Topology Optimization and Modal Analysis of Mono Leaf Spring using Finite Element Method

Thesis

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By

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Above all, my humble and whole heartily prostration to the Almighty for his Blessings.

Pantnagar
September, 2023

(Ashutosh Pandey)
Author

CERTIFICATE-I

This is to certify that the thesis entitled **"Topology Optimization and Modal Analysis of Mono Leaf Spring using Finite Element Method"** submitted in partial fulfillment of the requirements for the degree of **Master of Technology** in **Mechanical Engineering** with major in**Design and Production Engineering**, of the College of Post-Graduate Studies, G. B. Pant University of Agriculture and Technology, Pantnagar, is a record of bona fide research carried out by **Mr. Ashutosh Pandey,** ID. No. **57249,** under my supervision and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been acknowledged.

Pantnagar
September, 2023

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Chairman
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CERTIFICATE-II

We, the undersigned, members of the Advisory Committee of **Mr. Ashutosh Pandey,** ID. No. **57249,** a candidate for the degree **Master of Technology** in **Mechanical Engineering** with major in **Design and Production Engineering**, agree that the thesis entitled **“Topology Optimization and Modal Analysis of Mono Leaf Spring using Finite Element Method”** may be submitted in partial fulfillment of the requirements for the degree.

(Anadi Misra)
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Member

(Rakesh Saxena)
Member

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LIST OF ABBREVIATION

Abbreviation		Description
AM	:	Additive manufacturing
TO	:	Topology optimization
FEA	:	Finite element analysis
MMC	:	Metal matric composite
AL	:	Aluminum
wt	:	weight
Kg	:	Kilogram
MPa	:	Mega pascal
mJ	:	Milli joule
mm	:	Milli meter
et al	:	And others
FOS	:	Factor of safety
2D	:	Two dimension
g	:	gram
cc	:	Centimeter cube
e	:	Exponent
Hz	:	Hertz

LIST OF SYMBOLS

Symbols		Meaning
ρ	:	Density g\cc
%	:	percentage
<	:	Smaller than
∫	:	Integration
≤	:	Smaller than equal to
=	:	Equal to
–	:	Subraction

Chapter 1 INTRODUCTION

1.1 Overview

In the context of additive manufacturing, a structural component is systematically constructed by layering materials based on digital instructions. This strategy is currently in its early phases of development but has the potential to transform the manufacturing sector. One of the advantages provided by this approach is an enhanced level of design flexibility, along with the potential to use topology optimization techniques to reduce weight during the layer-by-layer manufacturing process. There is minimal to no waste of raw materials as a result of the life cycle, which includes conception, design, production, and validation, getting considerably shortened. Less raw material waste can significantly lower the cost of materials. AM also has the ability to "incorporate added functionality, such as internal cooling channels and thermo wells into components; manufacture highly complex geometries that would be impossible or very difficult to be realized with traditional methods".

1.2 Topology Optimization

Topology optimization is a method employed in additive manufacturing that makes use of mathematical algorithms to create materials with reduced weight. This makes it easier to increase the effectiveness of the manufacturing process. The component's strength, however, is unaffected by the TO method in any manner. Topology optimization is a tactical strategy that has the potential to improve component performance. The accomplishment of optimum material distribution in specific places is made possible by the use of software and the application of topology optimization techniques. The algorithm discerns areas characterized by low levels of stress and then eliminates any superfluous material present within such regions. The potential for improvement in certain features of a component is contingent upon a multitude of diverse factors. The key elements in this context are the boundary conditions, stiffness limits, loads, and deformation.

1.3 Benefits of Topology Optimization

The methodology of topology optimization enhances the range of design freedom while also offering a number of benefits. Due to its numerous benefits, additive manufacturing is becoming increasingly popular across a wide range of industries.

Furthermore, the use of topology optimization methodologies allows for the enhancement of component thickness in regions where it is most essential, achieved by eliminating material from portions of the component that are not prone to border stresses. This objective is achieved by reducing the quantity of material in the specified regions of the component. The aircraft industry is looking for parts that are lightweight and require few supporting structures. To an appropriate extent, the additive manufacturing technology known as TO is able to supply all of these qualities. Keeping the total weight of the payload as low as possible is one possible method for lowering the price of satellite launches. The aerospace firm STELIA Aerospace improved the stability of airplane fuselage panels by using the TO design methodology, outperforming the stability attained by conventional production techniques. Utilizing the TO technique lessens material waste and makes it possible to incorporate other attributes like pore diameter, density, and mechanical properties. Finite element analysis is used in conventional topology optimization methods to evaluate design effectiveness and produce structures that can meet specific objectives.

a. A decline in the stiffness to weight ratio.
b. Heightened weight in correlation with the magnitude of stress.
c. The safety factor was used to decrease the percentage of the overall volume of the drug.
d. The ratio of the natural frequency to the total mass.

1.4 Steps involved in Topology Optimization

1. **Discretized domain is provided as the design space materials are defined -** The materials used in the design space are specified at the same time as the domain is discretized. For each element in the design space, the optimizer claims that its aim is to reduce compliance while maintaining a volume restriction.

2. **Interpolation of data fields -** There is a noticeable divergence and declining consistency across different software programs when evaluating the results of density-based topology optimization. Discrete element densities are converted into continuous design variables through the interpolation process, making them better suited for optimization techniques. Because there are no intermediate states of material presence, the density of an element presents a continuum that ranges from 0 (which denotes an absence of material) to 1 (which denotes a solid substance).

3. **Geometry Reconstruction -** The utilization of implicit modeling technology addresses the challenge of geometry reconstruction. With a limited number of inputs, it is sometimes possible to obtain an implicit geometric representation directly from the outcome of a topology optimization. It is frequently acknowledged that the manual reconstruction of geometry following topology optimization is a considerable problem. The smooth geometry that is produced can be easily applied to other modeling tasks, such manufacturing and simulation. It materializes rapidly within a brief temporal interval.

4. **Boundary conditions are applied for finite element model -** The final step of the whole process flow involved a material test campaign to validate the findings. The following sections of this paper will contain more information about this campaign. A more thorough explanation of these specifics can be found in the book's later sections. In the course of this study, the investigation of TA convergence was not done.

5. **Contour slices for manufacturing -** The subsequent stage of the process is referred to as "manufacturing contour slices," and it is an essential element of the "layer-based additive manufacturing" technique. By employing the robust slicing technique, stereolithography (STL) models with a large number of triangles could be produced more quickly. This approach may be used to optimize time efficiency.

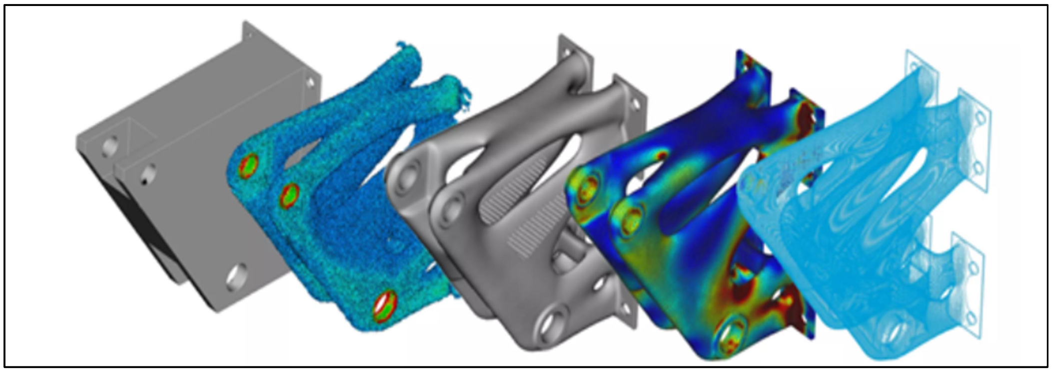

Figure. 1.1 Steps involved in additive manufacturing (Team, I., 2021)

1.5 Topology Optimization advantages

Advantages of topology optimization-

- **Optimized design** – It is often necessary to consider and evaluate a number of factors in order to find the optimum solution to a design dilemma. A technique called topology optimization makes it easier to quantify the best possible design solutions. Finite Element Analysis (FEA) reduces the possibility of manufacturing inferior items by incorporating a wide range of factors and avoiding making too many dangerous assumptions.
- **Minimize material –** The removal of extra material and an improvement in the stiffness-to-weight ratio are two strong benefits of topology optimization. Other benefits of weight and size reduction include decreased energy and resource consumption. Additionally, the design will require less raw materials, increasing its eco-friendliness through the process of simplification.
- **Cost-effective** – If the proper manufacturing technology is applied, topology optimization designs can be implemented at a reasonable cost. One can effectively reduce material consumption and associated costs by carefully positioning the material in its appropriate area. Additionally, when appropriately compacted, the process of transportation requires less energy for both locomotion and handling and takes up less space. The production of complex geometries that have been progressed by topology optimization is challenging with current technologies. When combined with the use of 3D

printing technology, the aforementioned intricacy does not lead to any additional financial costs being accrued.

- **Environmental impact reduction** – Compared to previous approaches, topology optimization design demonstrates greater sustainability by producing less waste. On the other hand, the aforementioned result might not be achieved if a flawed manufacturing procedure is employed. For instance, compared to traditional production techniques, additive manufacturing is thought to be more appropriate for topology optimization programs. To efficiently reduce the amount of material that is extracted and discarded, and hence optimize resource utilization, the design model for subtractive manufacturing must be started at the smallest scale that is practical.

