IJME

Int. J. of Applied Mechanics and Engineering, 2025, vol.30, No.1, pp.89-100
DOI: 10.59441/ijame/197392

WEIGHT OPTIMIZATION OF LEAF SPRING ASSEMBLY USING DESIGN FOR MANUFACTURING APPROACH AND FEM IN GRADUATED LEAVES FOR ELECTRIC VEHICLE

Mohammed Irfan Khan and Shubham Soni
Mechanical Engineering, Medi-Caps University, INDIA

Anil Patel and Chitresh Nayak*
Mechanical Engineering, Medi-Caps University Indore, INDIA
E-mail: chitresh2001@gmail.com

The aim of this study is to determine the ideal stress distribution for a multi-leaf spring assembly using finite element analysis. Furthermore, the topology enhanced model, based on associate load is included in this research work. This work is carried out by considering two different techniques involving design for manufacturing (DFM) after the attainment of results from topology optimization. The vehicle's overall load is bear by the main leaf spring and graduated leaves are used to support the main leaf thus the prospective techniques intend to create holes across the graduated leaves and cut a custom slot along the graduated leaves of the spring assembly. The disclosure manifest that it is feasible to lessen the leaf spring assembly weight in order to create a lightweight, structurally sound design and reduce energy consumption that can be employed to heavy-duty commercial electric vehicles. The suggested techniques promisingly anticipate that a significant proportion of weight deduction of about *3.4* percent with holes and *17.34* percent with slots can be attained in multi-leaf spring assembly.

Key words: multi-leaf spring, finite element method, topology optimization, electric vehicle.

1. Introduction

The huge requirement for lightweight components leads the automobile industries to design such components that can provide economical solutions in contemporary mobility and transportation [1]. In the industrial sector, a product’s weight can be reduced by using fewer resources during manufacturing which leads less energy in transportation, protecting natural resources and lowering hazardous emissions. With the development of numerical tools to simulate the complicated geometries of lightweight structures, lightweight design aims to construct structures with a minimal usage of materials and an optimal exploitation of the material strength [2].

The suspension systems of automobiles, including trucks, heavy-duty vehicles, train cars, etc., rely heavily on leaf springs. The leaf spring assembly has purposes other than only serving as a suspension component. It is also used to separate vibrations brought on by roads. Due to their inner leaf contact, leaf springs behaviour is far more intricate than their outside look [3]. FE analysis is a prominent approach for predicting the deflection and stresses in leaf springs among the different contemporary optimization techniques [4].

Since the leaf spring is a crucial component that keeps the entire weight of automobiles, it is crucial to understand how loads affect the spring. Some researchers have compared the static and fatigue life of leaf spring having different materials [5-6]. Some studies have been done on structural and fatigue load analysis to determine the design and strength of leaf springs [7]. The researches have been done on semi-analytical model to analyse large deformation elastic behaviour of leaf spring to suggest the variation of spring parameters when a load is applied [8]. In order to better understand the bending of two straight, uniform leaves, some researchers

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[*] To whom correspondence should be addressed

study how spring leaves interact when bent at the joint. This method will help determine how the leaves interact in more complex situations. [9-10].

A lot of work is currently being done to replace traditional leaf springs with composite materials. Numerous authors have concentrated on various fibre-reinforced composites, examining their numerous advantages over steel materials [11-13]. Several researches are conducted on natural fibre reinforced polymer composites that are environment friendly to improve the mechanical properties by hybridization and optimisation which will further enhance the performance and effectiveness of polymer-composites [14-15]. Composites reinforced with natural/synthetic fibres have multiple uses, including weight reduction that cannot be accomplished with a single fibre and a synergistic interaction between the reinforcements [16-17]. Hybrid composites – like those made of glass and carbon fiber combinations – offer a number of benefits. These include a high strength-to-weight ratio, greater fatigue resistance, and corrosion resistance, all of which extend vehicle lifespan and boost efficiency. Although the potential performance benefits, there are still obstacles that make their widespread adoption difficult, including the complexity of manufacturing, compatibility problems between various materials, and the increased prices connected with raw materials and production methods.

Currently, topology optimization is a well-researched theoretical idea and a common industrial design methodology. The available space, the loads, and the numerous boundary conditions are taken into account when developing the new design. Researchers use topology optimization to optimise the shape of the leaf spring using a variety of models, concluding that the technique can result in a sizable weight reduction [18-20]. Many researchers have found that the topology optimization of a materials may be solved using this strategy by applying dependent and static loads on a range of composite materials [21-22]. As per studies, topology optimization and additive manufacturing are useful techniques for creating lightweight automobiles [23].

