Stress Analysis of Composite Leaf Spring – Comparative Approach

Dr. Sheharyar Malik¹, Dr. Kamran S. Afaq²

¹ Instructor, Abu Dhabi Polytechnic, IAT, UAE.
² Head of Department Mechanical Engineering, HITEC University, Pakistan.

sheharyar.malik@adpoly.ac.ae

Abstract. Automobile manufacturers are focusing on weight reduction for saving natural resources and enhancing the fuel efficiency; automobiles are sharing almost half of the world’s fuel consumption and a major source of pollution, thus reducing the weight will directly result in the reduction of fuel consumption. The leaf spring is one of the main candidates for the weight reduction in an automobile as they still holds the worth although many shocks absorbing devices are in the market these days. This paper is aimed to present the comparative study of steel and composite leaf spring with the later type having the same geometrical characteristics of steel leaf spring. Validations are carried out by modelling leaf spring on ANSYS & comparing it with analytical results. The results showed that the stresses in composite leaf spring are 64.8% lower than the stresses in the steel leaf spring for the same geometrical characteristics. The results for deflections showed also good agreement with analytical results and a decrement of 51.3% is found for composite leaf spring. The proposed methodology helps us to reduce the weight of leaf spring by approximately 74.39% without compromising on allowable stresses and thus also increasing the strain energy of the particular leaf spring.

1. Introduction

Vast and steep industrial growth causes great concern among the people for the consumption of natural resources. For this purpose scientists are trying to substitute new synthetic material for the structural parts that would replace the conventional material without any compromise on strength and performance. Composites are providing this breakthrough for researchers and although composites have replaced many conventional materials used for manufacturing, still great interest has been shown by automobile industry to use leaf spring made of composites due to their strength to weight ratio over conventional steel leaf springs. Leaf springs contribute around 10 to 20 % in the total body weight and the impact of weight reduction will be readily seen. Leaf springs can be primary candidates to be replaced by lighter materials like composites without any compromise on their load carrying ability [1], [2]. If the existing steel leaf springs are replaced with composite leaf springs, the impact in reduction of fuel consumption can be readily seen. Research activities devoted on the amount of vehicles in Pakistan and their fuel consumption found out that that 48 % of fuel is consumed by the transport sector [3], [4], [5].

Leaf springs are especially used due to their advantage over shocks and helical springs to carry heavy loads in terms of simplicity in maintenance and cost effectiveness and their significance is
especially evident when heavy load systems are under consideration [6], [7]. Apart from acting as energy absorbing device, leaf springs also serves as a structural member whose ends could be guided along the pre-defined path, thus if placed properly as structural member they can also carry brake and driving torque in addition to providing cushion to impact and shocks loading [8].

Apart from reducing weight, leaf spring when manufactured from composites also offers increased strength to weight ratio and also it is noted that strain energy increases, because composites provides the necessary material properties having maximum strength and minimum modulus of elasticity in the fiber direction [9], [10]. Literature review helped to decide the glass epoxy as the most suitable combination for composite [11]. Literature also present the variants of conventional leaf springs, like mono steel leaf spring but it can prove catastrophic under fatigue or impact failure and it is the most prominent reason that they are not commonly utilized, weather its composite or steel leaf spring [12].

Semi elliptical multi leaf spring shown in Fig. 1, is selected for the analyses in this work. Moreover, over hanged condition is assumed to correctly model the forces at the center of the multi leaf spring. Both the eyes of the multi leaf spring are provided with the rotational degree of freedom, however one of the leaf spring eye is allowed to have the translation degree of freedom along the longitudinal direction.

In the presented work, comparative study has been carried out for the semi elliptical leaf spring, results are compared for the analytical and numerical analyses. The following section II presents the mathematical model for the design of the leaf spring. Section III will give insight about the numerical modelling of the leaf spring.

