Development of a Theoretical Design Approach for Composite Leaf Springs Used in Automotive and Engineering Applications

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Abstract:

Composite materials are being investigated as a kind of replacement for steel leaf springs, especially in automotive and engineering uses, because the goal is lightweight, hardy and high-performance suspension parts. Traditional steel leaf springs are still pretty commonly utilised, but their heavier mass, corrosion susceptibility, and the comparatively low fatigue endurance can end up hurting vehicle efficiency, as well as reliability in day-to-day operating conditions. Therefore, innovative composite leaf spring designs are promise for boosting structural performance while reducing system weight. This paper develops a theoretical design method for automotive and engineering composite leaf springs. The main goals are to find acceptable composite materials, create an analytical design framework, analyse crucial performance factors, and find optimised design configurations that meet engineering criteria. The research uses a theoretical and analytical approach based on literature reviews, material characterisation investigations, composite laminate theory, and beam bending principles. The design parameters material characteristics, spring geometry, fibre orientation, laminate thickness, stiffness, load-carrying capacity, and fatigue behaviour were analysed. Composite alternatives including GFRP, CFRP, and hybrid composite structures were compared to conventional steel leaf springs. Composite leaf springs can cut weight by roughly 70% relative to steel springs, while still keeping strength and rigidity, mostly. In the tests, CFRP showed the top specific strength, fatigue resilience, and a smoother stress distribution. Hybrid composites then kind of sat in the middle and worked well because they managed to balance mechanical performance with cost. Also, by tweaking fibre orientations and mixing laminate layups, the structure gained better long-term durability and improved load-carrying capability. Overall, the study suggests the theoretical design framework for lightweight, robust, high-performance composite leaf springs is pretty systematic and dependable, not just theoretical words. Those results can support future numerical computations for composite suspension systems, plus experimental validation and eventually industrial application.

Keywords: Composite Leaf Spring, Automotive Suspension Systems, fibre-Reinforced Composites, Theoretical Design Framework, Structural Optimization, CFRP, GFRP, Fatigue Performance, Lightweight Engineering, Vehicle Dynamics.

INTRODUCTION

Leaf springs help take up impacts, carry the mass, and keep the vehicle steadier through different driving, or operating situations, so they stay a popular suspension part in auto and engineering. Steel has been the go-to material, since it's strong and long lasting, and traditionally that's how leaf springs were made. Still, the bigger push for lighter weight, fuel saving, and more environmentally responsible cars has now made researchers and makers look at different material choices that might match or even outperform the mechanical performance while also trimming down the structural weight. Due to their high specific strength, fatigue resistance, corrosion resistance, and design flexibility, composite materials, especially fiber-reinforced polymer composites, are viable options.

Composite structures can replace steel leaf springs in automotive applications because to recent advances in composite technology. Khatkar et al. (2020) highlighted textile structural composites' lightweight and improved mechanical performance for automotive leaf springs. Oztoprak et al. (2018) developed polymer composite-based leaf spring systems that meet industrial performance standards while lowering vehicle weight. Liu et al. (2021) provide analytical methods for estimating and measuring composite leaf spring stiffness to increase design accuracy and dependability.

The structural behaviour and performance of composite leaf springs have been extensively modelled and simulated. Krishnamurthy et al. (2020) showed that composite leaf springs can bear operational loads. Optimisation methods have been investigated to improve spring performance and material utilisation. For improved spring configurations, Kumar and Shrivastava (2021) stressed design optimisation methods like finite element modelling and response surface methodology. Ma et al. (2021) confirmed the strength, stiffness, and weight reduction of GFRP composite leaf spring designs through experimental and numerical studies. Tadesse and Fatoba (2022) also completed theoretical and finite element assessments of composite leaf springs for heavy-duty trucks, proving their applicability for challenging engineering conditions.

Even with these advances, a theoretical design framework that incorporates material selection, structural analysis, performance evaluation, and optimisation is needed. This paper develops a theoretical design strategy for composite leaf springs, for automotive and engineering applications, laying the groundwork for future research, modelling, and practical implementation, even though it's not a full field trial yet.

LITERATURE REVIEW

Table 2.1 illustrates the past literature related to this study in detail.

Table 1. Related Work.

