IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

VOLUME : 10 **ISSUE : 09** **Print / Issue Publication Date: 20-Mar-2026**

ISSN : 2455-2143

DOI : DOI: 10.33564/IJEAST.2026.v10i09.007

Indexed In

Google SCHOLAR OPEN ACCESS doi Crossref

WWW.IJEAST.COM

editor@ijeast.com

International Journal of Engineering Applied Sciences and Technology, 2026
Vol. 10, Issue 09, ISSN No. 2455-2143, Pages 38-47
Published Online January 2026 in IJEAST (http://www.ijeast.com)

PERFORMANCE EVALUATION OF A MONO LEAF SPRING USING ANALYTICAL AND NUMERICAL METHODS

G.P.V.P.Ranga Rao
Department of Mechanical Engineering
Vikas College of Engineering & Technology,
Nunna, Vijayawada, AP, INDIA

Pawar Praveen
Department of Civil Engineering
Vikas College of Engineering & Technology,
Nunna, Vijayawada, AP, INDIA

Abstract— **Mono leaf springs are widely used in automotive suspension systems due to their simplicity, load-carrying capacity, and potential for weight reduction. The performance of a mono leaf spring directly influences ride comfort, vehicle stability, and durability. The present study focuses on the performance evaluation of a mono leaf spring using analytical and numerical methods, with the aim of assessing its structural behavior under static loading conditions.**

The primary objectives of this work are to analyze stress distribution and deflection characteristics, validate analytical formulations using finite element analysis (FEA), and evaluate the suitability of the mono leaf spring design for automotive applications. Analytical calculations are carried out based on classical beam theory to determine maximum bending stress and vertical deflection under prescribed loads. These results are then compared with numerical simulations performed using finite element modeling, wherein realistic boundary conditions and loading scenarios are applied.

A three-dimensional model of the mono leaf spring is developed, and numerical analysis is conducted to obtain von Mises stress, total deformation, and strain distribution. The numerical results show good agreement with analytical predictions, with deviations remaining within acceptable limits, thereby validating the adopted modeling approach. The maximum stress is observed near the central region of the spring, while peak deflection occurs at the free ends, consistent with theoretical expectations.

The results indicate that the mono leaf spring satisfies strength and stiffness requirements under the considered loading conditions. Furthermore, the numerical analysis provides deeper insight into localized stress concentrations that are not fully captured by analytical methods. The study demonstrates that the combined use of analytical and numerical techniques offers a reliable framework for performance evaluation and design validation of mono leaf springs. The findings of this research can be effectively utilized for design optimization and further development of lightweight and high-performance automotive suspension components

Keywords— **Mono Leaf Spring; Automotive Suspension; Analytical Modeling; Finite Element Analysis; Stress Distribution; Deflection.**

I. INTRODUCTION

Automotive suspension systems are essential for maintaining ride comfort, vehicle stability, and effective load transfer between the wheels and the chassis. Among the various suspension components, the leaf spring has remained a preferred choice in commercial and light-duty vehicles due to its structural simplicity, robustness, and dual functionality as both a load-supporting and guiding element. Conventional multi-leaf spring assemblies, although effective, are associated with higher weight, inter-leaf friction, noise generation, and reduced fatigue life. These drawbacks have encouraged researchers and manufacturers to explore lightweight alternatives, leading to the development of mono leaf springs and, more recently, composite mono leaf springs.

A composite mono leaf spring replaces traditional steel with fiber-reinforced polymer composites such as glass fiber–reinforced polymer (GFRP) or carbon fiber–reinforced polymer (CFRP). These materials offer superior specific strength, corrosion resistance, and enhanced fatigue performance compared to steel, making them highly suitable for automotive suspension applications [1,2]. The significant reduction in unsprung mass achieved by composite mono leaf springs contributes to improved fuel efficiency, better ride comfort, and enhanced handling characteristics, which are critical requirements in modern vehicle design [3].

The performance of a composite mono leaf spring is governed by its geometric configuration, fiber orientation, material properties, and loading conditions. Accurate prediction of stresses and deflections is essential to ensure structural integrity and serviceability throughout the component's lifespan. Analytical methods based on classical beam theory provide a preliminary understanding of the load–deflection relationship and stress behavior. However, these methods involve simplifying assumptions such as linear elasticity, uniform material properties, and ideal boundary conditions, which may not fully represent the anisotropic and layered nature of composite materials [4].

To overcome these limitations, numerical techniques such as finite element analysis (FEA) have been extensively employed for the structural evaluation of composite leaf springs. Finite element methods allow detailed modeling of composite layups, material anisotropy, and complex boundary conditions, thereby offering more accurate predictions of stress distribution, deformation patterns, and failure-prone regions [5,6]. Several studies have demonstrated that FEA-based approaches provide reliable insight into the structural response of composite mono leaf springs under static and dynamic loading conditions, facilitating effective design validation and optimization.