2. Design of Leaf spring

2.1. Preliminary design

It is well known that the 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. It can be easily observed that material having lower modulus and density will have a greater specific strain energy capacity. The introduction of composite materials made it possible to reduce the weight of the 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 to those of steel. The For simplicity leaf spring are idealized as cantilever beams. Mathematical modeling of leaf spring starts from simple assumptions and basic relation of bending stress and deflection for cantilever beam [3]:

$$\sigma = \frac{M y}{I}$$  \hspace{1cm} (1)

Whereas, ‘M’ is bending moment, ‘y’ is the distance from neutral axis to surface and ‘I’ is moment of inertia.
2.2. Mathematical design
A little consideration will show that the spring become compact so that the space occupied by the
graduated springs is considerably reduced. The graduated leaves may have zero width at the loaded
end. But sufficient metal must be provided to support the shear stress. Therefore it becomes necessary
to have one or more leaves of uniform cross section extended clear to end. Since the master leaf has to
with the stand vertical bending load as well as load due to sideways of a vehicle and twisting it is
usually to provide at least two full length leaves and the rest graduated leaves. The equations of
bending stress and deflection can be rewritten as a special case for different number of full length
leaves \( \sigma_F \) and graduated leaves \( \sigma_G \):

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

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

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

Where, ‘W’ represents the force on the eye of the leaf spring, ‘L’ represents the total length, ‘E’
represents the modulus of elasticity, ‘b’ represents the breadth of the leaf spring cross section, ‘t’
represents the thickness of the leaf spring cross section. Number of graduated leaves and full length
leaves are represented by \( n_G \) and \( n_F \), respectively.

3. Numerical Modelling
While designing the composite leaf spring, several design criteria are considered. In the presented
work, similar geometrical properties are chosen and the difference in the stresses is noted for the steel
and composite leaf spring. Commercially available software, ANSYS is used to design the model and
to carry out the analysis on leaf spring. Element type, SOLID 45 is selected for the analysis. The
movement of the graduated leaves in the transverse direction is limited by constraining the leaves in
the transverse direction and allowing a slip in the longitudinal direction.

3.1. Contact definition
It is obvious from Fig. 1, the leaves of the spring are in contact with each other while allowing a slip
motion along the longitudinal direction. This calls for the definition of appropriate surface to surface
contact mechanism where it permits the motion of the leaves along the longitudinal direction. In order
to examine the correct surface to surface contact the supplementary analysis is carried out, in which two
beams are modeled as shown in Fig. 2, validations are carried out for different contact types by
comparing it with the analytical results.

Nodes are selected to make the flexible sliding contact between two surfaces of two leaves with the
help of CONTACT 174 and TARGET 170 elements. Several contact types definitions are available in
the literature, most prominent are rough, bonded and no separation contact type. Rough contact type
models perfectly the rough frictional contact where there is no sliding and this corresponds to an infinite
friction coefficient. Bonded, models a contact in which the surfaces are bonded in all directions. For the
presented case, ‘no separation’ is found to be the most suitable contact type which models a contact in
which the surfaces are tied (although sliding is permitted) with the value of normal penalty stiffness as
1.0 and penetration tolerance is chosen as 0.1. Path plots were also plotted to infer the behavior of
stresses within the leaves in Fig. 3. Comparison for no separation, rough and bonded contact type are
presented in Table 1.
Figure 2. Numerical analysis - Contact type - No Separation – Load 100N

Figure 3. Load vs. Stress - Contact Types

Table 1. Comparison of surface contact

| Load (N) | Analytical | Bonded | Error | No Separation | Error | Rough | Error |
|----------|------------|--------|-------|---------------|-------|-------|-------|
| 500      | 1200       | 7.92   | 600   | 1.946         | 50    | 75.4  | 115   |
|          |            |        |       |               |       |       |       |
| 500      | 1200       | 7.92   | 600   | 1.946         | 50    | 75.4  | 115   | 7.771 | 4.17  | 1.881 | 870   | 3.326 | 27.5  | 58.0  |
3.2. Modelling of composite
The leaf is designed to provide the strength in the direction along which major portion of load is distributed i.e. we can direct fibre orientation in the direction of load. Glass/Epoxy in the direction of fibres has good characteristics for storing strain energy. Table 2, presents the comparison of the steel and Glass/Epoxy composite.

