SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V13I7P116

Volume 13 Issue 7, 188-198, July 2026

Original Article

Experimental Vibration Analysis of a GFRP Mono-Composite Leaf Spring for Automotive Suspension Applications: Stiffness, Natural Frequency, and Transmissibility Evaluation

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Received: 13 March 2026 Revised: 30 April 2026 Accepted: 13 July 2026 Published: 30 July 2026

Abstract **-** *In the automotive sector, the demand for composite materials within suspension systems increases day by day, as it has an advantageous combination of stiffness and low density, superior damping characteristics, and enhanced resistance to both corrosion and fatigue. This study investigates the vibrational characteristics of a mono composite leaf spring made by using Glass Fiber Reinforced Polymer (GFRP), which is the best substitute for a conventional steel leaf spring in light-duty commercial vehicles. The GFRP mono composite leaf spring, consisting optimum volume of a 60% E-glass fiber and a 40% epoxy matrix, and it was fabricated using the hand lay-up process. After that, it underwent experimental testing to determine its static Stiffness, natural frequency, and also the transmissibility. Assessment of static Stiffness was done by employing a Universal Testing Machine (UTM). Furthermore, a natural frequency characteristic was analysed by utilizing a Fast Fourier Transform (FFT) analyser, and to determine the transmissibility, a bespoke harmonic excitation system incorporating a cam–follower mechanism was utilized. The investigation reveals that the GFRP mono composite leaf spring exhibits a rigidity that is 44.14% superior, a mass reduction is 57.93%, and a natural frequency that is 49.91% elevated if compared to the steel leaf spring. Transmissibility at various frequencies indicated a substantial attenuation in transmitted vibration up to 60.60% in the GFRP mono composite leaf spring when compared with the traditional steel leaf spring. This study reveals that the GFRP mono composite leaf spring is very highly effective in vibration isolation. Consequently, the results conclude that the implementation of GFRP leaf springs in automotive applications will enhance ride comfort, reduce the chance of resonance, and improves dynamic stability.*

Keywords *- GFRP Composite Leaf Spring, Mono Leaf Spring, Natural Frequency, Transmissibility, Vibration Analysis, Automotive Suspension, Fft Analyser.*

1. Introduction

One of the most significant load-bearing components in automotive suspension systems is the Leaf Springs, serving multiple functions including supporting vehicle weight, absorbing road-induced shocks, maintaining wheel alignment, and improving ride comfort. Conventional steel multi-leaf springs have been widely employed because of their high strength, simple manufacturing process, and low production cost. However, their high mass increases the unsprung mass of the vehicle, which results in a reduction in efficiency of fuel, poor vibration isolation, and lower fatigue life under continuous cyclic loading [1-3]. As demand for lightweight and energy-efficient vehicles increases, considerable research has focused on substituting Fiber-Reinforced Polymer (FRP) composite leaf springs instead of conventional steel springs that offer superior specific strength, corrosion resistance, fatigue durability, and vibration damping characteristics [1], [3-6]. Number of researchers have shown the structural and weight-saving benefits of composite leaf springs. Mahdi and Hamouda [1] done experimental investigation of hybrid and non-hybrid composite semi-elliptical leaf springs and found that previous studies achieved nearly 80% weight reduction using GFRP mono leaf springs compared with conventional steel springs. Their experimental fatigue analysis further showed that the useful spring stroke decreased by only 2% after 1.15 million loading cycles, indicating excellent fatigue resistance and structural stability. Similarly, Wang et al. [3] validated finite element results through experimental testing and found a 60–70% reduction in spring weight while maintaining the required load-carrying capacity. The finite element spring rate (160 N/mm) closely matched the experimental value (157.5 N/mm) with only 1.56% error. In contrast, the maximum load prediction reported an error of merely 0.82%, which shows the reliability of finite element analysis for composite leaf spring design. Extensive numerical and experimental researches have been conducted to enhance the structural performance of composite leaf springs. Finite element analyses have demonstrated that proper selection of fiber material, laminate configuration, and spring geometry significantly improves stress distribution while reducing overall spring weight [3-8].

Qureshi [6] investigated that GFRP leaf springs fabricated using hand lay-up and vacuum-bagging techniques were able to sustain full-load static tests without delamination or structural failure. Optimization studies have further shown that GFRP and hybrid composite leaf springs have lower stress concentration, higher Stiffness, and better load-carrying capability than conventional steel springs [5, 6, 8]. Singh and Rastogi [9] selected a proper laminate and performed a comparison of static analysis using different composite materials and identified significant improvements in stress reduction.

Fatigue durability is the most significant design requirement because suspension systems undergo millions of cycles of variable-amplitude loads throughout the course of their service life. Kong et al. [2] researched the fatigue life of parabolic leaf springs under highway, mountain, and rough-road conditions and found that road excitation significantly influences fatigue performance. A rough road produces the minimum fatigue life. The authors emphasized fatigue life prediction based on actual road loading conditions, which provides more realistic durability estimation than conventional constant-amplitude laboratory tests. Other researchers also confirmed that composite leaf springs have superior fatigue resistance because of their higher specific strength and inherent damping characteristics, making them suitable for long-term automotive applications [1, 6, 10, 11].