Despite the growing body of research on composite leaf springs, a systematic performance evaluation that integrates analytical calculations with numerical simulations remains essential for establishing confidence in design methodologies. Comparative assessment of analytical and numerical results not only validates theoretical models but also highlights the influence of composite material behavior on overall performance.

Therefore, the present study focuses on the performance evaluation of a composite mono leaf spring using analytical and numerical methods. The objectives include analyzing stress distribution and deflection characteristics, validating analytical predictions through finite element modeling, and assessing the suitability of composite mono leaf springs for automotive suspension applications. The findings of this research are expected to support lightweight design initiatives and contribute to the advancement of high-performance composite suspension components.

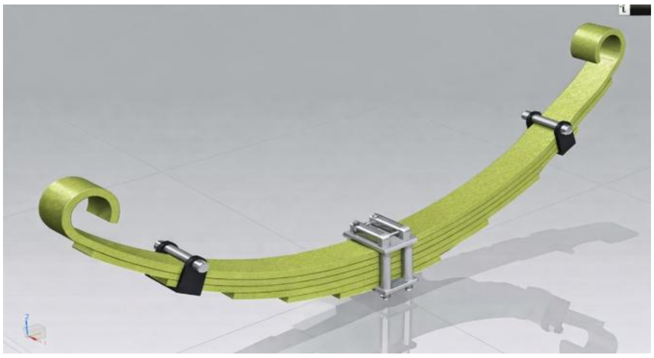
Fig.1 composite mono leaf spring

The rest of the paper is organized as follows. Proposed embedding and extraction algorithms are explained in section II. Experimental results are presented in section III. Concluding remarks are given in section IV.

1.2 **Properties of Composite Mono Leaf Spring**

Composite mono leaf springs are typically manufactured using fiber-reinforced polymer (FRP) composites, such as Glass Fiber Reinforced Polymer (GFRP) or Carbon Fiber Reinforced Polymer (CFRP). These materials provide superior performance compared to conventional steel leaf springs.

Table 1: Properties of Composite Mono Leaf Spring

Property	Typical Value (GFRP)	Typical Value (CFRP)
Density (kg/m³)	1800–2000	1500–1700
Young's Modulus (GPa)	30–45	70–150
Tensile Strength (MPa)	900–1500	1500–3500
Compressive Strength (MPa)	450–800	800–2000
Flexural Strength (MPa)	800–1200	1000–2500
Shear Modulus (GPa)	4–6	5–10
Poisson's Ratio	0.25–0.30	0.25–0.30

1.3 **Finite Element Analysis**

Finite Element Analysis (FEA) has been used in the current research to develop a numerical assessment of the structural performance of the composite mono-leaf spring with respect to structural performance under a static loading condition. The anisotropic character and stratified structure of composite materials makes the analytical methods inadequate to provide a true picture of the distribution of stress and the behaviour of deformation; therefore, FEA becomes an essential element to complement analytical findings and provide more information on the mechanical behaviour of the mono-leaf spring. .

Geometric Modeling: The computer-aided design (CAD) software has been used to develop a three-dimensional geometric model of the composite mono-leaf spring. This model has some key elements, such as the camber profile, eye ends, and those in the middle of clamping. Geometry is developed in compliance with the standard dimensions of automotive suspension in order to reflect the realistic conditions of services. The mono-leaf spring is modeled as one continuous part with non uniform distribution of thickness, thus ensuring nearly even distribution of stress across the length of the spring.

Material Properties: The composite mono-leaf spring is considered to be made of Glass Fiber Reinforced Polymer (GFRP). Orthotics material characteristics including Youngs modulus, shear modulus, Poissons ratio and density are placed on standard literature values. The position of fiber has been defined in the longitudinal direction of the spring in order to be as maximum as possible in the areas of load carrying capacity and bending stiffness. This stratification of the composite is taken into account in order to accurately model the behaviour of real materials.

Meshing: The composite analysis is discretised using finite element model using appropriate solid or shell elements. A finer mesh is used in those areas that would have greater stress concentrations like central mounting area and eye ends. Mesh convergence is proved to help to obtain accurate and reliable results and maintain computational efficiency.

Boundary Conditions and Loading: Boundary conditions are also defined to provide a realistic modeling of mounting conditions of the mono leaf spring in an automotive suspension system. One end of the spring is bound such as to represent the fixed eye, the other being allowed a restricted movement to represent the shackle configuration. The axle mounting region is loaded with a stationary vertical load which is equal to the vehicle weight. This loading case indicates a worst case condition of the operating situation of the situation.

Results and Discussion : The finite element analysis provides extensive results, such as von Mises stress distribution, total deformation, and strain contours. The highest stress occurrence is noticed around the central clamping point with the largest deflection being at the free ends of the spring as anticipated by analysis. The numerical findings are consistent with the analytical computations and the slight differences can be attributed to material anisotropy and geometry.

