Stress, Deformation and Failure Analysis of Parabolic Leaf Spring by Finite Element Analysis with Material Optimization

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Abstract. A leaf spring is a simple form of spring commonly used for the suspension system in heavy duty vehicles which is originally called laminated or carriage spring. It performs the isolation task in transferring the vibration due to road irregularities to the passenger’s body or goods transported on it. The advantage of leaf spring over helical spring is that the ends of the spring have been guided along a definite path as it deflect to act as a structural member in addition to an energy absorbing device. Increasing competition and innovations in the automobile sector, tends to modify the existing products with new or advanced material products. To improve the performance of the suspension system, many modifications have been taken place overtime but the recent innovations imply parabolic leaf spring and application of composite materials, as the composite materials have high strength-to-weight ratio compared to the conventional steels. The present work attempts to analyze the comparison between the conventional steel (AISI1030) leaf spring and the composite (Carbon/Epoxy) leaf spring with respect to static and fatigue analysis. Here static analysis determines the safe stress, deformation and corresponding pay load and also studies the behavior of structures under practical conditions. The research also focuses on fatigue analysis to determine its life cycle and also to observe its fatigue failure characteristics. The model of the leaf spring has been carried out into the CAD software. The analysis of the steel leaf spring has been divided into theoretical, experimental and simulation sections .The simulation of steel leaf spring has been validated with the theoretical and the experimental results. Further simulation has been done for composite leaf spring by FEA software. Finally, the result shows that the composite leaf spring has better load carrying capacity in reduced weight, and better fatigue behavior rather than the conventional steel material for the leaf spring.

1. Introduction

The main focus of the present automobile manufacturer has been the weight reduction due to conservation of natural resources, emission gas regulation and economization of energy. The main approach of the weight reduction can be achieved by design optimization, introduction of better material and better manufacturing process [4]. Leaf spring is the simple form of spring commonly for the suspension system.
of the vehicle. It is one of the potential items for weight reduction in the automobiles as it accounts for ten to twenty percent of the un-sprung weight. 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 [3]. Generally the capacity of absorbing strain energy, makes the suspension system more comfortable. So the strain energy plays a vital role in designing the suspension system. Besides the introduction of composite materials have made it possible to reduce the weight of the leaf spring without any reduction of stiffness and load carrying capacity.

Figure 1. Leaf spring.

2. Experimental Analysis

Table 1. Dimension for the specimen leaf spring

| Parameter                        | Dimension (mm) |
|----------------------------------|----------------|
| Length of the Span               | 581            |
| Number of Full length Leaves     | 2              |
| Number of Graduated Leaves       | 4              |
| Length of the Master Leaf        | 596            |
| Thickness of the Leaf            | 6              |
| Width of the Leaf                | 49.6           |
| Height of Camber Profile         | 79             |

The experiment has been done in a Universal Testing machine. Load has been applied on the center of the leaf spring. The range of operating load for this spring is 1800 N-2200 N.

Figure 2. UTM machine.  
Figure 3. Experimental Setup for Leaf spring.

Table 2. Deformation of the steel leaf spring

| Load (N) | Deformation (mm) |
|----------|------------------|
| 543      | 2.69             |
| 1033     | 5.12             |
| 1542     | 7.65             |
| 2200     | 10.91            |
| 2544     | 12.59            |
The chemical composition test for the specimen leaf spring has been done. From the result of the test, specimen is a medium carbon steel (Grade AISI 1030).

| Element in Leaf spring | % of Element (standard) | % of Element (obtained) |
|------------------------|-------------------------|-------------------------|
| Carbon                 | 0.28-0.34               | 0.310                   |
| Manganese             | 0.60-0.90               | 0.731                   |
| Phosphorous           | 0.04 (max)              | 0.012                   |
| Sulfur                | 0.05 (max)              | 0.012                   |

3. Analytical Stress and Deformation for Steel Leaf Spring

The bending stress and deformation of the leaf spring is calculated using following equations,

\[
s_F = \frac{6WL}{n_Fbt^2} = \frac{6L}{n_Fbt^2} \left( \frac{3n_F}{2n_G + 3n_F} \right) W = \frac{18WL}{bt^2(2n_G + 3n_F)}
\]

As, \( \sigma_F = \frac{3}{2} \sigma_G \) \( \text{(1)} \)

