

**A REPORT
ON
MULTI-DOMAIN OPTIMIZATION OF AUTOMOTIVE LEAF
SPRINGS VIA STRUCTURAL GEOMETRY, JOINT
ARCHITECTURE, AND HYBRID MATERIAL
INTEGRATION**

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Any exclusion or error in report is solely my responsibility.

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Abstract:

Traditional automotive leaf springs, predominantly used by light to heavy load carrying vehicles, are manufactured from steel, faces a significant limitation in meeting the evolving trend in technology and increasing demand in the better damping and vibration isolating leaf spring systems. The inherent heavy weight of the leaf spring assemblies affects fuel efficiency, where the limited fatigue resistance under the cyclic loading leads to fatigue failure. Additionally, steel has low damping properties and poor vibration isolation properties leads to uncomfortable drive quality and unpredictable fatigue failure overall. Despite the advancement in leaf spring domain as hybrid material and fiber reinforced leaf, widespread adoption of this hybrid leaf spring remains a struggle due to insufficient optimization.

This study indulges in the comprehensive multi-domain optimization of the automotive leaf springs through geometric modification and hybrid material integration. The study investigates the diverse material combinations include Traditional steel, and Carbon fiber-reinforced Polymer, Glass fiber-reinforced Polymer and innovative method of hybrid arrangements to identify the best performance characteristics. The methodology explores the systematic evaluation of the geometric parameters like width, length, thickness and leaf count variation alongside analysis of layer architecture like sandwich and alternating layers.

The research employs advanced finite element analysis (FEA) simulation coupled with experimental validation to assess critical performance parameters including weight reduction, stress distribution, fatigue life enhancement, and vibration damping improvement. A parameter-driven experimental matrix is established to benchmark key geometric and material variables, enabling systematic comparison and optimization of design configurations.

The anticipated outcome of this study is the identification of the scalable, cost-effective leaf spring design suitable for next generation usage in the automotive light and heavy loading vehicles, with recommendation of the geometric combination and leaf material arrangements.

Keywords: Leaf springs, hybrid materials, multi-domain optimization, finite element analysis, composite materials, vibration damping

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1.0. Introduction

The suspension system is a critical component in automobiles possess a great part in influencing vehicle performance, ride comfort and stability. Among the various suspension systems and components, the leaf spring system has been a fundamental element for centuries, particularly in heavy and light duty vehicles, mainly because of the simplicity and variable load carrying capacity. Hower, the modern automotive trend with emergence in the Electric Vehicle (EV) and modern emission standards has made company and engineers to work towards aggressive lightweighting the vehicle. This has made the re-evaluation of traditional components, with the traditional steel leaf spring emerging as a prime candidate for innovation.

Pursuit of lighter vehicle is the central theme of Automobile engineering. In internal combustion engine vehicles, a 10% reduction in the total weight results in 6-8% increase in fuel efficiency. For electric vehicles, where battery packs decide the range of the vehicle, minimizing the vehicle weight is difficult to counterpart.

Leaf spring system in vehicle accounts for 10-20% of “unsprang mass” – Mass of the component does not support by suspension system like Wheels, tiers, brakes and suspension itself. Reducing the unspring mass improves vehicle fuel efficiency and ride comfort. This makes the focus on reducing the leaf spring weight important.

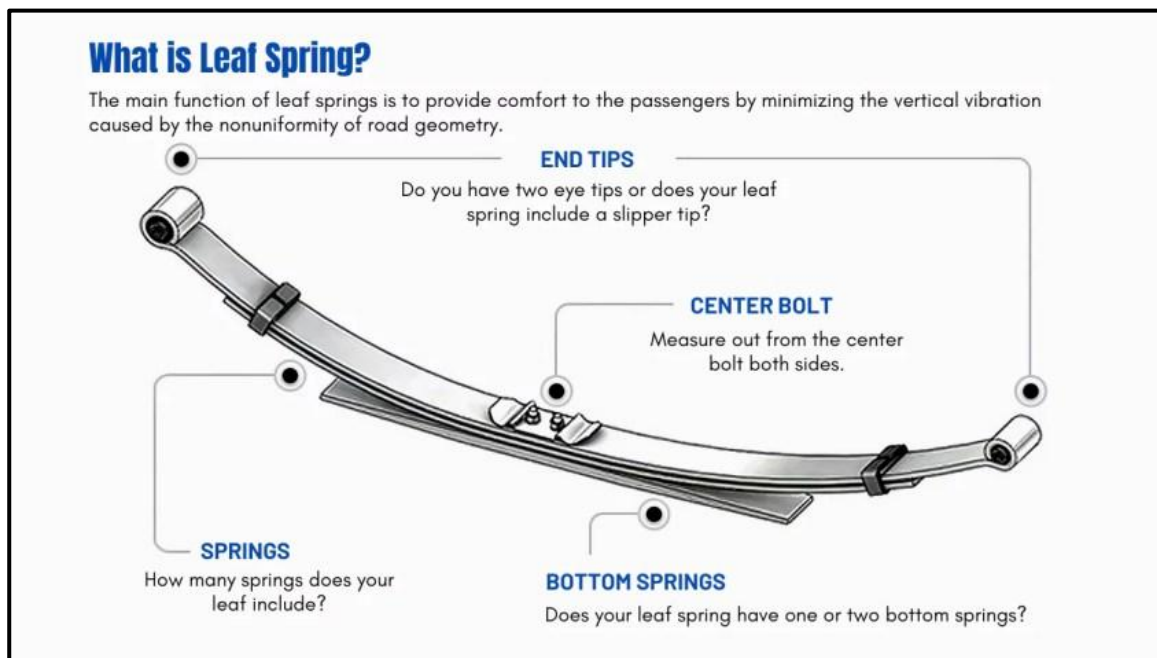


Figure 1.1. Leaf Spring dissection. Source: <https://www.mendmotor.com/what-is-leaf-spring/>

1.1. The Leaf Spring: Function and conventional design

Leaf spring serves two purposes at once; it acts as a flexible linkage absorbing shocks and vibration from the road and as a structural member that locates the axle and controls its movement relative to the vehicle chassis³. The traditional design consists of multiple layers of steel plates, or "leaves," clamped together. The main leaf is the master leaf, that is bent at the ends to form eyes for mounting to the vehicle frame. The remaining leaves are progressively shorter, creating a tapered, semi-elliptical shape that provides the desired spring rate⁴. The introduction of multi-leaf arrangements creates inter-leaf friction which provides a degree of inherent damping and possess some disadvantages.

1.2. Limitation of Conventional Steel Leaf Spring

Even with long history of proven reliability and unmatched functional importance, conventional steel leaf spring have several limitations in context with modern automobile design.

- **Increased Mass:** Steel has high density approximately 7.85 g/cm^3 , making traditional steel leaf spring arrangements heavy. A typical multi-leaf spring assembly can weigh up to 50Kg. This mass adds up as unsprung mass of the vehicle.
- **Unreliable stress distribution:** The stepped geometry of the multi-leaf spring arrangements creates an uneven stress distribution near the clamp area and at the end or eye.
- **Noise, Vibration and Harshness (NVH):** The friction between the leaf layers, despite providing damping creates harshness in the ride quality. The friction also creates squeaking noise in while driving.
- **Corrosion Susceptibility:** Steel is in general prone to corrosion, which can degrade its mechanical property over time. This makes traditional steel leaf spring less reliable, resulting in premature failure.

1.3. Composite Materials: A shift in Suspension design

For leaf spring applications, fibre-reinforced polymer (FRP) composites have become a strong substitute for steel. These materials provide a special set of qualities that directly address the drawbacks of steel. They are made up of high-strength fibres embedded in a polymer matrix.

- **High Strength-weight ratio:** The primary advantage of the using composite is the exceptional specific strength and stiffness. Materials like E-Glass/ Epoxy and Carbon Fiber/ Epoxy can achieve same load carrying capacity as steel with fraction of total weight contributing towards the unsprung mass of the

vehicle.

- **Extraordinary Fatigue Resistance:** Composite materials exhibit excelling fatigue resistance. The internal damping of the polymer fiber matrix and load sharing tendency of the fibers result in improved life service of composite leaf spring in comparison with traditional leaf springs.
- **Corrosion Resistance:** Unlike steel, Composite materials have a great corrosion resistance property from normal travelling condition to extreme chemical exposed condition.
- **Design Flexibility:** The manufacturing process for composites allows for creating complex optimized shapes. This allows the design of leaf spring in multiple width and thickness, leads to prevention of inter-leaf friction and allow uniform stress distribution, this leads to increased fuel efficiency.

1.4. The Leaf Spring: Function and conventional design

This dissertation indulges into a comprehensive study aimed at optimizing the design of the leaf spring in terms of geometric study, material optimization study and arrangement study. The primary objective of this research is:

- Investigating varied materials, including traditional steel, carbon fibre-reinforced polymer (CFRP), glass fibre-reinforced polymer (GFRP) and hybrid arrangements.
- Evaluating various geometries (width, thickness, leaf count) and layer architectures (full material, alternate layers, sandwich structures).
- Comparing performance parameters like weight, stress, fatigue life, and vibration damping using simulation (FEA) and experimental methods.
- Recommending best configurations for next-generation leaf spring design suitable for modern automotive requirements.
- Establish a parameter-driven experimental matrix for benchmarking key geometric and material parameters.
- Identify scalable, cost-effective designs for future automotive adoption.

2.0. Literature Review

This section reviews the publication that discusses composite materials, their manufacturing processes, and the application of composites in leaf spring design. The insights derived from this review will help identify potential directions for future research and development in this area.

2.1. Composite Materials for Leaf Spring Weight Reduction

In their 2014 paper, "A Review on Design and Optimization of Composite Leaf Spring," **Mankar, Katake, and Deshmukh** provide a comprehensive review of the research trends in replacing conventional steel leaf springs with composite materials. The paper surveys various studies, noting that the primary driver for this shift is the **high strength-to-weight ratio** of composites, leading to significant vehicle weight reduction (up to 70-80%) and improved fuel efficiency. It highlights that **E-glass/epoxy (GFRP)** is the most frequently studied material and that **Finite Element Analysis (FEA)** is the standard method used for design, analysis, and optimization. The review concludes that the existing literature confirms composites can offer **substantial weight savings** and superior ride comfort, making them a viable and efficient alternative to steel.[1]

2.2. Vibration Damping and Weight Advantages of GFRP Springs

In the paper "Performance comparison of conventional and composite leaf spring," **Papacz, Tertel, and Kurylo** present an experimental study comparing the vibration suppression capabilities of traditional steel springs and **Glass Fiber Reinforced Plastic (GFRP)** composite springs designed to replace them in a van. The study's **objective** was to measure and record the amplitude of vibrations and prop reactions to calculate and compare the coefficient of vibration suppression. The **key findings** were significant: the GFRP composite leaf springs were approximately **five times lighter** than their steel counterparts. More importantly, they demonstrated vastly superior damping properties, **suppressing vibrations about three times more effectively** than steel and generating smaller dynamic loads (around 20% less) on the vehicle body.[3]

2.3. FEA and Experimental Validation of GFRP Spring Design

In their paper, "Structure Design of GFRP Composite Leaf Spring: An Experimental and Finite Element Analysis," **Ma et al.** present a novel structural design for a GFRP leaf spring. The **methodology** involved using **Finite Element Analysis (FEA)** to optimize the structure (e.g., variable thickness/cross-section) with the goals of reducing stress concentration and overall weight. This optimized design was then fabricated and validated through **experimental static loading tests**. The **key finding** was the **excellent agreement between the FEA simulation and the experimental results**, which confirmed the accuracy and reliability of the FEA model. The study concludes that the newly designed GFRP spring successfully achieved a significant weight reduction and lower bending stress compared to conventional steel springs, proving the effectiveness of the optimized structure.[5]

2.4. A Review of GFRP as a High-Potential Steel Replacement in Suspension Systems

In their paper, "**A Comprehensive Review of Composite Leaf Spring**," N. Azhaguvel and S. Charles present a detailed literature review focused on the substitution of traditional steel leaf springs with composite materials. The **primary objective** is to compare the performance of **Glass Fiber Reinforced Plastic (GFRP)** with steel, highlighting GFRP's advantages, such as low cost, light weight, and high strength-to-weight ratio. The review synthesizes findings from various studies, noting that composite springs can achieve **weight reductions of 68-85%**, exhibit significantly **lower stress** (67% less), and possess **higher stiffness** and **natural frequency** (up to 126% higher), which reduces the chance of resonance. The authors **conclude** that the literature strongly supports GFRP as a highly viable and superior alternative to steel for automotive suspension systems.[6]

2.5. Holistic Design of Carbon-Fiber Composite Body Structures for Affordability

In their paper, "**Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure**," David R. Cramer and David F. Taggart (Hypercar, Inc.) describe the design and manufacturing approach for the **carbon-fiber composite body** of the "Revolution" concept vehicle. The primary **objective** was to overcome the high cost and volume-production challenges that have historically limited the use of advanced composites. The **methodology** involved a "clean sheet," holistic design approach, creating a passenger safety cell that integrates multiple components, thus simplifying the production process. The **key outcome** was a body structure that was **57% lighter** (187 kg) than a comparable steel body, while also providing superior crash protection, stiffness, and thermal/acoustic properties. The authors **conclude** that their novel design and high-volume manufacturing process make lightweight, advanced-composite body structures economically competitive with traditional steel [7]

2.6. Influence of Ply-Stacking and Fiber Content on Mechanical Performance

In their 2014 paper, "**Mechanical Properties of Carbon Fiber/Epoxy Composites: Effects of Number of Plies, Fiber Contents, and Angle-Ply Layers**," Rahmani et al. experimentally investigate how key structural and material parameters influence the mechanical behaviour of carbon fibre/epoxy laminates. The **objective** was to quantify the effects of (1) the total number of plies, (2) the fibre content (by weight), and (3) the orientation of angle-ply layers. The **method** involved fabricating and testing specimens with varying parameters, such as 4, 6, and 8 plies, fibre contents from 40-60%, and different angle-ply layups. The **key findings** demonstrate that increasing both the number of plies and the fibre content generally leads to a

significant increase in tensile and flexural strength. The study also confirms that ply orientation is a critical variable, directly controlling the composite's anisotropic properties (e.g., strength and stiffness in different directions).[8]

3.0. Materials

The selection of material is key part for the design of high-performance leaf springs. This chapter discusses a detailed overview of the materials that are viable candidate for the study and their mechanical properties.

3.1. Traditional Material: Steel Spring

Since the origin of leaf spring suspension system, some type of steel is being used as the major component. For the past decades, high carbon steels, such as 51CrV4 and SUP9, have been the main choice of the lead spring system, reason being their high yield strength, resilience and Cost-effectiveness. These materials have mechanical properties uniform in all directions (Isotropic).

The manufacturing process for steel leaf spring involves hot rolling into desired shape, followed by the heat treatment process like quenching and tempering to achieve the required hardness.

