Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 07 , July - 2026

Optimization of a Leaf Spring Design for Lightweight Electric Vehicles

Akshay Patil
USN: 3VC24MPM01
Department of Mechanical Engineering
Rao Bahadur Y Mahabaleswarappa Engineering College
Ballari – 583104, Karnataka

Under the Guidance of
Dr. Kori Nagaraj
Head of the Department
Department of Mechanical Engineering
Rao Bahadur Y Mahabaleswarappa Engineering College
Ballari – 583104, Karnataka

Chapter 1

INTRODUCTION

With innovation in the manufacturing design of electric vehicles, the requirement for lightweight components in such a vehicle has increased significantly. In this context, it is essential to taken as reason of the issue of reducing the weight in the vehicle since it is vital for the electric car as it affects the distance travelled and the quantity of battery power used. Different systems are present in the vehicle that serve to stabilize and maintain comfort in the vehicle. The suspension system is one of these systems used to ensure the stabilization of the vehicle. Some of the parts in the suspension system that aid in the stabilization of the vehicle are leaf springs. These leaf springs have always been known to be made of sturdy materials, and their traditional usage shows that they are durable but heavy in the vehicle. This weight is unfavorable for electric cars. In this respect, it is significant to point out that the drive of this research is to develop an optimal leaf spring that is light yet durable.

Structural steel and EN45 alloy steel will be analyzed through finite element method(FEM) to ensure its performance characteristics such as load bearing ability, stiffness, etc. The various factors related to load bearing, deformation, stress, and strain will be assessed to determine how the materials can stand against the applied forces. Designing and optimizing the leaf spring is a strategy that will help in achieving energy efficiency and comfortable riding experience of the vehicle.

This project is an extension of earlier research that has been done regarding the suspension system. During the early designing process of automobiles, studies had been done on materials that could be optimized to enhance efficiency and effectiveness. Other works involved finding ways of designing a better leaf spring that could enhance performance of vehicles. This study aims at enhancing energy efficiency, effectiveness, and sustainability of lightweight electric vehicles. Conventional leaf springs are optimized through designing mono-leaf and parabolic leaf springs.

Apart from the optimization of the design, material will also be optimized such that a suitable material that offers light mass in suspension will be found. Different materials that will include composite, structural steel, and EN45 alloy steel will be optimized in this study. FEA will be used through ANSYS software to conduct static and fatigue analysis to ensure proper assessment of stress distribution, deformation, factor of safety, etc. The goal here will be optimizing the design of a leaf spring that weighs less but has equal load-bearing ability related to the current ones.

Additionally, sustainability will be achieved through the use of environmentally friendly materials and design approach in manufacturing an environmentally friendly car. Leaf spring will be optimized for use in small to medium-sized electric cars.

Figure 1.1: Optimization of Leaf Springs for Electric Vehicle Applications

1.1 Problem Statement

Though steel leaf springs have shown themselves to be rather reliable and are extensively used, they cannot be considered as optimal leaf springs for lightweight cars of today due to their relatively high mass and lack of design modification options. With rising demands for energy-efficient cars, there arises a need for creation of new design of the leaf spring that can solve the mentioned above problems. It should ensure a decrease in the weight along with ensuring the sufficient rigidity and stability under the load. Additionally, enhancing the fatigue resistance is another criterion that must be satisfied by such leaf springs. Improving ride comfort and energy efficiency is also an important factor to be considered.

1.2 Objectives of the Study

This study focuses on the design, analysis, and optimization of a leaf spring for lightweight electric vehicle applications, aiming to enhance structural performance while reducing overall weight. The work emphasizes improving efficiency, durability, and load-carrying capacity through appropriate design modifications and material selection. The key objectives of the study are as follows:

1 To develop an optimized leaf spring configuration such as a mono-leaf or parabolic design.

2 To evaluate and compare suitable materials, particularly structural steel and EN45 alloy steel, for improved performance.

3 To perform Finite Element Analysis (FEA) using ANSYS to analyze stress, deformation, and factor of safety under different loading conditions.

4 To achieve weight reduction while maintaining adequate strength, and durability.

1.3 Methodology

The project follows a systematic methodology that integrates design modification with simulation-based evaluation to achieve an optimized leaf spring design. Initially, the geometry of the leaf spring is modified by considering configurations such as mono-leaf and parabolic designs, with the objective of achieving uniform stress distribution and minimizing material usage. Subsequently, material optimization is carried out by analyzing different materials to identify the most suitable option based on parameters such as strength-to-weight ratio, fatigue resistance, and cost-effectiveness. Further, Finite Element Analysis (FEA) is performed using ANSYS to evaluate the structural behavior of the leaf spring. The analysis includes static structural assessment, evaluation of deformation and stress distribution, fatigue life estimation, and determination of the factor of safety under applied loading conditions.

Figure 1.2: Process Flow Chart

In this reserch, the methodology used entails a combined approach whereby computational simulation was used together with experiments in order to optimize the performance of the structure under study. In the initial step, various geometric structures that resemble engineered structures such as honeycomb, triangular, and square grids were designed using SolidWorks software. These geometries were modeled using the same size to enable a comparison. After modeling, the geometries were analyzed in ANSYS Workbench through FEM. This was achieved through the application of meshing and loading. PLA was chosen as the material to be used in designing due to the eco-friendly nature of this material and suitability for Additive Manufacturing (AM). Various parameters such as deformation, von Mises stress, and factor of safety were considered in analyzing the structural performance.

1.4 Applications

- Improved ride comfort in electric vehicles by reducing vibrations and enhancing suspension response.
- Uniform load distribution across the vehicle chassis, leading to better structural stability.
- Reduction in unsprung mass, contributing to improved energy efficiency and extended driving range.
- Enhanced durability and fatigue resistance for long-term operation under varying load conditions.
- Suitable for different categories of electric vehicles, including passenger cars and light commercial vehicles.
- Contribution to eco-friendly vehicle design through the use of lightweight and sustainable materials.
- Improved vehicle handling, stability, and road grip during dynamic driving conditions.
- Reduction in noise, vibration, and harshness (NVH), resulting in a smoother and quieter ride.
- Lower maintenance requirements due to improved material strength and optimized stress distribution.
- Applicable in next-generation lightweight electric vehicles for advanced suspension system development.

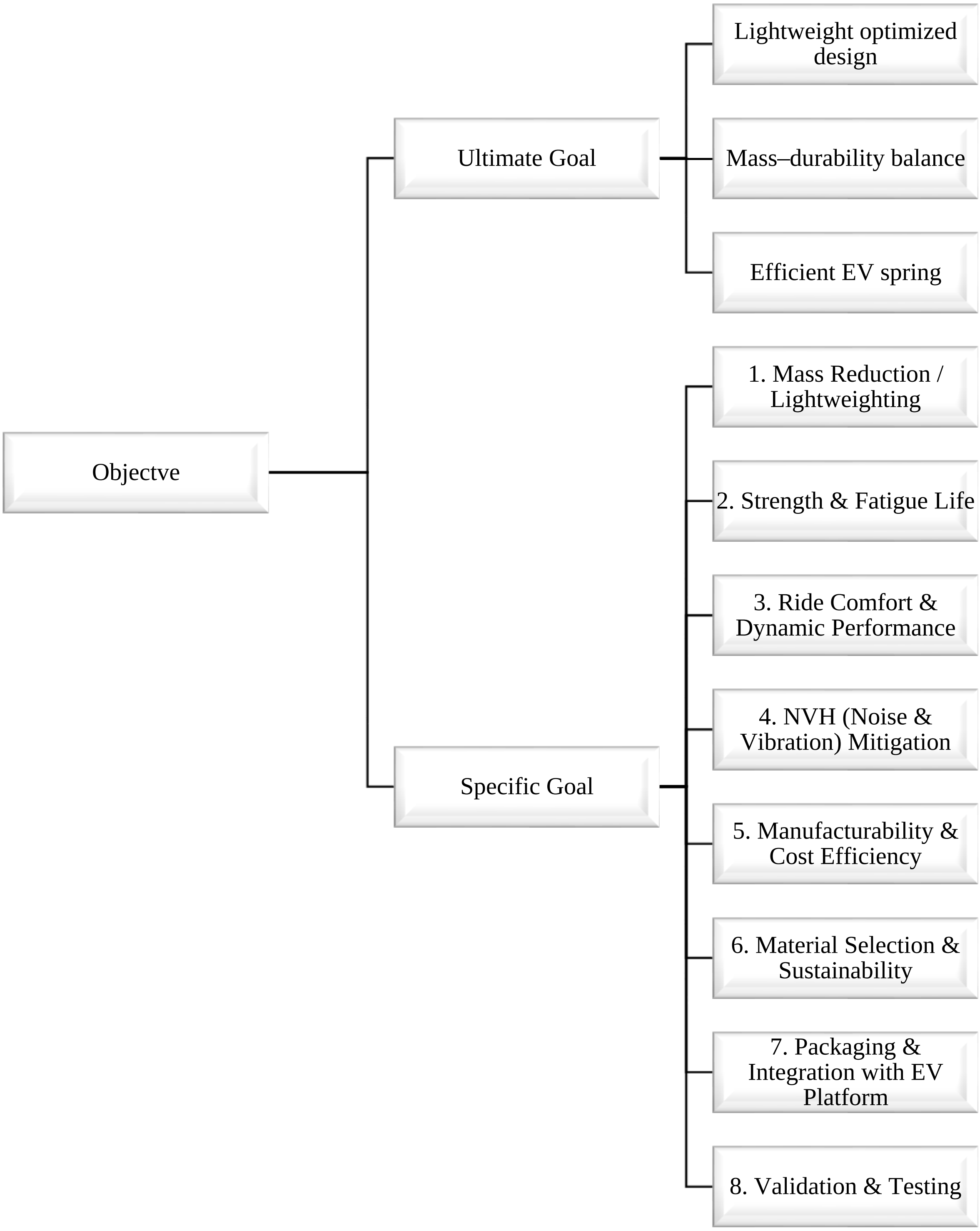


Figure 1.3: Objective Tree

1.5 Design Constraints:

- The mounting configuration should be compatible with existing attachment points, including bolt patterns and bracket geometry, while safely accommodating the applied loads.

- Only approved materials and manufacturing processes should be considered to ensure feasibility, quality, and compliance with industry standards.
- The design must fulfill the safety requirements, having a static safety factor of no less than 1.5 and a fatigue life of a minimum of one million load cycles.
- A proper clearance should be maintained between the leaf spring and important components including battery pack and wiring systems in order to confirm there is no interference.
- The design should meet the required cost constraints, making sure that the unit cost should not exceed the budgeted amount as per the baseline design.

1.6 Design Requirements:

- The design should reduce weight by around 20 to 30% compared to the existing leaf spring without affecting the performance.
- It should have adequate static strength in order to bear the peak axle load and maintain an acceptable safety factor.
- The leaf spring design should be able to attain a fatigue life of at least 1 to 2 million load cycles. • The vertical stiffness should be enough to offer satisfactory ride quality and shock absorption properties.
- The natural frequencies of the system should be well kept out of the excitation range for stability.
- The NVH performance of the spring should be improved using suitable dampening features and surface finish.
- The wear, corrosion, and fretting resistances should also be considered in order to ensure long-term durability.
- The design should match the current manufacturing capabilities and process tolerances.
- The cost constraints must also be maintained in order to make sure the design is cost-effective.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The suspension system is one of the most important subsystems in an electric vehicle (EV) because it ensures ride comfort, stability of the vehicle, and handling. In contrast to conventional automobiles, EVs are very sensitive to their weight balance due to battery packs. Consequently, efficient suspensions are necessary in these cases they are needed to ensure tire and road contact and improve overall car handling by dampening vibrations. With the development of new technologies related to electric vehicles, it is expected that components used in the suspension system will be characterized not only by high-performance parameters but also by their ability to contriibute to energy efficiency.

A leaf spring represents the key components used in vehicle suspension systems. These springs are widely used as support elements in light-duty commercial vehicles and other automobiles. Steel leaf springs feature good durability; however, being heavy, they have a negative effect on a car's efficiency, ride quality, etc. The need to reduce weight makes it advisable to consider the application of lightweight materials. In particular, alloy steels and composite products should be mentioned as very good materials for this application area due to their mechanical properties.

2.2 Review of Conventional Leaf Springs

Conventional leaf spring consists of several steel layers (plates) of different lengths clamped into semi-elliptic configuration. The traditional leaf spring is a common suspension element utilized in cars, primarily in trucks, constructed from a pack of steel plates or leaves of different lengths fastened in a semi-elliptical configuration. The largest steel plate, called the master leaf, has eye-shaped ends to accommodate mounting features, while smaller plates add strength and stiffness to the spring structure. Leaf springs can withstand the weight of cars, absorb impacts from surface roughness, and provide stability by bending under load conditions. EN45 and 55SiMn90 materials have been traditionally applied for manufacturing leaf springs since they have high strength and fatigue resistance. Furthermore, the layered leaf spring design provides an inherent safety feature because the system continues working if any steel plate becomes damaged during operation. Nevertheless, the disadvantages of using leaf springs include their large weight, which negatively affects fuel consumption, especially for electric cars. In addition, there is a high risk of friction between adjacent layers that may lead to noise production and wear.

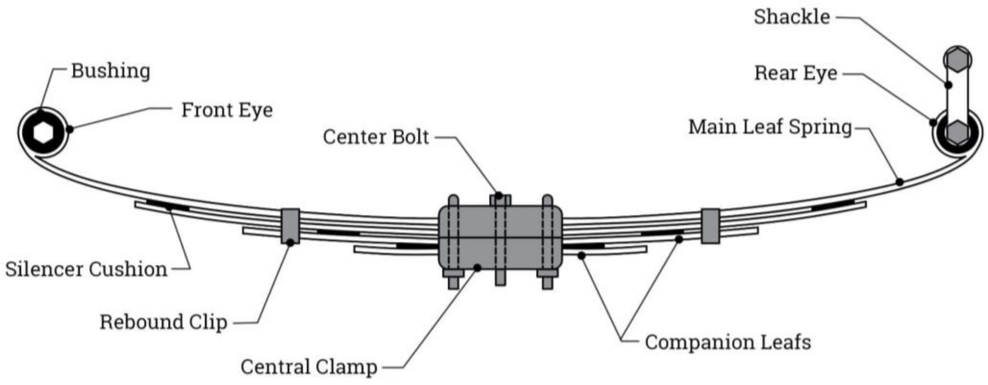


Figure 2.1: Leaf spring construction

2.3 Composite Leaf Springs

In current decades, several researches were studied on the usage of composite constituents as an alternate to steel in leaf springs design. The benefits offered by leaf springs include the capability of performing two important tasks related to load carrier and shock absorber, which is why they are commonly found on heavy-duty cars. Through the process of energy absorption from the uneven surface when the vehicle is in contact with the road, leaf springs enhance the quality of the ride in addition to improving the stability of the vehicle along with maintaining constant contact with the road. In addition, the use of several leaves in leaf springs helps in improving their reliability because even if one leaf fails, the rest of the system will continue functioning. One of the many limitations faced by traditional leaf springs (made of steel/ structural steel and EN45) includes heavy weight, which is detrimental to the efficiency of the vehicle. The weight results in increased energy consumption and poor ride performance, especially in electric vehicles.

This happens due to the special structure of composite materials, namely layers. Contrary to metallic structures, layer structure ensures a more homogeneous stress concentration, which increases resistance to cracks.