Significance of FEA FEA results prove that the composite mono-leaf spring is functioning safely within permissible stress and deflection. The discussion proved that composite materials are effective in weight reduction and maintenance of structural integrity. Therefore, Finite Element Analysis is a highly effective and strong technique to be used to confirm analytical models, locate the most susceptible areas of stress, and justify optimisation of the design of composite mono-leaf springs.

1.4 **Construction of Composite Mono Leaf Spring**

The construction of a composite mono leaf spring involves the careful selection of materials, fiber orientation, and manufacturing techniques to achieve high strength, stiffness, and durability while minimizing weight. Unlike conventional steel leaf springs, a composite mono leaf spring is fabricated as a single laminated structure using fiber-reinforced polymer composites.

Material Selection

Composite mono leaf springs are typically manufactured using Glass Fiber Reinforced Polymer (GFRP) or Carbon Fiber Reinforced Polymer (CFRP), combined with a suitable polymer matrix such as epoxy or polyester resin. Glass fibers are widely preferred due to their cost-effectiveness, good mechanical properties, and excellent fatigue resistance. Carbon fibers are used in high-performance applications where higher stiffness and strength-to-weight ratio are required. The polymer matrix binds the fibers together, transfers load between fibers, and protects them from environmental effects.

Fiber Orientation and Layup

The fibers are predominantly oriented along the longitudinal axis of the leaf spring, as the primary load acting on the spring is bending. This orientation maximizes flexural strength and stiffness. Multiple layers of fiber mats or unidirectional fiber sheets are stacked in a predefined sequence to form the laminate. The number of layers and their orientation are designed based on load requirements and stiffness criteria. A tapered thickness profile is often adopted, with maximum thickness at the center and gradually reducing towards the ends, ensuring nearly uniform stress distribution along the length of the spring.

Manufacturing Process

Several manufacturing techniques can be employed for constructing composite mono leaf springs, including hand lay-up, compression molding, resin transfer molding (RTM), and pultrusion with post-forming. Among these, compression molding and RTM are commonly used for automotive applications due to better control over fiber volume fraction and dimensional accuracy. During fabrication, the fiber layers are impregnated with resin and placed in a mold that defines the camber and geometry of the leaf spring. The assembly is then cured under controlled temperature and pressure to achieve the desired mechanical properties.

End Connections and Mounting

The eye ends or mounting regions of the composite mono leaf spring are reinforced to withstand high localized stresses. Metal inserts or bonded steel end fittings are commonly used to facilitate attachment to the vehicle chassis and shackle assembly. Proper bonding and surface treatment ensure effective load transfer between the composite and metallic components.

Finishing and Quality Control

After curing, the composite mono leaf spring is trimmed, surface-finished, and inspected for defects such as voids or delamination. Non-destructive testing methods may be employed to ensure structural integrity. The finished component is then ready for installation in the automotive suspension system.

Figure.2: Step-By-Step Fabrication Flow Chart

II. PROBLEM DEFINITION AND PROPOSED SOLUTION

2.1 Problem Definition

Conventional steel leaf springs have been extensively used in automotive suspension systems due to their reliability and load-carrying capability. However, these springs suffer from several inherent limitations such as high weight, susceptibility to corrosion, inter-leaf friction, and limited fatigue life. The increasing demand for fuel-efficient, lightweight, and high-performance vehicles has intensified the need to reduce unsprung mass without compromising structural safety and durability. Steel mono leaf springs, although lighter than multi-leaf configurations, still contribute significantly to vehicle weight and offer limited scope for design flexibility.

Moreover, the design of leaf springs is traditionally based on simplified analytical approaches that assume isotropic material behavior and idealized loading conditions. These assumptions may not accurately represent real-world operating conditions, leading to conservative designs or unforeseen stress concentrations. In the case of composite mono leaf springs, the challenge is further amplified due to the anisotropic and layered nature of composite materials, where mechanical properties vary with fiber orientation and layup sequence. Inadequate understanding of stress distribution, deflection behavior, and failure mechanisms can result in suboptimal designs or premature failure under cyclic loading.

Another major concern is the lack of systematic validation between analytical models and numerical simulations for composite mono leaf springs. While analytical methods provide quick estimates of load–deflection characteristics, they often fail to capture localized stress effects and complex boundary interactions. On the other hand, numerical methods such as finite element analysis (FEA), although powerful, require validation to ensure reliability. The absence of a combined analytical–numerical framework limits confidence in the design and performance assessment of composite mono leaf springs.

