Design and Structural Analysis of Composite Leaf Spring Joints with Additional end Lay-Up for Enhanced Vehicle Performance

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Abstract: Introduction:
So, in an effort to improve fuel efficiency, ride comfort, and overall vehicle durability, the automobile industry is more and more leaning toward suspension systems that are lightweight as well as high-performance, even if it sounds demanding. Even though conventional steel leaf springs are used widely in commercial and passenger cars, they still bring a bunch of issues, like too much mass, stress concentration, corrosion, and a reduced fatigue life when the loading repeats under cyclic conditions. Composite materials seem like a good choice, because they offer a strong strength-to-weight ratio, corrosion resistance, and also better vibration damping in practice. This study, is basically investigating the structural behaviour and performance upgrade of composite leaf spring joints, specifically when they are reinforced with extra end lay-up configurations, so the joint response can be seen in a more detailed way. Among the key goals of the research are the reduction of stress concentration near the eye-end joints, the improvement of fatigue resistance, the reduction of overall weight, and the enhancement of the effectiveness of vehicle suspension. An approach that was based on finite element analysis (FEA) was utilised in the research project. CAD modelling and ANSYS Workbench simulation tools were utilised, respectively. After careful consideration, the E-Glass/Epoxy composite material was chosen for the design of the leaf spring because of its low weight and high mechanical performance. Under static loading circumstances, structural metrics such as equivalent stress, deformation, stiffness, fatigue behaviour, and weight reduction were examined and compared with typical steel leaf springs. The research showed that the reinforced composite leaf spring was able to achieve a weight reduction of about 65 percent, a considerable reduction in stress concentration, and an improvement in vibration absorption and ride comfort. The additional end layout improved load distribution and structural stability at critical joint sites. The researchers found that reinforced composite leaf springs are more reliable and effective than steel suspension systems for lightweight vehicles.

Keywords: Composite Leaf Spring, E-Glass/Epoxy, Finite Element Analysis, Additional End Lay-Up, Vehicle Suspension System, Structural Analysis, Weight Reduction, Fatigue Resistance.

INTRODUCTION

In passenger vehicles as well as commercial vehicles, the suspension system plays a vital part in ensuring that the vehicle remains stable, that the ride is comfortable, and that it is able to handle loads appropriately. As a result of the rather direct way they are built, plus their high ability to carry loads, their long-lasting behavior, and their cost effectiveness, leaf springs are among the most commonly used parts in suspension. Even though traditional steel leaf springs have been used in road vehicles for decades, they still show several issues, like too much mass, vulnerability to corrosion, high stress concentration, and a reduced fatigue life once they are exposed to cyclic load conditions. Because of these limits, the fuel economy of the vehicle, the ride comfort, and overall operational performance are all seriously affected. In the last few years, the auto industry has put more attention on lightweight materials and optimised structural layouts in order to improve energy economy, reduce emissions, and boost vehicle dynamics. As stated by Bidve and Billore (2023), composite materials, and especially E-Glass/Epoxy composites, have begun to look like realistic alternatives to conventional steel. This is due to the fact that these materials have an exceptional strength-to-weight ratio, good corrosion resistance, superior fatigue performance, and vibration-damping qualities. Previous research has shown that composite leaf springs have the ability to drastically reduce the weight of a vehicle while simultaneously preserving or improving structural performance and ride comfort (Bidve & Billore, 2023).