This research presents a new way of looking at leaf spring analysis and design. The performance of electric vehicles is being improved and optimized through this research. Additionally, a lightweight vehicle may be built by distributing the load and understanding the stresses on the leaf spring. The finite element method was used to study the leaf spring's stress distribution. Additional FE evaluations of topology optimization were performed using the structural steel's material properties. Two novel strategies for leaf spring assembly weight reduction are suggested in this work. The methods demonstrate the weight reduction by creating uniform slots and producing circular holes throughout the leaf spring's length.

2. Material selection and design methodology

Structural steel and aluminium are commonly chosen for their strength, durability, lightweight nature, corrosion resistance, and recyclability. Steel is ideal for load-bearing structures due to its high tensile strength and availability, while aluminium is favoured for applications requiring lightweight materials. However, alternative materials like composites, titanium, and magnesium alloys offer benefits such as higher strength-to-weight ratios, corrosion resistance, and fatigue durability. Despite these advantages, the higher cost of alternatives, particularly composites and titanium, limits their use to specialized applications where weight reduction, fatigue resistance, or corrosion protection justify the expense.

Choosing the right material is essential for withstanding the varying loads exerted on the spring. Aluminium, magnesium, beryllium, titanium, titanium aluminides, structural ceramics, and composites with polymer, metal, and ceramic matrices are examples of lightweight materials that are typically used in weight reduction strategies.

Table 1. Materials properties.

material	elastic modulus (MPa)	Poison's coefficient	material density $\left(g/cm^3\right)$	ultimate tensile strength (MPa)	yield strength (MPa)
structural steel	$2 \cdot 10^5$	0.3	7.85	500	250
aluminium steel	$68.9 \cdot 10^3$	0.32	2.7	290	276

Heavy load applications frequently use alloy steel. The material strength to absorb the vibrations produced in the vehicle should be taken into primary consideration during selection of the leaf spring material.
To complete design optimization process following methodology is adopted shown in flow chart.

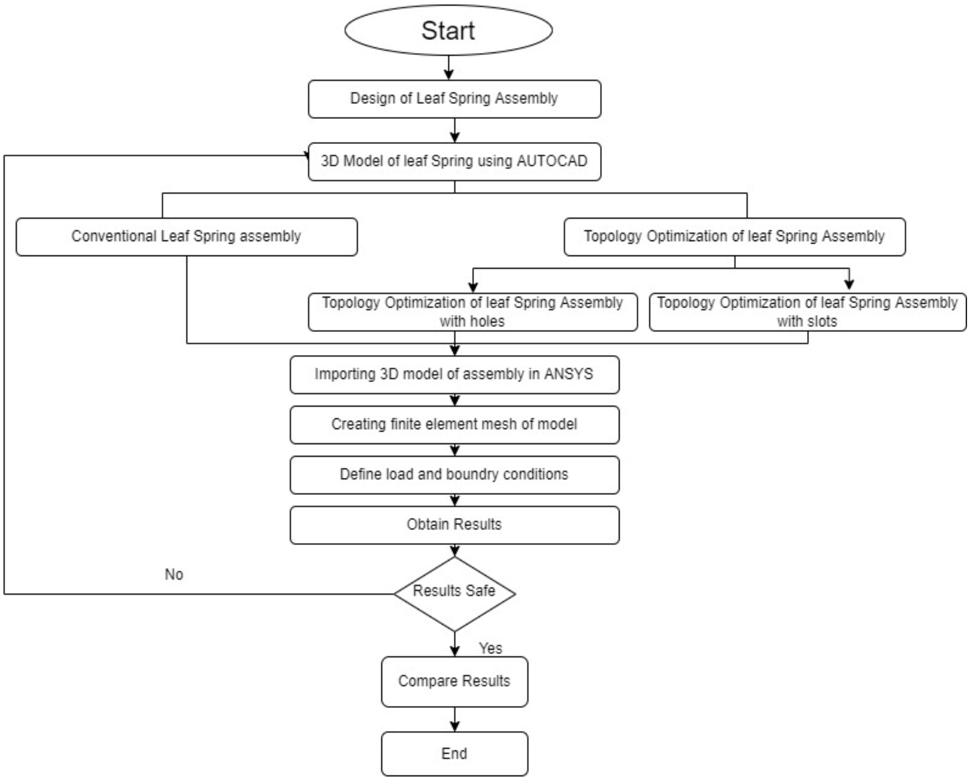

Fig.1. Topology optimization process of a leaf spring assembly.

The optimization process starts with designing the leaf spring having proper design parameters. The assembly is then modelled in the AUTOCAD with the parameters obtained during the designing process. The models are then transported into ANSYS for FE analysis. For the present research two models of spring assembly having holes and slots in the graduated leaves are imported for FE analysis. The meshing of the models is then done and proper load and constraints are then imposed to draw the results. The outcomes are later compared with the results of the conventional leaf spring assembly.

