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MULTI-LEAF SPRING USING ALUMINIUM METAL MATRIX COMPOSITES: DESIGN AND ANALYSIS

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Abstract

The development of lightweight and high-performance materials has become a pivotal focus in automotive engineering due to the growing demand for energy-efficient and environmentally friendly vehicles. This research focuses on the use of Aluminium Metal Matrix Composites (Al-MMCs) as substitute materials for steel in the design and improvement of leaf springs, which are vital in vehicle suspension systems. By employing CAD modelling and FEA, the mechanical behaviour of the developed Al/SiC MMC and Al/B4C MMC leaf springs are analysed and compared under different static load conditions of 12,500 N & 17,500 N. The analysis focuses on deformation, stress distribution, and weight reduction compared to conventional steel leaf springs. These outcomes indicate that Al-MMCs can achieve up to 60% weight reduction with an improvement or comparable stress-handling capacity. Among all the materials, the stiffness and lower deformation at the maximum load indicate that Al/B4C MMC is a potential material for high-performance and lightweight vehicles. This study focuses on the potential of enhancing Al-MMCs for better fuel economy and vehicle performance by using sustainable automotive material choices. The results of this research will provide possibilities for other high-risk automotive applications of composite material by explaining the behaviour and performance of the material and new designs.

***Keywords**:* Aluminium Metal Matrix Composites, Leaf Springs, Finite Element Analysis, Static Structural Analysis, Deformation, Stress Distribution.

1. Introduction

Leaf springs are usually applied in automobile suspension systems, which serve the purpose of load carrying as well as stability during the vehicle's functions. Traditionally, these springs are produced from steel due to its stiffness and outstanding wear resistance properties. Nevertheless, the primary challenge of the steel used in this car is weighing which reduces the fuel efficiency and the performance-to-weight ratio, making it necessary for the automobile industry to seek lighter materials.

The adoption of lightweight materials within the automotive engineering sector has gained prominence as manufacturers aim to improve fuel efficiency and reduce emissions. Aluminium Metal Matrix Composites (Al-MMCs) have emerged as viable solutions for the replacement of steel in the fabrication of leaf springs. These materials incorporate the lightweight nature of aluminium and improve the mechanical features through the

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reinforcement of ceramics such as SiC and B4C. These reinforcements not only minimise the overall weight of the component but also improve mechanical characteristics like tensile strength, stiffness, and wear resistance perfect for high-stress applications.

This research investigates the viability of using Al/SiC MMC and Al/B4C MMC for use in automotive leaf springs to employ lightweight high-performance materials. The study also compares these composites with structural steel to elaborate more on their significance and limitations. This paper extends the research on the efficient and sustainable design of automobile elements by utilising advanced modelling techniques and numerical analysis.

2. Literature Review

Recent advances in leaf springs have been a result of changes necessary to meet the ever-increasing expectations for performing, long-lasting, and lightweight suspension systems. In the past, they were made of steel because of its high strength and relatively low cost was also a factor. Nevertheless, its high weight has been a disadvantage because it contributes negatively to vehicle fuel efficiency and manoeuvrability. (Sayyad, Kulkarni, Patel, & Jadhav, 2020)Discussed the drawbacks of steel and revealed how the application of more sophisticated simulation methods such as Finite Element Analysis (FEA) can help to improve the parameters of conventional steel leaf springs. Their work was a reference of how researchers could shift toward light-weighting without compromising on strength.

The employment of the composite material spearheaded a revolution in the development of the leaf spring. In the work published by (Ali, Manuel, Balamurugan, & Murugan, 2021), the application of FEA on glass fibre-reinforced polymers (GFRP) described revealed weight reductions and enhancements of other mechanical characteristics including stress and strain at load. Similarly, (Linlin, et al., 2021)analysed the composite variable cross-section impact leaf springs and indicated that such designs were useful in fulfilling automotive stiffness and strength demands while leading to significant weight reductions. (Noronha, Yesudasan, & Chacko, 2020) Conducted a comparative study of kevlar/epoxy, carbon/glass epoxy, and isotropic aluminium-based leaf springs, revealing that kevlar/epoxy exhibited superior stress resistance, energy storage capacity, and natural frequency.(Khatkar & Behera, 2020) Highlighted the potential of newer fibre architecture which showed that 3D woven composites had higher specific energy absorption and damping characteristics than unidirectional and bidirectional fibre reinforcements.