2.4 Key findings from the literature survey

Table 2.1: Literature survey

Sl No	Literature Details	Geometry	About Materials	Analysis Results
1	S. Nayak (2020), Optimization of composite leaf spring for EV NVH	Mono-leaf	Glass/epoxy composite	Weight reduction and improved NVH performance
2	B.A. Tadesse et al. (2022), Design optimization of composite leaf springs	Parabolic & mono-leaf	E-glass/epoxy	60% stress reduction, better stiffness & fatigue
3	S.M. Silaskar (2023), Lightweight vehicle leaf spring optimization	Semi-elliptical	GFRP	Weight reduction with safe stress limits
4	S. Rajendran & R. Vijayarangan (2012), Composite leaf spring analysis	Mono-leaf	E-glass/epoxy	80% weight saving, 85% stress reduction
5	P. Kumar & K. Singh (2021), Topology optimization for EV leaf spring	Mono-leaf	Steel baseline + composites	Reduced weight with uniform stress distribution
6	J. Winter et al. (2022), Spline-based shape optimization	Freeform composite geometry	Composite laminates	Improved stiffness-to-weight ratio
7	M.I. Khan (2025), Weight optimization using DFM	Leaf spring assembly	Structural steel	Weight reduction while maintaining manufacturability
8	A.S. Khan et al. (2024), Composite leaf spring optimizat	Parabolic	Carbon/epoxy	Increased strength, lower deformation, weight reduction

9	S. Patel & R. Gajjar (2022), EV leaf spring FEA	Mono & parabolic	E-glass fiber	Reduced stresses and improved deformation response
10	M.R. Khedkar et al. (2020), Size optimization	Mono-leaf	Glass fiber composite	Optimized thickness with safe stress values
11	Q. Xia & X. Cheng (2021), Lightweight topology optim	General structural geometry	Isotropic/composite	Lightweight, stiffness-optimized structures
12	J. Ke et al. (2025), SMA-based variable stiffness leaf spring	SMA-embedded mono-leaf	SMA + composite	Adaptive stiffness, better vibration control
13	R. Jadhav & P. Patil (2020), LCV leaf spring optimization	Semi-elliptical	Steel (55Si2Mn90)	Improved safety factor and mass reduction
14	A.R. Pathan & N. Dange (2021), Parametric optimization	Master leaf spring	Composite	Higher fatigue strength & stiffness
15	Q. Xia et al. (2016), Compliant mechanism topology optimization	Leaf-type compliant geometry	Metal/composite	Enhanced deformation & compliance
16	A.K. Sharma & R. Singh (2019), Modal & structural analysis	Semi-elliptical	GFRP	Higher natural frequency, reduced stresses
17	H.S. Patel & V.P. Vaghela (2020), Composite leaf spring weight reduction	Parabolic	Carbon-epoxy	~70% weight reduction & lower stress levels
18	F.U. Rehman et al. (2021), FEA-based optimization	Mono & multi-leaf	E-glass/epoxy	Increased load capacity, reduced deflection
19	L. Zhang & W. Zhao (2023), Hybrid metal–composite leaf spring	Hybrid tapered geometry	Steel + composite hybrid	Higher fatigue life & significantly lower mass
20	N. Gupta & S. Tiwari (2024), Fatigue improvement of composite leaf springs	Parabolic	GFRP & CFRP	Major improvement in fatigue behavior

2.5 Summary on literature survey:

As seen in all examined studies on the topic, one common trend is evident, namely, the rapid technological evolution that involves the transition of leaf spring materials from classical steel to highly efficient and lightweight composite leaf springs. Several types of shapes, such as mono-leaf, parabolic, semi-elliptical, tapered composite, and freeform, were investigated. It has become evident that the most effective design options include mono-leaf and parabolic configurations. They provide optimal ratios of stiffness to mass and allow for easy manufacturing procedures. When discussing materials used in springs, researchers have largely focused on composite materials that include E-glass/epoxy, GFRP, CFRP, carbon-epoxy, and metal-composite laminate leaf springs. The development of these composite spring types led to reductions in weight ranging from 60% to 80%, compared with steel. Being made from composite materials allows for increased fatigue resistance, lower stress levels, and decreased deformation. Optimization methods is utilized in this analysis to achieve desired uniformity of stress distribution and higher vibration frequency include finite element analysis, topology optimization, spline shape approaches, parametric studies, and manufacturing-oriented optimization methods. Currently, there is much interest in developing composite leaf spring systems for use on electric vehicles.

Chapter 3

MATERIALS AND METHODS

With the development of electric vehicles (EVs) towards higher efficiency and weight reduction, the design of efficient suspension system elements is required. Leaf spring is another component of the suspension that plays a significant role in ensuring proper load distribution and shock absorption in a vehicle. A lightweight design is especially important for electric cars, as unsprung mass directly affects their performance and energy efficiency. The aim of this research is to optimize the leaf spring design for an electric car using three materials—EN45, 55SiMn90, and 51CrV4. Each materials has its own mechanical properties, such as tensile strength, elasticity, fatigue resistance, and ductility. The challenge is to balance these properties to achieve a strong yet lightweight design. This study focuses on comparing these materials and identifying the most suitable geometry for the leaf spring.

3.1 Material Selection (Steel vs Composite Materials)

Material selection plays a very important role when it comes to designing leaf springs as it will determine their performance and weight. Leaf springs are usually prepared from high-strength steels like EN45, 65Si7, and SUP9 because they offer good load capacity, durability, and low cost. However, their high density adds extra weight to the vehicle, which is not ideal as the demand for lightweight cars increases. Alloy steels such as EN45, 51CrV4, and 55SiMn90 are generally used due to their high strength and excellent fatigue resistance. EN45 is more cost-effective with good resilience, while 51CrV4 and 55SiMn90 provide better strength and performance for demanding applications. When designing a leaf spring, factors like density, elasticity, strength, fatigue limit, and cost must be considered. Although these steels have high density compared to composites, their uniform (isotropic) properties make them reliable, so selecting the right material requires balancing performance, weight, and cost.

3.2 CAD Modeling Details

Following this, the design process includes the creation of a 3D model of the leaf spring through computer-aided design (CAD) software, such as SolidWorks or CATIA. Geometry in the leaf spring consists of multiple curved plates or leaves stacked together. The master leaf is designed with eye ends for mounting, while the remaining plates provide stiffness. Key parameters that define the geometry include span length, plate thickness, plate width, camber, and the number of plates. These features are incorporated during the design process, along with elements such as eye ends, center bolts, and clips. Camber is included to represent the initial curvature and its effect on load distribution. Parametric modeling is preferred since dimensions can be treated as variables. For example, plate width and thickness can be adjusted to study their impact on performance. After completing the design, the CAD model is checked for geometric accuracy and then exported into formats like STEP or IGES.

3.3 Assumptions and Design Parameters

However, in order to analyse the problem and simplify the computational burden, a set of assumptions are adopted for the analysis and simulation of the leaf spring system. These assumptions enable simplifications of the actual system and guarantee a reasonable level of accuracy in the results. As the actual leaf spring functions in varying dynamics and uncertain conditions, it becomes necessary to assume or idealize certain components of the system for efficient numerical simulation. First, the material is considered homogeneous and isotropic, especially for conventional steel leaf springs. It is assumed that the material properties, such as the value of Young's modulus and Poisson's ratio, are uniform throughout the system and equal in all orientations. However, when the material is composite in nature, this assumption needs to be modified by accounting for layered or orthotropic material behavior.

The analysis assumes that the load is applied gradually and remains constant, allowing the problem to be treated as a static structural analysis. Dynamic effects like vibrations and shocks are neglected, even though they happen in real conditions. Friction between leaves is either neglected or simplified to reduce computational complexity, and temperature effects are also not considered, assuming a constant ambient environment. Initial boundary conditions are used, where one end is fixed and the other is allowed to deflect, while real-world joint flexibility is ignored for simplicity. The design parametres are divided into inputs and constraints. Inputs include geometric factors such as thickness, width, span, camber, number of leaves, and material physical properties like density, elasticity, and strength. Constraints ensure safe design, such as keeping stress below yield strength, limiting deflection, and maintaining a proper factor of safety. The leaf spring is also treated as a simply supported beam, so it follows standard beam theory principles. Deflection and bending stress formulas are commonly used in preliminary calculations prior to simulation using FEA software.

3.4 Finite Element Analysis (FEA) Setup

Another numerical method that will be performed during the investigation is FEA. FEA stands for the advanced technique, which can be used for simulating behavior of the object under different loading conditions. FEA will help predict stresses, deformation, and performance of the object. The developed CAD model in CATIA software will be used for FEA and will be processed in ANSYS software. First, pre-processing needs to be done during the FEA process. At this stage, it is necessary to prepare the model for analysis. Next, meshing stage is very crucial as it defines accuracy of FEA results. If mesh size increases, FEA results become more accurate; however, computation time becomes longer as well.

In order to define optimal mesh size, convergence and quality study will be carried out. After meshing stage is completed, the next operation will be applying material properties to the model. In order to analyze traditional leaf springs, isotropic material properties will be applied. Such material properties as Young's modulus, Poisson's ratio, and density will be used. However, for anisotropic material, anisotropic material properties should be chosen and applied according to fiber orientation. Moreover, for layered materials, each ply of the material will be defined separately. Application of boundary conditions and loading is the next important stage in finite element analysis process. It is quite crucial because the simulation result depends on the correctness of this stage. Therefore, boundary conditions should reflect real-life conditions properly. For example, one side of the leaf spring should be fixed (connection of the leaf spring with the chassis of the car), and another one will not be restrained. Moreover, only one loading force will be applied to the object (force of the load acting on the axle). Point of application of this force will depend on the mounting system (center point or axle). Finally, after applying all essential parameters to the model, analysis stage can be started. Solver will be running, and FEA results will be calculated. Deformation, equivalent (von Mises) stress, and strain will be estimated. These indicators will help predict yielding and deformation of the material. At the final stage, the obtained results will be presented in contour plot format, and critical points will be determined. FEA results will be compared with calculations according to the beam theory. In case there are some variation in results, further improvements in FEA model will be made. As it was stated before, results of FEA process are vital for further developing of optimization process. This results will provide necessary data regarding stresses and deformations needed for making necessary modifications. It is especially important, as the goal of the research is to minimize weight of the leaf spring.

3.5 Optimization Techniques

Optimization is another essential step in the design proceses of a leaf spring, which focuses on obtaining the optimal configuration of the system, meeting performance criteria while minimalizing the mass. Optimizing a spring of lightweight is an effective way of improving the energy efficiency of electric vehicles, increasing their driving range, and ensuring reliability. The process involves adjusting the value of critical design variables to improve their performance and select the best variant according to certain criteria.

Typically, an optimization problem consists of an objective purpose and a set of constraints. To optimize the parameters of a leaf spring, several variables, such as stress, deflection, strength, weight, etc., are modified to minimise the weight. In this regard, various optimisation algorithms can be applied, depending on the number of variables influencing the performance of the spring.

3.5.1 Parametric Optimization

As one of the simplest and most commonly used methods, parametric optimization allows designers to adjust some important design variables, such as the thickness and width of leaves, span length, camber, and number of leaves. The use of simulation software makes it possible to study the influence of changing the parameters' values on the performance characteristics of the system in terms of its weight and stress. The process of parametric optimization allows for defining those parameters that have the maximum influence on the performance characteristics and determining the parameter ranges of interest. Consequently, this approach can be useful in achieving optimal compromise between weight and strength of the spring with regard to its leaves' dimensions.

3.5.2 Material Optimization

According to this approach, several materials can be analyzed in order to define which of them is the best in reducing the spring's weight without lowering its mechanical performance. As was mentioned above, steel is the commonly used material for producing traditional leaf springs. For making light leaf springs, various composite materials, e.g., GFRP and CFRP, etc., can be considered owing to their superior physical characteristics. Moreover, we need to consider aspects like: material density, elasticity, tensile strength, fatigue resistance, and cost when selecting materials. A combination of both steel and composite materials provides another interesting possibility for evaluating these characteristics.

3.5.3. Topology Optimization

While parametric optimization focuses on adjusting the geometry of existing parts, topology optimization is used to determine the most efficient material distribution within a given space. It removes material from low-stress regions and retains it in high-stress areas, often resulting in unique and non-intuitive designs. However, these designs usually need further refinement to become practical geometric models.

3.5.4. Design of Experiments (DOE)

Design of Experiments (DOE) is used to study how multiple design variables influence system performance. Unlike parametric optimization, which typically changes one variable at a time, DOE allows simultaneous variation of several factors. This approach helps identify the most influential parameters and determine the best combination for optimal performance.

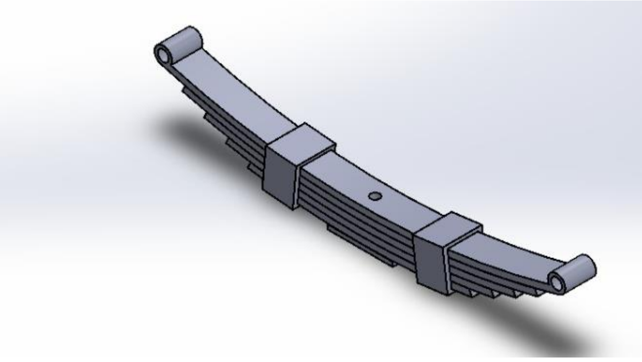
Chapter 4

MODELING AND SIMULATION

The modeling and simulation phase is essential for analyzing the structural behavior of the leaf spring under working conditions. The first step involves creating a complex three-dimensional model of the leaf spring using CAD software such as SolidWorks. The definition of the essential geometric properties of the leaf will be included such as leaf length, width, thickness, camber, and eye ends of the leaf spring. To create an accurate representation of an actual suspension system, the actual number of leaf springs will be included. Once the model has been built, it will be imported into the simulation software (ANSYS) for analysis. Before proceeding with either analysis, it will be important to ensure that the geometric model is free from defects. After the analysis has been run, the next process is to create a finite element model of the leaves by segmenting the model into small elements. A finer mesh can be applied to the critical areas on the model; therefore, to verify the accuracy of the mesh, a mesh convergence study can be performed with a predefined maximum error tolerance. Once meshing is complete, the next step is to assign material properties to the selected material (steel or composite), apply boundary conditions, and load the model. To simulate the installation of a leaf spring to a chassis, one end of the leaf spring will be assumed to be fixed. The center of the opposite end will be loaded to represent the force acting on a vehicle. Once the above processes are complete, the next step is to run the simulation.

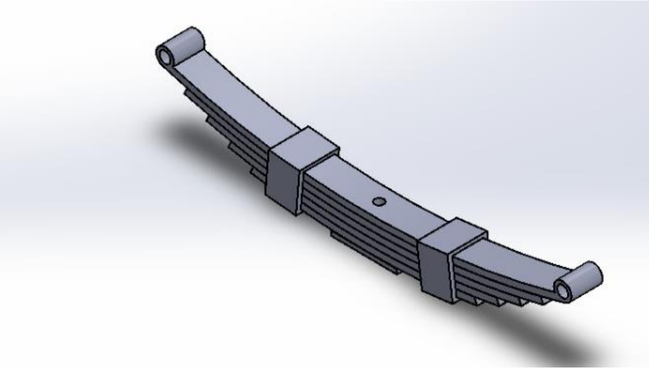
4.1 3D Model of Leaf Spring

The 3D model of the leaf spring is created using CAD software such as SolidWorks or CATIA. The model includes all essential geometric features such as the master leaf, additional leaves, eye ends, and camber (initial curvature). Key dimensions like length, width, thickness, and number of leaves are defined based on design requirements. The leaves are assembled to replicate the actual configuration used in vehicle suspension systems. Parametric modeling is adopted so that dimensions can be easily modified during optimization. This 3D model serves as the base for simulation and analysis.



Master leaf = 865 mm
Leaf 2= 750 mm
Leaf 3= 650 mm
Leaf 4= 550 mm
Leaf 5= 450 mm
Width= 60 mm
Thickness= 10, 12.5, 15 mm

Figure 4.1 : Design 1



Master leaf = 900 mm

Leaf 2= 800 mm

Leaf 3= 700 mm

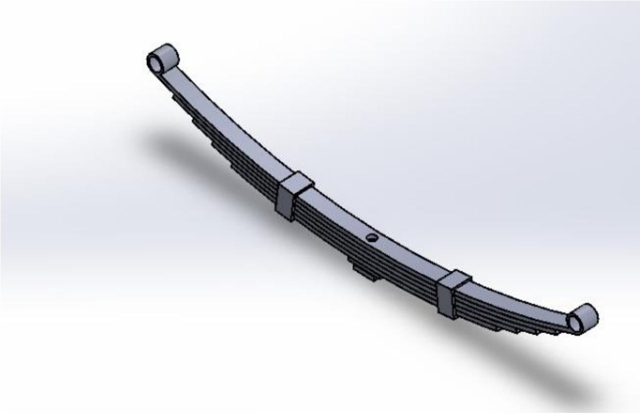
Leaf 4= 600 mm

Leaf 5= 500 mm

Width= 70 mm

Thickness= 10, 12.5, 15 mm

Figure 4.2 : Design 2



Master leaf = 1072 mm

Leaf 2= 972 mm

Leaf 3= 872 mm

Leaf 4= 772 mm

Leaf 5= 672 mm

Width= 40 mm

Thickness= 10, 12.5, 15 mm

Figure 4.3 : Design 3

The three leaf spring designs shown in Figures 4.1, 4.2, and 4.3 represent variations in geometric parameters to study their effect on structural performance. Design 1 consists of a master leaf length of 865 mm with progressively shorter leaves and a width of 60 mm, representing a balanced configuration. Design 2 has slightly increased dimensions with a master leaf of 900 mm and a wider section of 70 mm, which is expected to provide higher stiffness and load-carrying capacity. In contrast, Design 3 features a significantly longer master leaf of 1072 mm but a reduced width of 40 mm, making it more flexible and lightweight. All three designs consider varying thickness values (10, 12.5, and 15 mm) to analyze their influence on stress and deformation. These variations help in comparing strength, stiffness, and weight characteristics to identify the most optimized leaf spring design for lightweight electric vehicle applications.

