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Design and Static Analysis of Sandwiched Leaf Spring with Hyper-elastic Material

Manav Kumar*, **Dheeraj Kumar and Sharifuddin Mondal**

National Institute of Technology Patna, Bihar, India

***Correspondence to:**
Manav Kumar
National Institute of Technology Patna,
Bihar, India.
E-mail: sjpawar@mnnit.ac.in

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Abstract

To satisfy the needs and demands of customers, there are constant developments in automobile suspension systems to improve riding comfort. The vibration and impact caused by road irregularities are absorbed by the leaf spring. In this work, rubber is sandwiched between the metal leaves to configure a new leaf spring to provide better riding comfort and lighter vehicles. The leaf spring is modeled in CATIA V5 and static structural analyses are performed in the ANSYS environment. Different hyper-elastic models such as the Mooney Rivlin Model, Yeoh Model, and Arruda Boynce Model are used for analyzing the rubber material by curve fitting. Five different rubber materials, such as chloroprene rubber (CR), strene-butadiene rubber (SBR), carbon-filled natural rubber (CFR), and natural rubber (NR55) are selected for comparative analysis. According to the findings, a rubber-sandwiched leaf spring increases the total energy-storing capability of the leaf spring, resulting in improved riding comfort.

Keywords

Riding comfort, Hyper-elastic, Static analysis, Sandwich

Introduction

Nowadays, the automobile industries involved in design, development, and manufacturing pay special attention to the design of suspension systems to fulfill customers' desired comforts. There are two primary functions that the vehicle suspension system must complete. The first is for the comfort of the passengers by shielding the vehicle body from road noise, and the second is to maintain the displacement of the vehicle body and provide constant close contact between the route of the vehicle and the wheel to provide guidance along the path [1, 2]. The purpose of suspension is to absorb the kinetic energy generated by road disturbances in a gradual manner [3]. The simplest and oldest kind of suspension is a leaf spring, which consists of a stack of curved steel plates. A spring is designed in such a way that it absorbs and stores energy and then dissipates it slowly [4]. In a metal to rubber bonded suspension system, the metal plate distributes the load and the sandwich hyper elastic material recitals as a spring that permits lateral stiffness while the steel plate guarantees the system's strong load bearing capability. The hysteresis phenomenon of rubber material provides vibration damping and noiseless application [5, 6]. There are some references found to the application of hyper-elastic sandwich leaf springs, i.e., rubber to metal bonded meta-core suspension systems in different rail and metro services. Rahnavard et al. [7] used the high damping laminated elastomeric bearing for seismic isolation, which minimizes the earthquake forces and abnormal vibration imparted to the structure and protects the secondary element from damage. Sebeşan and Sebesan [8] used a rubber-to-metal bonded spring as an antivibration component, which is commonly used in the rail industry. Luo and Wu [9] have also used a metal-bonded engine mount rubber component for rail suspension systems.

In much of the research, analysis was performed to find the deflection, stress, and optimum design of leaf springs. Only a few works present ways to improve comfort by introducing hyper elastic materials between the leaves of multi-leaf springs. In this work, a new configuration of leaf spring was created by inserting rubber as a sandwich in between metal plates to get better riding comfort and lighter vehicles. The leaf spring is modelled in CATIA V5 and static structural analysis is performed in the ANSYS environment. Different hyper-elastic models namely Mooney Rivlin model, Yeoh model, and Arruda Boynce model are used for analyzing the rubber material by curve fitting. Five different rubber materials such as CR, SBR, CFR, and NR55 are selected for comparative analysis.

The rest of the paper is presented in the following sequence: In section 2, the design and modeling of leaf springs are presented. Different selected hyper-elastic models and material model constants obtained through curve fitting are introduced in section 3. In section 4, meshing, boundary conditions, and load calculation are described. The simulation results and discussion are given in section 5. Finally, the paper is summarized in section 6.

Experimentation

Design and modeling of leaf spring

Leaf spring

A leaf spring has a number of leaves stacked together and connected with the chassis of the vehicle. It offers a large amount of support between the wheel, axle, and the chassis, distributing the load throughout the length of the leaf spring. The longest leaf is known as the master leaf spring, containing two eyes at each end. The eye is used for connection with the chassis of the vehicle. The vehicle's frame is where one eye is fastened, and the shackle end is where the opposite eye is fastened. The 3D modelling of the leaf spring is created in the CATIAV5R20 as shown in figure 1 using the parameters taken from the E-rickshaw as shown in table 1.