Some of the potential enhancements have been made in Metal Matrix Composites (MMCs) and these have offered even more potential to the lightweight and higher strength of the leaf springs.(Mallesh, Balaji, Kumar, & Jani, 2021) Explored the use of aluminium-based MMCs with varying reinforcement angles and materials, such as glass carbon, to optimise structural performance under fatigue and dynamic loads. Their research highlighted the versatility of MMCs in achieving tailored mechanical properties.(Sharma, Jha, Kakkar, Kamboj, & Sharma, 2017) Used SiC and B4C to reinforce the aluminium matrices to enhance the stiffness, wear resistance and fatigue strength properties. (Kumar, Dabade, & Wankhade, 2021) Studied the effects of different reinforcement types and their volume fractions, where they revealed the flexibility of MMCs in addressing a wide range of applications based on the desired mechanical characteristics. (Singh, Brar, Kumar, & Aggarwal, 2021)also concentrated on processes like stir casting and squeeze casting for the better distribution of reinforcements and uniformity in order to have a standard quality of the MMC-based leaf springs. Such studies show that MMCs have become crucial in the modernisation of suspension systems to offer automotive industries superb solutions that are efficient, long-lasting and entirely sustainable.

3. Methodology

3.1 Design Calculations

While working on the design and response analysis of the leaf spring, some assumptions are made to make theoretical analysis manageable. It is assumed that the overall length of the leaf spring is 1100 mm which is used in most vehicle suspensions. This length is deemed suitable given the spring's capability to flex and allow additional space constraints inherent within most vehicle chassis. It is decided that the width of the spring should be 260 mm which includes an ineffective part on the spring as it requires some lengths to be provided for mounting and structural purposes only.

The leaf spring structure is envisaged to consist of the main design complemented by two full-length leaves and five graduated ones. This arrangement helps to distribute the load effectively on the spring while maintaining the reasonable dimensions of stress concentrated by varying the length and position of the leaves. The effective length of the spring is the portion of the total length that the actual load bearing and deflection occur, as it is calculated to be 840mm, offering a balance of both mechanical strength and elasticity for optimal performance.

Consequently, for each leaf, the thickness is established to 11mm and the width to 65mm. These dimensions are chosen so that the spring can take on the required loads without becoming too rigid and therefore too brittle to sustain. Additionally, the camber of the spring is taken as 90 mm so that the spring is sufficiently curvilinear vertically to be able to take shocks and impacts and provide adequate stability and comfort to the vehicle.

Table 1: Assumed Parameters

Parameter Assumed	**Value**
Overall length of the spring (**$2L_1$**)	1100 mm
Width of the band (ineffective length) (**i**)	260 mm
Number of full-length leaves (**nF**)	2
Number of full graduated leaves (**nG**)	5
Total number of leaves (**n**)	7
The effective length of the spring (**2L**) =**$2L_1$-i**	840 mm
Thickness of each leaf (**t**)	11 mm
Width of each leaf (**b**)	65 mm
Camber of the leaf spring (**y**)	90 mm

The values of the parameters from the above table are used in the following equations to calculate the length of the individual leaves of the spring.

$$\text{Length of smallest leaf} = \frac{\text{effective length}}{(n-1)} + \text{ineffective length} = \frac{2L}{n-1} + i \quad (1)$$

$$\text{Length of nth leaf} = n * \frac{\text{effective length}}{(n-1)} + \text{ineffective length} = n * \frac{2L}{n-1} + i \quad (2)$$

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Table 2: Length Calculations of the leaves

Leaf Number	Length Formula	Length (mm)
Smallest leaf	$\frac{\text{effective length}}{(n-1)}$ + ineffective length = $\frac{2L}{n-1}$ + i= $\frac{840}{7-1}$ + 260	400
2nd leaf	$2 * \frac{\text{effective length}}{(n-1)}$ + ineffective length = $2* \frac{2L}{n-1}$ + i = $2 * \frac{840}{7-1}$ + 260	540
3rd leaf	$3 * \frac{\text{effective length}}{(n-1)}$ + ineffective length = $3* \frac{2L}{n-1}$ + i = $3* \frac{840}{7-1}$ + 260	680
4th leaf	$4 * \frac{\text{effective length}}{(n-1)}$ + ineffective length = $4* \frac{2L}{n-1}$ + i = $4* \frac{840}{7-1}$ + 260	820
5th leaf	$5 * \frac{\text{effective length}}{(n-1)}$ + ineffective length = $5* \frac{2L}{n-1}$ + i = $5* \frac{840}{7-1}$ + 260	960
6th leaf	$6 * \frac{\text{effective length}}{(n-1)}$ + ineffective length = $6* \frac{2L}{n-1}$ + i = $6* \frac{840}{7-1}$ + 260	1100
Master Leaf	Same length as 6th leaf	1100

3.2 CAD Modelling

Detailed 3D models of the selected components of the leaf spring assembly are modelled using CAD software, SolidWorks. The first step in modelling the leaf spring is to model all the assembly components of the spring as independent objects in SolidWorks; these include the seven individual leaves, two rollers, and a variety of different clamps. This approach also makes the design flexible, and this makes it convenient to adjust and fine-tune suggested changes in each of these components. After developing a detailed model of the individual components, they are assembled to create a complete model of the leaf spring. The 3D model of the considered leaf spring is illustrated in Figure 1.