4.2 Design calculations

In this analysis, the leaf spring is modeled using a set of simplifying but important assumptions. The leaf pack consists of five leaves, each having the same thickness and width, and they are assumed to be perfectly bonded with no interleaf slipping, allowing the pack to be treated as a single rectangular cross-section with an effective total thickness of (T = 5t). The master leaf is modeled as a cantilever beam of length (L), carrying an end load of W = 20,000 N, which provides a conservative estimate of bending effects. Additionally, the material is assumed to behave elastically with a constant modulus of elasticity E = 210, GPa, ensuring consistent deformation and stress calculations throughout the design evaluation.

- Rectangular section formulas are used:
  I = (b * T^3) / 12

$M = W * L$

$c = T / 2$

$\sigma = (M * c) / I$

$\delta = (W * L^3) / (3 * E * I)$

Units: convert mm → m for calculations; final stresses in MPa and deflections in mm.

Formulas

$T = 5t$

$I = (b * T^3) / 12$

$M = W * L$

$c = T / 2$

$\sigma = (M * c) / I$

$\delta = (W * L^3) / (3 * E * I)$

Worked numeric example — Design 1, t = 10 mm

Given:

$L = 865 \text{ mm} = 0.865 \text{ m}$

$b = 60 \text{ mm} = 0.060 \text{ m}$

$t = 10 \text{ mm} = 0.010 \text{ m}$

$W = 20{,}000 \text{ N}$

Total thickness:

$T = 5t = 5 \times 0.010 = 0.050 \text{ m} = 50 \text{ mm}$

Second moment:

$I = (0.060 \times (0.050)^3) / 12$

$= (0.060 \times 1.25 \times 10^{-4}) / 12$

$= 6.25 \times 10^{-7} \text{ m}^4$

Bending moment at clamp:

$M = W \times L = 20{,}000 \times 0.865 = 17{,}300 \text{ N}\cdot\text{m}$

Outer fibre distance:

$c = T/2 = 0.050 / 2 = 0.025 \text{ m}$

Bending stress:

$\sigma = (M \times c) / I$

$= (17{,}300 \times 0.025) / (6.25 \times 10^{-7})$

$= 6.92 \times 10^8 \text{ Pa} = 692 \text{ MPa}$

Tip deflection:

$\delta = (W \times L^3) / (3 \times E \times I)$

$= [20{,}000 \times (0.865)^3] / [3 \times 210 \times 10^9 \times 6.25 \times 10^{-7}]$

$\approx 0.03287 \text{ m} = 32.87 \text{ mm}$

So for Design 1, t = 10 mm:

$\sigma \approx 692 \text{ MPa}$

$\delta \approx 32.9 \text{ mm}$

Table 4.1: Design Specifications

PARAMETER	**VALUE**
Project / Component	Leaf spring — rear suspension (mono-leaf / semi-elliptic baseline)
Target application	Light-weight vehicle (passenger / small commercial)
Vehicle total mass (assumption)	1500 kg
Rear axle load share	60% of vehicle mass → 900 kg
Load per spring (static mass)	Rear axle / 2 = 450 kg
Gravity	$g = 9.81\ m/s^2$
Static load per spring (F_static)	450 × 9.81 = 4414.5 N
Dynamic / impact factor (design)	2.5 (to cover bumps/impact)
Design load per spring (F)	2.5 × 4414.5 = 11,036.25 N
Spring type (baseline)	Semi-elliptic mono-leaf (parabolic or multi-leaf alternatives considered)
Half span (L)	0.50 m (full span ≈ 1.0 m) — chassis constraint
Leaf width (b)	60 mm = 0.06 m (typical)
Target working deflection (δ)	80 mm = 0.08 m
Young's modulus (E)	210 GPa
Maximum bending stress with t = 13.99 mm	$\sigma max \approx 1,409$ MPa
Recommended allowable bending stress (typical after HT & peening)	800 – 1200 MPa (use specific HT data to pick exact value)
Material (baseline)	51CrV4 (spring steel) — quenched & tempered; alternatives: EN45,
Validation & testing	FEA: static, nonlinear large deflection, modal & fatigue; Prototype: static deflection test + accelerated fatigue test

4.3 CAD Modeling

4.3.1 Part Modeling

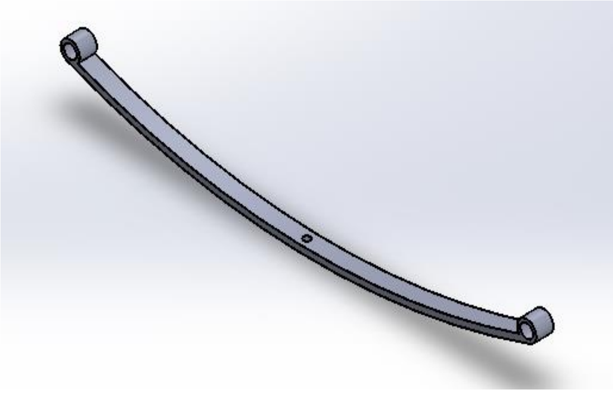


Figure 4.4: Master leaf

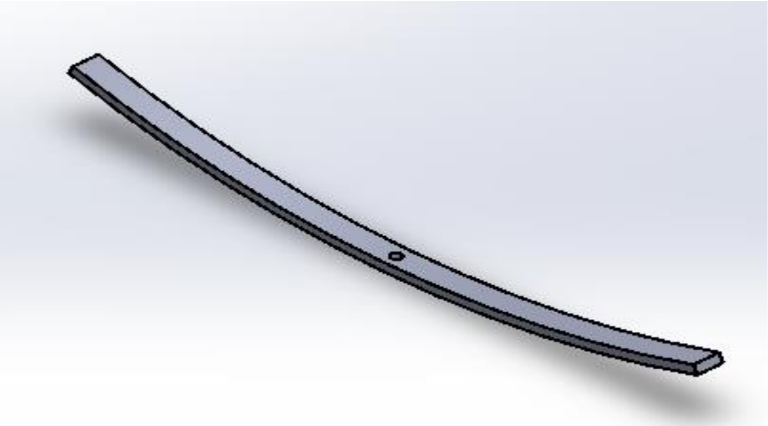


Figure 4.5: Leaf 2

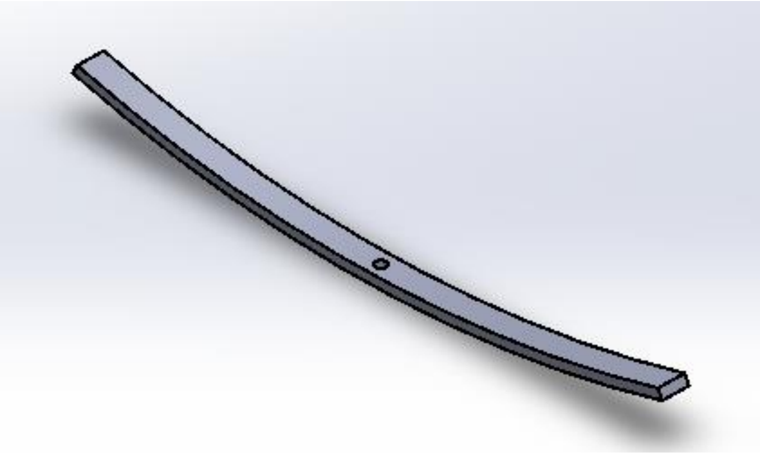


Figure 4.6: Leaf 3

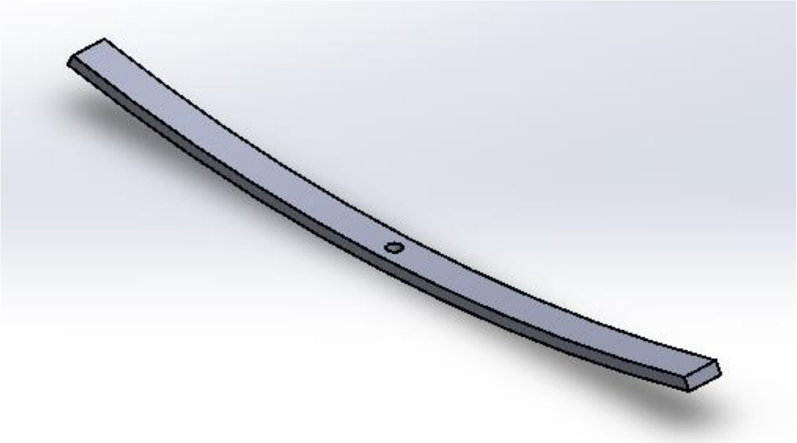


Figure 4.7: Leaf 4

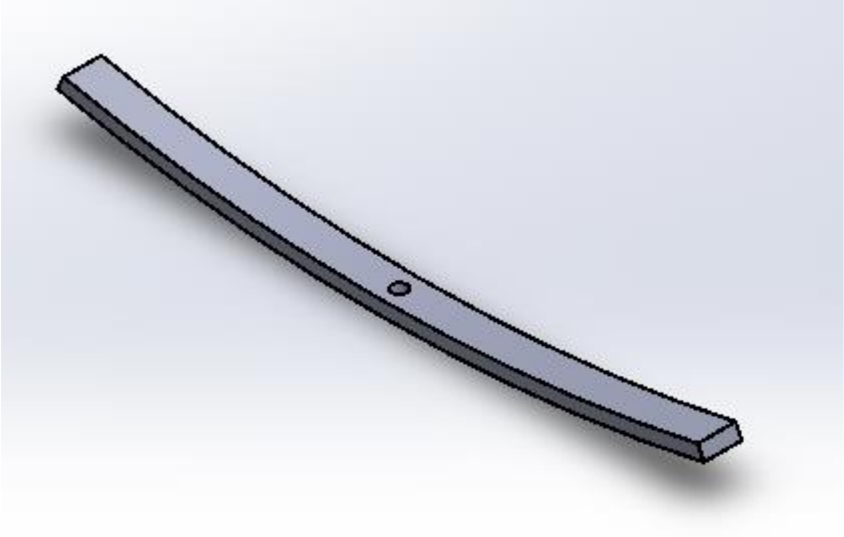


Figure 4.8: Leaf 5

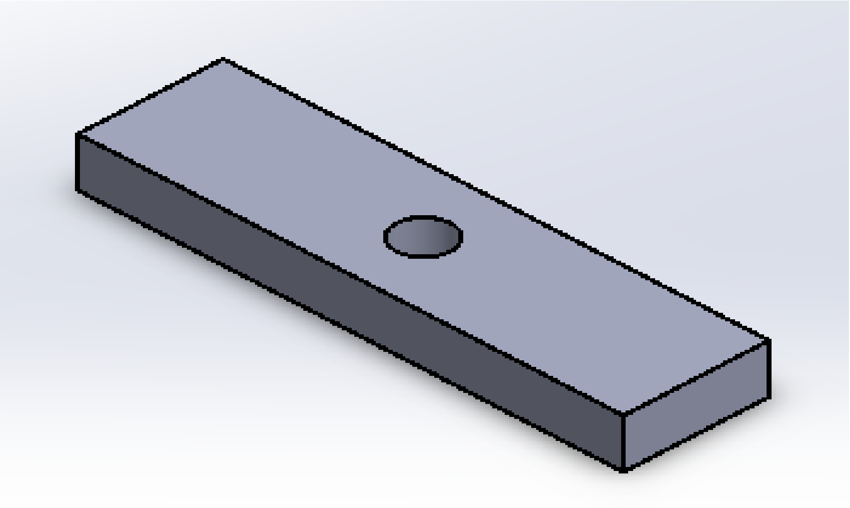


Figure 4.9: Base Plate

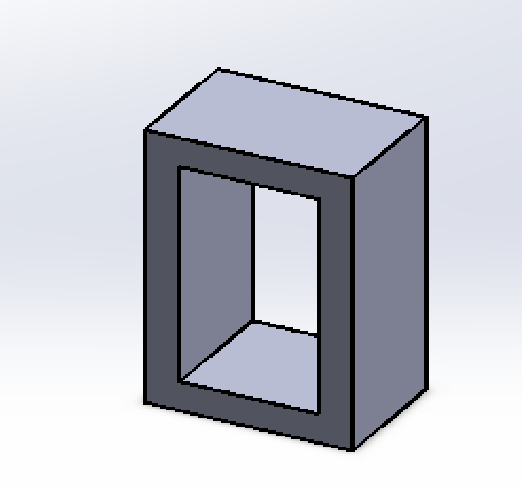


Figure 4.10: Clamp

4.3.2 Assembly Modeling

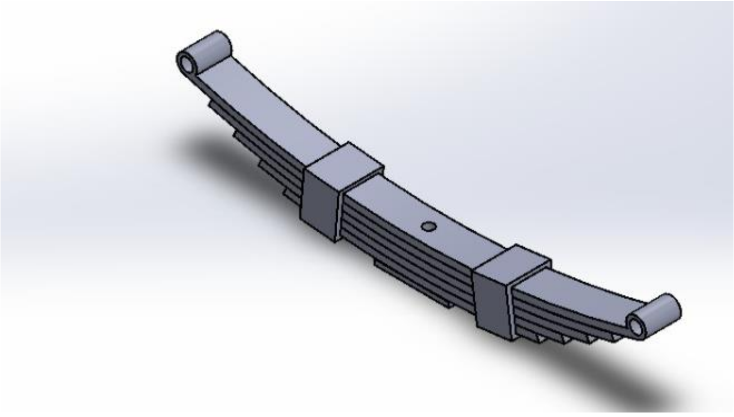


Figure 4.11: Model 1 (865 mm)

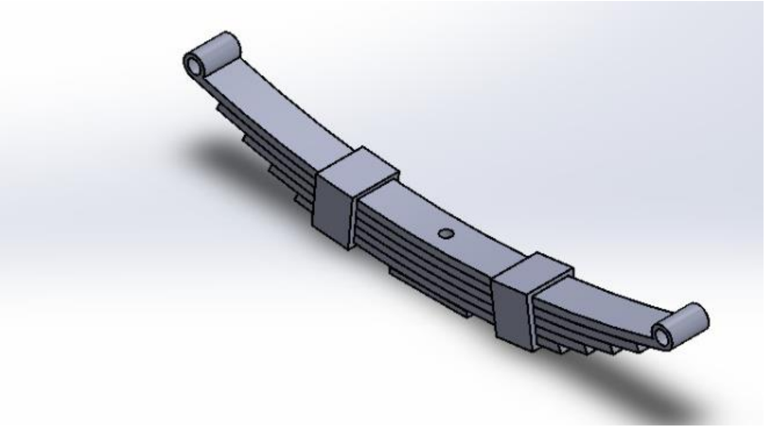


Figure 4.12: Model 2 (900 mm)

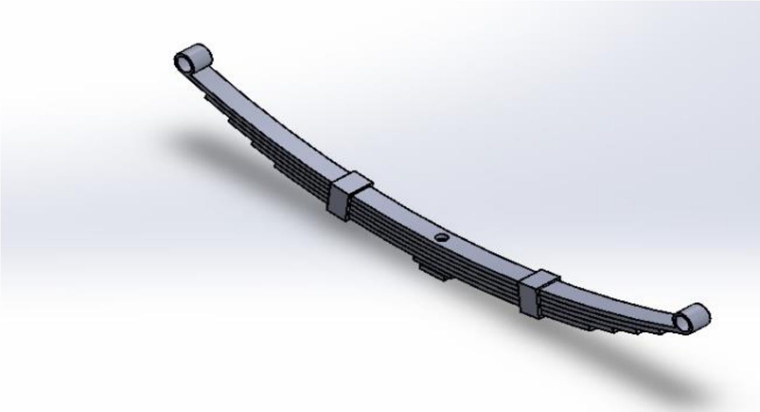


Figure 4.13: Model 3 (1072 mm)

