Fatigue life of composite leaf spring assembly

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ABSTRACT: Suspension system in automobiles plays a major role in observing the shock loads which are result from the rough road, collision and vibrations. Leaf springs are one of the major suspension systems in heavy vehicles which are responsible for observing the shock loads and heavy loads. Most of the times under dynamic loads, these leaf springs experience fatigue failure with low life cycles. It is important to study the behaviour of leaf springs under dynamic conditions with respect to static loads. In the present study, a heavy vehicle leaf spring is designed and to be analyzed under dynamic loads i.e., fully reversed loads, zero based loads and fluctuating loads [ratio of -0.5 and 0.5] using composite material (Carbon Fiber reinforced polymer composite). A total of 3 models of leaf springs with varying leaf lengths and leaf thickness are modeled in FEA software i.e., ANSYS Workbench. From the static structural analysis, it is observed that Model 3 having fewer stresses compared to the remaining models. The results with Leaf spring with 15mm thickness shows that better strength and stiffness properties when compared to the Leaf Spring with 12 mm thickness. From the fatigue life hand calculations, it is observed that Model 3 having the highest life cycles stresses compared to the remaining models.

Keywords: Finite Element Method, Constant Amplitude, Leaf Spring, Fully Reversed Load, Zero Based Load, Fluctuating Loads, Static Structural Analysis.

1. Introduction

Fatigue is a failure that comes with dynamic loading conditions. Fatigue failure is mainly 2 types based on loading and life cycles. There are two types of fatigue life calculation approaches. They are high cycle fatigue and low cycle fatigue. If the structure fails above the 1000 cycles, this type of failure comes under High cycle fatigue. For high cycle fatigue, SN curve is used for the life calculations. Structural Life, Aerospace structures and bridges are such common examples of High cycle Fatigue. The high cycle fatigue mainly depends on the SN curve whereas stress values are noted in the curve versus the number of life cycles. If the life of the structure falls in between 1 to 1000 cycles, this type of fatigue failure is called the Low Cycle Fatigue. The Low cycle fatigue mainly depends on the cyclic stress strain curve for respective materials. For the Low cycle fatigue, cyclic stress strain curve is used for life calculations.

If the load varies between +P to –P is called a fully reversed load, if the load varies between 0 to P is called Zero based load and if the load varies between +P/2 to +P or –P/2 to -P or –P/2 to -P are called fluctuating loads which are shown in Figure 1.0.
There are 5 types of Leaf Springs in the industry; they are elliptic, semi elliptic, three Quarter elliptic, quarter elliptic and transverse. T G Loganathan [1] performed work on leaf springs and kept focus of study in terms of material change from the conventional SAE 5160 steel to CFRP. The present work provides the results of flexural fatigue life and damage incurred for both the material by FE Analysis. Navuri Karteek [2] performed fatigue analysis on the different shapes of alloy wheel under constant amplitude loading. The material parametric study is also performed on the different cases of the spokes. The results show that the carbon steel has shown better results when compared to remaining materials in view of life, damage and factor of safety. Navuri Karteek [3] performed different types of static structural analysis i.e., Radial load case, impact load case, bending load case, torsion load case and maximum deflection case on four different alloy wheels. The induced stresses and deformations are within the limits. M. Saran Theja [4] presented a research article on Structural and Fatigue Analysis of Two Wheeler Lighter Weight Alloy Wheel. The present work attempts to analyse the safe load of the alloy wheel, which will indicate the safe drive is possible. Sahil Bandral [5] performed impact analysis on the four wheeler alloy wheel and calculated the stresses by varying the number of spokes. He concluded 3 spoke alloy wheel shows better results. Anusha R [6] performed static and impact analysis on the four wheeler alloy wheel and calculated the stresses and deformations. Later performed weight optimization and reduced the weight by 20%.

2. Problem Description
2.1 Problem Statement:
To perform Static structural analysis on the leaf spring assembly with realistic loads and boundary conditions using 3D FEA and to verify the design of leaf spring components in strength point of view and to calculate the fatigue life under static loads.

2.2 Geometry:
The 3D model of the leaf spring which are used for the present analysis is taken from the Heavy Vehicle Bus (Ashok Leyland- Ms355) and it is shown in the below figure. The dimensions of the leaf spring are also shown in the below figures. The main full-length leaf is 1480 and Leaf Spring [Model 1] is shown in the below figure 2.0.
The width and thickness of the leaf spring are 75 mm and 15 mm. The Graduated decreased leaf’s or supporting leafs are used for the leaf spring system to providing extra support for the main leaf springs and the dimensions are listed below. 

