as 60 mm to suffice the packing constraints. By varying the lengths of the leaf spring, we get the following DOE table. The properties of carbon fiber are:

SYT = 1125 Mpa
E = 50 Gpa
Width, b = 60 mm
Load, W = 5625 N

By using the above values, we get the following Design of Experiments.

TABLE II
DESIGN OF EXPERIMENTS FOR CARBON FIBER LEAF SPRING

Sr. No.	Width (b) mm	Length mm	Load (W) N	Sigma (N/mm^2)	E (N/mm^2)	Thickness (t) mm	Maximum Delta (mm)	Moment of Inertia (I)	Defelction (Delta) mm
1	60	500	5625	500	50000	23.7	120	66704	70.27
2	60	600	5625	500	50000	26.0	120	87685	92.38
3	60	650	5625	500	50000	27.0	120	98871	104.16
4	60	700	5625	500	50000	28.1	120	110496	116.41
5	60	800	5625	500	50000	30.0	120	135000	142.22
6	60	900	5625	500	50000	31.8	120	161088	169.71
7	60	950	5625	500	50000	32.7	120	174696	184.04
8	60	1000	5625	500	50000	33.5	120	188668	198.76
9	60	1050	5625	500	50000	34.4	120	202994	213.85
10	60	1100	5625	500	50000	35.2	120	217665	229.31

From the above DOE table, we select the carbon fiber leaf with 27 mm thickness and the length 650 mm.

V. FINITE ELEMENT ANALYSIS

We have performed FEA Analysis on multi leaf spring design finalized by DOE is performed for service load of 4625 N. As multiple leaves are to be used for the purpose of contacts generation solid shell element (solsh 190) is used for modelling. So that bending forces are accounted for and we get both the surfaces for the contacts. Results plots are as shown below.

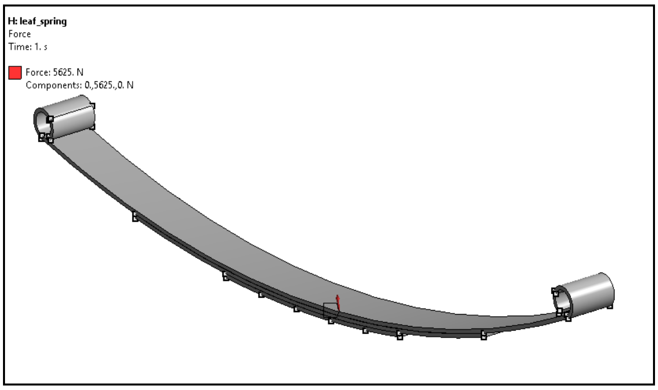

Fig.2. Loading for steel multi leaf spring

While building FEA model all components are modelled as solid model and Element type 185 is used for meshing them. Figure below shows the meshed model for the assembly. Standard element size of 1 mm is used for the good results in the analysis.

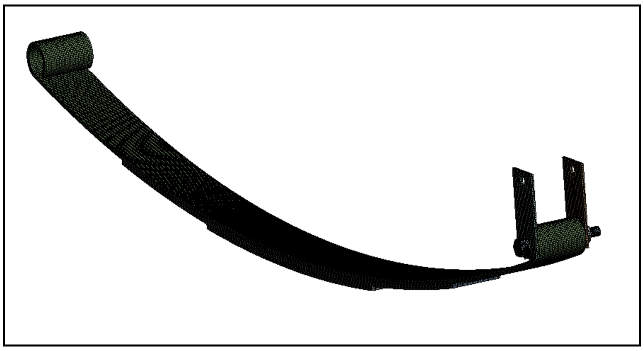

Fig.3. Meshed model of leaf spring

Modal analysis results for steel leaf spring results are shown for first 5 natural frequencies for the multi leaf spring made up of steel.

