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DESIGN OPTIMIZATION OF COMPOSITE LEAF SPRINGS USING RESPONSE SURFACE METHODOLOGY: A REVIEW

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Abstract
Leaf springs remain the most widely used suspension elements in commercial and heavy-duty vehicles because of their simplicity, load-carrying capacity and ability to combine the functions of a structural link and an energy-absorbing spring. Conventional multi-leaf steel springs, however, are heavy, corrosion-prone and susceptible to fatigue cracking at the eye ends and centre-clamp region, and their mass contributes directly to unsprung weight, ride discomfort and higher fuel consumption. Fibre-reinforced polymer (FRP) composites, particularly E-glass/epoxy and carbon/epoxy systems, have therefore been investigated extensively as replacements, offering high specific strength, corrosion immunity and superior fatigue resistance. Because composite performance is highly sensitive to geometric and laminate parameters, design optimization is essential; Response Surface Methodology (RSM), built on structured Design of Experiments such as Central Composite Design, has emerged as a computationally efficient tool for relating parameters such as thickness, width, fibre orientation and number of layers to stress, deflection and weight through regression-based surrogate models. This review synthesises the published literature on steel and composite leaf spring design, finite element analysis, fatigue behaviour and optimization methods (Taguchi, Genetic Algorithms and RSM), summarises the reported findings and limitations of representative studies, and identifies the research gaps that motivate continued work on RSM-based, experimentally validated composite leaf spring design.

Keywords: Composite Leaf Spring; Response Surface Methodology (RSM); Finite Element Analysis (FEA); Design Optimization; Fibre-Reinforced Polymer (FRP

1. Introduction
A leaf spring supports the sprung mass of a vehicle while isolating it from road-induced shocks, and in commercial vehicles it also participates in transmitting braking and traction forces. Structurally it is a curved elastic beam, or a stack of such beams, that stores strain energy under load and releases it on unloading. Because leaf springs are manufactured largely from high-carbon or alloy steel, they represent a significant fraction — commonly cited as 10 to 20 percent — of a vehicle's unsprung mass. Increased unsprung mass is well known to degrade ride comfort, tyre-road contact, braking response and fuel economy, which has motivated a long-running search for lighter alternatives. Fibre-reinforced polymer composites, and E-glass/epoxy in particular, have attracted sustained research interest as leaf spring materials because of their high specific strength and specific stiffness, excellent corrosion resistance and favourable fatigue behaviour compared with steel [1]. A recent and comprehensive synthesis of this body of work is provided by Ke et al. [5], who reviewed material selection, joint and eye-end design, and stiffness-prediction methods for composite leaf springs and noted that most reported studies still treat analysis and optimization as separate, sequential steps rather than as an integrated, statistically driven design process. This review paper revisits that literature with a specific focus on the design-optimization stage, and in particular on the role of Response Surface Methodology, the design optimization of a composite leaf spring using RSM with finite element analysis and experimental validation within its research context.

2. Conventional Steel Leaf Springs: Behaviour and Limitations
Early analytical treatments of leaf springs relied on classical curved-beam and leaf theory to estimate stress and deflection under static load. With the growth of computational tools, finite element analysis (FEA) largely replaced purely analytical estimation for practical design verification. Rajendran and Vijayarangan [7] performed a three-dimensional nonlinear contact finite element analysis of a multi-leaf steel spring assembly, explicitly modelling inter-leaf contact, the centre clamp and U-bolts, and compared the predicted static stress and natural frequencies

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with experimental measurements, reporting good agreement. Their results, along with a substantial body of subsequent FEA work, consistently identify the eye ends and the centre-clamp region as the locations of highest stress concentration and the most probable sites of fatigue crack initiation.