Bending stress for the graduated leaves,

\[
\sigma_G = \frac{2}{3} \sigma_F = \frac{2}{3} \times \frac{18WL}{bt^2(2n_G + 3n_F)} = \frac{12WL}{bt^2(2n_G + 3n_F)} \text{ \( \text{(2)} \)}
\]

Total bending stress,

\[
\sigma = \sigma_F + \sigma_G \text{ \( \text{(3)} \)}
\]

Deformation,

\[
\delta = \frac{12WL^3}{Et^3(2n_G + 3n_F)} \text{ \( \text{(4)} \)}
\]

Where, \((t = \text{thickness of the leaf}, b=\text{width of the leaf}, L=\text{length of the leaf}, E=\text{modulus of elasticity}, W=\text{load applied on the spring}, n_F = \text{number of full length leaves}, n_G = \text{number of graduated leaves})\)

Now, for the operating load 2200 N, \( W= 2200/2 = 1100 \text{ N} \), effective length \( L = 581 \text{ mm} \), width \( b = 49.6 \text{ mm} \), thickness \( t = 6 \text{ mm} \), modulus of elasticity \( E= 200 \text{ GPa} \), number of full length leaves, \( n_F = 2 \), number of graduated leaves, \( n_G = 4 \)

Putting these values in equation (1), stress for full length leaves, \( \sigma_F = 232.90 \text{ MPa} \)

And from equation (2), stress for graduated leaves, \( \sigma_G = 155.26 \text{ MPa} \)

So, total bending stress, \( \sigma = \sigma_F + \sigma_G = 232.90 + 155.26 = 388.16 \text{ MPa} \)

And from equation (3), deformation, \( \delta = 10.91 \text{ mm} \)

4. FEA Analysis of Leaf spring

The modeling of leaf spring has been done from the dimensions of experimental specimen leaf spring in
the SOLIDWORKS 2017.

**Figure 5.** Modeling of Leaf spring.

The FEA analysis has been done in simulation software ANSYS workbench 17.1 for the AISI 1030 steel leaf spring and also for the Carbon Epoxy composite leaf spring.

**Table 4.** Material properties of existing leaf spring (AISI 1030).

| Parameter                     | Value  |
|-------------------------------|--------|
| Young’s Modulus (E)           | 200 GPa|
| Poisson’s Ratio               | 0.29   |
| Tensile Strength Ultimate     | 586 MPa|
| Tensile Strength Yield        | 441 MPa|
| Density                       | 7850 kg/m³|

**Table 5.** Mechanical properties of Carbon Epoxy.

| Properties                        | Value  |
|-----------------------------------|--------|
| Tensile modulus along X-direction (Ex) | 121000 MPa |
| Tensile modulus along Y-direction (Ey) | 8600 MPa |
| Tensile modulus along Z-direction (Ez) | 8600 MPa |
| Shear modulus along XY-direction (Gxy) | 4700 MPa |
| Shear modulus along YZ-direction (Gyz) | 3100 MPa |
| Shear modulus along ZX-direction (Gzx) | 4700 MPa |
| Poisson ratio along XY-direction (PRxy) | 0.27 |
| Poisson ratio along YZ-direction (PRyz) | 0.40 |
| Poisson ratio along ZX-direction (PRzx) | 0.27 |
| Density                           | 1490 kg/m³ |

After importing the assembly file from SOLIDWORKS 2017 into ANSYS Workbench 17.1, proper boundary conditions have been applied as the one eye as a fixed support and the other eye can translate in the X direction only. The operating load 2200 N has been applied at the center of the spring. The failure analysis has been done with fully reversed load of 2200 N.

The maximum von mises stress has generated in (AISI 1030) steel leaf spring 389.8 MPa.

**Figure 6.** Von mises stress in steel leaf spring.
The maximum deformation has been obtained 8.62 mm.

![Figure 7. Deformation of steel leaf spring.](image1)

The maximum strain energy has been obtained 13.96 MJ.

![Figure 8. Strain energy of steel leaf spring.](image2)

The minimum life cycle of the steel leaf spring has been obtained 95966.

![Figure 9. Life Cycle of steel leaf spring.](image3)

The maximum von mises stress has generated in Carbon Epoxy leaf spring 106.66 MPa. And the maximum deformation has been obtained 2.32 mm.

![Figure 10. Von mises stress in composite leaf spring.](image4)

![Figure 11. Deformation of composite leaf spring.](image5)

The maximum strain energy has been obtained 7.56 MJ.