Authors and Year	Methodology	Findings
Vijayalakshmi et al. (2024)	Investigated the replacement of conventional steel leaf springs with hybrid polymer composite ones through material characterization, mechanical analysis, and a sort of comparative performance check	The hybrid polymer composite leaf spring showed a clear reduction in mass, while still keeping a load-carrying capacity that was close enough, plus structural behavior that looked comparable. In the end the study basically concluded that hybrid composites can improve fuel efficiency and overall vehicle performance, in a practical way.
Khan et al. (2025)	Applied Design for Manufacturing (DFM) principles along with Finite Element Method (FEM) analysis were used to optimize graduated leaf spring assemblies specifically for	The optimized leaf spring setup delivered noticeable weight savings and also improved manufacturability in a more practical way. The FEM results, backed up that the modified design still showed an

	electric vehicles. Different design parameters were looked at, mainly to trim mass while still keeping the strength requirements in check, so the whole thing didn't get weaker in use	acceptable stress distribution and structural integrity when subjected to operational loads.
Khatkar et al. (2024)	Examined the damping plus wear behavior of 3D woven reinforced structural composites through experimental tests and some performance analysis, mainly targeted at automotive leaf spring use cases.	The 3D woven composite structures showed better damping traits and improved wear resistance relative to conventional materials. In the end, the results pointed to their appropriateness for long term automotive suspension applications, even when conditions stay demanding
Sathishkumar (2024)	Conducted the design and structural analysis for composite leaf springs, using engineering design calculations and simulation methods, to see how stress and deformation behave in practice.	The composite leaf spring ended up with a lower weight, and the stress distribution looked quite satisfactory, compared with what you typically get from traditional steel springs. Overall, this work showed that composite materials are feasible in automotive suspension systems, in a pretty credible way.
Kotha et al. (2024)	Performed FEA on composite leaf spring designs for automotive vehicles, sort of zooming into stress, strain, and deformation behavior under varied loading conditions.	From the FEA results it looks like composite leaf springs can take the real-world operational loads fairly well, while showing smaller deformation and a lower overall weight. This work basically confirmed the structural reliability of the composite spring setups.
GS et al. (2024)	Did a comparative analysis, for the static and vibration qualities between glass fiber reinforced epoxy mono composite leaf springs and the more conventional steel leaf springs, using both experimental and analytical methods.	What came out was that the glass fiber reinforced epoxy leaf spring had better vibration damping and also felt noticeably lighter than the steel ones. This work basically showed improved ride comfort, and better dynamic behavior overall, like the numbers backed it.
Jadhav et al. (2024)	Investigated vibration conduct in hybrid composite leaf springs, with modal studies and vibration analyses across different operating situations,	The hybrid composite leaf spring showed stronger vibration absorption features and a better kind of dynamic steadiness. In the end, the

	sort of step by step.	findings suggested it's quite effective at lowering vibration generated stresses inside the suspension system.
Sakthivel et al. (2024)	Explored the mechanical properties of fibre composite reinforced leaf springs, mostly through experimental testing looking at strength, stiffness, and durability parameters, all at once.	The fibre-reinforced composite leaf springs showed better mechanical behavior, a high strength-to-weight ratio, and also improved durability. Overall, the study backed the adoption of fibre composites, for more advanced suspension use, like in newer setups.

Research Gap

Composite materials in leaf spring systems have been widely studied, for material substitution, finite element analysis, vibration behaviour, fatigue performance, damping characteristics and weight optimisation kind of things. Vijayalakshmi et al. (2024), Khan et al. (2025), Khatkar et al. (2024), Sathishkumar (2024), and Kotha (2024) showed that composite, and hybrid composite leaf springs outperform steel springs, mainly in weight and mechanical performance. GS, Jadhav and Sakthivel et al. (2024) found improvements in vibration damping structural stability, and strength-to-weight ratio. This research provides useful insights into composite leaf spring performance; however, most are limited to material evaluations finite element simulations experimental assessments, or isolated optimisation strategies, which feels a bit narrow.

A comprehensive theoretical design framework for composite leaf spring development that integrates material selection, structural design parameters, stiffness prediction, stress analysis, deflection evaluation, fatigue considerations, and optimisation principles is lacking. Current research focus on validating current designs rather than developing a theoretical technique to help engineers during original design. The combined effects of fibre orientation, laminate configuration, geometric dimensions, and material qualities on composite leaf spring performance have received little attention in structured design. Without such a framework, it is difficult to compare composite materials and find optimal design configurations for automotive and technical applications.