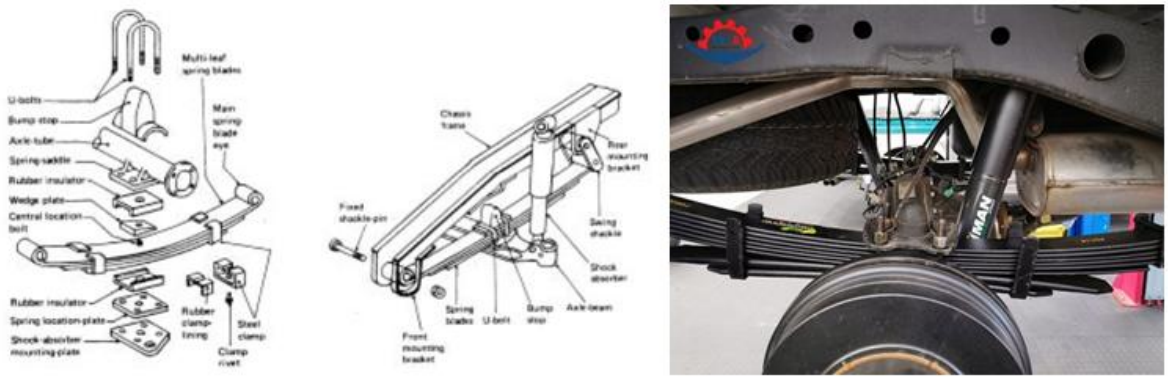


Figure 1 – Conventional multi-leaf steel spring assembly

In an industrial context, Kurna, Sharma and Mathur [13] analyzed a multi-stage suspension leaf spring of a heavy-duty commercial vehicle, correlating rig-test stiffness and strain-gauge stress measurements against a full finite element model, and demonstrated that a validated FEA route can substitute for costly and time-consuming endurance and rig testing during early design iterations. Studies of this kind confirm that, while steel leaf springs are structurally reliable and well understood, their non-uniform stress distribution, susceptibility to corrosion and contribution to vehicle mass constitute genuine, well-documented engineering limitations that justify the search for alternative materials and more systematic design procedures.

3. Composite Leaf Springs: Materials and Mechanical Performance

Al-Qureshi [1] provided one of the earliest comprehensive treatments of automobile leaf springs made from composite materials, outlining the manufacturing routes, mechanical requirements and the substantial weight-saving potential of FRP springs relative to steel, and this paper remains a frequently cited starting point in the field. Sancaktar and Gratton [10] subsequently designed, fabricated and tested a functional unidirectional E-glass/epoxy leaf spring for a light, solar-powered vehicle, confirming the practical manufacturability of composite springs using hand lay-up style processes similar to those still used in laboratory-scale fabrication today.

Shokrieh and Rezaei [11] carried out a detailed structural analysis and optimization of a composite leaf spring, using finite element modelling to evaluate stress and deflection under design constraints and reporting significant weight reduction relative to an equivalent steel spring while respecting strength and stiffness limits. Patunkar and Dolas [6] modelled and analysed a composite leaf spring under static load using FEA and confirmed that the stress and deflection behaviour of composite mono-leaf configurations can be predicted with reasonable accuracy using standard shell or solid element formulations. Collectively, this line of work established that mono-leaf composite springs, by eliminating the inter-leaf friction and contact nonlinearity present in steel multi-leaf assemblies, tend to produce smoother, more uniform stress distributions, and that weight reductions in the range commonly reported as 60 to 70 percent are achievable without violating stress or deflection limits — a finding also emphasised in the review by Ke et al. [5].

4. Finite Element Analysis of Leaf Springs

Finite element analysis has become the standard tool for evaluating leaf spring structural performance prior to fabrication, since it allows rapid comparison of many candidate geometries and materials without the cost of physical prototyping. Commercial packages such as ANSYS and ABAQUS have been used to model both steel and composite leaf springs, typically with a fixed support at one eye, a sliding or shackle support at the other, and a

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distributed or point load representing the vehicle mass applied at the spring centre. Rajendran and Vijayarangan [7] combined static and modal FEA with experimental verification to validate both stress and natural-frequency predictions, while Kurna et al. correlated FEA stiffness and stress results against rig-test data for a heavy-duty vehicle spring, and Patunkar and Dolas [6] used FEA specifically to characterise the static response of a composite mono-leaf design. A consistent conclusion across these studies is that composite leaf springs exhibit lower peak von Mises stress and a more uniform stress field than steel springs of equivalent stiffness, which in turn supports longer fatigue life and more efficient material utilisation.