2.1. Leaf spring design

The entire design process for designing a leaf spring is outlined in this section. Static loading is used for designing the leaf spring as it provides a straightforward way to assess structural integrity and can be sufficient for preliminary design. The vehicle's net weight is taken into account first. Net weight is the total of the vehicle's weight and its maximum load carrying capacity. Assume the safety factor $\left(f = 2\right)$ for the design [24] to get the overall weight of the vehicle, and then use the data at hand to compute the bending stress and total deflection with the help of following formulas.

Maximum bending stress: $\sigma = \dfrac{6fl}{nbt^2}$.

Total deformation: $\delta = \dfrac{6fl^3}{Enbt^3}$.

By using the above procedure, the spring assembly's width, thickness, and number of graduated leaves are obtained.

Table 2. Calculated values of leaf spring assembly.

Parameter	Dimensions
main leaf length *l*	*1072 mm*
width of leaf *b*	*60 mm*
camber size *c*	*94.5 mm*
thickness *t*	*8 mm*
number of graduated leaves *n*	*3*

2.2. 3D Modelling of leaf spring assembly

Software is used to model the leaf spring assembly, which is seen in Fig.2a, using parameters given in Tab.2. Currently, an effective technique for reducing the weights of the various components without varying the boundary conditions is topology optimization. In order to get the desired results, the traditional leaf spring is subsequently sent into the ANSYS for optimization. Considering the findings, two leaf spring assembly designs are prepared in software adopting the DFM technique. In the first design material is removed by creating holes spaced equally apart, and in the second design by cutting a slot in the leaf spring, as seen in Fig.2b.

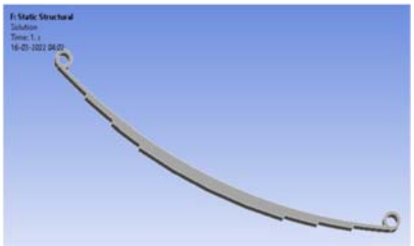

Fig.2a. 3D model of leaf spring assembly.

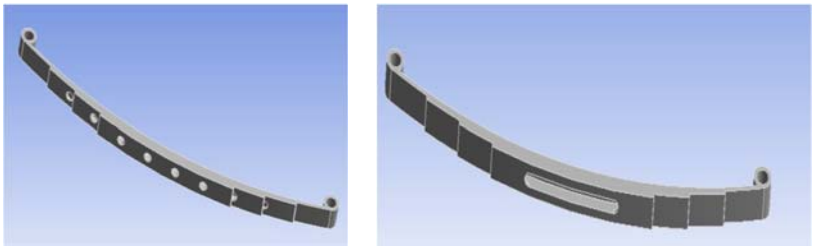

Fig.2b. Topology optimization in graduated leaves of assembly having uniform holes and uniform slot.

Figure 3 shows the unassembled view of main leaf and graduated leaves of the leaf spring assembly. The graduated leaves are topology optimized using design for manufacturing approach and is then assembled with the main leaf spring for further analysis.

Fig.3. Unassembeld view of leaf spring assembly.

2.3. Finite element meshing of leaf spring assembly

After modelling the leaf spring assembly in AUTOCAD, the 3D models are sequentially imported into ANSYS 21. Various limiting conditions are imposed to achieve the convenient results, followed by mesh generation for further analysis. To enhance the results, fine meshing is selected and tetrahedral elements are

Fig.4. Fine meshing of traditional leaf spring assembly and the proposed designs.

selected for analysis. Tetrahedral elements are preferred because of their geometric flexibility, ease of meshing, and ability to handle complex and irregular shapes with greater accuracy. Their adaptability makes them particularly effective for modelling intricate structures and complex boundary conditions, improving numerical stability and convergence in many analyses. The conventional leaf spring assembly model generates and analyses approximately *71333* nodes and *14376* elements. Similarly, for leaf spring assemblies with holes, *44775* nodes and *25200* elements are analysed, while assemblies with slots produce and examine *32517* nodes and *17317* elements. Figure 4 illustrates the meshed models of the leaf springs. In the context of grid independence, author have established that the selected fine mesh size provides accurate results without further significant changes after multiple refinements [25].

