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PERFORMANCE ANALYSIS OF LEAF SPRING BY CONTACT MECHANICS APPROACH BASED ON THE NATURE OF MATERIAL PROPERTIES

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Summary

In an automotive system, a curved leaf spring is used for the purpose of suspension and for reducing the transient vibration of the system. Composite materials are widely used in automobile industries as a replacement for steel to reduce the weight and to increase the strength of an automotive system. In this study, various materials have been considered for an analysis based on the Young modulus-to-yield strength ratio. The study has been carried out by considering the material properties. The contact analysis is performed with a curved beam of three leaves which is an equivalent to a semi-elliptical leaf spring used for an automotive suspension system. A comparison between analytical and simulation results shows that the material properties, such as the Young modulus and the yield strength, are very important in the design and development of a composite leaf spring. The composite material is compared with other materials, with the former showing good suspension function and better reliability.

Key words: *contact analysis, composite material, leaf spring, Young's Modulus, yield strength*

1. Introduction

In the current scenario, weight reduction is the main focus of automobile industries. A multi-leaf spring acts as a structural member carrying lateral loads, brake torque, driving torque in addition to shock absorbing. The springs are designed to absorb and store energy in order to release it slowly. 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. For a comfortable suspension system, the spring has an ability to store and absorb a large quantity of strain energy. In the weight reduction aspects, the composite leaf spring takes a major part of the automobile suspension system.

2. Literature Review

Leaf spring, one of the oldest suspension components, is still frequently used in commercial vehicles. The literature survey shows that leaf springs are designed as generalized force elements where the position, velocity and orientation of the axle mounting give reaction forces in the chassis attachment positions. Al-Qureshi [1] presented a general study on the analysis, design and fabrication of a composite leaf spring .He utilised a hand lay-up vacuum bag process for fabricating a composite leaf spring with variable thickness using fibre glass epoxy resin. Mahmood M. Shokrieh [2] analysed and optimised the design of a fibre glass epoxy resin composite leaf spring using the ANSYS V 5.4 software and concluded that the optimum spring width decreases hyperbolically and the thickness increases linearly from the spring eye towards the axle seat. Hou, *et al* [3] evolved the eye end design of a composite leaf spring for heavy axle loads by analysing there different designs of eye end attachments and found that in the first and the second design the delamination failure occurred at the interface of fibres that have passed around the eye and the spring body. The third design, i.e. the open eye end design, which was analysed, overcame the delaminating failure by ending the fibres at the end of the eye section. Mahdi et al [4] concluded that it is essential for the composites to control the failure by utilizing their strength in the principal direction instead of shear during suspension. Subramaninan [5] declared that in glass fibre-reinforced polypropylene leaf springs, the joint strength can be increased by decreasing the clearance between the fastener and the composite plate hole and that the endurance strength of the joint is higher than that of the leaf spring design load and this can be used to improve the strength of joints. Rahim et al [6] carried out a modal analysis of composite-based elliptic spring in structural mechanics to determine the natural shapes and frequencies of an object, or structure modes, and concluded that it is an alternative to solving the full set of equations for ‘n’ unknown displacements. Digambar et al [7] presented a static analysis of two conventional steel leaf springs made of SUP 10 & EN 45. These springs are compared with respect to maximum stress, deflection and stiffness. SUP 10 springs have lower values of maximum stress, deflection and stiffness in comparison to the 55 Si 2 Mn 90 spring. Ramakanth and Sowjanya [8] conducted the fatigue analysis on multi leaf springs (nine leaves) used by a commercial vehicle. Dara Ashok et al [9] presented the FE analysis of the leaf spring performed by the discretization of the model in infinite nodes and elements and refining them under a defined boundary condition. Vinkel Arora et al. [10] studied the CAE analysis of the leaf spring for various parameters like deflection, von-Mises stress, etc. This paper is to determine a better eye end design and to reduce the time and cost related to the actual experimental testing by providing a CAE solution. Nadargi et al [11] presented the performance evaluation of a leaf spring being replaced by a composite leaf spring. Compared to the steel spring, the composite spring has stresses that are much lower, the natural frequency is higher, and the spring weight is reduced by nearly 85 % with a bonded end joint and with a complete eye unit. Gebremeskel [12] presented the design and simulation of a composite leaf spring for lightweight three wheelers. The stresses are much below the strength properties of the material, satisfying the maximum stress failure criterion. The designed composite leaf spring has also achieved its acceptable fatigue life. Venkatesan and Devaraj [13] presented the design and analysis of composite leaf springs in light vehicles. Compared to the steel spring, the composite leaf spring is found to have 67.35% lower stress, 64.95% higher stiffness and 126.98% higher natural frequency than the existing steel leaf spring. A weight reduction of 76.4% is achieved by using the optimized composite leaf spring. In the present study, the contact analysis of a multi-leaf spring with three curved leaves, which is an equivalent to a solid triangle beam, is performed. The design and analysis have been made for both a solid triangle beam and a curved beam for different materials based on the E/Y ratio.