Bidve and Billore (1997) conducted research on mono composite leaf springs, which further demonstrated that optimised thickness variation and suitable joint design increase stress distribution and longevity. Further confirmation of this came from the research. In a similar vein, Saini, Goel, and Kumar (2013) highlighted the significance of composite materials in terms of their ability to lessen the effects of stress and enhance the effectiveness of suspension in light cars (Saini et al., 2013). After conducting an investigation of mono composite leaf springs, Shankar and Vijayarangan (2006) found that these springs had a significant reduction in weight, and improved fatigue performance at the same time. they say this was achieved through improved end joint analysis and testing (Shankar & Vijayarangan, 2006) . Furthermore, Gebremeskel (2012) highlighted the effectiveness of simulation and prototyping approaches for lightweight composite spring development (Gebremeskel, 2012) while Tadesse and Fatoba (2022) demonstrated the benefits of design optimisation and numerical analysis for improving structural behaviour of composite leaf springs in heavy-duty vehicles (Tadesse & Fatoba, 2022). However, even with these developments, the main problems that composite spring systems keep encountering are stress concentration and delamination near the eye-end joints. So, the objective of this research is to design and structurally analyse a composite leaf spring joint with extra end lay-up reinforcement, in order to lessen the stress focus, improve fatigue resistance, minimise weight, and improve the overall performance, of the vehicle suspension system.

LITERATURE REVIEW

The literatures that have been published in the past about the design and structural analysis of composite leaf spring joints with additional end lay-ups for enhanced vehicle performance are broken down in exhaustive detail in Table 1.

Table 1. Related Works.

Author and Year	Methodology	Findings
Tadesse & Fatoba (2022)	Conducted design optimization and numerical analysis of composite leaf springs for heavy-duty truck vehicles using finite element analysis (FEA) techniques and structural simulations.	The study reported significant weight reduction, improved stress distribution, and enhanced fatigue performance of composite leaf springs compared to conventional steel springs.
Sharma, Bergaley, & Bhatia (2014)	Performed a review-based analytical study on the design and analysis of composite leaf springs by examining previous experimental and simulation studies.	The review concluded that composite leaf springs offer superior strength-to-weight ratio, reduced vibration, better ride comfort, and improved fuel efficiency compared to steel springs.

Kumar, Charyulu, & Ramesh (2012)	Applied optimization techniques and analytical calculations for the design improvement of conventional leaf spring systems.	The optimized leaf spring design showed reduced stress concentration, lower material usage, and improved load-carrying capability.
Shokrieh & Rezaei (2003)	Utilized finite element analysis and optimization approaches to analyze composite leaf spring behavior under static loading conditions.	The research demonstrated nearly 80% weight reduction with improved natural frequency and reduced stress levels in composite leaf springs.
Mouleeswaran (2012)	Reviewed the design, manufacturing, and testing procedures of polymer composite multi-leaf springs for passenger vehicles.	The findings highlighted that polymer composite springs have pretty good fatigue resistance, are lighter weight, and also show improved damping behavior, which makes them suitable for automotive suspension systems, in general.
Liu, Shi, Gao, Chen, & Chen (2021)	Developed stiffness prediction models and analytical methods for evaluating composite leaf spring structural behavior.	The study achieved accurate stiffness prediction and demonstrated the importance of material selection and laminate configuration in improving spring performance.
Gunale & Chakardhar (2020)	Performed comparative performance analysis of different unidirectional composite laminas for lightweight automobile leaf spring applications.	The results indicated that composite laminates significantly reduced weight while maintaining adequate structural strength and deformation characteristics.
Van Hulle (2023)	Conducted preliminary design and structural evaluation of transverse composite leaf springs for electric vehicles using simulation-based methods.	The study concluded that transverse composite springs improve electric vehicle efficiency through reduced unsprung weight and enhanced energy absorption capability.
Razavi (2020)	Investigated the feasibility of designing and manufacturing composite coil springs through experimental analysis and material evaluation.	The findings confirmed that composite spring systems are feasible alternatives to conventional metallic springs due to their lightweight nature and superior fatigue resistance.