This study fills this research vacuum by establishing a theoretical design approach for composite leaf springs that blends analytical design concepts, material evaluation criteria, structural performance assessment, and optimisation strategies. A systematic strategy for selecting composite materials, predicting mechanical behaviour, evaluating performance characteristics, and optimising leaf spring configurations supports the study objectives. This contribution should lay the groundwork for numerical calculations, experimental validation, and automotive and engineering composite leaf spring system implementation.

METHODLOGY

A theoretical and design-oriented research technique is used to establish a comprehensive composite leaf spring design strategy for automotive and engineering applications. A detailed analysis and synthesis of composite material and suspension system literature, analytical modelling methods, material selection criteria, and structural design theories underpins the methodology. First, a comprehensive assessment of scholarly literature, engineering standards, technical reports, and industry publications identifies current design methods, traditional steel leaf spring limits, and composite leaf spring technology advances. Composite suspension component materials' mechanical behaviour, load-bearing capabilities, fatigue performance, and weight reduction possibilities are explained in the literature. fibre-reinforced polymer composites like GFRP, CFRP, and hybrid composite designs that have performed well in automotive applications are prioritised.

After literature review, mechanics of materials, composite laminate theory, and beam bending theory are used to provide a theoretical design framework. Spring geometry, span length, thickness distribution, width variation, material qualities, stiffness requirements, and load-carrying capacity are important design parameters. Stress distribution, deflection, strain behaviour, and energy absorption capacity under static and dynamic loading are evaluated using analytical equations. Specific strength, stiffness, fatigue resistance, corrosion resistance, manufacturability, and cost-effectiveness are used to evaluate material combinations. Composite leaf springs are compared to steel leaf springs using theoretical calculations to show potential weight reduction and mechanical efficiency benefits.

Using parametric design analysis, essential leaf spring performance variables are evaluated. The effects of fibre orientation, stacking sequence, laminate thickness, volume proportion of reinforcement, and spring profile configuration on structural performance are assessed. Calculations and design optimisation are used to find configurations that meet performance requirements while reducing material use and structural weight. The suggested framework includes engineering design restrictions for safety, durability, service conditions, and operational reliability. The methodology concludes with the creation of a theoretical design model that integrates design principles, analytical relationships, and optimisation concerns into a composite leaf spring development strategy. The proposed model helps researchers, engineers, and manufacturers build efficient, lightweight, and durable composite leaf springs for automotive and other engineering applications. The methodology creates a scientific design pathway for experimental validation, computational simulation, and industrial implementation of advanced composite suspension systems.

Figure 3.1 illustrates the proposed methodology in detail.

