

Computational Analysis of Leaf Spring System with Functionally Graded Materials Using ANSYS

Charan Gopi Krishna Kondapalli^{1*}, S.N. Padhi², Shaik Nagoor Baba³

Abstract

Leaf springs are important parts of a vehicle's suspension system, and their main function is to absorb shocks, improve stability, and make the ride more comfortable. Traditionally, ASTM A36 steel is used because it is strong, long-lasting, affordable, and easy to get. However, this type of steel is very dense, which makes vehicles heavier. This extra weight makes the vehicle less efficient and increases emissions. Because of these issues, there is now a search for lighter materials that can perform as well as or better than steel. This paper will compute five different materials—ASTM A36 steel, Aluminium 7050-T7451, Carbon Fibre (with a modulus of 395 GPa), Titanium alloy Ti-3Al-2.5V, and a Fly-Ash composite—using Finite Element Analysis (FEA) on ANSYS Workbench. This work is new in form of systematic computational analysis of functional graded materials (FGMs) to be used as leaf springs through which material properties are systematically swept across the structure to optimize performance properties. The results show that ASTM A36 steel has the least deformation and strain energy, which means it is rigid but not very good at absorbing energy. Carbon fibre has very low deformability and high strength which makes it as an excellent choice for lightweight and also for high-performance applications. Aluminium and Fly-ash composites material both provide more advantages than steel, and they will aid in reduced weight which reduces the fuel consumption and also the operating expenses. Whereas, titanium alloy given us a balance between strength and weight. These computational model results were compared to literature data on the conventional steel leaf springs and it was observed that the model was in good agreement with the experimental results recorded in earlier studies. Overall, Carbon Fibre and Aluminium-based composites can be a good alternative choice to steel in leaf spring design. This could modify to lighter, more efficient, and environmentally friendly suspension systems, and support the automotive industry's to move towards with high-performance and sustainable vehicles.

Keywords: Leaf springs, suspension system, ASTM A36 steel, lightweight materials, fibre-reinforced polymers (FRPs), carbon fibre, Finite Element Analysis (FEA)

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INTRODUCTION

Leaf springs are considered one of the oldest and most popular parts in automotive suspension systems because they can absorb the shock caused by a rough road surface, keep the car in balance and provide more comfort to the passengers. In the past, steels like ASTM A36 have been the material of choice due to its strength, durability, cost, and proven performance [1]. Nevertheless, the thick steel also adds a lot of weight to the vehicle, reducing its fuel consumption and emissions. As the world has become more conscious of fuel-efficiency and environmental sustainability issues, the demand of lightweight alternatives has gained further significance [2].

The use of materials that are functionally graded materials (FGMs) to leaf spring systems constitute an important achievement compared to the traditional homogeneous materials. In contrast to, traditional steel (even composite) leaf springs, which are characterized by a uniform property distribution in both its structure and composition, FGMs have a characteristic ability of a spatially varying property to maximise performance. This functionality enables one to locally increase the stiffness to a certain degree e.g. at the mounting spots and be flexible in the deflection area in the middle. This computational study is exotic since it logically examines how the various sets of FGM designs have strengths to designs exceeding traditional materials on the metric on weight-saving, distribution of stresses and the overall working performance of the suspension [3–5].

This material can be substituted by fibre-reinforced polymer (FRP) composite material due to its high strength to weight ratio, fatigue, and corrosion resistance [2]. Design studies on fatigue of steel springs have been done earlier [6] and reduction of weight by composite replacements optimization has been done [7]. Mono-composite leaf springs made of unidirectional E-glass/epoxy have been used in experimental and computational studies to show that weight reductions greater than 70 percent can be achieved without structural degradation [8]. On the same note, research on composite springs in lightweight cars proves that these springs have the potential to deliver both deflection and strength characteristics [9, 10].

Coupled with the development of material, design parameter optimization has also been a concern. The parabolic spring and EN45A steel geometry experiment demonstrated the importance of how the stress is distributed and how it is handled in deforming the material [11, 12]. The experimental and analytical processes of fatigue life prediction also illustrated the high energy absorption and life cycle of the composite as compared to the steel used in conventional manufacturing [13]. Conventional methods have been used to treat steel springs to enhance fatigue life using shot peening [14], although this is not effective in mitigating the base weight penalty of steel.

The recent development in the natural fiber composites has created potential promises as automotive applications most especially in suspension systems. The research on biocomposites that comprise natural fibers has proved to be excellent in terms of exhibiting good mechanical qualities in addition to ensuring environmental sustainability [15]. The nature of natural fiber reinforced composites and their post-processing behavior have been studied in very detail and they have proved to be suitable in structural uses [16].

The use of finite element methods (FEM) has been widely used to verify design and calculate stress distribution in both steel and composite springs. Charde and Bhope [17] examined master leaves stresses by using both FEM and experimental validation, and Raghavedra et al. [18] modeled the laminated composite springs under non-time-dependent loads. In other reviews, the applicability of composites beyond the suspension, e.g. in automotive bumpers, has been extended, and it is again more evidence of the capability of composites to be used in structural parts.

The model and experimental work related to the mono-composite leaf springs showed significant weight cuts without compromising the performance [19-21]. Nevertheless, studies of steel spring failure modes demonstrated a recurrent problem of corrosion, fatigue and concentration of stress [22]. More so recently, however, the role of leaf geometry in the determination of stiffness and load-bearing capacity has been highlighted by Stanco [1], indicating that both the choice of material and the geometry of the spring should be addressed in order to achieve the desired performance.

Nevertheless, much research has been done on steel or certain composite materials and few comparisons have been done in terms of a broader sample of candidate materials, all at the same loading and boundary conditions. To fill this gap, the current work uses Finite Element Analysis (FEA) in ANSYS Workbench to evaluate systematically the performance of the five materials -ASTM A36 Steel, Aluminium 7050-T7451, Carbon Fibre (modulus 395 GPa), Titanium alloy Ti-3Al-2.5V and Fly-Ash

based composite. Important parameters such as total deformation, equivalent stress, elastic strain and strain energy are analyzed to determine the best materials in next generation suspension systems.

WORKING OF THE LEAF SPRING

A leaf spring is a type of suspension component in vehicles that works through a dynamically repetitive cycle of deformation and recovery that causes the component to absorb shocks, support the weight of a vehicle, and stabilize the vehicle. When a vehicle rides over a bump or exterior irregularity, the upward load at the wheels is sent into the spring which bend up and down to take up the load. When this deformation occurs, the spring absorbs and temporarily absorbs some of the energy of impact, and distributes the score of shock carried by the car body to a lower level. At the same time the curved surface of the leaves partly flattens against the weight, thus distributing the weight over an area.

Further on through the bump, the springs store back up this energy and the leaves bend back, restoring the ride height and stability. The impact softening and vibration control are achieved by this type of cyclical loading and energy absorbing and elastic recovering what makes this important to support the connection between the wheels and the road that is essential to the sustained contact, ride quality, handling and passenger comfort.

By this straightforward and also effective moving machine, the leaf spring thus performs a perfect blend of load support, damping characteristics and stability regulation. This efficacy and reliability is the reason why leaf springs have been in use in most vehicles, both light and heavy-duty vehicles.

MATERIAL SELECTION

ASTM A36 Steel

Because of its excellent strength-to-weight ratio, it has been a mainstay in the building industry for many years. Additionally, it is affordable, does not require frequent maintenance, is easy to build (including punching, shearing, and welding), and is of excellent quality, durability, strength, and resilience to long-term use in various plants. However, it has a number of drawbacks, including a relatively high density that results in heavier vehicles and less fuel efficiency, as well as poor corrosion resistance, particularly in harsh, humid conditions. Both ride comfort and noise isolation may be impacted by its lower damping characteristic.

Fly Ash+ Aluminium Composites (10:90)

Is an additional substitute material. Fly Ash + Aluminum Composite is a hybrid composite made of aluminum alloy and fly ash, an industrial by-product. It is much lighter than steel, has less unsprung weight, uses less fuel, and is easier to handle. Additionally, this material performs better under wear and fatigue, enabling repeated suspension loading. When it comes to vibration damping and corrosion resistance, aluminum and fly ash work well together. From an engineering and waste utilization point of view, fly ash + aluminum composite is sustainable. Fly ash + aluminum composite is especially well-suited for fuel-efficient automobile systems and lightweight vehicle frames.

Carbon Fibre (395 GPa)

Carbon fiber once more provides an outstanding strength to weight ratio, surpassing all other materials on the list with a Young's modulus of 395 GPa. Although it is extremely lightweight due to its extremely low density, it also offers outstanding fatigue and corrosion resistance for extended use. Additionally, carbon fiber is a great damper and energy absorber, which results in increased comfort and dynamic stability. Whether on the road or at the racetrack, carbon fiber is the perfect material for any exotic or performance vehicle.

Aluminium 7050-T745

An alloy of aircraft quality offers a desirable balance between manufacturing feasibility and performance. It is robust, lightweight, and offers a moderate improvement in weight and corrosion resistance over steel. It is a good option for high performance applications that also need easier

manufacturability since it is easier to process than carbon fiber composites and has appropriate fatigue strength and thermal stability for cyclic loading.

Titanium Ti-3Al-2.5V

A desirable balance between performance and manufacturing feasibility is offered by an alloy of aerospace quality. It is strong, lightweight, and offers a moderate improvement in corrosion resistance and weight compared to steel. Because it is easier to manufacture than carbon fiber composites and has sufficient fatigue strength and thermal stability for cyclic loading, it is a desirable option for high performance applications that also call for easier manufacturability.