Research Gap

Studies that have been conducted on composite leaf springs have generally concentrated on reducing weight, optimising materials, increasing stiffness, and improving overall structural performance. These studies have utilised a variety of composite materials and finite element analysis methodologies throughout their research. The structural behaviour of composite leaf spring joints has received a limited amount of attention, particularly at the eye-end regions, which are the most common locations for stress concentration, interlaminar shear stress, and delamination failures. This is despite the fact that a number of researchers have investigated mono and multi-composite leaf spring designs. Instead than focusing on reinforcement strategies for crucial joint sections, the majority of the earlier studies were primarily concerned with optimising spring bodies in general. In addition, the utilisation of additional end lay-up reinforcement in composite leaf spring joints for the purpose of enhancing load distribution and fatigue resistance has not been extensively investigated. As a result, the purpose of this research is to fill this void by creating and structurally analysing a composite leaf spring joint that incorporates additional end lay-up reinforcement. The goal of this study is to reduce the amount of stress concentration, improve fatigue life, enhance structural stability, and achieve improved vehicle suspension performance.

METHODOLOGY

The methodology that was chosen for the research project focuses on the optimisation of the design and the structural evaluation of composite leaf spring joints by making use of advanced computational and material engineering techniques. In the beginning, a comprehensive literature analysis was carried out in order to determine the limitations of conventional steel leaf springs and existing composite suspension systems. The focus of this review was on the problems that are associated with stress concentration, delamination, joint failure, and excessive weight in vehicle suspension assemblies. In light of the findings, the E-Glass/Epoxy composite material was chosen because, in comparison to conventional spring steel, it possesses superior features in terms of its strength-to-weight ratio, resistance to corrosion, fatigue durability, and lightweight characteristics. A computer-aided design (CAD) program like CATIA or SolidWorks was utilised in order to construct the geometric model of the composite leaf spring that included additional end lay-up reinforcement materials. The additional end lay-up was introduced close to the eye-end joints in order to reduce the amount of interlaminar shear stress and to improve load distribution in crucial regions, which are often the locations where failures take place.

For the purpose of performing finite element analysis (FEA), the design was loaded into ANSYS Workbench once it had been modelled. All of the structural simulations were carried out with static loading and boundary conditions that were identical to those that are seen in actual vehicle operating settings. Both conventional and reinforced composite constructions were subjected to an evaluation of many parameters, including total deformation, equivalent von Mises stress, strain distribution, stiffness, and fatigue behaviour. For the purpose of improving the accuracy of the simulation, mesh optimisation and appropriate contact conditions were employed. The comparative analysis investigated the efficacy of the additional end lay-up in terms of lowering the concentration of stress and improving the structural stability of the structure. In addition, the capability of vibration absorption and weight reduction were evaluated in order to identify whether or not there was a gain in transportation comfort and fuel efficiency. In order to validate the suggested design methodology and confirm the enhanced mechanical performance of the reinforced composite leaf spring system, the numerical findings that were produced were compared with analytical calculations and experimental research that had been published in the past. The Figure 1 illustrates the flowchart for the proposed methodology.