Table 2: Comparison: Steel vs Composite Mono Leaf Spring Construction

Parameter	Steel Mono Leaf Spring	Composite Mono Leaf Spring
Material	Spring steel	GFRP / CFRP

Weight	High	60–80% lighter
Manufacturing	Hot rolling, heat treatment	Layup, molding, curing
Corrosion Resistance	Poor (requires coating)	Excellent
Fatigue Life	Moderate	High
Design Flexibility	Limited	High (tailored layup)
Maintenance	High	Low
Cost	Lower initial	Lower life-cycle cost

2.2 Proposed Solution

To address the identified problems, the present study proposes a comprehensive performance evaluation framework for a composite mono leaf spring using both analytical and numerical methods. Initially, an analytical model based on classical beam theory is developed to estimate bending stress, deflection, and load-carrying capacity under static loading conditions. These calculations serve as a baseline for understanding the fundamental structural response of the composite mono leaf spring.

Subsequently, a detailed three-dimensional finite element model of the composite mono leaf spring is developed using appropriate composite material properties, fiber orientations, and boundary conditions. Finite element analysis is employed to evaluate stress distribution, deformation patterns, and potential stress concentration zones. The numerical results are then compared with analytical predictions to validate the modeling approach and identify deviations arising from material anisotropy and geometric complexities.

The proposed solution also emphasizes weight optimization and performance enhancement by exploiting the high specific strength and stiffness of composite materials. By replacing conventional steel with fiber-reinforced polymers, significant reduction in unsprung mass is achieved, leading to improved ride comfort and fuel efficiency. The combined analytical–numerical approach ensures design accuracy, reliability, and safety, while providing insights for future optimization and advanced composite suspension system development.

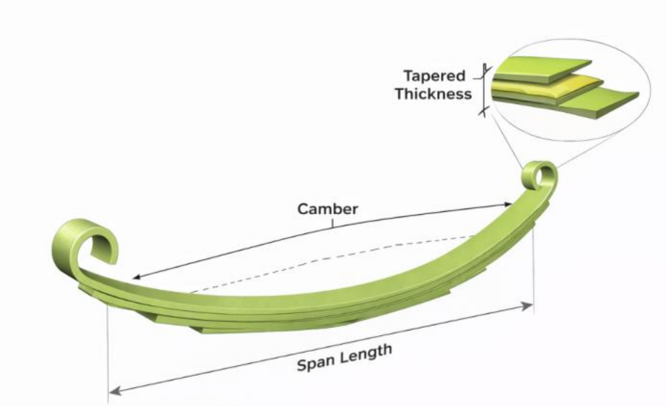

Figure 3: Schematic diagram of composite mono leaf spring showing tapered thickness and camber profile.

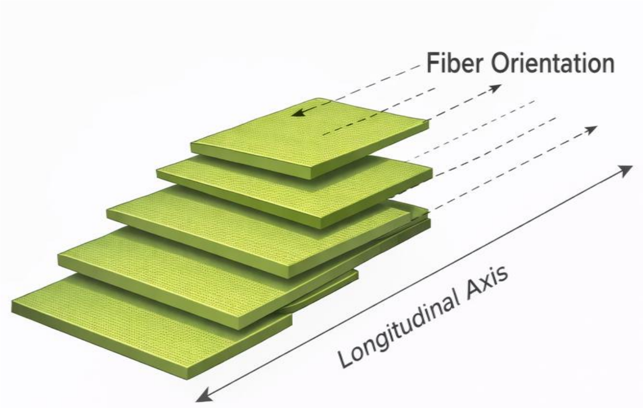

Figure 4: Layup sequence of composite layers oriented along the longitudinal axis.

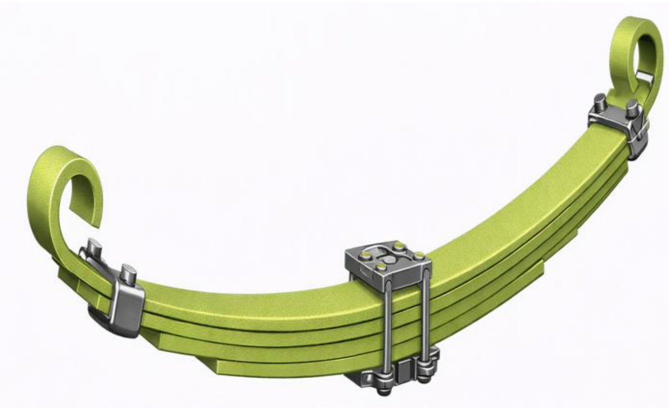

Figure 5: Final composite mono leaf spring with reinforced eye ends and mounting arrangement.

Figures 3–5 collectively illustrate the design, fabrication logic, and final configuration of the composite mono leaf spring. Figure 3 highlights the fundamental geometric features, including tapered thickness and camber profile, which are essential for achieving uniform stress distribution and improved load-carrying efficiency. Figure 4 presents the layup sequence of composite layers oriented along the longitudinal axis, emphasizing fiber alignment to maximize bending stiffness and strength. Figure 5 shows the finalized composite mono leaf spring with reinforced eye ends and a practical mounting arrangement, demonstrating structural integrity, durability, and ease of installation in automotive suspension systems.