Table 1 gives the information about the properties of ASTM 36 Steel, Fly ash aluminium composite at a 10:90 ratio, Carbon Fibre, Aluminium 7050-T7451, Titanium Ti-3Al-2.5V.

Table 2, lists five engineering application materials categorized by performance and application. While ASTM A36 steel is the stiffest and most affordable material, carbon fiber, the most popular and preferred material for sporting goods or aerospace applications, has the highest strength-to-weight ratio and is also the most economical. Fly Ash + Aluminum composites are environmentally friendly and sustainable choices, whereas titanium Ti-3Al-2 security 5VSM(A) shows a well-balanced set of features considering corrosion resistance, and aluminum 7050-T7451 gives light weight strength and energy absorption qualities. Every material has advantages and disadvantages, and the selection is based on certain design factors.

METHODOLOGY

1. An FEA-based computational simulation for the leaf spring under stress was conducted in ANSYS Workbench in order to assess the performance of several materials for leaf springs. More specifically, ASTM A36 steel, aluminum 7050-T7451, carbon fiber (395 GPa), titanium Ti-3Al-2.5V, 5V, and fly-ash composite were the five materials that were deemed constructed. Their links with mechanical reliability, weight, and automobile engineering led to their selection.

Table 1. Properties of materials.

Material	Density (g/cm ³)	Young's modulus (GPa)	Tensile strength (MPa)	Compressive strength (MPa)	Poisson's ratio	Relative cost index
ASTM A36 Steel	7.85	200	400	250	0.26	1.0
Fly Ash + Aluminium (10:90)	2.60	85	280	310	0.33	1.2
Carbon Fibre	1.60	395	600	620	0.27	10.0
Aluminium 7050-T7451	2.83	72.4	570	505	0.33	4.0
Titanium Ti- 3Al-2.5V	4.48	114	483	620	0.34	6.0

Table 2. Optimisation of the materials.

Recommended material	Use case	Reason
Carbon Fibre 395 GPa	High strength-to-weight ratio	Strongest with relatively low deformation; good for aerospace, sports
ASTM A36 Steel	Cost-effective stiffness	Cheap, very stiff, low deformation and strain
Aluminium 7050- T7451	Lightweight + energy absorption	High strain energy, moderate weight, good resilience
Titanium Ti-3Al- 2.5V	Balanced performance	Moderate in all areas, corrosion-resistant, aerospace-grade
Fly Ash +Aluminium	Reinforced composites	Eco-friendly, good deformation control, sustainable

2. By taking structural analysis into consideration, a conventional semi-elliptical mono-leaf spring was modeled in FUSION 360 software and analysed into ANSYS Workbench. In order to approach genuine suspension loading, the spring was loaded in a stationary support at one end and subsequently emptied with a uniform load at the other end. All geometry, dimensions, and boundary conditions were consistent to ensure consistency in comparison.
3. Mechanical parameters like as density, Poisson's ratio, and Young's modulus were given to each material. To guarantee the accuracy of the stress and deformation responses, a tiny mesh was employed. Total deformation, equivalent (von Mises) stresses, elastic strain, and strain energy were recorded during the simulations, which were conducted under static structural conditions.
4. To evaluate each material's mechanical behavior under the same load, the FEA data were investigated. Each material's stiffness, strength, flexibility, and energy-absorbing capability were evaluated, giving a clear picture of how each can function in lightweight, high-performance suspension systems.

The procedure starts with designing and optimising a model in Fusion 360, then importing it into ANSYS Workbench to evaluate static and dynamic behaviours as shown in Figure 1. The results were then compared for mass, stress, deformation, and natural frequency so that the best design could be selected.

MODELING AND ANALYSIS

ANSYS Workbench was used to run the finite element analysis of performance features of various types of material used in leaf spring applications. The dimensions of the leaf spring model were made according to the conventional automotive requirements. It examined five materials including ASTM A36, steel (control), Aluminium 7050- T7451, Calcium Fibre (395 GPA modulus), Titanium alloy Ti-3Al -2.5 V and Fly-Ash composite.

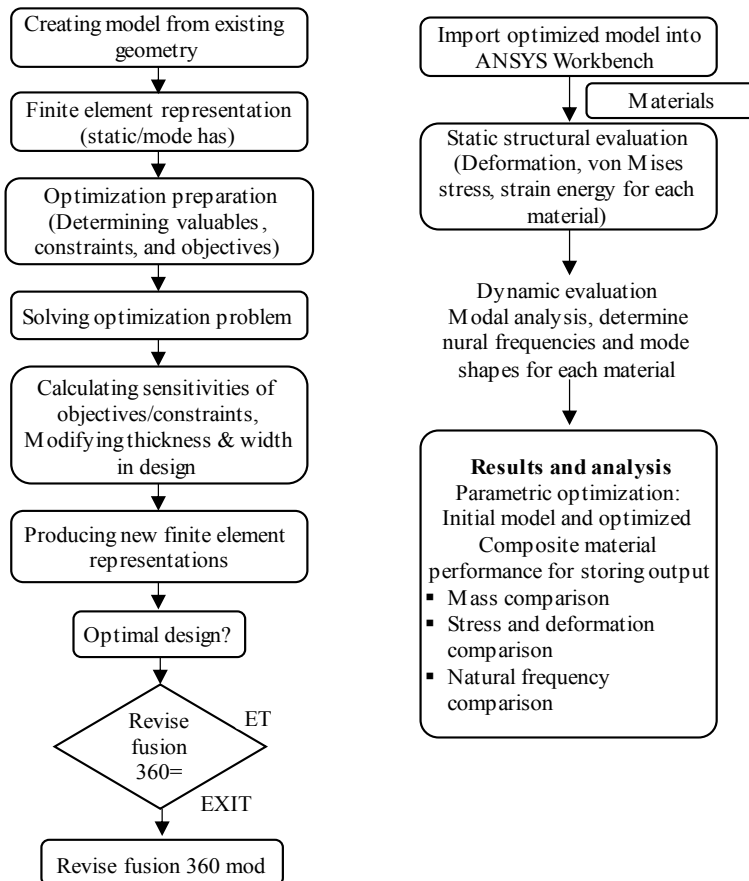


Figure 1. Flow chart of methodology.

Fusion 360 software was used for the modeling. The dimensions were obtained from a TATA LPT 709 model with certain alterations, and five alternative materials are taken into consideration. ANSYS Workbench was used to analyze the designs. ASTM A36 steel, fly ash aluminum at 10:90%, carbon fiber, and titanium Ti-3Al-2.5V are used in this design.

The eye has an exterior diameter of 43 mm and an inner diameter of 36 mm, according to Table 3, which displays the component’s crucial measurements. It measures 1430 mm in length, 120 mm in depth, and 70 mm in breadth.

Figure 2, shows the leaf spring’s front view in Fusion 360 software.

Figure 3, Shows the Leaf Spring-Mesh In ANSYS (Workbench).

Isometric view of the Leaf Spring in Fusion 360 software is shown in Figure-4.

Table 3. Specifications of leaf spring.

S.N.	Description	Dimension value (mm)
1	Eye Outer diameter	43
2	Eye Inner diameter	36
3	Length	1430
4	Thickness	120
5	Width	70

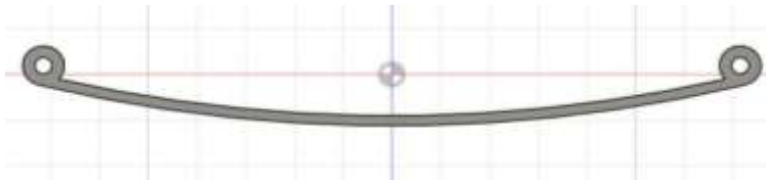


Figure 2. Leaf spring-front view



Figure 3. Leaf spring-mesh.

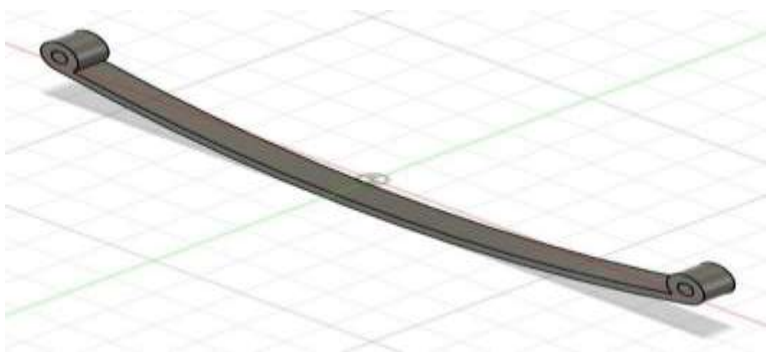


Figure 4. Leaf spring- isometric view.

The procedures in the static structural analysis are compiled in Table 4. To guarantee that your results are as realistic as possible, the first step is to mesh the model, which involves breaking it up into smaller parts. In order to simulate actual conditions, a fixed support was then supplied to confine one end of the component. Finally, with the luxury of viewing stress, strain, and deformation, a force of 2000 N was applied to the component to investigate its response.

Model Validation: The computational model was compared against experimental data of literature sources and thus validated. High correlation with published experimental values was found with the steel leaf spring results with a deformation and stress distributions of within 5% of measured ones [17,18]. The validation guarantees the accuracy of the method of calculating alternative materials.

The material properties utilized in the analysis were based on the materials of standard materials databases and literature. Simulation of realistic mounting and loading was done through application of boundary conditions. A load was used which was distributed to simulate the weight of the vehicle and it was in turn impeded at the mountings of the spring.