- **Faster iterative design process –** When the iterative design approach incorporates the exploration of several modes and the consideration of component stress, it results in a more expedited completion.

1.6 Topology Optimization disadvantages

Disadvantages of topology optimization

- **Manufacturability limitations –** Limitations on production arise when considering the suitability of designs with tunable topology for additive manufacturing as opposed to subtractive manufacturing. The subtractive manufacturing method requires a certain amount of time due to its inherent nature of material removal. The elevated expenses may be partly ascribed to the surplus of material waste.

- **Higher cost** – The increased cost might be attributed to the use of certain materials and methods, such as 3D printing, injection molding, or die casting, which are necessary for the production of superior designs in certain circumstances. Nevertheless, as comparison to conventional production processes, additive manufacturing (AM) is still seen as somewhat expensive in terms of cost.

- **Strength reduction** – The results of any program are greatly influenced by human involvement; this is true for all programs. Hence, it is plausible that the act of decreasing body weight might sporadically lead to a decline in physical strength.

- **Lack of understanding –** Topology optimization has gained increasing significance in recent times, mostly attributed to the advent of additive manufacturing (AM), despite its existence for many decades. This newfound importance might be attributed to a better comprehension of the subject matter. Despite the emergence of novel instruments, a considerable period will be required for their maturation and subsequent use within the industry.

1.7 Topology Optimization Application

Topology shape optimization tools provide the best means of optimizing a shape for a given requirement.

I. Aerospace – TO is a natural fit for aeronautical engineering because of weight reduction.

II. Automotive – TO in the automobile industry strikes a compromise between the desire for lightweight parts for increased fuel economy and power and the stability and strength of a body that can sustain torque and impact.

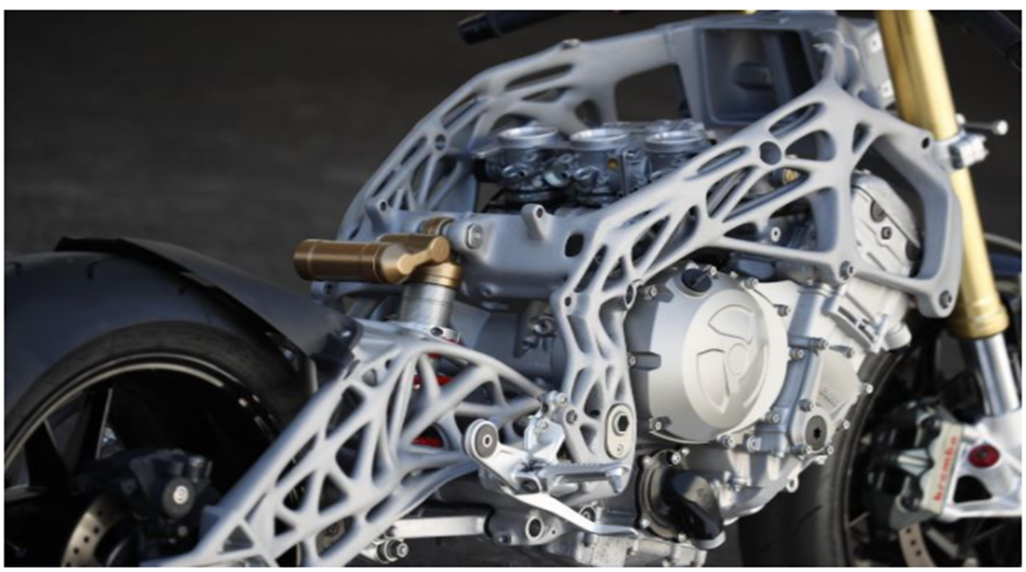

Figure. 1.2 Topology Optimized 3d Printed Frame (Abdi, Ashcroft and Wildman, 2018)

1.8 Mono Leaf Spring -an overview

Mono leaf springs, usually referred to as single leaf springs, are a typical form of suspension component used in automobiles to dampen shocks and support the extra weight of the automobile. A single, curved steel or composite leaf serves as the primary structural component in this straightforward and portable design. The mono leaf spring is connected to the axle and the vehicle's chassis at the front and the rear. The leaf spring extends and stores potential energy whenever an automobile runs over bumps and uneven ground. This flexion enables the spring to absorb and minimize the impact, resulting in a smoother ride for the passengers and reduced stress on the automobile's chassis and internal parts.

One end of the leaf spring is fixed to the chassis using mounting bolts or shackles, while the other end is attached to the axle or suspension system. The design of the mono leaf spring allows it to provide both vertical support and limited lateral stability, which helps control the vehicle's body roll during turns.

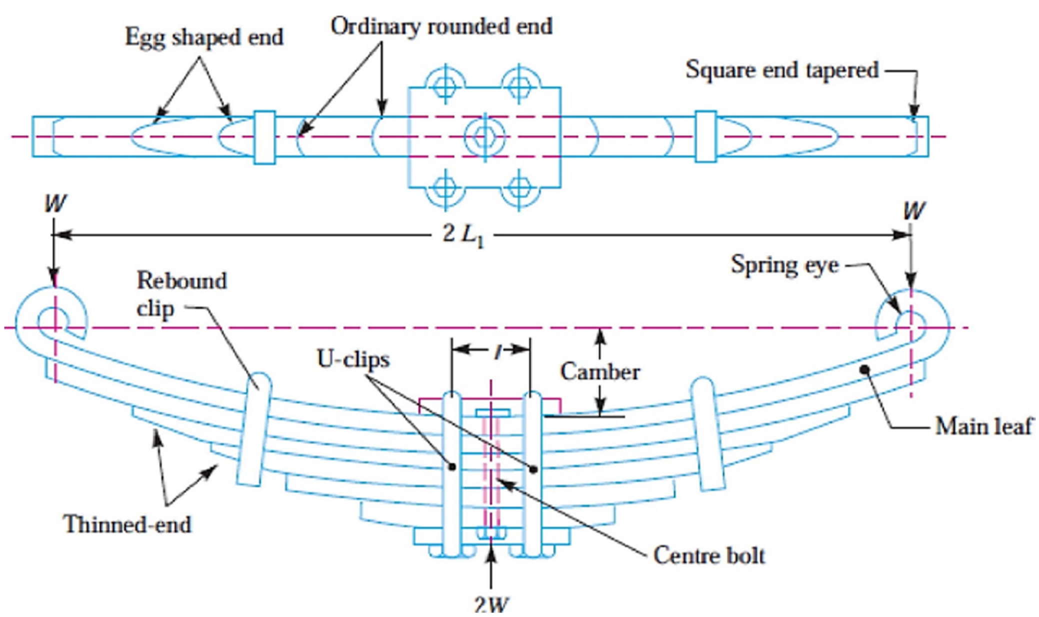

Fig 1.3 Schematic diagram of leaf spring (Tadesse and Fatoba, 2022)

Lightweight vehicles, such as compact automobiles, trucks, and cargo trailers, frequently employ mono leaf springs. They are particularly advantageous in applications where cost, simplicity, and physical space are important considerations. They might not offer a ride that is as smooth as more sophisticated suspension systems, and they might not be able to bear as much weight as coil or multi-leaf springs.

In conclusion, a mono leaf spring is a type of suspension part used in automobiles to give support, absorb shocks, and maintain stability. It has become an attractive choice in many automotive applications because to its affordability and simplicity.

1.9 Lattice Optimization

Lattice optimization, commonly referred to as lattice structure optimization, is a technique used in engineering and design to optimize the internal lattice-like geometries of structures to improve their performance. Lattice structures constitute three-dimensional arrangements that consist of recurring unit cells that arrange themselves in a manner similar to a grid or mesh. These structures are renowned for having excellent strength-to-weight ratios, which makes them especially useful in areas like aerospace, automotive, as well as medical device manufacture where using lightweight yet durable materials is critical.

By customizing the internal architecture of these structures to specific performance needs, lattice optimization aims to optimize the advantages of these structures. Advanced computational methods like finite element analysis (FEA) and topology optimization are frequently used in this optimization procedure. Here is an overview of the lattice optimization process

Design Space Definition- Engineers begin by determining the available design space, which represents the volume inside which the lattice structure will be positioned, and which can be restricted by features like the general shape of the product, necessary interfaces, and other design concerns.

Load and Boundary Conditions- The structure's expected loads, forces, and boundary conditions must then be defined in order for it to be implemented. This knowledge is essential for figuring out where stresses and strains are most likely to happen.

Topology Optimization- Engineers perform topology optimization using computational techniques like FEA to decide how material should be distributed throughout the specified design area. The software concentrates material in locations under greater stress while iteratively removing material from areas not under significant amounts of stress.

Lattice Generation- Engineers create a lattice structure that complies with the design space and integrates the optimum material layout once the optimized material distribution has been found through topology optimization. These unit cells, which repeat, form the lattice structure's basis and provide it the desired mechanical qualities.

Validation and Refinement- The lattice structure is then put through additional inspection to make sure it satisfies the required performance standards. To achieve the ideal balance between strength, weight, and other requirements, the lattice's properties, such as cell size, shape, and orientation, can be changed as desired.

