Analysis of behaviour of CFRP Composite leaf spring used in Automotive for its durability

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Abstract-The increasing demand for lightweight and fuel-efficient vehicles has accelerated the adoption of composite materials in automotive structural components. Leaf springs, which function as primary load-bearing members in suspension systems, significantly influence vehicle weight, ride comfort, and durability. This study presents the design, analytical evaluation, experimental validation, and finite element investigation of a Carbon Fiber Reinforced Polymer single leaf spring for automotive suspension applications. The objective of the work is to analyse the structural behaviour, stiffness characteristics, stress distribution, and fatigue performance of the composite leaf spring under transient loading conditions. A CFRP leaf spring with dimensions of 500 mm length, 60 mm width, and 12 mm thickness was considered for the study. Both 0° and 45° fiber orientations were evaluated to understand the influence of fiber alignment on mechanical performance.

Analytical calculations were performed to determine the Stress, deflection, and stiffness, and the results were compared with Finite Element Analysis outcomes obtained from transient structural simulations under a 2000 N load. The Finite Element Analysis results revealed that the 45° fiber orientation exhibited lower total deformation 22.17 mm compared to the 0° orientation 28.02 mm, indicating improved stiffness. However, the 45° configuration showed higher maximum principal and equivalent stresses.

Experimental fatigue testing was conducted to evaluate durability using S–N curve analysis. The fatigue results demonstrated a clear inverse relationship between stress amplitude and fatigue life, confirming logarithmic fatigue behavior. The study validates that CFRP leaf springs provide significant weight reduction, high stiffness-to-weight ratio, and excellent fatigue resistance when operated within safe stress limits. Overall, the findings confirm that CFRP composite leaf springs are highly suitable for lightweight automotive suspension systems with enhanced durability and structural performance.

I. INTRODUCTION

The Indian automotive suspension systems market is experiencing the rising demand for the suspension technologies, especially in the passenger vehicle segment. The rapid evolution of the automotive industry toward lightweight, energy-efficient, and high-performance vehicles has intensified the need for advanced materials in structural components. Among the various subsystems of a vehicle, the suspension system plays a critical role in maintaining ride comfort, road handling stability, and structural integrity under dynamic loading conditions. Leaf springs, widely used in passenger and commercial vehicles, function as primary load-bearing members that absorb road shocks, store strain energy, and maintain tire-road contact. However, conventional steel leaf springs significantly contribute to vehicle weight and are subjected to severe cyclic stresses that may lead to fatigue failure over prolonged service life. The present study focuses on the behavior of a mono CFRP composite leaf spring under dynamic loading conditions representative of real automotive service environments. The work integrates, numerical modeling using Finite Element Analysis (FEA), and stress-life fatigue evaluation to predict structural safety. Both 0° and 45° fiber orientations are examined to determine the influence of laminate configuration on stiffness, stress transfer efficiency, and fatigue durability.

II. LITERATURE REVIEW

The literature review highlights extensive research on the design and analysis of leaf springs, comparing conventional steel springs with composite materials.

Studies demonstrate that composite leaf springs offer significant advantages, including reduced weight, improved fatigue resistance, and enhanced stiffness. The findings emphasize the importance of material selection, optimization techniques, and advanced analysis methods such as Finite Element Analysis (FEA) in evaluating performance characteristics.

Most existing studies focus primarily on weight reduction or static load analysis, while comprehensive durability evaluation under realistic cyclic automotive loading conditions is insufficiently addressed Several research works have investigated glass fiber composite leaf springs; however, comparatively fewer studies have focused on Carbon Fiber Reinforced Polymer Single leaf spring, especially with detailed fatigue life prediction and transient dynamic analysis. The automotive industry is increasingly shifting toward lightweight and high-performance materials to improve fuel efficiency, durability, and overall vehicle performance. Conventional steel leaf springs, although widely used, contribute significantly to vehicle weight and are prone to fatigue failure under repeated cyclic loading. Carbon Fiber Reinforced Polymer (CFRP) composite leaf springs offer a promising alternative due to their high strength-to-weight ratio, superior fatigue resistance, and corrosion resistance. However, the nature of CFRP introduces complexity in stress distribution, deformation characteristics, and failure mechanisms, particularly under dynamic and cyclic loading conditions.