5. Fatigue and Durability of Composite Leaf Springs

Because leaf springs experience millions of load cycles in service, fatigue behaviour is a primary design consideration alongside static strength. Kumar and Vijayarangan [3] carried out combined analytical and experimental fatigue-life studies comparing steel and E-glass/epoxy composite multi-leaf springs for light passenger vehicles, using life-data analysis to estimate fatigue life from static FEA results and experimental load-deflection data; they reported that the composite spring achieved lower stress, higher stiffness-to-weight ratio and a longer predicted fatigue life than the steel counterpart of equivalent load capacity. Bhanage and Padmanabhan [2] similarly addressed fatigue design and simulation of a glass fibre/epoxy composite automobile leaf spring, reinforcing the observation that the layered, anisotropic structure of FRP composites provides favourable energy-absorption and crack-resistance characteristics relative to isotropic steel. These findings support the premise, adopted in the present project, that a properly optimized composite leaf spring can match or exceed the durability of a conventional steel spring while achieving substantial weight savings.

6. Optimization Techniques in Leaf Spring Design

Trial-and-error and purely analytical sizing procedures tend to produce over-designed, unnecessarily heavy components because they do not systematically explore the interaction between design variables. Consequently, a range of formal optimization techniques has been applied to leaf spring design.

Genetic Algorithms (GA): Rajendran and Vijayarangan [8] applied a genetic algorithm to the optimal design of a composite leaf spring, treating thickness, width and number of plies as design variables and minimising weight subject to stress and deflection constraints; the optimized composite design achieved a substantial weight reduction relative to the baseline steel spring. GA-based approaches can explore large, non-convex design spaces effectively but generally require many objective-function evaluations, which becomes computationally expensive when each evaluation involves a full finite element simulation.

Taguchi Method: Hamadi and Salman [4] used the Taguchi technique, based on orthogonal-array experiments and signal-to-noise ratio analysis, to identify optimal combinations of leaf spring thickness, length and step spacing for several commercial vehicle case studies. The Taguchi approach is attractive because it drastically reduces the number of required experiments or simulations, but because it evaluates only a small number of discrete factor levels it cannot, by itself, construct a continuous quadratic response surface or capture curvature and interaction effects with the same fidelity as RSM.

Response Surface Methodology (RSM): RSM addresses this limitation by fitting a second-order polynomial regression model to responses obtained at a structured set of design points, most commonly generated using a Central Composite Design, and then using that surrogate model to predict optimal parameter combinations across a continuous design space. Rajesh et al. [9] applied RSM to a glass/carbon hybrid composite leaf spring, identifying the geometry that minimised stress, strain and deflection and confirming the RSM-predicted optimum through experimental testing under the Tsai-Wu failure criterion. The statistical foundations of this approach, including central composite and Box-Behnken designs, analysis of variance and model-adequacy checking through R-squared and lack-of-fit statistics, are set out in standard texts such as Montgomery [12].

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7. Comparative Summary of the Literature

Table 1 summarises the material, method, principal findings and identified limitations of the representative studies discussed above.