Manufacturing Considerations- It must be possible to manufacture the final optimal lattice structure using readily available materials and techniques. Engineers consider factors like additive manufacturing techniques, material compatibility, and production feasibility.

1.10 Organization of thesis

This section provides the brief description of all the chapter's. There are 5 chapters in the current thesis.

Chapter 1: Introduction of the research work.

Chapter 2: A literature review gives a concise account of past work done by various researchers in the field of monoleaf spring and its weight optimization techniques.

Chapter 3: A brief description of the materials and methods used under study. From a numerical standpoint, this chapter provides a description of the research approach applied in the current investigation.

Chapter 4: Provides results and discussions. This chapter presents all such results that were numerically investigated by ANSYS.

Chapter 5: Contain summary and conclusions. The summary and findings from the previous chapters are presented in this chapter, in addition to recommendations for future research work.

Chapter 2 REVIEW OF LITERATURE

The objective of this chapter is to provide the background knowledge and data on the different works on mono leaf springs. The purpose is also to discuss the work on weight minimization techniques as done by various researches in past.It provides through understanding for the various aspect and work done on weight minimizations.

Bendsøe *et al.* (1998) the primary contributions of research include the introduction of a homogenization approach for topology optimization, which was implemented using MATLAB. Sigmund's contributions are often regarded as pioneering in this regard. The study conducted formed the basis for the current TO methodologies that are used in contemporary practices. Within the realm of topology optimization (TO), there are several methodologies that have gained recognition. Notable examples include density-based techniques, level-set approaches, evolutionary/genetic algorithms, topological derivatives, and phase field methods.

Rodrigues *et al.* (2002) examined the feasibility of devising an algorithm to facilitate the topology optimization of localized microstructures. The method was devised with the aim of enhancing both the physical properties and the microstructural characteristics of the immediate vicinity. In instances when concurrent multiscale structural optimization was not practicable, a two-fold computational strategy was used to conduct three-dimensional structural optimization. This included the utilization of distinct computing methodologies for the microstructure and macrostructure, respectively.

Liu *et al.* (2008) have both undertaken studies pertaining to the topology optimization technique in the context of additive manufacturing. Both macro- and micro-structures are viable options for implementing the concurrent type topology optimization approach. The product has a significant level of manufacturability while maintaining an affordable price point.

Arora *et al.* (2011) uses experimental design principles and loading conditions to perform computer-aided design and analysis of a standard leaf spring. There are 37 parts in this typical leaf spring model. The leaf spring is made of 65Si7.The leaf spring's CAD model is created in CATIA and put through an ANSYS analysis. ANSYS is used to perform the CAE analysis of the leaf spring for the deflection and stresses under certain loading conditions. To validate the findings, the experimental and CAE data are compared. The ideal type of contact and meshing element for a leaf spring model is determined using CAE tools.

Patunkar and Dolas (2011) investigated spring to check cyclic creep and cyclic deformation for each kinematic and dynamic sort loading conditions exploitation 60SI7 (BIS) and Glass/Epoxy for composite spring. The analysis is carried out using ANSYS code, and Pro-E code is used to create the CAD design. The findings of the research, steel and composite leaf springs exhibit significantly different deflection and stresses under the identical static load circumstances. When subjected to the same force conditions, the Composite leaf spring exhibits less deflection than the Steel leaf spring. Additionally, a smart weight reduction of 84.40% was accomplished for the same level of performance.

Charde and Bhope (2012) use the scientific method, finite part methodology, and analytical methodology to investigate the failure of the spring. On the basis of spring stresses, deformation, and bending behavior, comparative analysis was developed. At 15, 125, 235, and 345 mm from the left finish, the strain calculations were made. The results have demonstrated that analytical approach fails to survive the majority of master leaf stresses and may only compute at supports. The experimental and finite part approaches are the most successful in detecting stresses at the remaining spring components.

Gebremeskel (2012) investigated spring with one E-glass/Epoxy material underneath static loading conditions exploitation FEA simulation studies. The results have demonstrated that style stresses are significantly lower than the fabric's yield purpose stresses, satisfying most stress failure criteria and resulting in a shorter fatigue life for the material. The 3-wheeler applications are the most suitable for the planning.

Mehul *et al.* (2012) conducted a static analysis of steel leaf spring and laminated composite Multi leaf spring. The goal is to evaluate the steel leaf spring's load carrying capacity, rigidity, and weight savings to that of the composite leaf spring. The dimensions of a Light design calculations' existing conventional steel leaf spring. Utilizing ANSYS 11.0 and hyper mesh, static analysis is carried out on a 3-D model of a typical leaf spring. Composite multi-leaf springs made of unidirectional laminates of carbon/epoxy and graphite/epoxy employ the same dimensions. According to the results, the weight of the composite material was reduced by 79.617% for the same amount of leaves. Weight savings of up to 90.09% is possible when mono composite leaf springs are taken into account.

Mouleeswaran (2012) have been involved in the development, testing, and design of composite compound multi-springs for lightweight motorized vehicles. A spring stores potential energy as it is strained and dispersed gradually. As a result of this, increasing the standard and longitudinally decreasing the flexibility modulus are both crucial issues that must be addressed when supporting spring material. Investigation of the material's exhaustion and disappointment under load is part of the study done here. With the aid of exploratory and procedure copies, the entire investigation is carried out here.

Dubey *et al.* (2013) examined the use of the parabolic spring in the Maruti Omni car Analysis of finite parts in static circumstances. For the analysis, high-speed compound materials were employed. When composite springs are used instead of conventional leaf springs, mechanical qualities such as load bearing capacity, stiffness, and weight reduction are increased.

Satpule *et al.* (2013) investigated and compared a glass-fiber 7781 spring with a 55SI2MN90 spring for a steel leaf. Making a spring using a picket design and a hand basketball shot technique that corresponds to the spring's dimensions. According to the research, a glass-fiber 7781 spring has a stronger strength-to-weight quantitative relationship than a 55SI2MN90 spring.

Tang *et al.* (2015) used a lattice skin structural method to maximize the functional volumes. Figure 2.1 illustrates the preservation of volumes, surfaces, and functional solids.

Figure. 2.1 An engine bracket in filled with strut-based lattice (Tang *et al*. 2015)

Zhang *et al*. (2015) performed a study on the use of the topology optimization methodology. They utilized the "variable-density hexagonal cellular" strategy as a methodological approach. The homogenization procedure, as seen in figure 2.4, yielded an optimal density distribution within the mixture.

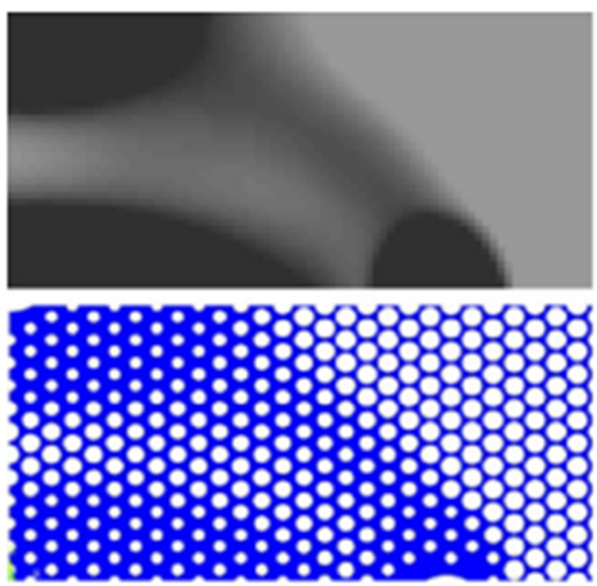

Figure. 2.2 Optimized beam infill with hexagonal lattice (Zhang *et al.* 2015)

Gaynor *et al*. (2016) conducted a quantitative investigation on the technology of additive manufacturing topology optimization. The design of a tension-only structure is notably impacted by various restrictions and the angles at which it may sustain itself.

Qian *et al.* (2017) the authors conducted a numerical investigation on the technology of additive manufacturing topology optimization. In order to effectively establish clear delineations, the approach of "heavy side" projection was used. The results of topology optimization are produced by using a greyness constraint. The inclusion of a certain level of ambiguity in the answer facilitated the process of identifying the correct solution. Figure 2.2 demonstrates the use of a minimal number of viable overhang angles in order to optimize the cantilever beam. In order to address the gradient limitation and the overhang angle, it is essential to enhance compliance levels and make simultaneous adjustments.

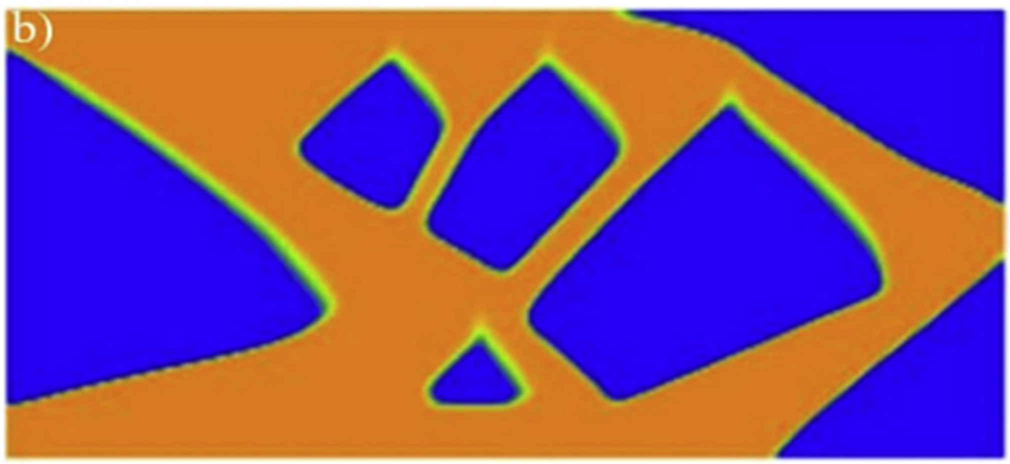

Figure. 2.3 Cantilever beam designs for an overhang angle constraint of 30^0 (Qian*et al.* 2017)

Song *et al.* (2017) investigated the use of cellular lattice structure as a means of achieving mass reduction. This technique utilizes tangent circles to automatically construct the primary form of an irregular cellular structure. Topology optimization techniques may be used to generate objects that exhibit a cellular morphology.