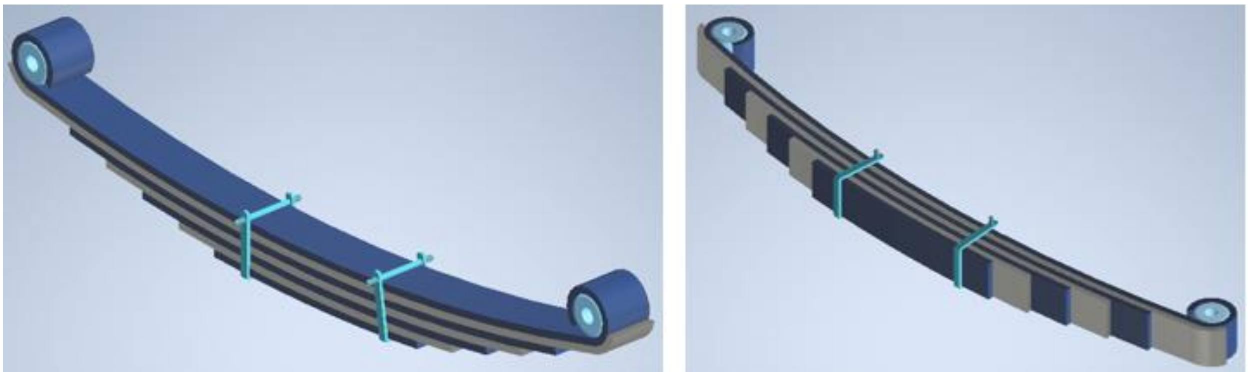

Figure 1: 3D Model of the Leaf Spring

3.3 Material Selection

Material selection is a pivotal aspect of this research, as it directly influences the mechanical performance, weight reduction, and suitability of the leaf springs for high-stress automotive applications. Three materials are chosen for

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detailed evaluation: structural steel, Al/SiC MMC, and Al/B4C MMC. Each material is selected based on its unique properties and potential to meet the design requirements of lightweight and durable suspension systems.

3.3.1 Structural Steel

Structural steel has been chosen as the base material since it is extensively used in conventional or ordinary leaf springs. It is a material with a great tensile strength that has often been used for many years due to its durability. However, the notably heavy mass of steel complicates itself with fuel economy and manoeuvrability in today's automobiles. Material properties of this material and the weight of the leaf spring using this material are presented in Figure 2.

Properties of Outline Row 9: Structural Steel

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	7850	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young...			
8	Young's Modulus	200	GPa		
9	Poisson's Ratio	0.3			
10	Bulk Modulus	1.6667E+11	Pa		
11	Shear Modulus	7.6923E+10	Pa		
12	Strain-Life Parameters				
20	S-N Curve	Tabular			
24	Tensile Yield Strength	0.25	GPa		
25	Compressive Yield Strength	0.25	GPa		
26	Tensile Ultimate Strength	0.46	GPa		
27	Compressive Ultimate Strength	0	Pa		

Properties	
Volume	4.7299e+006 mm^3
Mass	37.13 kg

Figure 2: Material Properties of Structural Steel and Weight of Leaf Spring Employing Steel

3.3.2 Al/SiC MMC

Al/SiC MMC is a metal matrix composite where silicon carbide particles are incorporated in an aluminium matrix, which provides high stiffness, wear resistance, and high load-carrying capacity. The incorporation of SiC enhances the thermal stability and mechanical properties of the matrix which makes it suitable for application areas that require high durability and lower weight. Al6092/SiC/40p-T6 is selected to investigate its feasibility as a direct replacement for steel in leaf springs. Figure 3 shows the material properties of Al/SiC MMC and the weight of the leaf spring employing it.

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Properties of Outline Row 5: Al6092/SiC/40p-T6

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2920	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young...			
8	Young's Modulus	138	GPa		
9	Poisson's Ratio	0.296			
10	Bulk Modulus	1.1275E+11	Pa		
11	Shear Modulus	5.3241E+10	Pa		
12	Tensile Yield Strength	517	MPa		
13	Tensile Ultimate Strength	565	MPa		

Properties	
Volume	4.7299e+006 mm³
Mass	15.536 kg

Figure 3: Material Properties of Al/SiC MMC (Al6092/SiC/40p-T6) and Weight of Leaf Spring

3.3.3 Al/B4C MMC

Al/B4C MMC is reinforced with boron carbide particles, known for their exceptional hardness, high stiffness, and superior strength-to-weight ratio. These reinforcements enhance the composite's fracture toughness and impact resistance, making it ideal for high-stress automotive applications. Its lightweight nature and robust mechanical properties make Al/B4C MMC a promising candidate for replacing steel in modern suspension systems. Figure 4 depicts the material properties of the Al/B4C MMC employed in Ansys and the weight of the leaf spring using this material.