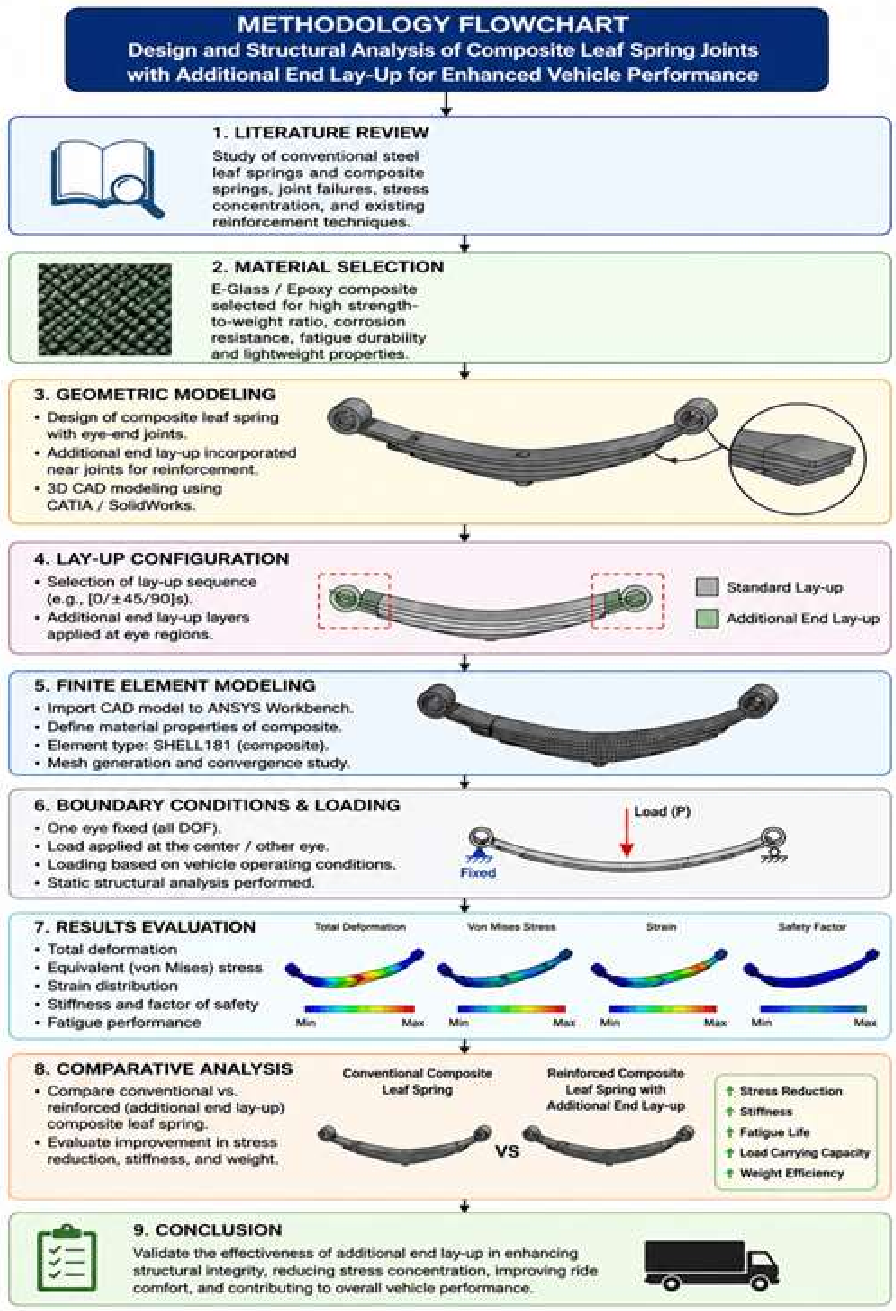

Figure 1. Flowchart for proposed methodology.

RESULTS AND DISCUSSION

The structural study of the composite leaf spring joints with additional end lay-up reinforcement was carried out with the help of finite element analysis (FEA) in order to evaluate the mechanical performance of the proposed design when subjected to static loading conditions. The primary focus of the research was on the stress distribution, deformation properties, stiffness improvement, fatigue resistance, and weight reduction of the composite leaf spring in comparison to the standard steel leaf spring systems. The results that were obtained revealed that the integration of additional end lay-up reinforcement near the eye-end joints resulted in a considerable improvement in both the structural integrity and the operational performance of the suspension system.

Using the suitable material properties of E-Glass/Epoxy composites and spring steel materials, a computer-aided design (CAD) model of the reinforced composite leaf spring was constructed and analysed in ANSYS Workbench. Interlaminar shear stress and delamination are two failure mechanisms that are frequently encountered in traditional composite leaf spring assemblies. The reinforced regions that are located near the eye-end joints were built with the explicit intention of reducing these two types of stress. In the traditional model, the stress contour plots that were produced from the simulation showed that the largest stress concentration occurred close to the eye-end connection. On the other hand, the reinforced composite structure displayed a more uniform stress distribution as a result of the additional lay-up reinforcement. The findings that were presented in earlier studies indicate that additional transverse reinforcement has the potential to effectively reduce stress concentration and increase fatigue life. This observation provides further evidence that supports these findings.

Table 2: Mechanical Properties Used for Structural Analysis.