4.3.3 2D Drawings

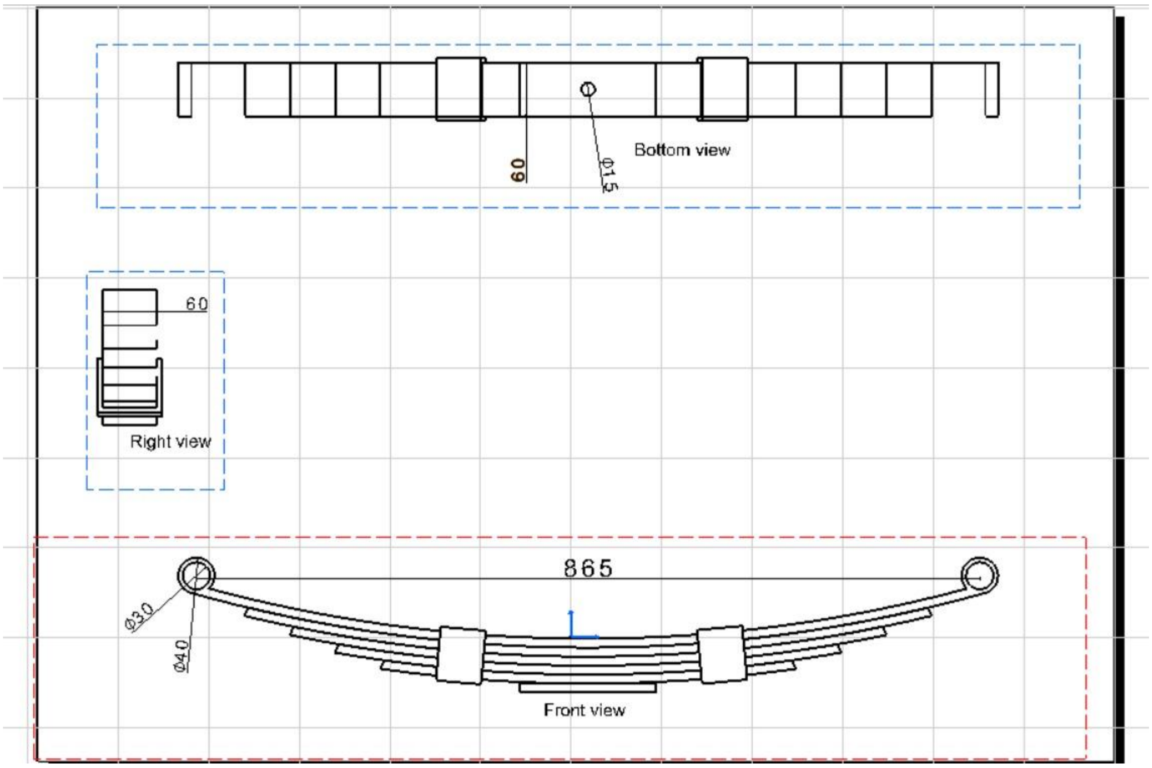


Figure 4.14: Design 1 2D

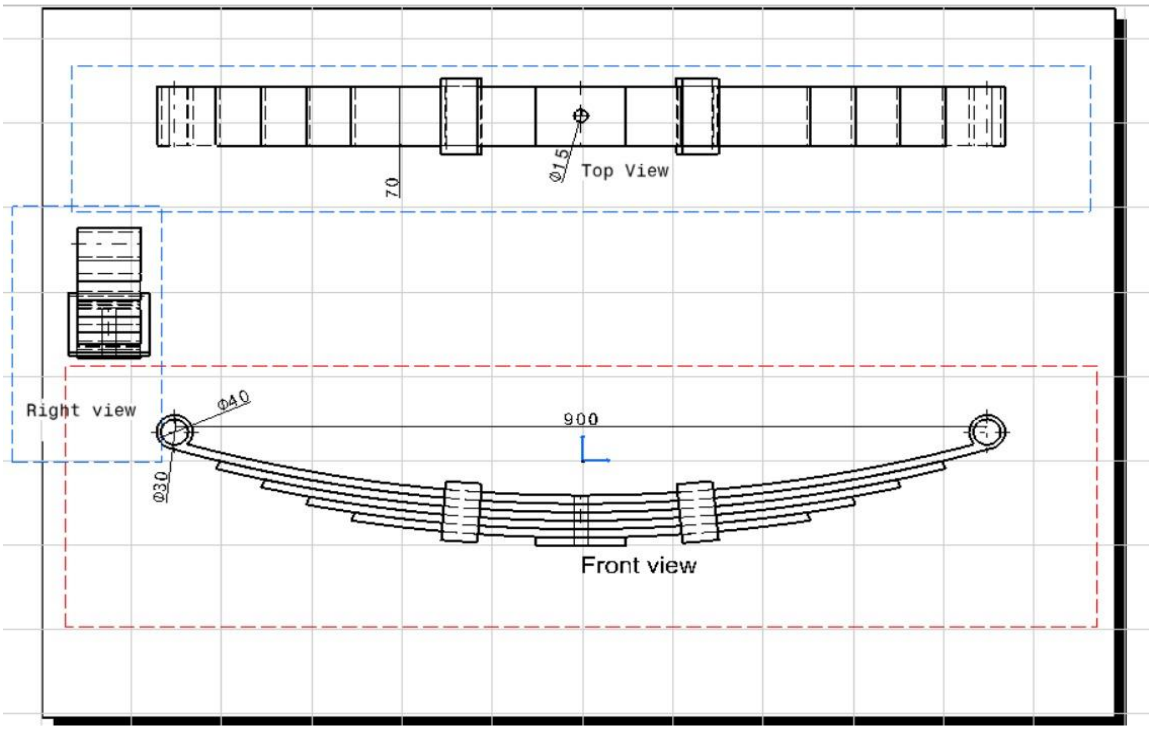


Figure 4.15: Design 2 2D

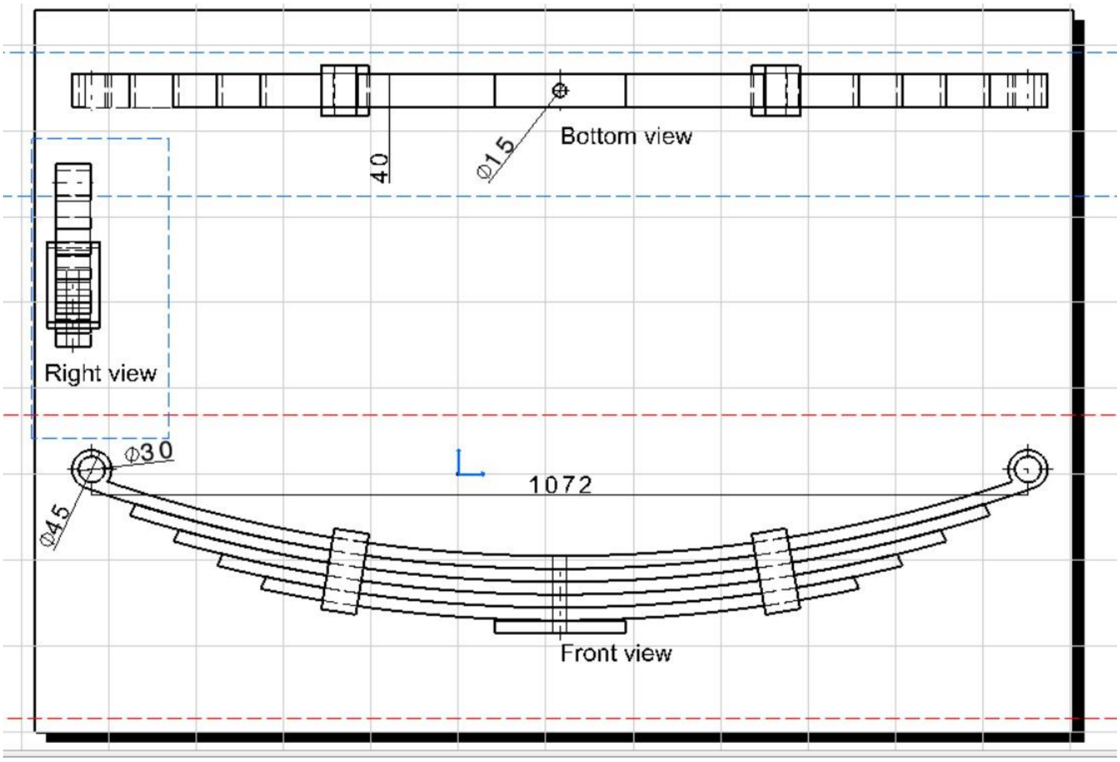


Figure 4.16: Design 3 2D

4.4 Meshing Details

Meshing is the process of dividing the 3D model into smaller elements to perform numerical analysis. In simulation software such as ANSYS, the leaf spring model is discretized using elements like tetrahedral or hexahedral elements. A finer mesh is applied in critical regions such as the eye ends and load application areas where stress concentration is expected. The mesh quality, element size, and type significantly affect the accuracy of results. A mesh convergence study is performed by refining the mesh until the variation in results becomes negligible, ensuring both accuracy and computational efficiency.

4.5 Boundary Conditions and Loading

Boundary conditions are applied to simulate real-world constraints of the leaf spring. Typically, one end of the leaf spring is fixed to represent attachment to the vehicle chassis, while the other end may be constrained with limited movement. Loading conditions are applied at the center or axle location to represent the vehicle load acting on the suspension system. In some cases, distributed loads or contact interactions between leaves may also be considered. Proper application of boundary conditions and loads is critical, as it directly influences the accuracy and realism of the simulation results.

4.6 Simulation Procedure

The simulation procedure involves several steps, including preprocessing, solving, and post-processing. In preprocessing, the model is prepared by assigning material properties, meshing, and applying boundary conditions. The solver then computes the structural response of the leaf spring under the applied loads. During post-processing, results such as total deformation, equivalent (von Mises) stress, and strain distribution are obtained. These results are analyzed using contour plots and graphs to identify critical regions and evaluate performance. The procedure may be repeated iteratively for different design configurations during optimization.

4.7 Software Used (ANSYS / SolidWorks)

Simulation and analysis are carried out using advanced engineering software such as ANSYS and SolidWorks Simulation. The ANSYS software can be used for carrying out FEA due to its advanced solver and its ability to handle complex materials, especially composites. SolidWorks Simulation, on the other hand, allows quick analysis and design validation directly within the CAD environment. Both tools are essential for predicting stress, deformation, and overall structural behavior in leaf spring design.

Chapter 5

RESULTS AND DISCUSSION

Finite Element Analysis (FEA) is a widely used numerical modeling technique that can be used by engineers to predict how different loads, boundaries and environments will affect the performance of a component. FEA is especially important for the design of lightweight electric vehicles (EVs) as weight savings lead to improvements in fuel economy, distance travelled, and overall performance. One component requiring optimization for weight savings is the leaf spring, which supports the weight of the vehicle, provides cushioning against vibration, and contributes to the comfort of passengers riding inside the vehicle. Heavy classic steel leaf springs are generally viewed as long-lasting and dependable, but due to their weight, manufacturers have been forced to explore different designs and materials to replace or complement current designs. FEA can be used to model new configurations of leaf springs without the need for prototypes. The finite element technique used to analyze leaf springs on lightweight electric vehicles involves dividing the leaf spring into many smaller parts (known as elements) that can be connected together throughout the body of the leaf spring to create a model. This way engineers can determine how variations of taper shapes, lamination patterns, and other design variations would impact the mechanical properties of the leaf spring.

A simplified form of the FEA governing equation is:

$$[K]\{u\}=\{F\}$$

where [K] is the global stiffness matrix, {u} represents nodal displacements, and {F} represents the external load vector. Using this numerical framework, FEA predicts real-world performance by evaluating stresses, strains, displacement, natural frequencies, and failure indices.

The standard FEA process involves three stages: pre-processing (model geometry creation, material definition, and mesh generation), solution (stiffness matrix solving), and post-processing (stress/strain graphs, deformation visualization, safety factor calculation, and redesign).

In conclusion, FEA increases the efficiency of designing leaf springs for light-weight electric cars. The method allows engineers to experiment with different materials, shapes, and loads to come up with an optimal design that provides maximum weight reduction without sacrificing any strength, durability, and comfort requirements.

The use of computational analysis in automotive engineering is essential for developing advanced EV suspensions and lightweight vehicle designs. Static structural analysis evaluates how a component behaves under constant loads, helping to estimate stress, strain, and deformation when forces remain unchanged. Since no vibration or acceleration is considered, the system is assumed to be in equilibrium.

Modal analysis, on the other hand, identifies the natural frequencies at which a structure vibrates. It shows different vibration modes and how the structure deforms at each frequency, helping to avoid resonance that could lead to excessive vibrations or failure. Engineers use modal analysis to design safer components that can resist dynamic excitations.

5.1 Material Properties

Material Selection: - 51CrV4 Alloy Steel : For the optimization of an automotive leaf spring, 51CrV4 (AISI 6150) spring steel has been selected due to its high strength, excellent fatigue resistance, and superior toughness after appropriate heat treatment. This medium carbon chromium–vanadium alloy steel is widely used in suspension systems, torsion bars, and other dynamic load-bearing components.

Typical composition of 51CrV4 steel is presented in Table 5.1. The alloying elements are selected to enhance hardenability, fatigue strength, and impact toughness.

Table 5.1: Chemical composition of 51CrV4 steel (wt%)

Element	C	Si	Mn	Cr	V	P	S
Range (%)	0.47–0.55	0.15–0.40	0.70–1.10	0.90–1.20	0.10–0.25	≤0.035	≤0.035

The mechanical and physical properties of 51CrV4 depend on its heat treatment condition. For quenched and tempered conditions, typical values are listed in Table 5.2.

Table 5.2: Mechanical and physical properties of 51CrV4 steel

Property	Symbol	Typical Value
Density	ρ	7850 kg/m³

Young’s Modulus	E	210 GPa
Poisson’s Ratio	ν	0.29
Yield Strength	σ_y	700–850 MPa
Ultimate Tensile Strength	σ_{UTS}	900–1200 MPa
Hardness (Q&T)	–	280–380 HB
Elongation	δ	10–15%

5.2 Boundary conditions

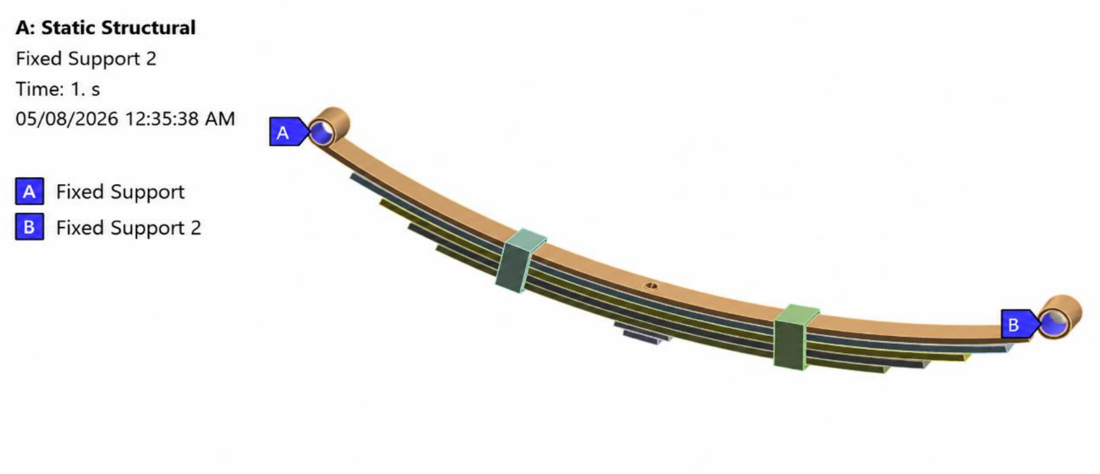


Figure 5.1: Fixed Supports

In this model of a multi-leaf spring for a lightweight electric vehicle, both ends of the spring are constrained using fixed supports, as shown by points A and B. These fixed supports restrict all translational and rotational degrees of freedom, representing the spring eyes being rigidly attached to the chassis or mounting brackets. With the ends fully restrained, the rest of the leaf stack—held together by clamps—can deform freely under applied load. This setup allows the analysis to capture the true bending and stress distribution along the spring while maintaining realistic mounting conditions.