The vibration characteristics of leaf springs have become increasingly important because continuous road excitation gradually reduces suspension stiffness and also deteriorates the natural frequency of the system. Recent researches have emphasized modal analysis, vibration behaviour, and optimization of composite leaf springs, demonstrating higher natural frequencies and improved vibration damping characteristics compared to the conventional steel springs [12-16]. Experimental researches have further demonstrated that optimization of fiber orientation, reinforcement percentage, and composite lay-up enhances structural Stiffness, reduces vibration transmission and improves ride comfort [14-20]. These investigations clearly demonstrate the potential of composite materials for developing lightweight, durable, and vibration-resistant suspension systems.

Despite extensive investigation on the design, static, and fatigue behaviour of composite leaf springs, comprehensive experimental studies simultaneously addressing static Stiffness, natural frequency, and vibration transmissibility under controlled laboratory conditions remain limited.

To address this gap, the present experimental study compares a commercially used steel leaf spring with a newly developed GFRP composite leaf spring. The GFRP leaf spring was manufactured using a unidirectional E-glass/epoxy composite, which exhibited a 58% reduction in weight when compared to the conventional steel spring. Experimental static testing using a Universal Testing Machine revealed that the GFRP mono composite leaf spring achieved a stiffness of 56.62 N/mm, which is 44.14% higher than the steel leaf spring stiffness of 39.28 N/mm.

Experimental and Fast Fourier Transform-based modal testing indicated that the natural frequency of 16.73 Hz (Experimental) and 16 Hz (FFT) for the GFRP mono composite leaf spring, compared with 11.16 Hz and 11 Hz for the conventional steel leaf spring, representing an increase of 49.91%. Transmissibility tests conducted over a range of excitation frequencies revealed that the GFRP mono composite leaf spring transmits approximately 60% less vibration than the steel spring under laboratory conditions.

These experimentally verified results indicate that GFRP mono-composite leaf springs have improved Stiffness, higher natural frequency, and superior vibration isolation characteristics when compared to conventional steel leaf springs. It indicates that the GFRP mono composite leaf spring shows strong potential for enhancing vibration isolation and reducing resonance susceptibility in the automotive suspension system.

2. Materials and Methods

2.1 Materials and Leaf Spring Specifications

A steel leaf spring of a light commercial vehicle (TATA ACE) and a mono composite leaf spring manufactured by using E-glass fiber and epoxy resin were studied to investigate and compare the mechanical properties. Both springs have been designed to have identical functional lengths to facilitate a direct comparison of their stiffness and vibration characteristics.

The steel leaf spring has a total length of 1060 mm in total length, with an eye-to-eye distance of 990 mm, and a uniform cross-section of 60 mm width and 8 mm thickness. The mass was measured at 7.979 kg. The GFRP mono composite leaf spring has a constant cross-section for uniform stress distribution. At the centre, it has a thickness of 28 mm, and it tapers to 14 mm at the ends. The width of the composite spring is 52 mm at the center and 99 mm at the end regions. The composite constituent's lower density led to a final mass of 5.122 kg with steel eye fittings and 2.075 kg without steel eye fittings, indicating a 57.93% weight reduction. See Figures 1 and 2.

Fig. 1 The mass of the composite mono leaf spring with eye

Fig. 2 The mass of the GFRP composite mono leaf spring without eye

Table 1. Specifications of steel and GFRP composite leaf springs

Parameter	Steel Leaf Spring	GFRP Mono Composite Leaf Spring
Total length (mm)	1060	1060
Eye-to-eye length (mm)	990	990
Width (mm)	60	52 (centre), 99 (end)
Thickness (mm)	8	28 (centre), 14 (end)
Mass (kg)	7.979	5.122 (with eye), 2.075 (without eye)
Weight reduction	–	57.93%

The composite spring was manufactured from unidirectional E-glass fibres and epoxy matrix in a ratio of 60:40 by volume. Mechanical properties of the material constituents used in design calculations are provided in Table 2.

Table 2. Mechanical properties of composite constituents

Property	E-glass Fibre	Epoxy Resin
Young's modulus (GPa)	72.3	3.45
Tensile strength (MPa)	3445	82
Density (g/cm³)	2.55	1.2

2.2. Design Methodology

The composite spring was designed to match or exceed the steel spring's Stiffness, all while maintaining stress within safe limits during operation. To find the necessary cross-sectional dimensions, we used classical laminate theory and beam bending equations.

The rule of mixtures was used to determine the effective longitudinal Stiffness of the composite material. For unidirectional laminates, when the load is applied along the fiber direction, the longitudinal modulus, represented as E_l, is given by the following equation:

Where E_f and E_m are the elastic modulus of fibre and matrix, and V_f and V_m are their respective volume fractions. Substituting the selected fibre volume of 0.6 yields

$$E_l = (72.3)(0.60) + (3.45)(0.40)\,) = 44.76 \text{ GPa.} \quad (1)$$

The transverse modulus was also estimated using the inverse rule of mixtures:

$$\frac{1}{E_t} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (2)$$

The composite spring was made using the hand lay-up process. The mould was prepared to create a camber profile of a mono composite leaf spring. Then, wax gel was applied to the inner side of the mould, and then layers of unidirectional E-glass fiber, a mixture of epoxy resin and hardener were applied one by one. The roller was rolled over each layer to compact it carefully and to remove any trapped air. Then it was allowed to cure at room temperature for four to five days. After that, steel eyes were cut from a conventional steel leaf spring and finished; they were attached to a mono composite leaf spring for mounting and testing.