Author(s) & Year	Material	Method	Key Findings	Limitations / Gap
Rajendran & Vijayarangan (2001a) [7]	Steel	3-D nonlinear contact FEA + experiment	Predicted stress/deflection and natural frequencies of a multi-leaf assembly with good experimental agreement	Steel design remains heavy; no material substitution considered
Rajendran & Vijayarangan (2001b) [8]	E-glass/epoxy composite	Genetic Algorithm optimization	Composite mono-leaf spring optimized for minimum weight; large weight saving over steel	GA is computationally expensive for repeated re-optimization
Sancaktar & Gratton (1999) [10]	Unidirectional E-glass/epoxy	Design, fabrication and testing	Demonstrated a functional composite leaf spring for a light solar vehicle	Limited to a single vehicle case; no systematic DOE-based optimization
Shokrieh & Rezaei (2003) [11]	Composite (multi-layer)	FEA-based structural analysis and optimization	Composite spring optimized under stress and deflection constraints; substantial weight reduction reported	Optimization limited to a small parameter set; no experimental validation of optimized design
Kumar & Vijayarangan (2007) [3]	Steel vs. E-glass/epoxy	Static FEA + life-data (fatigue) analysis	Composite spring showed lower stress, higher stiffness-to-weight ratio and longer fatigue life than steel	Constant-amplitude loading only; road-load spectra not considered
Patunkar & Dolas (2011) [6]	Composite leaf spring	Static FEA modelling	Verified stress and deflection behaviour of composite spring under static load	Confined to static analysis; optimization not attempted
Bhanage & Padmanabhan (2014) [2]	Glass fibre/epoxy	Fatigue design & simulation	Fatigue life of composite spring simulated and compared with design targets	Simulation-based; limited physical fatigue testing
Hamadi & Salman (2017) [4]	Steel/composite leaf spring	Taguchi method (L9/L27 arrays)	Identified optimal thickness, length and step combinations using S/N ratios	Screens few discrete levels; cannot fit continuous quadratic response surfaces
Rajesh et al. (2017) [9]	Glass/carbon hybrid composite	Response Surface Methodology	RSM identified optimal geometry for minimum stress-strain and deflection; results verified experimentally	Limited to the specific hybrid layup studied; single-objective focus
Ke et al. (2019) [5]	Various FRP composites (review)	Literature synthesis	Comprehensive review of material selection, joint/eye-end design and stiffness prediction methods for composite leaf springs	Identifies scarcity of studies combining RSM-based multi-variable optimization with experimental validation

Table 1. Summary of representative literature on steel and composite leaf spring analysis and optimization.

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8. Research Gaps

The reviewed literature demonstrates broad consensus that composite materials outperform steel in strength-to-weight ratio, corrosion resistance and fatigue life, and that formal optimization outperforms trial-and-error sizing. However, several gaps recur across the body of work:

• Relatively few studies integrate composite material selection, systematic RSM-based optimization and experimental validation within a single, coherent framework; RSM has more often been applied either to metallic components or to a single composite configuration rather than across a full multi-variable design space (thickness, width, number of layers, fibre orientation and curvature) [5], [9].

• Genetic Algorithm and Taguchi studies [4], [8] optimize effectively within their respective frameworks, but GA is computationally costly for FEA-coupled problems while Taguchi's discrete-level screening limits its ability to model curvature and interaction effects that a second-order RSM model captures naturally.

• Experimental validation, where reported, is frequently limited to static load-deflection comparison; fatigue validation under realistic, variable-amplitude road-load spectra remains comparatively rare [2], [3].

• The simultaneous influence of multiple geometric and material variables on stress, deflection and weight is not always explored jointly, so reported optimal designs may not represent a true multi-objective optimum.

These gaps directly motivate the approach adopted in the present project, which couples finite element analysis, a Central Composite Design-based RSM optimization of thickness, width, number of layers, fibre orientation and radius of curvature, and static experimental validation of the optimized E-glass/epoxy composite leaf spring.

9. Conclusion

The literature consistently shows that replacing conventional steel leaf springs with fibre-reinforced polymer composites, most commonly E-glass/epoxy, can deliver weight reductions on the order of 60 to 70 percent while maintaining or improving stress, deflection and fatigue performance. Finite element analysis is well established as the primary tool for predicting this behaviour, and a range of optimization methods — Genetic Algorithms, the Taguchi method and Response Surface Methodology — have each been shown to improve on unoptimized, trial-and-error designs. Among these, RSM offers a favourable balance between the number of required simulations and the ability to model curvature and interaction among multiple design variables, making it particularly suitable for expensive FEA-coupled optimization problems such as composite leaf spring design. The comparatively limited number of studies that combine RSM-based multi-variable optimization with rigorous experimental validation represents the principal research gap this review identifies, and it is this gap that the present M.Tech project on the design optimization of a composite leaf spring using Response Surface Methodology seeks to address.

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