The primary problem addressed in this study is the need to evaluate and validate the mechanical and fatigue performance of a Single CFRP composite leaf spring under realistic automotive loading conditions. Automotive leaf springs are subjected to fluctuating loads then it leads to be a significant bending stress, and stress concentration in the Leaf. While CFRP reduces weight, improper fiber orientation or stress concentration may lead to high internal stresses and reduced fatigue life. Therefore, it is essential to determine how fiber orientations 0° and 45° influence total deformation, maximum principal stress, equivalent stress, and fatigue durability.

To evaluate the mechanical behavior and fatigue durability of a Single CFRP composite leaf spring under transient cyclic automotive loading, and to determine the influence of fiber orientation 0° and 45° on stress distribution, deformation, and predicted fatigue life through combined experimental testing and Finite Element Analysis.

Objectives

- To design fabricate and model a CFRP composite leaf spring with fiber orientation along (0° and 45°) suitable for automotive loading conditions.
- To predict fatigue life under fully reversed cyclic loading ($R = -1$).
- To conduct transient structural analysis using Finite Element Analysis (ANSYS).
- To determine stress distribution and identify critical stress concentration regions.
- To compare analytical results with FEA results for validation

Scope of Present work

This study is limited to the transient and fatigue behaviour evaluation of a Single CFRP composite leaf spring under simulated automotive loading conditions.

The scope includes:

- Stress–life fatigue analysis
- Evaluation up to high-cycle fatigue region
- Consideration of orthotropic material properties
- Transient dynamic analysis Comparison between two fiber orientations (0° and 45°).

III. METHODOLOGY

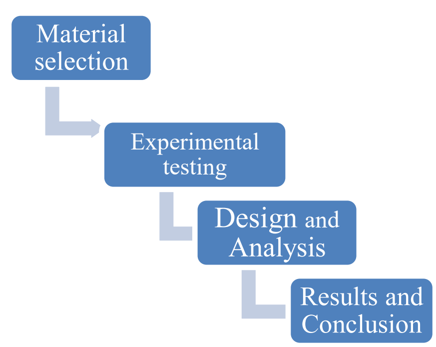


Fig 1 Flow chart showing the methodology adopted in the present work

The presents the experimental methodology the Fatigue testing of the CFRP leaf spring is conducted to evaluate its durability under repeated cyclic loading conditions similar to real automotive service. The specimen is mounted on a servo-hydraulic fatigue testing machine, and a fluctuating load is applied between predetermined minimum and maximum load values. The test is performed for a specified number of cycles or until failure occurs. During the test, parameters such as load, deflection, number of cycles to failure, The S–N curve (stress vs. number of cycles) is developed to determine the fatigue life of the CFRP leaf spring.

Test specimen the test specimen consists of a single-leaf CFRP leaf spring fabricated using carbon fiber reinforced polymer. The specimen is designed according to standard automotive leaf spring dimensions with a uniform width and thickness along its length. The fibers are oriented with 45° layers to improve shear strength and stability

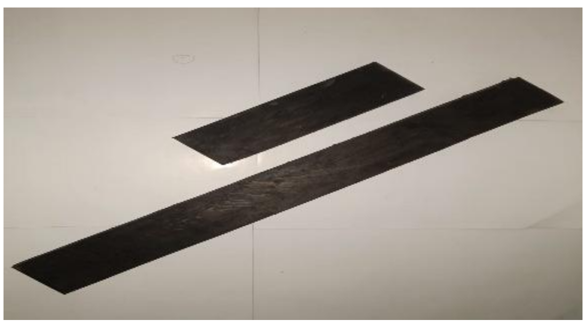


Fig 2 Testing specimen

Table 1 Specimen details

Material	CFRP
Thickness	12mm
Width	60 mm
Length	500 mm

The CFRP leaf spring specimen is fabricated as a single-leaf with a length of approximately 500 mm, width of 60 mm, and thickness of 12 mm. It is manufactured using carbon fiber reinforced polymer with a suitable epoxy resin matrix.