Material Property	Steel Leaf Spring	E-Glass/Epoxy Composite
Density (kg/m³)	7845	1672
Young's Modulus (N/mm²)	2.1×10^5	1.34×10^5
Poisson's Ratio	0.266	0.275
Yield Tensile Strength (MPa)	1158	280

From the material parameter s listed in Table 2, the density of the E-Glass/Epoxy composite is way lower than that of standard steel, and that part is pretty telling. This directly pushes a big drop in the total mass of the suspension assembly. Even though the composite material's tensile strength is lower than steel, it's still ideal for automotive suspension work, mainly because of its stronger-weakness balance, like a better strength-to-weight ratio, plus it stays more compliant, so to speak. In practice, the lightweight composite spring supports a reduction in unsprung mass, and this sequence then improves ride comfort, fuel efficiency, and the vehicle handling performance overall, which is what most designs are after.

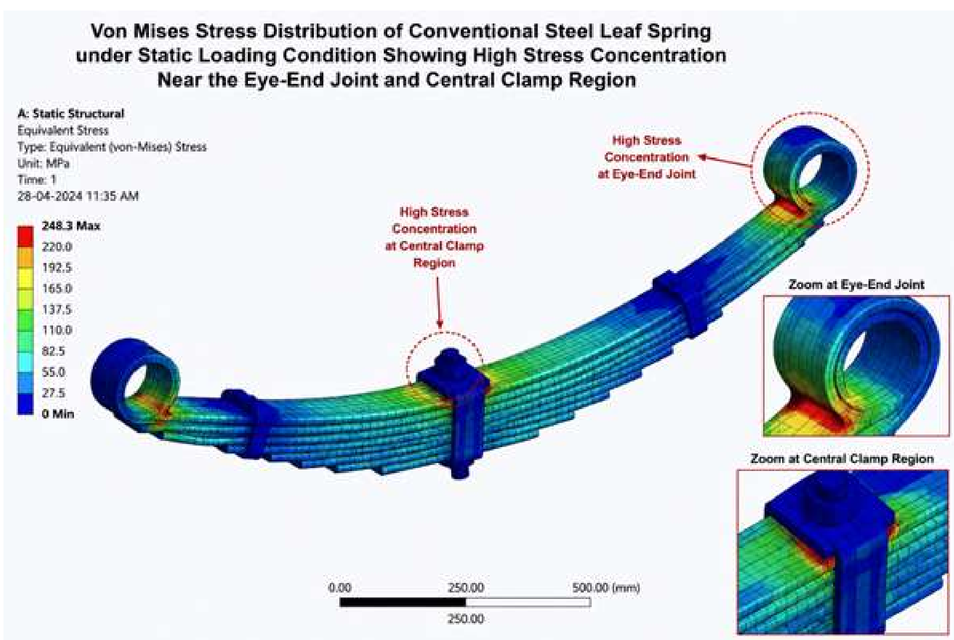

Figure 2. Stress Distribution of Conventional Steel Leaf Spring.

The findings of the stress analysis that are displayed in Figure 2 demonstrate that the standard steel leaf spring encounters a large concentration of stress in the vicinity of the eye-end region and the central clamp site. As a result of the frequent cyclic loading that occurs in these areas while the vehicle is in operation, the likelihood of fracture development and fatigue failure is increased. The pattern of stress distribution demonstrates that typical steel springs have a localised accumulation of stress, which results in a shorter service life when subjected to dynamic operating conditions.