Wang *et al.* (2017) an experimental investigation was carried out to assess the efficacy of lattice structure technology in attaining weight reduction. The study results suggest that the idea of imperfection stability should be carefully considered throughout all stages of the optimization process. This research is based on the load deviation, sometimes referred to as bulking, which arises from both ideal and defective shell designs.

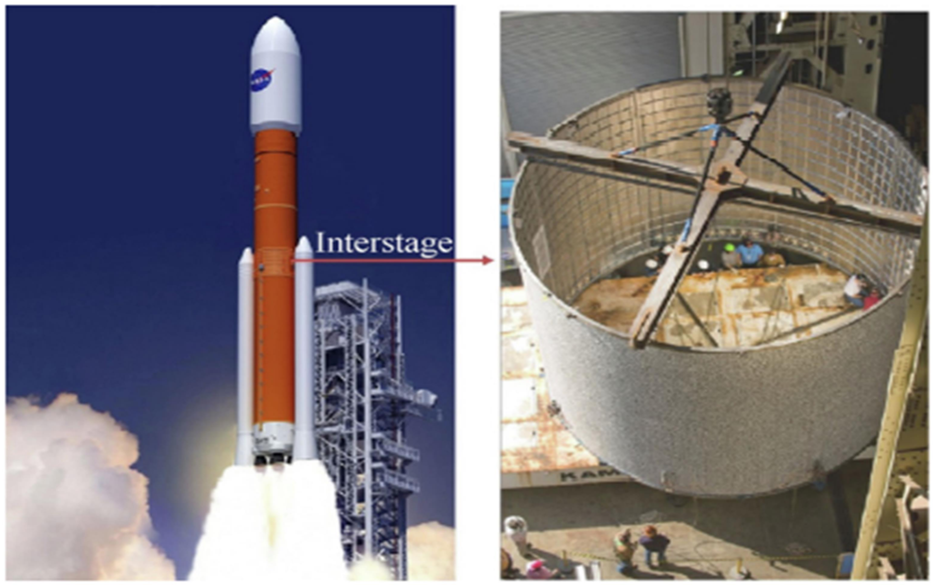

Figure. 2.4 NASA Space Launch System rocket and stiffened shell (Wang *et al.* 2017)

Abdi *et al.* (2018) the use of topological optimization techniques in additive manufacturing facilitates the production of lightweight components. One factor contributing to the growing use of additive manufacturing in the aerospace and car industries is as follows. Additive manufacturing encompasses two separate methodologies: the expertise-driven approach and the mathematically-driven approach. Despite the disparities between the two techniques, they exhibit equivalent levels of efficacy. The automated method employs an iterative numerical technique to optimize the attainment of a measurable target by following a mathematically driven strategy. Topology optimization (TO) is a widely employed approach in various fields. It has become customary in commercial software to perform post-processing on TO-solutions by optimizing the size or shape of the final structure. This is done to ensure compliance with minimum feature sizes that align with the resolution capabilities of the printer (p. 1). The use of lattice structures is a common approach in optimizing structures by the application of expert knowledge, but at the cost of reduced rigidity. The researchers used the Iso-XFEM methodology in order to optimize the design of a lightweight brake pedal and successfully accomplish their objectives. The use of a partial cellular infill for additive manufacturing (AM), specifically using Body Centered Cubic (BCC) unit cells, resulted in a notable improvement in performance, as seen in figure 2.1. To mitigate the occurrence of warpage resulting from residual stresses, the loading conditions were selected in a non-deterministic manner. Based on the study findings, the use of both latticing TO and the integration of these two approaches may provide remarkable outcomes.

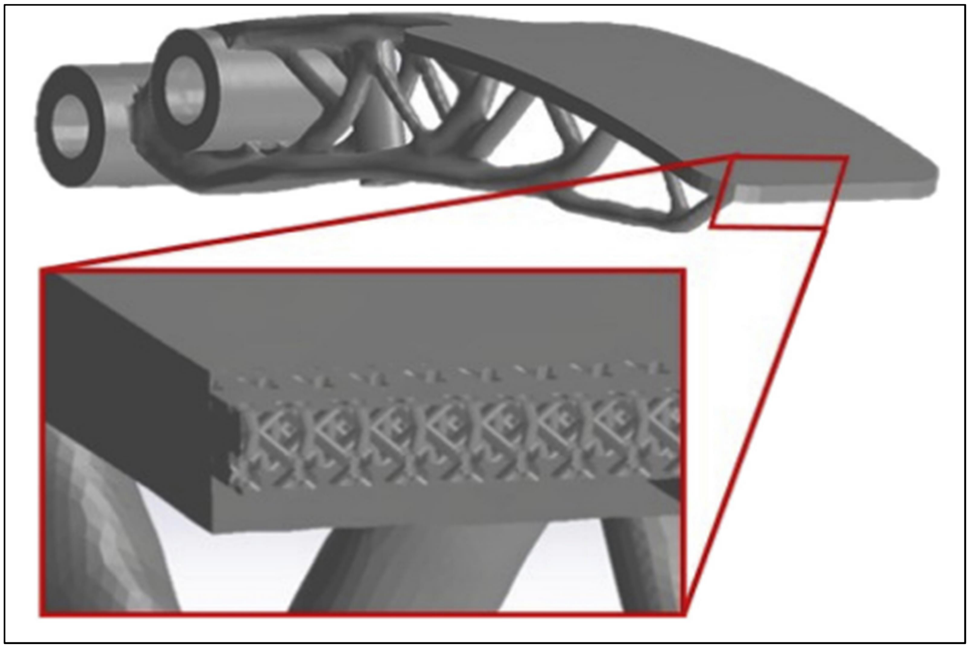

Figure. 2.5 Topologically optimized brake pedal with lattice structure in footpad.(Abdi*et al.* 2018)

Chen *et al.* (2018) proposed a novel approach for conducting topology optimization by incorporating the "iso-surface threshold" and "sizing optimization" techniques. Furthermore, with the use of pre-determined lattice cells, a hybrid meshing technique was employed. This technique utilizes interconnected nodes and element interactions to replicate an enlarged parametric lattice structure. The attainment of an optimal graded lattice structure necessitates the combined use of the "iso-surface threshold" approach and the "sizing optimization" method. The use of the procedures outlined in this discussion is advantageous and superior to previous methods due to the inherent challenges associated with constructing a lattice structure devoid of any functional solids or surfaces.

Langelaar *et al.* (2018) investigated optimization techniques via the use of the AM filter approach. According to the author, the support-filter is founded on the principle of layer-wise additive manufacturing (AM), whereby an evaluation is conducted to determine whether the base components in the lower layer provide support while considering the required support-free inclination angle of 45^0.

Liu *et al.* (2018) provide a novel approach to topological optimization by using the "GreyscaleSimp" methodology. Author outlined an approach that included the execution of the following procedures: The proposed methods include: 1) the application of density thresholding and mesh refinement techniques; 2) the process of skeletonization; 3) the identification and enhancement of small features by increasing their elemental density; 4) the utilization of density filtering methods; 5) the implementation of density thresholding while ensuring preservation of volume fraction; 6) the generation of STL files using a specific approach; 7) the interpretation of boundaries through the application of spline fitting techniques; and 8) the acquisition of IGES files through the utilization of an internal MATLAB function. The use of the adaptive boundary fitting approach, as seen in figure 2.3, was employed to get the most favorable form.

