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"LEAF SPRING SUSPENSION FOR ROAD VEHICLES: A REVIEW OF DESIGN, SPRING MATERIALS, COMPOSITE ALTERNATIVES, AND FINITE ELEMENT ANALYSIS"

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ABSTRACT

The leaf spring is one of the oldest and most widely used suspension elements in light and heavy road vehicles. It supports the weight of the vehicle, absorbs shocks from the road, and at the same time locates the axle, so its geometry and material directly influence ride comfort, fuel economy, and safety. Because the spring forms part of the unsprung mass and is loaded repeatedly in service, considerable research has been devoted to reducing its weight while maintaining its strength, stiffness, and fatigue life. This review paper presents an assessment of published work on leaf springs, with emphasis on the construction and design of multi-leaf springs, the use of finite element analysis (FEA) in ANSYS for static, vibration, and fatigue studies, the comparison of conventional spring steels, and the substitution of steel by composite and hybrid materials. Studies on steel springs, glass-fibre and carbon-fibre composite springs, hybrid springs with rubber sleeves or composite leaves, and optimisation by grey relational analysis are examined. The reviewed literature indicates that FEA is the standard tool for evaluating stress, deflection, and safety factor, that composite and hybrid springs offer large weight savings with lower stress, and that alloy steels remain essential for heavily loaded conventional springs. Research gaps are identified, including few systematic comparisons of different spring steels in the same geometry, limited reporting of the combined effect of camber and leaf thickness, limited relation of road-excitation frequency to vehicle speed, and scarce experimental validation. The findings are intended to guide the design and material selection of leaf springs for road vehicles.

Key Words: *Leaf spring; suspension system; finite element analysis; ANSYS; spring steel; composite leaf spring; hybrid spring; factor of safety; fatigue.*

I. INTRODUCTION

The suspension system links the wheels to the body of the vehicle and controls how road and load disturbances are transmitted to the passengers and cargo. Its tasks are to support the weight of the vehicle, to isolate the body from road shocks and vibrations, to keep the tyres in contact with the road so that traction, braking, and steering forces can be developed, and to maintain the correct geometry of the wheels and axles. Among the spring elements used for this purpose, the leaf spring remains common in commercial vehicles, light trucks, and pick-up vehicles because it is simple, robust, inexpensive, and able to carry large loads [1], [2]. Besides its springing action, it locates the axle, transmits driving and braking forces, and provides a small amount of damping by friction between the leaves.

The most common form is the semi-elliptic leaf spring, which consists of steel leaves of different lengths stacked one above the other. The longest leaf, the master leaf, is rolled at its ends into eyes through which the spring is attached to the frame, and the shorter graduated leaves are placed below it and held together by a centre bolt and clips. Other forms include quarter-elliptic (cantilever), transverse, taper, and auxiliary or progressive springs [3]. The principal terms used

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in design are the span, camber, spring rate, rated load, stepping, and nipping, in which the full-length leaves are pre-stressed to reduce the stress that they would otherwise carry in excess of the graduated leaves. The material should combine high strength-to-weight ratio, high strain-energy capacity, high fatigue strength, and good corrosion resistance, and leaf springs have traditionally been made of medium-carbon and alloy spring steels, such as chrome vanadium and chrome nickel molybdenum steel.

Reducing the unsprung mass improves ride comfort and road holding and reduces fuel consumption, so a saving in the weight of the spring is valuable. This has led to many studies of alternative materials and of numerical methods for evaluating them. The finite element method divides the spring into small elements and gives the distribution of displacement, strain, and stress for a given load, allowing alternative materials and geometries to be compared before prototypes are built [4]. This paper reviews the published work on these topics and identifies the gaps that remain.

II. Problem Identification

A leaf spring carries the vertical load of the vehicle and is subjected to repeated loading from the road. A spring that is too weak yields or fatigues prematurely, whereas a spring that is too heavy or too stiff increases the unsprung mass, reduces ride comfort, and wastes material. The stresses are highest near the eyes and the centre clamp, where the loads are introduced, and failure in these regions can endanger the vehicle and its occupants, so the designer must select a geometry and a material that provide adequate strength and stiffness at the lowest weight.

The published literature is large but dispersed. Many studies compare steel with composite materials for one particular vehicle, others consider a single steel in a single geometry, and the reporting of results varies: some studies give only deflection and stress, while others give safety factor, strain, fatigue life, or vibration. The geometry of the spring, such as camber and leaf thickness, is usually held constant, so the combined effect of material and geometry is not always available. The relation between the frequency with which the road excites the suspension and the speed of the vehicle is seldom considered together with the static analysis. A consolidated review is therefore needed to summarise the available evidence and to identify the gaps.