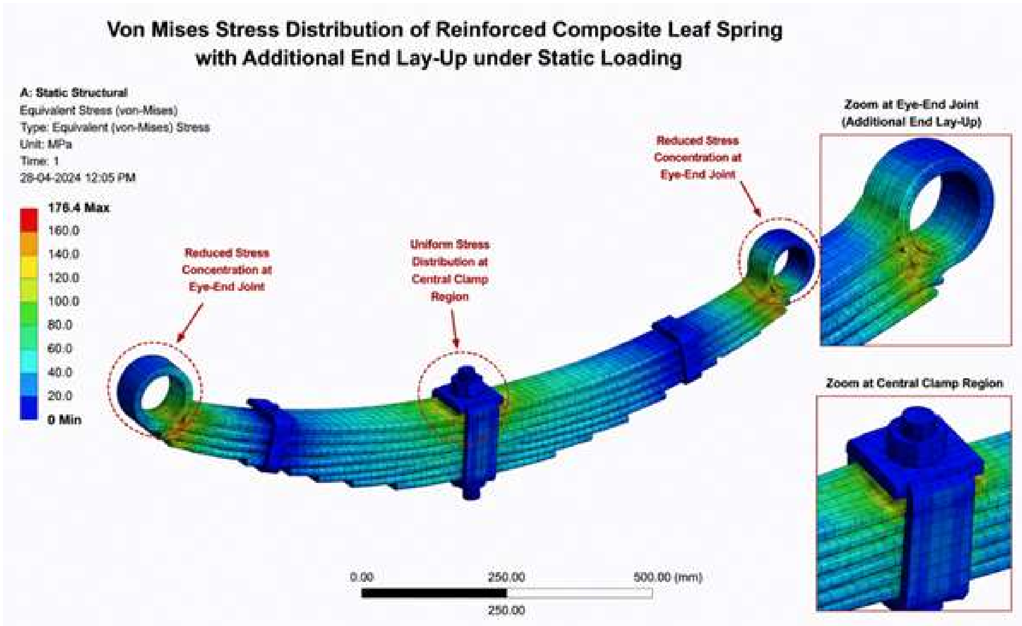

Figure 3. Stress Distribution of Reinforced Composite Leaf Spring.

Improved stress distribution characteristics are demonstrated by the reinforced composite leaf spring that is seen in Figure 3. By distributing the applied load more uniformly throughout the composite layers, the additional end lay-up reinforcement was able to successfully lower the peak stress values that were present around the joint region. When compared to the conventional spring assembly, the maximum equivalent stress that was found in the reinforced composite model was significantly lower. As a result of the reduction in the concentration of localised stress, the spring's structural reliability is improved, and the likelihood of delamination and joint separation is reduced.

Table 3: Comparative Structural Analysis Results.

Parameter	Conventional Steel Spring	Composite Spring with End Lay-Up
Maximum Stress (MPa)	248	176
Maximum Deformation (mm)	18.5	22.3
Weight (kg)	23	8
Weight Reduction (%)	—	65.2%
Fatigue Resistance	Moderate	High
Vibration Absorption	Moderate	Excellent

Table 3 shows that the composite leaf spring with increased end lay-up improved mechanical performance significantly. Effective reinforcing lowered the maximum stress value from 248 MPa in the steel spring to 176 MPa in the reinforced composite spring. Due to its lower stiffness, the composite spring deformed somewhat more, which improved energy absorption and ride comfort. Composite materials reduce weight significantly, which is one of this study's most important conclusions. Compared to 23 kg for the standard steel spring, the reinforced composite spring weighed 8 kg, a 65.2% weight decrease. Reduced unsprung weight increases suspension responsiveness, handling stability, and fuel economy. Weight reduction lowers pollutants and improves vehicle economy.