Table 2.1: Baseline Material Properties:

<i>Property</i>	<i>Value (51CrV4 / SUP9)</i>
<i>Density (g/cm³)</i>	~7.85
<i>Young's Modulus (GPa)</i>	210
<i>Tensile Strength (Ultimate)(MPa)</i>	1272
<i>Yield Strength (MPa)</i>	1158
<i>Poisson's Ratio</i>	0.266 - 0.3

3.2. Composite Material System

Composite materials offer a huge leap in material engineering providing a synergetic way of modifying the material properties for the required functions. A composite material is formed by combining two or more

distinct material on the microscopic level. a reinforcement fiber that provides strength and stiffness, and a matrix that binds the fibers together, transfers load between them and protects them from environmental damage.

3.2.1. Reinforced Fibers

- **E-Glass (Electrical Glass):** This is the most common and cost-effective fiber reinforcement. It offers a good balance of strength, stiffness, and chemical resistance, making it an excellent candidate for replacing steel in many applications. E-Glass is a low-alkali glass with a nominal composition of 54% SiO₂, 22% CaO+MgO, 14% Al₂O₃, and 10% B₂O₃. Its primary advantages are its low cost and high electrical insulation properties.²³
- **S-Glass (High-Strength Glass):** A higher-performance variant of glass fiber, S-glass has a higher silica content and provides significantly greater tensile strength and modulus compared to E-glass. It is approximately 10% stiffer than E-glass and exhibits excellent temperature resistance and fatigue life, making it suitable for more demanding applications where performance justifies the increased cost.
- **Carbon Fiber (CFRP):** Carbon fiber reinforced polymers (CFRP) represent the pinnacle of lightweight structural materials. They possess exceptional specific strength and specific stiffness, far exceeding those of metals and glass fibers. This allows for dramatic weight reductions of up to 70% compared to steel.²⁶ However, the high cost of both the raw carbon fiber and the associated manufacturing processes has historically limited its use to high-end automotive and aerospace applications.
- **Aramid Fiber (e.g., Kevlar®):** Aramid fibers are known for their unique combination of high strength, low density, and exceptional toughness and impact resistance. Unlike carbon and glass fibers, which are brittle, aramid fibers exhibit high elongation at break, allowing them to absorb significant energy before fracturing. This property is valuable for applications requiring high damage tolerance. However, Aramids have relatively low compressive strength and are susceptible to degradation from UV radiation and moisture, requiring protective coatings.

3.2.2. Matrix System - Epoxy Resin

For this study, an epoxy resin system is considered as the matrix material for all composite variants. Epoxy resins are a class of thermoset polymers widely used in high-performance composites due to their excellent mechanical properties, superior adhesion to fibers, and good chemical and environmental resistance. The epoxy

matrix serves several critical functions:

- It binds the reinforcement fibers together, maintaining the desired shape and orientation.
- It transfers the applied load to and between the high-strength fibers.
- It protects the fibers from abrasion and environmental degradation.
- It largely determines the composite's compressive strength, interlaminar shear strength (ILSS), and service temperature limits.

The quality of the interface and adhesion between the fiber and the epoxy matrix is paramount to achieving the desired mechanical properties in the final composite part.

3.3. Comparative Material Properties

The selection of the optimal material needed to satisfy the functional requirements of the Leaf Spring assembly involves harmony and compensation for the performance and cost. The table below shows the comparison of material and properties of material used in this study.

Table 2.2: Comparative Material Properties:

<i>Property</i>	<i>Steel (51CrV4)</i>	<i>E-Glass/Epoxy</i>	<i>S-Glass/Epoxy</i>	<i>Carbon/Epoxy</i>	<i>Aramid/Epoxy (Kevlar 49)</i>
<i>Density (g/cm³)</i>	7.85	1.8 - 2.0	2.53	1.5 - 1.8	1.44
<i>Tensile Modulus (GPa)</i>	210	22 - 50	89	120 - 600	124
<i>Tensile Strength (MPa)</i>	1272	170 - 1300	4600	600 - 6000	3600
<i>Elongation at Break (%)</i>	~10-14	1.5 - 3.5	5.2	1.5 - 2.0	2.9

This comparative material properties table shows the significant advantages of using composite materials in terms of specific properties per unit mass. For instance, while carbon fiber's has higher stiffness than steel, the density is one-fourth in comparison, thus providing a much higher stiffness to weight ratio. This is the fundamental reason for the savings in weight without sacrificing performance with composites. The ideology of composite materials with fiber's emerges as a practical substitute for traditional steel and balance out the cost and performance.

4.0. Finite Element Analysis (FEA) Methodology

The performance of several leaf spring designs and materials was systematically assessed through the establishment of a thorough Finite Element Analysis (FEA) technique. FEA eliminates the need for time-consuming and expensive physical prototyping by enabling the virtual testing of several configurations under controlled conditions, offering comprehensive insights into stress distribution, deflection, and dynamic behaviour. A digital model is created, material characteristics are specified, realistic loads and limitations are applied, and the outcomes are analysed as part of the simulation process.

4.1. Geometric Modelling

The foundation of the FEA is the actual digital representation of the leaf spring's geometry. The baseline model was created based on the dimensions of a conventional multi-leaf steel spring. From this baseline a design of experiment (DOE) matrix comprising of 58 unique variation was devised. These variations explore the design matrix by altering key geometric properties.

- **Number of Leaves:** Ranging from Single steel leaf spring, composite single leaf spring to varying number of leaves of composite and Steel (i.e. Mono, 3-layer, 5-layer and 7-layer)
- **Cross-sectional Profile:** The steel spring and composite spring has different geometrical section depends on their functional capability. The Steel leaf spring has a thickness of 12mm and Composite leaf spring has thickness of 24mm. The geometrical profile also varied for difference in width of the leaf to study. Variable cross sectional of the leaf spring along with the material variation will allow for a more efficient distribution of materials and stress along the lead length.
- **Overall Length:** The overall length of the leaf spring is maintained at a fixed and standard point to accommodate mountings.

All the geometric models were created using Computer Aided Design software (i.e., UGNX, SolidWorks) an industry standard practice that ensures high accuracy and seamless integration with FEA tools like Ansys.

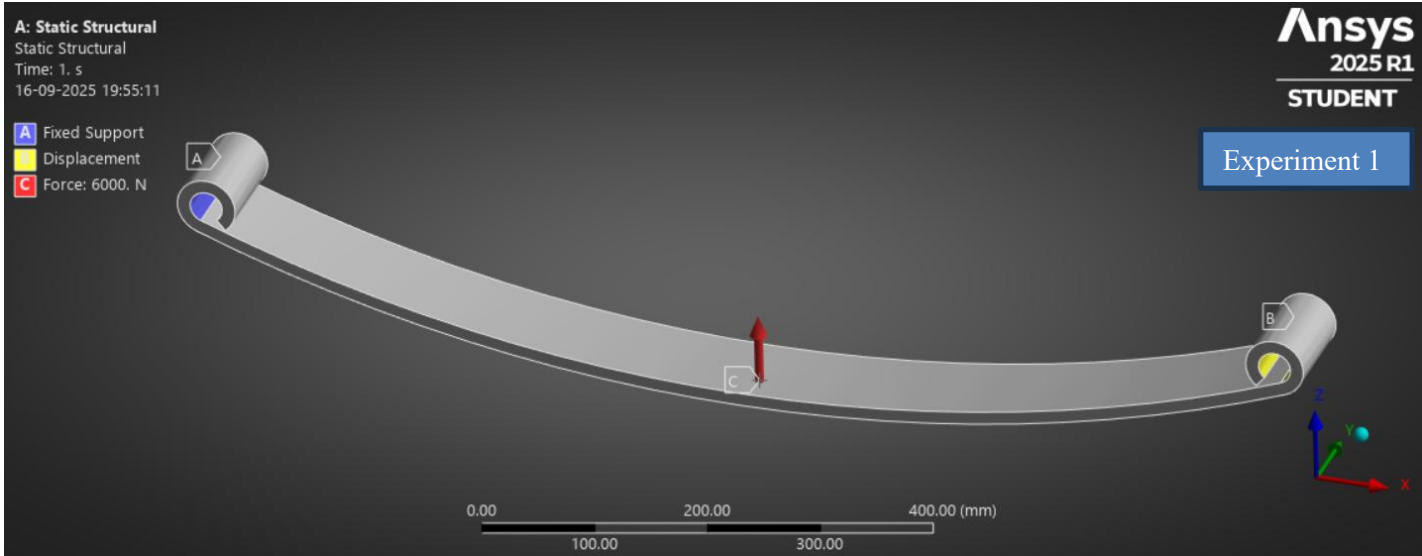


Figure 3.1. Constrained Mono-steel Lead variation

4.2. Material Modelling

Each geometric model was assigned with specific material properties corresponding to the specific material being evaluated (steel, E-glass/epoxy, S-glass/epoxy, carbon/epoxy, or a hybrid combination).

- **Steel:** Modelled as an isotropic material, requiring only Young's Modulus (E) and Poisson's Ratio (ν) to define the elastic behavior of the steel to depict the spring functionality.
- **Composite:** Modeled as orthotropic materials, reflecting their direction-dependent properties. This requires defining elastic moduli (E_x , E_y , E_z), shear moduli (G_{xy} , G_{yz} , G_{xz}), and Poisson's ratios (ν_{xy} , ν_{yz} , ν_{xz}) for each layer or ply.²³ For this study, a primary fiber orientation along the length of the spring (0°) was assumed for mono-leaf designs to maximize bending stiffness and strength, a common and effective approach. For hybrid designs, specific layers within the model were assigned different material properties (e.g., carbon fiber for outer layers, E-glass for the core).

A critical assumption is made in the study is there is a perfect bond between the fibre and matrix within the specified Composite material and between layers in the hybrid configuration. This is a standard simplification in the macro-scale FEA that provided reliable results for overall structural behaviour. The material properties and material considered for the study are tabulated in **Table 2.2: Comparative Material Properties**.

4.3. Analysis Types

Three primary types of analysis were conducted in this study for all the 75 combinations of design variation to provide a comprehensive evaluation of performance.

- **Static Structural Analysis:** This analysis calculates the displacement and stresses within the spring

under the act of loading. Key outputs include maximum deflection and the maximum stress values. For steel, the Von Mises Stress criterion was used to assess the risk of yielding.

- **Modal Analysis:** This analysis determines the natural frequency and corresponding mode shapes of the leaf spring. The primary goal is to ensure the frequency of the leaf spring is enough to sustain the frequency of the road bumps.

Systematically applying the FEA methods for all the 75 variations, a comprehensive database of performance metrics was generated, forming basis for the comparative analysis and final design selection.

4.4. Boundary Condition:

To accurately simulate the leaf spring for real-world condition and function, the boundary condition as assumed as per the below mentioned list.

- **Constraints:** To imitate the real-life hanging part of the leaf spring. Fixed constraints are provided to the one eye region (“Fixed End”) constraining all degrees of freedom, representing a pivot point. The other end (“Shackle Eye”) of the leaf spring constrained for vertical (Y) and lateral (Z) directions and longitudinal (X) direction translation is set free.
- **Load Application:** The load, representing the vehicle weight and dynamic forces from terrain input, was applied to the central area of the spring where axle seat is located. The magnitude of the load was based on the “Full Bump” condition specified in the objective, representing a loading scenario.

5.0. Simulation Results and Discussion

The comprehensive Finite Element Analysis (FEA) of 75 distinct leaf spring configurations will yield a rich dataset, enabling a thorough evaluation of the interplay between structural geometry and material selection. This section presents and discusses the key findings from these simulations, focusing on the influence of design parameters and comparing the performance of composite materials against the traditional steel baseline.

5.1. Influence of Structural Geometry

The geometric design of a leaf spring is as critical as the material from which it is made. The simulations explored variations in cross-sectional profile (constant vs. variable) and the number of leaves, revealing significant impacts on performance.

- **Effect of Number of Leaves:** The transition from traditional mono-leaf structure in the suspension system

to multiple layers of composite material leaves tends to improve the deformation properties and has less maximum equivalent stress in compared with the single leaf and has lower shear between the leaves spring system. Having multiple leaf arrangements in the place of the mono-leaf arrangements will have shortcomings in weight but the forthcoming of better deformation properties and mechanical structural properties.

- **Effect of Material Variation:** The transition from traditional method of single material leaf assembly to multiple variation of the material arrangements is required for the improvement of the structural integrity of the leaf spring assembly and to improve the weight reduction properties. The ideology of the multiple material usage in different variation assembly will be a great addition to the existing method of similar material variation leaf spring assembly in weight reduction and improve efficiency of the leaf spring damping properties and improve suspension system.

Discussion below shows the simulation data for different iteration of **same materials** leaf arrangements for comparison of the deformation, Maximum Equivalent stress, Maximum shear stress and Nodal Frequency Node-1.

Steel:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	Maximum			Modal Frequency - MODE1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress - Mpa	
STEEL	90	12	1	Single Materials	EXP 0	10.66	6.45	242.89	26.29	55.12
STEEL	60	12	3	All Same Material	EXP 2	13.59	2.45	211.68	58.69	80.87
STEEL	90	12	3	All Same Material	EXP 3	20.38	1.63	141.84	39.80	81.11
STEEL	60	12	5	All Same Material	EXP 4	20.43	0.88	123.34	12.60	105.43
STEEL	90	12	5	All Same Material	EXP 5	30.65	0.58	80.29	10.28	105.66
STEEL	60	12	7	All Same Material	EXP 6	27.37	0.43	85.14	8.88	119.78
STEEL	90	12	7	All Same Material	EXP 7	41.06	0.28	56.43	6.13	124.89

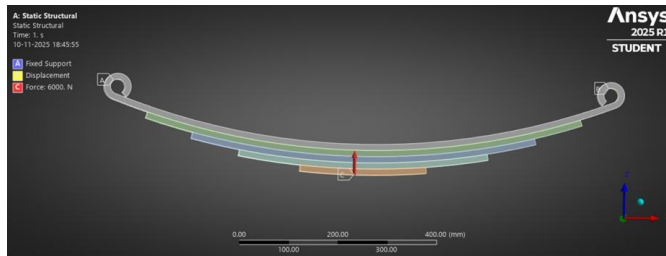
Table 5.1 – Comparative Simulation Data of Steel(All Material) Leaf Spring arrangement

From table 5.1. We can see the number of leaves influences the structural properties and vibrational properties for All Steel Materials Leaf Spring combination. In this case,

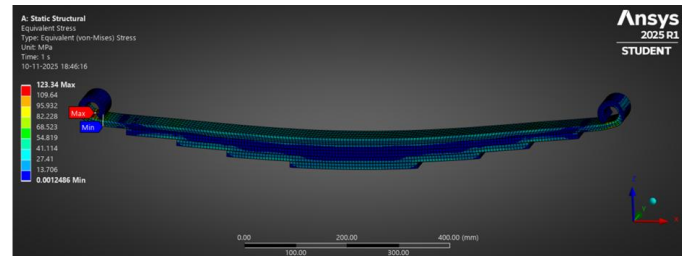
- **Best Performance:** EXP 7 (90mm Width, 7 Leaves)
 - Pros: This is the most durable and stiffest steel option. It has the lowest deformation (0.28 mm) and the lowest equivalent stress (56.43 Mpa).
 - Cons: It is extremely heavy (41.06 Kg).
- **Optimum (Balanced):** EXP 4 (60mm, 5 Leaves)
 - Pros: This arrangement offers a good compromise. It cuts the weight in half (20.43 Kg)

compared to the "Best" option while maintaining respectable performance (0.88 mm deformation, 123.34 Mpa stress).