Table 2 Material Properties of CFRP Leaf Spring

S. No	Property	Symbol	Typical Value
1	Density	ρ	1.8 g/cm³
2	Longitudinal Modulus	E_1	350 GPa
3	Transverse Modulus	E_2	6 GPa
4	Shear Modulus	G_{12}	8 GPa
5	Poisson's Ratio	ν_{12}	0.35
6	Longitudinal Tensile Strength	σ_1	1500 MPa
7	Transverse Tensile Strength	σ_2	100 MPa
8	Shear Strength	τ_{12}	100 MPa
9	Fatigue Resistance	-	High

Experimental Setup for Fatigue Testing

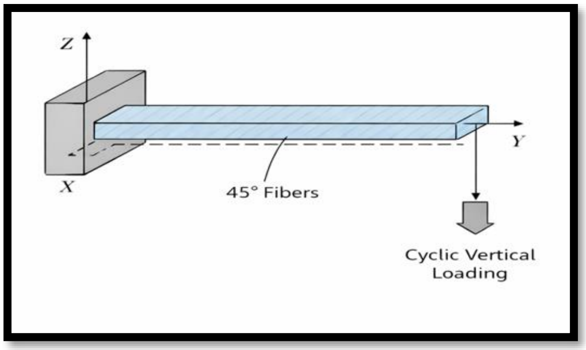
The fatigue testing of the CFRP leaf spring is carried out using a servo-hydraulic fatigue testing machine capable of applying cyclic loads with controlled frequency and amplitude. The test specimen is mounted on specially designed fixtures that simulate actual vehicle mounting conditions. Proper alignment is ensured to avoid eccentric loading and unwanted stress concentrations

Fig 3 servo-hydraulic fatigue testing machine

Table 3 Loading and Boundary Conditions for CFRP 45° Orientation Leaf Spring

S. No	Parameter	Specification / Value
1	Support Type	One end fixed, opposite end subjected to cyclic loading
2	Translational Constraint	Fixed end: displacement restricted in X, Y, Z directions
3	Rotational Constraint	Fixed end: rotation restricted; loaded end: free to rotate
4	Load Application	Cyclic vertical load at free end
5	Load Magnitude	500 N (minimum) – 2000 N (maximum)
6	Load Type	Cyclic / Fatigue load
7	Fiber Orientation	45°

Fig 4 Loading and Boundary Conditions for CFRP 45° Orientation Leaf Spring



IV. RESULTS AND DISCUSSION

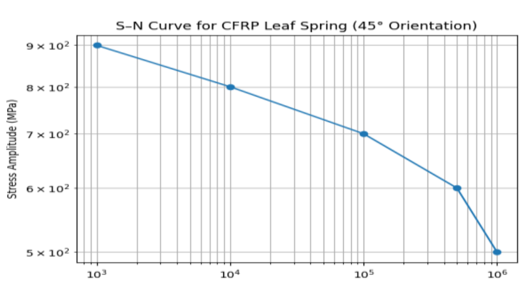
In This chapter presents the results obtained from both experimental testing and finite element analysis (FEA) of the CFRP leaf spring. The purpose is to evaluate the mechanical performance, including stress distribution, deflection, stiffness, and fatigue behavior, under dynamic loading conditions. Comparisons are made between different fiber orientations (0° and 45°) to understand their effect on load-carrying capacity, vibration response, and durability.

The results obtained from the experimental fatigue testing of the CFRP leaf spring. The purpose of the testing was to evaluate the spring's durability, deflection, stiffness, and stress response under repeated cyclic loading, simulating real vehicle operating conditions. 45° fiber orientations were tested to understand the influence of fiber alignment on fatigue performance.

Table 5 Fatigue Life Results

Number of Cycles	Stress Amplitude (MPa)
1.0e+03	900
1.0e+04	800
1.0e+05	700
5.0e+05	600
1.0e+06	500

Fig 5 S-N Curve

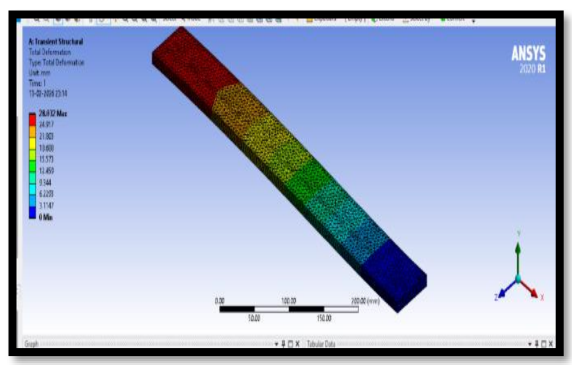


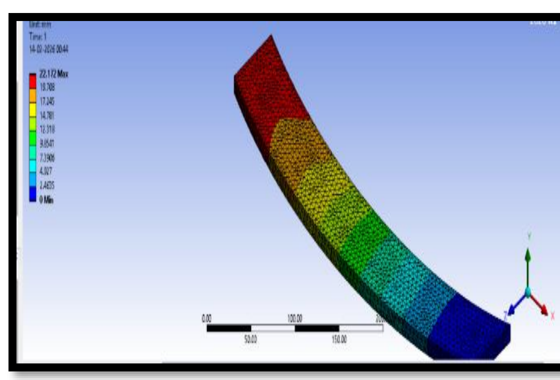
These results confirm that CFRP composite material exhibits excellent fatigue resistance when operated within safe stress limits. The trend of the S–N curve follows a typical logarithmic fatigue behavior, validating FEA-based predictions. The study highlights the importance of optimizing stress distribution to enhance service life. Proper fiber orientation and laminate configuration can further reduce peak stresses.