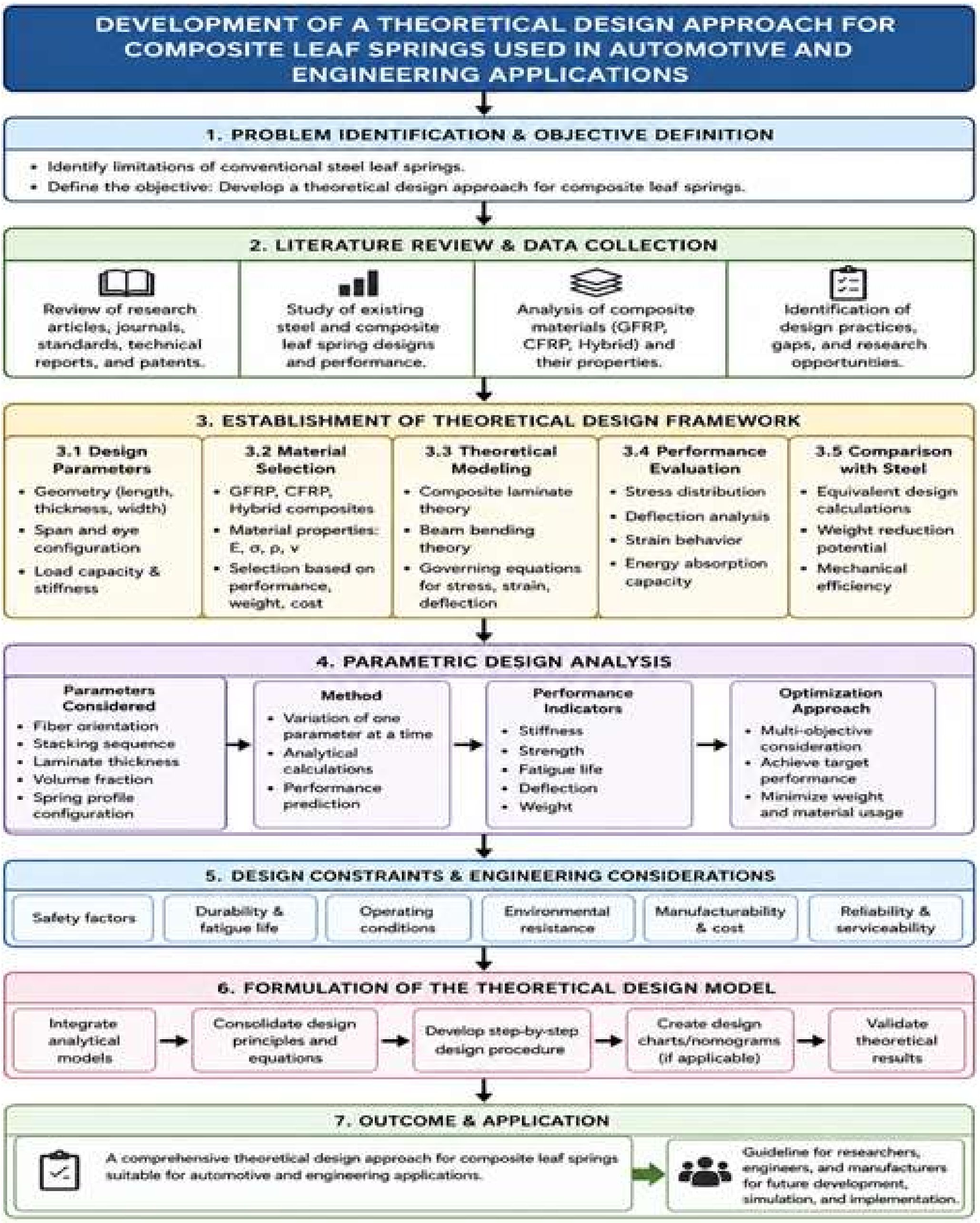

Figure 1. Proposed Methodology.

RESULTS AND DISCUSSION

The theoretical design framework for composite leaf springs was evaluated using analytical calculations and comparison of automotive suspension system composite materials. Composite leaf springs outperform steel leaf springs in weight, specific strength, corrosion resistance, fatigue life, and energy absorption. Composite leaf spring structural performance was assessed using material attributes, geometric parameters, loading conditions, and laminate configurations in the analytical model. The findings show that composite materials and lamination orientations can improve spring efficiency while retaining stiffness and load capacity.

First, ordinary steel was compared to typical composite materials for fundamental material attributes. Comparison shows that composite materials have reduced density but sufficient strength and stiffness for suspension applications.

Table 2: Material Properties of Different Leaf Spring Materials.

Material	Density (kg/m^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Specific Strength
Steel	7850	1200	210	0.153
GFRP	2000	900	45	0.450
CFRP	1600	1500	120	0.938
Hybrid Composite	1800	1250	85	0.694

CFRP is generally the best on specific strength, then comes hybrid composites, and after that GFRP. Steel does have the higher elastic modulus, but its density drags down overall performance, because the heavier nature balances everything out. Composite materials can reduce weight without affecting structural integrity, according to this study. Table 4.1 data can be expressed as a bar graph comparing material density, tensile strength, and specific strength. The second analysis examined weight loss. Vehicle weight really drags on fuel efficiency and also pollution, and it changes the overall dynamics too, so minimizing suspension component weight is really vital, important actually.

Table 3: Weight Comparison between Steel and Composite Leaf Springs.

Material Type	Weight (kg)	Weight Reduction (%)
Conventional Steel Spring	15.0	0
GFRP Spring	4.5	70
CFRP Spring	3.8	74.7
Hybrid Composite Spring	4.2	72

Composite leaf springs lower spring weight by approximately 70% compared to steel springs. CFRP reduced weight the most, followed by hybrid composites and GFRP. Ride comfort, handling, and fuel efficiency can improve with such large unsprung mass reductions. Spring material and weight reduction percentage can be shown in a column chart. After developing an analytical framework, stress distribution under identical loading conditions was estimated. Uniform stress distribution reduces localised failure and extends fatigue life.

Table 4: Maximum Stress under Applied Load.