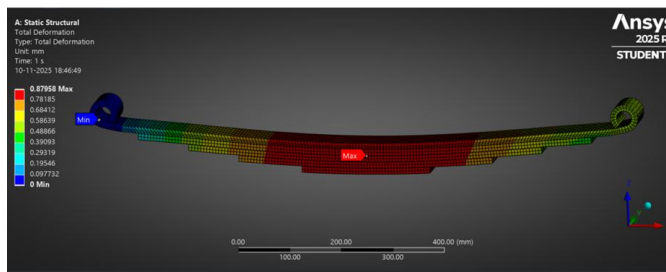
Figure 5.1. Optimum Single Material (Steel) Arrangement



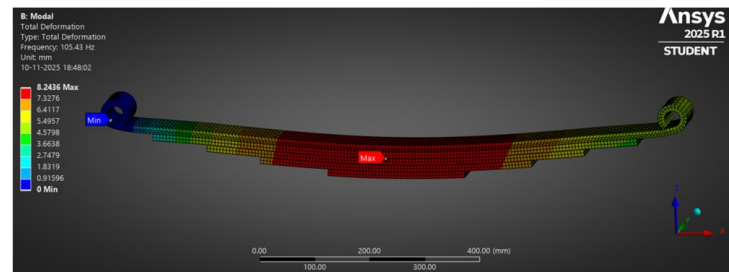
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

E-Glass/Epoxy:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	Maximum			Modal Frequency - MODE1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress - Mpa	
E-GLASS	90	24	1	Single Materials	EXP 1	6.48	4.02	83.37	9.91	97.14
E-GLASS	60	24	3	All Same Material	EXP 2_2	8.31	1.57	547.19	29.13	129.04
E-GLASS	90	24	3	All Same Material	EXP 3_2	12.47	0.87	38.19	4.50	144.20
E-GLASS	60	24	5	All Same Material	EXP 4_2	11.98	0.54	39.01	4.11	129.10
E-GLASS	90	24	5	All Same Material	EXP 5_2	17.97	0.36	23.88	2.69	170.14
E-GLASS	60	24	7	All Same Material	EXP 6_2	15.31	0.31	31.10	6.45	102.98
E-GLASS	90	24	7	All Same Material	EXP 7_2	22.96	0.30	144.47	11.98	114.81

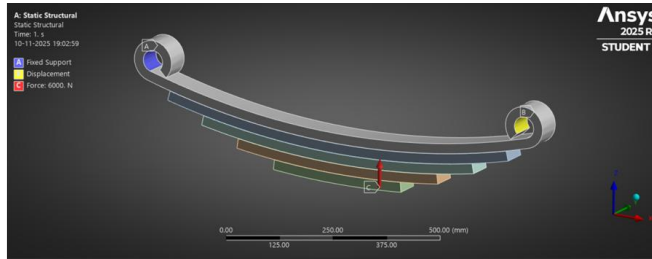
Table 5.2 – Comparative Simulation Data of E-Glass/Epoxy (All Material) Leaf Spring arrangement

From the table 5.2. We can see the number of leaves influences the structural properties and vibrational properties for E-Glass/Epoxy. In this case,

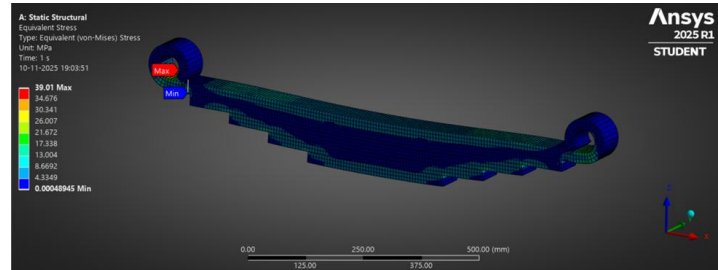
- **Best Performance: EXP 5_2 (90mm, 5 Leaves)**
 - Pros: This arrangement has the lowest equivalent stress (23.88 Mpa) and very low deformation (0.36 mm), making it the most durable E-Glass option.
 - Cons: It is the heaviest E-Glass design (17.97 Kg).
- **Optimum (Balanced): EXP 4_2 (60mm, 5 Leaves)**

- Pros: This is an excellent balanced choice. It's very light (11.98 Kg) and has performance metrics (0.54 mm deformation, 39.01 Mpa stress) that are still significantly better than even the best steel option.

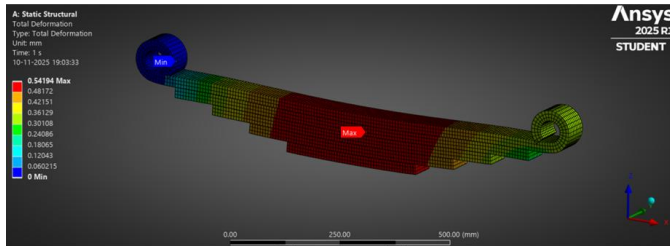
Figure 5.2. Optimum Single Material (E-Glass/Epoxy) Arrangement



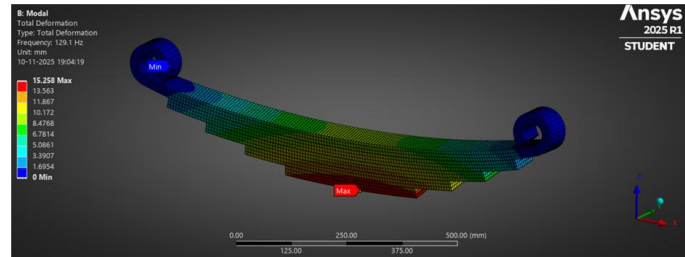
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

S-Glass/Epoxy:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	Maximum			Modal Frequency - MODE1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress - Mpa	
S-GLASS	90	24	1	Single Materials	EXP 1	6.17	3.30	83.54	8.99	109.93
S-GLASS	60	24	3	All Same Material	EXP 2 2	7.92	1.29	548.22	30.37	146.23
S-GLASS	90	24	3	All Same Material	EXP 3 2	11.88	0.71	38.38	4.08	163.12
S-GLASS	60	24	5	All Same Material	EXP 4 2	11.41	0.44	39.10	3.71	146.78
S-GLASS	90	24	5	All Same Material	EXP 5 2	17.11	0.30	24.00	2.80	193.43
S-GLASS	60	24	7	All Same Material	EXP 6 2	14.58	0.26	31.21	6.64	117.26
S-GLASS	90	24	7	All Same Material	EXP 7 2	21.87	0.25	145.10	12.12	130.46

Table 5.3 – Comparative Simulation Data of S-Glass/Epoxy (All Material) Leaf Spring arrangement

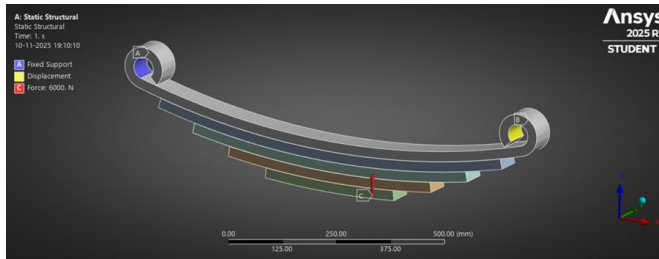
From table 5.3. We can see the number of leaves influences the structural properties and vibrational properties for S-Glass/Epoxy. In this case,

- **Best Performance: EXP 5_2 (90mm, 5 Leaves)**

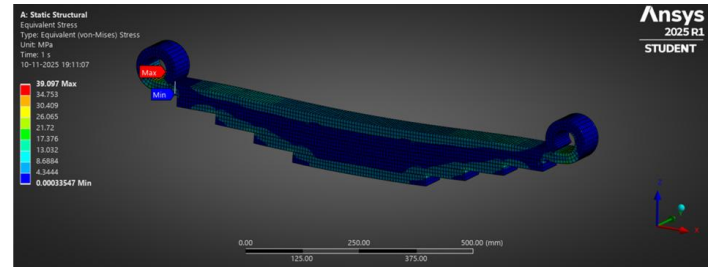
- Pros: This is the clear performance winner. It has the lowest equivalent stress (24.00 Mpa) and very low deformation (0.30 mm).

- Cons: It is the second heaviest S-Glass option (17.11 Kg).
- **Optimum (Balanced): EXP 4_2 (60mm, 5 Leaves)**
 - Pros: This design is exceptionally light (11.41 Kg) and delivers fantastic performance (0.44 mm deformation, 39.10 Mpa stress). It weighs almost half as much as the best-performing steel spring and outperforms it in every way.

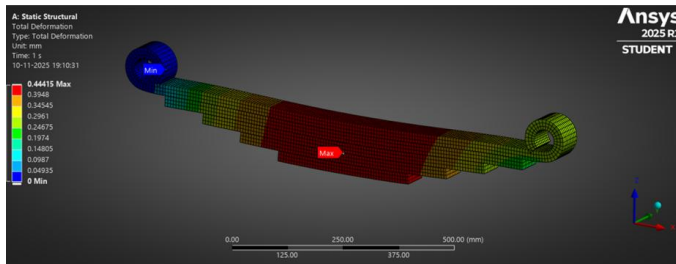
Figure 5.3. Optimum Single Material (S-Glass/Epoxy) Arrangement



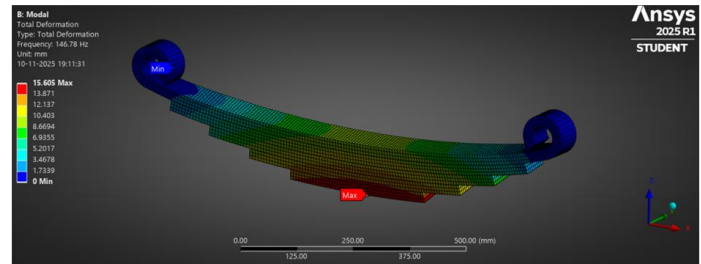
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Aramid/Epoxy:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	Maximum			Modal Frequency - MODE1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress - Mpa	
ARAMID REINFORCED FIBRE	90	24	1	Single Materials	EXP 1	4.26	2.37	83.01	11.68	156.30
ARAMID REINFORCED FIBRE	60	24	3	All Same Material	EXP 2_2	5.46	0.93	545.73	26.85	207.12
ARAMID REINFORCED FIBRE	90	24	3	All Same Material	EXP 3_2	8.19	0.51	37.87	5.32	232.09
ARAMID REINFORCED FIBRE	60	24	5	All Same Material	EXP 4_2	7.87	0.32	38.93	4.88	206.31
ARAMID REINFORCED FIBRE	90	24	5	All Same Material	EXP 5_2	11.81	0.21	23.68	3.14	271.45
ARAMID REINFORCED FIBRE	60	24	7	All Same Material	EXP 6_2	10.06	0.19	30.95	6.02	164.30
ARAMID REINFORCED FIBRE	90	24	7	All Same Material	EXP 7_2	15.09	0.18	143.23	11.71	183.59

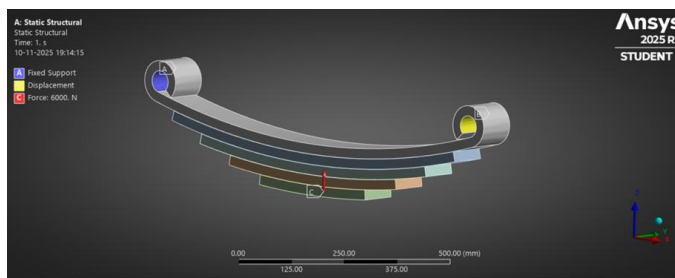
Table 5.4 – Comparative Simulation Data of Aramid/Epoxy (All Material) Leaf Spring arrangement

From table 5.4. We can see the number of leaves influences the structural properties and vibrational properties for Aramid/Epoxy. In this case,

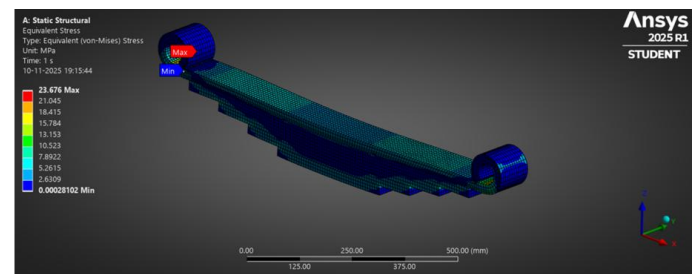
- **Best Performance: EXP 5_2 (90mm, 5 Leaves)**

- Pros: This is the most durable spring in the entire study. It has the lowest equivalent stress (23.68 Mpa) of any material and exceptionally low deformation (0.21 mm).
- Cons: It is one of the heavier Aramid options (11.81 Kg), but it's still lighter than most other materials.
- **Optimum (Balanced): EXP 5_2 (60mm, 5 Leaves)**
 - Pros: This is arguably the best "real-world" design. It is incredibly light (7.87 Kg) and has performance (0.32 mm deformation, 38.93 Mpa stress) that is still elite. It provides a near-perfect balance of weight savings and durability.

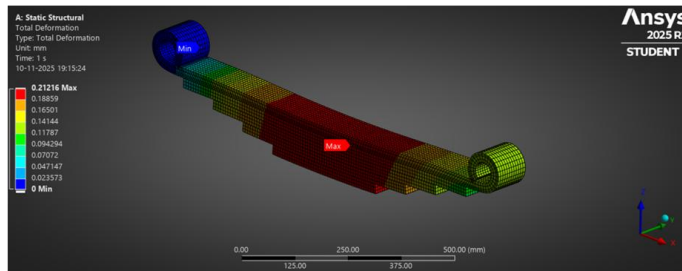
Figure 5.4. Optimum Single Material (Aramid Reinforced Epoxy) Arrangement



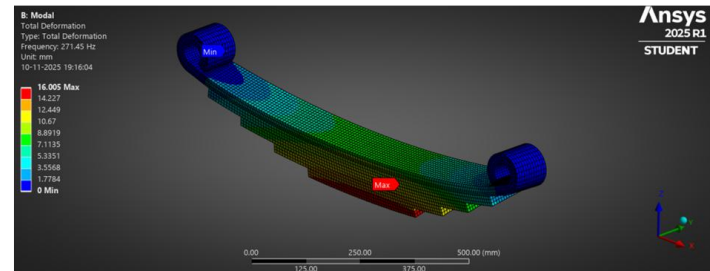
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Carbon Fiber Reinforced:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	Maximum			Modal Frequency - MODE1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress - Mpa	
CARBON REINFORCED FIBRE	90	24	1	Single Materials	EXP 1	4.93	1.34	83.37	9.91	192.90
CARBON REINFORCED FIBRE	60	24	3	All Same Material	EXP 2 2	6.33	0.52	547.19	29.13	256.37
CARBON REINFORCED FIBRE	90	24	3	All Same Material	EXP 3 2	9.50	0.29	38.19	4.50	286.20
CARBON REINFORCED FIBRE	60	24	5	All Same Material	EXP 4 2	9.13	0.18	39.01	4.11	256.92
CARBON REINFORCED FIBRE	90	24	5	All Same Material	EXP 5 2	13.69	0.12	23.88	2.69	338.04
CARBON REINFORCED FIBRE	60	24	7	All Same Material	EXP 6 2	11.66	0.10	31.10	6.45	205.14
CARBON REINFORCED FIBRE	90	24	7	All Same Material	EXP 7 2	17.50	0.10	144.47	11.98	228.29

Table 5.5 – Comparative Simulation Data of Carbon Fiber Reinforced Epoxy (All Material) Leaf Spring arrangement

From table 5.5. We can see the number of leaves influences the structural properties and vibrational

properties for Carbon Fiber reinforced. In this case,

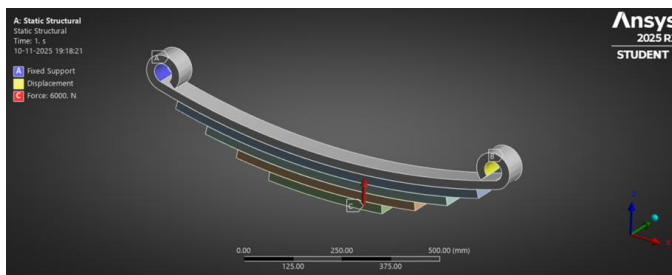
- **Best Performance / Optimum (Balanced): EXP 4_2 (60mm, 5 Leaves)**

- Pros: For Carbon, one design is the clear winner for both categories. It has the lowest equivalent stress (23.88 Mpa), extremely low deformation (0.18 mm), and a very high modal frequency, all while being remarkably light (9.13 Kg).