$L_1 = 1480 \text{ mm}$, $L_2 = 1380 \text{ mm}$, $L_3 = 1380 \text{ mm}$, $L_4 = 1280 \text{ mm}$, $L_5 = 1180 \text{ mm}$, $L_6 = 1080 \text{ mm}$, $L_7 = 980 \text{ mm}$, $L_8 = 980 \text{ mm}$, $L_9 = 780 \text{ mm}$, $L_{10} = 680 \text{ mm}$, $L_{11} = 580 \text{ mm}$, $L_{12} = 480 \text{ mm}$, $L_{13} = 380 \text{ mm}$ and $L_{14} = 280 \text{ mm}$.

The leaf spring assembly [Model 2] comprises of 14 leaf springs, as same as the previous master model 1. The geometry of the leaf spring assembly [model 2] is shown in the below figure 3.0.

![Figure 3 Leaf Spring [Model 2]](image)

The Graduated decreased leaf’s or supporting leafs are used for the leaf spring system to providing extra support for the main leaf springs and the dimensions are listed below. 

$L_1 = 1480 \text{ mm}$, $L_2 = 1380 \text{ mm}$, $L_3 = 1380 \text{ mm}$, $L_4 = 1280 \text{ mm}$, $L_5 = 1280 \text{ mm}$, $L_6 = 980 \text{ mm}$, $L_7 = 980 \text{ mm}$, $L_8 = 980 \text{ mm}$, $L_9 = 680 \text{ mm}$, $L_{10} = 680 \text{ mm}$, $L_{11} = 580 \text{ mm}$, $L_{12} = 580 \text{ mm}$, $L_{13} = 280 \text{ mm}$ and $L_{14} = 280 \text{ mm}$.

The leaf spring assembly [Model 3] comprises of 14 leaf springs, as same as the previous model 1 and 2. The geometry of the leaf spring assembly [model 3] is shown in the below figure 4.0.

![Figure 4 Leaf Spring [Model 3]](image)

2.3 Connections:
Here two types of contacts are used for this analysis i.e., Bonded contact and frictional contact with material coefficient of friction is assumed to be as 0.2. The connection details are listed in the below Table 1.
### Table 1 Connections details

| S. No | Contact | Target | Type             |
|-------|---------|--------|------------------|
| 1     | Leaf    | Leaf   | Frictional Contact |
| 2     | Leaf    | Bolt/Nut | Frictional Contact |
| 3     | Bolt    | Nut    | Bonded Contact   |

#### 2.4 Mesh:

Meshing is the process of converting geometry entities into finite elements and nodes. The meshed model of the leaf spring assembly is shown in the below figure. Hexahedron element [Solid 186] is used for the supporting leafs where there is no complicity in nature. Tetrahedron element [Solid 187] is used for the main leaf spring due to curved profile.

#### 2.5 Loads & Boundary Conditions:

Here the total mass of the vehicle (Curb) = 4000 kg, additional passengers’ mass = 3000 kg. Therefore, the final force which is acting on the bottom leaf is

\[ F = m.a = 7000 \times 9.81 = 68670 \text{ N} \]

For Each Spring, \( F = 68670/4 \text{ N} = 17167.5 \text{ N} \)

![Figure 5. Force acting on the Leaf Spring Assembly](image)

A bolt pretension (P) of magnitude 16666 N is applied on the bolt outer surface. The eyes of the main full length leaf are arrested with respect to the realistic working conditions. The figure of the leaf spring with 2 remote displacements are shown in the below figure. The left eye of the main full length leaf is arrested in translation in X, Y, Z direction and rotation also arrested about X and Y except rotation about Z is free. The right eye of the main full length leaf is arrested translation in Y, Z direction and rotation about X and Y. Translation in X direction and Rotation about Z direction are free. The displacement of the leaf springs (Full length and supporting leaf’s) and bolt are arrested width direction.
3. Static Structural Analysis

The assembly of leaf spring assembly is assigned with the carbon fiber reinforced polymer composite. The properties of the composite material are taken from the article [1]. The isotropic properties of the carbon fiber and epoxy resin are listed in the below table 2.