3. Material, design and analysis of a leaf spring

Initially, the leaf spring was considered as a single cantilever solid triangle beam having three leaf springs of uniform strength. Then, a curved beam of rectangular cross section is considered as an equivalent beam for a spring with three leaves. The analysis is carried out for a maximum load of 2000 N (equivalent for an experimental work). Different materials have been considered in the analysis. The E/Y ratios of the materials are listed in Table 1.

Table 1 E/Y ratios of the considered materials

No.	Materials	E/Y ratio
1	GFRP - D	34
2	GFRP - A	46
3	GFRP - C	53
4	GFRP - E	84
5	Titanium	138
6	C45 steel	552
7	304 Austenitic steel	975

3.1 Design of a cantilever solid triangle beam

The following specification of the leaf spring was considered for the design and analysis [14]. The master leaf which is 520 mm in length and the rest are graduated leaves of a length determined with respect to the width ‘b’.

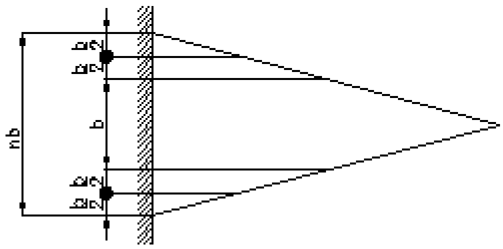

Fig. 1 Design parameters of a cantilever solid triangle beam

Fig. 1 shows the design parameters of a cantilever solid triangle beam which is an equivalent to a beam of uniform strength and a 3-beam model with three leaves. The bending stress and deflection of the beam are calculated from Equations (1) and (2).

$$\text{Bending stress, } \sigma_b = \frac{6PL}{nbt^3} \tag{1}$$

$$\text{Deflection, } y = \frac{6PL^3}{Enbt^3} \tag{2}$$

where,

Width of the spring,	b= 50 mm
Thickness of the spring,	t= 25 mm
Length of the cantilever beam (spring),	L= 520 mm
Number of leaves in the spring,	n= 3
Load,	P= 2000 N

3.2 FE analysis of a cantilever solid triangle beam

The modelling of a cantilever solid triangle beam that is equivalent to that of a spring with three leaves is carried out in Ansys V10 software by designing the co-ordinates. The element type selected is solid 45. The finite element model of cantilever solid triangle beam is shown in Fig.2. In this model, the master leaf is converged to a single node and the load step options are carried out at the free end of the spring. The boundary conditions are that all the deflection and rotations are arrested at the left end of the beam (fixed) and the beam is permitted to move in the vertical direction only. The load is applied at the converged point in the right side node.

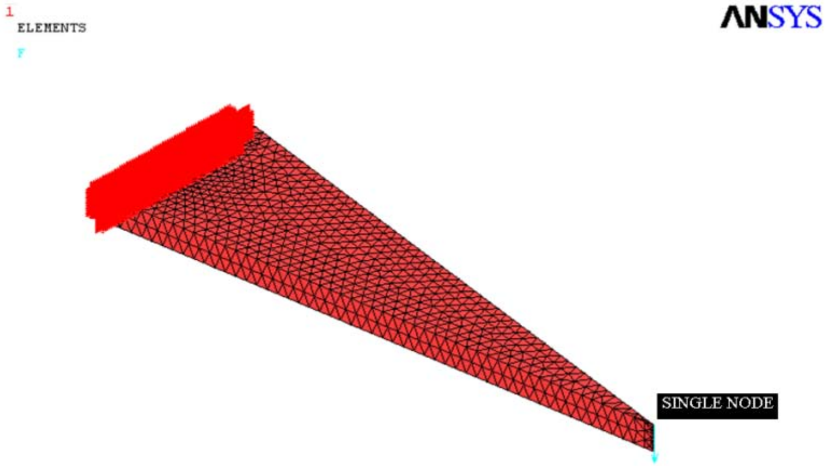

Fig. 2 FEA model of a cantilever solid triangular beam

3.2.1 Stress analysis

The stress analysis is carried out within the elastic limit. The base end of the triangle is fully constrained and the load of 2000N is applied at the single node. The bending stress induced in the cantilever solid triangle beam of C45 material in the X-direction is shown in Fig. 3. The magnitude of the cantilever solid triangle beam stress at the free end is 51 N/mm^2. The maximum bending stress is developed at the fixed end of the beam.