Properties of Outline Row 8: Al-B4C MMC

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2600	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young...			
8	Young's Modulus	190	GPa		
9	Poisson's Ratio	0.296			
10	Bulk Modulus	1.5523E+11	Pa		
11	Shear Modulus	7.3302E+10	Pa		
12	Tensile Ultimate Strength	380	MPa		

Properties	
Volume	4.7299e+006 mm³
Mass	14.135 kg

Figure 4: Material Properties of Al/B4C MMC and Weight of Leaf Spring

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3.4 Static Structural Analysis

Ansys Workbench is employed to perform the static structural analysis of the leaf spring. The static structural analysis of the leaf springs is conducted using three materials: structural steel, Aluminium Silicon Carbide composite (Al/SiC MMC), and Aluminium Boron Carbide composite (Al/B4C MMC). The material properties of these materials are assigned in the engineering data section. The modelled leaf spring is imported in the geometry section as a step file.

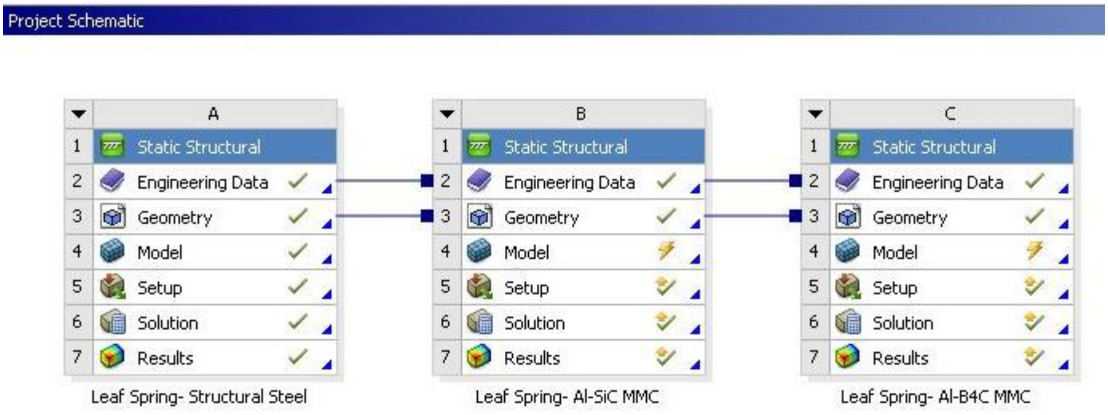

Figure 5: Ansys Interface for Static Structural Analysis of Leaf Spring

3.4.1 Meshing

For the mesh generation of the leaf spring model, body sizing and local refinement approaches have been employed. For general areas, a mesh size of 7 mm is employed but subsequently reduced to 5 mm around the mounting points where stress concentrations would be more intensely exhibited. The meshing quality is confirmed to ensure computational efficiency and the accuracy of the solutions. The meshed profile of the leaf spring and the details of nodes and elements are shown in Figure 6.

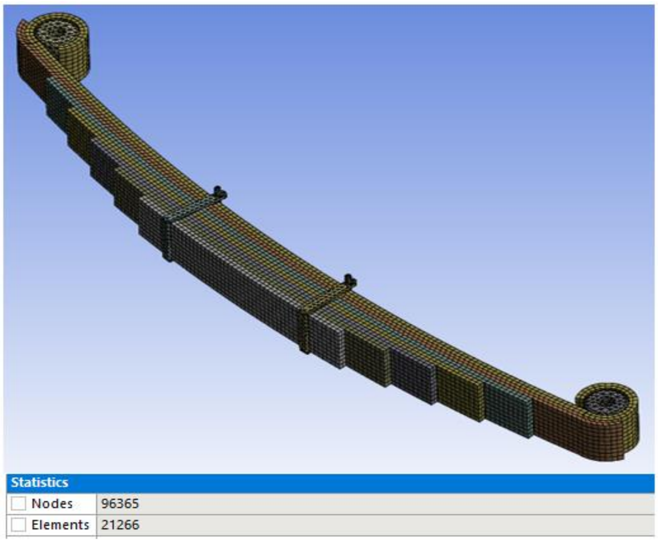

Figure 6: Meshed Profile

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3.4.2 Loading Conditions

When performing the simulation of the leaf spring, the loading conditions are set up to resemble actual working conditions and the forces acting at the interface between the spring and its attachment points. The initial procedure of creating the analysis involves defining the local coordinate systems for both ends of the dimensional leaf spring, to which the loading conditions are to be applied.

At End-1, the displacement in the x, y, and z directions is fixed to the inside surface of the roller, but rotation around the z-axis is unconstrained. At the other end, while there is no restriction of horizontal displacement in the x-direction, vertical and lateral displacements are restrained. Rotation is restricted along the x and y-axes but it is free along the z-axis.

Forces acting upward are applied on the base of the last leaf to counterbalance the force of the vehicle weight, payload, and uneven roads. These forces together with the displacement restrictions represent the actual contact of the leaf spring with its supporting structure and external loading during the operation of the vehicle. Applied loading conditions are shown in Figure 7.