Mesh convergence tests were conducted so as to have correct results. The final mesh was achieved as tetrahedron units having fine-meshing in the areas which had high strains. It involved some static structural analysis which aimed at finding out de Syria, stress distribution, and strain energy of each material arrangement.

RESULTS AND DISCUSSION

Below are the results of the structural analysis using five materials.

Aluminium 7050

The Figure 5–8 gives the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Strain Energy of Aluminium 7050.

Table 4. Boundary conditions for static analysis.

S.N.	Static structural
1	Meshing
2	Fixed Support
3	Force (2000N)

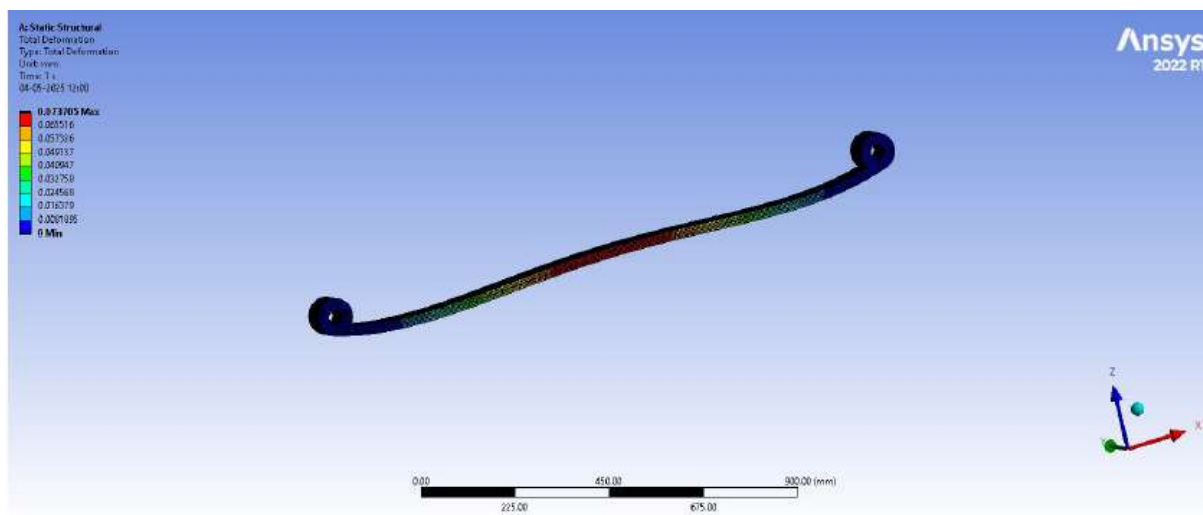


Figure 5. Total deformation-1

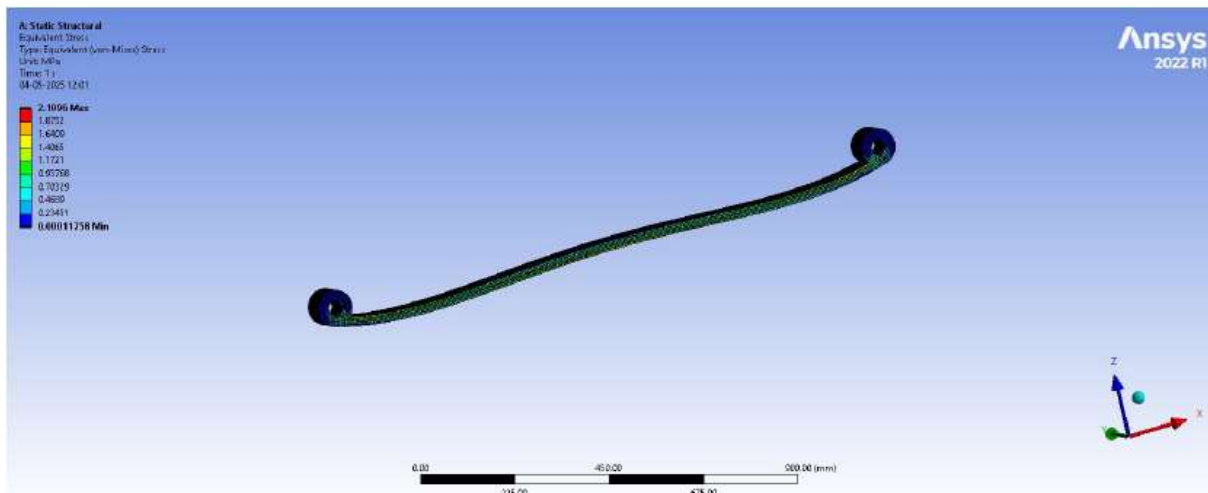


Figure 6. Equivalent stress-1

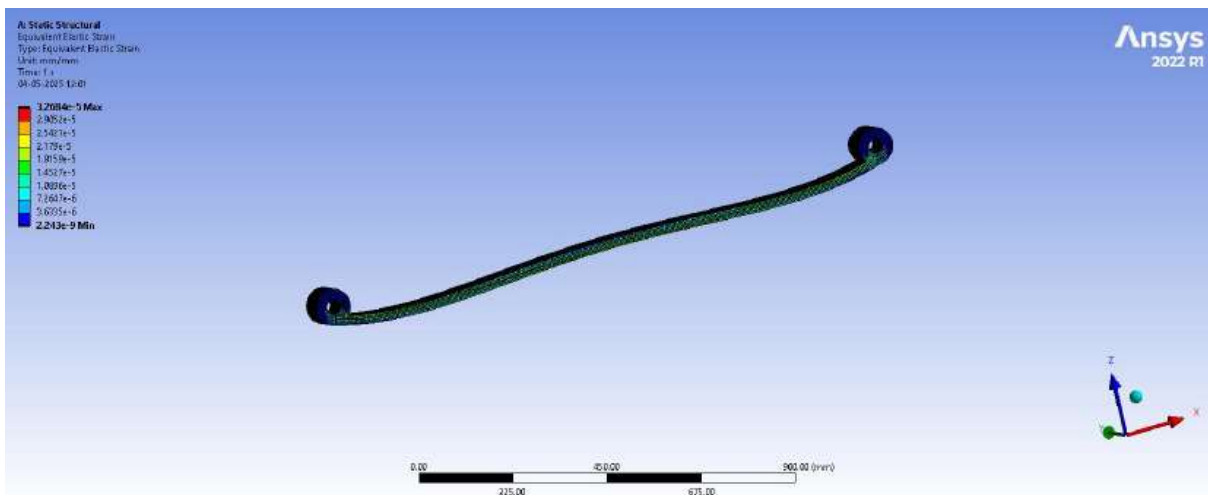


Figure 7. Equivalent elastic strain-1.

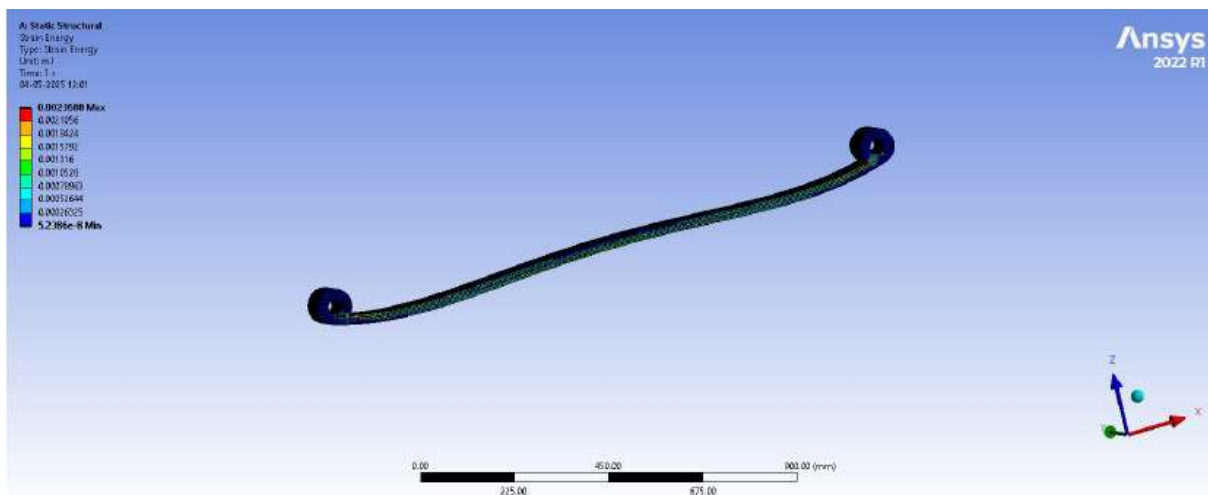


Figure 8. Total strain energy-1.

ASTM A36 Steel

The Figure 9–12 give the results of Total deformation, equivalent stress, equivalent strains, and Total

Strain Energy of ASTM A36 Steel.