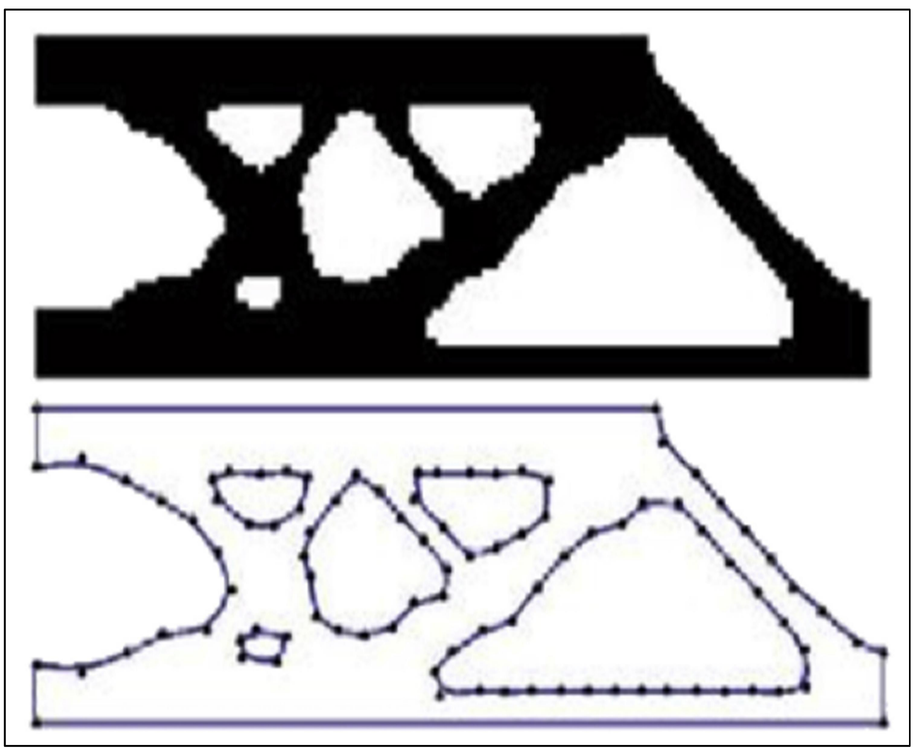

Figure. 2.6 Binarized image of a topologically optimized cantilever beam after boundary-refinement procedures (top) and the final adaptive B-spline fitting (bottom) (Liu *et al.* 2018)

Panesar *et al.* (2018) an investigation was carried out on the topology optimization method known as "SIMP." The researchers found this methodology to be of particular interest. By using this methodology, the production of scaled type and a "solid-lattice hybrid structure" was achieved. Based on the results obtained from the computational analysis, it can be shown that the strength of the lattice solution is much inferior in comparison to that of solid geometry. When considering performance, it has been shown that lattice structures known as "scaled lattice" and "graded lattice" outperform the lattice structure referred to as "uniform type." Based on the study results, it can be seen that the use of the density-based mapping approach is characterized by its simplicity. However, it is important to note that the development of diverse lattice topologies is a significant problem.

Nabaki *et al.* (2019) the Discrete TO approach, is based on the principle of optimum element connection. The continuum TO approach was used in order to ascertain the most advantageous spatial arrangement of the content.

Wang *et al.* (2020) have developed a hierarchical optimization technique in their study. This study is centered on the examination of parameterized microstructure lattice designs. The topology optimization approach was guided by density and included the examination of two unique kinds of design features. Prior to the optimization process, a polynomial function of a certain order was formulated to establish a connection between the lattice control variables and the effective mechanical characteristics. This was done with the aim of reducing the expenditure on computing. The method referred to as Parameterized Interpolation for Lattice Material (PILM) is the designated nomenclature for this particular approach. Comparison studies are conducted to examine the differences between uniform and non-uniform lattice systems, using both experimental and computational approaches. The study's results are shown in Figure 2.6, revealing that non-uniform lattice designs exhibit greater strength. Fabricating the parameterized lattice is a straightforward process.

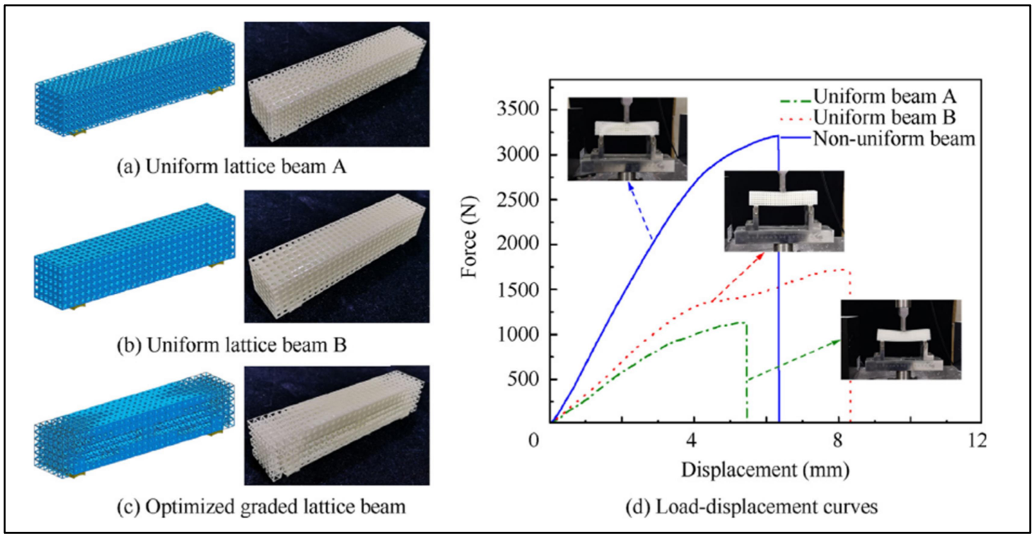

Figure. 2.7: Three-point bending beam in filled with uniform and graded lattice (Wang *et al.* 2020)

Agarwal *et al.* (2020) investigated the application of Graphite Aluminum MMC on leaf spring for mass reduction using Finite Element Method. The ANSYS Design Modeler is used to create and evaluate the CAD model. The design is then optimized utilizing the Central Composite Design scheme and the Taguchi Response Surface approach. The RSM optimization produced a sensitivity plot, a goodness of fit curve, and particular set values for the optimization variables (inner and outer radius). When compared to standard steel material, the use of graphite aluminum MMC led to a 56.1% mass reduction without an increase in stress. Comparing leaf spring deformation to typical steel material, the former is greater. The calculated optimal dimensions for minimal mass are the outer radius between 1020 mm and 1025 mm and inner radius more than 995 mm.

Tadesse and Fatoba (2022) undertook a study to improve the mono-leaf spring's design by swapping out its constituent parts for composite materials for a wider range of automotive applications. composite materials like carbon epoxy, bamboo polyester, E-glass/epoxy, and graphite epoxy made them choice materials to be compared with the conventional steel leaf. The model and the numerical analyses of the composite materials and the steel leaf were conducted using CATIAVR9 and ANSYS software, respectively. The findings demonstrated that, as compared to the typical steel leaf, the weight of all four composite materials was reduced. The Von Misses stresses of the composite materials and the traditional steel leaf were also compared, with the results substantiated. Carbon epoxy came in second with a deflection of 1.5469 mm, followed by Bamboo polyester with a maximum displacement of 1.5726 mm. Compared to standard steel leaf, which had a displacement of 1.2144 mm, e-glass/epoxy had the lowest displacement of 1.5172 mm.

2.1 Summary of Literature Review

From the review of literature, it is found that weight minimization is one of the important design prospects for any automobile component and mono leaf spring is one of them. Because leaf springs add a significant amount of weight to the vehicle, they must be robust. Using additive manufacturing techniques for topology optimization, the weight of the leaf spring can be reduced.

The primary goal of the current study is to identify the ideal leaf spring design for usage in automobiles. The research intends to fill in the information gaps through thorough examinations, especially the limiting design of leaf springs in comparison to their strength-to-weight ratio. The goal of the current research is to identify the optimal leaf spring design for the best strength-to-weight ratio.

2.2 Research Gap

The following gaps are identified from the review of literature:

(i) By using the technique of topology optimization, we can find the best design of mono leaf spring for achieving optimum strength-to-weight ratio.

(ii) Lattice Structure optimization technique is used to find best structural design against minimum weight and maximum strength of the mono leaf spring.

(iii) Comparative analysis of these two techniques is carried out to most suitable design for achieving maximum strength-to-weight ratio.

2.3 Objectives of proposed work:

The objective of current research is to achieve weight reduction of automobile components (mono leaf spring) using techniques of additive manufacturing. The detailed objectives are:

1. CAD modelling of generic design of component (leaf spring) using ANSYS design modeler and conducting FEA analysis on the same using ANSYS simulation package.
2. Generating lattice structure design of leaf spring and re-conducting FEA analysis.
3. Generating topological optimization design of leaf spring and conducting FEA analysis.
4. Modal analysis of the above-discussed design for natural frequencies and mode shapes.
5. Comparative analysis of all designs based on stresses, deformation, and safety factors

Chapter 3 MATERIALS AND METHODS

This chapter discusses about materials and methodology used for conducting the analysis of mono leaf spring for achieving the best design for most suitable strength-to-weight ratio. The procedure and methodology of this analysis is carried out by referring the base paper. The material used for mono leaf spring is Structural steel. The CAD model of mono leaf spring is developed in ANSYS design modeler using sketch and extrude tools. After the validation is done, topology optimized and lattice structural design of this mono leaf spring is produced and under same loading condition finite element analysis of above produced design is carried out.

Table 3.1: Specification of leaf spring

S.No	Specification	Values
1	Length of leave (mm)	965
2	Number of full- length leave	01
3	Width of all leave (mm)	45
4	Thickness of all leave (mm)	30
5	Inner radius of the eye (mm)	23
6	Outer radius of the eye (mm)	50
7	Camber (mm)	15

3.1 Methodology Flow Chart

The methodology of this analysis begins with the selection of materials and the selection of leaf spring design. After selecting the design, solid CAD modelling of the leaf spring is developed in ANSYS software. Now the finite element analysis of the generic design of a leaf spring is carried out in ANSYS software. After completing the analysis of generic design, the development of lattice structure design and topology-optimized design of leaf springs is begin.Now conducting FE analysis of topology-optimized design and lattice structure design. Conclude a detailed comparative analysis of the obtained results on the basis of deformation, stress, and safety factors.