2.4. Load and boundary conditions.

Only rotatory movement in z axis is allowed, and the lateral movement of the spring in the x, y and z directions is restricted. As this end is coupled to the shackle, the opposite end has a small longitudinal displacement of *5 mm* in the horizontal direction. The movement in the y and z directions is kept fixed, and only rotatory movement is available along the z axis. Point contact is used between the components in the leaf spring assembly and around *4745 N* of load is exerted at the spring's center is shown in Fig.5. To analyse the total deformation, elastic strain and equivalent von-Mises stress produced in the leaf spring are achieved by implementing these boundary conditions.

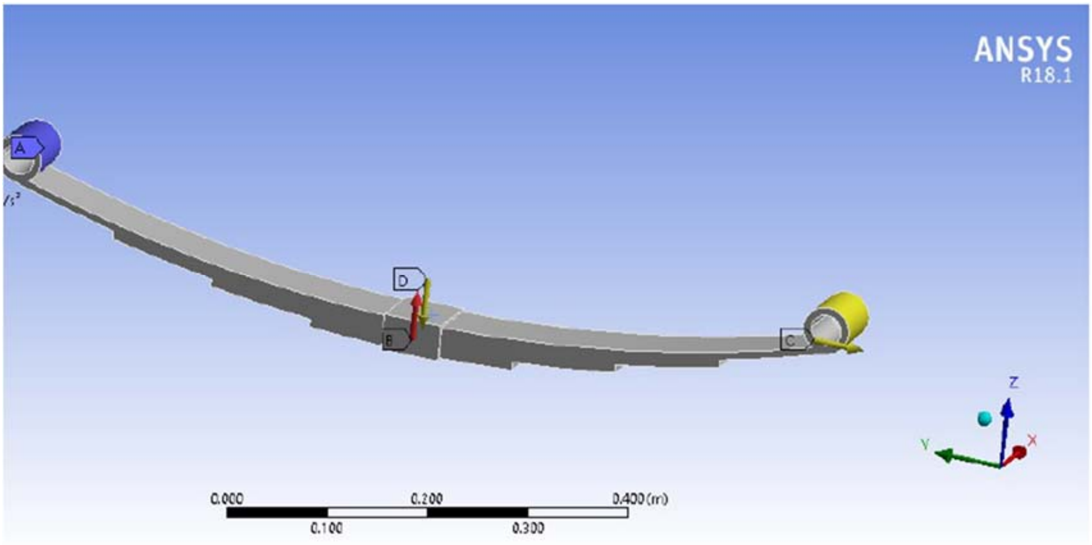

Fig.5. Boundary conditions on leaf spring assembly.

3. Results and discussion

Figure 6 displays the stress distribution and deflection for a leaf spring. The distribution and displacement (in y direction) of von Mises stress at the center. The results show that the highest deflection produced for a downward vertical load of *4745 N* is *6.50 mm*, and the maximum stresses detected were *274.84 MPa*.

Regions where material can be eliminated to save weight are found through topology optimization. The proposed designs are based on the design for manufacturing. The end results of proposed designs point to a long-term replacement for the current leaf spring assembly.

Figure 7 displays the deflection and stress distribution for a leaf spring assembly with holes. The distribution and displacement (in y direction) of von Mises stress at the center. The results show that the highest deflection produced for a downward vertical load of *4745 N* is *6.67 mm*, and the maximum stresses detected were *402.52 MPa*.