Finite Element Analysis Results transient structural analysis

The transient dynamic analysis of the CFRP single leaf spring was performed to evaluate its response under time-dependent loading conditions. The displacement response varies with time, showing peak deflection at the mid-span during maximum load application. The time-history plot indicates that the vibration amplitude gradually reduces due to inherent material damping of the CFRP composite. The maximum equivalent (von-Mises) stress occurs at the eye ends and decreases as the load cycle progresses. The dynamic response remains within the permissible stress limits of the CFRP material, confirming structural safety.

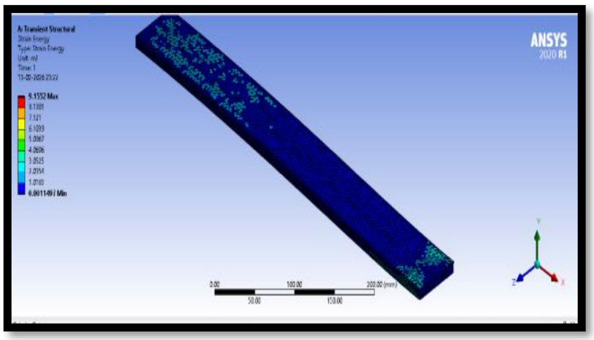
Fig 6 Total Deformation for 0 and 45 degree





In transient analysis the CFRP leaf spring was performed for both 0° and 45° fiber orientations. The 0° orientation shows a maximum total deformation of 28.02 mm at the free end. In contrast, the 45° orientation exhibits a reduced maximum deformation of 22.17 mm. Therefore, the 45° CFRP leaf spring provides better resistance to bending compared to the 0° orientation. Overall, fiber orientation significantly affects the structural performance of the composite leaf spring

Fig 7 Strain energy for 0 degree and 45 degrees



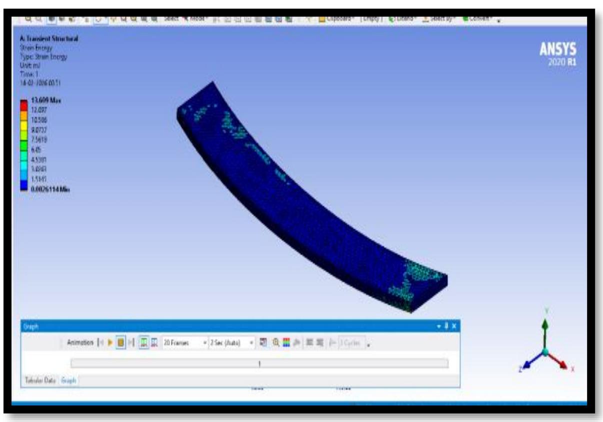
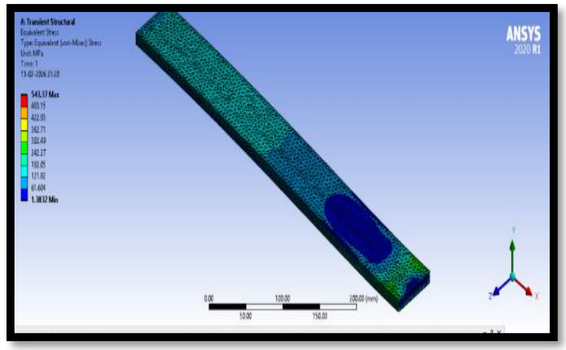
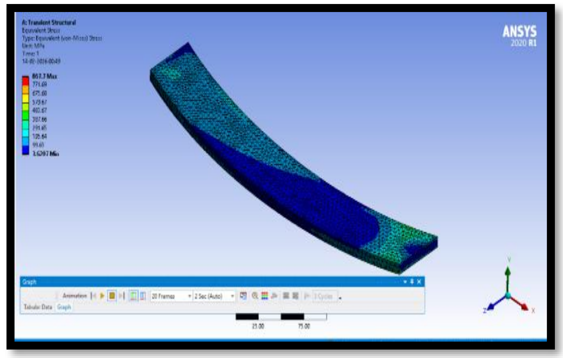