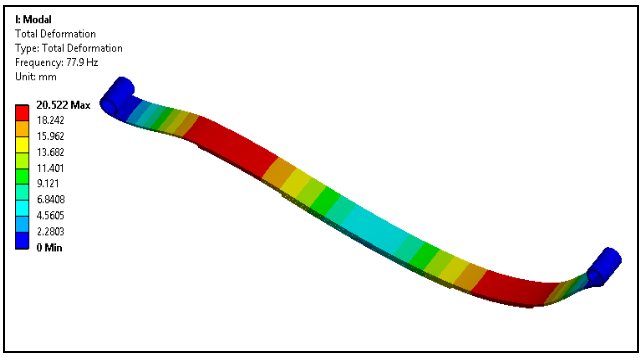

Fig.4. Mode shape plot 1 – 77.9 Hz

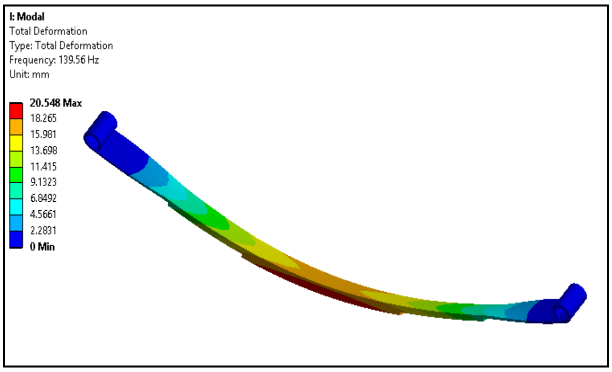

Fig.5. Mode Shape plot 2 – 139.6 Hz

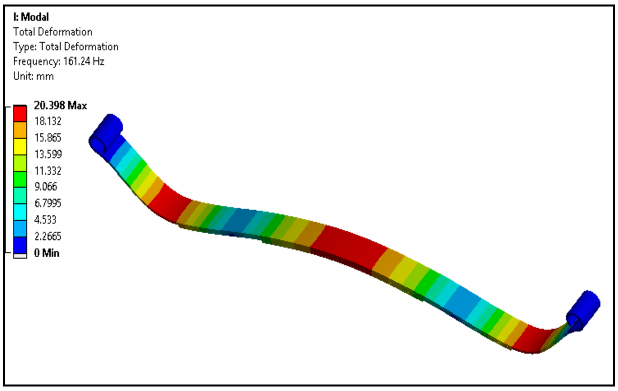

Fig.6. Mode Shape plot 3 – 161.24 Hz

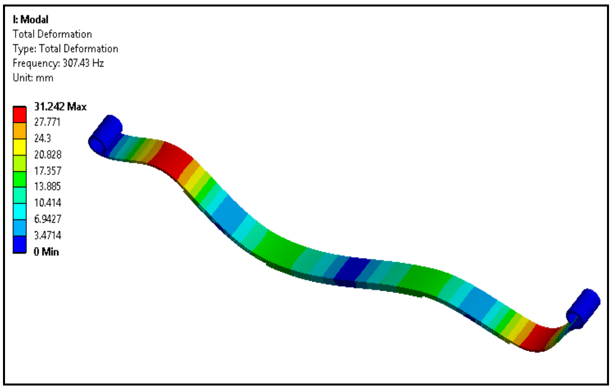

Fig.7. Mode Shape plot 4 – 307.4 Hz

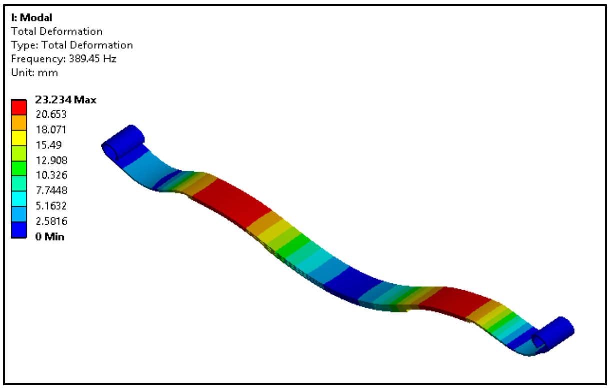

Fig.8. Mode Shape plot 5 – 389.5 Hz

We have performed FEA analysis on geometric model of composite leaf spring design selected from DOE sheet performed in the design chapter above. Shell element 181 type is used to mesh the model. Loading conditions, meshing and results images are shown below.