The methodology flow chart of research is shown below

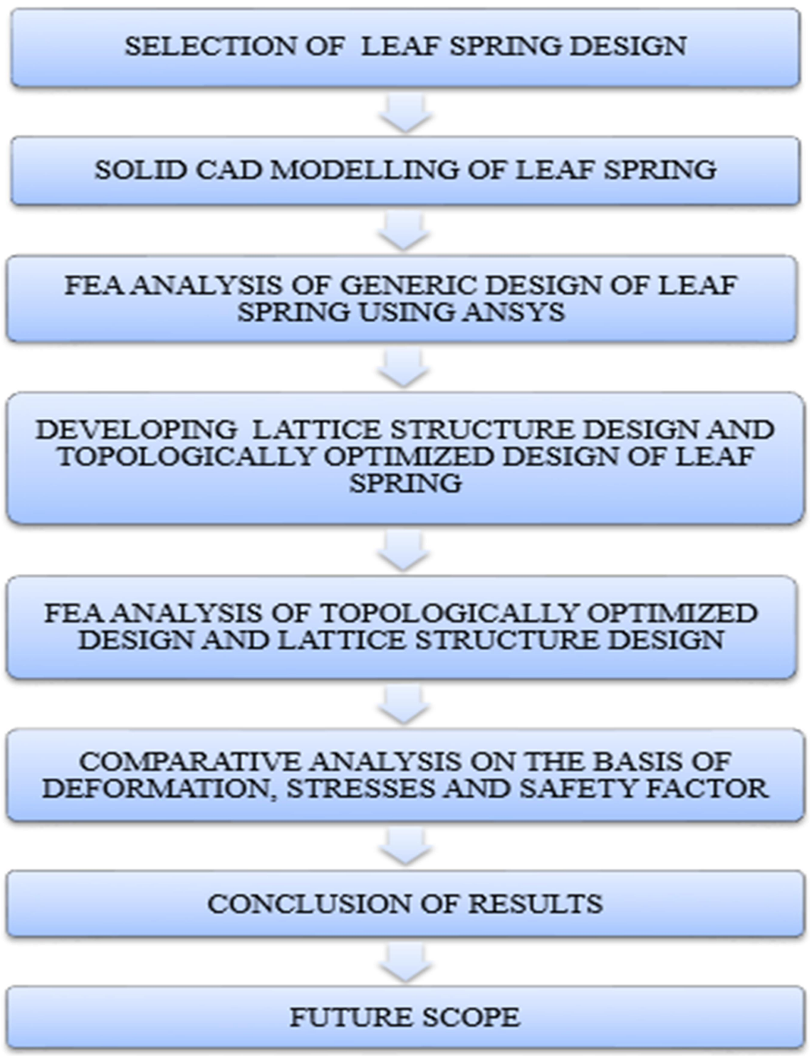

Figure. 3.1 Illustrate the methodology flow chart

3.2 FEA Analysis

The FEA analysis is conducted on mono leaf spring. There are various steps in the FEA analysis process. The details of these actions are provided below.

3.2.1 CAD Modelling

The leaf spring model was created using ANSYS Design Modeler.

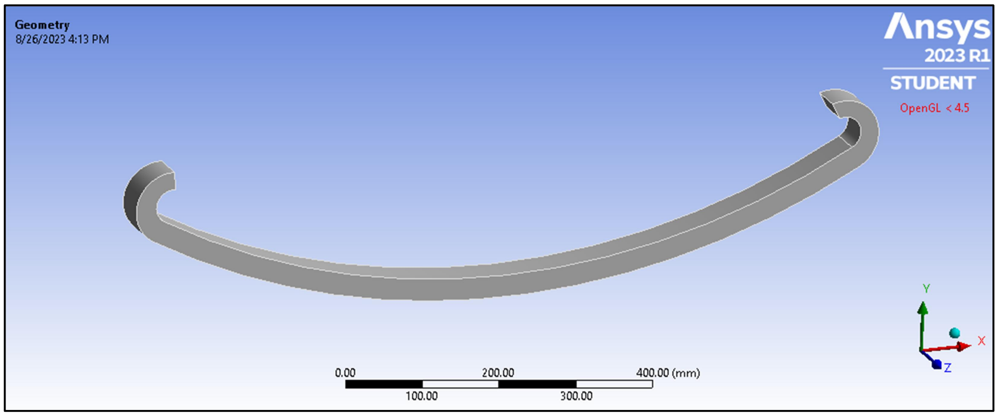

Figure. 3.2 CAD model of leaf spring

3.2.2 Meshing

Here, the mono leaf spring is discretized using the hexahedral element type. The degree of complexity, topological consistency, and other geometric form constraints all have an impact on an element's size and shape. There are 474 total elements and 3268 total nodes that were produced.

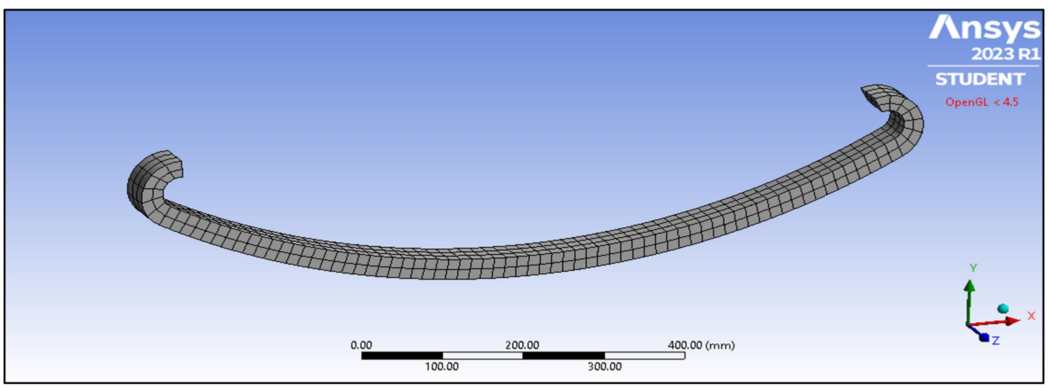

Figure. 3.3 Meshed model of leaf spring

Table 3.2: Structural Steel Properties

S.No	Property	Value
1	Density (kg/m^3)	7850
2	Young's Modulus (MPa)	210000
3	Tensile Yield Strength (MPa)	250
4	Compressive Yield strength (MPa)	250
5	Tensile Ultimate Strength (MPa)	460

3.2.3 Loads and Boundary Condition

By employing the leaf spring's structural loads and boundary conditions as inputs to the calculation, the equivalent stress, safety factor, and deformation will be calculated.

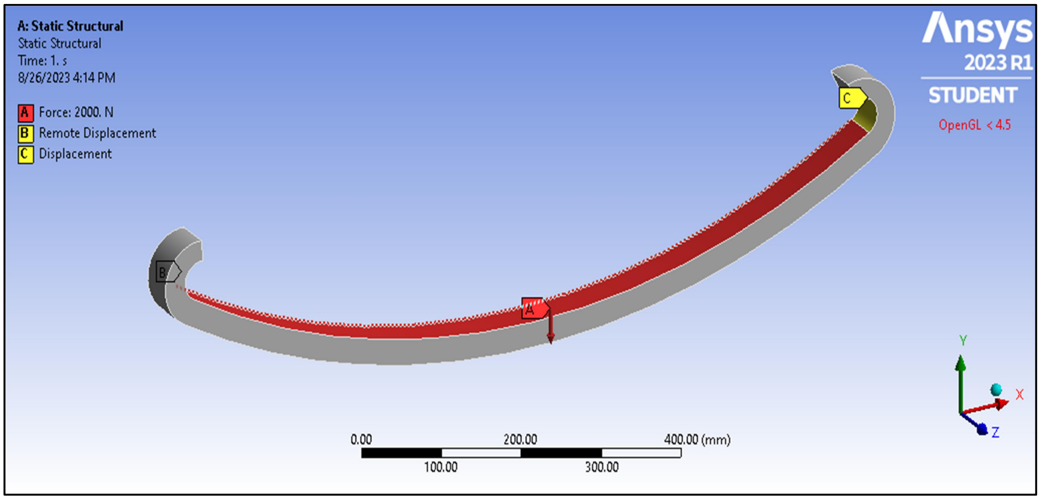

Figure. 3.4 Loads and boundary condition

3.2.4 Solution

The solution stage begins with the selection of the appropriate solver type, which is followed by the beginning of the software simulation. The global stiffness matrix is created by combining the element stiffness matrices once they have been built. The additional calculations are carried out at each of the element's nodes, and an estimate is then extrapolated for the full element's edge lengths.

3.2.5 Lattice structure Model

A section of a leaf spring that was under minimal stress had to be eliminated in order to create the lattice structure model. Lattice structures of varying densities and types are spread out throughout the surface of the region.