Material selection

The suspension system's performance is significantly influenced by the material. For the metal leaf spring, a material with a significant strength to elasticity modulus ratio should always be chosen in accordance with the particular strain energy. For sandwiched conditions, materials having good damping properties, vibration and jerk absorbing ability should be selected. For the metal plate, commonly used materials in the industry for the manifesting of the leaf spring are selected. As

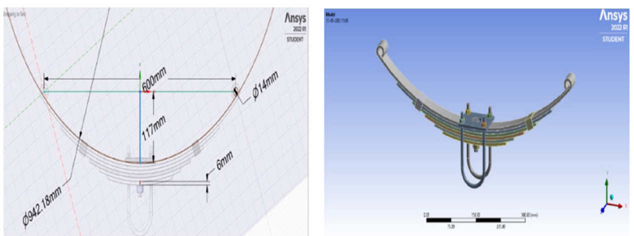

Figure 1: 2D and 3D sketches of leaf spring developed in CATIAV5R20.

Table 1: Design specification of leaf spring.

Parameters	Value
Length of Master Leaf (2L)	600 mm
Diameter of Master Leaf (R)	942.18 mm
Number of Full Leaves	2
Number of Graduated Leaves	4
Leaf Width (b)	50 mm
Thickness (t)	6 mm
Camber Length	117 mm
Eye Diameter	14 mm
Centre bolt Diameter	10 mm
Deflection of Leaf Spring	117 mm

a result of its extensive range of product applications, rubber is subjected to a wide range of loading situations. In terms of mechanical behavior, hyper-elastic modal differs from elastic modal [10]. Different mechanical properties of selected materials are shown in table 2.

Hyper-elastic models

A hyper-elastic model is defined as a strain energy (U) potential function. There are two common ways of representing hyper elastic material models, namely principal stretch, and strain invariants. The mathematical expression of the deviatoric strain potential differs from one model to another, depending on whether the model is invariant-based or stretch-based [6].

Selected hyper-elastic models

Here, the most common and popular hyper-elastic models are briefly presented by describing the respective mathematical expressions. Here, the general terms used in the math expression are the first invariant (I_1), shear modulus (μ), material constant (C_1), compressibility index (D_1), and elastic volumetric index (J) of the material, unless otherwise stated.

Mooney Rivlin model

This model may be used to forecast rubber deformations of a mild to moderate degree. The stiffening at high deformation that is often seen with natural rubber cannot be seen with synthetic rubber.

$$U = \mu(I_1 - 3) + \mu(I_2 - 3) + D_1(J-1)^2 D_1(J-1)^2 \qquad (1)$$

Arruda Boyce model

This model can be easily calibrated up to 600% elongation. Simulating multiple modes of deformation reduced the model's accuracy, making it best suited for a single mode of deformation. Here, α_i represents degradation rate. Here, $\beta = (1/N) = (1/\lambda_m^2)$ and $\overline{I}^i = I_1 J^{-2/3}$, in which N reflects how many chains are present in a cross-linked polymer's network, and λ_m is the stretch at locked polymer chain network.

$$U = D_1\left(\frac{(J-1)^2}{2} \quad lnJ\right) \quad \mu\sum_{i=1}^{N} \alpha_i \beta^{i-1}\left(\overline{I}^i - 3^i\right) \qquad (2)$$

Yeoh model

The Yeoh model is often referred to as the reduced poly-

Table 2: Materials for leaf spring and their mechanical properties [11].

Properties	EN45A	55Si2Mn90	50Cr1V23	65Si6	S. Steel
Young Modulus (MPa)	210	210	210	210	210
Tensile yield Strength (MPa)	1158	1800	1800	1158	250
Ultimate Yield Strength (MPa)	1275	1950	1962	1272	460
Poisson's Ratio	0.266	0.266	0.266	0.266	0.266
Density (kg/m³)	7850	7850	7850	7860	7850

nomial model. Yeoh said that the finding should be added to the hyper elastic model by adding a term that decreases in an exponential way to the model's strain energy density.

$$U = \mu \sum_{i=1}^{5} \frac{C_i}{\lambda_m^{2i-2}} \left(I_1^i - 3^i \right) + D_1 \left(J - 1 \right)^2 \quad (3)$$

Curve fitting

The test data of stress-strain from the axial tensile tests of CR rubber material [5] are used for curve fitting of considered hyper-elastic models to represent the rubber's realistic behavior. The obtained curves and material model constants are shown in figure 2.