![Figure 12. Strain energy of composite leaf spring.](image6)
The Minimum life cycle of the composite leaf spring has been obtained 10000000.

![Figure 13. Life cycle of composite leaf spring.](image)

5. Results and Discussion
The stress and deformation analysis of the Steel leaf spring has been done by analytical, experimental and simulation sections. The validation of the results has been shown in Table 6 and Table 7.

| Load (N) | Stress (MPa) | Stress (MPa) | Stress (MPa) | Variation (%) | Variation (%) | Variation (%) |
|---------|--------------|--------------|--------------|---------------|---------------|---------------|
|         | (Analytical) | (Experimental) | (Simulation) | (Analytical vs. Experimental) | (Analytical vs. Simulation) | (Experimental vs. Simulation) |
| 543     | 95.8         | 84.01        | 96.2         | 12.30         | 0.41          | 14.51         |
| 1033    | 182.26       | 165.67       | 183.03       | 9.10          | 0.42          | 10.47         |
| 1542    | 272.07       | 254.55       | 273.21       | 6.43          | 0.41          | 7.3           |
| 2200    | 388.16       | 390.85       | 389.80       | 0.68          | 0.42          | 0.27          |

Table 7. Validation of Deformation.

| Load (N) | Deformation (mm) | Deformation (mm) | Deformation (mm) | Variation (%) | Variation (%) | Variation (%) |
|---------|------------------|------------------|------------------|---------------|---------------|---------------|
|         | (Analytical)     | (Experimental)   | (Simulation)     | (Analytical vs. Experimental) | (Analytical vs. Simulation) | (Experimental vs. Simulation) |
| 543     | 2.69             | 2.36             | 2.12             | 12.26         | 21.18         | 10.16         |
| 1033    | 5.12             | 4.66             | 4.05             | 8.98          | 20.89         | 13.09         |
| 1542    | 7.65             | 7.16             | 6.04             | 6.27          | 20.89         | 15.76         |
| 2200    | 10.91            | 11.01            | 8.62             | 0.91          | 20.98         | 21.70         |

Table 8. Comparison between Steel and Composite leaf Spring.

| Material       | Stress (MPa) | Deformation (mm) | Stiffness (N/mm) | Minimum Life Cycle | Strain Energy (MJ) | Weight (kg) |
|----------------|--------------|------------------|------------------|--------------------|--------------------|-------------|
| AISI 1030 Steel | 389.80       | 8.62             | 255.22           | 95966              | 13.96              | 7.01        |
| Carbon Epoxy    | 106.66       | 2.32             | 948.27           | 10000000           | 7.56               | 1.14        |

![Figure 14. Comparison of Stress.](image)

Carbon Epoxy composite leaf spring generates 72.65% less stress compared to steel leaf spring.

![Figure 15. Comparison of deformation.](image)

Deformation for the Carbon Epoxy leaf spring is 73% lower than the steel leaf spring.
Figure 16. Comparison of Strain Energy.
Strain energy for the composite leaf spring is 45.8% lesser than the steel leaf spring.

Figure 17. Comparison of weight.
Weight of composite leaf is 83.73% lesser than the steel leaf spring.

The main objective of this research work is to study the stress, deformation and the failure analysis of an existing steel (AISI1030) leaf spring by analytical, experimental and simulation method, and also to compare it with the composite (Carbon Epoxy) leaf spring. From the static analysis it has been obtained that the maximum stress has generated in the master leaf near the eye of fixed end. For an operating load 2200N, results has been validated by analytical, experimental and simulation process with slight deviation. The stress variation for the analytical, experimental and simulation are 388.16 MPa, 390.85 MPa and 389.80 MPa respectively. And the variation for the deformation are 10.91 mm, 11.01 mm and 8.62 mm respectively. The failure analysis of these models have been done by finite element method in the ANSYS 17.1 for fully reversed load of 2200 N. From the fatigue analysis it has been obtained that the maximum probability for the crack initiation is on the master leaf near the eye of fixed end. The life cycle for the composite leaf spring has been obtained $10^7$ cycles and for the steel leaf spring 95966 cycles.

6. Conclusion
From this research it can be concluded that with respect to, load carrying capacity and longevity the composite (Carbon Epoxy) leaf spring will ensure a better performance in all aspects compared to AISI 1030 steel leaf spring for the same dimensions and for the same load, in reduced weight.

7. References
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