III. Research Objective

The main objective of this review paper is to critically examine published work on the design, materials, and finite element analysis of leaf springs. The specific research objectives are as follows:

- To review leaf spring construction and design: Describe the types of leaf spring, the design terminology, and the loads acting on the spring.
- To evaluate static finite element analyses: Review studies that use ANSYS to obtain the deflection, stress, and safety factor of steel leaf springs.
- To examine vibration and fatigue studies: Review the evaluation of vibration behaviour, damage, and fatigue life of leaf springs.
- To review composite and hybrid springs: Examine the use of glass-fibre, carbon-fibre, and hybrid materials and the weight saving that they offer.
- To compare spring materials: Review studies that compare different materials and use optimisation methods to select the best combination.
- To identify research gaps: Identify limitations in existing studies relevant to the choice of spring steel and geometry.

IV. Literature Review

The studies reviewed below were published between 2021 and 2022 and are grouped by topic. For each study the scope and principal findings are summarised as reported by the authors, and its relevance to leaf spring design is highlighted. Where a study is described only through its stated scope, no quantitative results are attributed to it.

Reviews. Solanki and Kumar (2025) [1] reviewed earlier work on leaf springs, covering material composition, experimental testing, and types of loading, with the aim of improving the load-carrying capacity and working conditions of the spring. Kothari and Patel (2024) [2], Kumar and Biradar (2023) [3], and Dwivedi and Jain (2026) [4] presented review papers on the design, analysis, and fatigue analysis of leaf springs for automobile suspensions, with emphasis on the effect of alternative materials on the efficiency of the spring. Together these reviews indicate that finite element analysis and composite materials are the main directions of research.

Static analysis of steel springs. Gowd and Goud (2022) [5] carried out a static analysis of the leaf spring of a TATA-407 light commercial vehicle to determine the safe stress and payload. The spring was modelled and analysed in ANSYS, and the safe load was found to be 7700 N, with the highest stress on the inner side of the eyes, which shows that the eye region needs particular attention in design, manufacture, and material selection. Sharma et al. (2023) [6] analysed a steel leaf spring in ANSYS and compared it with a glass-fibre reinforced plastic spring, with the contact between the leaves considered. Static finite element analyses of leaf springs in ANSYS were also reported by Krishna et al. (2024) [7] and by Kumar and Reddy (2017) [8], the latter comparing three materials and a multi-layer composite spring and finding much lower stress in the composite spring. Magdum (2025) [9] used ANSYS for a dynamic analysis of a leaf spring.

Vibration and fatigue. Sharma et al. (2026) [10] observed that loss of a leaf spring through vibration is more common than failure of its material, so vibration analysis is important in the design of steel springs. They modelled a multi-leaf spring in Pro-E, imported it into ANSYS 14, and studied its vibration under complex loading. Moulali et al. (2024) [11] presented the design and fatigue analysis of a mono leaf spring for a Maruti 800 passenger vehicle made of steel and of carbon/epoxy, taking stress, deflection, damage, and life as governing quantities in a three-dimensional fatigue analysis in ANSYS Workbench.

Composite and hybrid springs. Saini et al. (2023) [12] designed and analysed a composite leaf spring for a light vehicle and compared it with the steel spring on stress and weight, considering E-glass/epoxy, carbon/epoxy, and graphite/epoxy; they concluded that the composite spring is attractive because of its high strength-to-weight ratio and fatigue resistance. Pozhilarasu and Pillai (2023) [13] compared a steel leaf spring with an E-glass/epoxy composite spring in ANSYS under identical conditions and fabricated the composite spring by hand lay-up. Yinhuan et al. (2021) [14] studied a glass-fibre composite spring in ANSYS with the interleaf contact included and reported lower stresses and a lower weight than the steel spring. Kalwaghe and Sontakke (2024) [15] compared analytical and finite element results for a composite spring and concluded that it provides the same load capacity and stiffness at a much smaller weight. Rao and Feroz (2024) [16] modelled a laminated composite leaf spring under static load, and Mundale et al. (2023) [17] designed and analysed a composite spring for a light vehicle. Chavhan et al. (2022) [18] analysed the leaf spring of a Mahindra pick-up in ANSYS 15.0 for steel and for AS4 and T300 composites, and Clive (2024) [19] compared the deflection, equivalent elastic strain, and equivalent stress of E-glass/epoxy and carbon-fibre springs with those of a conventional steel spring.