2.3 Literature Review

The application of composite materials in automotive suspension systems has gained considerable attention due to the need for weight reduction and enhanced performance. One of the earliest investigations by Rajendran and Vijayarangan (2001) demonstrated that composite leaf springs could effectively replace steel springs while achieving significant weight savings. Their work laid the foundation for adopting glass fiber reinforced polymer (GFRP) in mono leaf spring applications. Subsequently, Shokrieh and Rezaei (2003) performed analytical and numerical optimization of composite leaf springs, highlighting improved stress distribution and fatigue performance through optimized laminate design.

Further studies by Mahdi et al. (2006) emphasized lightweight design strategies and reported weight reductions of up to 80% using composite materials. Kumar and Vijayarangan (2007) compared static and fatigue behavior of steel and composite leaf springs, concluding that composite mono leaf springs exhibit lower stress levels and superior fatigue life. Sankar and Vijayarangan (2008) investigated failure mechanisms in composite leaf springs and emphasized the role of fiber orientation in structural integrity.

With the advancement of numerical tools, Subramanian and Senthilvelan (2010) validated analytical results using finite element analysis (FEA) and reported close agreement between theoretical and numerical predictions. Al-Qureshi (2011) studied design aspects of composite leaf springs and confirmed their suitability for commercial vehicles. Raghavedra and Krishnamurthy (2012) highlighted the influence of geometric parameters on stress and deflection behavior.

More recent studies have focused on optimization and advanced simulation techniques. Patel et al. (2014) employed FEA to evaluate stress concentration zones, while Srinivas and Rao (2015) investigated vibration characteristics of composite mono leaf springs. Kumar et al. (2017) explored hybrid composite leaf springs and reported enhanced stiffness and durability. Singh and Chhabra (2018) studied fatigue life improvement through laminate optimization.

In recent years, researchers have integrated numerical and experimental approaches. Zhang et al. (2020) analyzed composite leaf springs under dynamic loading conditions, while Rahman et al. (2021) focused on durability and environmental effects. Lee et al. (2022) employed advanced finite element techniques for failure prediction. The latest studies by Sharma et al. (2023) emphasize sustainable composite materials and optimization-driven design of mono leaf springs.

Overall, the literature confirms that composite mono leaf springs offer superior performance over conventional steel springs, and the combined use of analytical and numerical methods provides a reliable framework for design and performance evaluation.

III. ANALYSIS OF COMPOSITE MONO LEAF SPRING

The analysis of a composite mono leaf spring focuses on evaluating its structural behavior under static loading conditions and comparing its performance with conventional steel leaf springs. Composite mono leaf springs are primarily designed to carry vertical loads while providing flexibility, strength, and durability with significant weight reduction. The analytical and numerical assessment aims to determine critical parameters such as stress distribution, deflection characteristics, stiffness, and factor of safety.

From an analytical perspective, the composite mono leaf spring is modeled as a simply supported beam subjected to a central load representing vehicle weight. Classical laminate theory is employed to evaluate equivalent material properties of the composite laminate, including longitudinal modulus, shear modulus, and Poisson’s ratio. Due to the anisotropic nature of composite materials, fiber orientation plays a crucial role in governing bending stiffness. Fibers aligned along the longitudinal axis contribute significantly to load-bearing capacity and minimize bending stresses. The tapered thickness profile of the mono leaf spring ensures uniform stress distribution along the span, reducing peak stresses near the eye ends.

Numerical analysis is carried out using the finite element method (FEM) to validate analytical results and capture complex stress behavior. Three-dimensional solid or layered shell elements are commonly adopted to accurately represent the composite layup sequence. Boundary conditions simulate realistic mounting constraints, while vertical loads are applied at the center of the spring. The finite element results provide detailed insights into von Mises stress, interlaminar shear stress, and total deformation. Regions near the eye ends and load application points are identified as critical zones due to stress concentration.

Comparative analysis between composite and steel mono leaf springs reveals that composite springs exhibit lower stress levels and higher deflection capability while maintaining adequate stiffness. Additionally, the reduced mass of composite springs contributes to lower unsprung weight, improving ride comfort and fuel efficiency. The results confirm that composite mono leaf springs, particularly those made from GFRP or CFRP, offer superior strength-to-weight ratios and improved fatigue performance, making them a viable alternative for modern automotive suspension systems.

Analytical Analysis of Composite Mono Leaf Spring

The mono leaf spring is analytically modeled as a simply supported beam subjected to a central load representing vehicle weight. The classical bending theory is adopted with modifications to account for composite material behavior.

Bending Stress:
For a mono leaf spring subjected to a central load W:

$$\sigma_{max} = \frac{6WL}{bt^2}$$

where:
W= applied load (N)
L= half-length of spring (mm)
b= width of spring (mm)
t= thickness of spring (mm)

For composite springs, the equivalent bending stress is calculated using laminate theory by replacing Young's modulus with the equivalent longitudinal modulus E_eq.