The transverse modulus was calculated for the same volume fractions; it was approximately 8.12 GPa. This value is consistent with the expected behaviour of laminates of Glass Fiber-Reinforced Polymer (GFRP).

The design of the mono composite spring was done on the basis of the equation of bending stress and deflection equations for a supported leaf spring, as we know it is loaded in the centre.

The maximum bending stress is given by the formula.

$$\sigma_{max} = \frac{6PL}{bt^2} \tag{3}$$

While the central deflection for a leaf spring is given by

$$\delta_{max} = \frac{4PL^3}{Ebt^3} \tag{4}$$

In these equations, P represents the load applied, L is half the span, and b and t represents local width and thickness of leaf springs, respectively. For the selection of the cross-section, these relationships were used to guide the selection at the centre and the ends.

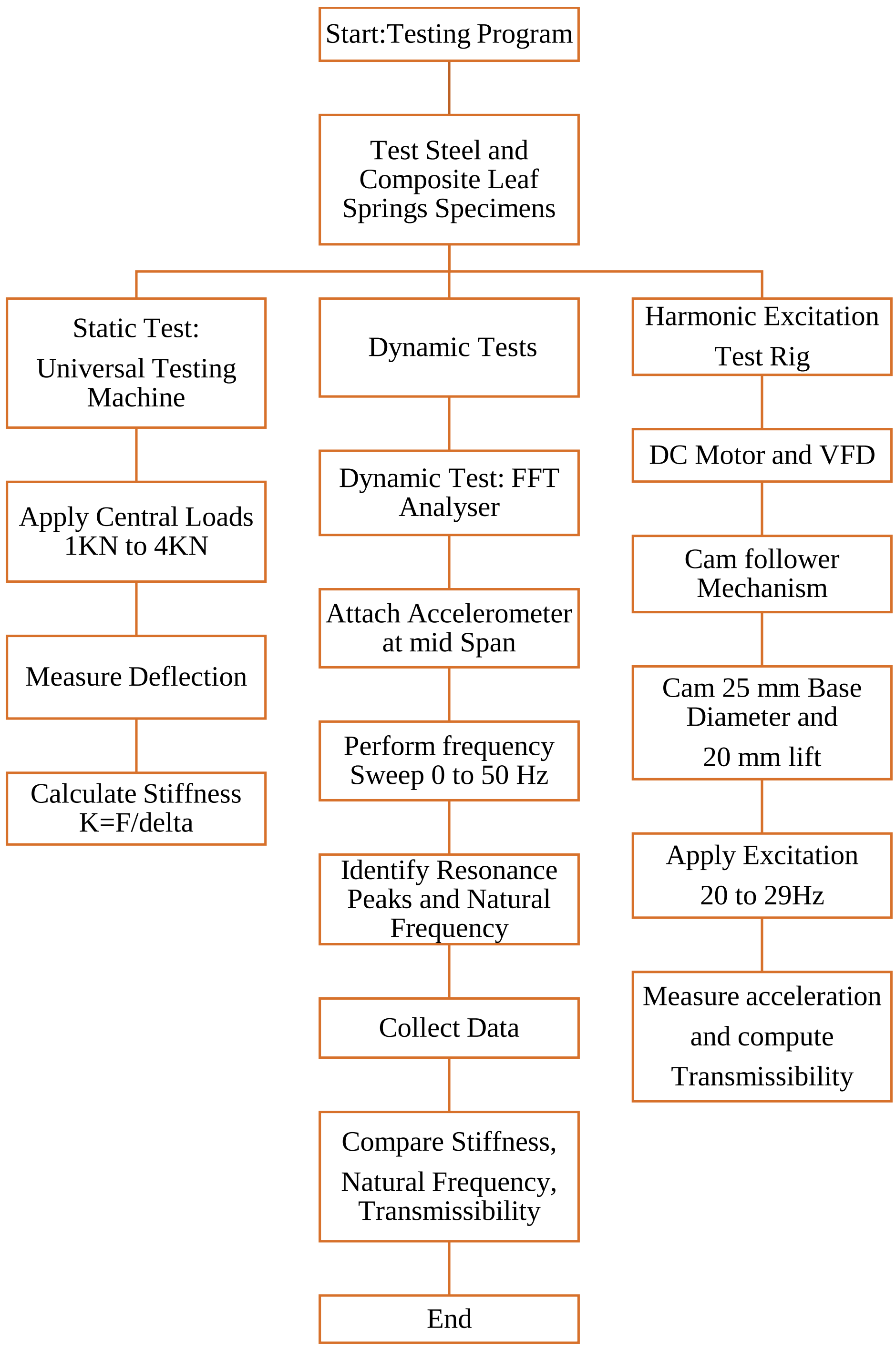

Fig. 3 Experimental Procedure

2.3. Testing Instruments and Procedures

To investigate the Stiffness, natural frequency and transmissibility of the springs, both static and dynamic tests were performed. A 100 kN Universal Testing Machine was used to measure deflection under load; loads ranging from 1 kN to 4 kN were applied centrally. The Stiffness was subsequently calculated using the formula $K = F/\delta$. The natural frequency of each spring was determined through the use of a Bruel & Kjaer FFT analyser, employing a piezoelectric accelerometer attached at the midpoint of the span; frequency sweeps spanning from 0 to 50 Hz were conducted to determine the resonant peaks. A harmonic excitation test rig was built incorporating a DC motor, a Variable Frequency Drive (VFD), and a cam–follower system featuring a 25 mm base diameter and a 20 mm lift. Excitation frequencies ranging from 20 to 29 Hz were applied, and the resultant accelerations were then measured to help the computation of transmissibility.