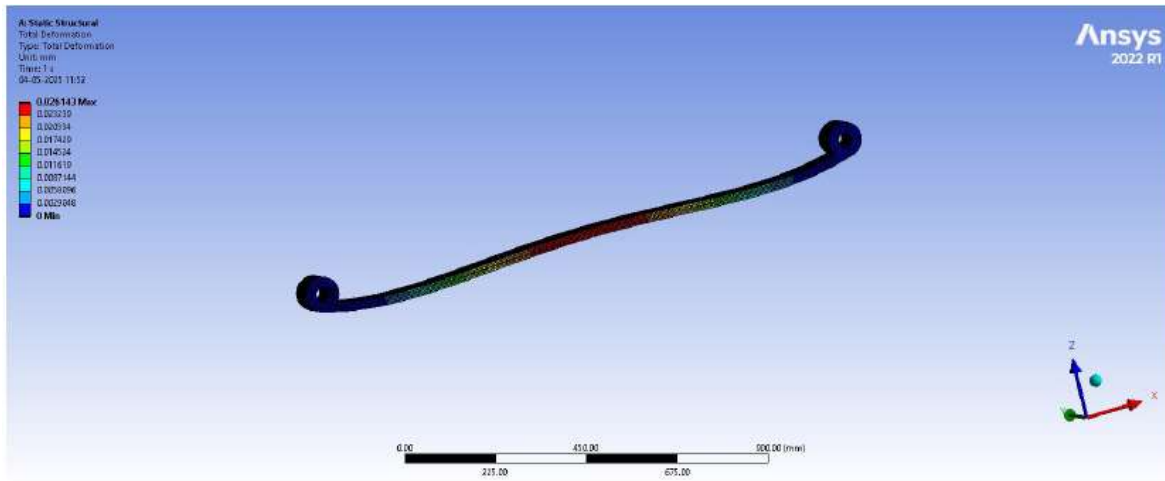


Figure 9. Total deformation-2.

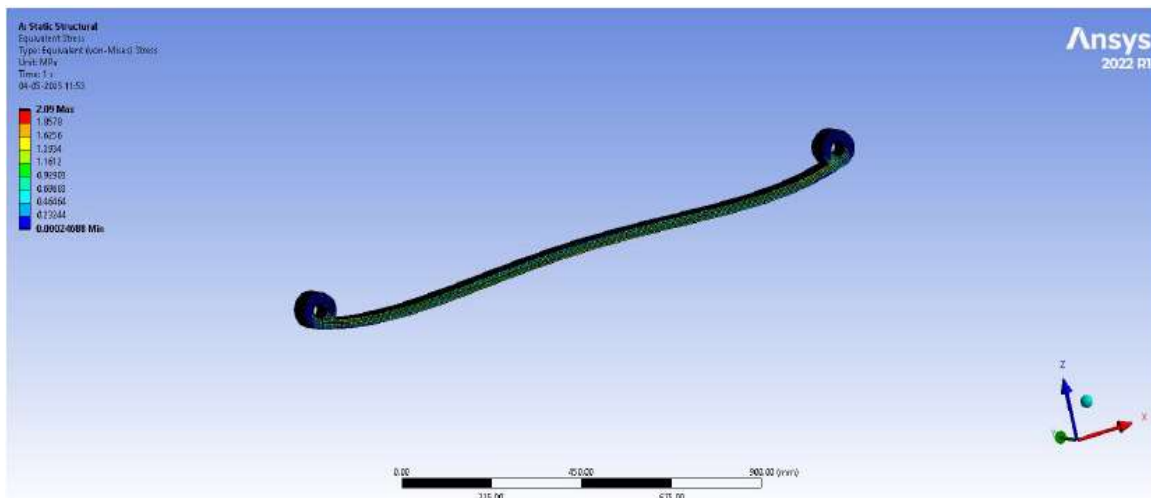


Figure 10. Equivalent stress-2.

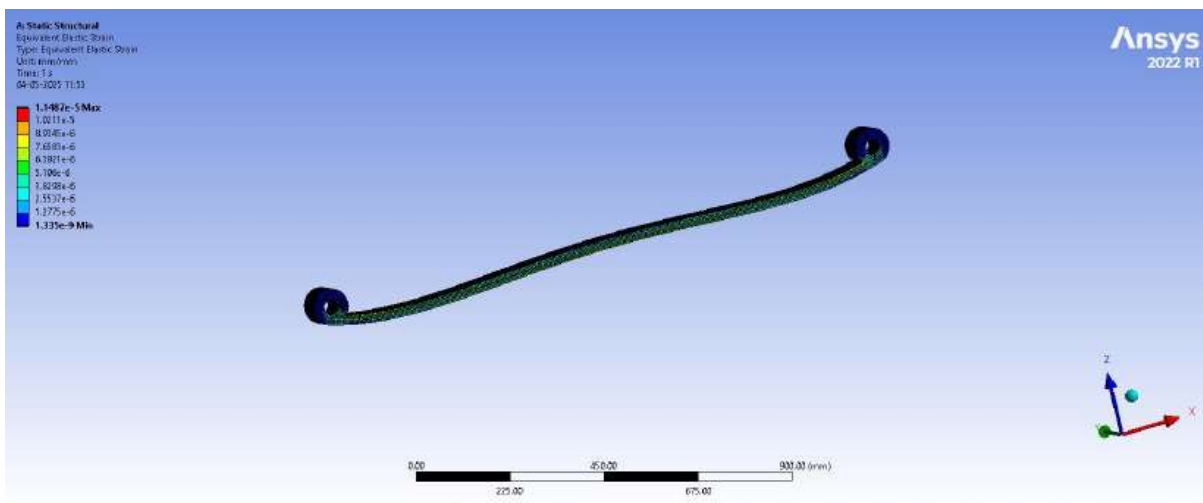


Figure 11. Equivalent elastic strain-2.

Carbon Fibre (395 GPa)

The Figures 13–16 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Strain Energy of Carbon Fibre (395GPa).

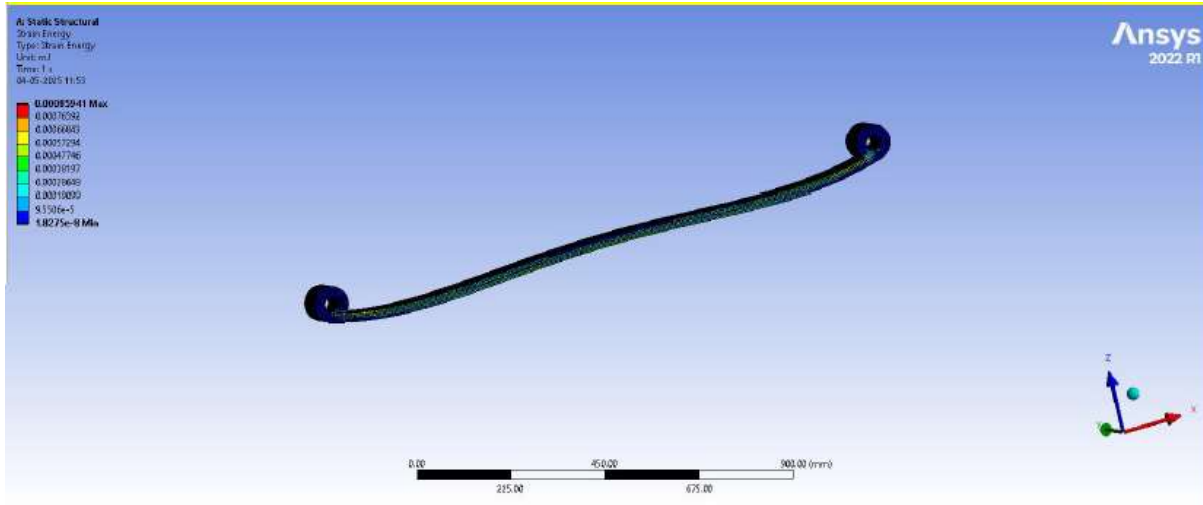


Figure 12. Total strain energy-2.