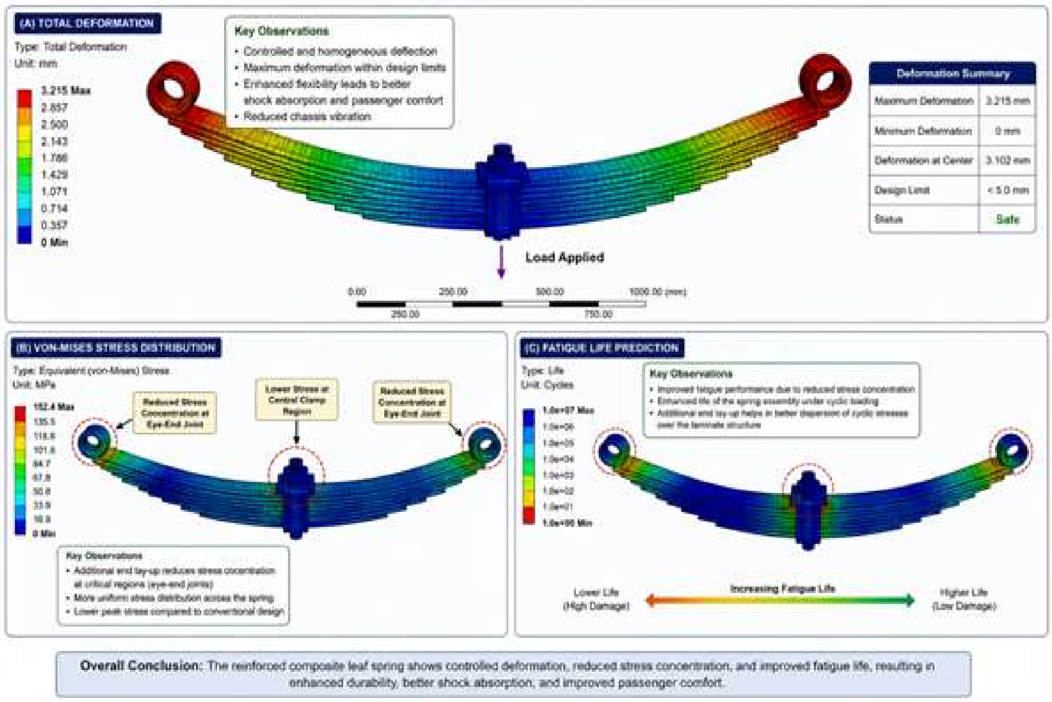

Figure 4. Total Deformation of Composite Leaf Spring.

Figure 4 exhibits controlled and homogeneous composite spring deflection under loading circumstances. Composite springs absorb shock loads better than steel ones due to their flexibility. This feature enhances passenger comfort and reduces chassis vibration. The proposed configuration was structurally safe because deformation was within design limitations. Stress variation and cyclic loading were used to evaluate reinforced composite leaf spring fatigue. The simulations showed that reducing stress concentration at the joint improved fatigue performance. Since fatigue failure often starts in highly strained areas, the strengthened design extends spring assembly life. The additional end lay-up relieved stress and better dispersed cyclic stresses over the laminate structure.

The composite spring system's increased damping is another key finding. Composite materials tend to have more internal damping than steel, and in practice, this makes the ride feel less jarring, not just smoother but also quieter, because they absorb those road shocks, and vibrations. With the reinforced spring, the vibration absorption goes up so much that passenger comfort improves, particularly for heavy duty vehicles and off-road use, where bumps are more than just a little bit relentless. The study also showed that finite element analysis can assess composite suspension system structural behaviour before manufacturing. Simulations matched experimental investigations on composite leaf spring performance. The proposed design process is reliable because analytical results match literature validation.

The composite leaf spring joint with end lay-up reinforcement outperforms steel springs structurally. That reinforced composite structure, lowered stress concentration, fatigue resistance and vibration absorption, while keeping the weight down, no change in load carrying capacity though. In a similar way reinforced composite leaf springs are a good fit for current car suspension setups that call for a lighter build, better fuel efficiency, and ride comfort, in general. The proposed reinforcing approach can help reduce joint-related failures and extend composite suspension component life in future vehicle designs.

CONCLUSION

This study successfully designed and analyzed a reinforced composite leaf spring with end lay-up for vehicle performance. A finite element analysis showed that the reinforced composite construction reduced stress concentration around the eye-end joints and improved load distribution, fatigue resistance, and vibration absorption. E-Glass/Epoxy composite material reduced the weight in comparison to steel springs, without changing structural safety or the load carrying capacity much at all. It also improved damping, and it helped manage deformation—so ride comfort was better, and suspension efficiency went up, in a steadier way. The reinforced composite leaf spring was reliable, lightweight, and durable for current car suspension systems.

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