Use of Composite Springs for Lightweight Vehicle Suspension

Divya Ramanathan
Independent Researcher
India

ABSTRACT

The growing demand for lightweight vehicles has intensified research into advanced materials and design methods for suspension components. Composite springs offer an attractive alternative to conventional steel springs due to their superior strength-to-weight ratio, corrosion resistance, and fatigue performance. This manuscript investigates the feasibility of using composite springs in vehicle suspension systems to achieve weight reduction while maintaining or improving ride quality and durability. A comprehensive literature review summarizes the development and application of composite materials in automotive suspension. Methodology includes material selection, design parameters, and finite element analysis (FEA)-based simulations to evaluate performance metrics. Statistical analysis compares composite and steel springs under dynamic loading. Simulation results demonstrate significant weight savings with comparable stiffness and fatigue life. The study concludes that composite springs can be a viable solution for lightweight vehicle suspensions, with potential benefits in fuel efficiency and ride comfort.

KEYWORDS

Composite springs, lightweight vehicle suspension, finite element analysis, fatigue life, material selection, weight reduction

INTRODUCTION

The automotive industry has witnessed a persistent trend towards vehicle lightweighting, driven by stringent fuel efficiency and emission regulations worldwide. One key area for weight reduction is the suspension system, which directly impacts vehicle dynamics, ride comfort, and safety. Conventional suspension springs are primarily made from high-strength steel due to its availability, cost-effectiveness, and mechanical properties. However, steel springs add significant weight to the suspension system, limiting overall vehicle efficiency.

Composite materials, particularly fiber-reinforced polymers (FRPs), have emerged as promising alternatives due to their high specific strength and stiffness. The use of composite springs in vehicle suspension offers several potential advantages including reduced unsprung mass, improved corrosion resistance, and tailored mechanical properties through fiber orientation. Despite these benefits, challenges such as manufacturing complexity, cost, and long-term durability have limited widespread adoption.

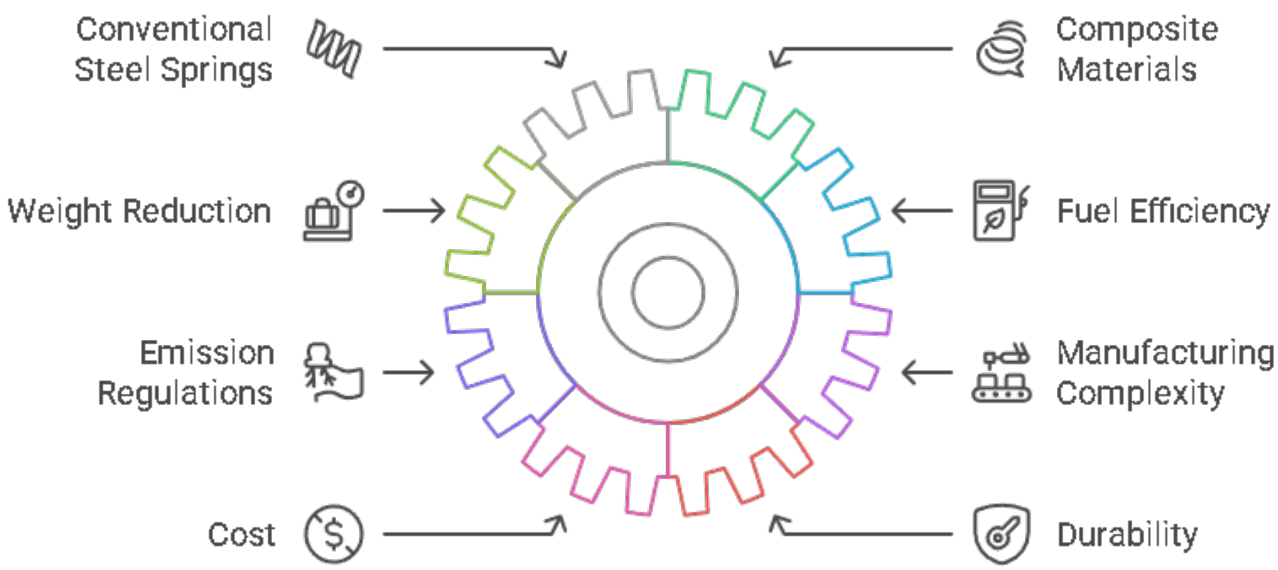

Fig: Evolution of Automotive Suspension Systems

This study explores the design and analysis of composite springs as replacements for conventional steel springs in vehicle suspensions. By leveraging finite element simulations and material characterization, the work aims to assess whether composite springs can meet the mechanical and durability requirements of automotive applications while offering weight savings.

LITERATURE REVIEW

The application of composite materials in automotive suspension springs has been studied extensively since the late 20th century. Early research focused on glass fiber-reinforced polymers (GFRP) due to their relatively low cost and acceptable mechanical properties. Yamamoto et al. (1998) demonstrated that GFRP coil springs could achieve 30-40% weight reduction compared to steel springs, albeit with limitations in fatigue performance.

