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Design Optimization and Performance Evaluation of a Lightweight Leaf Spring for Automotive Applications

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Abstract
Leaf springs are widely used in automotive suspension systems because of their simplicity, high load carrying capability, and low manufacturing cost. However, conventional steel leaf springs increase vehicle weight and reduce fuel efficiency. This paper focuses on the design and optimization of composite leaf springs for lightweight automotive applications. Finite Element Analysis (FEA) is used to evaluate stress distribution, deformation, and weight reduction characteristics of different composite materials. The study aims to improve ride comfort, reduce unsprung mass, and enhance suspension performance without compromising structural integrity.
Keywords: *Index Terms—Leaf Spring, Composite Materials, Finite Element Analysis (FEA), Optimization, Automotive Suspension, Weight Reduction, Stress Analysis*

1. Introduction
Leaf springs are important components of automotive suspension systems used to absorb shocks and vibrations generated during vehicle motion. Traditional steel leaf springs possess high strength but contribute significantly to vehicle weight. In modern automotive industries, reducing weight while maintaining strength and durability has become an important requirement. Composite materials such as E-glass epoxy, carbon fiber epoxy, and hybrid composites provide high strength-to-weight ratio and improved fatigue performance

2. Literature Review
- Birhan Alemu Tadesse investigated the replacement of conventional steel leaf springs using composite materials such as carbon epoxy, bamboo polyester, E-glass/epoxy, and graphite epoxy. CATIA V5 and ANSYS software were used for modeling and numerical analysis. The study reported considerable weight reduction in all composite materials compared to steel leaf springs.
- Sarbindu Kumar reviewed the existing work related to leaf spring design, FEM analysis, durability testing, manufacturing process optimization, and failure analysis. The study discussed failure mechanisms such as improper heat treatment, corrosion pitting, hydrogen embrittlement, and fretting fatigue.
- Alexander Savaidis presented the design and optimization of parabolic leaf springs for truck applications using finite element methods and durability analysis.
- David Mantilla focused on the nonlinear dynamic behavior of leaf spring suspension systems using multibody simulation coupled with FEM analysis in ANSYS APDL.
- Tauseef Aized applied Failure Mode and Effects Analysis (FMEA) to analyze possible failure modes in automotive leaf springs.
- Shad Mohammad Shohel investigated mono

composite leaf springs for electric vehicles using carbon fiber and glass fiber reinforced epoxy resin.

- Jenish Lakshmanan proposed a hybrid composite laminate consisting of carbon fiber, glass fiber, and Lantor Soric XF core materials for leaf spring applications.
- Bao Zhang studied stiffness optimization of transverse leaf spring suspension systems using finite element analysis.
- Mangesh Angadrao Bidve utilized Ant Colony Optimization (ACO) for optimizing composite leaf springs made from glass fiber reinforced epoxy resin.
- Adeyinka Oluwo introduced a Taguchi–Pareto optimization method for leaf spring parameter optimization.
- Amol Todkar experimentally optimized elliptical composite leaf spring systems for passive vibration isolation.
- Shraddha R. Gunjawate performed topology optimization of leaf spring brackets for light commercial vehicles using ANSYS software.
- Shiva Shankar designed and fabricated mono composite leaf springs using unidirectional glass fiber reinforced plastic (GFRP).
- Bathuka Mallesh modeled and analyzed composite leaf springs using mild steel and glass-carbon composites.
- Thippeswamy Ekbote replaced conventional steel leaf springs with optimized E-glass/epoxy composite monoleaf springs.
- Nahit Oztoprak experimentally validated compositebased mono-leaf spring systems for light commercial vehicles.
- Sagarsingh Kushwah reviewed studies related to the design and analysis of conventional and composite leaf springs.
- A. Sivasankar proposed a heterogeneous leaf spring model incorporating synthetic rubber sleeves between spring leaves.
- K. Krishnamurthy investigated the replacement of conventional steel leaf springs using various composite materials.
- Kamal Pokhrel analyzed Epoxy/E-glass, Epoxy/Carbon, and Epoxy/Bamboo composite leaf springs using ANSYS static structural analysis.
- Kala Shiva Kumar compared Structural Steel, Al-SiC Metal Matrix Composite (MMC), and E-glass epoxy materials for multi-leaf spring applications.
- D. Sameer Kumar proposed Ant Colony Optimization for achieving minimum weight composite mono-leaf springs.
- Vijayalakshmi P designed and fabricated natural fiber reinforced hybrid polymer composite parabolic leaf springs.
- J. Jancirani provided a comprehensive review on material selection, fabrication methods, CAD modeling, and experimental analysis of composite leaf springs.
- M. Nataraj investigated fatigue failure in heavy truck leaf spring suspension systems using finite element analysis.
- M. Venkatesan analyzed composite leaf springs using different epoxy and E-fiberglass ratios.
- Vivek Ra replaced conventional multi-leaf steel springs with mono composite leaf springs using GFRP.
- Erol Sancaktar designed and manufactured composite leaf springs using unidirectional E-glass roving impregnated with epoxy resin.
- Foard J.H.D., Rollason D., and Thite A.N. investigated mathematical modelling and manufacturing of polymer composite Belleville springs and demonstrated improved vehicle dynamic performance.
- Ke J., Wu Z., and Chen X. presented a comprehensive review on material selection, stiffness calculation, optimization methods, damping behavior, and fatigue performance of composite leaf springs.