In current analysis of lattice structure model two type of lattice is used –

1. Square lattice structure
2. Triangular lattice structure

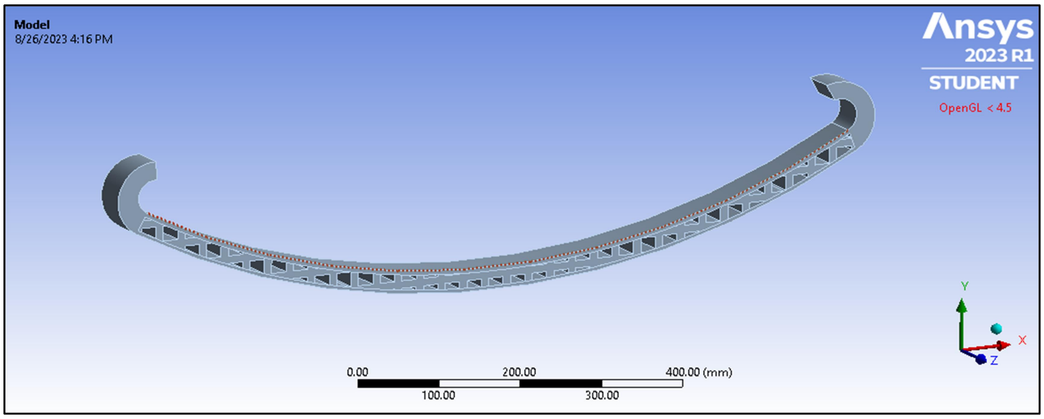

Figure. 3.5 Square lattice structure

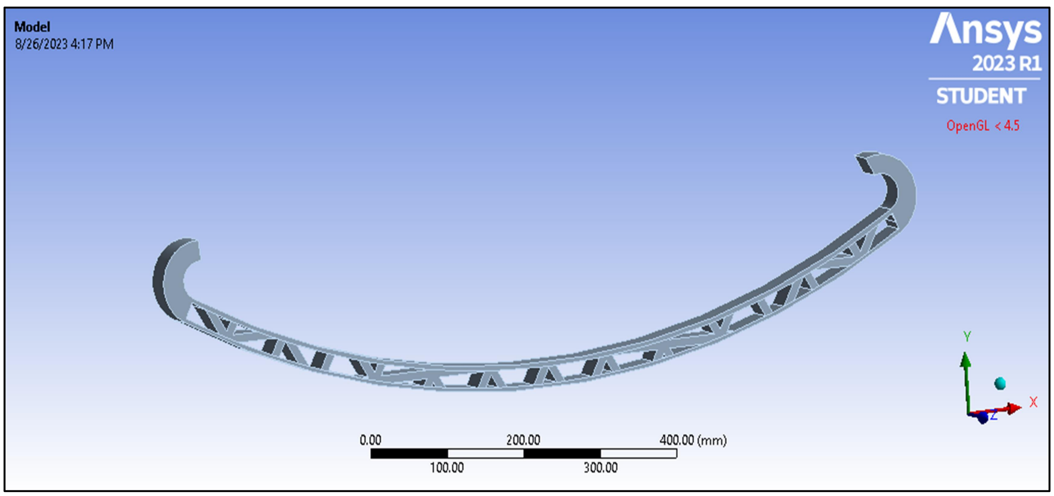

Figure. 3.6 Triangular lattice structure

3.2.6 Topologically Optimized Model

In order to achieve topological optimization, it is important to remove a specific section of the leaf spring. In the context of the specific language, these places are frequently referred to as "zones characterized by mass density". The topologically optimized design is then evaluated using ANSYS Finite Element Analysis (FEA) software under the same loading conditions as specified in Point 3.The following illustration showcases the formulation of a topological optimization issue, according to the conventional structure of an optimization problem.

$$F = F(u(\rho), \rho) = \int_{\Omega} f(u(\rho),\rho)\, dV$$

$$G_0(\rho) = \int_{\Omega} \rho dV - V_0 \leq 0$$

$$G_j(u(\rho),\rho) \leq 0 \text{ with } j=1,\dots,m$$

- The notation often used to represent an objective function is denoted as F(u(u(,)). The function in question reflects the variable that is being reduced in order to achieve the highest attainable degree of performance. The objective function most often used is compliance because to its correlation with an increase in stiffness as compliance decreases. The allocation of resources might be seen as a variable in the quandary.
- The attribute in question, represented by the symbol (u), is defined by the spatial distribution of the material's density. A numerical number of 1 signifies the existence of material, whereas a numerical value of 0 signifies the nonexistence of material. A state may be characterized by a linear or nonlinear equation if said equation is fulfilled by the state field u. This denotes the maximum allowable capacity for the given design. In order to identify this particular area, it is important to take into account many criteria, such as the specifications for assembly and packing, the availability of equipment, as well as the accessibility for both human operators and tools. Non-design areas refer to certain regions or components inside a model that are deemed unsuitable for alteration during the optimization process, particularly after the design space has been defined.
- In order to meet the criteria for correctness, the answer must possess the ability to fulfill a set of m requirements. Two examples of restrictions in engineering applications are the maximum permitted amount of material that may be spread, commonly referred to as a volume limitation, and the maximum allowable stress levels.

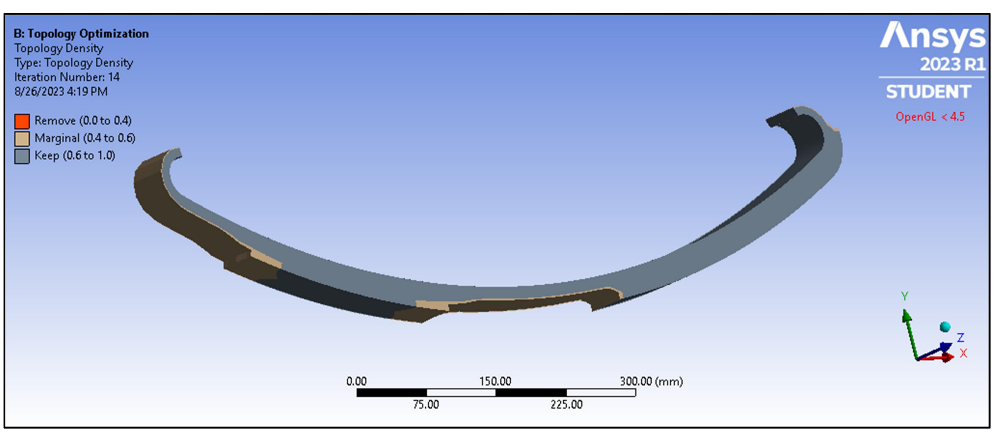

Figure. 3.7 Topology optimized design of leaf spring

Solver Report

“ANSYS Mechanical Enterprise

BATCH MODE REQUESTED (-b) = NOLIST

INPUT FILE COPY MODE (-c) = COPY

DISTRIBUTED MEMORY PARALLEL REQUESTED

2 PARALLEL PROCESSES REQUESTED WITH SINGLE THREAD PER PROCESS

TOTAL OF 2 CORES REQUESTED

MPI OPTION = INTELMPI

START-UP FILE MODE = NOREAD

STOP FILE MODE = NOREAD

/INPUT FILE= ds.dat LINE = 0

GET _WALLSTRT FROM ACTI ITEM=TIME WALL VALUE= 23.4055556

USE DOUBLE PRECISION RESULTS FILE FORMAT

TITLE=

test1--Static Structural (A5)

ACT Extensions:

MechanicalDropTest, 2.0

f0fd899f-9d88-4f46-8cf1-36bf5c218d65, wbex

SET PARAMETER DIMENSIONS ON _WB_SOLVERFILES_DIR

TYPE=STRI DIMENSIONS= 248 1 1

SET PARAMETER DIMENSIONS ON _WB_USERFILES_DIR

TYPE=STRI DIMENSIONS= 248 1 1

MPA UNITS SPECIFIED FOR INTERNAL

LENGTH = MILLIMETERS (mm)

MASS = TONNE (Mg)

TIME = SECONDS (sec)

TEMPERATURE = CELSIUS (C)

TOFFSET = 273.0

FORCE = NEWTON (N)

HEAT = MILLIJOULES (mJ)

INPUT UNITS ARE ALSO SET TO MPA

test1--Static Structural (A5)

ROUTINE COMPLETED

Number of total nodes

Number of contact elements

Number of spring elements

Number of bearing elements

Number of solid elements

Number of condensed parts

Number of total elements

PERFORM A STATIC ANALYSIS

THIS WILL BE A NEW ANALYSIS

USE SPARSE MATRIX DIRECT SOLVER

CONTACT INFORMATION PRINTOUT LEVEL 1

NLDIAG: Nonlinear diagnostics CONT option is set to ON.

Writing frequency : each ITERATION.

SELECT FOR ITEM=TYPE COMPONENT=

IN RANGE 2 TO 2 STEP 1

198 ELEMENTS (OF 691 DEFINED) SELECTED BY ESEL COMMAND.

SELECT ALL NODES HAVING ANY ELEMENT IN ELEMENT SET.