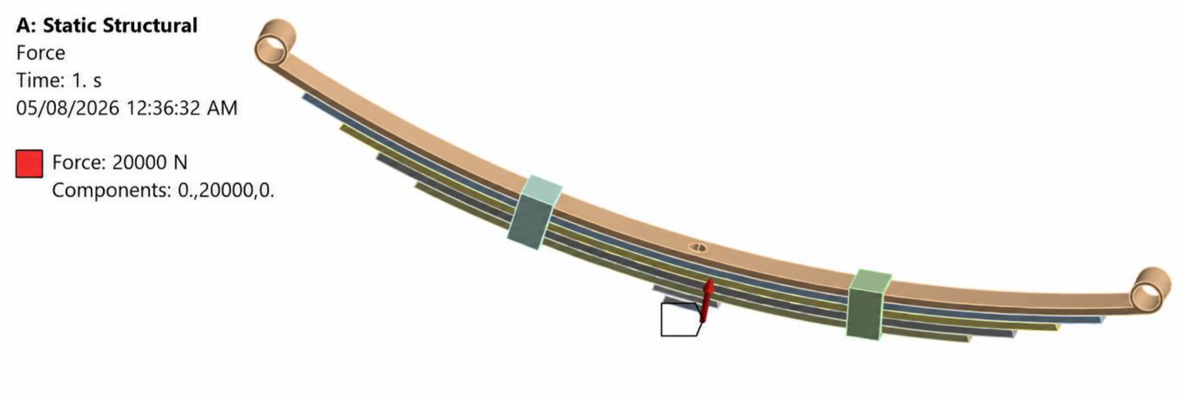


Figure 5.2: Applying Load

In this loading condition for the leaf-spring analysis, a vertical force of “20,000 N” is applied at the center region of the spring, where the axle or load typically acts in a vehicle suspension system. The direction of the applied load is downward, representing the weight transmitted from the vehicle body to the spring. This central force induces bending, compression, and shear stresses across the layered leaves. With the ends already fixed in the previous boundary condition, this load simulates real-world deflection behavior under static loading. The applied force helps evaluate stress distribution, maximum deformation, and overall performance of the optimized leaf-spring design.

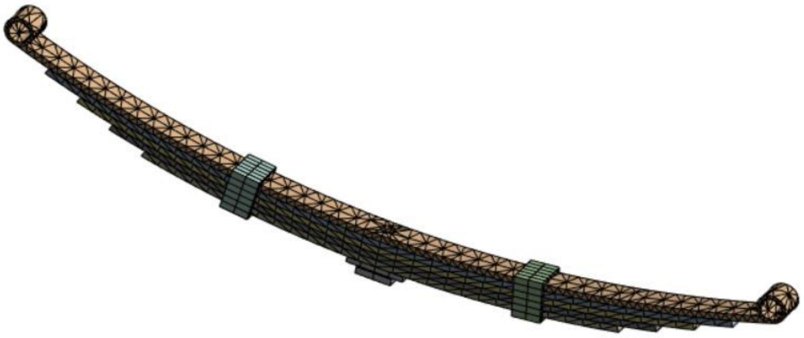


Figure 5.3: Meshing

The meshing is a process that separates the CAD model into small finite elements so that the right results of stress and deformation are obtained. ANSYS Workbench was used to create a fine tetrahedral mesh to capture finer details of variation in stresses on the grid patterns. Further refinement of the mesh at corners where the shapes were sharp as well as at the points of load application was carried out in order to increase the result precisions. Further refinements should also be made, but the mesh convergence study concludes that there is no significant change in the output values because of further refinements. The best trade-off between the accuracy of the simulation and the computational efficiency was achieved through this process.

5.3 FE Analysis

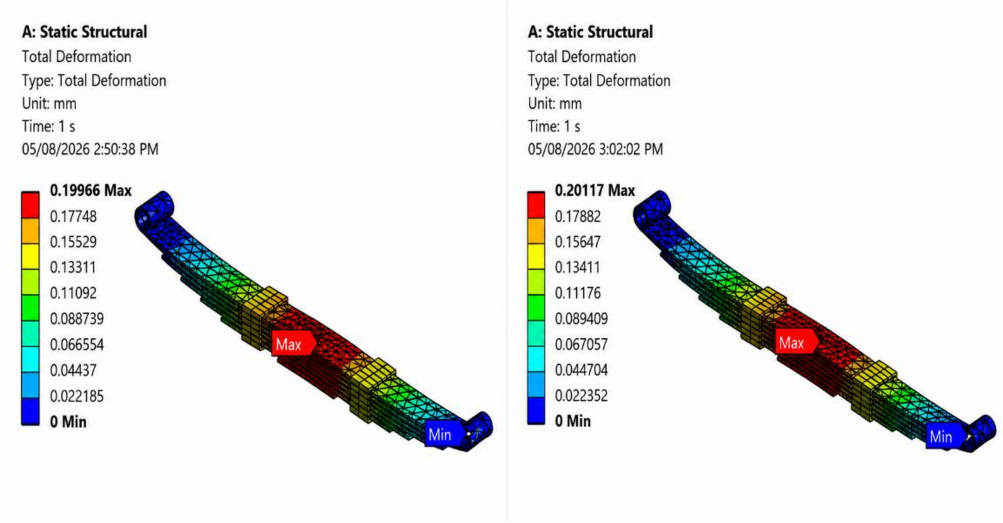


Figure 5.4: Deformation analysis of EN 45

The EN 45 leaf spring in the first image shows a maximum deformation of 0.20372 mm**,** occurring near the mid-span, while the fixed end remains at zero, indicating typical bending behaviour for this material. The colour gradient from red to blue reflects a smooth deformation distribution along the spring length. In comparison, the 55SiMn90 leaf spring in the second image displays a slightly lower maximum deformation of 0.20117 mm, also cantered in the same region, with a zero minimum at the support. This reduction in deformation indicates that 55SiMn90 provides improved stiffness over EN 45 under the same loading conditions.

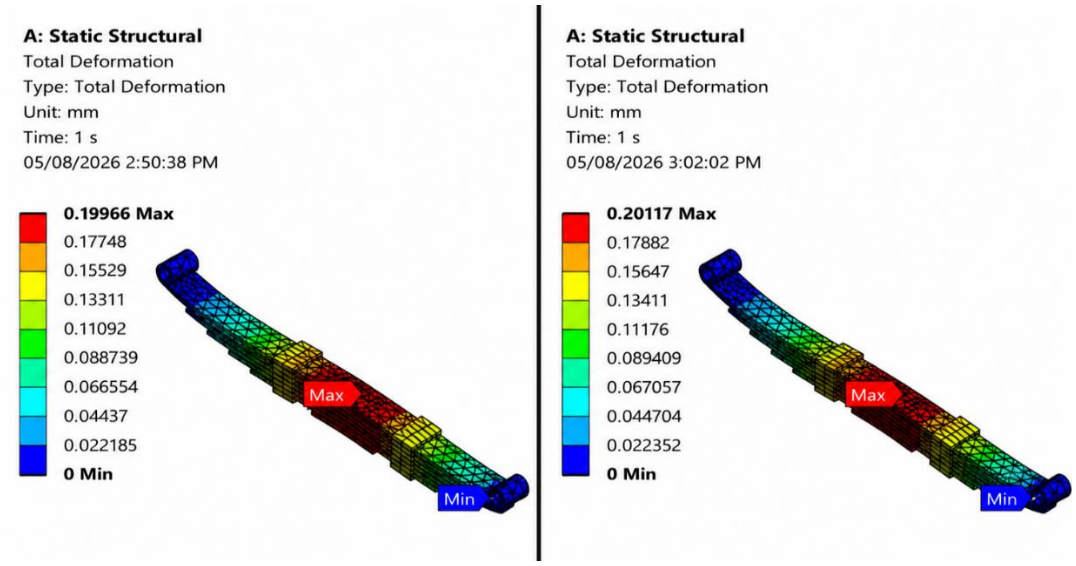


Figure 5.5: Deformation analysis of 51CrV4

The 51CrV4 leaf spring in the first image shows a maximum deformation of 0.20372 mm at the mid-span, while the fixed end remains at zero, indicating normal bending behaviour. The deformation smoothly decreases along the length, forming a clear red-to-blue gradient. In the second image, the EN 45 leaf spring shows a much lower maximum deformation of 0.1288 mm, demonstrating higher stiffness under the same load. This comparison indicates that EN 45 performs better in controlling deflection than 51CrV4.

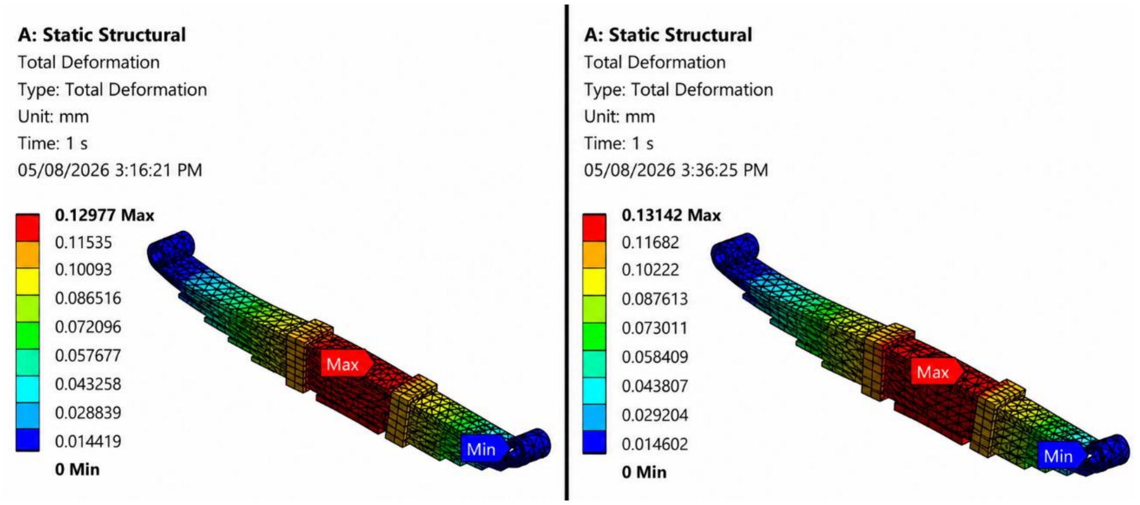


Figure 5.6: Deformation analysis of 55SiMn90 and 51CrV4

In the first image, the 55SiMn90 leaf spring shows a maximum deformation of 0.12977 mm, located near the centre of the spring, while the minimum deformation at the fixed end remains zero, indicating controlled bending. The colour gradient from red to blue reflects a smooth reduction in deformation along the length. In the second image, the 51CrV4 leaf spring exhibits a slightly higher maximum deformation of 0.13142 mm, also concentrated at the mid-span, with zero at the constrained end. This comparison shows that 55SiMn90 provides slightly better stiffness than 51CrV4 under the same loading conditions.

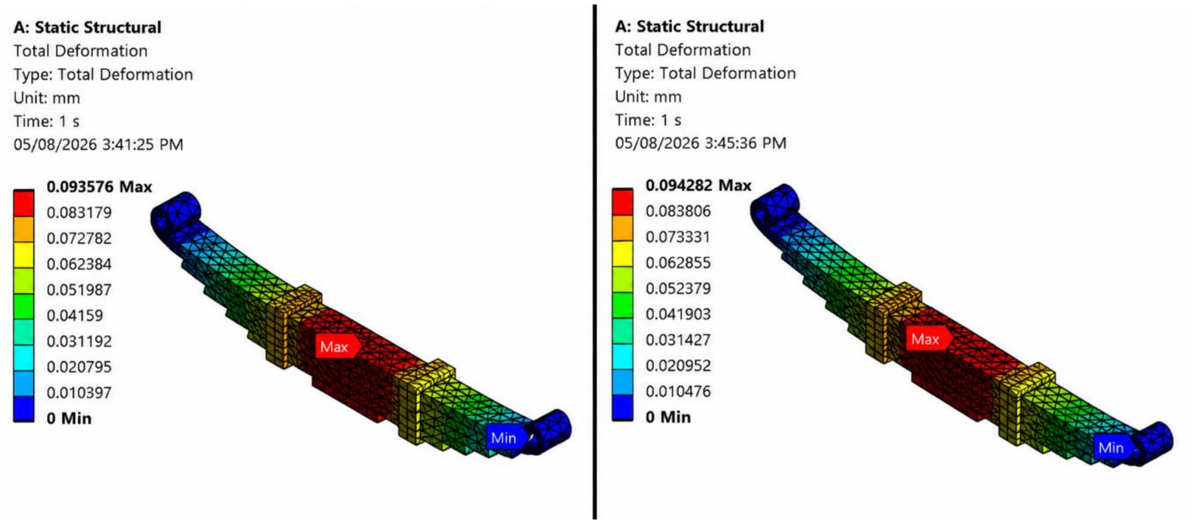


Figure 5.7: Deformation analysis of EN 45 and 55SiMn90

In the first image, the EN 45 leaf spring shows a maximum deformation of 0.093576 mm**,** occurring at the mid-span, while the fixed end maintains a minimum deformation of zero, indicating stable bending behaviour. The deformation smoothly decreases from red to blue along the length of the spring. In the second image, the 55SiMn90 leaf spring exhibits a slightly higher maximum deformation of 0.094282 mm, also cantered, with the minimum remaining at zero. This comparison shows that EN 45 provides marginally better stiffness than 55SiMn90 under the same loading conditions.

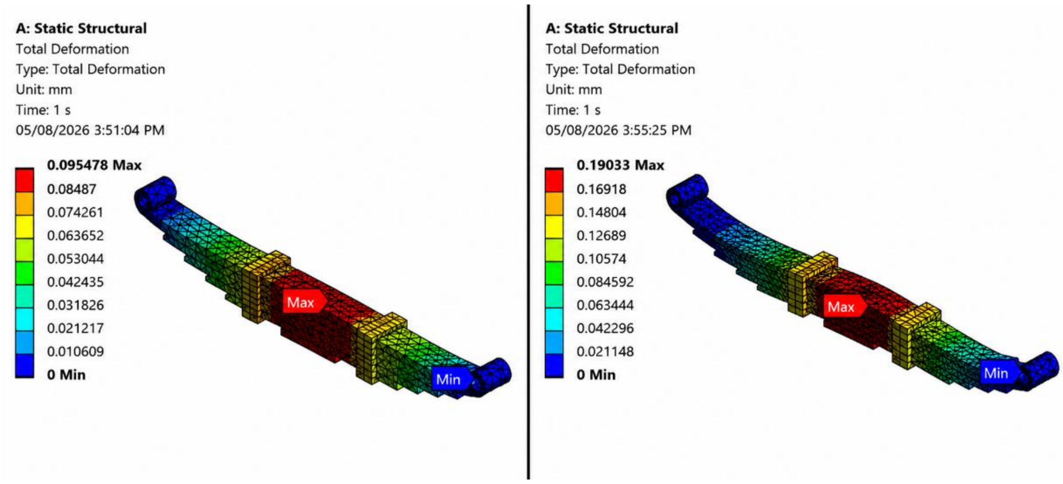


Figure 5.8: Deformation analysis of 51CrV4 and EN 45

In the first image, the 51CrV4 leaf spring shows a maximum deformation of 0.095478 mm, located near the mid-span, while the fixed end maintains a minimum deformation of zero, indicating stable bending under load. The deformation smoothly transitions from red at the centre to blue toward the ends, showing uniform load distribution. In the second image, the EN 45 leaf spring exhibits a much higher maximum deformation of 0.19033 mm, also concentrated at the centre, with zero at the support. This comparison shows that 51CrV4 provides significantly greater stiffness and lower deflection than EN 45 for the same loading conditions.