Material	Applied Load (N)	Maximum Stress (MPa)	Safety Factor
Steel	5000	680	1.76
GFRP	5000	520	1.73
CFRP	5000	470	3.19
Hybrid Composite	5000	495	2.53

CFRP-based springs have the lowest maximum stress under identical loading conditions. Due to their load-sharing and rigidity, carbon fibres are better. Compared to pure CFRP systems, hybrid composites have appropriate stress levels and lower cost. This study found that composite leaf springs can maintain safety margins under operational loads. Spring flexibility and suspension performance were assessed by deflection analysis. Not enough deflection can really reduce ride comfort, like everything feels a bit off, but too much deflection may lead to structural instability, and that can be pretty risky too.

Table 5: Deflection Characteristics of Leaf Springs.

Material	Maximum Deflection (mm)	Stiffness (N/mm)
Steel	65	76.9
GFRP	72	69.4
CFRP	58	86.2
Hybrid Composite	61	82.0

Due of its lower modulus of elasticity, GFRP has the maximum deflection, while CFRP has the lowest and highest stiffness. Hybrid composites balance flexibility and stiffness. These findings suggest that fibre orientation and laminate architecture can customise composite materials for specific applications. Line graphs showing stiffness-deflection relationships can be made from Table 4.4 data. Because of repetitive cyclic loading, leaf spring fatigue performance is crucial. Fatigue was considered in the design technique to predict material life cycles.

Table 6: Estimated Fatigue Life Performance.

Material	Fatigue Life (Cycles × 10^6)	Relative Improvement (%)
Steel	1.8	0
GFRP	3.2	77.8
CFRP	4.6	155.6
Hybrid Composite	4.0	122.2

Composite materials have longer service life than steel, according to fatigue study. Due to its crack propagation and energy dispersion, CFRP has the highest fatigue resistance. Results indicate that composite leaf springs can greatly reduce car maintenance and replacement frequency. Additional research examined how fibre orientation affects composite spring performance. Fibre orientation is a major strength and stiffness factor.

Table 7: Influence of fibre Orientation on Composite Spring Performance.

fibre Orientation	Maximum Stress (MPa)	Deflection (mm)	Performance Index
0°	450	56	95
30°	475	59	91
45°	505	63	87
60°	540	67	82
90°	610	74	76

The results show that fibre orientations closer to loads improve structural performance. The 0° orientation had the lowest stress and deflection, suggesting greatest load-carrying capacity. Performance decreased as orientation angle grew due to fibre misalignment with the principal loading direction. Composite spring development requires adequate laminate design, as shown by these data. The theoretical framework optimised weight minimisation, stiffness maximisation, and fatigue enhancement.

Table 8. Optimized Composite Leaf Spring Design Parameters.

Parameter	Optimized Value
Spring Length	1200 mm
Spring Width	60 mm
Thickness	18 mm
Material	Hybrid CFRP/GFRP
fibre Orientation	0°/30°/0°
Estimated Weight	4.1 kg
Safety Factor	2.6
Fatigue Life	4.2 × 10^6 Cycles

The optimal arrangement balances structural performance, durability, and manufacturing cost. The hybrid composite arrangement improves mechanical performance while saving material compared to pure CFRP systems. The results demonstrate that the theoretical design methodology finds viable material systems and design combinations for composite leaf spring applications. Evaluation of material selection, stress behaviour, deflection characteristics, fatigue performance, and optimisation requirements is methodical using the analytical framework. Composite leaf springs consistently surpass steel springs in weight reduction, fatigue resistance, and mechanical qualities. CFRP performed best, whereas hybrid composites balanced performance and cost best. Thus, the theoretical design approach provides a solid foundation for finite element analysis, experimental validation, prototype development, and industrial implementation of advanced composite leaf spring systems in automotive and engineering applications.

CONCLUSION

This study successfully created a theoretical design method for automotive and engineering composite leaf springs. The research showed that composite materials can replace steel leaf springs by analysing material attributes, structural design factors, composite laminate theory, and performance assessment criteria. The results showed that CFRP and hybrid composite leaf springs have significant advantages in weight reduction, specific strength, fatigue resistance, corrosion resistance, and structural efficiency. Material selection, stress analysis, deflection assessment, and optimisation are integrated in the suggested design framework to improve suspension performance and meet engineering criteria. Furthermore, the study found ideal fibre orientations and laminate combinations that improve load-bearing and durability. The theoretical methodology provides a solid foundation for computational simulations, experimental validation, and industrial implementation of lightweight, high-performance composite leaf spring systems in modern engineering applications.

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