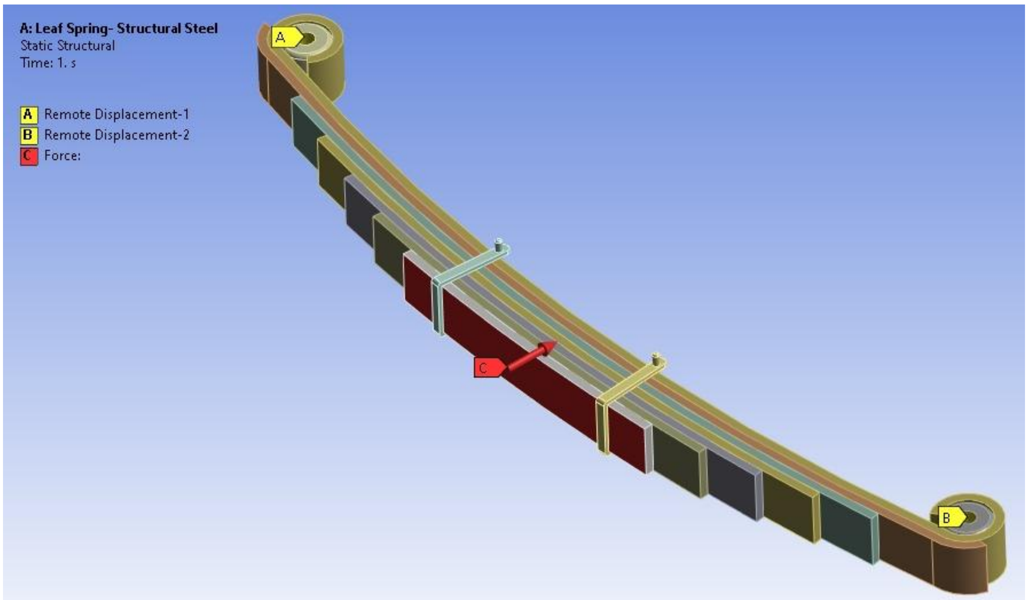

Figure 7: Loading Conditions

First, the structural steel is tested with an applied load of 12,500 N and 17,500 N to monitor stress distribution and structural deformation of the structure under various conditions. Subsequently, the material is changed to Al/SiC MMC to compute the deformation as well as von Mises stress that indicates the potential failure zones. Finally, a similar analysis is done using Al/B4C MMC maintaining consistent conditions for comparison.

The von Mises stress criterion is used to determine the regions of maximum stress while deformation analysis highlighted the flexibility and shock-absorbing capacities. Hence, comparing these three materials allowed for evaluating their characteristics for the possibility of usage in automotive leaf springs in terms of load-carrying capacity, durability, and working under stress.

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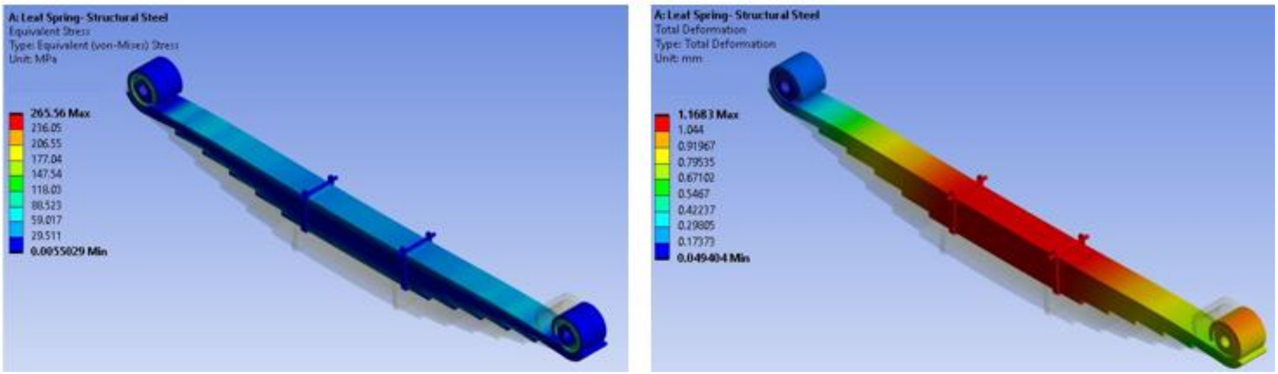

Figure 8: (a) Equivalent Stress and (b) Total Deformation using Structural Steel at 12500 N Load