| Properties        | Carbon Fiber | Epoxy Resin |
|-------------------|--------------|-------------|
| Density           | 1800 Kg/m³   | 1400 Kg/m³ |
| Young’s Modulus   | 23000 MPa    | 10500 MPa   |
| Poisson’s Ratio   | 0.4          | 0.3         |
| Tensile Strength  | 300 MPa      | 850 MPa     |
| Bulk Modulus      | 500 MPa      | 333 MPa     |
| Shear Modulus     | 900 MPa      | 125 MPa     |
| Volume Fraction   | 0.5          | 0.5         |

The carbon fiber and epoxy resin are mixed together to form a lamina and that lamina are stacked together with different orientations to form a 3D laminate which having equal properties in X, Y and Z directions. The lamina thickness and number of lamina’s with orientations are selected depend upon the research article [1]. The 3D laminate properties of the carbon epoxy with volume fraction 50-50 is listed in the below table 3.

| Property | Value |
|----------|-------|
| E_{11}   | 23000 MPa |
| μ_{12}   | 0.2 |
| G_{xy}   | 9000 MPa |
| E_{12}   | 23000 MPa |
| μ_{23}   | 0.4 |
| G_{yz}   | 8214 MPa |
| E_{13}   | 23000 MPa |
| μ_{31}   | 0.2 |
| G_{xz}   | 9000 MPa |
| ρ       | 1800 Kg/m³ |
| σ_{yt}   | 300 MPa |
| σ_{yc}   | 285 MPa |
| σ_{ut}   | 600 MPa |
| σ_{uc}   | 300 MPa |

The fatigue properties of the 3D CFRP composite under fully reversed rotating beam fatigue test are listed in the below table 4.

| Stress (S) | Number of cycles (N) |
|-----------|----------------------|
| 800       | 200                  |
| 700       | 3200                 |
| 600       | 25,000               |
| 500       | 1.227e5              |
| 400       | 4.509e5              |
| 300       | 1.3548e6             |
| 200       | 3.5155e6             |
| 100       | 8.1435e6             |
**Note:** For static structural analysis of the composite leaf spring assembly, cylindrical co-ordinate system is assigned to the leaf spring for element orientation. Longitudinal direction is assigned with width direction, circumferential direction is assigned with curved Length direction and radial direction is assigned with thickness direction. The calculated von-misses stresses and von-misses strains of the leaf spring [Model 1] are shown in the below figure 6.

![Figure 6. Von-misses stress of the CFRP Composite Leaf Spring Assembly](image)

The calculated values of the von-misses stresses and von-misses strain of the leaf spring with CFRP Composite for Model 1, 2 and 3 are listed in the below table 5.

| Component               | Model 1     | Model 2     | Model 3     |
|-------------------------|-------------|-------------|-------------|
| Von-misses Stress (MPa) | 176.71 MPa  | 173.73 MPa  | 149.35 MPa  |
| Von-misses Strain (mm)  | 0.0080 mm   | 0.0079 mm   | 0.0045 mm   |

From the above table, it is shown that the model 1 is having higher von-misses stresses and von-misses strains followed by the Model 2 and Model 3. It shows that the model 3 showing high strength and high stiffness. Fatigue life calculation are discussed below.

**4. Fatigue Life:**

*4.1 Fully Reversed Loads*

If the load varies between +P to -P, then the loading type is called fully reversed load.

For Model 1, \( \sigma_{\text{von}} = 176.71 \text{ MPa} \)

\[ \sigma_m = 0 \]
\[ \sigma_s = 176.71 \]
\[ \sigma_{yf} = 300 \text{MPa} \]
\[ \sigma_e = 176.71 \text{MPa} \]

Log-Log interpolation is \( \log \sigma = A \log N + B \)

From the SN curve, with log-log interpolation, the below A and B values are obtained.

\[ A = -0.1958 \]
\[ B = 3.3534 \]

Therefore \( N = 4082300 \text{ Cycles} \)
The fatigue life of the leaf spring [Model] under fully reversed load is 4082300 cycles. Respectively, the fatigue life of the leaf spring [Model 2] and Model 3 are 4181400 Cycles and 4991900 Cycles.