Analysis

Meshing, boundary condition and convergence criteria

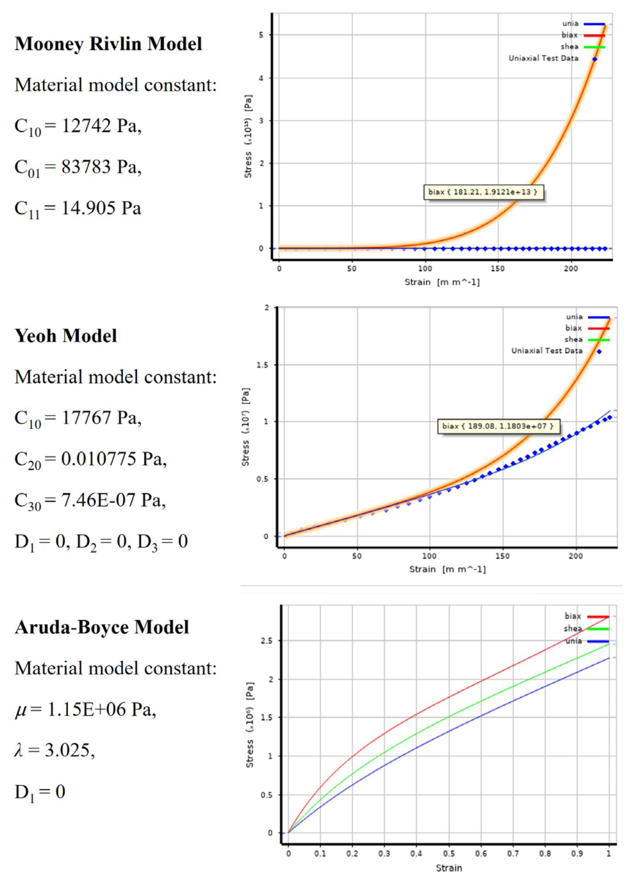

Figure 2: Curve fitting of different hyper-elastic model based on axial test data from.

Meshing

This is done to discretize the geometry into a number of parts for an accurate result. As shown in figure 3, each mesh is connected with other meshes with a common node, and all properties and behavior are transferred by this meshes with a common node. As per requirements and mesh quality, the elements created were tetrahedral and hexahedral. Nodes were replaced to avoid trio tetra, and density was smoothened to avoid maximum element failure. The details of meshing are as follows; type of mesh-tetrahedra and hexahedral; order - first order; minimum mesh size - 0.5375 mm; maximum mesh size - 1 mm; growth order - 1.2; maximum Layer - 5; No of elements - 57130; number of nodes - 13872.

Boundary conditions

Particular attention must be paid while applying loads and constraints to elements. One of the eyes of the leaf spring, which is fastened to the chassis of the vehicle, has a fixed support. All translational degree of freedom is arrested and two rotational about x, y axis is arrested. It has only one degree of freedom that it can only freely rotate about z axis. A second leaf spring eye is fastened to the shackle of the leaf spring on the vehicle's rear. It can translate in x direction and freely rotate about z axis.

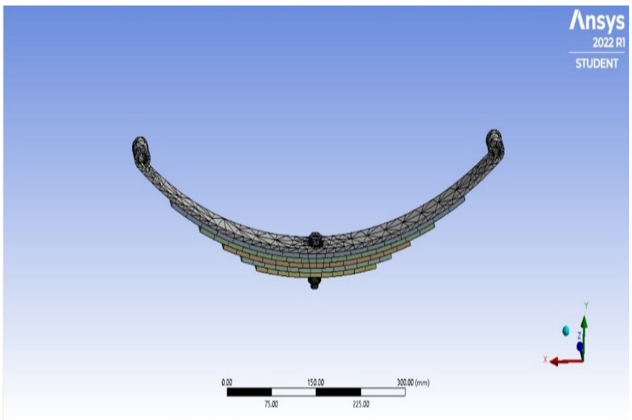

Figure 3: Meshing of leaf spring.

Convergence criteria

A convergence experiment is carried out by adjusting the size of the mesh element. The number of equations that ANSYS solves will be decreased by enhancing the size of the meshing element. A computer with greater specifications is needed in order to reduce running response times. The drawback of growing element mesh size is that complex geometry cannot be accurately covered by a mesh that exactly covers the whole surface. There will be variations from the exact solutions as a result of this approximation. The simulator employed in this work is now academic (student version) and unable to do advanced studies, but the converging study concept is nevertheless used by enlarging the element size used to mesh the leaf spring's complete shape.