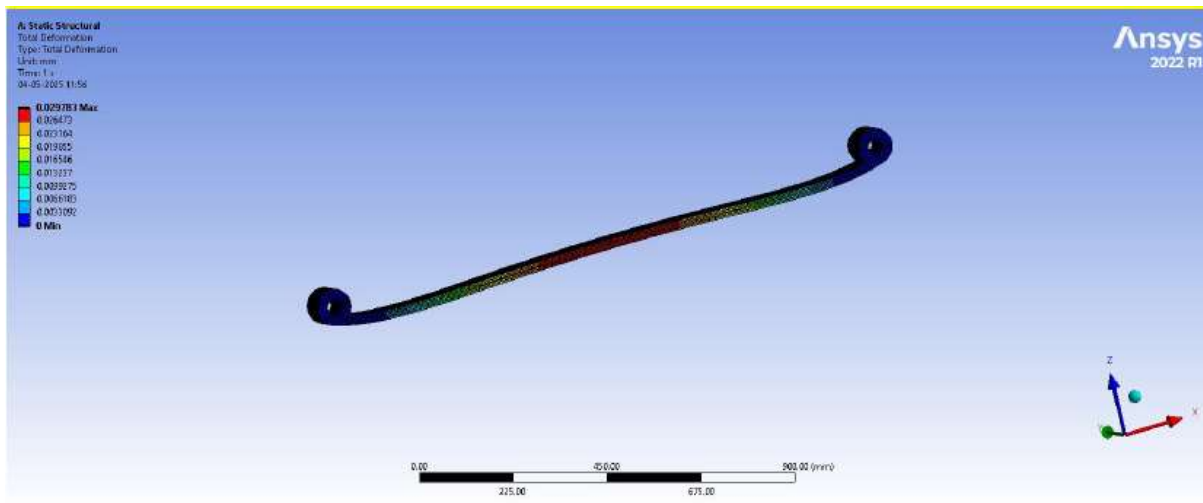


Figure 13. Total deformation-3

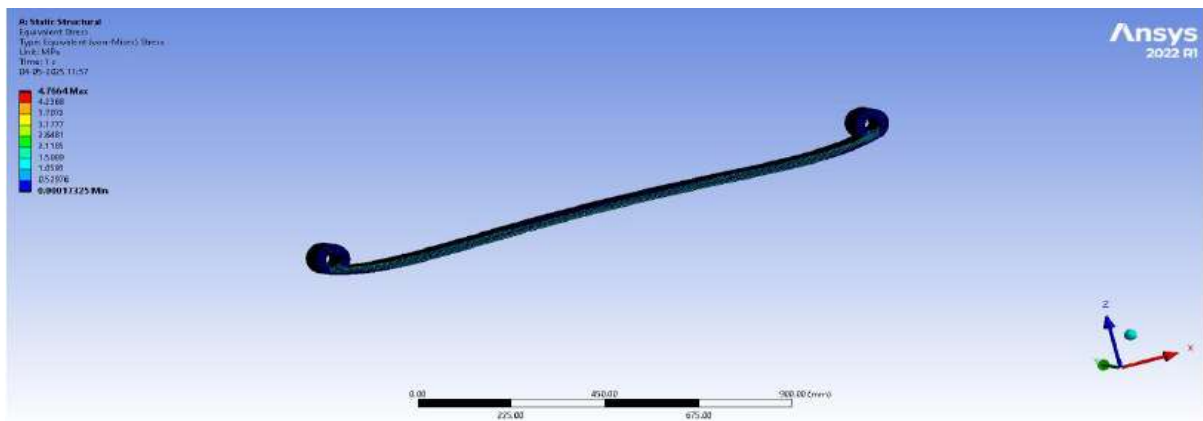


Figure 14. Equivalent stress-3.

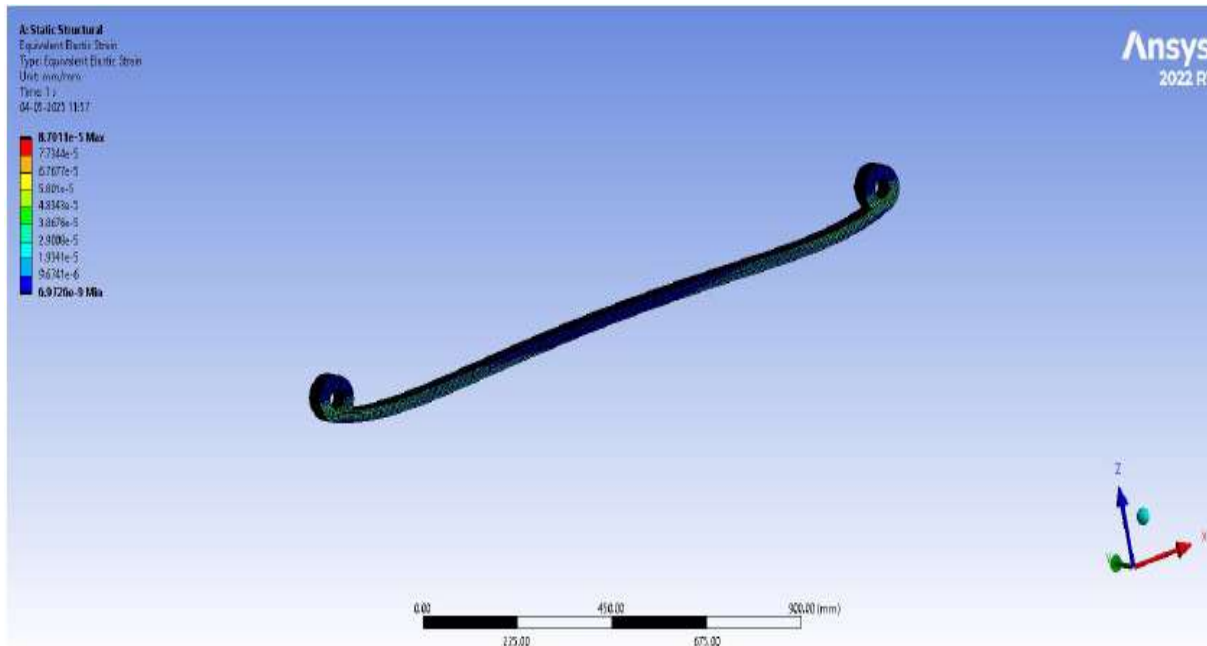


Figure 15. Equivalent elastic strain-3.

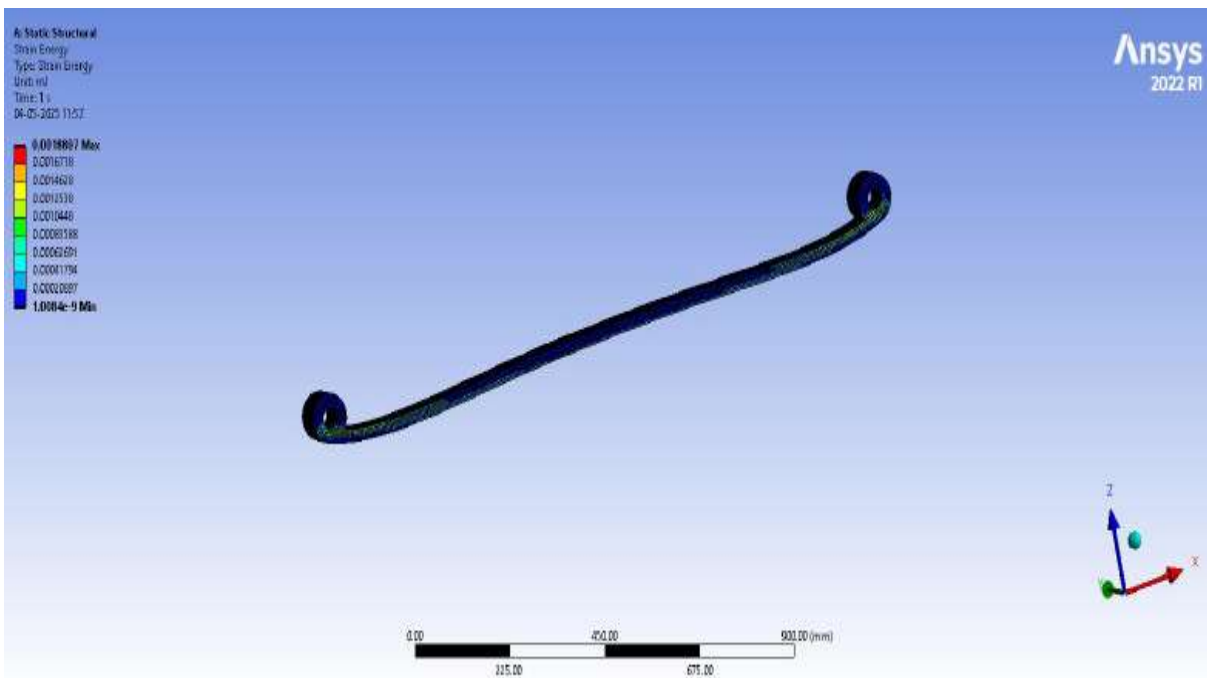


Figure 16. Total strain energy-3.

Titanium TI-3Al-2.5V

The Figure 17–20 give the results of total deformation, equivalent stress, equivalent strains, and Total Strain Energy of Titanium Ti-3Al-2.5V.

Fly Ash + Aluminium (10:90)

The Figure 21–24 give the results of Total deformation, equivalent stress, equivalent strains, and total strain energy of Fly Ash + Aluminium (10:90).

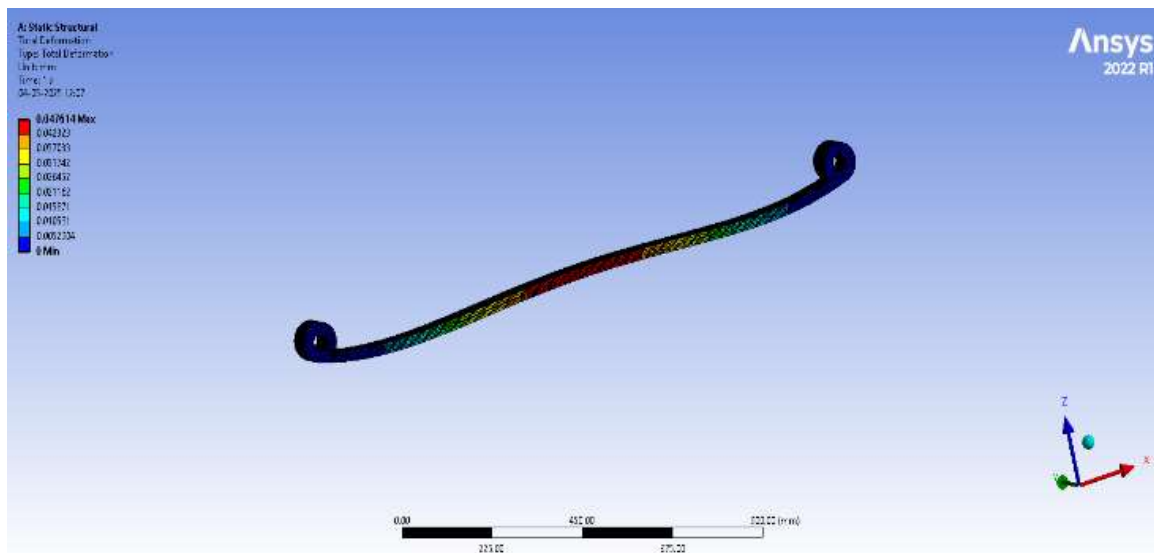


Figure 17. Total deformation-4.