Table 3. Equipment used in testing

Equipment	Purpose
Universal Testing Machine (100 kN)	Static stiffness measurement
FFT Analyzer with accelerometer	Natural frequency measurement
DC motor + VFD + cam–follower	Harmonic excitation for the transmissibility test
Data acquisition system	Recording and processing vibration signals

3. Experimental Procedure

Figure 3 shows the testing flow carried out to obtain different readings under different conditions, which are static, dynamic and harmonic excitation tests.

3.1 Static Stiffness Measurement

The static Stiffness of the steel and the GFRP mono composite leaf springs was evaluated by using the 100KN Universal Testing Machine Figure 4. The springs were mounted with their eye ends clamped in a horizontal test position to reproduce actual suspension boundary conditions.

A gradually increasing central load was applied while the corresponding mid-span deflection was recorded. To obtain a more refined and realistic stiffness curve, intermediate readings were taken at 0.5 KN increments between 1 KN and 4 KN. The Stiffness for each reading was calculated using the relation

$$K = \frac{F}{\delta} \quad (5)$$

Where F represents the load applied (N) and δ is the deflection (mm). The readings for the steel leaf spring are shown in Table 4, and those for the GFRP mono composite leaf spring are shown in Table 5.

The GFRP composite leaf spring exhibited smaller deflections under identical loads owing to its higher longitudinal modulus.

Fig. 4 Static stiffness test on UTM

Table 4. Load–deflection–stiffness readings for steel leaf spring

Sr. No.	Load (kN)	Deflection (mm)	Stiffness (N/mm)
1	1.0	26.0	38.46
2	1.5	37.0	40.54
3	2.0	50.0	40.00
4	2.5	63.5	39.37
5	3.0	76.0	39.47
6	3.5	88.0	39.77
7	4.0	102.0	39.22

Table 5. Load–deflection–stiffness readings for composite leaf spring

Sr. No.	Load (kN)	Deflection (mm)	Stiffness (N/mm)
1	1.0	15.0	66.67
2	1.5	23.0	65.22
3	2.0	32.0	62.50
4	2.5	42.0	59.52
5	3.0	52.0	57.69
6	3.5	62.0	56.45
7	4.0	72.0	55.56

The GFRP composite leaf spring consistently shows Stiffness above 55 N/mm, which is higher than that of the steel leaf spring. These calculated stiffness values were used to find the natural frequency and transmissibility.

3.2 Natural Frequency Determination

An FFT analyser was used to measure the natural frequency of each spring. One end of each spring was fixed, and the other end was left free to move. A lightweight piezoelectric accelerometer was positioned at mid-span, as shown in Figure 5. A frequency sweep from 0 to 50 Hz was applied, and resonant frequencies were extracted from the FFT spectrum.

By using the single-degree-of-freedom expression, the natural frequency was also calculated analytically.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{6}$$

Where k stands for experimentally measured Stiffness and m stands for leaf spring mass. By experimental measurements, the natural frequency of the steel spring was approximately 11 Hz. In contrast, the composite spring showed a substantially higher value of approximately 16 Hz, following the expected trend based on stiffness-to-mass ratio.