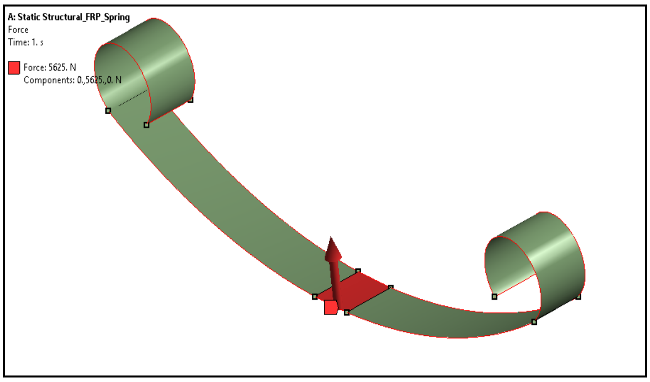

Fig.9. Carbon Fiber Leaf spring loading image

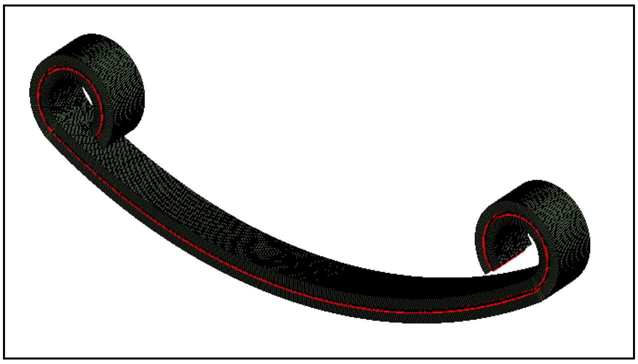

Fig.10. Meshed model of leaf spring

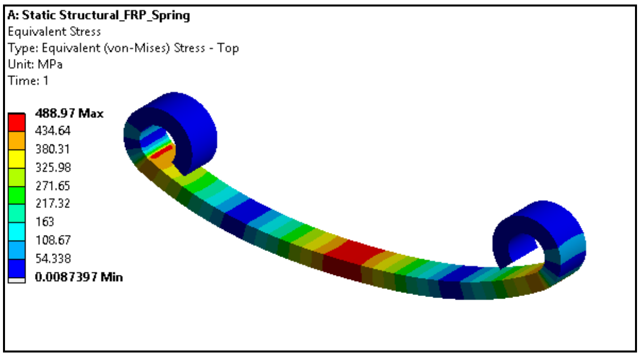

Fig.11. von Mises Stress plot for carbon fibre leaf spring

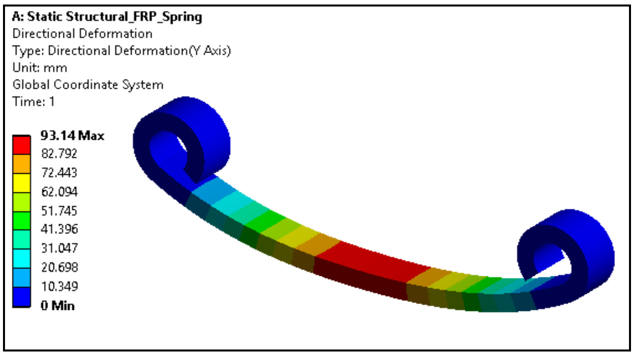

Fig.12. Deformation plot

Modal Analysis is performed on the same model to find out the first 5 natural frequencies of the suspension system. Results plots of mode shapes are shown in the images below. It should be noted that total deformation values in mode shape plots are not to be given any thought to as they are just mode shape plots representing the shape of the modal frequency deformation pattern. Both ends of the leaf spring are considered fixed while performing modal analysis as shown in the loading plot below.