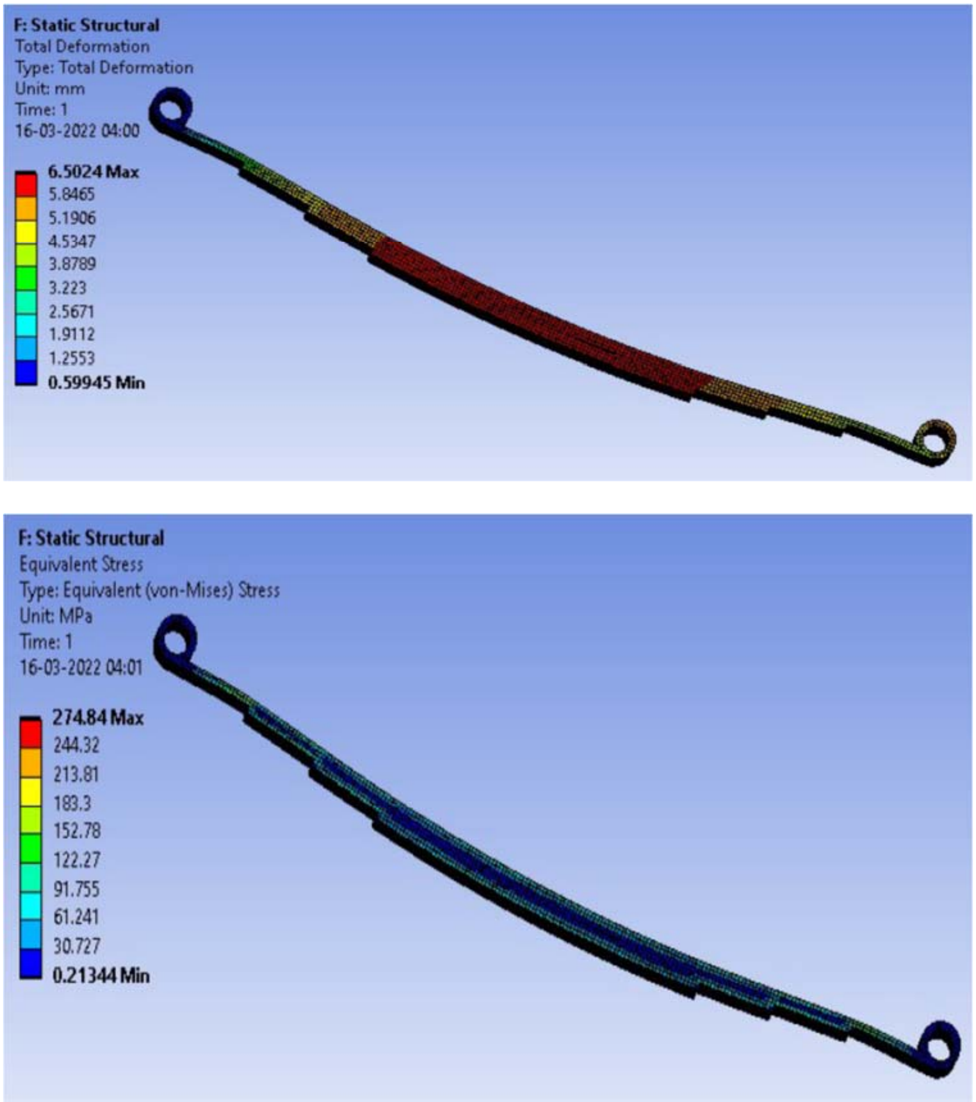

Fig.6. Von Mises stress distribution and deformation in leaf spring assembly.

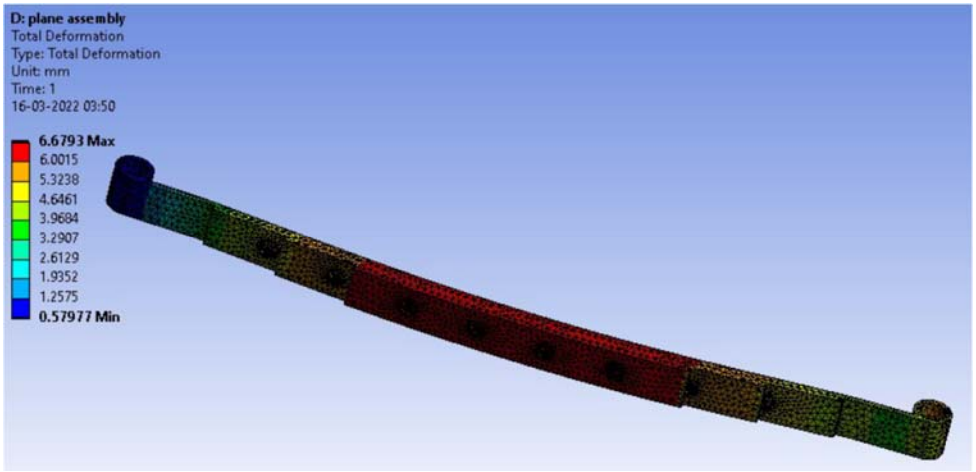

Fig.7. Stress distribution and deformation in leaf spring assembly with holes.