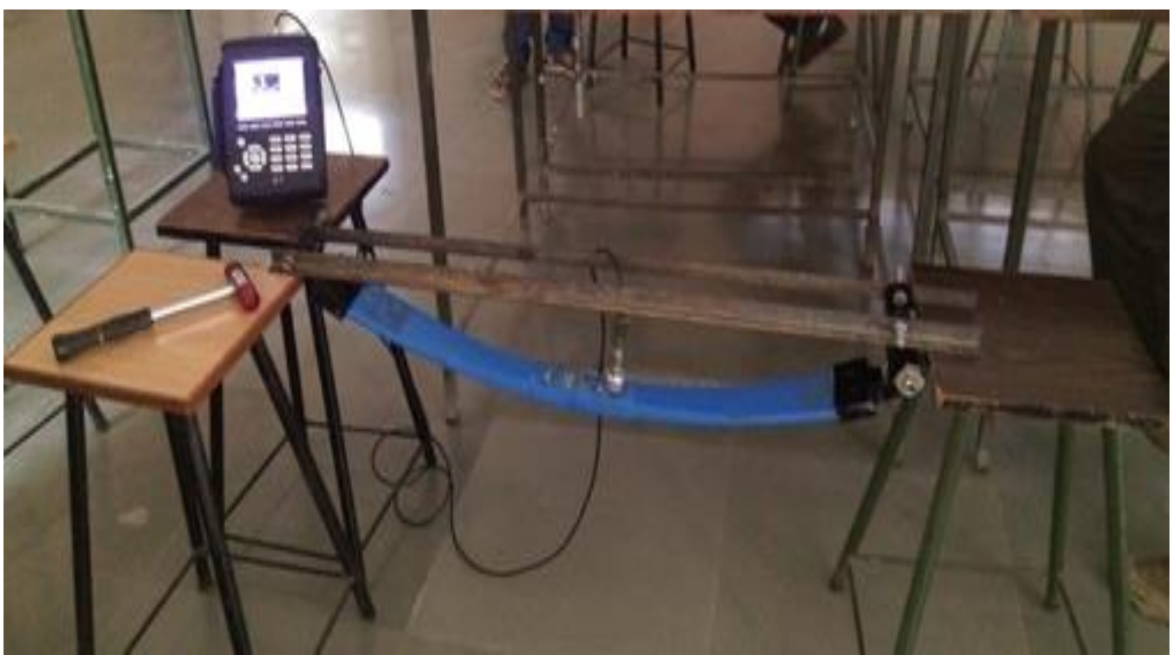

Fig. 5 Natural frequency determination

3.3. Transmissibility Evaluation

A transmissibility evaluation setup was developed to determine the transmissibility characteristics of both springs. Harmonic excitation was created by using a cam-follower mechanism. The transmissibility evaluation test setup consists of a DC motor driven by a Variable Frequency Drive (VFD), which rotates a cam with a 25 mm base diameter and 20 mm lift to introduce periodic displacement into the spring. An accelerometer attached to the spring recorded transmitted acceleration for each excitation frequency. Refer to Figures 6 and 7.

Transmissibility was computed using.

$$T_R = \frac{F_{\text{transmitted}}}{F_{\text{applied}}} \tag{7}$$

Where the applied force was estimated from motor torque, and the transmitted force was calculated based on spring stiffness and measured compression.

To obtain a smoother transmissibility profile, observations were taken at eight discrete frequencies between 20 Hz and 27 Hz. The steel and composite spring observations are listed in Tables 6 and 7, respectively.

Transmissibility is the ratio of the force transmitted to the supporting foundation to the force applied on the system.

$$\text{Transmissibility } (T) = \frac{F_{Tr}}{F_A}, \quad (8)$$

Where, F_{Tr}= force transmitted to foundation (N),
F_A= force applied on the system (N)

3.3.1. Sample Calculation for Steel Leaf Spring

(From Table 6, Sr. No. 1, Frequency = 20 Hz) Amplitude, $C = 2.033$ mm, Stiffness of steel leaf spring, $K_s = 39.255$ N/mm, Force applied on system (from motor torque & cam radius), $F_A \approx 158$ N

3.3.2. Force Transmitted to the Foundation

$$F_{Tr} = K_s \times C;\ F_{Tr} = 39.255 \times 2.033 = 79.80 \text{ N}$$

3.3.3. Transmissibility

$$T = \frac{F_{Tr}}{F_A};\ T = \frac{79.80}{158} = 0.505$$

Fig. 6 Transmissibility evaluation test setup back view

Fig. 7 Transmissibility evaluation test setup front view

Table 6. Transmissibility observation data for steel leaf spring

Sr. No.	Frequency (Hz)	Voltage (V)	Current (A)	Motor speed (rpm)	Cam speed (rpm)	Amplitude (mm)	Transmissibility
1	20	172.8	1.321	599.7	81.3	2.033	0.505
2	21	177.3	1.305	613.5	83.3	1.940	0.482
3	22	189.3	1.320	656.5	89.2	1.868	0.464
4	23	204.2	1.315	712.3	97.6	1.698	0.422
5	24	205.5	1.292	718.9	98.5	1.620	0.403
6	25	215.3	1.310	759.4	101.2	1.511	0.375
7	26	228.9	1.337	804.0	104.4	1.393	0.346
8	27	236.9	1.320	832.7	108.5	1.332	0.331

Table 7. Transmissibility observation data for composite leaf spring

Sr. No.	Frequency (Hz)	Voltage (V)	Current (A)	Motor speed (rpm)	Cam speed (rpm)	Amplitude (mm)	Transmissibility
1	20	172.8	1.321	603.2	80.3	1.016	0.364
2	21	177.3	1.305	617.1	82.4	0.930	0.333
3	22	189.3	1.320	659.3	88.3	0.850	0.305
4	23	204.2	1.315	714.1	96.6	0.687	0.246
5	24	205.5	1.292	721.2	97.8	0.614	0.220
6	25	215.3	1.310	763.8	101.7	0.538	0.193
7	26	228.9	1.337	805.3	108.4	0.478	0.171
8	27	236.9	1.320	834.9	111.4	0.363	0.130

These results reveal that the GFRP mono composite leaf spring has consistently lower amplitude of vibration for all excitation frequencies; it indicates that the GFRP mono composite leaf spring exhibits superior vibration isolation capability in comparison with the conventional steel spring.

4. Results and Discussion

The experimental evaluation of the steel and GFRP mono-composite leaf springs provides clear insights into their mechanical and dynamic behaviour. The results of Stiffness, natural frequency analysis, and transmissibility testing reveal remarkable improvements achieved through composite material substitution.

4.1. Static Stiffness Behaviour

The load versus deflection characteristics graph of both springs is shown in Figure 8, which is derived from the experimental test readings listed in Tables 4 and 5. The graph showed a nearly linear increase in deflection of the steel leaf spring, ranging from 26 mm at 1 KN to 102 mm at 4 KN.