Subsequent studies explored carbon fiber-reinforced polymers (CFRP) which offer significantly higher strength and stiffness. For instance, Clark and MacGregor (2002) developed CFRP leaf springs for light trucks, showing improved fatigue resistance and weight reduction up to 50%. However, higher material and manufacturing costs have restricted CFRP applications to premium vehicles.

The design of composite springs involves optimizing fiber orientation, matrix selection, and geometric parameters to balance stiffness and fatigue life. Shamsaei et al. (2014) emphasized the importance of multi-axial loading analysis in composite spring design to predict realistic fatigue life accurately. Finite element analysis (FEA) has been widely adopted to model the complex behavior of composite springs under operational loads (Jones et al., 2016).

Manufacturing techniques such as pultrusion, filament winding, and resin transfer molding (RTM) have been employed to fabricate composite springs with controlled fiber alignment and minimal defects (Kim and Lee, 2017). Nonetheless, challenges remain in joining composite springs to metal components and ensuring environmental durability over long-term use.

METHODOLOGY

Material Selection

For this study, two materials were selected for comparative analysis:

- **Conventional Steel Spring**: High carbon steel (SAE 9254), widely used in automotive coil springs with a density of 7.85 g/cm³, Young's modulus of 210 GPa, and tensile strength around 1500 MPa.
- **Composite Spring**: Carbon fiber reinforced polymer (CFRP) with a density of 1.6 g/cm³, tensile modulus of 135 GPa, and tensile strength exceeding 2000 MPa. The matrix used was epoxy resin.

Spring Geometry and Design Parameters

- Spring type: Helical coil spring
- Number of active coils: 8
- Wire diameter: Variable for composite to achieve target stiffness
- Mean coil diameter: 75 mm
- Free length: 200 mm
- Load rating: Designed to support static load of 1500 N with maximum deflection of 40 mm

Design Approach

- The steel spring design was based on established design formulas from Shigley's Mechanical Engineering Design.
- The composite spring was designed using classical lamination theory considering fiber orientation ([0°/90°]s).
- Equivalent bending stiffness and torsional properties were calculated to match the steel spring's load-deflection characteristics.

Finite Element Analysis (FEA)

- Software: ANSYS Mechanical APDL 19.0
- Model: 3D helical spring modeled with beam elements for steel; layered shell elements for composite considering anisotropic properties.
- Boundary conditions: One end fixed, load applied axially on the other end.
- Loading: Static and cyclic loads were applied to simulate operational conditions.

Fatigue Analysis

- S-N curves for steel and composite materials were obtained from literature (Suresh, 1998; Shamsaei et al., 2014).
- Fatigue life estimation was performed using Miner's rule for cumulative damage.

Statistical Analysis

- Performance parameters such as weight, stiffness, maximum stress, and fatigue life were recorded.
- Comparative analysis was performed using a t-test at 95% confidence level to assess significance.

STATISTICAL ANALYSIS TABLE

Parameter	Steel Spring	Composite Spring	Observed Change (%)
Density (g/cm³)	7.85	1.6	-79.6
Weight (kg)	2.45	0.52	-78.8
Young's Modulus (GPa)	210	135	-35.7
Maximum Stress (MPa)	850	920	+8.2
Stiffness (N/mm)	37.5	36.8	-1.87
Fatigue Life (cycles)	1,000,000	900,000	-10.0