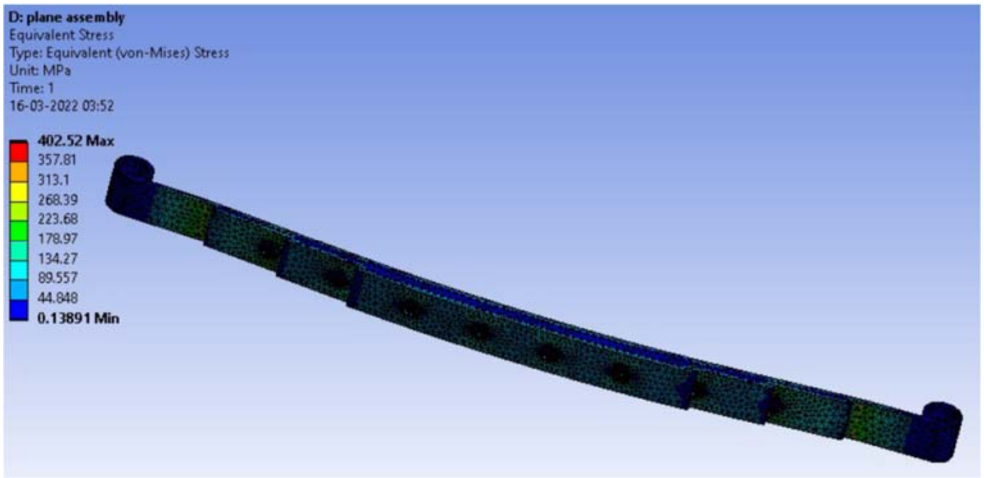

Fig.7 cont. Stress distribution and deformation in leaf spring assembly with holes.

Figure 8 displays the stress distribution and deformation for a leaf spring assembly with slots. The distribution and displacement (in y direction) of von Mises stress at the center. The results show that the highest deflection produced for a downward vertical load of *4745 N* is *6.76 mm*, and the maximum stresses detected were *247.86 MPa*.

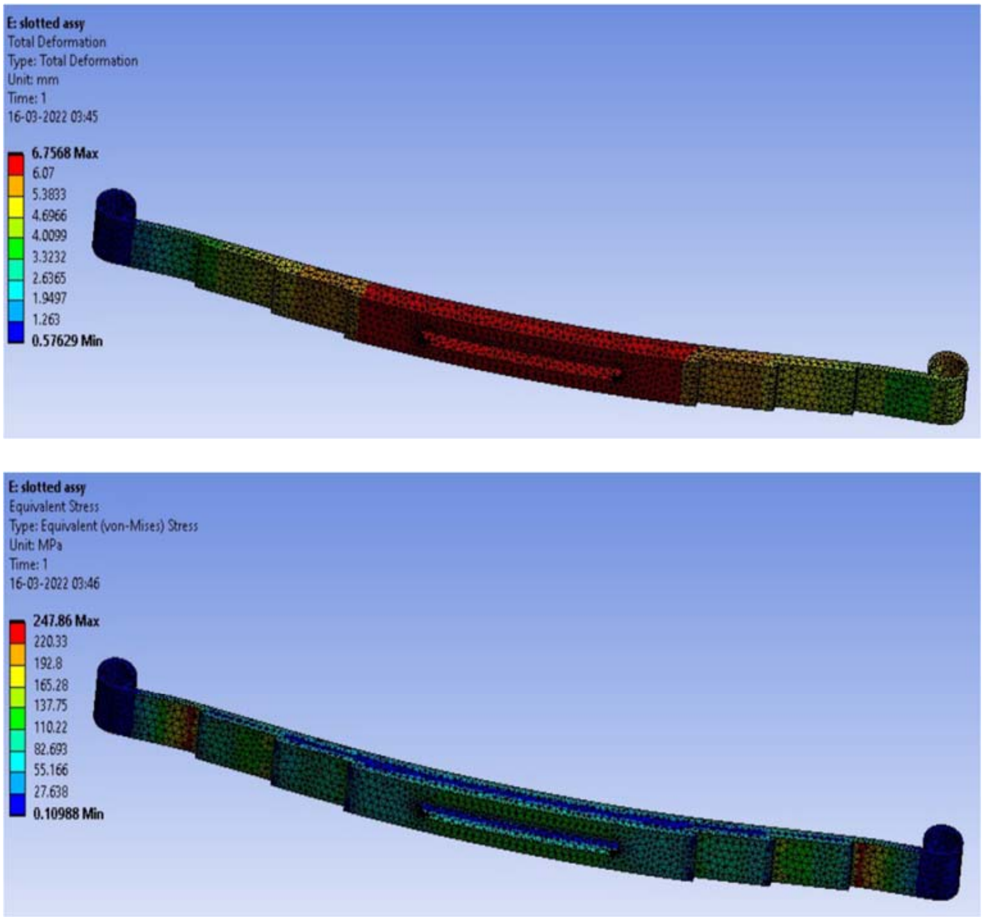

Fig.8. Stress distribution and deformation in leaf spring assembly with slots.

Equivalent elastic strain: Fig.9 displays the equivalent elastic strain that was achieved after the imposing the limiting conditions to the three springs. According to the results, the highest strain produced in a leaf spring assembly is $1.37 \cdot 10^{-3}\, mm/mm$. This is followed by $2.02 \cdot 10^{-3}\, mm/mm$ and $1.23 \cdot 10^{-3}\, mm/mm$ in topology-optimized leaf spring assemblies with holes and slots, respectively. When the values of elastic strain in proposed designs are relatively low, the optimized leaf springs are safe, and reduction in weight is feasible. The equivalent elastic strain demonstrates how the bonds within the material are stretched.