| Material          | \(\sigma/\rho\) | \(E/\rho\) |
|-------------------|-----------------|------------|
| Steel             | 2.7             | 2.7        |
| Glass/Epoxy       | 13.6            | 2.9        |

The unidirectional lay up along the longitudinal direction of the spring is selected with a minimum of 10 \% layers in each direction as shown in Table 3 and depicted in Fig. 4. Moreover, maximum fibres are orientated along the longitudinal direction. Thickness of each layer is also important part of design. Total height was 26mm for leaf spring, so it was divided into 100 layers of thickness 0.26 mm in the \(z\)-direction. The density and weight of weight of composite leaf spring for fibre fraction of 60\% can be evaluated as follows:

\[
\rho_c = V_f \rho_f + V_m \rho_m
\]

Whereas, \(V_f = 0.6\),
\(V_m = 1 - V_f\),
\(\rho_f = 2540\) Kg/m\(^3\) \(\rho_m = 1100\) Kg/m\(^3\) is selected for Glass/Epoxy.

![Figure 4. Orientation of Layers](image)

Table 3 shows the results for composite leaf spring.

| Glass Epoxy Combinations | Stress(\(\sigma\)) MPa |
|--------------------------|------------------------|
| [(0/0/45/0/0/-45/0/0/90/0/0)]\(_s\) | 85.82 |
| [(90/90/45/90/90/-45/90/0/90/0/90)]\(_s\) | 150.29 |
| [(45/90/0/0/-45/45/90/0/0/-45)]\(_s\) | 140.82 |
Comparison is also carried out for the changed geometry i.e. comprising of two leaves and mono leaf spring. Multi leaf spring analysis is preferred due to catastrophic fatigue failure of leaf spring comprising of single/mono leaf [4].

Weight reduction of 74.39 % is achieved when steel leaf spring is replaced with composite leaf spring as shown in Fig. 1b., while Fig. 1a. shows one of the analysed case. Fig. 2a. and Fig. 2b. shows the deflection and stress along the main leaf spring, respectively. Weight reduction of 74.39 % is achieved when steel leaf spring is replaced with composite leaf spring. Several combinations for layer orientations were analysed. It was found out that minimum stress in leaf spring were when maximum layers were placed in the longitudinal direction. It is further illustrated with the help of figures and Table 4 presents the comparison for the steel and composite leaf spring.

Table 4. Comparison of steel and composite leaf spring

| Load | Composite Leaf Spring | Steel leaf spring | Difference |
|------|------------------------|-------------------|------------|
| N    | σ                      | δ                  | σ          | δ          | %            | %            |
| 500  | 4.29E+07               | 5.839             | 1.26E+08   | 11.492     | 65.8%        | 49.19074     |

Figure 5. Stess Analysis of composite leaf spring
4. Conclusion
The results showed that the stresses in composite leaf spring are 64.7% lower than the stresses in the steel leaf spring of the same dimensions. The results for deflections showed good agreement with theoretical results and when compared with steel leaf spring, a decrement of 51.3% is found for deflection in the composite leaf spring. This methodology helps us to reduce the weight of the leaf spring by approximately 74.39% without compromising on allowable stresses and thus also increasing the strain energy for the particular leaf spring case. Numerical analysis is used to illustrate the stresses along the leaves in full length and graduated length leaves, it is found to be corresponding to the theory for the beams that stress in the graduated leaf should be nearly 2/3 of the stress in full length leaf.

Leaf spring is used in almost every heavy vehicle used for transportation of goods and passengers. In Pakistan leaf spring can also be found in light vehicles such as Suzuki Mehran, Bolan and Ravi (Pickup). By reducing the weight of existing steel leaf spring will help to reduce the weight of these vehicles by 10 – 20% percent, which will help in reducing the fuel consumption up to nearly 6%.
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