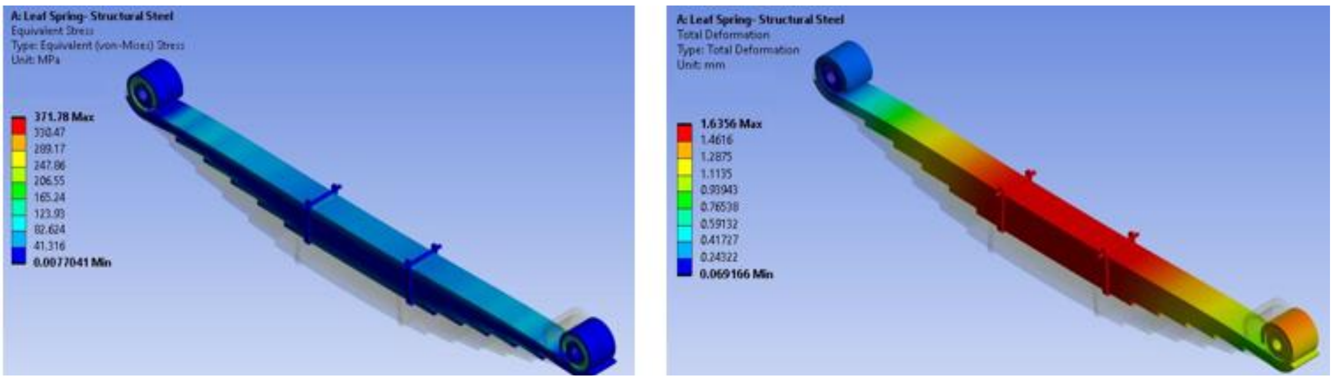

Figure 9: (a) Equivalent Stress and (b) Total Deformation using Structural Steel at 17500 N Load

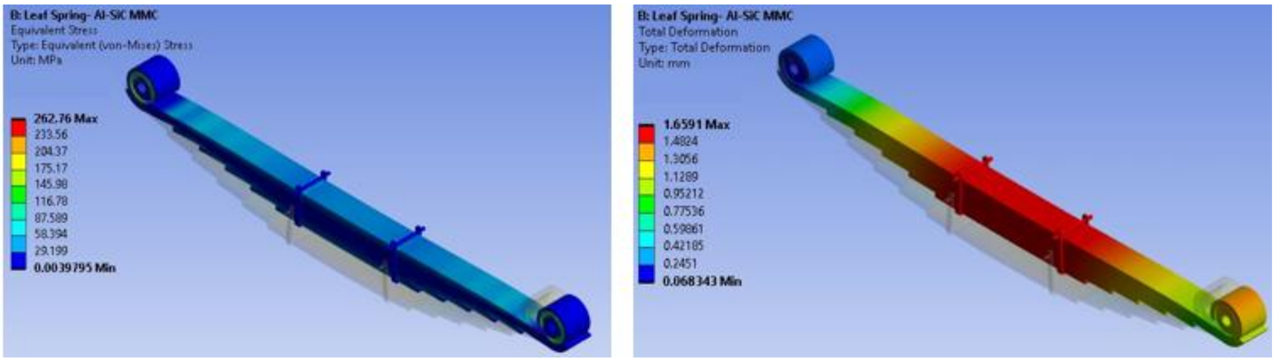

Figure 10: (a) Equivalent Stress and (b) Total Deformation using Al/SiC MMC at 12500 N Load

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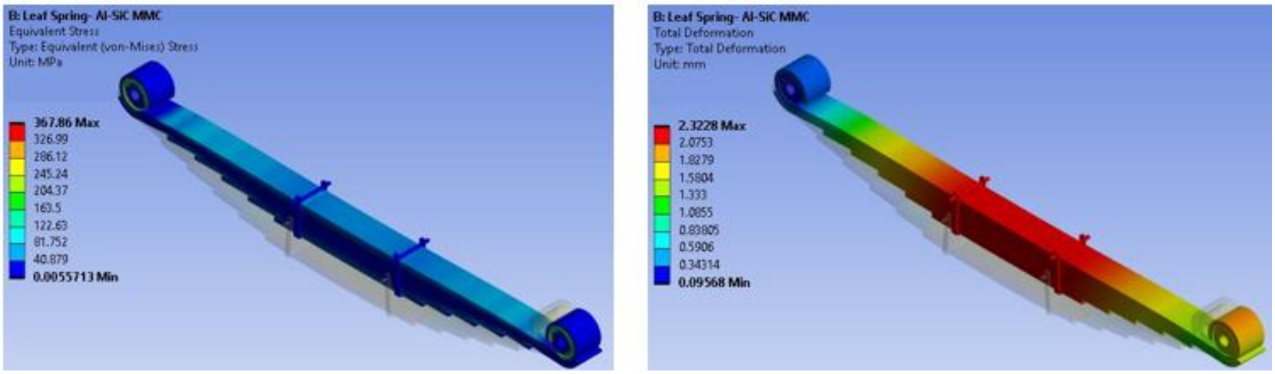

Figure 11: (a) Equivalent Stress and (b) Total Deformation using Al/SiC MMC at 17500 N Load