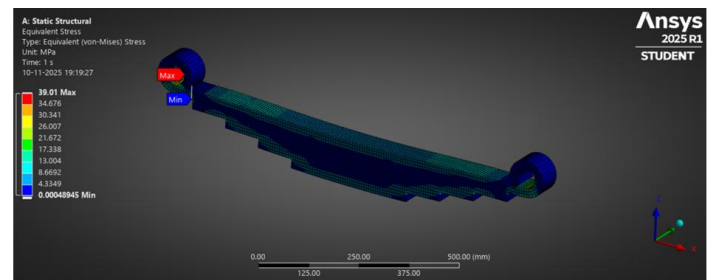
Note: The (60mm, 7 Leaves) option has the absolute lowest deformation (0.10 mm), but it is heavier (11.66 Kg) and has higher stress, making the (60mm, 5 Leaves) a better all-around choice.

Here is a combined comparison of all materials to find the absolute best arrangements across the entire study of Same Materials.

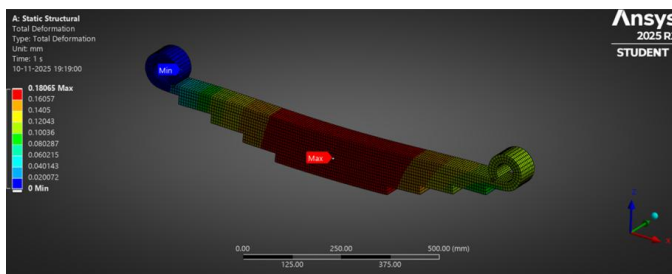
Figure 5.5. Optimum Single Material (Carbon Fiber Reinforced Epoxy) Arrangement



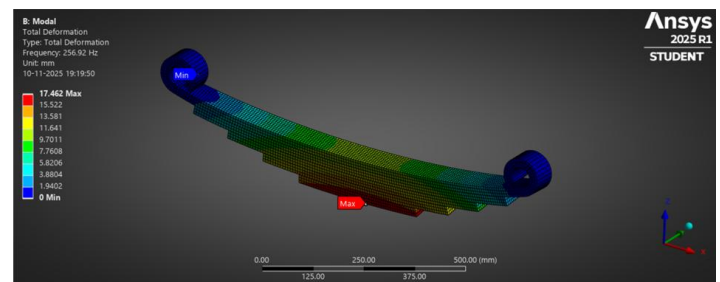
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Best Overall Performance (Most Durable & Stiff)

This category is for the arrangement that provides the absolute best performance, prioritizing low stress and low deformation, even if it isn't the lightest.

Aramid/Epoxy (90mm, 5 Leaves, EXP 5_2) This arrangement is the most durable and reliable design in the entire table.

Weight: 11.81 Kg

Equivalent Stress: 23.68 Mpa (The lowest of all 35 experiments)

Deformation: 0.21 mm (Extremely low)

Modal Frequency: 271.45 Hz (Excellent vibration resistance)

Best "Optimum" Balanced Design (Best Performance-to-Weight)

This is the arrangement that provides the best all-around combination of low weight, low stress, and low deformation.

Carbon Fiber Reinforced Epoxy (60mm, 5 Leaves, EXP 4_2) This design is arguably the true optimum for a real-world application. It is incredibly light while delivering elite, near-best-in-class performance.

Weight: 9.13 Kg (Extremely light)

Equivalent Stress: 23.88 Mpa (Second lowest in the study)

Deformation: 0.18 mm (Third lowest in the study)

Shear Stress: 2.69 Mpa (The lowest of all 35 experiments) **Lightest Best for Low Weight (Lightest Overall)**

This category is for the arrangement where minimizing weight is the single most important goal.

Aramid/Epoxy (90mm, 1 Leaf, EXP 1_2) This arrangement is, by a significant margin, the lightest spring in the entire study.

Weight: 4.26 Kg (The lowest of all 35 experiments (Same Materials))

Performance: Its performance (2.37 mm deformation, 83.01 Mpa stress) is average compared to other composites, but it is still lighter and performs better than the best-balanced steel spring (EXP 4).

Note: These Above results are of the same materials used for leaf spring. Below is the data for hybrid arrangements.

5.2. Hybrid Arrangements Material integration

The data in this table moves beyond single-material designs to explore hybrid integration, specifically combining advanced composites (like Carbon and Glass Fibre) with traditional Steel.

The engineering goal here is to create a new, synergistic material that captures the best qualities of both components. By layering or sandwiching these materials, the aim is to:

- Retain the proven strength and cost-effectiveness of steel.
- Integrate the high-performance properties of composites, such as low weight, high stiffness, and superior vibration damping.

This analysis will show how these different hybrid arrangements trade-off weight, stiffness (deformation), and durability (stress) to find an even better "optimum" design.

E-Glass Epoxy+ Steel:

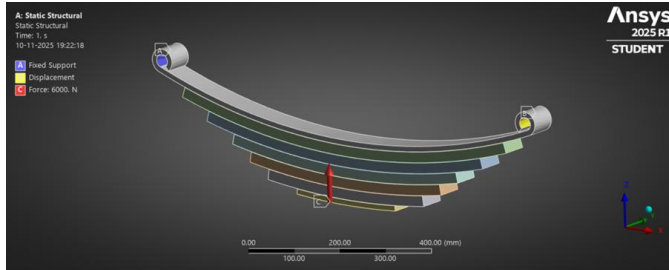
Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	MAXIMUM			Frequency Mode 1 (Hz)
							Deformstion (mm)	Equivalent Stress (Mpa)	Shear Stress (Mpa)	
E-GLASS + Steel	60	C=24, S=12	3	Alternate Layers	EXP 2_3	16.90	1.46	159.36	17.69	144.51
E-GLASS + Steel	90	C=24, S=12	3	Alternate Layers	EXP 3_3	18.57	0.91	109.95	10.97	110.99
E-GLASS + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 4_3	15.01	0.57	106.17	10.67	135.15
E-GLASS + Steel	60	C=24, S=12	5	Alternate Layers	EXP 4_4	16.84	0.61	106.81	10.77	132.26
E-GLASS + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 5_3	22.52	0.38	68.17	8.36	150.42
E-GLASS + Steel	90	C=24, S=12	5	Alternate Layers	EXP 5_4	25.26	0.41	68.23	6.76	138.18
E-GLASS + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 6_3	18.40	0.36	92.79	11.74	103.05
E-GLASS + Steel	60	C=24, S=12	7	Alternate Layers	EXP 6_4	22.56	0.29	72.26	7.13	111.90
E-GLASS + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 7_3	27.61	0.24	59.36	6.87	132.48
E-GLASS + Steel	90	C=24, S=12	7	Alternate Layers	EXP 7_4	33.83	0.19	46.10	4.53	146.38

Table 5.6 – Comparative Simulation Data of E-Glass Epoxy Hybrid Leaf Spring arrangements

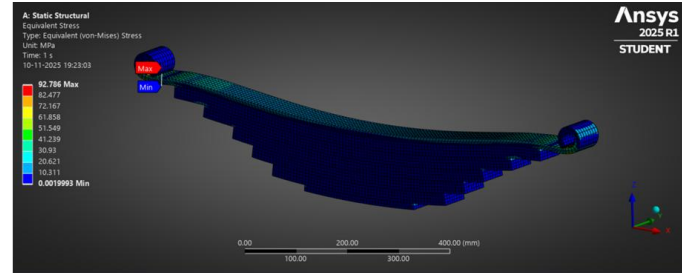
From table 5.6. We can see the number of leaves and the hybrid arrangement of the E-Glass Epoxy and Steel.

- Best Performance: EXP 7_4 (90mm, 7 Alternate Layers)
 - Pros: This is the clear performance champion. It has the **lowest deformation (0.193 mm)** and the **lowest equivalent stress (46.10 Mpa)** of all the E-Glass options.
 - Cons: This performance comes at a cost, as it is the **heaviest arrangement (33.83 Kg)** by a significant margin.
- Optimum (Balanced): EXP 6_3 (60mm, 7 Sandwich Layers)
 - Pros: This is an excellent balanced design. It's relatively light (**18.40 Kg**) but offers very high stiffness for its weight (only **0.356 mm deformation**). It provides a massive performance jump over the lighter 5-leaf options.
 - Cons: Its equivalent stress (92.78 Mpa) is good but not as low as some heavier arrangements.

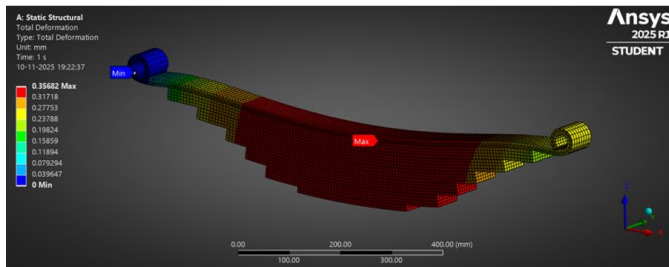
Figure 5.6. Optimum Hybrid Material (E-Glass Epoxy+ Steel) Arrangement



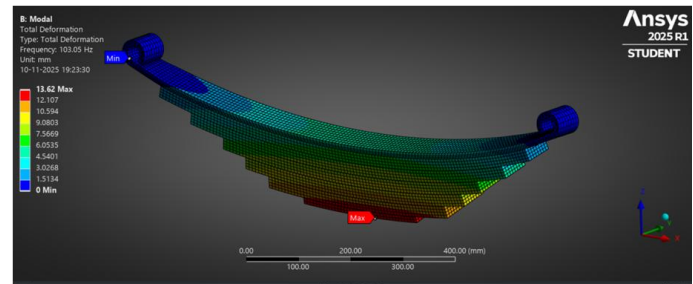
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

S-Glass Epoxy+ Steel:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	MAXIMUM			Frequency Mode 1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress (Mpa)	
S-GLASS + Steel	60	C=24, S=12	3	Alternate Layers	EXP 2_3	16.86	1.41	158.00	17.54	145.01
S-GLASS + Steel	90	C=24, S=12	3	Alternate Layers	EXP 3_3	18.40	0.87	107.65	10.74	113.80
S-GLASS + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 4_3	14.70	0.53	102.09	10.25	139.71
S-GLASS + Steel	60	C=24, S=12	5	Alternate Layers	EXP 4_4	16.63	0.58	103.99	10.48	135.28
S-GLASS + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 5_3	22.06	0.35	65.50	8.17	158.70
S-GLASS + Steel	90	C=24, S=12	5	Alternate Layers	EXP 5_4	24.95	0.39	66.35	6.57	142.72
S-GLASS + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 6_3	17.94	0.33	89.72	12.66	106.76
S-GLASS + Steel	60	C=24, S=12	7	Alternate Layers	EXP 6_4	22.26	0.28	69.99	6.91	115.09
S-GLASS + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 7_3	26.91	0.22	57.33	7.62	137.31
S-GLASS + Steel	90	C=24, S=12	7	Alternate Layers	EXP 7_4	33.39	0.18	44.55	4.85	150.82

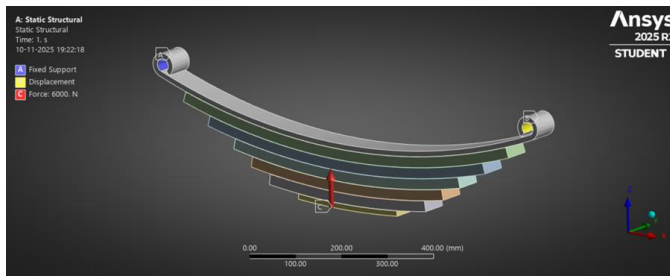
Table 5.7 – Comparative Simulation Data of S-Glass Epoxy Hybrid Leaf Spring arrangement

From the table 5.7. We can see the number of leaves and the hybrid arrangement of the S-Glass Epoxy and Steel.

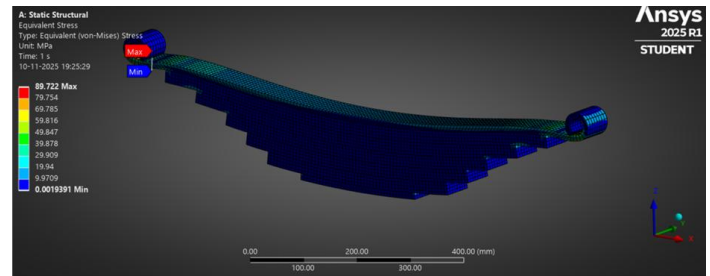
- Best Performance: EXP 7_4 (90mm, 7 Alternate Layers)
 - Pros: The clear performance winner for S-Glass. It boasts the lowest deformation (0.18 mm) and the lowest equivalent stress (44.55 Mpa).
 - Cons: This top-tier performance comes with the **highest weight (33.39 Kg)**.

- Optimum (Balanced): EXP 6_3 (60mm, 7 Sandwich Layers)
 - Pros: This arrangement is an excellent balanced choice. It's very light (**17.94 Kg**) but delivers fantastic stiffness for its weight (only **0.33 mm deformation**).
 - Cons: Its equivalent stress (89.72 Mpa) is good, but not as low as the heavier 5-leaf and 7-leaf options.