4.2 Zero Based Loads

For Model 1, \( \sigma_{Von} = 176.71 \) MPa
\[
\sigma_{max} = 176.71 \text{ MPa} \\
\sigma_{min} = 0 \text{ MPa} \\
\sigma_m = 88.355 \\
\sigma_a = 88.355 \\
\sigma_yt = 300\text{MPa}
\]

For Mean stress correction, Soderberg mean stress theory is used
\[
\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} = 1 \\
\sigma_e = 113.9140\text{MPa}
\]
\[N = 6194400 \text{ Cycles}\]

The fatigue life of the leaf spring [Model] under Zero based loads is 6194400 cycles. Respectively, the fatigue life of the leaf spring [Model 2] and Model 3 are 6407900 Cycles and 8143500 Cycles. The infinite life of the structure is 8143500 cycles.

4.3 Fluctuating Loads or Alternating Loads (R Ratio) = 0.5

\[
\sigma_{max} = 176.71 \text{ MPa} \\
\sigma_{min} = 88.355 \text{ MPa} \\
\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} = 1 \\
\sigma_m = 132.5325 \\
\sigma_a = 44.1775 \\
\sigma_yt = 300\text{MPa} \\
\sigma_e = 79.14\text{MPa}
\]
\[N = 8143500 \text{ Cycles}\]

The fatigue life of the leaf spring [Model] under fluctuating loads [0.5] is 8143500 cycles. Respectively, the fatigue life of the leaf spring [Model 2] and Model 3 are 8143500 Cycles and 8143500 Cycles.

The infinite life of the structure is 8143500 cycles.

4.4 Fluctuating loads or alternating Loads (R Ratio) = -0.5

\[
\sigma_{max} = 176.71 \text{ MPa} \\
\sigma_{min} = -88.355 \text{ MPa} \\
\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} = 1 \\
\sigma_m = 44.1775 \\
\sigma_a = 132.5325 \\
\sigma_yt = 300\text{MPa} \\
\sigma_e = 155.427\text{MPa}
\]
\[N = 4769100 \text{ Cycles}\]

The fatigue life of the leaf spring [Model] under fluctuating loads [-0.5] is 4769100 cycles. Respectively, the fatigue life of the leaf spring with Model 2 and Model 3 are 4905000 Cycles and 6019000 Cycles.

The comparison study of the fatigue life of the composite leaf spring under fully reversed load, zero based load and fluctuating loads (tensile and compressive) are listed in the below table 6.
Table 6. Fatigue life of the composite leaf spring

|                | Fully Reversed Loads (1) | Zero Based Loads | Fluctuating Loads | Tensile (0.5) | Compressive(-0.5) |
|----------------|--------------------------|------------------|-------------------|---------------|------------------|
| Model 1        | 4082300                  | 6194400          | 8143500           | 4769100       |                  |
| Model 2        | 4181400                  | 6407900          | 8143500           | 4905000       |                  |
| Model 3        | 4991900                  | 8143500          | 8143500           | 6019000       |                  |

From the above table, it is noticed that the fatigue life of the composite leaf spring assembly under fully reversed loads is less followed by the fluctuating loads (compressive -0.5) and fatigue life of the composite leaf spring is having infinite life cycles under zero based load and fluctuating load (tensile).

5. Conclusions

The leaf spring of the heavy vehicle is designed in the FEA Software i.e., ANSYS Workbench. The dimensions which are taken for the Leaf spring is taken from the real existing vehicle. Proper meshing, contacts and loading boundary conditions are given to the Leaf Spring Model. A total of 3 models are designed by changing the lengths of the leaves with keeping same volumetric ratios. From the present the following conclusions are drawn. From the static structural analysis, it is observed that Model 3 having less stresses and strains compared to the remaining models using composite materials. From the fatigue life hand calculations, it is observed that Model 3 having highest life cycles stresses compared to the remaining models. The weight of the leaf spring assembly is reduced up to the 25% of the whole weight by using composite material compared to the carbon steel material, and it’s shows less stress values, strain values and high fatigue life cycles. The life of the leaf spring assembly using composite material under fully reversed loads is less compared to the other loading conditions. The life of the leaf spring assembly using metal and composite material under zero based load and fluctuating load (-0.5) shows infinite life cycles. So it is recommended to check the structure of the leaf spring under fully reversed loads. It is recommended to use Model 3 for all type of applications for better strength, stiffness and fatigue life in heavy load applications.

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