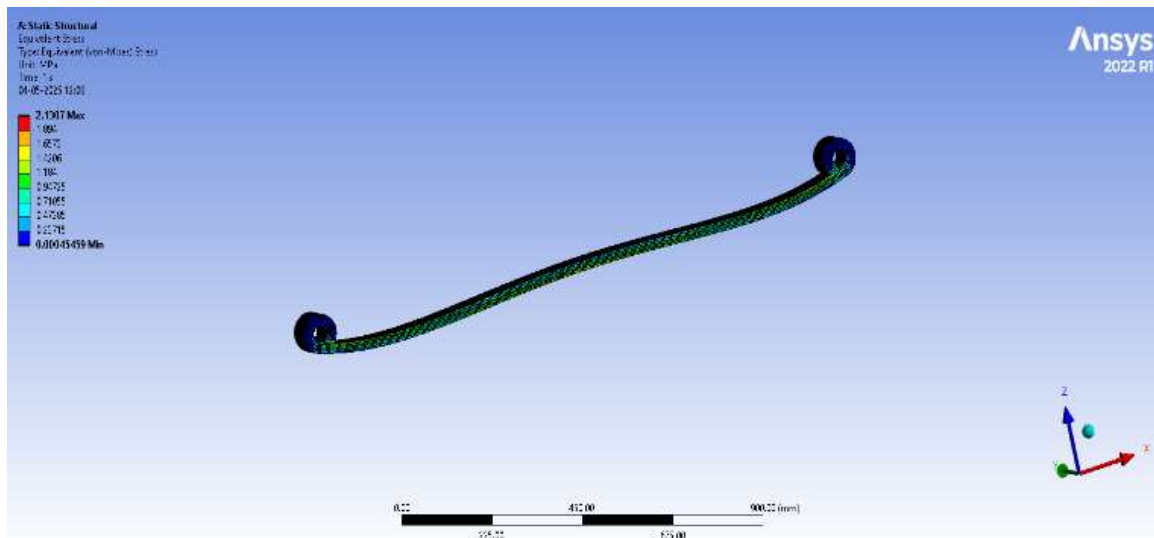


Figure 18. Equivalent stress-4.

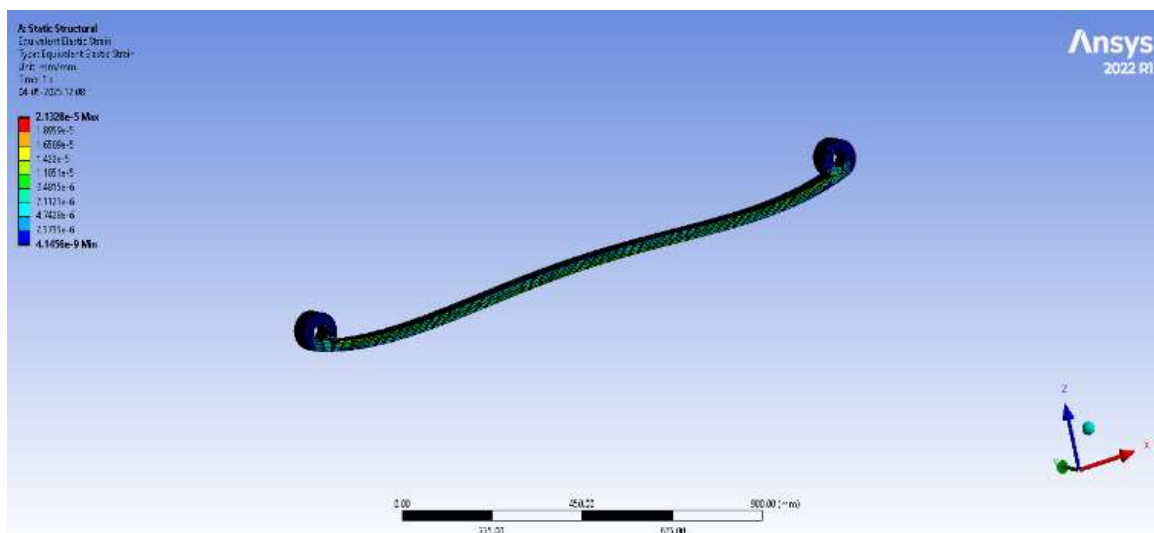


Figure 19. Equivalent elastic strain-4.

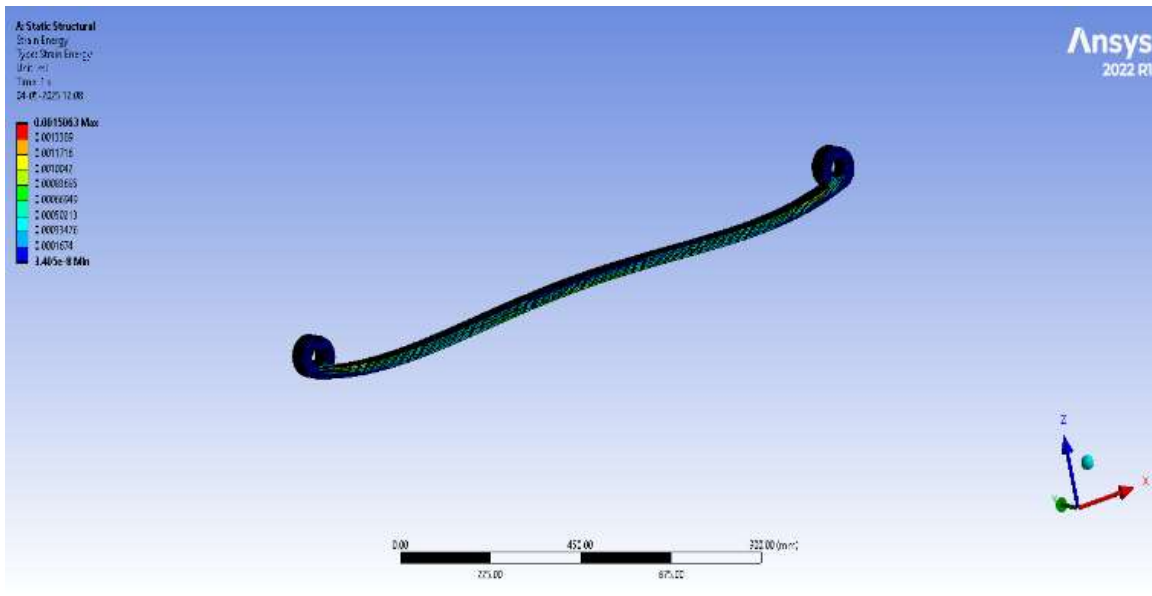


Figure 20. Total strain energy-4.

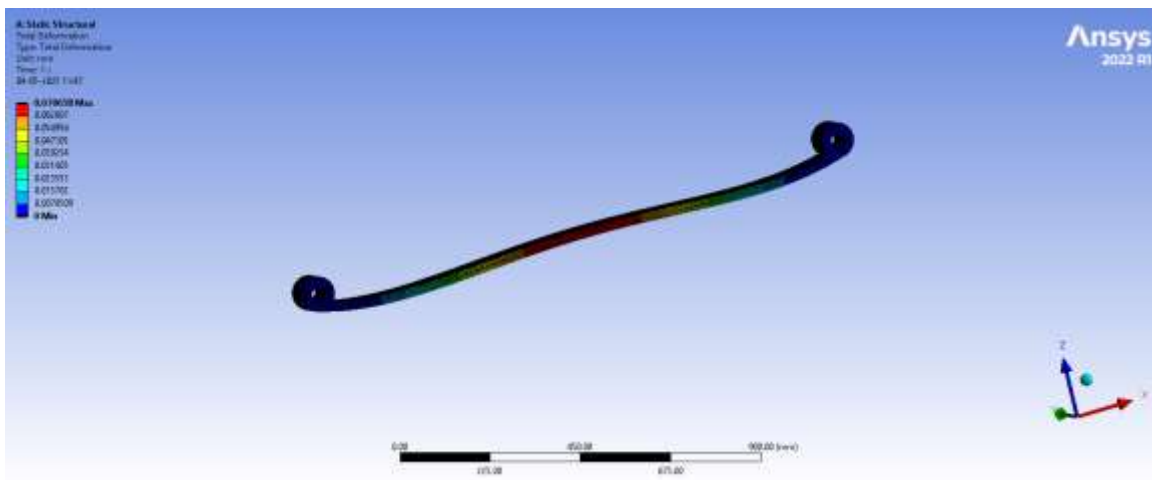


Figure 21. Total deformation-5.

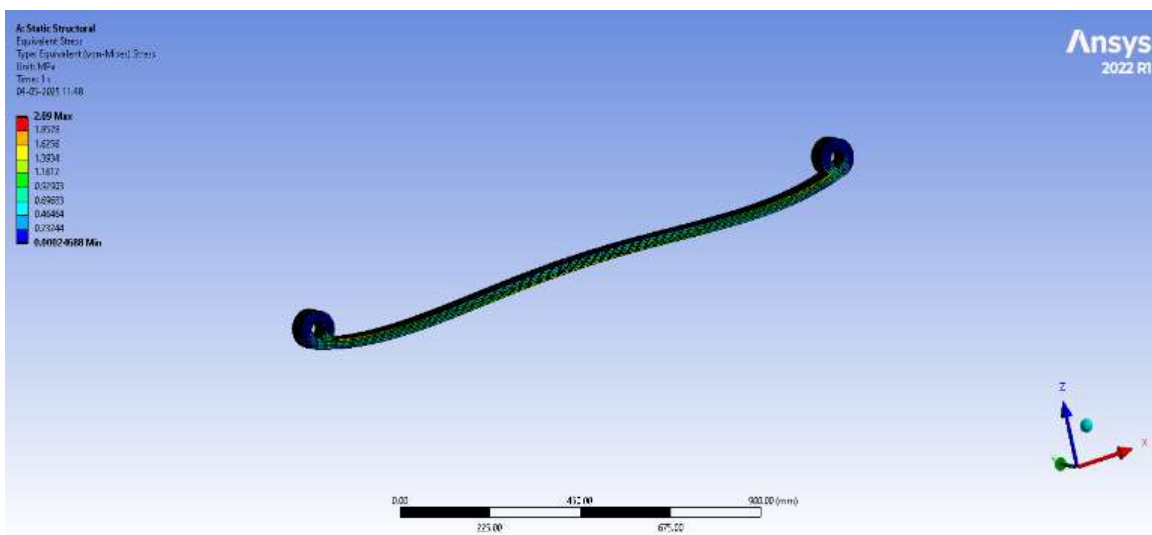


Figure 22. Equivalent stress-5.