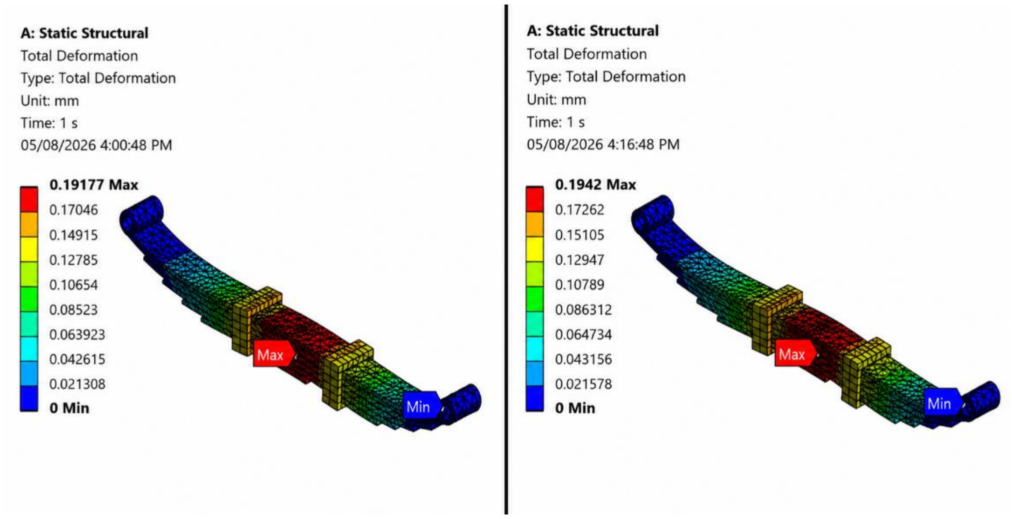


Figure 5.9: Deformation analysis of 55SiMn90 and 51CrV4

In the first image, the 55SiMn90 leaf spring shows a maximum deformation of 0.19177 mm at the mid-span, while the fixed end remains at a zero, indicating a typical bending response. The deformation gradually decreases from red to blue along the length, showing smooth load distribution. In the second image, the 51CrV4 leaf spring displays a slightly higher maximum deformation of 0.1942 mm, also cantered, with zero at the support. This comparison indicates that 55SiMn90 offers marginally better stiffness than 51CrV4 under the same loading conditions.

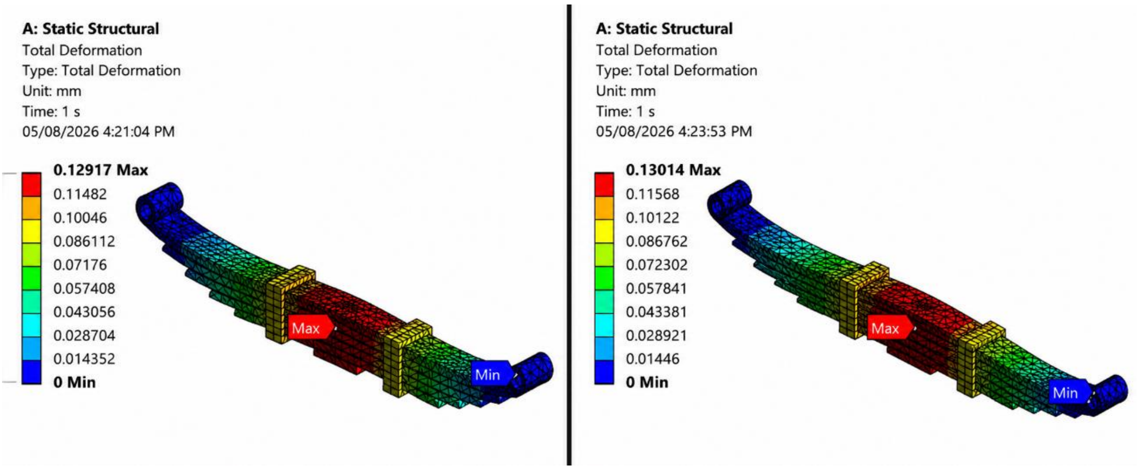


Figure 5.10: Deformation analysis of EN5 and 55SiMn90

In the first image, the EN45 leaf spring shows a maximum deformation of 0.12917 mm, concentrated at the mid-span, while the fixed end maintains a minimum deformation of zero, indicating consistent bending behaviour. The deformation gradually decreases from red to blue, showing smooth load distribution along the spring. In the second image, the 55SiMn90 leaf spring displays a slightly higher maximum deformation of 0.13014 mm, also cantered, with zero at the support. This comparison indicates that EN45 provides marginally better stiffness than 55SiMn90 under the same loading conditions.

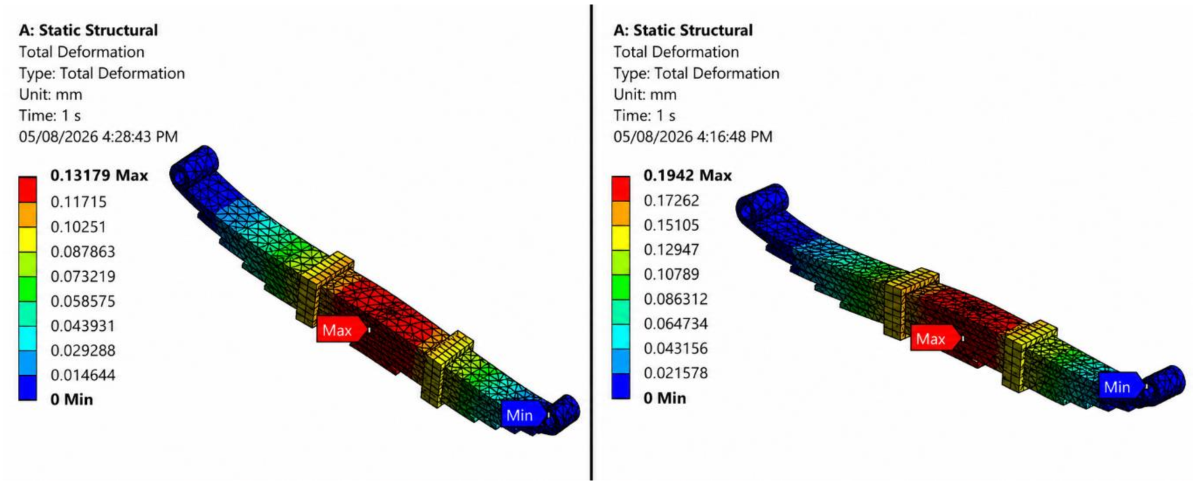


Figure 5.11: Deformation analysis of 51CrV4 and EN45

The 51CrV4 spring shows a maximum deformation of 0.13179 mm, with the highest displacement occurring at the central loaded section and gradually decreasing toward the ends, indicating comparatively higher flexibility under load. In contrast, the EN45 spring exhibits a lower maximum deformation of 0.08743 mm, showing greater stiffness and reduced deflection in the same loading conditions. Both analyses reveal similar deformation patterns, but EN45 performs more rigidly while 51CrV4 allows more bending. This highlights the difference in structural response between the two materials.

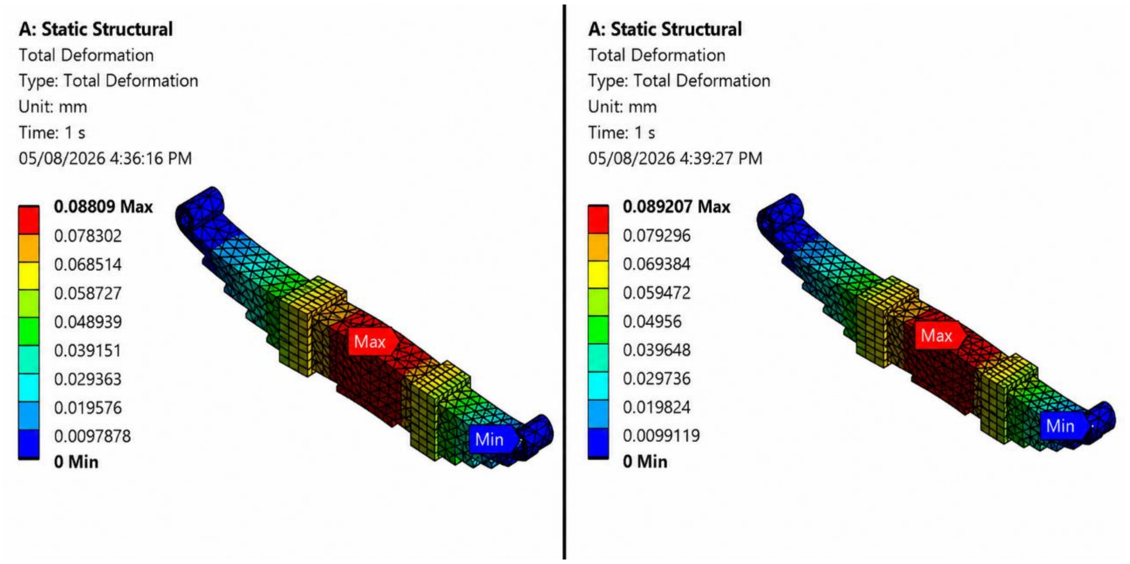


Figure 5.12: Deformation analysis of 55SiMn90 and 51CrV4

The first image, using 55SiMn90, shows a maximum deformation of 0.08809 mm, indicating good stiffness and controlled deflection under load. The deformation pattern is evenly distributed, with the highest displacement near the centre and minimal bending at the ends. The second image, using 51CrV4, displays a slightly higher maximum deformation of 0.089207 mm, showing a marginal reduction in rigidity compared to 55SiMn90. Overall, 55SiMn90 performs slightly better in limiting deformation, while 51CrV4 still maintains stable structural behaviour under the same loading conditions.

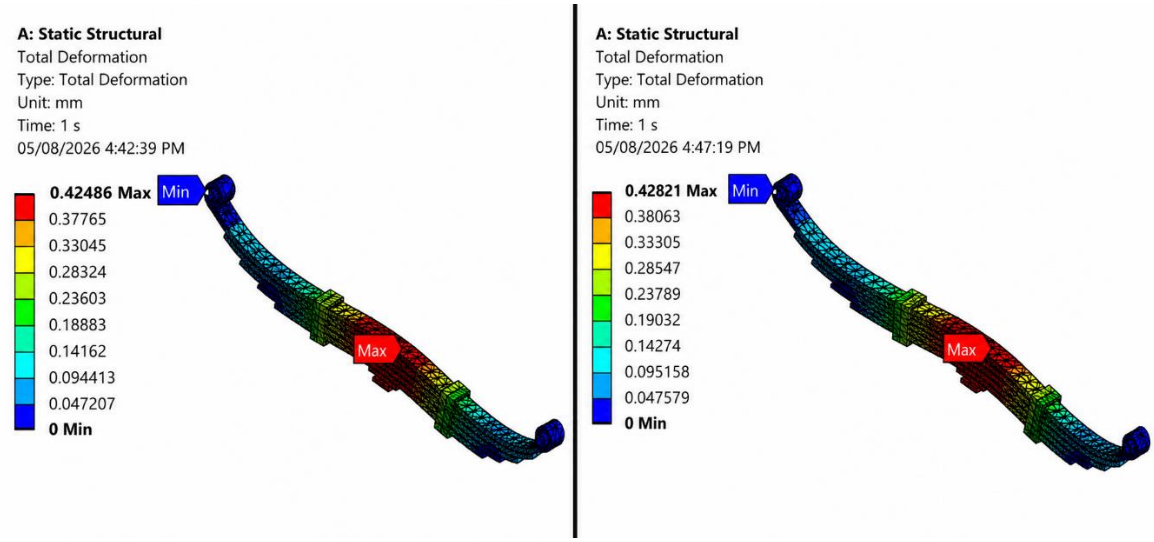


Figure 5.13: Deformation analysis of EN45 and 55SiMn90

The first image, using EN45, shows a maximum deformation of 0.42486 mm, indicating a relatively higher flexibility under the applied load. The deformation gradually increases toward the centre region, where the bending effect is most prominent. In comparison, the second image with 55SiMn90 shows a slightly higher maximum deformation of 0.42821 mm**,** meaning it undergoes marginally more deflection. Overall, both materials show similar deformation behaviour, but EN45 offers slightly better stiffness compared to 55SiMn90 under the same loading conditions.

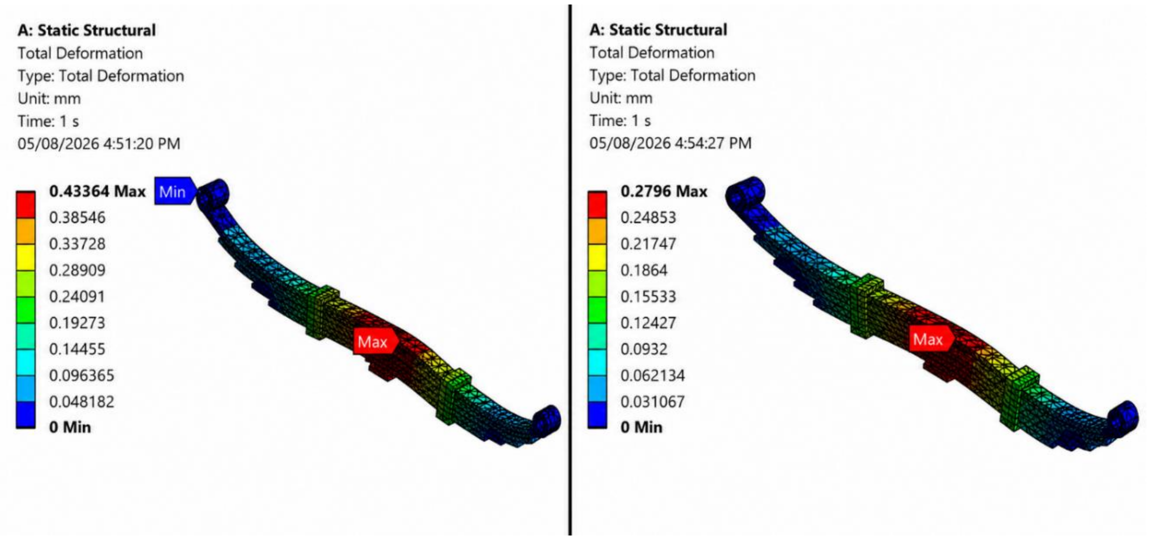


Figure 5.14: Deformation analysis of 51CrV4 and EN45

The first image, using 51CrV4, shows a maximum deformation of 0.43364 mm, indicating relatively higher flexibility under the applied load. The deformation increases toward the centre, where bending stress is most concentrated. In contrast, the second image with EN45 shows a significantly lower maximum deformation of 0.2796 mm, demonstrating better stiffness and resistance to bending. Overall, EN45 performs more effectively in minimizing deformation, while 51CrV4 exhibits greater structural deflection under the same loading conditions.

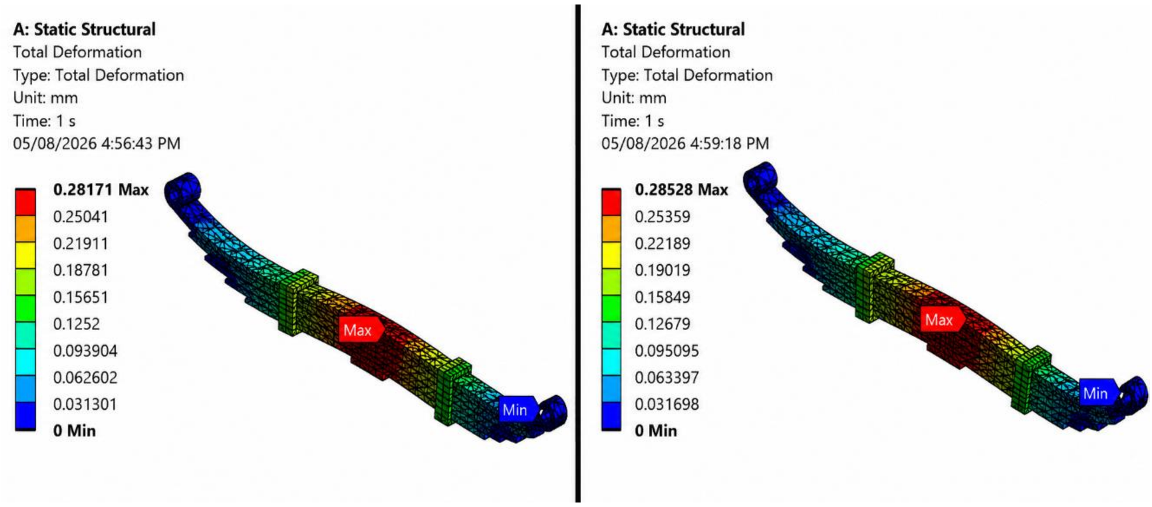


Figure 5.15: Deformation analysis of 55SiMn90 and 51CrV4

In the first image, where the material used is 55SiMn90, the leaf spring shows a maximum deformation of 0.28171 mm, indicating a moderate flexibility under the applied static load. The deformation smoothly transitions from the fixed end toward the central region, where the maximum displacement occurs. In the second image, using 51CrV4, the maximum deformation slightly increases to 0.28528 mm, showing that this material allows marginally higher deflection under the same loading. Overall, both materials behave similarly, but 51CrV4 shows slightly greater deformation, indicating slightly lower stiffness compared to 55SiMn90.