3. Problem Statement

Conventional steel leaf springs increase unsprung mass and reduce fuel efficiency. Therefore, there is a need to develop lightweight composite leaf springs with sufficient strength and durability for automotive applications.

4. Proposed Methodology

- Literature review of existing leaf spring systems.

- CAD modeling using CATIA/SolidWorks.
- Material selection for composite leaf spring.
- Finite Element Analysis using ANSYS.
- Comparison of results with conventional steel spring.

5. Experimental Work

The experimental phase validates computational findings and assesses the real-world performance of the EV crash energy absorbing bumper system, ensuring safety, structural integrity, and battery protection under various impact conditions.

5.1.Prototype Fabrication

Scaled and full-scale prototypes are fabricated using Carbon Fiber Reinforced Polymer (CFRP), aluminium alloys, and metallic foam materials. Resin Transfer Moulding (RTM) is adopted to ensure uniform fiber distribution in composite structures, while additive manufacturing techniques are utilized for the fabrication of auxetic and bio-inspired geometries to improve energy absorption and load distribution characteristics.

5.2.Testing Procedures

- Impact Testing: Pendulum and drop-weight impact tests are conducted to simulate frontal and offset crash conditions at different impact velocities.
- Thermal and Electrical Safety Testing: Battery enclosure systems are evaluated under combined thermal and mechanical loading conditions to prevent short circuits, thermal runaway, and ignition.
- High-Speed Imaging: Digital Image Correlation (DIC) systems and high-speed cameras are employed to capture deformation behavior and failure mechanisms during impact events.
- Force and Energy Measurement: Precision instrumentation systems are used to measure impact forces, absorbed energy, deformation characteristics, and crash pulse profiles for validation of Finite Element Analysis (FEA) results.

5.3.Safety Materials

Carbon fiber composite structures and aluminium honeycomb panels are incorporated to achieve improved energy absorption and structural rigidity. Thermally resistant coatings, fire-retardant insulation layers, Phase Change Materials (PCMs), and electrically insulating barriers are integrated to prevent heat transfer, electrolyte leakage, short circuits, thermal runaway, and mechanical deformation under severe crash conditions.

5.4.Computational Work

Finite Element Method (FEM) based simulations are performed to analyze multi-axial and high-velocity crash scenarios. Optimization techniques such as Genetic Algorithms (GA) and Response Surface Methodology (RSM) are utilized to optimize bumper geometry, material selection, wall thickness, and cellular structures for achieving maximum Specific Energy Absorption (SEA), minimum intrusion, and reduced structural weight while maintaining manufacturability. Comparative analyses are carried out based on parameters such as SEA, peak impact force, intrusion depth, and weight-toperformance ratio. Sensitivity analysis is also performed to study the influence of material and geometric variations on crashworthiness performance.

6. Scope Of Work

This research focuses on the design and optimization of a crash energy absorbing bumper system for Electric Vehicles (EVs) using advanced lightweight materials and computational techniques. The scope of work includes the design and modeling of lightweight bumper structures using Finite Element Analysis (FEA) to evaluate impact behavior, stress distribution, deformation characteristics, and energy absorption efficiency. Experimental testing of fabricated prototypes is conducted to validate simulation results under different crash conditions. The study also emphasizes the integration of battery protection mechanisms to ensure occupant safety and minimize intrusion risks during collisions. Furthermore, the feasibility of manufacturing processes such as Resin Transfer Moulding (RTM) and additive manufacturing is evaluated for large-scale production applications. Comparative studies are performed on various bumper materials and structural configurations based on energy absorption capability, weight reduction potential, manufacturability, and cost-effectiveness. Finally, environmental and economic assessments are carried out to support sustainable industrial implementation, leading to the development of optimized design guidelines for EV crash energy absorbing bumper systems.

7. Results And Discussion

The composite leaf spring is expected to provide significant weight reduction with acceptable stress and deformation values. The results will be compared using static structural analysis and fatigue analysis.

Conclusion

Composite leaf springs provide an effective alternative to conventional steel springs due to their lightweight properties, improved fatigue strength, and better vibration characteristics. The optimized composite spring design can improve vehicle performance and fuel efficiency.

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Literature Review

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