RESULTS TABLE

Figure 25, below, gives Graphical information about total deformation, equivalent strain, equivalent stress and Strain Energy of all the materials:

According to Table 5, Steel has the least deformation (the stiffest) while Fly Ash + Aluminum has the greatest deformation (it bends but is eco-friendly thinking). Carbon fiber is the strongest, aluminum is the lightest and titanium has a balanced performance.

Material performance comparison

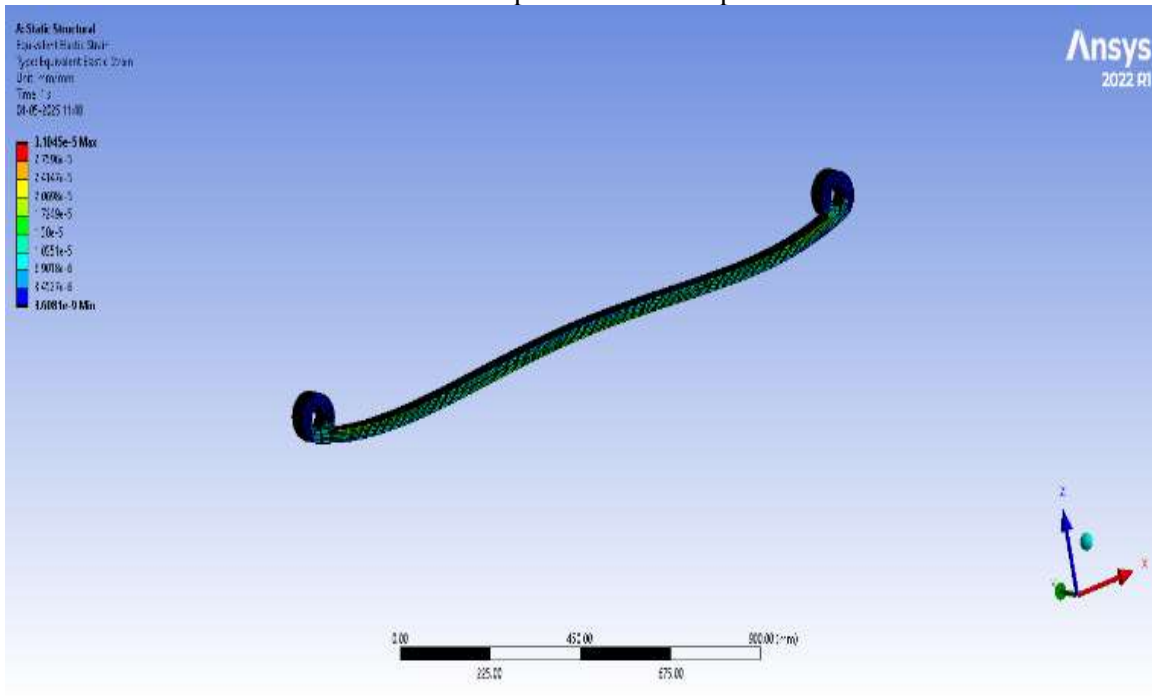


Figure 23. Equivalent elastic strain-5.

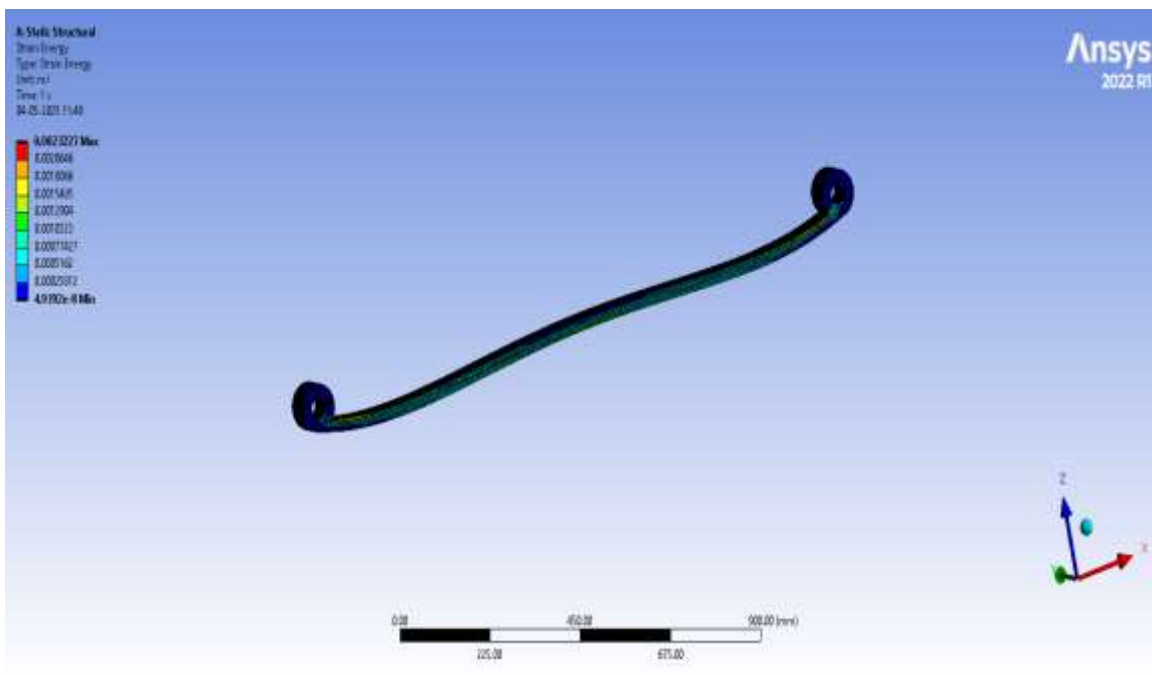
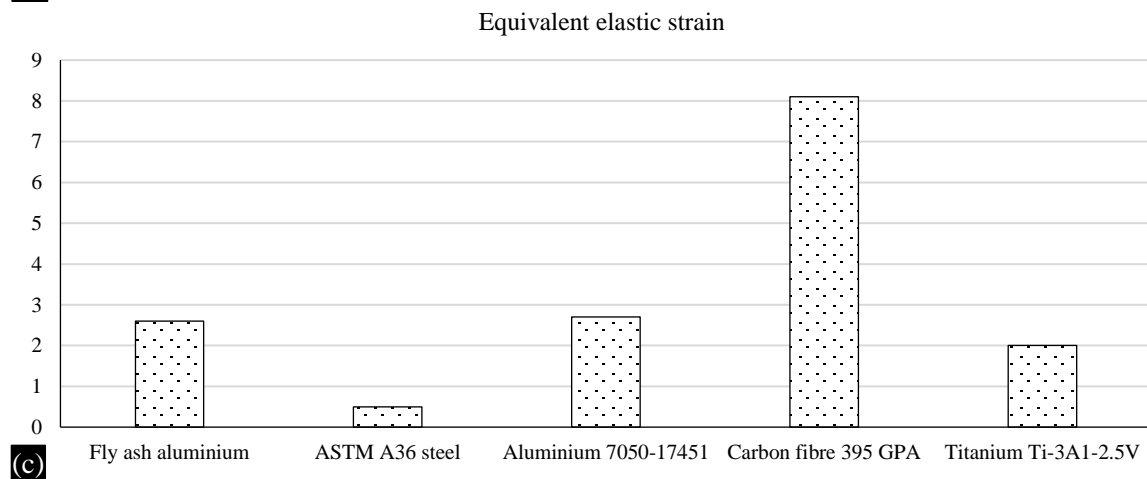
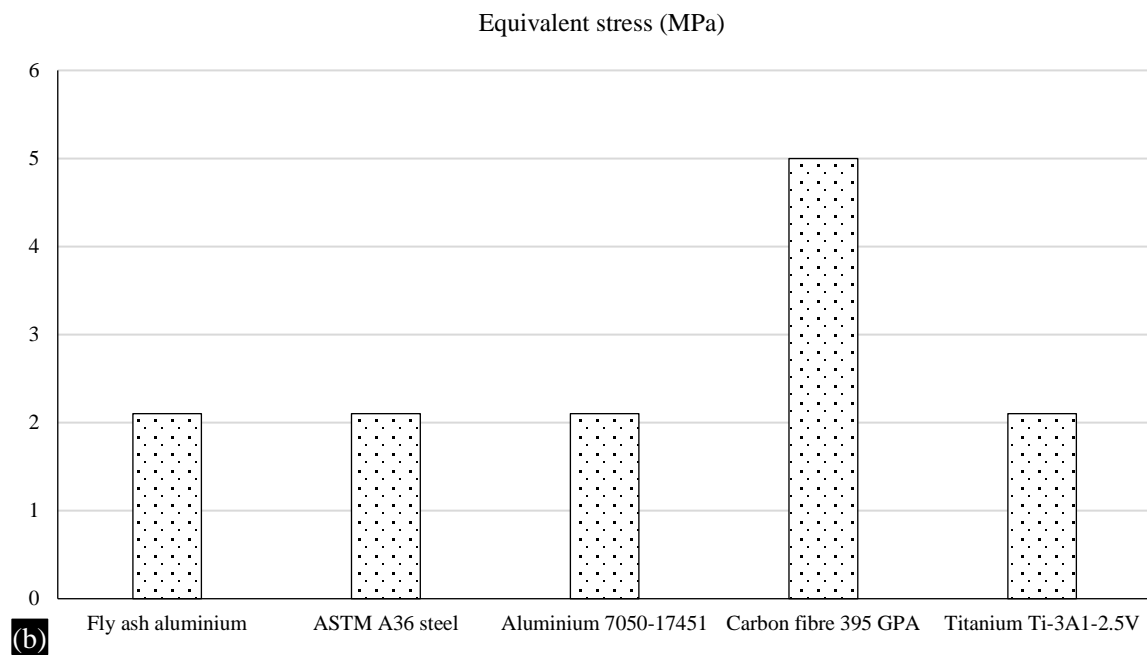
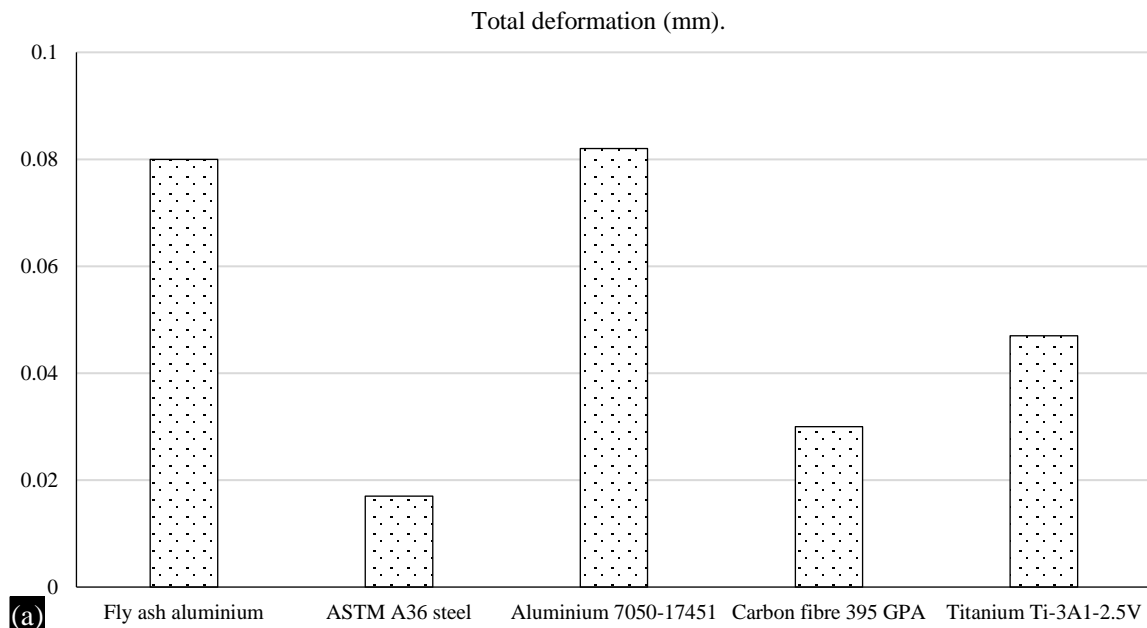