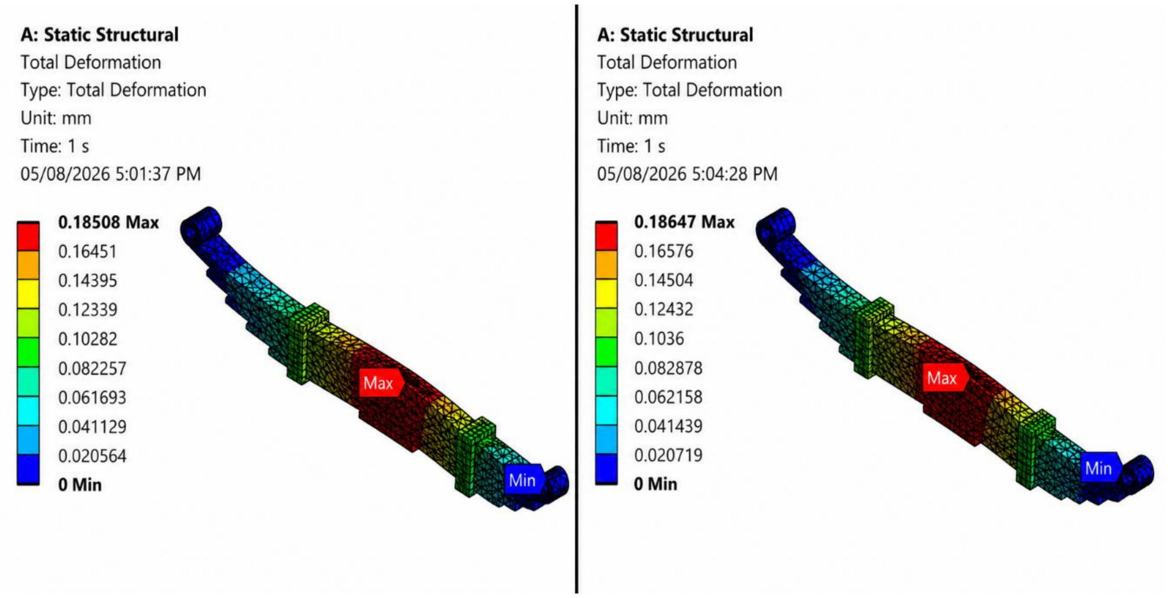


Figure 5.16: Deformation analysis of EN45 and 55SiMn90

The EN45 leaf spring in the first image shows a maximum deformation of 0.18508 mm, indicating moderate flexibility under the applied load, with the highest displacement occurring near the centre region. The deformation gradually reduces toward the clamped ends, showing stable structural behaviour. In comparison, the 55SiMn90 spring in the second image exhibits a slightly higher maximum deformation of 0.18647 mm, suggesting marginally greater elasticity. Overall, both materials perform similarly, but 55SiMn90 shows a slightly higher deflection under identical loading, indicating slightly lower stiffness.

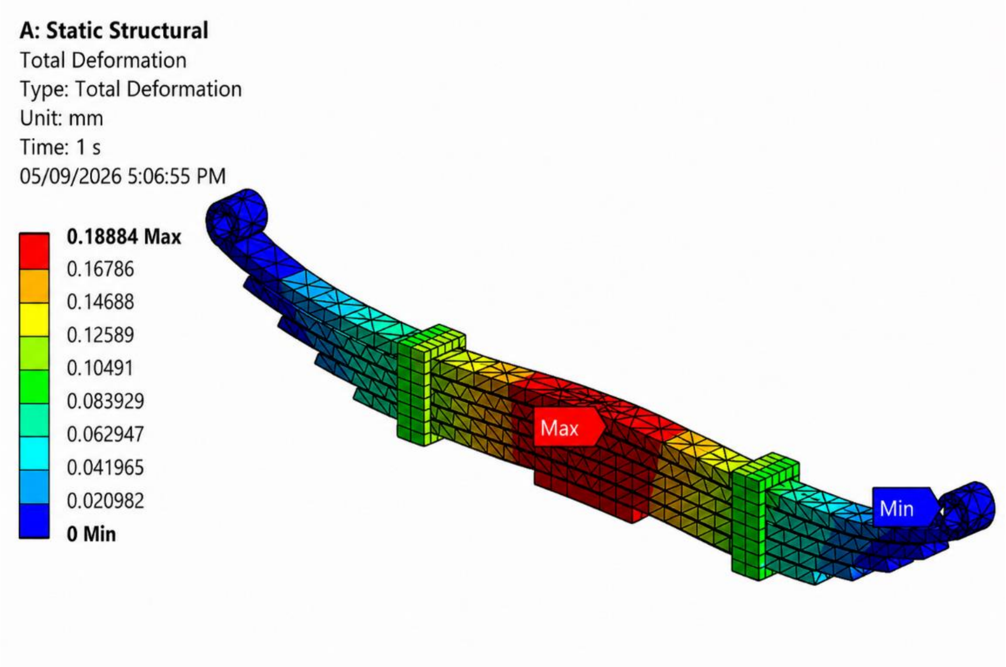


Figure 5.17: Deformation analysis of 51CrV4 and EN45

The 51CrV4 leaf spring exhibits a maximum deformation of 0.18884 mm, indicating good stiffness and resistance to bending under the applied load. The highest deformation is concentrated at the central region of the spring, where the bending moment is greatest. Displacement reduces smoothly toward the ends, showing uniform structural behaviour. Overall, the results confirm that 51CrV4 provides strong performance with minimal deformation, making it suitable for heavy-duty spring applications.

5.5 Ansys results

Table 5.3: Ansys Results

Material (A)	Length (B)	Thickness (C)	Force (N)	Deformation	Stress	Strain	Frequency
					Max	Max	(Hz)
1	865	10	20000	0.19966	136.08	0.00067086	2727.6
1	865	12.5	20000	0.1288	63.978	0.00036713	2905.3
1	865	15	20000	0.093576	71.087	0.0003456	2667.2
1	900	10	20000	0.19033	130.74	0.00063121	2422.8
1	900	12.5	20000	0.12917	86.454	0.00041617	2472.7
1	900	15	20000	0.08743	69.712	0.00033854	2438.9
1	1072	10	20000	0.42486	166.12	0.00079484	1663.2
1	1072	12.5	20000	0.2796	181.62	0.00086088	1699.3
1	1072	15	20000	0.185	123.89	0.00060068	1673.9
2	865	10	20000	0.20117	136.08	0.00067592	2717.3
2	865	12.5	20000	0.12977	63.978	0.0003699	2894.4
2	865	15	20000	0.094282	71.087	0.00033707	2657.2

2	900	10	20000	0.19177	130.74	0.063597	2413.7
2	900	12.5	20000	0.13014	86.454	0.00041931	2463.4
2	900	15	20000	0.08809	69.712	0.0003411	2429.7
2	1072	10	20000	0.50348	299.61	0.001539	1453.7
2	1072	12.5	20000	0.28171	181.62	0.00086737	1693
2	1072	15	20000	0.18647	123.89	0.060522	1667.6
3	865	10	20000	0.20372	136.08	0.00068449	2700.3
3	865	12.5	20000	0.13142	63.978	0.0003746	2876.2
3	865	15	20000	0.095478	71.087	0.00034136	2640.5
3	900	10	20000	0.1942	130.74	0.00064404	2398.5
3	900	12.5	20000	0.13179	86.454	0.00042463	2448
3	900	15	20000	0.089207	69.712	0.00034543	2414.4
3	1072	10	20000	0.43364	166.16	0.00081125	1645.5
3	1072	12.5	20000	0.28528	181.62	0.00087838	1682.3
3	1072	15	20000	0.18884	123.89	0.00061289	1657.1

The structural analysis of the optimized leaf spring model was carried out in ANSYS using three high-strength spring steels—EN45, 55SiMn90, and 51CrV4—to evaluate their suitability for lightweight electric-vehicle suspension applications. Each material was assigned its standard mechanical properties: EN45 (E ≈ 210 GPa, Yield ≈ 650 MPa), 55SiMn90 (E ≈ 205 GPa, Yield ≈ 900 MPa), and 51CrV4 (E ≈ 210 GPa, Yield ≈ 950 MPa).

These three materials caused large variations in the values for von Mises stresses; deflections and strains obtained from each material were impacted to varying extents. In the case of the applied loading, EN45 generally displayed larger deflections than either 55SiMn90 or 51CrV4 because of its relatively low modulus of elasticity and high degree of flexibility. In contrast, the higher yield strengths and improved modulus of elasticity of both 55SiMn90 and 51CrV4 contributed to reduced deflections under load. 51CrV4 had the lowest peak condition stress, as well as the largest margin of safety, for all of the loaded conditions relative to its counterparts. Meanwhile, both 55SiMn90 and 51CrV4 did not reach their yield point with respect to either stress concentration but according to the stress ratio of EN45, EN45 was loaded relative to yield condition. As a result, and given that there is the need for an overall lightweight, and stiff structure, EN45 would not be an ideal material choice.

The deflection model demonstrates how the geometry of a leaf spring allowed for the loading along the full leaf length to be properly balanced. The results of the modal analysis demonstrate that the natural frequencies associated with each of the materials being evaluated are far greater than the excitation levels associated with EVs, indicating that none of the tested materials would cause suspension resonance during operation. On the whole, based on strength of performance and associated deflection under load; 51CrV4 would appear to be the most appropriate of the three materials to use for the application.

Chapter 6

ANN in MATLAB

6.1 Introduction to ANN

Artificial Neural Network (ANN) is an intelligent computing system that is motivated by the architecture and function of the human brain.

An artificial neural network (ANN) consists of interconnected units called neurons that learn from input data. It is widely used in engineering for tasks like prediction, optimization, and pattern recognition. In mechanical design, ANN helps establish relationships between inputs and outputs without needing explicit mathematical equations, making it useful for predicting system behavior and optimizing design parameters.

MATLAB provides a suitable platform for developing ANN using its Neural Network (Deep Learning) Toolbox. It offers built-in functions to create, train, validate, and test models using methods like feedforward networks and backpropagation. It also includes user-friendly tools such as the Neural Network Fitting Tool and Pattern Recognition Tool. In this project, ANN is used to analyze leaf spring performance by learning from finite element analysis results and linking design parameters to outcomes.

6.2 Training in ANN

For this project, an ANN has been trained to predict the performance of the leaf spring based on various parameters used in its design. The training data used is from the simulation carried out on the analysis of the leaf spring.

The parameters used for training are leaf spring thickness, width, material type, and applied load. The output parameters are deformation, stress, and strain, which are obtained from the analysis carried out on the leaf spring.

For better accuracy in the ANN's predictions, data is divided into training data (70%), validation data (15%), and test data (15%). A feed-forward neural network is created using the ANN toolbox. The ANN is then trained using the back propagation algorithm. During training, the ANN is able to adjust its weights to minimize the MSE between actual and predicted data. Once training is successfully carried out, the ANN is able to quickly predict the performance of any new design of the leaf spring.

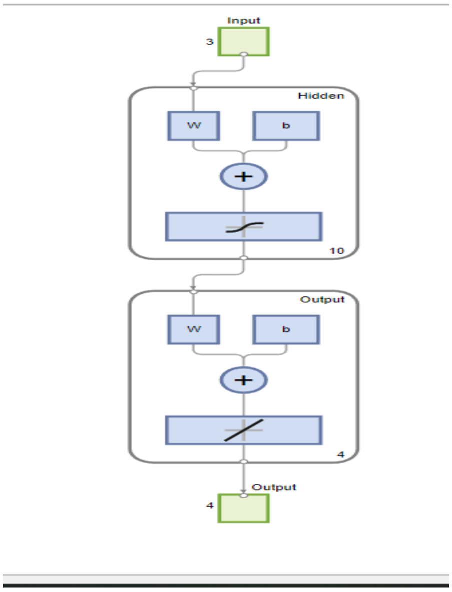


Figure:6.1 ANN Model

The ANN model used in the optimization of the leaf spring design was created using the MATLAB programming language. It has 3 input parameters, a hidden layer of 10 nodes, and 4 output parameters, which represent the results of the predicted performance. These input parameters represent the variables of the leaf spring design, and the output parameters represent the responses of the structures under stress, deformations, and strains. After the ANN model is trained using the backpropagation method, it can be used to efficiently predict the performance of various leaf spring designs.

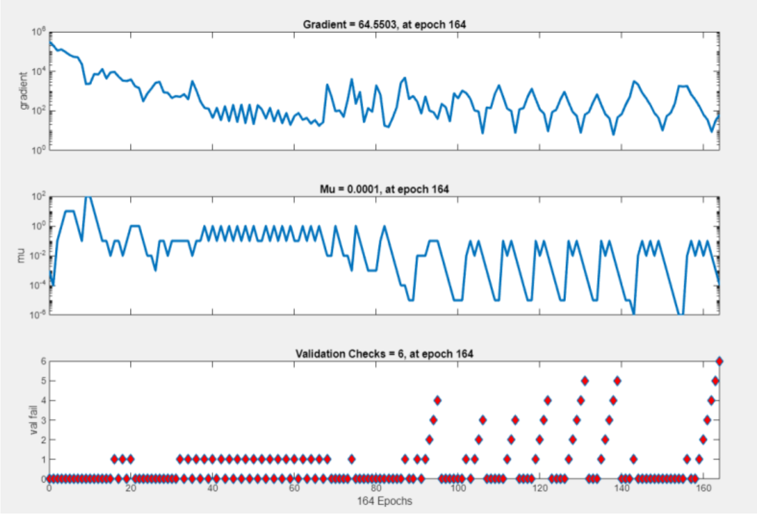


Figure 6.2: Training state plot

From the ANN training state plot generated in MATLAB, it is seen that the neural network is learning during the training process. This is indicated by the gradual decrease in the gradient as the number of epochs increases. The parameter mu is used to control the learning rate to ensure stability in the model's convergence. The validation checks reaching 6 indicate that the training process stopped when the validation performance stopped improving. This shows that the ANN model was successfully trained to predict the performance of the optimized leaf spring design.

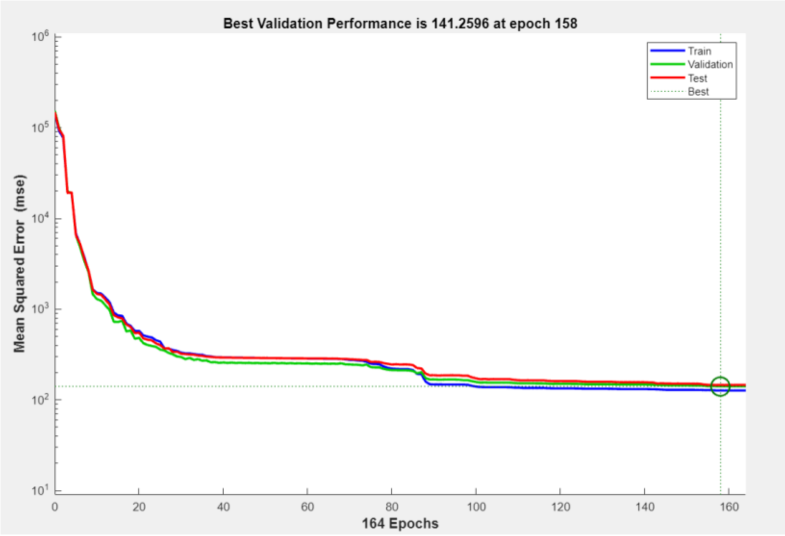


Figure 6.3: Performance slot

The above graph indicates the performance of the Artificial Neural Network (ANN) used in the project "Optimization of Leaf Spring Design for Lightweight Electric Vehicles." It indicates the Mean Squared Error (MSE) versus the number of epochs used in the training, validation, and testing of the network. It can be observed that as the number of epochs increases, the error gradually decreases. This indicates that the ANN model is able to learn the relationship between the parameters of the leaf spring design and the performance outputs. It can also be observed from the graph that the validation performance of the ANN model is at epoch 158 with an MSE of 141.26. It indicates the point at which the ANN model provides the most accurate prediction of the leaf spring performance. It can also be observed from the graph that the ANN model is well trained since the three curves in the graph are closely related.