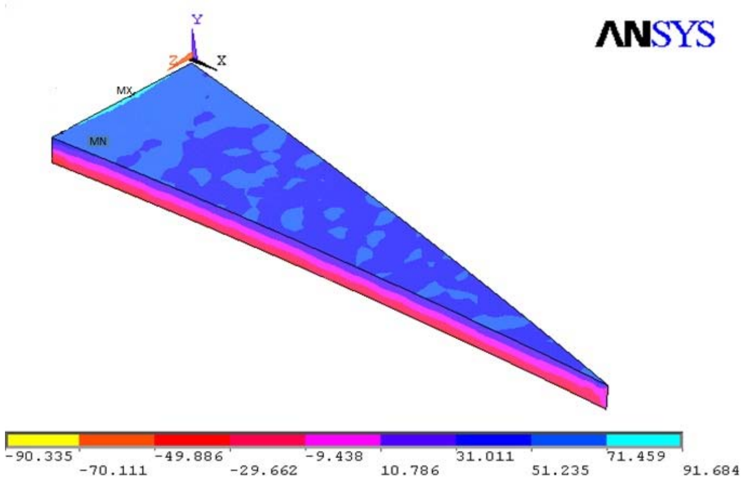

Fig. 3 Bending stress - cantilever solid triangular beam (N/ mm^2)

3.2.2 Deflection analysis

The deflection analysis is also carried out within the elastic limit. The base end of the triangle is fully constrained and the load of 2000N is applied at the single node. The displacement occurs in the Y-direction. The maximum displacement at the free end is 2.9 mm. The deflection of cantilever solid triangle beam for C45 steel is shown in Fig. 4.

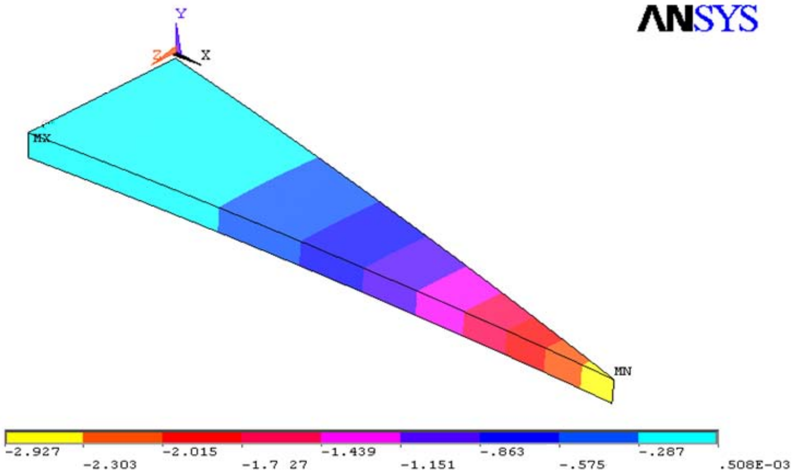

Fig. 4 Deflection - cantilever solid triangular beam (mm)

3.3 Contact analysis of a curved leaf spring

The 3-curved beam shows similar characteristics to those of springs with three leaves. In this design and modelling, the length of the master leaf is considered alone and the graduated leaf length is considered in the ratio of b/2. The contact area is created between two surfaces. The contact area is created between the master leaf (blue region) and the first graduated leaf (green region). Fig. 5 shows the contact creation between the master and the first graduated leaf.

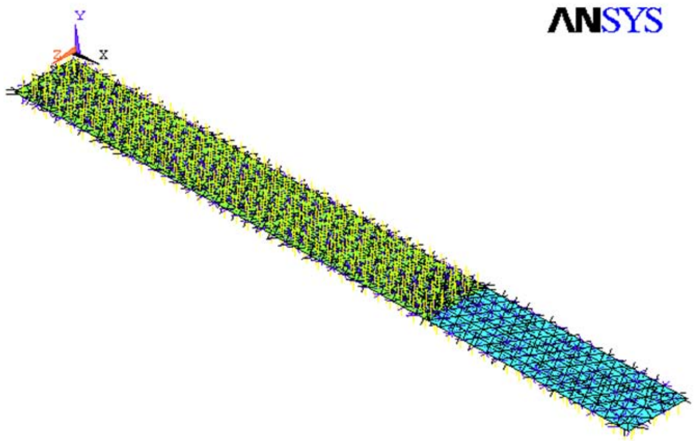

Fig. 5 The contact creation between the master and the first graduated leaf

The modelling of a cantilever curved beam equivalent is carried out in ANSYS V10 software by designing the co-ordinates. The element type selected is solid 45. The finite element model of the cantilever curved beam is shown in Fig.6. In this model, the master leaf is converged to a single node and the load step options are carried out at the free end of the spring. The boundary conditions determine that all the DOFs at the left end of the beam are fixed and the beam is permitted to move in the vertical direction only.