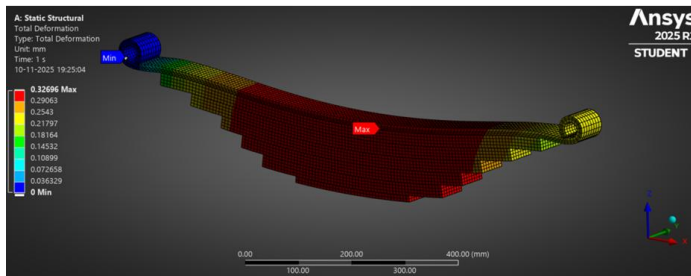
Figure 5.7. Optimum Hybrid Material (S-Glass Epoxy+ Steel) Arrangement



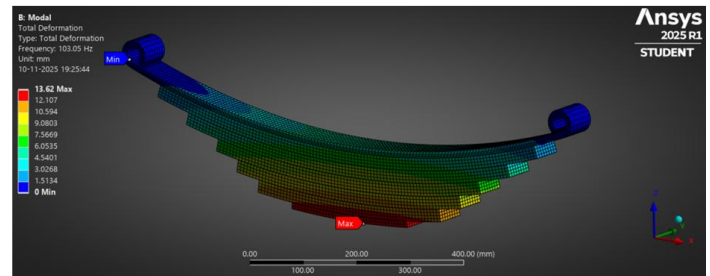
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

ARAMID EPOXY + Steel:

Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	MAXIMUM			Frequency Mode 1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress (Mpa)	
ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	3	Alternate Layers	EXP 2_3	16.64	1.33	155.57	17.27	147.40
ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	3	Alternate Layers	EXP 3_3	17.33	0.83	104.34	10.42	121.31
ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 4_3	12.81	0.46	96.17	9.63	157.24
ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	5	Alternate Layers	EXP 4_4	15.38	0.53	99.75	10.03	144.94
ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 5_3	19.21	0.30	61.66	8.19	183.46
ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	5	Alternate Layers	EXP 5_4	23.06	0.35	63.51	6.28	155.51
ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 6_3	15.05	0.29	85.38	14.68	122.48
ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	7	Alternate Layers	EXP 6_4	20.45	0.25	66.51	6.56	124.37
ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 7_3	22.58	0.19	54.39	9.11	157.67
ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	7	Alternate Layers	EXP 7_4	30.67	0.17	42.14	4.92	163.35

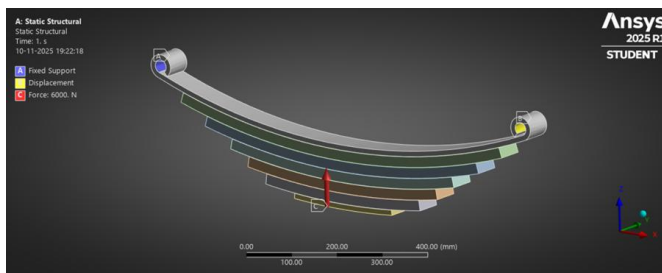
Table 5.8 – Comparative Simulation Data of Aramid Epoxy Hybrid Leaf Spring arrangement

From table 5.8. We can see the number of leaves and the hybrid arrangement of the Aramid Reinforced Fiber Epoxy and Steel.

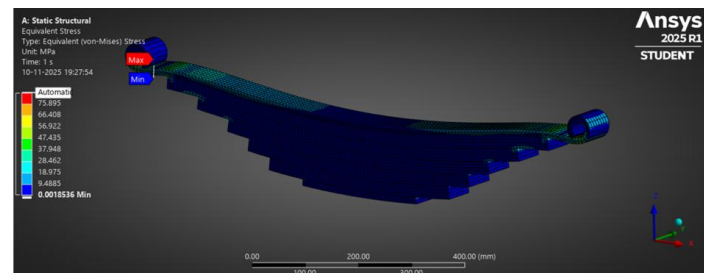
- Best Performance: EXP 7_4 (90mm, 7 Alternate Layers)

- Pros: This is the most robust Aramid hybrid. It has the **lowest deformation (0.17 mm)** and the **lowest equivalent stress (42.14 Mpa)** in this group.
- Cons: It is the **heaviest arrangement (30.67 Kg)**, sacrificing weight for maximum durability.
- Optimum (Balanced): EXP 6_3 (60mm, 7 Sandwich Layers)
 - Pros: This is an exceptionally balanced design. It is extremely light at **15.05 Kg** (the second-lightest option) while delivering elite stiffness (only **0.29 mm deformation**).
 - Cons: Its equivalent stress (85.38 Mpa) is higher than the heavier options, but this is a very good trade-off for the significant weight savings.

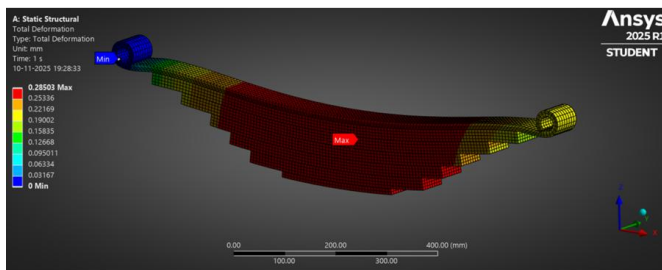
Figure 5.8. Optimum Hybrid Material (Aramid Reinforced + Steel) Arrangement



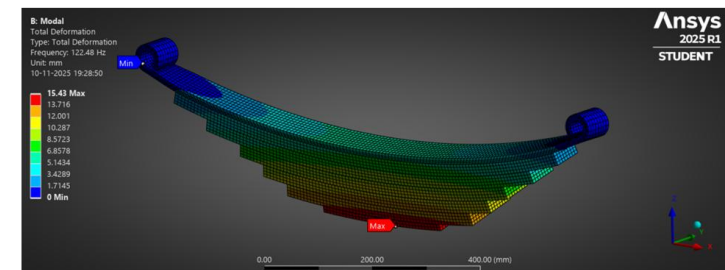
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

CARBON-FIBER REINFORCED EPOXY + Steel:

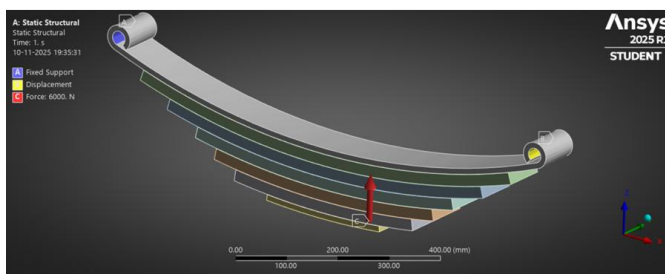
Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Experiment	Weight(Kg)	MAXIMUM			Frequency Mode 1 (Hz)
							Deformation (mm)	Equivalent Stress (Mpa)	Shear Stress (Mpa)	
CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	3	Alternate Layers	EXP 2_3	16.72	1.18	151.19	16.78	147.55
CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	3	Alternate Layers	EXP 3_3	17.71	0.76	103.92	35.58	125.16
CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 4_3	13.48	0.37	90.68	20.14	158.17
CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	5	Alternate Layers	EXP 4_4	15.82	0.46	93.89	30.26	148.83
CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	EXP 5_3	20.22	0.24	57.50	5.67	198.13
CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	5	Alternate Layers	EXP 5_4	23.73	0.30	60.29	5.96	164.90
CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 6_3	16.08	0.23	111.79	37.16	122.17
CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	7	Alternate Layers	EXP 6_4	21.09	0.21	61.81	6.09	128.97
CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	EXP 7_3	24.12	0.15	51.56	4.90	156.75
CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	7	Alternate Layers	EXP 7_4	31.64	0.14	38.90	3.69	170.69

Table 5.9 – Comparative Simulation Data of Carbon Fiber Reinforced Epoxy Hybrid Leaf Spring arrangement

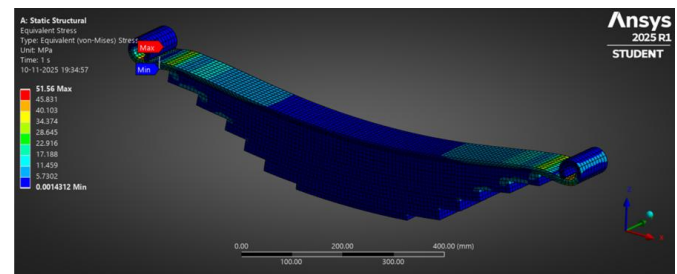
From table 5.9. We can see the number of leaves and the hybrid arrangement of the Aramid Reinforced Fiber Epoxy and Steel.

- Best Performance: EXP 7_4 (90mm, 7 Alternate Layers)
 - Pros: This is the undisputed performance champion of all 10 arrangements. It has the **lowest deformation (0.14 mm)** and the **lowest equivalent stress (38.90 Mpa)**.
 - Cons: It is the **heaviest design (31.64 Kg)**, sacrificing weight for pure strength.
- Optimum (Balanced): EXP 7_3 (90mm, 7 Sandwich Layers)
 - Pros: This is an outstanding balanced design. It delivers performance that is *almost identical* to the "Best" option, with the **second-lowest deformation (0.15 mm)** and **second-lowest stress (51.56 Mpa)**.
 - Cons: At 24.12 Kg, it is still a heavy spring, but it saves 7.5 Kg compared to the absolute best performer.

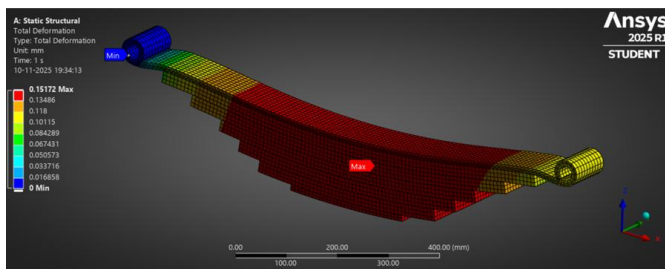
Figure 5.9. Optimum Hybrid Material (Carbon Fiber Reinforced + Steel) Arrangement



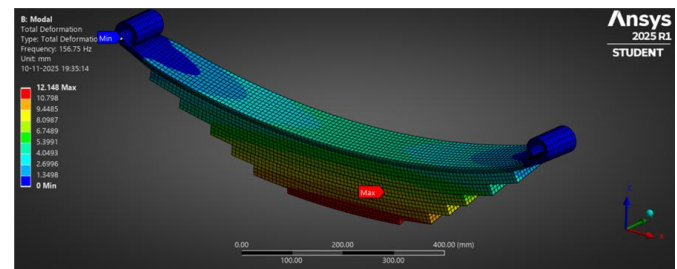
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Here is a combined comparison of all materials to find the absolute best arrangements across the entire study of Hybrid Arrangements.

Best Overall Performance (Most Durable & Stiff):

This category is for the arrangement that provides the absolute best performance, prioritizing low stress and low deformation, even if it isn't the lightest.

CARBON FIBER REINFORCED EPOXY (90mm, 7 Alternate Layers, EXP 7_4) This arrangement is the undisputed performance champion, offering the highest strength and stiffness in the study.

Weight: 31.64 Kg

Equivalent Stress: 38.90 Mpa (The lowest of all 40 hybrid experiments)

Deformation: 0.14 mm (The lowest of all 40 hybrid experiments)

Shear Stress: 3.69 Mpa (The lowest of all 40 hybrid experiments)

Best "Optimum" Balanced Design (Best Performance-to-Weight):

This is the arrangement that provides the best all-around combination of low weight, low stress, and low deformation.

ARAMID R (60mm, 7 Sandwich Layers, EXP 6_3) This design is the best-balanced choice, offering a massive leap in performance (low deformation) over the lightest models for only a small weight penalty.

Weight: 15.05 Kg (Extremely light for a 7-leaf spring)

Equivalent Stress: 85.38 Mpa (A good, safe value for its weight)

Deformation: 0.29 mm (Excellent stiffness, far superior to the lightest options)

Lightest Best for Low Weight (Lightest Overall):

This category is for the arrangement where minimizing weight is the single most important goal.

ARAMID R (60mm, 5 Sandwich Layers, EXP 4_3) This arrangement is, by a significant margin, the lightest spring in the entire hybrid study.

Weight: 12.81 Kg (The lowest of all 40 hybrid experiments)

Performance: Its performance (0.46 mm deformation, 96.17 Mpa stress) is a clear compromise, but it is the best choice when mass is the only critical factor

6.0. Optimal Design Selection and Validation

The objective of this analysis is to establish a systematic, data-driven methodology for selecting an optimal leaf spring design from a comprehensive set of alternatives. The design space under consideration encompasses 75 unique leaf spring configurations, which were evaluated using Finite Element Analysis (FEA). This extensive design of experiments (DOE) provides the necessary data to perform a rigorous trade-

off study. The configurations were generated by systematically varying four key design parameters, as detailed in the experimental matrix.

The parameters defining the design space are as follows:

1. **Material System:** The study evaluates a range of materials, from the traditional incumbent, 51CrV4 spring steel, to several advanced composite systems. These include monolithic composites made from E-Glass/Epoxy, S-Glass/Epoxy, and Aramid/Epoxy. Furthermore, hybrid configurations combining steel and composite layers are explored to leverage the benefits of both material classes.
2. **Geometric Parameters:** Two fundamental geometric variables were considered: the width of the leaf spring (60 mm and 90 mm) and the thickness of individual leaves. A distinction is made based on material type, with steel leaves having a nominal thickness of 12 mm and composite leaves having a thickness of 24 mm to account for the difference in material modulus and strength.
3. **Number of Leaves:** To investigate the effect of spring architecture on performance, configurations with 1, 3, 5, and 7 leaves were simulated. This range covers mono-leaf designs, often favored for ride comfort, to multi-leaf stacks designed for higher load capacities.
4. **Arrangement Type:** For designs with multiple leaves and hybrid material systems, the stacking arrangement is a critical variable. The study includes three distinct arrangements: "All Same Material" for monolithic stacks, "Alternate Layers" for interleaved hybrid designs, and "Sandwich (Steel-Comp-Steel)" for configurations where a composite core is protected by outer steel layers.

The complexity arising from these 75 distinct alternatives necessitates a structured decision-making framework. A simple comparison of individual performance metrics is insufficient to identify a truly optimal design that balances multiple, often conflicting, engineering requirements. The Pugh Concept Selection Method, detailed in subsequent sections, provides the necessary rigor for this task.

To facilitate the analysis, the design parameters from the experimental matrix were merged with the corresponding simulation output data. The Exp No column serves as the unique identifier or primary key to link each design configuration to its calculated performance metrics. This consolidation creates a master dataset that forms the single source of truth for the entire evaluation process.

The key performance indicators (KPIs) derived from the FEA simulations are critical for evaluating the efficacy of each design. These metrics are defined as follows :

- **Weight (Kg):** The total mass of the leaf spring assembly. This is a primary indicator for evaluating unsprung mass, which has significant implications for vehicle dynamics, handling, and fuel efficiency.

- **Deformation MAX (mm):** The maximum vertical displacement of the spring under a standardized static load. This metric is an inverse measure of the spring's stiffness or spring rate. A lower deformation value corresponds to a higher stiffness.
- **Equivalent Stress (von Mises) MAX (MPa):** The peak von Mises stress experienced anywhere within the spring assembly under load. This is the most critical metric for assessing structural integrity and predicting failure by yielding (in ductile materials like steel) or fracture.
- **Shear MAX (MPa):** The maximum shear stress within the assembly. In composite and hybrid designs, this metric is particularly important for evaluating the risk of interlaminar shear failure, a common failure mode in laminated materials.
- **Frequency (Hz) MODE1-MODE6:** The first six natural frequencies of the spring assembly. The first natural frequency (MODE1) is especially important for assessing the system's dynamic performance and its susceptibility to resonance from external excitations, such as road inputs or engine vibrations.