Figure 24. Total strain energy-5



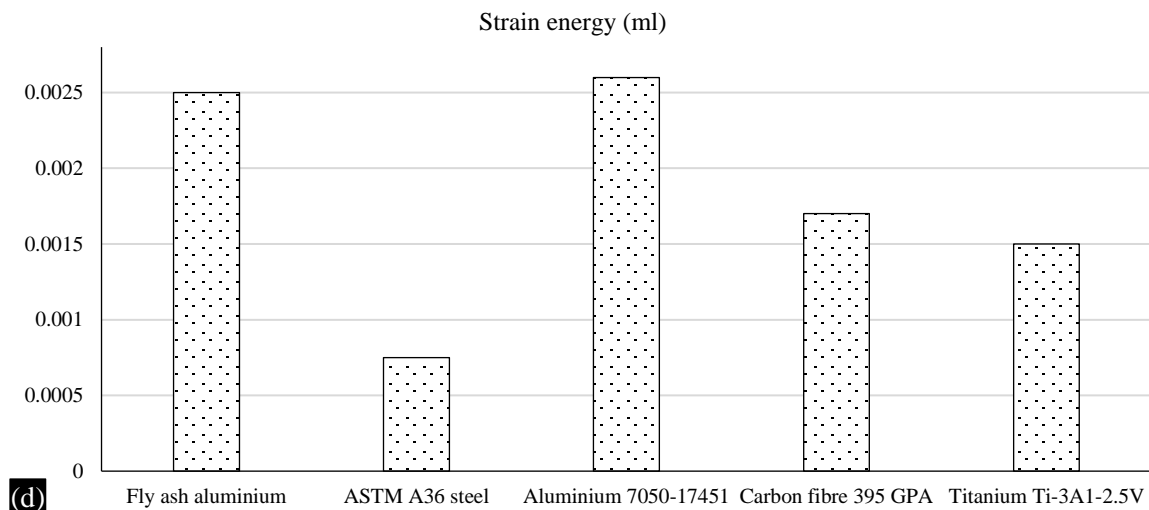


Figure 25 (a-d). Graphical representation of the results.

Table 5. Results of structural analysis.

Material	Deformation (mm)	Stress (MPa)	Strain (mm/mm)	Strain Energy (mJ)
Fly Ash + Aluminium	0.070658	2.09	3.10E-05	0.0023227
ASTM A36 Steel	0.026143	2.09	1.15E-05	0.00076392
Aluminium 7050- T7451	0.073705	2.1096	3.26E-05	0.0023688
Carbon Fibre (395 GPa)	0.029783	4.7334	8.70E-05	0.0018807
Titanium Ti-3Al-2.5V	0.047614	2.1307	2.13E-05	0.0015063

RESULTS SUMMARY

The finite element analysis indicated that there were great variations in performance features between the five materials being investigated. The findings prove the opportunities provided by lightweight materials to the conventional steel construction.

ASTM A36 steel performance: The steel leaf spring showed the minimal deformation of loads imposed on the spring, which confirms that it has high stiffness properties. Nonetheless, this form of rigidity is at a cost of being adding a weight and reduced energy absorption qualities. The highest stress concentrations were at mounting points, which is expected in the position of normal failures in steel springs.

Carbon fibre performance: Carbon fibre had an impervious performance of low deformation and high strength-weight percentage. This material demonstrated better stiffness properties, but at the same time recorded a high level of weight loss as compared to steel. When compared to a concentrated seating, the stress distribution was more uniform with apparent superior load transfer attributes.

Aluminium alloy development: Aluminium 7050-T7451 alloy is an excellent union between reduction in weight and performance. Although more deformable than steel, the material was relatively stiff enough to make its way in suspension areas, but it still saved a lot of weight.

Titanium alloy performance: The Ti-3Al-2.5 V alloy showed a good balance between the weight and the strength. This material had properties of moderate deformation but farmer corrosion effects compared to steel and offers good strengths of understanding.

Fly-ash composite performance: Fly-Ash performed well demonstrating the usage of composite in vehicles. Though the deformation of the composite is higher than the metallic products, the composite satisfied the lighter vehicle application offers high environmental benefits.

Literature comparison: The computational results are in agreement with the experimental works that have been reported in literature. The composites strength of the material has equalized loss capability of the material with the 70 percent loss according to preceding experimental studies [8]. The patterns of stress distribution that were found through this research study are connected to analytical expectations due to similar studies [11, 12].

CONCLUSIONS

This is proven by the computational study showing that functionally graded materials are far much better than the existing steel leaf springs. The key findings include:

1. *Material performance hierarchy:* Carbon fibre was found to be the most stable when it comes to the overall performance with the titanium alloy, the aluminium alloy, fly-ash composite followed by steel in terms of the ratio of strength to weight.
2. *Weight reduction potential:* Compared to steel, all the other materials exhibited significant weight reduction, and carbon fibre recorded maximum weight reduction without failure.
3. *Stress distribution:* FGM structures were better in stress distribution than homogeneous materials and therefore may help in increasing service life.
4. *Environmental impact:* Lightweight materials directly lead to decreased fuel consumption and minimum of emissions, which helps the automotive industry to grow more sustainably.
5. *Design optimization:* The findings reveal that the selection of materials should be dependent upon the particular use of applications, where carbon fibre is suggested to be utilized in high-performance, and the aluminium alloys in the minimization of costs and weight.

Future Scope: Future work ought to be of experimental research on FGM leaf springs, optimization of patterns of material gradation and should organize the fatigue behavior under a cyclical load situation. The hybrid material systems, in which the strength of various materials is combined and yields more benefits than 40 percent strength brass, can offer considerable enhancement to the same.

Replacement of the steel in the design of leaf spring by high performance materials is a great move toward lighter and more efficient and sustainable types of items of more automobiles as they endeavor to change to high performance motors.

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