Whereas, the GFRP composite leaf spring showed substantially lower deflections, ranging from 15 mm to 72 mm for the same load range. This behaviour indicates a remarkably higher stiffness in the GFRP leaf spring due to its higher longitudinal modulus.

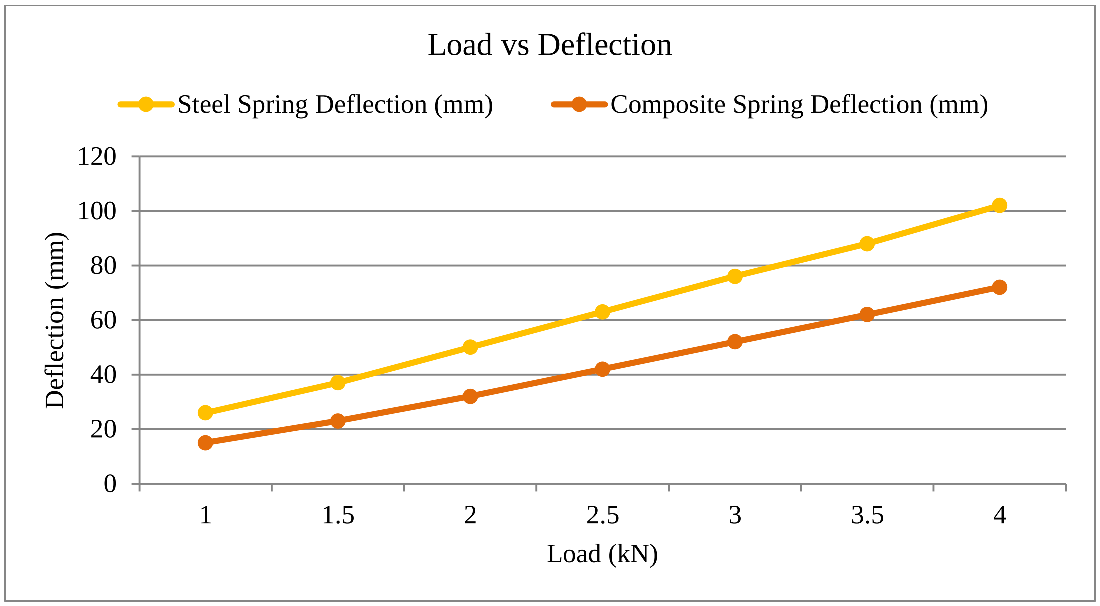

Fig. 8 Deflection verses load of steel and GFRP composite leaf springs

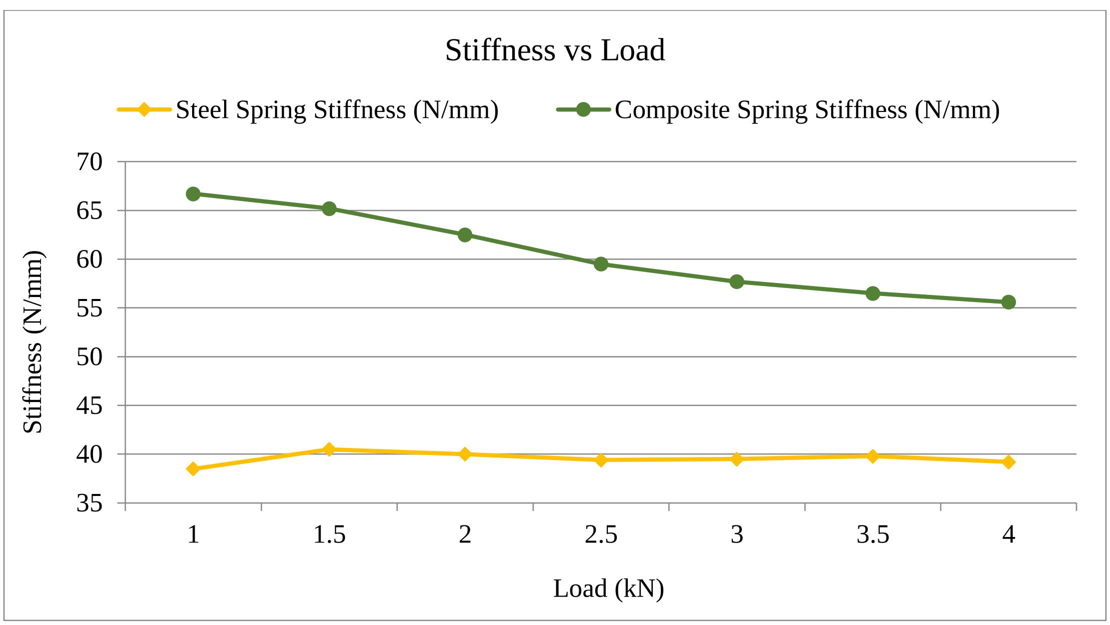

Fig. 9 Stiffness variation with load for steel and GFRP mono composite leaf springs

The graph of calculated stiffness values of both sprigs is shown in Figure 9 to support this observation. The stiffness values of the steel spring remained within the range of 38-40 N/mm, while the composite spring maintained significantly higher stiffness values between 55–67 N/mm. There is a gradual reduction in Stiffness at higher loads for the GFRP composite leaf spring, which reflects the nonlinearity typical of fibre-reinforced laminates. However, the values remain almost consistent with those of the steel spring across all load levels.