6.1. Pugh Matrix Criteria and Weighting

The selection of appropriate evaluation criteria and the assignment of their respective weights are the most critical intellectual steps in the Pugh analysis. These choices must directly reflect the project's primary objectives and engineering priorities. The criteria for this study are derived from engineering first principles, the stated goals of replacing steel with composites, and the available performance data.

Five key criteria have been defined. Each is assigned a weight, with the total sum of weight equaling 100%. The rationale for each criterion and its assigned weight is detailed below and summarized in the table below.

Criterion	Definition	Rationale	Data Source(s)	Weight
Weight Reduction	Minimization of total component mass.	Core objective for using composites; improves handling and fuel efficiency.	Weight (Kg) from Material densities from.	25%
Structural Integrity	Factor of Safety against material failure.	Paramount concern for safety and reliability of a critical component.	Equivalent Stress MAX (MPa) from ; Material strengths from.	30%
Stiffness / Performance	Resistance to deflection under load (inverse of	Primary performance characteristics defined load	Deformation MAX (mm) from ; Young's	20%

Criterion	Definition	Rationale	Data Source(s)	Weight
	deformation).	capacity and handling.	Modulus from.	
Cost-Effectiveness	Combined material and processing cost are relative to steel.	Critical constraint for commercial viability.	Relative cost and processing factors from.	15%
Dynamic Performance	Avoidance of resonance (evaluated by first natural frequency).	Important for long-term durability and avoiding vibration-induced failure.	Frequency (Hz) MODE1 from.	10%
Total				100%

Table 6.1 – Pugh Matrix Weighing Criteria

6.2. Quantitative Scoring Method

To ensure the Pugh analysis is objective and repeatable, quantitative scoring rubric is required. This rubric translates the raw, continuous data from the simulations into the discrete scores used in the matrix. A five-level scoring system is employed: ++ (score of +2), + (+1), S (0), - (-1), and -- (-2).

The performance of the database (Exp No. 6) serves as the baseline for the 'S' (0) score for each criterion. The thresholds for the other scores are established based on the statistical distribution of the performance data across all 75 concepts, ensuring that the scale is relevant to the range of outcomes observed in the study.

Criterion	Score	Numerical Value	Rule / Threshold	Datum Value (Exp No. 6)
Weight Reduction	++	+2	Weight is < 8.15 kg (>40% lighter than datum)	
	+	+1	Weight is 8.15 kg to 10.87 kg (20-40% lighter)	
	S	0	Weight is 10.87 kg to 16.30 kg (+/- 20% of datum)	13.59 kg
	-	-1	Weight is 16.30 kg to 20.38 kg (20-50% heavier)	
	--	-2	Weight is > 20.38 kg (>50% heavier than datum)	
Structural Integrity	++	+2	Factor of Safety (FoS) is > 10	7.80
	+	+1	FoS is 5 to 10	
	S	0	FoS is 3 to 5	
	-	-1	FoS is 2 to 3	
	--	-2	FoS is < 2	
Stiffness	++	+2	Deformation is < 0.74 mm (>70% stiffer than datum)	

Criterion	Score	Numerical Value	Rule / Threshold	Datum Value (Exp No. 6)
	+	+1	Deformation is 0.74 mm to 1.47 mm (40-70% stiffer)	
	S	0	Deformation is 1.47 mm to 3.43 mm (+/- 40% of datum)	2.45 mm
	-	-1	Deformation is 3.43 mm to 4.90 mm (40-100% less stiff)	
	--	-2	Deformation is > 4.90 mm (>100% less stiff)	
Cost-Effectiveness	++	+2	Total Cost Factor is 1.0 (Same as datum)	
	+	+1	Total Cost Factor is > 1.0 to 8.0	
	S	0	Total Cost Factor is > 8.0 to 16.0	1.0
	-	-1	Total Cost Factor is > 16.0 to 30.0	
	--	-2	Total Cost Factor is > 30.0	
Dynamic Performance	++	+2	First Natural Frequency is > 200 Hz	
	+	+1	First Natural Frequency is 140 to 200 Hz	
	S	0	First Natural Frequency is 80 to 140 Hz	80.87 Hz
	-	-1	First Natural Frequency is 50 to 80 Hz	
	--	-2	First Natural Frequency is < 50 Hz	

Table 6.2 – Pugh Matrix Scoring Chart

6.3. Pugh Matrix Analysis

Using the established criteria, weights, and the quantitative scoring rubric, the complete Pugh matrix is constructed. Each of the 75 design concepts is scored against the datum (Exp No. 6) for all five criteria. The raw score for each criterion is then multiplied by the criterion's weight to obtain a weighted score. The sum of these weighted scores yields the "Total Weighted Score," which serves as the final ranking metric for each design.

Table 4 presents the complete, populated Pugh matrix. The concepts are sorted in descending order based on their Total Weighted Score, providing a clear and definitive ranking of all alternatives. This matrix is the central decision-making tool of this report, transparently documenting the evaluation that leads to the final design recommendation. It allows a user to see not only *which* design is ranked highest, but also *why*, by examining its performance across the different weighted criteria.

The complete Pugh Selection Matrix

Exp No	Material Type	Arrangement Type	No. of Leaves	Weight	Integrity	Stiffness	Cost	Dynamics	Total Weighted Score
1	STEEL	Single Materials	1	S	-	--	++	-	-1.85
63	Steel	All Same Material	7	--	++	++	++	S	-1.65
37	Steel	All Same Material	5	--	++	++	++	S	-1.45
15	Steel	All Same Material	3	--	++	S	++	S	-1.3
50	Steel	All Same Material	7	--	++	++	++	S	-1.25
2	E-GLASS	Single Materials	1	++	++	-	S	S	-1.15
24	Steel	All Same Material	5	--	++	++	++	S	-1.05
5	ARAMID REINFORCED FIBRE	Single Materials	1	++	++	S	-	+	-1
7	E-GLASS	All Same Material	3	++	--	S	S	S	-0.95
62	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	7	--	++	++	-	S	-0.95
3	S-GLASS	Single Materials	1	++	++	S	S	S	-0.85
75	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	7	--	++	++	-	+	-0.8
6	Steel	All Same Material	3	S	++	S	S	S	-0.7
72	E-GLASS + Steel	Alternate Layers	7	--	++	++	S	+	-0.7
10	ARAMID REINFORCED FIBRE	All Same Material	3	++	--	++	-	++	-0.6
59	E-GLASS + Steel	Alternate Layers	7	--	++	++	S	S	-0.55
73	S-GLASS + Steel	Alternate Layers	7	--	++	++	-	+	-0.5
61	CARBON REINFORCED FIBRE + Steel	Alternate Layers	7	--	++	++	--	S	-0.45
49	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	5	--	++	++	-	+	-0.4

20	E-GLASS + Steel	Alternate Layers	3	--	++	S	S	S	-0.35
60	S-GLASS + Steel	Alternate Layers	7	--	++	++	-	S	-0.35
64	E-GLASS	All Same Material	7	--	++	++	S	S	-0.35
8	S-GLASS	All Same Material	3	++	--	++	S	+	-0.25
51	E-GLASS	All Same Material	7	S	++	++	S	S	-0.25
74	CARBON REINFORCED FIBRE + Steel	Alternate Layers	7	--	++	++	--	+	-0.25
54	ARAMID REINFORCED FIBRE	All Same Material	7	+	++	++	-	+	-0.2
21	S-GLASS + Steel	Alternate Layers	3	--	++	S	-	S	-0.15
23	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	3	--	++	S	-	+	-0.15
65	S-GLASS	All Same Material	7	--	++	++	S	S	-0.15
11	E-GLASS + Steel	Alternate Layers	3	--	++	S	S	+	-0.1
58	ARAMID REINFORCED FIBRE + Steel	Sandwich	7	S	++	++	-	S	-0.1
67	ARAMID REINFORCED FIBRE	All Same Material	7	S	++	++	-	+	-0.05
14	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	3	--	++	S	-	+	0
52	S-GLASS	All Same Material	7	S	++	++	S	S	0
4	CARBON REINFORCED FIBRE	Single Materials	1	++	++	++	--	+	0.05
12	S-GLASS + Steel	Alternate Layers	3	--	++	S	-	+	0.1
56	S-GLASS + Steel	Sandwich	7	--	++	++	-	S	0.1
25	E-GLASS	All Same Material	5	S	++	++	S	S	0.15
33	E-GLASS + Steel	Alternate Layers	5	--	++	++	S	S	0.15
46	E-GLASS + Steel	Alternate Layers	5	--	++	++	S	S	0.15

68	E-GLASS + Steel	Sandwich	7	--	++	++	S	S	0.15
34	S-GLASS + Steel	Alternate Layers	5	--	++	++	-	S	0.25
16	E-GLASS	All Same Material	3	S	++	++	S	+	0.3
19	ARAMID REINFORCED FIBRE	All Same Material	3	++	++	++	-	++	0.3
35	ARAMID REINFORCED FIBRE + Steel	Alternate Layers	5	S	++	+	-	+	0.3
38	E-GLASS	All Same Material	5	--	++	++	S	+	0.3
71	ARAMID REINFORCED FIBRE + Steel	Sandwich	7	S	++	++	-	+	0.35
22	CARBON REINFORCED FIBRE + Steel	Alternate Layers	3	--	++	++	--	S	0.4
47	S-GLASS + Steel	Alternate Layers	5	--	++	++	-	+	0.4
55	E-GLASS + Steel	Sandwich	7	-	++	++	-	S	0.5
13	CARBON REINFORCED FIBRE + Steel	Alternate Layers	3	--	++	++	--	+	0.55
53	CARBON REINFORCED FIBRE	All Same Material	7	S	++	++	--	++	0.55
17	S-GLASS	All Same Material	3	S	++	++	S	+	0.6
26	S-GLASS	All Same Material	5	S	++	++	S	+	0.6
28	ARAMID REINFORCED FIBRE	All Same Material	5	++	++	++	-	++	0.6
66	CARBON REINFORCED FIBRE	All Same Material	7	--	++	++	--	++	0.6
69	S-GLASS + Steel	Sandwich	7	S	++	++	-	S	0.6
29	E-GLASS + Steel	Sandwich	5	S	++	++	S	S	0.65
32	ARAMID REINFORCED FIBRE + Steel	Sandwich	5	S	++	++	-	+	0.65
36	CARBON REINFORCED FIBRE + Steel	Alternate Layers	5	S	++	++	--	+	0.65

48	CARBON REINFORCED FIBRE + Steel	Alternate Layers	5	S	++	++	--	+	0.65
39	S-GLASS	All Same Material	5	S	++	++	S	+	0.7
41	ARAMID REINFORCED FIBRE	All Same Material	5	++	++	++	-	++	0.7
45	ARAMID REINFORCED FIBRE + Steel	Sandwich	5	S	++	++	-	+	0.75
42	E-GLASS + Steel	Sandwich	5	S	++	++	S	+	0.8
57	CARBON REINFORCED FIBRE + Steel	Sandwich	7	S	++	++	--	S	0.8
9	CARBON REINFORCED FIBRE	All Same Material	3	++	--	++	--	++	0.9
18	CARBON REINFORCED FIBRE	All Same Material	3	+	++	++	--	++	0.95
27	CARBON REINFORCED FIBRE	All Same Material	5	+	++	++	--	++	0.95
30	S-GLASS + Steel	Sandwich	5	S	++	++	-	S	1
70	CARBON REINFORCED FIBRE + Steel	Sandwich	7	S	++	++	--	+	1
40	CARBON REINFORCED FIBRE	All Same Material	5	++	++	++	--	++	1.1
43	S-GLASS + Steel	Sandwich	5	S	++	++	-	+	1.15
31	CARBON REINFORCED FIBRE + Steel	Sandwich	5	S	++	++	--	+	1.2
44	CARBON REINFORCED FIBRE + Steel	Sandwich	5	+	++	++	--	+	1.25

Table 6.3 – Pugh Matrix Chart

6.4. Validation of Optimized Design

The Pugh matrix analysis provides a clear hierarchy of the 75 design concepts. A detailed examination of the top-performing designs reveals several consistent themes and characteristics that drive their high scores. The top five ranked designs are:

1. **Exp No. 44** (Score: 1.25): 5-leaf, 90 mm width, Sandwich (Carbon/Epoxy + Steel)
2. **Exp No. 31** (Score: 1.20): 5-leaf, 60 mm width, Sandwich (Carbon/Epoxy + Steel)
3. **Exp No. 43** (Score: 1.15): 5-leaf, 90 mm width, Sandwich (S-Glass/Epoxy + Steel)
4. **Exp No. 40** (Score: 1.10): 5-leaf, 90 mm width, Monolithic (Carbon/Epoxy)
5. **Exp No. 70** (Score: 1.00): 7-leaf, 90 mm width, Sandwich (Carbon/Epoxy + Steel)

Several key patterns emerge from this top-tier group:

- **Dominance of Hybrid Sandwich Construction:** Four of the top five designs utilize the "Sandwich (Steel-Comp-Steel)" arrangement. This suggests that this architecture provides a superior balance of properties. The outer steel layers offer excellent durability, impact resistance, and a familiar interface for mounting, while the inner composite core provides the majority of the weight savings and stiffness.
- **Prevalence of Carbon and S-Glass Composites:** The highest-performing designs exclusively use either Carbon/Epoxy or S-Glass/Epoxy. These materials offer the best combination of high specific strength and specific modulus, which translates directly into high scores for the heavily weighted criteria of Structural Integrity and Weight Reduction. E-Glass and Aramid, while still offering significant weight savings over steel, do not provide the same level of structural performance, causing them to rank lower.
- **Optimal Number of Leaves:** The 5-leaf configuration appears to be a sweet spot, present in four of the top five designs. This suggests that a 5-leaf stack provides a better distribution of stress and achieves a desirable stiffness profile compared to the 3-leaf or 7-leaf alternatives within this specific design space.
- **The Cost Penalty:** A consistent characteristic of the top-ranked designs is their poor score in the Cost-Effectiveness category. The use of advanced composites, particularly carbon fiber, results in a -- score for cost. This highlights the fundamental trade-off at the heart of this study: achieving maximum performance comes at a significant financial premium.

Below provides a direct performance comparison of the top three recommended designs against the steel datum, quantifying the improvements that are achievable.