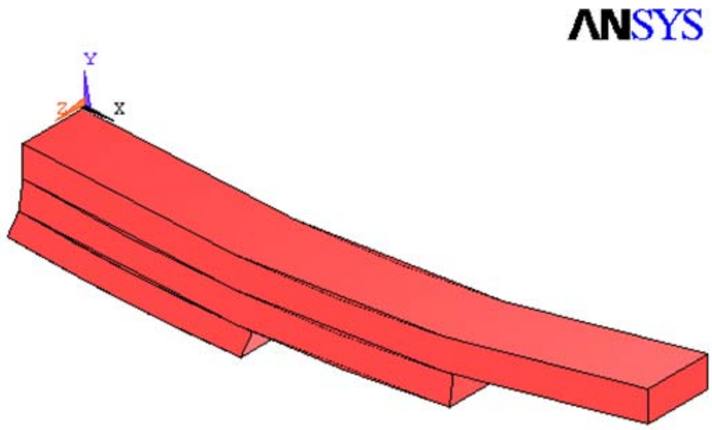

Fig. 6 Curved beam model

3.3.1 Analysis of contact stress for a 3-curved beam model

The Finite element contact analysis has been performed for a 3-curved beam at the load of 2000 N. The load is applied at the free end of the beam; the stress occurs between the two contact regions in the X-direction. Fig.7 shows the stress developed in the contact regions for the C45 material. The maximum stress developed is 76 N/mm^2.

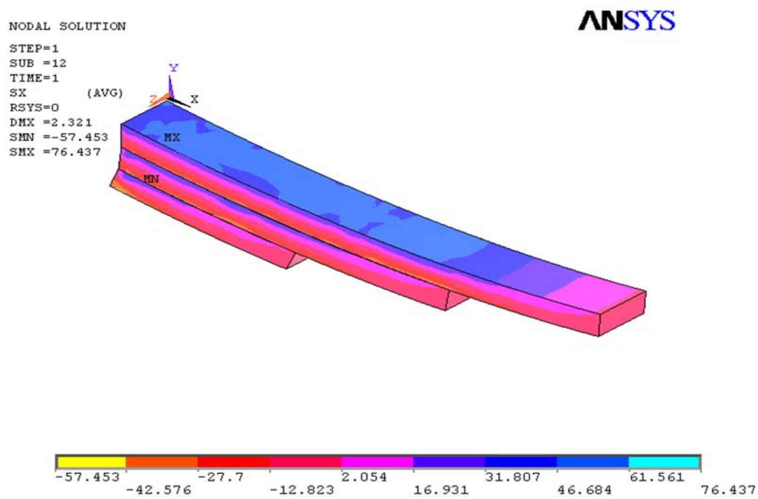

Fig. 7 Plot of the contact stress developed in the C45 material (N/ mm^2)

3.3.2 Analysis of displacement for a 3-curved beam model

The displacement analysis is performed in the 3-curved beam equivalent having three leaves. The displacement occurs in the Y-direction. The maximum displacement takes place at the free end of the beam. Fig. 8 shows the displacement plot of the spring with three leaves for the C45 material.

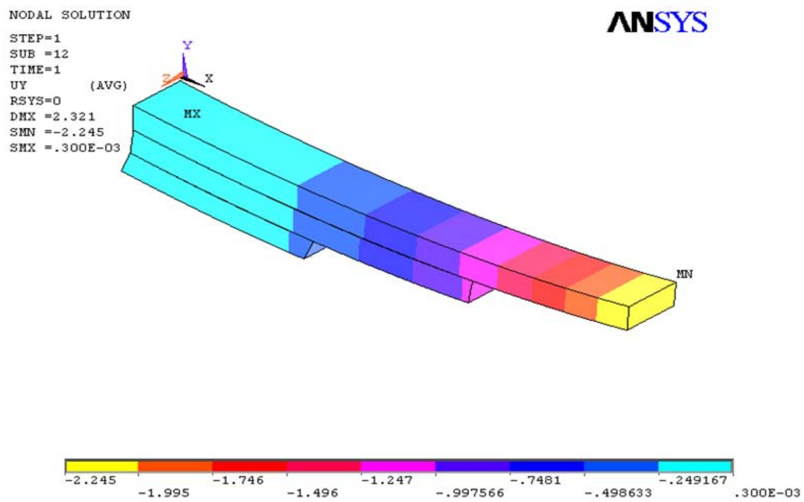

Fig. 8 Plot of the displacement for the C45 material (mm)