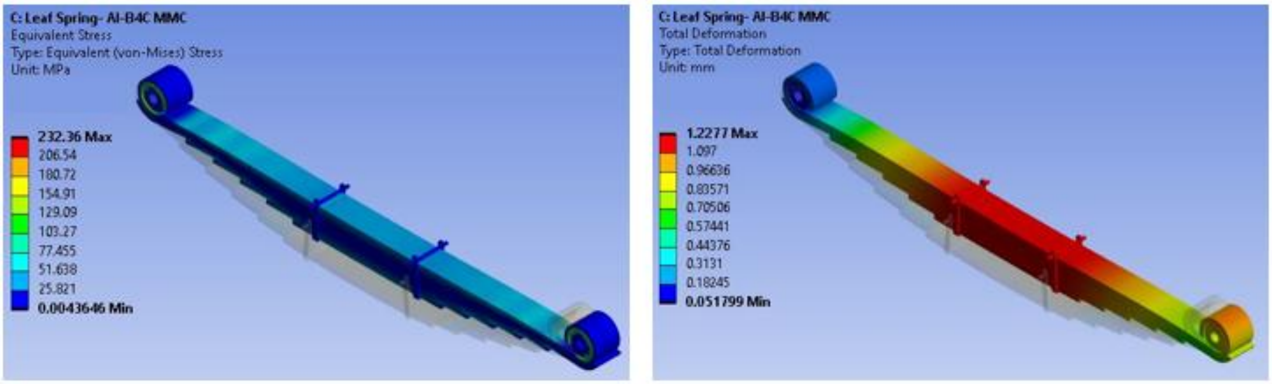

Figure 12: (a) Equivalent Stress and (b) Total Deformation using Al/B4C MMC at 12500 N Load

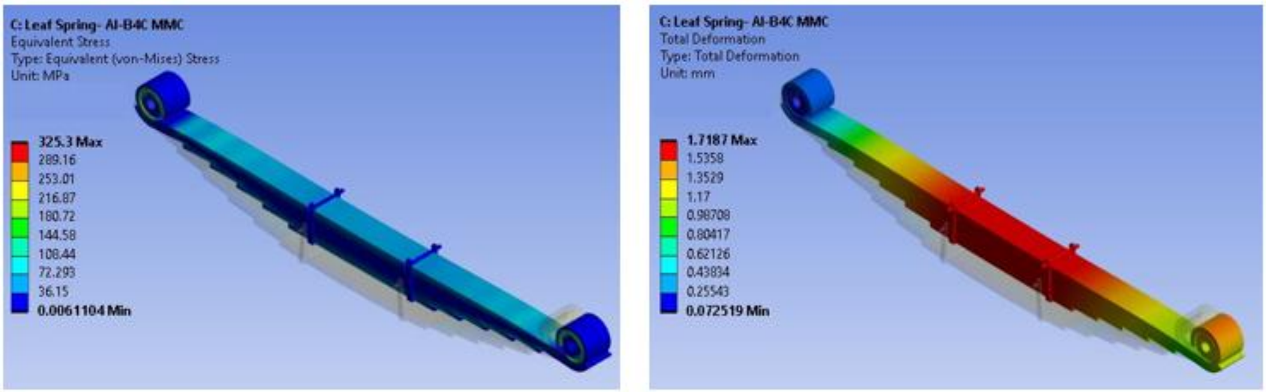

Figure 13: (a) Equivalent Stress and (b) Total Deformation using Al/B4C MMC at 17500 N Load

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4. Results and Discussion

The performance of the leaf spring under varying loads is assessed by examining deformation, stress, and weight for three materials: structural steel, Al/SiC MMC, and Al/B4C MMC. Each parameter is thoroughly analysed for both applied load values of 12,500 N and 17,500 N. The result values of leaf spring analysis for each material assigned are compared to find out the best materials for the leaf spring. Table 3 shows the results of the analysis.

Table 3: Results of Analysis of Leaf Spring

Materials	Load (N)	Deformation (mm)	Stress (MPa)	Weight (kg)
Structural Steel	12500	1.1683	265.56	37.130
	17500	1.6356	371.78	
Al/SiC MMC	12500	1.6591	262.76	15.536
	17500	2.3228	367.86	
Al/B4C MMC	12500	1.2277	232.36	14.135
	17500	1.7187	325.30	

4.1 Stress Comparison

At a load of 12,500 N, structural steel records a stress of 265.56 MPa, while Al/SiC MMC shows a slightly lower stress of 262.76 MPa, indicating its ability to maintain similar performance under comparable loads. Al/B4C MMC demonstrates the lowest stress at 232.36 MPa, reflecting its superior capacity to handle the load with minimal stress concentration.

When subjected to a higher load of 17,500 N, structural steel experiences a stress of 371.78 MPa, whereas Al/SiC MMC records 367.86 MPa, maintaining stress levels close to that of steel. Al/B4C MMC again outperforms, with a stress of 325.3 MPa, showcasing its efficient load distribution and reduced likelihood of failure under heavy loads. The lowered stresses in Al-MMCs suggest improved load-carrying capacity and increased failure tolerance. This shows how Al-MMCs can be effective in high-stress applications to the required standard of reliability. A bar graph showing the compared results of the von Mises stress for three materials under two loads is provided in Figure 14.