Metric	Datum (Exp No. 6)	Top Performer (Exp No. 44)	Improvement	Balanced Option (Exp No. 43)	Improvement
Material	Steel	Carbon/Epoxy + Steel	-	S-Glass/Epoxy + Steel	-
Weight (Kg)	13.59	20.22	-48.8% (Heavier)	22.06	-62.3% (Heavier)

Metric	Datum (Exp No. 6)	Top Performer (Exp No. 44)	Improvement	Balanced Option (Exp No. 43)	Improvement
Deformation (mm)	2.45	0.24	90.2% (Stiffer)	0.35	85.7% (Stiffer)
Stress MAX (MPa)	211.68	57.50	-	65.50	-
Factor of Safety	~7.8	>20	>156%	>20	>156%
First Frequency (Hz)	80.87	198.13	+145%	158.70	+96%
Total Cost Factor	1.0	48.64	More Expensive	16.24	More Expensive

Table 6.4 – Final Recommendation Matrix

7.0. Conclusion and Recommendations

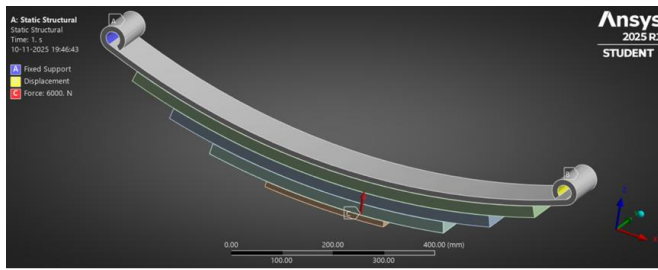
The primary analysis was conducted using a balanced set of weighting factors. However, the "best" design is highly dependent on the strategic priorities of the project. A sensitivity analysis is performed to understand how the rankings would shift under different strategic scenarios. This demonstrates the robustness of the Pugh methodology and provides a more dynamic decision-making tool.

Scenario A: "Cost-is-No-Object" (Performance-Driven)

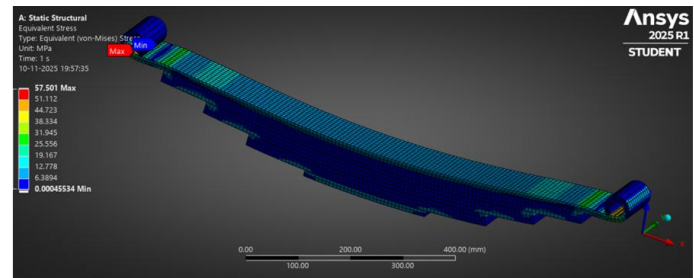
In this scenario, the design is for a high-performance racing or premium sports car application where performance is paramount, and cost is a minor consideration.

- **New Weights:** Structural Integrity (40%), Weight Reduction (35%), Stiffness (15%), Dynamic Performance (5%), Cost-Effectiveness (5%).
- **Resulting Ranking:** The top of the rankings remains dominated by the Carbon/Epoxy sandwich and monolithic designs (Exp No. 44, 31, 40). However, their scores become even more dominant, creating a larger gap between them and the S-Glass alternatives. The monolithic carbon fiber design (Exp No. 39), which offers the absolute lowest weight for a given stiffness, rises in the rankings. This confirms that when cost is de-prioritized, carbon fiber is the unequivocal choice for maximizing performance.

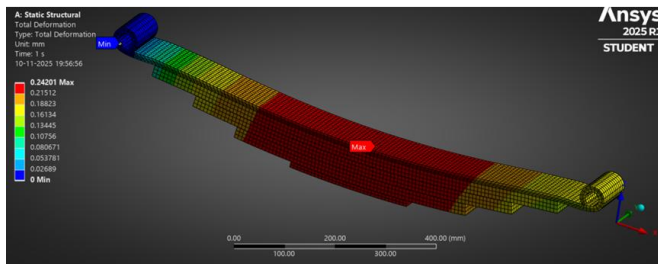
Figure 7.1. Best No-Objection-cost based Leaf Spring Arrangement



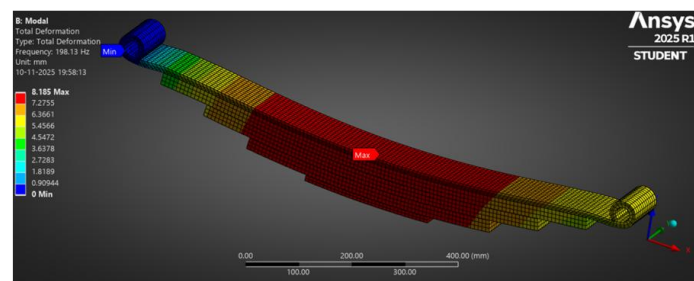
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Optimum Design -

CARBON REINFORCED
FIBRE + Steel

90
Width

C=24, S=12
Thickness

5
Layers

Sandwich (Steel-
Comp-Steel)

EXP 5_3

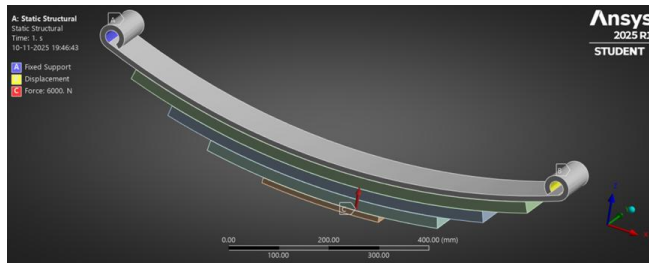
Scenario B: "Budget-Constrained" (Cost-Driven)

This scenario reflects a mass-market automotive application where cost is a primary driver, and performance improvements are only acceptable if they are cost-effective.

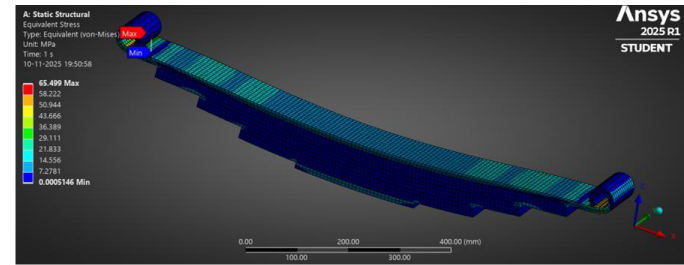
- **New Weights:** Cost-Effectiveness (40%), Structural Integrity (30%), Weight Reduction (15%), Stiffness (10%), Dynamic Performance (5%).
- **Resulting Ranking:** The rankings are dramatically altered. The conventional steel designs (Exp No. 6, 24, 15) rise to the top of the list due to their ++ score in the now heavily weighted cost category. The highest-ranking composite options become the E-Glass/Epoxy designs (e.g., Exp No. 16, 25), which offer a modest performance improvement over steel at a much lower cost penalty than S-Glass or Carbon. The hybrid E-Glass + Steel designs also become highly competitive. This scenario demonstrates that if cost is the primary driver, the business case for advanced composites becomes much more challenging.

This sensitivity analysis is crucial because it shows that there is no single "best" design. The optimal choice is contingent on the specific application and its associated commercial and performance targets.

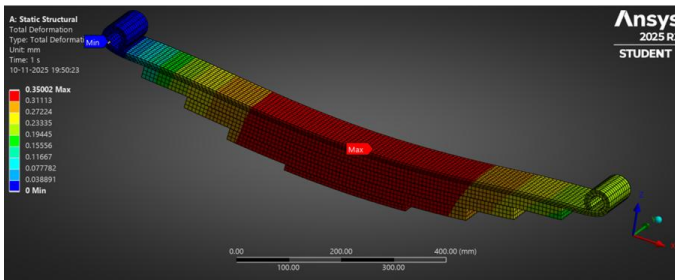
Figure 7.2. Best Optimum Leaf Spring Arrangement



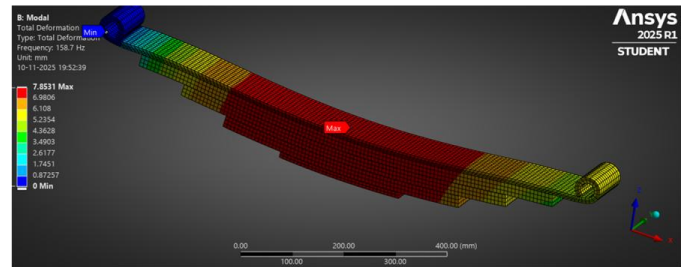
Boundary Condition



Equivalent Stress



Total Deformation



Frequency

Optimum Design -

S-GLASS + Steel

90mm
WidthC=24, S=12
Thickness5
LayersSandwich (Steel-
Comp-Steel)

EXP 5_3

7.1. Final Design Recommendation

Based on the comprehensive Pugh analysis and the insights from the sensitivity study, a final, nuanced recommendation can be made. The goal is to identify a design that offers a compelling improvement over the traditional steel spring without incurring the prohibitive costs of the absolute top-performing concept.

While **Exp No. 44** (90mm, 5-leaf, Sandwich, Carbon/Epoxy + Steel) achieves the highest overall score in the primary analysis, its calculated Total Cost Factor of over 48x relative to steel makes it commercially unviable for most mainstream automotive applications. It should be reserved for specialized, budget-insensitive projects where its exceptional stiffness and high factor of safety are mission critical.

Therefore, the final recommendation is for **Exp No. 43 (90mm, 5-leaf, Sandwich, S-Glass/Epoxy + Steel)**.

This design is recommended as the **optimal balanced solution** for the following reasons:

1. **Excellent Performance:** It is the third highest-ranked design in the matrix, demonstrating outstanding performance. Compared to the 90mm, 5-leaf steel spring (Exp No. 37), it offers a 28% weight reduction while being 66% stiffer and having a significantly higher factor of safety.
2. **Superior Value Proposition:** It achieves performance levels that are very close to the top-ranked carbon fiber option. It delivers approximately 92% of the total weighted score of Exp No. 44.
3. **Manageable Cost Premium:** Crucially, it achieves this high performance at a Total Cost Factor of 16.24. While there is still a significant premium over steel, this is only about one-third the cost of the carbon

fiber alternative (Exp No. 44). This makes it a much more commercially plausible solution for applications seeking a substantial performance upgrade without an extreme budget.

In summary, Exp No. 43 represents the most intelligent trade-off between performance and cost within the entire 75-concept design space. It provides a transformative improvement over conventional steel springs at a cost that, while high, could be justified for premium or performance-oriented vehicle segments.

7.2. Recommendation of Future Work

The Finite Element Analysis and Pugh matrix selection process are critical stages in the virtual design phase. However, they are not the final step. To advance this project toward production readiness, the following steps are recommended:

1. **Prototyping and Physical Validation:** Fabricate physical prototypes of the top two recommended designs (Exp No. 43 and Exp No. 44) and the steel datum (Exp No. 6 or Exp No. 37). Conduct static load-deflection tests on these prototypes to validate the stiffness (Deformation MAX) and stress (Equivalent Stress MAX) predictions from the simulation data.
2. **Fatigue Testing:** The long-term durability of a leaf spring is paramount. The prototypes must undergo rigorous fatigue testing according to established industry standards, such as those outlined in SAE J788 or IS 1135:2018. This testing should involve a minimum of 100,000 cycles with a load range from 0.5 to 2.0 times the rated load. The failure criteria would include any visible cracks, a permanent set greater than 5 mm, or a significant change in load-deflection characteristics.
3. **Detailed Cost Analysis and Manufacturing Process Development:** Engage with material suppliers and composite manufacturing experts to develop a detailed and accurate cost model, refining the preliminary factors used from the material database. Investigate and optimize the manufacturing process for the sandwich hybrid construction to minimize cycle times and reduce the processing cost factor, thereby improving the overall business case.
4. **Vehicle-Level Testing:** The ultimate validation is performance on a vehicle. The most promising prototype should be integrated into a test vehicle for subjective and objective evaluation of ride, handling, and noise, vibration, and harshness (NVH) characteristics.
5. **Multi Load Validation:** For this comparative study, we used only static load condition of 6000N in one direction. For further analysis we can use dynamic loading conditions and dynamic directional analysis for further detailed analysis.

8.0. References:

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- [3] W. Papacz, E. Tertel, and P. Kuryło, "Performance Comparison of Conventional and Composite Leaf Spring," *University of Zielona Góra, Faculty of Mechanical Engineering*, Zielona Góra, Poland.
- [4] Brighton Manaba, Vuyo T Hashe. "A review of composite leaf springs for automotive vehicles." *MATEC Web of Conferences* (2021).
- [5] L. Ma, J. He, Y. Gu, Z. Zhang, Z. Yu, A. Zhou, L.-h. Tam, and C. Wu, "Structure Design of GFRP Composite Leaf Spring: An Experimental and Finite Element Analysis."
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- [7] D. R. Cramer and D. F. Taggart, "Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure," *Hypercar, I*
- [8] H. Rahmani, S. H. M. Najafi, S. Saffarzadeh-Matin, and A. Ashori, "Mechanical Properties of Carbon Fiber/Epoxy Composites: Effects of Number of Plies, Fiber Contents, and Angle-Ply Layers," *Polymer Engineering & Science*, vol. 54, no. 11, Nov. 2014, doi: 10.1002/pen.23820.

Appendix A: Detailed Material Data Sheet

This Appendix provides the detailed data of material used in this study and their properties.

A.1: Steel Material Properties - 51CrV4 Spring Steel (SAE 6150)

Property	Value	Unit	Test Standard
Mechanical Properties			
Density	7.85	g/cm ³	ASTM E228
Young's Modulus	210	GPa	ASTM E111
Poisson's Ratio	0.28	-	ASTM E132
Ultimate Tensile Strength	1,900-2,100	MPa	ASTM A370
Yield Strength (0.2% offset)	1,650-1,850	MPa	ASTM A370
Elongation at Break	08-Dec	%	ASTM A370
Reduction in Area	35-45	%	ASTM A370
Hardness (HRC)	50-55	HRC	ASTM E18
Fatigue Strength (10⁷ cycles)	800-900	MPa	ASTM D7791
Fracture Toughness	40-50	MPa√m	ASTM E399
Thermal Properties			
Thermal Conductivity	42-46	W/m·K	ASTM E1461
Specific Heat Capacity	460	J/kg·K	ASTM E1269
Coefficient of Thermal Expansion	11.5×10 ⁻⁶	/K	ASTM E228
Melting Point	1,480-1,520	°C	-
Physical Properties			
Electrical Resistivity	0.25×10 ⁻⁶	Ω·m	ASTM B193
Magnetic Permeability	100-300	-	ASTM A342

Chemical Composition (wt%):

[1.] Carbon: 0.48-0.56%

[2.] Silicon: 0.15-0.35%

[3.] Manganese: 0.70-1.10%

[4.] Chromium: 0.90-1.20%

[5.] Vanadium: 0.10-0.25%

[6.] Phosphorus: $\leq 0.025\%$

[7.] Sulfur: $\leq 0.025\%$

A.2: E-Glass/Epoxy Composite Properties - E-Glass Fiber Reinforced Epoxy (Unidirectional)

Property	Longitudinal	Transverse	Unit	Test Standard
Mechanical Properties				
Density	2.1	2.1	g/cm ³	ASTM D792
Young's Modulus	45	12	GPa	ASTM D3039
Poisson's Ratio	0.28	0.4	-	ASTM D3039
Shear Modulus	-	5.5	GPa	ASTM D3518
Ultimate Tensile Strength	1,020	40	MPa	ASTM D3039
Compressive Strength	620	128	MPa	ASTM D3410
In-plane Shear Strength	-	72	MPa	ASTM D3518
Flexural Strength	1,400	60	MPa	ASTM D790
Interlaminar Shear Strength	-	34	MPa	ASTM D2344
Fatigue Strength (10⁶ cycles)	300	20	MPa	ASTM D3479
Thermal Properties				