4. Results and discussion

The multi-leaf spring has been analysed in the following two cases: (i) By considering a spring with three leaves as a cantilever solid triangular beam. (ii) Spring considered with three leaves as a 3-curved beam with uniform rectangular cross section. The following are the results obtained from this analysis. The stress values of different materials in the analytical and the finite element analysis are calculated as shown in Table 2. The analytical values are calculated without considering the material properties. Hence the values are the same for all the materials. The value of 66 N/mm^2 is calculated from Equation 1. On the other hand, in the finite element analysis the material properties are considered.

Table 2 Stress for a cantilever solid triangle beam

No.	Material	Analytical –Stress N/mm^2	FEA - Stress N/mm^2
1	GFRP - D	66	62
2	GFRP - A	66	61
3	GFRP - C	66	67
4	GFRP - E	66	62
5	Titanium	66	59
6	C45 Steel	66	51
7	304 Austenitic (Aust)	66	59

Table 3 Displacement for a cantilever solid triangle beam

No.	Material	Analytical Displacement mm	FEA Displacement mm
1	GFRP - D	13.9	10.9
2	GFRP - A	10.4	8.1
3	GFRP - C	10.4	7.9
4	GFRP - E	9.9	7.7
5	Titanium	6.3	4.9
6	C45 Steel	3.4	2.9
7	304 Austenitic (Aust)	3.6	2.6

The displacement values of different materials in the analytical and the finite element analysis are calculated as shown in Table 3. The analytical displacement values are calculated from Equation 2.

Table 4 Stress and displacement for a 3- curved beam model

No.	Material	FEA - Stress N/mm^2	FEA -Displacement mm
1	GFRP - D	68.6	9.5
2	GFRP - A	53.9	7.0
3	GFRP - C	57.9	6.9
4	GFRP - E	54.5	6.7
5	Titanium	53.2	4.3
6	C45 Steel	61.6	2.2
7	304 Austenitic (Aust)	68.2	2.2

Table 4 shows, the stress and the displacement value for different materials in the finite element analysis of a curved beam model. The material GFRP - D gives maximum stress and displacement compared with the rest of materials.

5. Experimental analysis of a curved leaf spring

In the experimental analysis of a curved leaf spring, a special attachment was made with a tensile testing machine, as shown in Fig.9.

Fig. 9 Tensile testing machine

The load is applied to the eye piece by lifting the bottom jaw with a suitable arrangement. The C45 material is chosen for the experimental work. The applied force is measured by a load dial gauge and deflection is measured for different loads at a maximum of 2000 N. The stress obtained at the free end of a curved beam by using FEM is validated by experimental analysis and is given in Table 5.

Table 5 Stress and deformation in the FEM and the experimental analysis

Analysis	Stress at free end N/mm^2	Deflection at free end mm
FEM analysis (1) (Cantilever curved beam)	61.6	2.2
Experimental analysis (2)	59	2.1
Percentage deviation {(1)- (2) / (1)}	4.2	4.5

6. Conclusion

The analysis has been carried out by considering the material properties for the cantilever triangle beam and the spring with three curved leaves model. The stress and deflection are computed for both models analytically and by using the finite element simulation. The results obtained from the simulation are compared with the results of experimental work. It is noted that the deviation of FEA results is almost negligible compared to the experimental results. The results also show that the composite material GFRP gives maximum stress and deflection in both models. It is concluded that the composite material is suitable for high loading capacity compared with that of the rest of materials considered in the analysis. It is also concluded that the contact mechanics approach is suitable for analysing contact pairs made of composite material.

Nomenclature

b	-	Width of the leaf spring	mm
t	-	Thickness of the leaf	mm
L	-	Length of the cantilever beam (Spring)	mm
n	-	Number of leaves in the spring	-
σ_b	-	Bending stress	N/mm^2
y	-	Deflection of spring	mm
P	-	Load applied	N
Y	-	Yield strength	N/mm^2
E	-	Young's modulus	N/mm^2
E/Y	-	Young's modulus-to-yield strength ratio	-
GFRP	-	Glass fibre-reinforced polymer	-

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