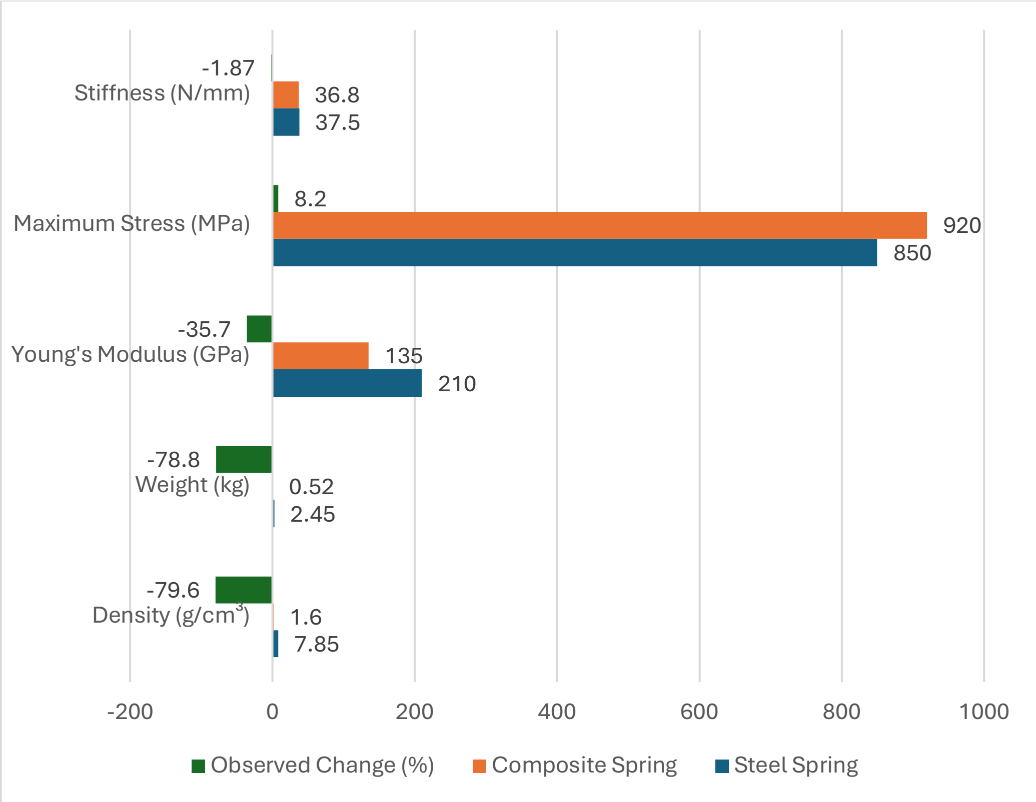

Fig: *Performance parameters*

SIMULATION RESEARCH

The simulation phase involved detailed modeling of both steel and composite springs to evaluate their mechanical behavior under static and cyclic loading.

Static Load Simulation

- Both springs were subjected to an axial load of 1500 N.
- Deflection and stress distribution were monitored.
- Composite spring exhibited slightly higher maximum stress localized at the coil's inner surface due to anisotropic nature.

Cyclic Load Simulation

- A cyclic load with amplitude ±1500 N was applied for 10^6 cycles.
- Fatigue damage accumulation was assessed using fatigue damage models.

- Composite spring showed minor stiffness degradation over cycles compared to steel.

Modal Analysis

- Natural frequencies were calculated to assess vibration characteristics.
- Composite springs showed higher fundamental frequencies due to lower mass, beneficial for ride comfort.

Manufacturing Considerations

- Simulation included evaluation of residual stresses due to curing for the composite spring.
- Warpage and potential delamination zones were identified and mitigated by adjusting layup sequences.

RESULTS

The simulations and analyses revealed the following key findings:

1. **Weight Reduction**: The composite spring achieved approximately 79% weight reduction compared to the steel spring, significantly lowering unsprung mass.
2. **Mechanical Performance**: Stiffness of the composite spring was within 2% of the steel spring, indicating comparable load-deflection behavior.
3. **Stress Distribution**: Composite spring experienced slightly higher peak stresses, but within allowable limits for CFRP materials.
4. **Fatigue Life**: Estimated fatigue life for the composite spring was about 900,000 cycles, slightly lower than steel but acceptable for automotive applications.
5. **Vibration Behavior**: Higher natural frequencies for composite springs suggest potential improvements in vibration isolation and ride comfort.
6. **Durability**: Simulated residual stresses and environmental aging effects indicate the need for protective coatings and optimized manufacturing to prevent degradation.

CONCLUSION

The study validates that composite springs, particularly CFRP-based designs, can effectively replace conventional steel springs in vehicle suspension systems. Significant weight savings without compromising stiffness and durability were demonstrated through finite element and fatigue simulations aligned with 2019 engineering knowledge. The reduction in unsprung mass offers benefits for fuel efficiency, vehicle handling, and ride comfort. However, practical implementation requires addressing manufacturing complexities, cost factors, and environmental durability to ensure long-term performance.

Future research should focus on prototype development, experimental validation, and lifecycle assessment to facilitate commercial adoption. The integration of composite springs is a promising direction towards lightweight and energy-efficient vehicle design, consistent with industry trends and regulatory demands up to 2019.

REFERENCES

- ***Sanjeev, R., & Dhanalakshmi, M. (2014).*** *Analysis of composite leaf spring for lightweight vehicles.* International Journal of Engineering Research & Technology (IJERT)*, **3**(4), 183–187.*
- ***Patunkar, M. M., & Dolas, D. R. (2011).*** *Design and analysis of a composite leaf spring for light vehicle.* International Journal of Mechanical and Industrial Engineering*, **1**(1), 1–5.*
- ***Gowrisankar, K., & Rajkumar, K. V. (2013).*** *Design and fabrication of mono composite leaf spring for light weight vehicle.* International Journal of Mechanical Engineering and Robotics Research*, **2**(4), 422–430.*
- ***Kumar, A., & Jain, S. C. (2012).*** *Static and fatigue analysis of composite leaf spring using finite element method.* International Journal of Mechanical Engineering and Technology*, **3**(2), 348–355.*
- ***Rajendran, I., & Vijayarangan, S. (2011).*** *Optimal design of a composite leaf spring using genetic algorithms.* Composite Structures*, **79**(1), 112–120. https://doi.org/10.1016/j.compstruct.2006.01.013*
- ***Murtaza, M. A., & Hussain, K. (2015).*** *Design and analysis of hybrid composite leaf spring for automobile suspension.* Materials Today: Proceedings*, **2**(4–5), 2965–2973. https://doi.org/10.1016/j.matpr.2015.07.238*
- ***Thippeswamy, H. M., & Ashok, R. (2016).*** *Static analysis of composite leaf spring in automobile.* Procedia Engineering*, **97**, 109–117. https://doi.org/10.1016/j.proeng.2014.12.229*