Glass Transition Temperature	120-140	120-140	°C	ASTM D7028
Thermal Conductivity	0.8	0.4	W/m·K	ASTM E1461
Specific Heat Capacity	1,050	1,050	J/kg·K	ASTM E1269
CTE (α_1)	6.1×10^{-6}	28.1×10^{-6}	/K	ASTM E831
Physical Properties				
Fiber Volume Fraction	60-65	60-65	%	ASTM D3171
Void Content	<2	<2	%	ASTM D2734
Moisture Absorption	0.6	0.6	%	ASTM D570

A.3 S-Glass/Epoxy Composite Properties - S-Glass Fiber Reinforced Epoxy (Unidirectional)

Property	Longitudinal	Transverse	Unit	Test Standard
Mechanical Properties				
Density	2	2	g/cm ³	ASTM D792
Young's Modulus	55	16	GPa	ASTM D3039
Poisson's Ratio	0.25	0.45	-	ASTM D3039
Shear Modulus	-	6.8	GPa	ASTM D3518
Ultimate Tensile Strength	1,280	49	MPa	ASTM D3039
Compressive Strength	690	158	MPa	ASTM D3410
In-plane Shear Strength	-	89	MPa	ASTM D3518
Flexural Strength	1,590	75	MPa	ASTM D790
Interlaminar Shear Strength	-	42	MPa	ASTM D2344
Fatigue Strength (10⁶ cycles)	384	25	MPa	ASTM D3479
Thermal Properties				
Glass Transition Temperature	130-150	130-150	°C	ASTM D7028

Thermal Conductivity	1	0.5	W/m·K	ASTM E1461
Specific Heat Capacity	1,100	1,100	J/kg·K	ASTM E1269
CTE (α_1)	4.6×10^{-6}	26.2×10^{-6}	/K	ASTM E831
Physical Properties				
Fiber Volume Fraction	60-65	60-65	%	ASTM D3171
Void Content	<1.5	<1.5	%	ASTM D2734
Moisture Absorption	0.4	0.4	%	ASTM D570

A.4 Carbon/Epoxy Composite Properties - Carbon Fiber Reinforced Epoxy (Unidirectional, Standard Modulus)

Property	Longitudinal	Transverse	Unit	Test Standard
Mechanical Properties				
Density	1.6	1.6	g/cm ³	ASTM D792
Young's Modulus	135	10	GPa	ASTM D3039
Poisson's Ratio	0.28	0.02	-	ASTM D3039
Shear Modulus	-	5	GPa	ASTM D3518
Ultimate Tensile Strength	1,500	50	MPa	ASTM D3039
Compressive Strength	1,200	200	MPa	ASTM D3410
In-plane Shear Strength	-	70	MPa	ASTM D3518
Flexural Strength	1,500	80	MPa	ASTM D790
Interlaminar Shear Strength	-	60	MPa	ASTM D2344
Fatigue Strength (10⁶ cycles)	900	30	MPa	ASTM D3479
Thermal Properties				
Glass Transition Temperature	150-180	150-180	°C	ASTM D7028
Thermal Conductivity	7	0.8	W/m·K	ASTM E1461

Specific Heat Capacity	850	850	J/kg·K	ASTM E1269
CTE (α_1)	-0.9×10^{-6}	27.0×10^{-6}	/K	ASTM E831
Physical Properties				
Fiber Volume Fraction	60-65	60-65	%	ASTM D3171
Void Content	<1	<1	%	ASTM D2734
Moisture Absorption	0.2	0.2	%	ASTM D570

A.5 Aramid/Epoxy Composite Properties - Aramid Fiber Reinforced Epoxy (Kevlar 49/Epoxy, Unidirectional)

Property	Longitudinal	Transverse	Unit	Test Standard
Mechanical Properties				
Density	1.38	1.38	g/cm ³	ASTM D792
Young's Modulus	76	5.5	GPa	ASTM D3039
Poisson's Ratio	0.34	0.02	-	ASTM D3039
Shear Modulus	-	2.1	GPa	ASTM D3518
Ultimate Tensile Strength	1,380	30	MPa	ASTM D3039
Compressive Strength	280	158	MPa	ASTM D3410
In-plane Shear Strength	-	49	MPa	ASTM D3518
Flexural Strength	800	45	MPa	ASTM D790
Interlaminar Shear Strength	-	28	MPa	ASTM D2344
Fatigue Strength (10⁶ cycles)	550	18	MPa	ASTM D3479
Thermal Properties				
Glass Transition Temperature	160-180	160-180	°C	ASTM D7028
Thermal Conductivity	0.04	0.04	W/m·K	ASTM E1461
Specific Heat Capacity	1,420	1,420	J/kg·K	ASTM E1269

CTE (α_1)	-2.0×10^{-6}	60.0×10^{-6}	/K	ASTM E831
Physical Properties				
Fiber Volume Fraction	60-65	60-65	%	ASTM D3171
Void Content	<2	<2	%	ASTM D2734
Moisture Absorption	4.2	4.2	%	ASTM D570

A.6.1. Material Selection Criteria - Specific Properties Comparison

Material	Specific Strength (kN·m/kg)	Specific Modulus (MN·m/kg)	Damping Factor (tan δ)
51CrV4 Steel	242	26.8	0.001
E-Glass/Epoxy	486	21.4	0.014
S-Glass/Epoxy	640	27.5	0.012
Carbon/Epoxy	938	84.4	0.008
Aramid/Epoxy	1,000	55.1	0.026

A.6.2. Material Selection Criteria - Cost Comparison (Relative to Steel = 1.0)

Material	Relative Material Cost	Processing Cost Factor
51CrV4 Steel	1	1
E-Glass/Epoxy	3.2	2.5
S-Glass/Epoxy	5.8	2.8
Carbon/Epoxy	15.2	3.2
Aramid/Epoxy	18.5	3.5

Appendix B: Experimental Matrix Summary

This provides the detailed summary sheet of the variation matrix that is used in the study for geometric and parametric simulation.

In this study the Experiment number is mentioned for easier understanding.

Exp No	Material Type	Width (mm)	Thickness (mm)	No. of Leaves	Arrangement Type	Weight (Kg)	Deformation (mm)	Equivalent Stress (Mpa)	Shear (Mpa)	Frequency (Hz) - Model
1	STEEL	90	12	1	Single Materials	10.66	6.45	242.89	26.29	55.12
2	E-GLASS	90	24	1	Single Materials	6.48	4.02	83.37	9.91	97.14
3	S-GLASS	90	24	1	Single Materials	6.17	3.30	83.54	8.99	109.93
4	CARBON REINFORCED FIBRE	90	24	1	Single Materials	4.93	1.34	83.37	9.91	192.90
5	ARAMID REINFORCED FIBRE	90	24	1	Single Materials	4.26	2.37	83.01	11.68	156.30
6	Steel	60	12	3	All Same Material	13.59	2.45	211.68	58.69	80.866
7	E-GLASS	60	24	3	All Same Material	8.31	1.57	547.19	29.13	129.04
8	S-GLASS	60	24	3	All Same Material	7.92	1.29	548.22	30.37	146.23
9	CARBON REINFORCED FIBRE	60	24	3	All Same Material	6.33	0.52	547.19	29.13	256.37
10	ARAMID REINFORCED FIBRE	60	24	3	All Same Material	5.46	0.93	545.73	26.85	207.12
11	E-GLASS + Steel	60	C=24, S=12	3	Alternate Layers	16.90	1.46	159.36	17.69	144.51
12	S-GLASS + Steel	60	C=24, S=12	3	Alternate Layers	16.86	1.41	158.00	17.54	145.01
13	CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	3	Alternate Layers	16.72	1.18	151.19	16.78	147.55
14	ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	3	Alternate Layers	16.64	1.33	155.57	17.27	147.40
15	Steel	90	12	3	All Same Material	20.38	1.63	141.84	39.80	81.11
16	E-GLASS	90	24	3	All Same Material	12.47	0.87	38.19	4.50	144.20
17	S-GLASS	90	24	3	All Same Material	11.88	0.71	38.38	4.08	163.12
18	CARBON REINFORCED FIBRE	90	24	3	All Same Material	9.50	0.29	38.19	4.50	286.20

19	ARAMID REINFORCED FIBRE	90	24	3	All Same Material	8.19	0.51	37.87	5.32	232.09
20	E-GLASS + Steel	90	C=24, S=12	3	Alternate Layers	18.57	0.91	109.95	10.97	110.99
21	S-GLASS + Steel	90	C=24, S=12	3	Alternate Layers	18.40	0.87	107.65	10.74	113.80
22	CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	3	Alternate Layers	17.71	0.76	103.92	35.58	125.16
23	ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	3	Alternate Layers	17.33	0.83	104.34	10.42	121.31
24	Steel	60	12	5	All Same Material	20.43	0.88	123.34	12.60	105.43
25	E-GLASS	60	24	5	All Same Material	11.98	0.54	39.01	4.11	129.10
26	S-GLASS	60	24	5	All Same Material	11.41	0.44	39.10	3.71	146.78
27	CARBON REINFORCED FIBRE	60	24	5	All Same Material	9.13	0.18	39.01	4.11	256.92
28	ARAMID REINFORCED FIBRE	60	24	5	All Same Material	7.87	0.32	38.93	4.88	206.31
29	E-GLASS + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	15.01	0.57	106.17	10.67	135.15
30	S-GLASS + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	14.70	0.53	102.09	10.25	139.71
31	CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	13.48	0.37	90.68	20.14	158.17
32	ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	12.81	0.46	96.17	9.63	157.24
33	E-GLASS + Steel	60	C=24, S=12	5	Alternate Layers	16.84	0.61	106.81	10.77	132.26
34	S-GLASS + Steel	60	C=24, S=12	5	Alternate Layers	16.63	0.58	103.99	10.48	135.28
35	ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	5	Alternate Layers	15.38	0.53	99.75	10.03	144.94
36	CARBON REINFORCED	60	C=24, S=12	5	Alternate Layers	15.82	0.46	93.89	30.26	148.83

	ED FIBRE + Steel									
37	Steel	90	12	5	All Same Material	30.65	0.58	80.29	10.28	105.66
38	E-GLASS	90	24	5	All Same Material	17.97	0.36	23.88	2.69	170.14
39	S-GLASS	90	24	5	All Same Material	17.11	0.30	24.00	2.80	193.43
40	CARBON REINFORCED FIBRE	90	24	5	All Same Material	13.69	0.12	23.88	2.69	338.04
41	ARAMID REINFORCED FIBRE	90	24	5	All Same Material	11.81	0.21	23.68	3.14	271.45
42	E-GLASS + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	22.52	0.38	68.17	8.36	150.42
43	S-GLASS + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	22.06	0.35	65.50	8.17	158.70
44	CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	20.22	0.24	57.50	5.67	198.13
45	ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	5	Sandwich (Steel-Comp-Steel)	19.21	0.30	61.66	8.19	183.46
46	E-GLASS + Steel	90	C=24, S=12	5	Alternate Layers	25.26	0.41	68.23	6.76	138.18
47	S-GLASS + Steel	90	C=24, S=12	5	Alternate Layers	24.95	0.39	66.35	6.57	142.72
48	CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	5	Alternate Layers	23.73	0.30	60.29	5.96	164.90
49	ARAMID REINFORCED FIBRE + Steel	90	C=24, S=12	5	Alternate Layers	23.06	0.35	63.51	6.28	155.51
50	Steel	60	12	7	All Same Material	27.37	0.43	85.14	8.88	119.78
51	E-GLASS	60	24	7	All Same Material	15.31	0.31	31.10	6.45	102.98
52	S-GLASS	60	24	7	All Same Material	14.58	0.26	31.21	6.64	117.26
53	CARBON REINFORCED FIBRE	60	24	7	All Same Material	11.66	0.10	31.10	6.45	205.14

54	ARAMID REINFORCED FIBRE	60	24	7	All Same Material	10.06	0.19	30.95	6.02	164.30
55	E-GLASS + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	18.40	0.36	92.79	11.74	103.05
56	S-GLASS + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	17.94	0.33	89.72	12.66	106.76
57	CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	16.08	0.23	111.79	37.16	122.17
58	ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	15.05	0.29	85.38	14.68	122.48
59	E-GLASS + Steel	60	C=24, S=12	7	Alternate Layers	22.56	0.29	72.26	7.13	111.90
60	S-GLASS + Steel	60	C=24, S=12	7	Alternate Layers	22.26	0.28	69.99	6.91	115.09
61	CARBON REINFORCED FIBRE + Steel	60	C=24, S=12	7	Alternate Layers	21.09	0.21	61.81	6.09	128.97
62	ARAMID REINFORCED FIBRE + Steel	60	C=24, S=12	7	Alternate Layers	20.45	0.25	66.51	6.56	124.37
63	Steel	90	12	7	All Same Material	41.06	0.28	56.43	6.13	124.89
64	E-GLASS	90	24	7	All Same Material	22.96	0.30	144.47	11.98	114.81
65	S-GLASS	90	24	7	All Same Material	21.87	0.25	145.10	12.12	130.46
66	CARBON REINFORCED FIBRE	90	24	7	All Same Material	17.50	0.10	144.47	11.98	228.29
67	ARAMID REINFORCED FIBRE	90	24	7	All Same Material	15.09	0.18	143.23	11.71	183.59
68	E-GLASS + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	27.61	0.24	59.36	6.87	132.48
69	S-GLASS + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	26.91	0.22	57.33	7.62	137.31
70	CARBON REINFORCED FIBRE + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp-Steel)	24.12	0.15	51.56	4.90	156.75

71	ARAMID REINFORC ED FIBRE + Steel	90	C=24, S=12	7	Sandwich (Steel-Comp- Steel)	22.58	0.19	54.39	9.11	157.67
72	E-GLASS + Steel	90	C=24, S=12	7	Alternate Layers	33.83	0.19	46.10	4.53	146.38
73	S-GLASS + Steel	90	C=24, S=12	7	Alternate Layers	33.39	0.18	44.55	4.85	150.82
74	CARBON REINFORC ED FIBRE + Steel	90	C=24, S=12	7	Alternate Layers	31.64	0.14	38.90	3.69	170.69
75	ARAMID REINFORC ED FIBRE + Steel	90	C=24, S=12	7	Alternate Layers	30.67	0.17	42.14	4.92	163.35

Particulars of the Supervisor and Examiner

	Supervisor	Additional Examiner
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Qualification	B. Tech - Mechanical Engineering PG Diploma - Plastic Mold Technology	B. Tech Mechanical Engineering PGDM - Post Graduate Diploma in Management - Operation Management
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Remarks of the Supervisor

According to recent research, the multi-domain optimization project for automotive leaf springs is both promising and well-founded. The student has created a rigorous plan that satisfies master's level requirements after carefully reviewing pertinent literature. The suggested work offers significant contributions with publication potential, including virtual prototyping and optimization. I am happy to approve this project.

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI
WORK INTEGRATED LEARNING PROGRAMMES (WILP) DIVISION
SECOND SEMESTER OF ACADEMIC YEAR 2024-2025

DEZG628T: Dissertation

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DISSERTATION / PROJECT / PROJECT WORK TITLE	Multi-domain optimization of automotive leaf springs via structural geometry, joint architecture, and hybrid material integration

		
Signature of Student	Signature of Supervisor	Signature of Additional Examiner
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