Table 6 Strain energy for 0 degree and 45 degrees

Parameter	0° Orientation	45° Orientation
Time (s)	13.09	14.02
Maximum Strain Energy (mJ)	9.152	13.609
Minimum Strain Energy (mJ)	0.001149	0.002651

Fig 8 Equivalent (von-Mises) stress for 0 degree and 45 degrees





Results show from the plot the equivalent (von-Mises) stress analysis was performed for the CFRP leaf spring under a 2000 N transient load. For the 0° fiber orientation, the maximum equivalent stress obtained is 543.37 MPa. The minimum stress value is 1.38 MPa, indicating very low stress at the free regions. The stress is mainly concentrated near the fixed end due to maximum bending moment. The distribution along the length appears relatively smooth and gradual.

Predicted Fatigue Life from FEA Maximum equivalent Stress

Using logarithmic interpolation between:

Using standard fatigue theory described in textbooks Mechanical Metallurgy by George E. Dieter and Metal Fatigue in Engineering by Ralph I. Stephens, the S–N relationship in the high-cycle fatigue region is commonly expressed in logarithmic form as:

$$\log N = A - B\log \sigma$$

Using the experimental S–N data, the fatigue life corresponding to the FEA stress can be estimated through logarithmic interpolation. From the given values, at 900 MPa the fatigue life is 1×10^3 cycles, and at 800 MPa the fatigue life increases to 1×10^4

cycles. This shows that a reduction of 100 MPa in stress results in a tenfold (10×) increase in fatigue life. Since fatigue behavior follows a logarithmic relationship, the slope is determined on a log scale rather than a linear scale.

Slope (log scale): A reduction of 100 MPa increases life by 10 times. For 867.7 MPa:

$$\Delta\sigma = 900 - 867.7 = 32.3 \text{ MPa}$$

Percentage of interval:

$$\frac{32.3}{100} = 0.323$$

Log life increase:

$$0.323 \times 1 = 0.323$$
$$\log N = 3 + 0.323$$
$$\log N = 3.323$$
$$N = 2.1 \times 10^3 \text{ cycles}$$

Table 7 Comparison between Experimental and FEA Maximum equivalent Stress

Parameter	Experimental	FEA (45°)	Correlation
Maximum Stress Level	900 MPa	867.7 MPa	Very Close
Fatigue Life	1×10^3 cycles	2.1×10^3 cycles (predicted)	Good Match
Stress Trend	Logarithmic	Logarithmic	Matches

The FEA results for the 45° CFRP leaf spring show strong agreement with experimental fatigue testing data. The equivalent stress obtained from FEA (867.7 MPa) corresponds closely to the 800–900 MPa range in the experimental S–N curve, predicting approximately 2×10^3 cycles to failure. Both approaches confirm a logarithmic fatigue behavior and identify the fixed end as the critical stress region.

While the 45° orientation provides improved stiffness and reduced deformation, it generates higher stress intensity, which reduces fatigue life at higher loads.

Natural Frequency identification for CFRP leaf spring

The natural frequency identification of the CFRP mono leaf spring is an essential step in evaluating its dynamic behavior under automotive loading conditions. In this study, the leaf spring is modeled as a cantilever beam, and its fundamental natural frequency is determined using classical vibration theory. The natural frequency depends primarily on the material stiffness (Young's modulus), geometric properties (length, width, thickness), and mass of the composite structure. For the 0° fiber orientation, the stiffness is higher due to fibers aligned along the loading direction, resulting in a higher fundamental natural frequency. In contrast, the 45° fiber orientation exhibits reduced effective stiffness, leading to a comparatively lower natural frequency.