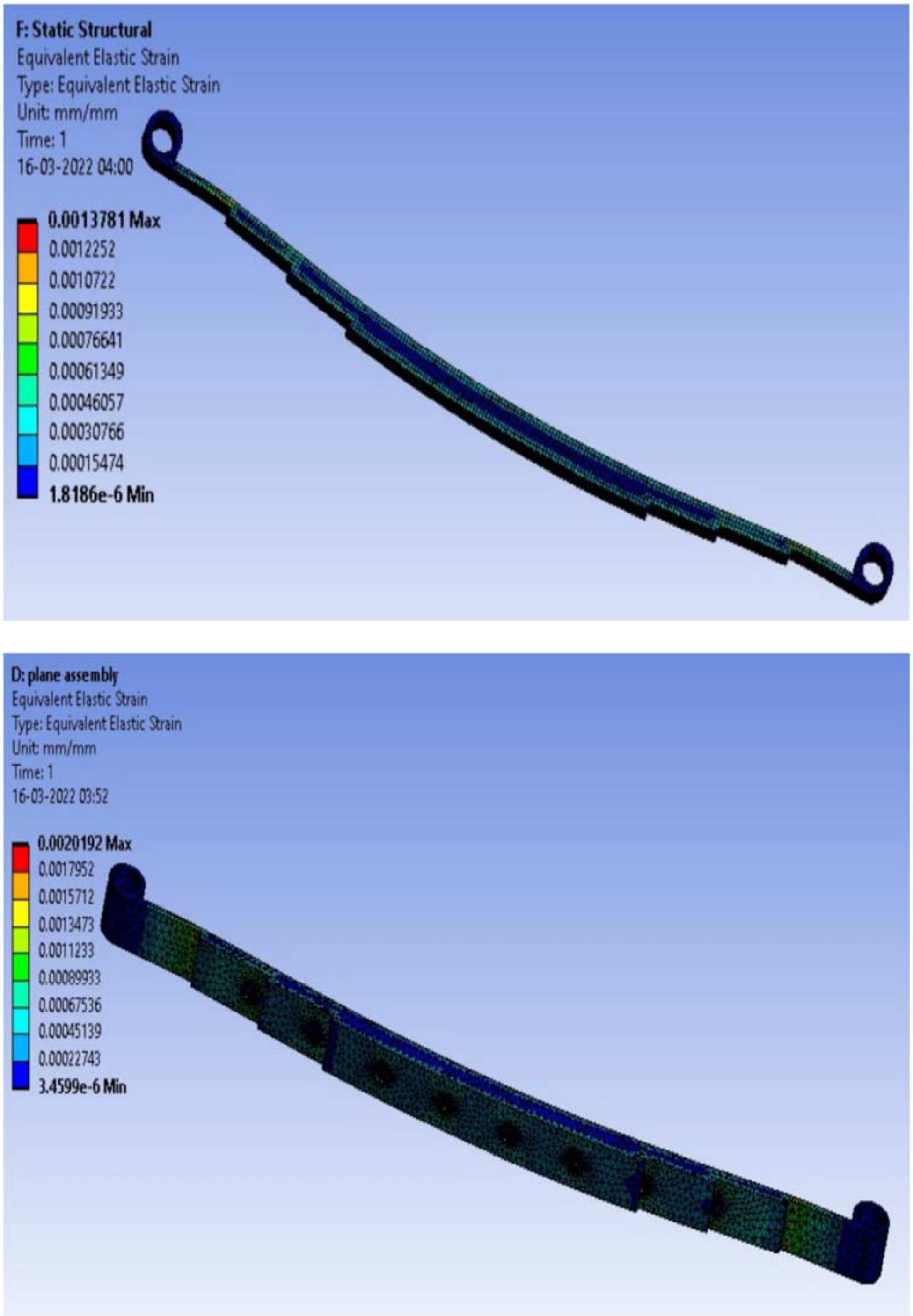

Fig.9. Equivalent elastic strain in standard leaf spring assembly and proposed designs.