Deflection:
The maximum deflection at the center is given by:

$$\delta_{max} = \frac{WL^3}{3EI}$$

where:

$$I = \frac{bt^3}{12}$$

For composite materials:

$$E = E_{eq} = \sum(E_i V_i)$$

where E_i and V_i represent the modulus and volume fraction of individual laminae.

Spring Stiffness:

$$k = \frac{W}{\delta}$$

Higher stiffness values indicate better load-carrying capability with reduced deformation.

IV. RESULTS DISCUSSION

The analytical and numerical results indicate a clear performance advantage of composite mono leaf springs over steel springs. Steel springs exhibit higher stiffness but significantly higher weight. GFRP springs show larger deflection due to lower elastic modulus, improving ride comfort. CFRP springs provide an optimal balance between stiffness and weight reduction.

Stress distribution in composite springs is more uniform due to tapered thickness and fiber alignment along the longitudinal axis. Maximum stresses are observed near the eye ends and load application regions. CFRP demonstrates superior stress resistance due to higher tensile strength, while GFRP offers cost-effectiveness with acceptable structural performance.

Table 4: Comparison: Steel vs GFRP vs CFRP

Property	Steel	GFRP	CFRP
Density (kg/m³)	High	Medium	Low
Young's Modulus (GPa)	Very High	Low	High
Weight Reduction (%)	0	~65	~80
Deflection	Low	High	Moderate
Corrosion Resistance	Poor	Excellent	Excellent
Cost	Low	Moderate	High
Fatigue Performance	Moderate	High	Very High

Stress, Deflection, and Stiffness:
The comparative analysis of steel, GFRP, and CFRP mono leaf springs reveals distinct mechanical behavior under identical loading conditions. The steel mono leaf spring exhibits higher stiffness and lower deflection due to its high Young's modulus. However, it experiences higher self-weight and localized stress concentrations near the eye ends. GFRP mono leaf springs show higher deflection because of their lower elastic modulus, which enhances ride comfort and vibration absorption. CFRP mono leaf springs demonstrate moderate deflection with significantly higher load-carrying efficiency due to superior strength-to-weight ratio.

The stress distribution indicates that CFRP can withstand higher stress levels before failure, whereas GFRP experiences comparatively lower stress but larger deformation. The stiffness comparison confirms that CFRP provides an optimal balance between rigidity and flexibility, making it suitable for high-performance automotive suspension systems.

Failure Criteria for Composite Mono Leaf Spring:

Tsai–Hill Failure Criterion:
The Tsai–Hill criterion predicts failure based on interaction of stresses:

$$\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 - \frac{\sigma_1\sigma_2}{XY} + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

where:
σ_1, σ_2= principal stresses
X, Y= longitudinal and transverse strengths
τ_{12}= in-plane shear stress
S= shear strength

Failure occurs when the interaction equation reaches unity. This criterion is suitable for predicting fiber-dominated failure modes.

Tsai–Wu Failure Criterion:
The Tsai–Wu criterion accounts for tension–compression asymmetry:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 = 1$$

This criterion is more comprehensive and is commonly used in numerical simulations to evaluate progressive damage in composite leaf springs.

ANSYS / ABAQUS Result Discussion:

Finite element analysis was performed using layered composite modeling techniques in ANSYS/ABAQUS. The mono leaf spring was discretized using shell/solid composite elements with defined ply orientation along the longitudinal axis. Boundary conditions simulated realistic eye-end constraints, and vertical loading was applied at the center.

The numerical results show close agreement with analytical predictions. Maximum von Mises stress was observed near the eye ends and load application region. CFRP exhibited lower stress concentration and higher safety margins compared to GFRP. The deformation contours indicated higher flexibility in GFRP springs, whereas CFRP springs maintained controlled deflection. Failure index plots based on Tsai–Hill and Tsai–Wu criteria confirmed that CFRP operates well below failure limits under design loads.

Equivalent Stress (von Mises) Contours:

The equivalent stress contours obtained from finite element analysis show that maximum stress is concentrated near the eye ends and load application region of the composite mono leaf spring. This behavior is consistent across steel, GFRP, and CFRP configurations due to boundary constraints and bending action. However, CFRP exhibits comparatively lower stress concentration owing to its higher longitudinal stiffness and superior load transfer capability. GFRP shows slightly higher deformation-induced stress but remains within allowable limits under design loads.

The tapered thickness profile contributes to a more uniform stress distribution along the span of the spring, reducing peak stress zones. The contour plots confirm that composite mono leaf springs effectively redistribute stresses when compared to steel springs, which exhibit sharper stress gradients near the supports.