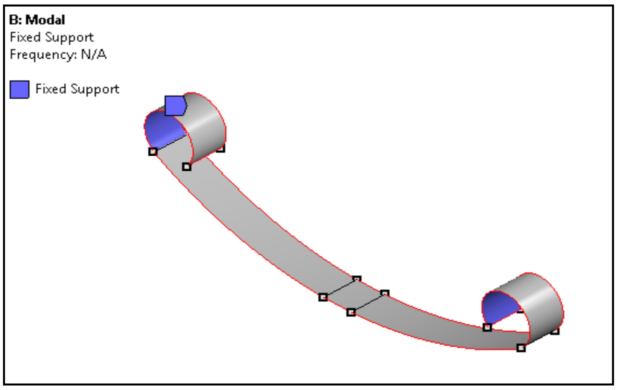

Fig.13. Boundary conditions plot for modal analysis

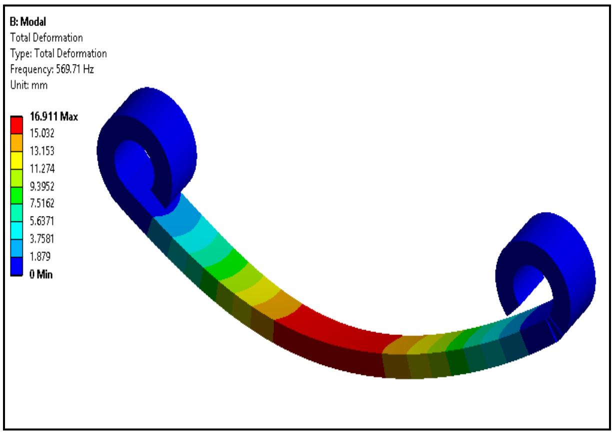

Fig.14. Mode shape 1 – 569.7 Hz

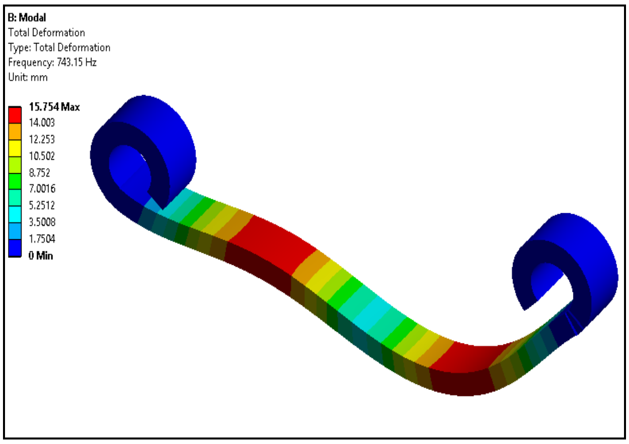

Fig.15. Mode shape 2 – 743.15 Hz

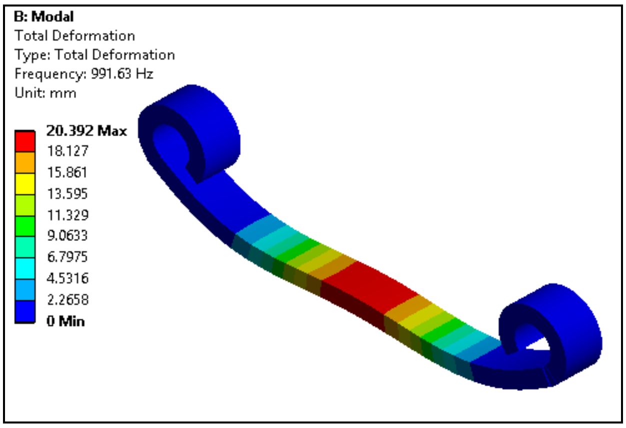

Fig.16. Mode Shape 3 – 991.6 Hz

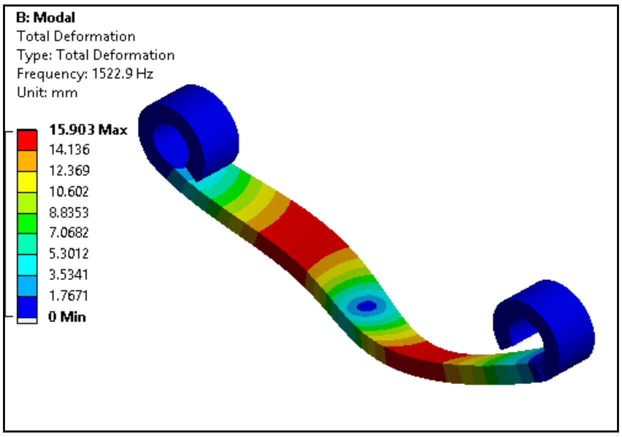

Fig.17. Mode Shape 4 – 1522.9 Hz

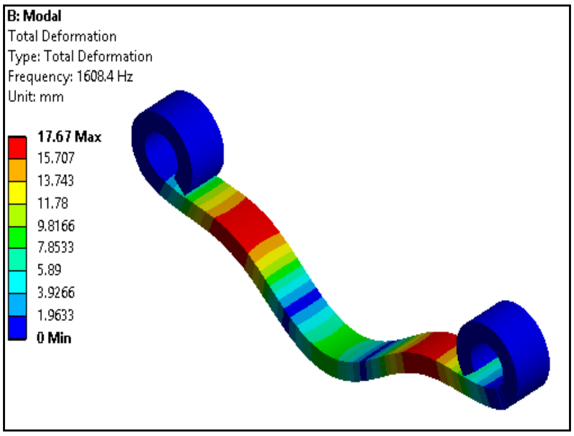

Fig.18. Mode Shape 5 – 1608.4 Hz

VI. RESULTS AND DISCUSSION

TABLE III
COMPARISON OF WEIGHT AND STRESS

Variable	Steel Leaf Spring	Carbon Fiber Leaf Spring
Weight	5.53	2.87
% Weight Reduction	-	48.16%
Maximum von Mises Stress FEA (MPa)	625.41	489
Total Deformation in Vertical Direction(mm)	106.02	93.14

TABLE IV
COMPARISON OF NATURAL FREQUENCIES

Mode Shape No	Frequency (Hz)	
	Steel Leaf Spring	Carbon Fiber Leaf Spring
1	77.9	569.71
2	139.56	743.15
3	161.24	991.63
4	307.43	1522.9
5	389.45	1608.4

VII. CONCLUSION

Total of 48.16 % weight reduction can be achieved by using carbon fiber as replacement material for steel leaf spring. All the stress and deformation values are within required limits for both conventional and composite leaf spring design. Frequency for carbon fiber leaf spring shows improved higher values due to high strength to weight ratio of the carbon fiber when compared with the steel leaf spring natural frequencies.

VIII. FUTURE SCOPE

We can compare other materials and their strength along with carbon fiber. Also, experimental testing of the studied design can be done.

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