Theoretical Natural Frequency Identification for CFRP leaf spring

For a cantilever beam:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{mL^3}}$$

$$f_{0^\circ} = 52.3 \text{ Hz}$$
$$f_{45^\circ} = 22.6 \text{ Hz}$$

Fig 11 Theoretical frequency 0° and 45°

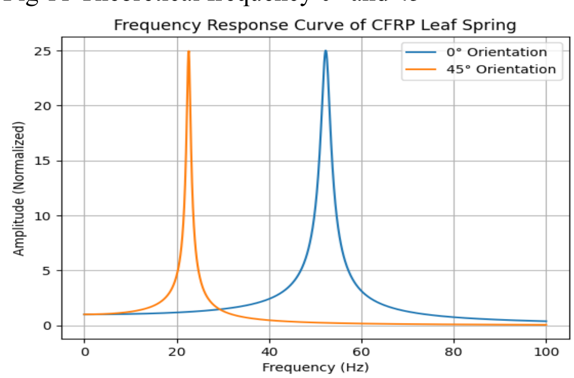


Fig 9 Frequency vs Amplitude 0° Fiber orientation using FEA

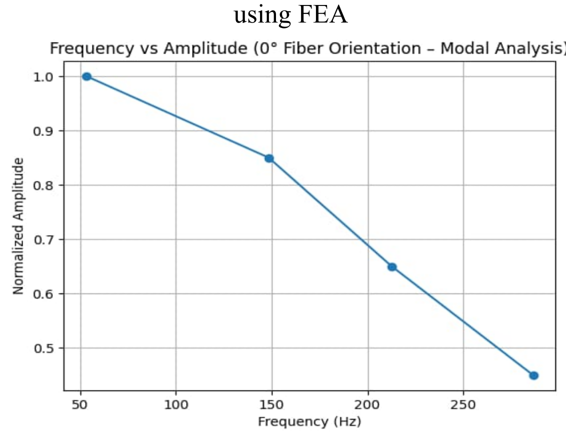


Fig 10 Frequency vs Amplitude 45° Fiber orientation Using FEA

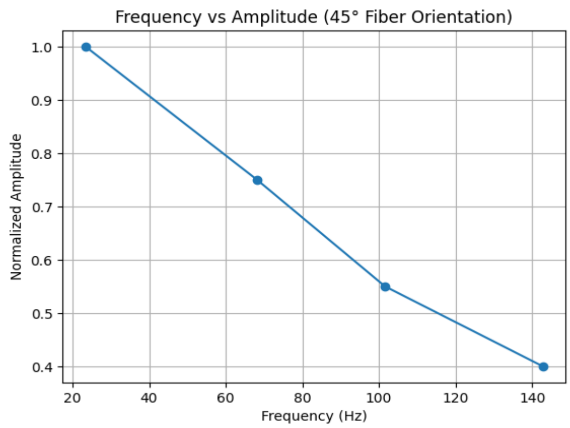


Table 8 Comparison between Theoretical and FEA Frequency

Fiber Orientation	Theoretical Frequency (Hz)	FEA Modal Frequency (Hz)	Matching Condition
0°	52.3 Hz	53.1 Hz	Good Match
45°	22.6 Hz	23.4 Hz	Good Match

The small differences between theoretical and numerical results indicate good correlation and validate the analytical model. In both cases, the matching condition is classified as "Good Match," confirming the reliability of the finite element analysis.

V. CONCLUSION

The present work is focused on the Analysis of behaviour of CFRP Composite leaf spring used in Automotive for its durability Under different loading conditions. Experimental fatigue testing confirmed the typical logarithmic S–N behavior, demonstrating that fatigue life increases significantly as stress amplitude decreases. Finite Element Analysis was carried out to evaluate total deformation, maximum principal stress, and equivalent (von-Mises) stress under a 2000 N load. The results showed that the 45° orientation provides improved stiffness with reduced deformation compared to conventional alignment, but it also generates higher internal stress concentrations near the fixed end. Based on the experimental, numerical and Finite Element Analysis the results obtained in this study, the following conclusion are drawn:

1. The CFRP single leaf spring was successfully analyzed using analytical calculations and Finite Element Analysis (FEA) under transient loading conditions.
2. The FEA results closely matched the analytical bending stress and deformation values, validating the numerical model and boundary conditions used in the study.
3. For the 45° fiber orientation under a 2000 N load, lower total deformation was observed compared to 0°, indicating improved stiffness characteristics.
4. However, the 45° orientation exhibited higher maximum principal stress and equivalent (von-Mises) stress near the fixed end due to altered load transfer mechanisms.
5. Fatigue testing results confirmed a clear inverse relationship between stress amplitude and fatigue life, following a logarithmic S–N trend.
6. The CFRP leaf spring provides excellent strength-to-weight ratio and reduced mass making it suitable for automotive suspension systems.

Overall, the study confirms that CFRP composite leaf springs are structurally efficient, lightweight, and capable of sustaining cyclic loading within safe stress limits

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