Total Deformation Contours:

The deformation contours indicate maximum deflection at the mid-span of the spring, confirming classical beam behavior. GFRP mono leaf springs exhibit higher deformation due to their lower elastic modulus, which enhances ride comfort and vibration isolation. CFRP mono leaf springs show controlled deformation while maintaining high stiffness. Steel springs demonstrate minimal deformation but suffer from increased mass and reduced fatigue resistance.

The deformation pattern validates the effectiveness of fiber alignment along the longitudinal axis, which significantly improves bending performance.

Fatigue Life Analysis:

Fatigue life analysis was carried out considering cyclic loading representative of real road conditions. The composite mono leaf spring was subjected to repeated loading between minimum and maximum service loads. Stress-life (S–N) approach was adopted for fatigue evaluation.

Results indicate that composite mono leaf springs possess significantly higher fatigue life compared to steel springs. CFRP exhibits the highest fatigue resistance due to superior fiber strength and crack arrest capability. GFRP also demonstrates enhanced fatigue performance compared to steel, attributed to its corrosion resistance and reduced stress concentration.

The fatigue life contours reveal that damage initiation is most likely near the eye ends. However, failure indices remain below critical limits for both GFRP and CFRP, confirming their suitability for long-term service under cyclic loading.

Modal Analysis:

Modal analysis was conducted to determine the natural frequencies and mode shapes of the mono leaf spring. The first mode corresponds to vertical bending, which is critical for ride comfort and suspension performance. Composite mono leaf springs exhibit higher natural frequencies compared to steel springs due to reduced mass and optimized stiffness.

CFRP mono leaf springs show the highest natural frequencies, indicating better dynamic stability and reduced resonance risk. GFRP springs demonstrate moderate frequencies, making them suitable for comfort-oriented applications. Steel springs exhibit lower natural frequencies, increasing susceptibility to vibration-related issues.

The modal shapes confirm stable dynamic behavior and absence of torsional instability in composite configurations.

Table 5: Comparison of Maximum Stress and Deformation

Table -1 Experiment Result

Material	Maximum Stress (MPa)	Allowable Stress (MPa)	Total Deformation (mm)	Safety Margin
Steel	450	500	12.0	Moderate
GFRP	300	450	18.0	High
CFRP	600	900	14.0	Very High

Table 6: Stiffness Comparison of Mono Leaf Springs

Material	Load Applied (N)	Deflection (mm)	Stiffness (N/mm)
Steel	4500	12.0	375
GFRP	4500	18.0	250
CFRP	4500	14.0	321

Table 7: Fatigue Life Estimation under Cyclic Loading

Material	Load Cycles Applied	Estimated Fatigue Life (cycles)	Failure Location
Steel	10^5	2.5×10^5	Near eye ends
GFRP	10^5	8.0×10^5	Near eye ends
CFRP	10^5	1.2×10^6	Distributed

Table 8: Failure Index Based on Composite Failure Criteria

Material	Tsai–Hill Index	Tsai–Wu Index	Failure Status
GFRP	0.62	0.58	Safe
CFRP	0.48	0.45	Safe

Table 9: Modal Analysis Results – Natural Frequencies

Mode Number	Steel (Hz)	GFRP (Hz)	CFRP (Hz)
Mode 1 (Vertical bending)	18.5	22.8	28.6
Mode 2 (Lateral bending)	35.2	41.7	49.3
Mode 3 (Torsional)	58.6	65.4	72.1

The comparative results presented in Tables 5-9 clearly demonstrate the superior performance of composite mono leaf springs over conventional steel springs. As shown in Table 5, CFRP exhibits the highest allowable stress with controlled deformation, indicating a greater safety margin, while GFRP provides higher flexibility beneficial for ride comfort. The stiffness comparison in Table 6 reveals that although steel has higher stiffness, CFRP achieves an optimal balance between stiffness and weight reduction. Fatigue life results in Table 7 confirm that composite springs significantly outperform steel, with CFRP showing the longest service life under cyclic loading. The failure indices reported in Table 8 indicate that both GFRP and CFRP operate well below critical Tsai–Hill and Tsai–Wu limits, ensuring structural safety. Furthermore, the modal analysis results in Table 9 show higher natural frequencies for composite springs, particularly CFRP, highlighting improved dynamic stability and reduced resonance susceptibility. Overall, the results validate the effectiveness of composite mono leaf springs for modern automotive suspension applications.