Load calculation

The loads acting on the suspension system are of two categories, namely static load and dynamic load. The weight of the vehicle, passengers, and luggage is included in the static load. Dynamic load refers to additional force exerted on the suspension system during acceleration and deceleration. The net load on one leaf is calculated as follows:

Static load

Weight of the vehicle = W1 = 200 kg

Additional weight (Including passengers and luggage) = W2 = 6 × 100 + 40 = 640 Kg

Total weight, $W_t = W_1 + W2 = 200 + 640 = 840$ Kg

Load acting on all four-leaf spring, $Fs = M \times g = W_t \times g = 720 \times 9.81 = 7063.2$ N

For one leaf spring, acting load,

$$F_1 = \frac{F}{3} = \frac{7063.2}{3} = 2223.6 \text{ N}$$

Dynamic load

Additional load acting on leaf spring during acceleration and deaccelerations are:

$F_D = W_t \times a = 840 \times 3.5 = 2940$ N

For one leaf spring dynamic load is

$$F_2 = \frac{F}{3} = \frac{2440}{3} = 980 \text{ N}$$

Net load on one leaf is sum of static and dynamic loads, i.e., $F_t = F_1 + F_2 = 3203.6$ N

Results and Discussion

Static structural analysis of a rubber sandwiched leaf spring is performed at a load of 3750 N, the boundary condition defined above. In the work, a multi-leaf spring with 6 leaves was used for the analysis. There is metal to metal or metal to rubber contact. Metal-to-metal sliding contact with friction of 0.3 was considered, whereas metal-to-rubber bonded contact was used. A leaf spring with 6 leaves was prepared in CATIA V5 and then each part was assembled in CATIA assembly. In figure 1, the assembly of the leaf spring was shown, in which two U-type bolts were present. It is used to tighten the leaf spring with the axle, but in the analysis, there was no need for that part in the analysis. That's why it was suppressed in the analysis. This similar approach is also used by different researchers and is available in literature.

For the analysis of the rubber material, the use of an elastic material model is not recommended because the stiffness of the rubber does not remain constant. It shows the nonlinear stress-strain curve. So, in order to analyze the rubber material, a hyperelastic model is prepared. This hyperelastic model is developed by taking three data sets, such as axial tensile, bi-axial, and shear test data. In ANSYS, the hyperelastic model is prepared by only using axial tensile data. For CR rubber material, axial tensile data is taken from the available literature and used for the preparation of hyperelastic material models. Axial tensile test data is the input to the ANSYS. The different material models such as Mooney Rivlin, Arruda Boynce, and Yeoh Model are selected, and then we do the curve fitting in order to best fit the material model with the axial test data and to obtain the material constants. After getting the model constant, the hyperelastic material model is developed and the data is validated with available literature. A similar step is carried out with other rubber materials and validated with the data available in the literature for the selected materials before using them in our model.

The sandwich of rubber material is arranged by inserting third and fourth leaves in between metal leaves. This arrangement is described as $M_m M_2 R_3 R_4 M_5 M_6$. Different sets of experiments are conducted by combining the hyper-elastic model and the materials selected. Here, only the optimal and comparable results with metal materials are presented. The maximum von Mises stress, deformation, and total strain energy obtained in this static analysis are shown in figure 4, figure 5, and figure 6, respectively.

In static structural analysis, maximum induced von Mises stress increases in all sandwich models as compared to metal leaf spring as shown in figure 7. A master leaf spring that has maximum curvature, camber, and distance to resist the bending moment. Each leaf together resists the bending moment, but when one of the leaf plates is replaced with rubber, the capability of the whole assembly to resist the bending moment decreases, which increases the stress induced in the leaf spring. It is well known that rubber plates resist less bending stress than metal plate. Hence, on replacing the metal leaf that resists more bending moments with rubber, it participates less in

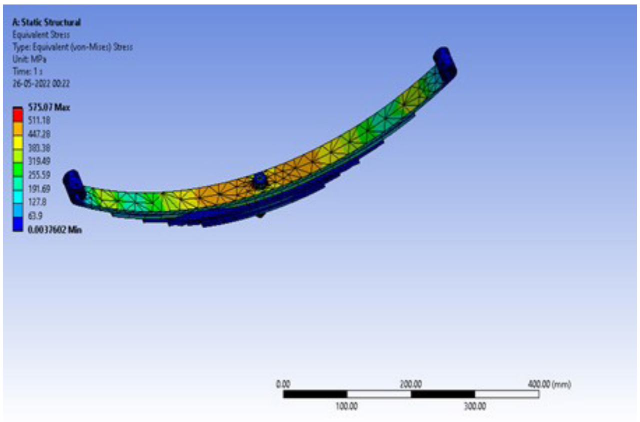

Figure 4: Maximum von Mises stress for Mooney Rivlin model of SBR rubber.