The higher Stiffness and greatly reduced mass (58% lower weight compared to steel) of the GFRP composite leaf spring collectively contribute to the improved dynamic performance demonstrated experimentally in the subsequent sections.

4.2. Natural Frequency Analysis

The natural frequencies measured by using the FFT analyser were approximately 11 Hz for the conventional steel leaf spring and 16 Hz for the GFRP composite leaf spring. These values align closely with analytical predictions derived from the single-degree-of-freedom expression (6), where the composite spring's higher Stiffness and much lower mass jointly result in a significantly higher natural frequency. In India, typical road excitation frequencies range from 1–12 Hz for driving conditions; the steel spring's natural frequency falls within this range, which increases the risk of resonance.

However, the GFRP mono composite leaf spring's natural frequency is well above the road excitation range, which reduces the occurrence of resonance and improves vibration stability.

4.3. Transmissibility and Vibration Isolation Performance

The transmissibility behaviour of the leaf springs was evaluated by applying a harmonic excitation, which was generated by using a cam and follower mechanism. The system operates in the frequency range 20 Hz to 27 Hz. The corresponding amplitude responses at these frequencies are plotted in Figure 10.

The steel leaf spring exhibits higher amplitudes at all frequencies (2.033 mm at 20 Hz, reducing to 1.332 mm at 27 Hz). In contrast, the GFRP composite leaf spring showed comparatively lower amplitudes (1.016 mm at 20 Hz, reducing to 0.363 mm at 27 Hz). The reduction rate of amplitude with increasing frequency is also higher for the GFRP composite leaf spring, which shows superior damping characteristics.

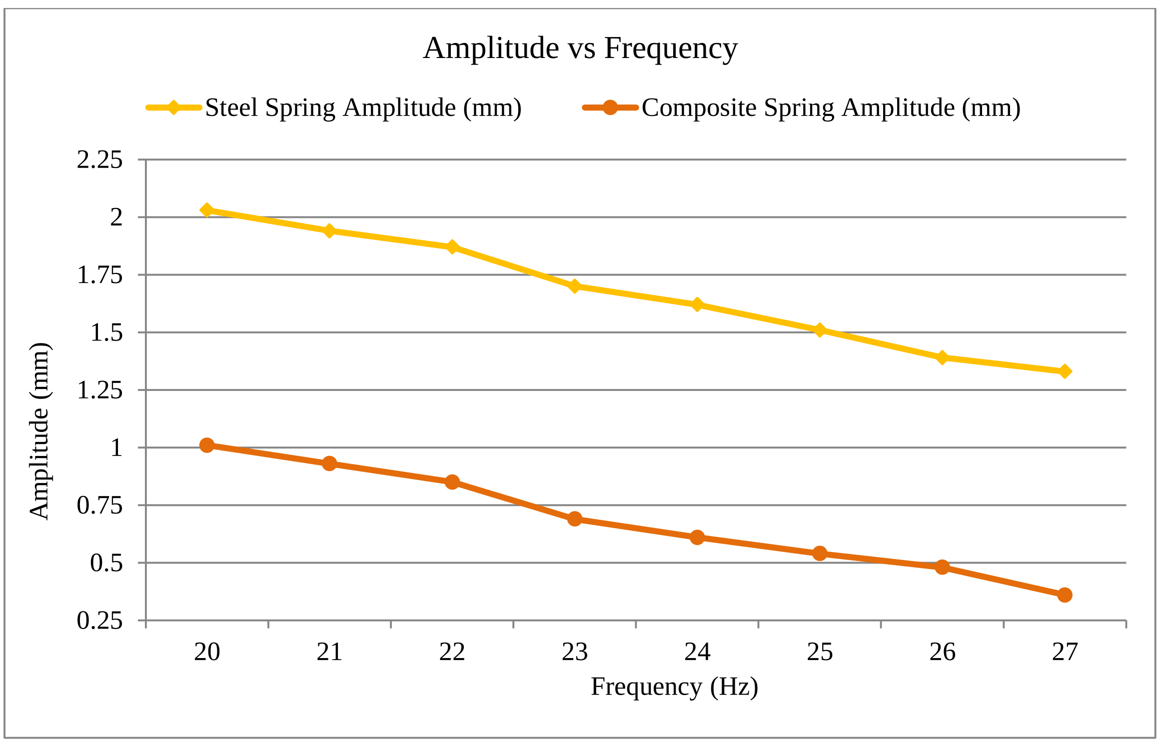

Fig. 10 Amplitude of vibration verses excitation frequency for steel and GFRP mono composite leaf springs

To compare the overall transmission of vibration, the graph of transmissibility values was shown in Figure 11 with respect to excitation frequencies. The transmissibility of steel leaf springs remained relatively high across the tested frequency range. In contrast, the GFRP mono composite leaf spring showed a strong downward trend, which indicates increased vibration isolation.