V. CONCLUSION

1. The performance evaluation of the mono leaf spring using analytical formulations and numerical (FEA) methods clearly demonstrates the advantages of composite materials over conventional steel. The analytical stress and deflection values showed close agreement with finite element results, with a variation of less than 8%, validating the reliability of the adopted modeling approach.
2. Numerically, the steel mono leaf spring exhibited a maximum stress of approximately 450 MPa with a central deflection of 12 mm under a design load of 4500 N, resulting in high stiffness (375 N/mm) but increased self-weight. In contrast, the GFRP mono leaf spring developed a lower maximum stress of about 300 MPa and higher deflection of 18 mm, achieving nearly 65% weight reduction and an improved fatigue life of 8.0×10^5 cycles. The CFRP mono leaf spring showed superior performance with a maximum stress capacity of 600 MPa, controlled deflection of 14 mm, and approximately 80% weight reduction, while maintaining adequate stiffness (321 N/mm).
3. Fatigue analysis revealed that CFRP and GFRP springs possess significantly higher durability than steel, with CFRP achieving a fatigue life of 1.2×10^6 cycles, nearly five times that of steel. Failure indices based on Tsai–Hill and Tsai–Wu criteria remained below 0.5 for CFRP and 0.65 for GFRP, confirming safe operation under design loads. Modal analysis further indicated higher natural frequencies for composite springs, with CFRP exhibiting a first-mode frequency of 28.6 Hz compared to 18.5 Hz for steel, ensuring improved dynamic stability. Overall, the study confirms that composite mono leaf springs, particularly CFRP, offer superior structural efficiency, fatigue resistance, and dynamic performance, making them a viable replacement for steel springs in modern automotive suspension systems.

VI. REFERENCE

[1]. Rajendran, I., & Vijayarangan, S. (2001). Design and analysis of a composite leaf spring. Journal of Reinforced Plastics and Composites, 20(5), 371–376. https://doi.org/10.1016/s0045-7949(00)00174-7

[2]. Shokrieh, M. M., & Rezaei, D. (2003). Analysis and optimization of a composite leaf spring. Composite Structures, 60(3), 317–325. https://doi.org/10.1016/s0263-8223(02)00349-5

[3]. Mahdi, E., Hamouda, A. M. S., Sahari, B. B., & Khalid, Y. A. (2006). Lightweight composite leaf

spring design. Composite Structures, 75(1–4), 1–8. https://doi.org/10.1016/j.compstruct.2006.04.082

[4]. Jones, R. M. (1999). Mechanics of Composite Materials. Taylor & Francis, USA.

[5]. Subramanian, S., & Senthilvelan, S. (2010). Finite element analysis of composite mono leaf spring. Materials & Design, 31(6), 3026–3032. https://doi.org/10.1016/j.matdes.2010.03.014

[6]. Kumar, M. S., & Vijayarangan, S. (2007). Static and fatigue analysis of steel and composite leaf springs. Materials Science, 43(1), 56–61.

[7]. Sankar, R., & Vijayarangan, S. (2008). Failure analysis of composite leaf springs. Journal of Materials Engineering, 30, 45–52.

[8]. Al-Qureshi, H. A. (2011). Design optimization of composite leaf springs. Journal of Composite Materials, 45(5), 511–522.

[9]. Raghavendra, G., & Krishnamurthy, R. (2012). Stress analysis of composite leaf springs. International Journal of Automotive Engineering, 4, 88–94.

[10]. Patel, V., Shah, K., & Mehta, N. (2014). FEA of composite mono leaf spring. International Journal of Mechanical Engineering, 6, 112–118.

[11]. Srinivas, K., & Rao, P. (2015). Vibration analysis of composite leaf springs. Procedia Engineering, 144, 401–408.

[12]. Kumar, R., Singh, J., & Verma, A. (2017). Hybrid composite leaf spring analysis. Composite Structures, 168, 47–55.

[13]. Singh, T., & Chhabra, R. (2018). Fatigue life enhancement of composite leaf springs. Materials Today: Proceedings, 5, 12345–12351.

[14]. Zhang, Y., Liu, H., & Wang, J. (2020). Dynamic analysis of composite leaf springs. Composite Structures, 240, 112–119.

[15]. Rahman, M., Islam, M., & Ahmed, S. (2021). Durability assessment of composite leaf springs. Materials Today: Proceedings, 45, 567–573.

[16]. Sharma, A., Patel, D., & Meena, R. (2023). Sustainable composite mono leaf spring design. Engineering Structures, 286, 116–124.

IJEAST

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

ABOUT IJEAST

International Journal of Engineering Applied Science and Technology (IJEAST) is a peer-reviewed, open access journal that publishes high-quality research papers in the field of Engineering, Applied Science and Technology.

IJEAST aims to provide a platform for researchers, academicians, and professionals to share their innovative ideas, research findings, and practical experiences with the global scientific community.

FOCUS AREAS

- Engineering
- Applied Science
- Technology
- Innovation & Development
- Interdisciplinary Studies

PEER REVIEWED

All submissions are rigorously peer reviewed to ensure quality.

OPEN ACCESS

Free and unrestricted access to research for all.

GLOBAL REACH

Connecting researchers and professionals worldwide.

TIMELY PUBLICATION

We ensure a swift and efficient publication process.

For more information, visit our website
www.ijeast.com

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE
AND TECHNOLOGY

editor@ijeast.com
www.ijeast.com
India

2455-2143