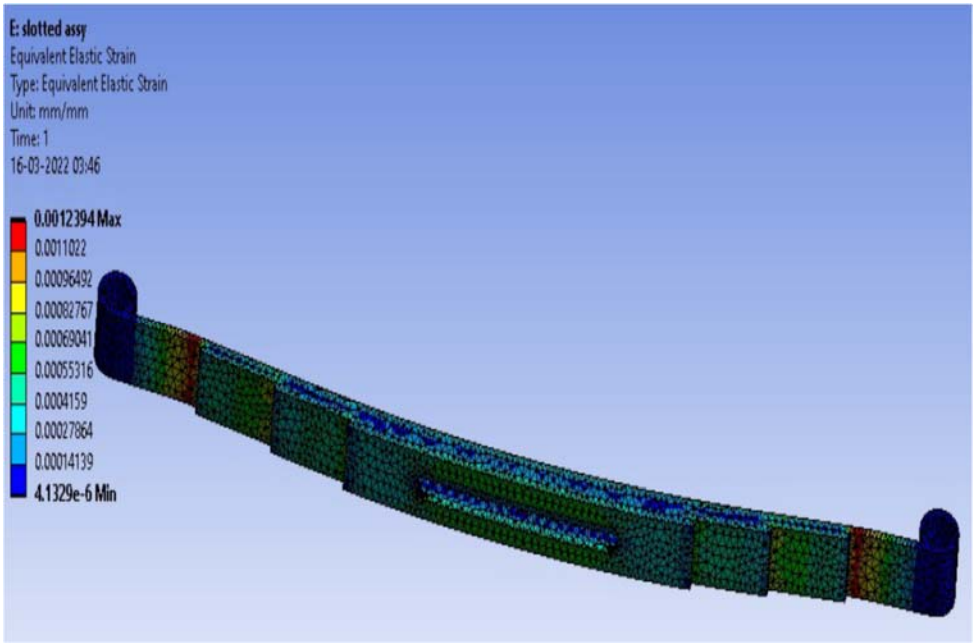

Fig.9 cont. Equivalent elastic strain in standard leaf spring assembly and proposed designs.

The results found from finite element analysis are tabulated in the Tab.3.
Table 3. Comparison of deformation, stress and strain for leaf spring assembly.

Material: structural steel								
	total deformation (in *mm*)		**equivalent stress (in *MPa*)**		**strain (in *mm/mm*)**		**weight (in *kg*)**	**percentage weight reduction**
	max	**min**	**max**	**min**	**max**	**min**		
leaf spring assembly	*6.50*	*0.599*	*247.84*	*0.213*	$1.38\cdot10^{-3}$	$1.81\cdot10^{-6}$	*12.455*	
leaf spring assembly with holes	*6.67*	*0.579*	*402.52*	*0.138*	$2.01\cdot10^{-3}$	$3.459\cdot10^{-6}$	*12.02*	*3.4 %*
leaf spring assembly with slot	*6.75*	*0.576*	*247.86*	*0.109*	$1.24\cdot10^{-3}$	$4.132\cdot10^{-6}$	*10.29*	*17.34 %*

The purpose of this study is to provide an innovative strategy to lessen the weight of traditional leaf springs. As per the survey, topology optimization for leaf spring assembly is not covered in any literature. The current study decreases the weight of the leaf spring, enhancing the performance and efficiency of an electric car.

The possible areas of weight reduction for electric vehicles can be found by using the two introduced methodologies. In this investigation, it was shown that, as compared to the conventional manufacturing procedure for leaf spring assembly, the final weight was reduced by *3.4%* and *17.34%.*

4. Conclusion

This paper provides a novel way to improve leaf spring design using FE analysis and topology optimization. Additionally, the research has proposed a feasible approach for e-vehicles that might lower weight and improve performance. It is evident from the results that the overall deformation values of both the recommended procedures and the conventional leaf spring assembly are more similar to each other. Furthermore, the stresses that remain after the material is removed are lower than the structural steel's yield strength. The findings show that even when the material is gone, the spring is still capable of sustaining the load. The weight of the other two designs with holes and slot, is *10.29 kg* and *12.02 kg*, respectively, whereas the weight of the leaf spring is *12.45 kg*. Leaf spring can achieve a weight reduction of around *3.4%* and *17.34%* by the application of the topology optimization technique. This weight loss may contribute to the e-vehicle's overall weight loss. The performance of e-vehicles has been enhanced by the development of a system for the modeling and topological optimization of leaf springs. It might be feasible to create new hybrid composite materials in the future to reduce the weight and cost of electric vehicles. Adding smooth fillets around sharp edges distributes stress more evenly; strengthening the areas surrounding holes with stronger materials enhances durability; placing holes in low-stress regions minimizes impact; and cold working processes like shot peening introduce compressive stresses that reduce fatigue crack initiation are some of the techniques that can be used to reduce stress concentration caused by holes and slots. These techniques aid in reducing concentrated stress and extending the material's fatigue life.

Nomenclature

b – width of leaf
c – camber size
E – elastic modulus
f – factor of safety
l – main length leaf
n – number of graduated leaves
t – thickness
δ – total deflection/deformation
σ – maximum bending stress

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Received: July 21, 2024
Revised: December 15, 2024