Shanmugham et al. (2025) [20] proposed a heterogeneous hybrid spring with synthetic rubber sleeves between the leaves, modelled in Pro-E and analysed statically, and reported a maximum stress of 263.33 MPa with reduced stress and deformation compared with the steel spring. Chowdhury and Islam (2022) [21] analysed a five-leaf steel spring of a light car by the finite element method and compared it with a single-leaf composite spring; they reported much lower stress and weight for the hybrid spring. Gupta and Verma (2021) [22] modelled a multi-leaf spring in CATIA V5, analysed it in ANSYS Workbench 16.0, compared several composites, and proposed a hybrid spring combining steel and composite leaves on the basis of performance and cost.

Material comparison and optimisation. Khan et al. (2021) [23] reviewed the influence of the alternative materials proposed by various researchers and compared stress, deflection, and fatigue for steel and composite springs, with the model prepared in Creo 2.0 and analysed in ANSYS 14.0. Pal and Kushwah (2022) [24] investigated composite materials for the leaf spring of a TATA ACE EDGE light commercial vehicle, compared load capacity, stress, stiffness, and weight with those of the steel spring, and used a grey relational method with sixteen experiments to select the best combination of input parameters. Arun Prakash et al. (2020) [25] studied the leaf spring of a TATA-407 light commercial vehicle to find the safe stress and payload, compared conventional and alternative spring steels in a static

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structural analysis in ANSYS Workbench, and reported maximum deformations of 1.409 mm for chrome vanadium steel and 1.264 mm for chrome nickel molybdenum steel. They found that plain carbon steel and structural steel have lower safety factors than chrome nickel molybdenum steel, which they judged the best of the materials considered.

Table 4.1: Summary of selected studies on leaf springs

Study	Focus	Principal finding reported
Gowd and Goud (2025) [5]	Static FEA, TATA-407 spring	Safe load 7700 N; stress highest at eyes
Yinhuan et al. (2026) [14]	Composite spring with interleaf contact	Lower stress and weight than steel
Saini et al. (2023) [12]	Composite spring for light vehicle	Weight saving with lower stress
Moulali et al. (2024) [11]	Fatigue of mono leaf spring	Damage and life from ANSYS
Shanmugham et al. (2025) [20]	Hybrid spring with rubber sleeves	Maximum stress 263.33 MPa
Sharma et al. (2026) [10]	Vibration of multi-leaf spring	Vibration important for steel springs
Pal and Kushwah (2024) [24]	Composite materials, grey relational method	Best material combination selected
Gupta and Verma (2025) [22]	Hybrid steel–composite spring	Hybrid design proposed
Chowdhury and Islam (2023) [21]	Five-leaf steel versus composite	Lower stress and weight
Arun Prakash et al. (2023) [25]	Four spring steels, static FEA	Deformation 1.264–1.409 mm

Summary and research gaps. Several themes emerge. First, ANSYS-based static analysis is the standard method for evaluating the deflection, stress, and safety factor of leaf springs [5]–[8], and vibration and fatigue studies show that these are also important in service [10], [11]. Second, composite and hybrid springs consistently show lower stress and much lower weight than steel springs [12]–[22], although their manufacture, cost, and fatigue behaviour need further evaluation. Third, steel springs still dominate the market, and alloy steels such as chrome vanadium and chrome nickel molybdenum steel are needed where the loads are high [25]. The reviewed studies also have limitations: systematic comparisons of different steels in the same geometry are few, the geometry (camber and leaf thickness) is usually held constant, many studies do not report the safety factor or the strain, the road-excitation frequency is seldom related to the vehicle speed, and experimental validation and mesh-convergence studies are not consistently reported. These gaps motivate a comparative static study of several spring steels in several geometries.

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V. CONCLUSION

This review examined published work on the design, materials, and finite element analysis of leaf springs for road vehicles. The literature shows that the leaf spring remains important because of its simplicity and load capacity, that finite element analysis in ANSYS is the principal tool for evaluating deflection, stress, safety factor, vibration, and fatigue, and that composite and hybrid springs can reduce the weight and the stress substantially. Alloy spring steels remain necessary for heavily loaded conventional springs, and the studies that compare steels indicate that the choice of the steel affects mainly the safety factor and only slightly the stiffness. Future research should compare spring steels systematically across several geometries, report deflection, stress, strain, and safety factor together, relate road-excitation frequency to vehicle speed, include modal and fatigue analyses, perform mesh-convergence studies, and validate the numerical results by load-deflection tests on prototype springs. These steps can support the design of lighter, safer, and more durable suspension springs.

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