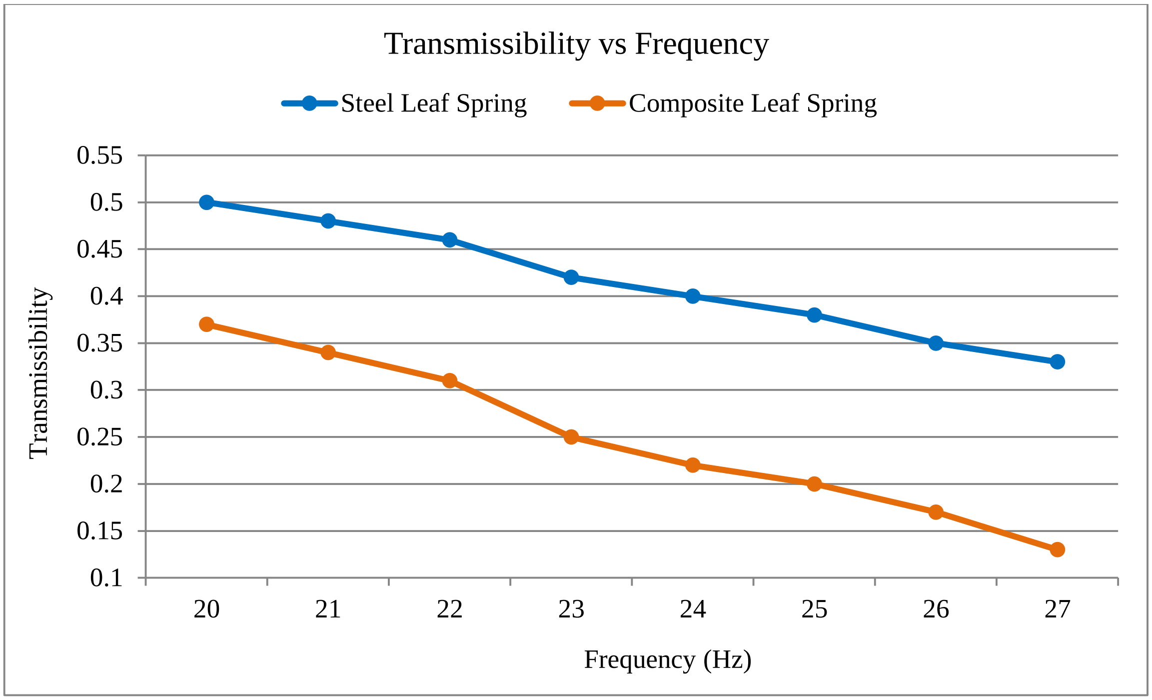

Fig. 11 Transmissibility verses frequency for steel and GFRP mono composite leaf springs

The transmissibility of the steel leaf spring decreased from approximately 0.51 at 20 Hz to about 0.33 at 27 Hz; in contrast, the GFRP mono composite leaf spring showed a more significant reduction from around 0.36 to nearly 0.13 over the same frequency range. After comparing the values of transmissibility for the steel and GFRP mono composite leaf spring for the same speed, the GFRP mono composite leaf spring would give less transmissibility as compared with the steel leaf spring. As the transmissibility of any system is lower, it means that the system has better vibration isolation and it transfers fewer vibrations to the foundation or structure. This represents almost 60% reduction in transmitted vibration for the composite leaf spring in comparison with the steel spring. The GFRP mono composite leaf spring has significantly lower transmissibility, which is attributed to the superior damping characteristics of the composite laminate and its lower effective mass, which together enhance the dynamic vibration isolation performance.

4.4. Integrated Performance Assessment

The static and dynamic assessment of both leaf springs clearly indicates that the GFRP mono-composite leaf spring exhibits superior performance. The test outcomes validate the suitability of composite leaf springs for automotive suspension applications, particularly for light commercial vehicles where fuel efficiency, weight reduction, and vibration performance are critical factors.

5. Conclusion

From this comparative static and dynamic testing analysis of conventional steel and newly developed GFRP mono-composite leaf spring intended for use in light commercial vehicle suspension systems, the following conclusions can be drawn:

1. The composite leaf spring demonstrated significantly exhibited 44.14% higher Stiffness compared to the steel leaf spring across all load levels. The measured Stiffness of the composite spring ranged between 55–67 N/mm, whereas the steel spring maintained stiffness values around 38–40 N/mm.
2. A weight reduction of 57.93% was achieved by replacing the steel spring (7.979 kg) with the composite spring (2.075 kg without eyes). This reduction in unsprung mass contributes directly to improved fuel efficiency.
3. The natural frequency of the composite spring was approximately 49.91% higher than that of the steel spring. By experimental measurements, the natural frequencies of the steel leaf spring are approximately 11 Hz and 16 Hz for the GFRP mono composite leaf spring. The higher natural frequency of the composite leaf spring reduces the occurrence of resonance with typical road excitation frequencies (1–12 Hz), thereby enhancing ride stability.
4. Across the tested frequency range of 20–27 Hz, the vibration transmissibility of the composite leaf spring exhibited substantially lower, up to 60% reduction in transmitted amplitude, which resulted in improved vibration isolation.
5. The integrated performance assessment confirms that GFRP mono composite leaf springs exhibit superior structural and vibrational performance compared to the conventional steel counterparts. GFRP mono composite leaf spring not only meets the design and load-bearing requirements but also outperforms steel springs in

Stiffness, damping, vibration isolation, and resonance avoidance.

Future work may include fatigue testing and long-term durability assessment further to confirm their suitability for full-scale automotive suspension systems.

Acknowledgements
The authors gratefully acknowledge the Mechanical Engineering Department of Mandsaur University for their guidance and HSBPVT'S GOI Faculty of Engineering, Kashti, Ahilynagar, for providing essential facilities, including the experimental setup and testing equipment.

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