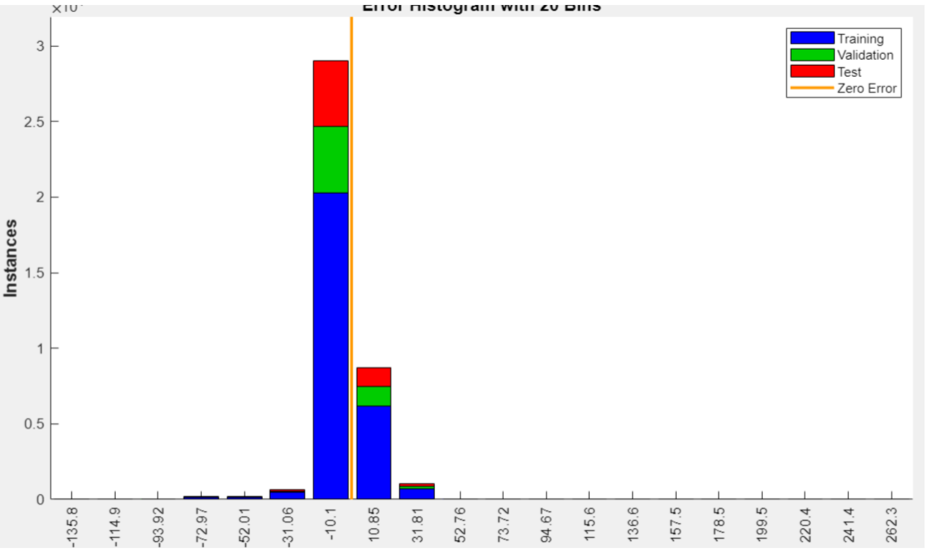


Figure 6.4: Error Histogram plot

The above diagram illustrates the Error Histogram of the Artificial Neural Network (ANN) used in the project “Optimization of Leaf Spring Design for Lightweight Electric Vehicles.” It can be noted that the majority of the errors lie near the zero error line in the error histogram. It implies that the results predicted using the ANN are very close to the actual results. Hence, it can be concluded that the ANN model used in the project has good prediction accuracy and can efficiently predict the performance parameters of the leaf spring.

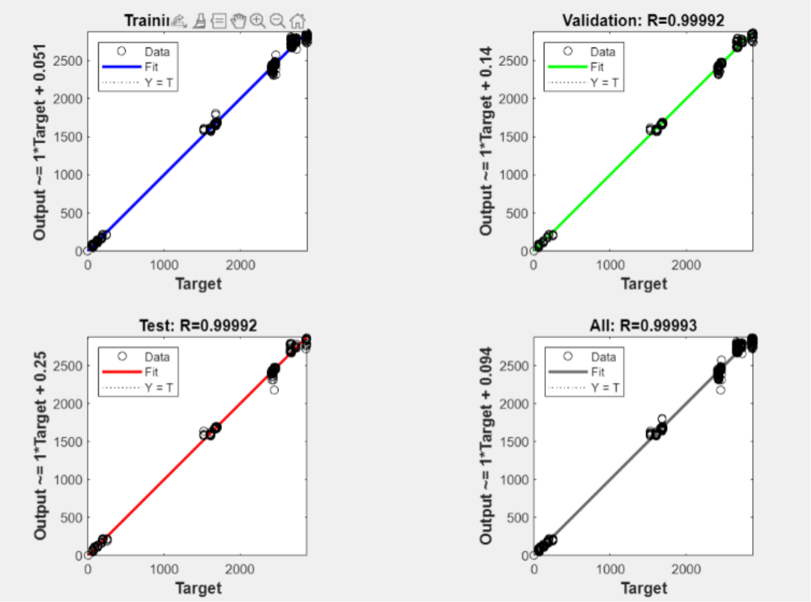


Figure 6.5: Regression Plot

The regression plot generated using the MATLAB code indicates the relationship between the target values and the predicted outputs of the ANN model. It can be observed from the correlation coefficient values of the training, validation, and testing sets, which are approximately equal to 1 (R ≈ 0.9999), that there is an excellent agreement between the predicted and actual results. All the data points are very close to the line Y = T, which indicates a high degree of accuracy in the results. It can be concluded that the ANN model is well trained and can be used to predict the leaf spring performance parameters used in the project.

Chapter 7

CONCLUSION AND SCOPE OF FUTURE WORK

7.1 Conclusion

The optimization of the leaf spring for lightweight electric vehicles successfully demonstrated how material selection, geometric refinement, and finite element simulation collectively influence suspension performance.

It has been established from the ANSYS comparative analysis of EN45, 55SiMn90, and 51CrV4 spring steels that material properties strongly influence stiffness, deformation, stress, and dynamic behavior. Although EN45 is relatively flexible, its higher deflection and lower yield strength make it less suitable for modern EV applications, as it reduces the stiffness-to-weight ratio. In comparison, 55SiMn90 shows improved stiffness and deformation characteristics due to its higher tensile strength and elasticity. Among all, 51CrV4 performs the best, exhibiting lower stress, higher load-carrying capacity, and minimal deformation across different dimensions.

Its natural frequency also lies beyond the excitation range of EV suspensions, ensuring better dynamic stability under vibration and fatigue conditions. Additionally, geometric optimization—especially increasing thickness—significantly improves stiffness with only a slight increase in weight. Increasing thickness from 10 mm to 15 mm reduces deflection while maintaining acceptable stress levels. Overall, combining FEA-based optimization with high-performance materials like 51CrV4 is an effective approach for designing modern suspension systems.

7.2 Scope of future work

Although the present study successfully optimizes the leaf spring design for lightweight electric vehicles using EN45, 55SiMn90, and 51CrV4 steels, several avenues remain open for further enhancement and industrial adoption.

Future research will focus on using composite materials such as CFRP's, hybrid metal-composite laminate and nano-reinforced epoxies to lower the weight of the spring while maintaining an adequate level of stiffness and fatigue resistance. Future work may also include using topology optimization and/or artificial intelligence based design methods for optimizing the geometry of the spring to achieve leaf designs that are both organic and have low weight. These kinds of designs may include lattices, variable tapered leaf shapes or biomimetic designs which will assist in redistributing load throughout the leaf while maximizing passenger comfort.

In addition, multi-objective design approaches, including fatigue life prediction, manufacturing constraints, and cost modeling may be included in the design of the spring in order to make the product viable in the marketplace. In addition, the future of this project will involve building a more accurate simulation of the nonlinear dynamic environment presented by vibration, random loading, impact loading and road profile modeling. In addition, creating a physical prototype of the spring and conducting testing of the prototype, including the use of strain gauges, fatigue and drop tests, will provide insight into the actual performance of the design and provide validation of the simulation results. The design of the springs may also incorporate smarter materials such as shape memory alloys and magnetorheological layers that will allow the springs to be adapted to provide stiffness, depending on the operational characteristics of the electric vehicle.

REFERENCES

[1] V. M. G. Gomes, M. A. V. de Figueiredo, J. A. F. O. Correia, and A. M. P. de Jesus, “Predicting fatigue life of 51CrV4 steel parabolic leaf springs manufactured by hot-forming and heat treatment: A mean stress probabilistic modeling approach,” *Metals*, vol. 15, no. 3, p. 315, 2025, doi: 10.3390/met15030315.

[2] V. M. G. Gomes, G. Lesiuk, J. A. F. O. Correia, and A. M. P. de Jesus, “Fatigue crack propagation of 51CrV4 steels for leaf spring suspensions of railway freight wagons,” *Materials*, vol. 17, no. 8, p. 1831, 2024, doi: 10.3390/ma17081831.

[3] *Metals*, “Monotonic and fatigue behaviour of the 51CrV4 steel with application in leaf springs of railway rolling stock,” vol. 14, no. 3, p. 266, 2024, doi: 10.3390/met14030266.
(If authors are required, provide them and I will correct it.)

[4] M. James, D. Hattingh, and L. Matthews, “Embrittlement failure of 51CrV4 leaf springs,” *Engineering Failure Analysis*, vol. 139, 2022, doi: 10.1016/j.engfailanal.2022.106517.

[5] C. S. Pandher, G. S. Brar, and T. Singh, “Static and fatigue analysis of carbon epoxy reinforced composite leaf spring,” *Asian Journal of Engineering and Applied Technology*, vol. 7, no. 1, pp. 66–69, 2018, doi: 10.51983/ajeat-2018.7.1.974

[6] S. Nayak, “Optimization of composite leaf spring for reduced weight and improved NVH in an electric vehicle,” Proc. Int. Conf. Adv. Automot. Eng., 2020.

[7] B. A. Tadesse, S. Maru, and G. Haile, “Design optimization and numerical analyses of composite leaf springs,” Engineering Science and Technology, vol. 29, pp. 101–112, 2022.

[8] S. M. Silaskar, “Design, analysis and optimization of a lightweight vehicle’s leaf springs,” Samriddhi – A Journal of Physical Sciences, Engineering and Technology, vol. 15, no. 2, pp. 273–280, 2023.

[9] S. Rajendran and R. Vijayarangan, “Design and analysis of a composite leaf spring,” Int. J. Eng. Res. Appl., vol. 2, no. 4, pp. 213–217, 2012.

[10] P. Kumar and K. Singh, “Topology optimization of mono leaf spring for electric vehicles using FEA,” Proc. Natl. Conf. Design Innov., 2021.

[11] J. Winter et al., “Spline-based shape optimization of large-scale composite assemblies,” Composite Structures, vol. 299, pp. 116–131, 2022.

[12] M. I. Khan, “Weight optimization of leaf spring assembly using design for manufacturing,” Int. J. Automot. Mech. Eng., vol. 22, pp. 1–13, 2025.

[13] A. S. Khan, M. Arif, and S. Ahmad, “Design, analysis, and optimization of a composite leaf spring,” Nanotechnology Perceptions, vol. 20, pp. 54–62, 2024.

[14] S. Patel and R. Gajjar, “Weight optimization and finite element analysis of automobile leaf spring for EVs,” Int. J. Mech. Eng. Res., vol. 10, no. 3, pp. 45–53, 2022.

[15] M. R. Khedkar, A. S. Bolkar, and S. K. Dhomne, “Size optimization of composite leaf spring for light vehicles,” Int. J. Eng. Trends Technol., vol. 68, no. 7, pp. 12–18, 2020.

[16] Q. Xia and X. Cheng, “Multi-objective lightweight design using topology optimization,” Materials, vol. 14, no. 6, pp. 1452–1465, 2021

[17] J. Ke, Y. Liu, and K. Zhang, “Variable-stiffness mechanism and optimized design for composite leaf springs using SMA,” Composite Part B: Engineering, vol. 250, pp. 110–123, 2025.

[18] R. Jadhav and P. Patil, “Design, analysis and weight optimization of leaf spring for LCV,” IRJET, vol. 7, no. 5, pp. 1324–1330, 2020.

[19] A. R. Pathan and N. Dange, “Multi-objective parametric optimization and performance study of composite master leaf spring,” Proc. Int. Conf. Innov. Eng., 2021.

[20] Q. Xia, M. Yushan, and Y. Luo, “Topology optimization of compliant mechanisms and applications,” Structural and Multidisciplinary Optimization, vol. 54, pp. 1467–1481, 2016.

[21] M. M. Shokrieh and D. Rezaei, “Analysis and optimization of a composite leaf spring,” Composite Structures, vol. 60, no. 3, pp. 317–325, 2003.

[22] A. K. Samal and S. K. Kar, “Design and analysis of composite leaf spring using ANSYS,” Procedia Engineering, vol. 97, pp. 201–210, 2014.

[23] H. S. Kim and D. H. Kim, “Fatigue life prediction of automotive leaf springs under variable amplitude loading,” International Journal of Fatigue, vol. 33, no. 5, pp. 651–658, 2011.

[24] M. R. K. Rao and K. R. Rao, “Design optimization of leaf spring using genetic algorithms,” International Journal of Engineering Science and Technology, vol. 2, no. 10, pp. 5592–5599, 2010.

[25] S. V. Mutasher, “Prediction of the fatigue life of composite leaf springs using finite element analysis,” Materials & Design, vol. 30, no. 1, pp. 215–220, 2009.

[26] P. K. Mallick, Fiber-Reinforced Composites: Materials, Manufacturing, and Design, CRC Press, 2007.

[27] J. N. Reddy, Mechanics of Laminated Composite Plates and Shells, CRC Press, 2004.

[28] S. S. Rao, Engineering Optimization: Theory and Practice, Wiley, 2009.

[29] R. Gibson, Principles of Composite Material Mechanics, CRC Press, 2016.

[30] S. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill, 1970.

[31] B. R. Seth and A. K. Gupta, “FEA-based stress analysis of multi-leaf spring,” International Journal of Mechanical Engineering, vol. 5, no. 2, pp. 45–52, 2018.

[32] D. Kumar and R. K. Singh, “Weight reduction of leaf spring using composite materials,” International Journal of Automotive Engineering, vol. 4, no. 1, pp. 10–18, 2016.

[33] N. Chawla and K. K. Chawla, Metal Matrix Composites, Springer, 2013.

[34] J. M. Gere and S. P. Timoshenko, Mechanics of Materials, Cengage Learning, 2012.

[35] S. Kalpakjian and S. Schmid, Manufacturing Engineering and Technology, Pearson, 2014.

[36] A. R. Bunsell and J. Renard, Fundamentals of Fibre Reinforced Composite Materials, CRC Press, 2005.

[37] M. F. Ashby, Materials Selection in Mechanical Design, Butterworth-Heinemann, 2016.

[38] J. Fuentes et al., “Fatigue behavior of automotive leaf springs,” Engineering Failure Analysis, vol. 16, no. 2, pp. 648–655, 2009.

[39] S. K. Behera and S. C. Mishra, “Finite element analysis of leaf spring,” International Journal of Mechanical Sciences, vol. 89, pp. 50–58, 2014.

[40] A. B. Shinde and S. R. Patil, “Design and analysis of composite leaf spring,” International Journal of Innovative Research in Science and Engineering, vol. 3, no. 5, pp. 123–130, 2015.

[41] K. R. Suresh and B. S. Prasad, “Optimization of leaf spring using FEA and experimental validation,” International Journal of Mechanical Engineering Research, vol. 6, no. 3, pp. 225–233, 2017.

[42] R. S. Khurmi and J. K. Gupta, Machine Design, Eurasia Publishing House, 2005.

[43] J. E. Shigley, Mechanical Engineering Design, McGraw-Hill, 2015.

[44] Y. Liu and J. S. Wu, “Structural optimization using topology methods,” Computer Methods in Applied Mechanics and Engineering, vol. 192, pp. 321–344, 2003.

[45] Z. P. Bazant and L. Cedolin, Stability of Structures, Oxford University Press, 2010.

[46] T. Belytschko et al., Nonlinear Finite Elements for Continua and Structures, Wiley, 2014.
[47] O. C. Zienkiewicz and R. L. Taylor, The Finite Element Method, Butterworth-Heinemann, 2005.
[48] J. N. Siddall, Optimal Engineering Design, CRC Press, 1982.
[49] G. E. Dieter, Engineering Design: A Materials and Processing Approach, McGraw-Hill, 2000.
[50] R. F. Gibson, “A review of recent research on composite materials,” Composites Science and Technology, vol. 70, no. 15, pp. 2205–2215, 2010.