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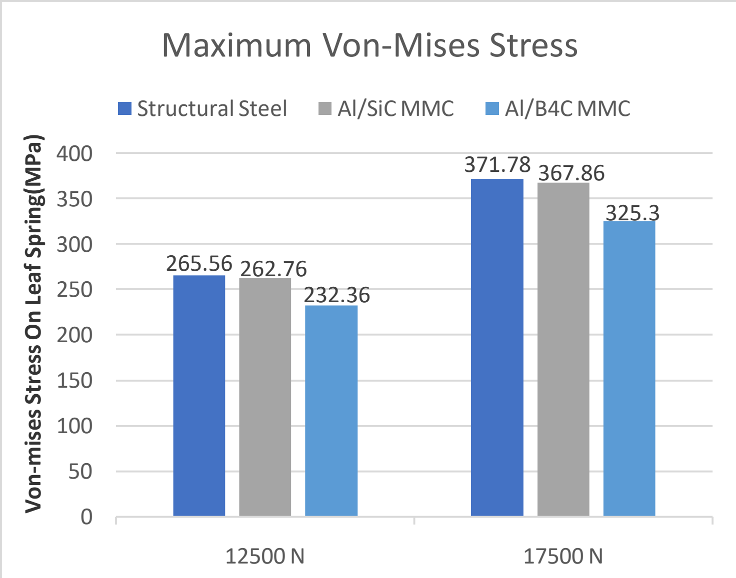

Figure 14: Stress Comparison

4.2 Deformation Comparison

At a load of 12,500 N, structural steel deforms by 1.1683 mm, demonstrating minimal deflection under load. Al/SiC MMC, with a deformation of 1.6591 mm, shows higher flexibility, which may enhance its shock-absorbing capacity. Al/B4C MMC records a deformation of 1.2277 mm, combining stiffness with adequate flexibility to meet performance requirements.

At a higher load of 17,500 N, structural steel deforms by 1.6356 mm, while Al/SiC MMC exhibits a larger deformation of 2.3228 mm, reflecting its relatively higher elasticity. Al/B4C MMC achieves a deformation of 1.7187 mm, indicating its superior stiffness and ability to maintain structural integrity under significant load.

The analysis highlights Al/B4C MMC's optimal performance in balancing deformation and stiffness, ensuring effective shock absorption without compromising structural integrity. Its lower deformation values under both load conditions make it an excellent choice for high-performance automotive applications. Figure 15 provides the graphical representation of the deformation in the leaf spring using three different materials under two different loading conditions.

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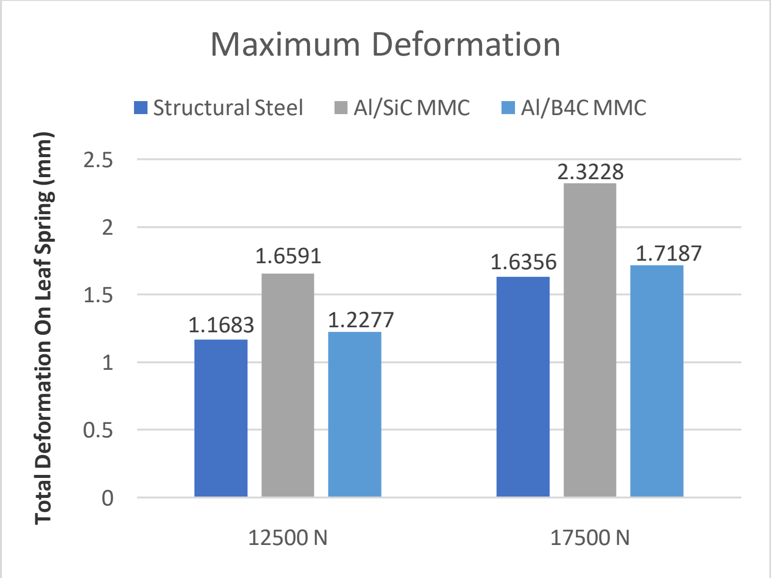

Figure 15: Deformation Comparison

4.3 Weight Reduction

The employment of Al/SiC MMC leads to a weight loss of roughly 58.2%, while Al/B4C MMC has a weight saving of roughly 61.9% against structural steel. These reductions prove vital when improving the vehicle dynamics by reducing the spring weight, and handling, and boost in shock absorptions. Moreover, Al-MMCs are less in weight help improve overall fuel economy, and assist with demanding environmental requirements.

5. Conclusion

This research work provides the possibility of using Aluminium Metal Matrix Composites (Al-MMC) as a viable substitute for steel in the manufacturing of automobile leaf springs. Using Al/SiC MMC and Al/B4C MMC, the total weight of the spring is reduced by up to 60% compared to steel without any significant compromise in mechanical properties. From all the analysed materials, Al/B4C MMC Al/B4C exhibits the highest strength-to-weight ratios and less deformability and this indicates its suitability for applications demanding high performance, durability and weight optimisation. These outcomes demonstrate potential benefits in Al-MMCs such as improved fuel efficiency, and overall vehicle stability. Additional data on dynamic loading and long-term behaviour can expand the utilisation of these composites in automotive applications and contribute to the development of lighter automotive parts.

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