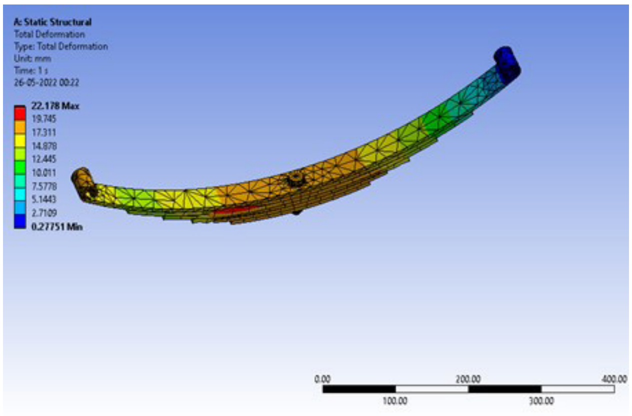

Figure 5: Deformation for Mooney Rivlin model of SBR rubber.

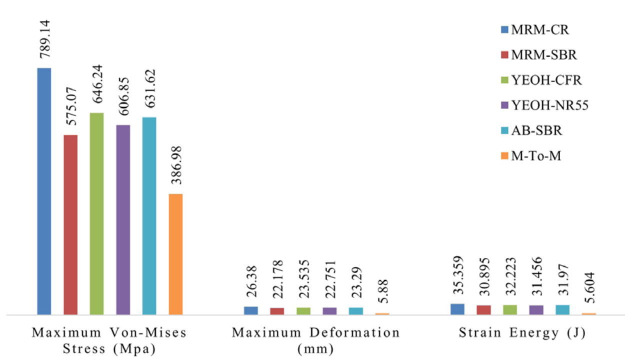

Figure 7: Comparison of maximum von Mises stress, maximum deformation, and strain energy for selected combination of hyper-elastic models and materials.

resisting the bending moments and the consequently induced stress increases. The maximum total deformation obtained is 26.3 mm, which is much less than the camber of a leaf spring (117 mm). Hence, it is a well-accepted range. In this case, the 3rd and 4th metal leaf springs are replaced by having more curvature to resist bending moments. Due to replacement, the leaf spring is not able to resist bending moments in the same way. Also, as the number of metal plates decreased, a reduced number of plates were available to sustain the complete load, resulting in increased deformation. For all the considered sandwich conditions, the strain energies are comparable but significantly increased by the metal leaf spring. The reason could be due to a decrease in the stiffness of the metal leaf, causing increased deflection of the leaf spring.

Conclusions

In this work, a new configuration of leaf spring by sandwiching rubber in between metal plates is investigated to get better riding comfort and lighter vehicles. The leaf spring is modelled in CATIA V5 and static structural analysis is performed in the ANSYS environment. Stresses induced in the proposed configuration $M_mM_2R_3R_4M_5M_6$ of the leaf spring model are smoother than the stresses induced in the existing metal leaf spring. The total energy storing capability of the sandwiched leaf spring is much higher than the existing metal leaf spring. More compliment suspension results from the leaf spring's increased strain energy capability.

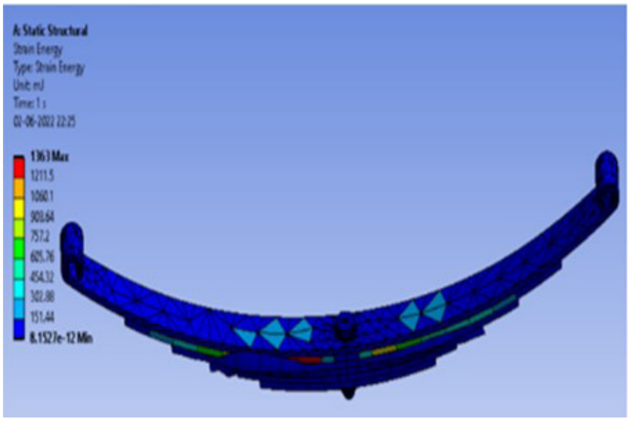

Figure 6: Strain energy for Mooney Rivlin model of CR rubber.

Out of all the hyper-elastic models, the Mooney Rivlin model with SBR material shows better performance than other considered models. This study will be further extended to perform a dynamic (transient) analysis and observe the frequency response of the suspension system (leaf spring).

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Conflict of Interest

Authors declare that they have no known conflict of interests.

Credit Author Statement

Manav Kumar: Writing - original draft preparation, Writing - review and editing; Dheeraj Kumar: Conceptualization, Investigation, Writing - original draft preparation; Sharifuddin Mondal: Conceptualization, Supervision. All the authors read and approved the manuscript.

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