733 NODES (OF 3269 DEFINED) SELECTED FROM

198 SELECTED ELEMENTS BY NSLE COMMAND.

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS LKEY = 1 KVAL = 1

SET ACCORDING TO TABLE PARAMETER = _LOADVARI31X

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS LKEY = 2 KVAL = 1

SET ACCORDING TO TABLE PARAMETER = _LOADVARI31Y

SPECIFIED SURFACE LOAD PRES FOR ALL SELECTED ELEMENTS LKEY = 3 KVAL = 1

SET ACCORDING TO TABLE PARAMETER = _LOADVARI31Z

ALL SELECT FOR ITEM=NODE COMPONENT=

IN RANGE 1 TO 9953 STEP 1

3269 NODES (OF 3269 DEFINED) SELECTED BY NSEL COMMAND.

ALL SELECT FOR ITEM=ELEM COMPONENT=

IN RANGE 1 TO 1943 STEP 1

691 ELEMENTS (OF 691 DEFINED) SELECTED BY ESEL COMMAND.

SPECIFIED CONSTRAINT UX FOR SELECTED NODES 9953 TO 9953

BY 1

SET ACCORDING TO TABLE PARAMETER = _LOADVARI48UX

SPECIFIED CONSTRAINT UZ FOR SELECTED NODES 9953 TO 9953

BY 1

SET ACCORDING TO TABLE PARAMETER = _LOADVARI48UZ

PRINTOUT RESUMED BY /GOP

USE 1 SUBSTEPS INITIALLY THIS LOAD STEP FOR ALL DEGREES OF FREEDOM

FOR AUTOMATIC TIME STEPPING:

USE 1 SUBSTEPS AS A MAXIMUM

USE 1 SUBSTEPS AS A MINIMUM

TIME= 1.0000

ERASE THE CURRENT DATABASE OUTPUT CONTROL TABLE.

WRITE ALL ITEMS TO THE DATABASE WITH A FREQUENCY OF NONE FOR ALL APPLICABLE ENTITIES

WRITE NSOL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

WRITE RSOL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

WRITE NLOA ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

WRITE STRS ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

WRITE EPEL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

WRITE EPPL ITEMS TO THE DATABASE WITH A FREQUENCY OF ALL FOR ALL APPLICABLE ENTITIES

NONLINEAR STABILIZATION CONTROL:
KEY=OFF
ALL CURRENT ANSYS DATA WRITTEN TO FILE NAME= file_Static20.db
FOR POSSIBLE RESUME FROM THIS POINT
CP =   0.859   TIME= 23:24:21
Element shape checking is currently inactive. Issue SHPP,ON or
SHPP,WARN to reactivate, if desired.
CP =   0.891   TIME= 23:24:21
The model data was checked and warning messages were found.
GIVE SUGGESTIONS AND RESET THE KEY OPTIONS
ELEMENT TYPE   1 IS SOLID186. KEYOPT(2)=0 IS SUGGESTED AND HAS
BEEN RESET.
KEYOPT(1-12)=   0   0   0   0   0   0   0   0   0   0   0   0
ANSYS - ENGINEERING ANALYSIS SYSTEM RELEASE
DISTRIBUTED ANSYS Mechanical Enterprise
VERSION=WINDOWS x64   23:24:21 DEC 11, 2021 CP=   0.906
test1--Static Structural (A5)
S O L U T I O N   O P T I O N S
PROBLEM DIMENSIONALITY. 3-D
DEGREES OF FREEDOM. . . . . . UX   UY   UZ   ROTX ROTY ROTZ
ANALYSIS TYPE . . . . .STATIC (STEADY-STATE)
OFFSET TEMPERATURE FROM ABSOLUTE ZERO 273.15
EQUATION SOLVER OPTION. . . . . .SPARSE
GLOBALLY ASSEMBLED MATRIX . . . . .SYMMETRIC
CP =   0.922   TIME= 23:24:21
Material number 2 (used by element 1727) should normally have at least
one MP or one TB type command associated with it. Output of energy by
material may not be available.
CP =   0.922   TIME= 23:24:21
The step data was checked and warning messages were found.
CP =   0.922   TIME= 23:24:21
The conditions for direct assembly have been met. No .emat or .erot

files will be produced.

CP = 0.938 TIME= 23:24:21

Internal nodes from 9954 to 9954 are created.

1 internal nodes are used for handling degrees of freedom on pilot nodes of rigid target surfaces.

CP = 0.938 TIME= 23:24:21

Internal nodes from 9954 to 9954 are created.

1 internal nodes are used for handling degrees of freedom on pilot nodes of rigid target surfaces.

CP = 0.984 TIME= 23:24:21

Force-distributed-surface identified by real constant set 3 and contact element type 3 has been set up. The pilot node 9953 is used to apply the force. Internal MPC will be built.

The used degrees of freedom set is UX UY UZ ROTX ROTY ROTZ

Please verify constraints (including rotational degrees of freedom) on the pilot node by yourself.

CP = 0.984 TIME= 23:24:21

Internal nodes from 9954 to 9954 are created.

1 internal nodes are used for handling degrees of freedom on pilot nodes of rigid target surfaces.

D I S T R I B U T E D D O M A I N D E C O M P O S E R

Number of elements: 691

Number of nodes: 3270

Decompose to 2 CPU domains

Element load balance ratio = 1.009

LOAD STEP NUMBER. 1

TIME AT END OF THE LOAD STEP. 1.0000

NUMBER OF SUBSTEPS. 1

STEP CHANGE BOUNDARY CONDITIONS . . . . NO

PRINT OUTPUT CONTROLS . . . . .NO PRINTOUT

DATABASE OUTPUT CONTROLS

ITEM FREQUENCY COMPONENT

ALL NONE
NSOL ALL
RSOL ALL
NLOA ALL
STRS ALL
EPEL ALL
EPPL ALL
SOLUTION MONITORING INFO IS WRITTEN TO FILE=
file.mntr
CP = 1.156 TIME= 23:24:21
Force-distributed-surface identified by real constant set 3 and
contact element type 3 has been set up. The pilot node 9953 is used
to apply the force. Internal MPC will be built.
The used degrees of freedom set is UX UY UZ ROTX ROTY ROTZ
Please verify constraints (including rotational degrees of freedom)
on the pilot node by yourself.
The FEA model contains 0 external CE equations and 6 internal CE
equations.
TOTAL RIGID BODY MASS MATRIX ABOUT ORIGIN

```
Translational mass                 |  Coupled translational/rotational mass
0.12766E-01   0.0000      0.0000   |   0.0000      0.28724     0.63048
0.0000      0.12766E-01   0.0000   |  -0.28724     0.0000      0.71877E-02
0.0000      0.0000      0.12766E-01 | -0.63048    -0.71877E-02  0.0000
  ---------------------------------------- | ----------------------------------------
                                   |      Rotational mass (inertia)
                                   |    82.174     -1.3751     -0.16172
                                   |   -1.3751     1385.3      14.186
                                   |  -0.16172     14.186      1450.3
```

TOTAL MASS = 0.12766E-01
The mass principal axes coincide with the global Cartesian axes
CENTER OF MASS (X,Y,Z)= 0.56301 -49.386 22.500

TOTAL INERTIA ABOUT CENTER OF MASS

44.575	-1.7300	0.29178E-13
-1.7300	1378.9	-0.53116E-14
0.29178E-13	-0.53116E-14	1419.1

The inertia principal axes coincide with the global Cartesian axes

TYPE	MASS
1	0.127664E-01

Range of element maximum matrix coefficients in global coordinates

Maximum = 3938044.51 at element 4.

Minimum = 2451752.56 at element 13.

TYPE	NUMBER	ENAME	TOTAL CP	AVE CP
1	474	SOLID186	0.125	0.000264
2	198	SURF154	0.000	0.000000
3	18	CONTA174	0.016	0.000868
4	1	TARGE170	0.000	0.000000

Time at end of element matrix formulation CP = 1.40625.

DISTRIBUTED SPARSE MATRIX DIRECT SOLVER.

Number of equations = 9550, Maximum wavefront = 798

Local memory allocated for solver = 18.687 MB

Local memory required for in-core solution = 18.051 MB

Local memory required for out-of-core solution = 12.780 MB

Total memory allocated for solver = 37.421 MB

Total memory required for in-core solution = 36.118 MB

Total memory required for out-of-core solution = 25.096 MB

The Distributed Sparse Matrix Solver is currently running in the in-core memory mode. This memory mode uses the most amount of memory in order to avoid using the hard drive as much as possible, which most often results in the fastest solution time. This mode is recommended if enough physical memory is present to accommodate all of the solver data.

curEqn= 4923 totEqn= 4923 Job CP sec= 1.656

Factor Done= 100% Factor Wall sec= 0.117 rate= 1674.4 Mflops

Distributed sparse solver maximum pivot= 9834785.31 at node 999 UZ.

Distributed sparse solver minimum pivot= 286.217268 at node 3091 UY.

Distributed sparse solver minimum pivot in absolute value= 286.217268 at node 3091 UY.

ELEMENT RESULT CALCULATION TIMES

TYPE	NUMBER	ENAME	TOTAL CP	AVE CP
1	474	SOLID186	0.031	0.000066
2	198	SURF154	0.047	0.000237
3	18	CONTA174	0.000	0.000000

NODAL LOAD CALCULATION TIMES

TYPE	NUMBER	ENAME	TOTAL CP	AVE CP
1	474	SOLID186	0.000	0.000000
2	198	SURF154	0.000	0.000000
3	18	CONTA174	0.000	0.000000

LOAD STEP 1 SUBSTEP 1 COMPLETED. CUM ITER = 1

TIME = 1.00000 TIME INC = 1.00000 NEW TRIANG MATRIX

ANSYS BINARY FILE STATISTICS

BUFFER SIZE USED= 16384

0.500 MB WRITTEN ON ELEMENT SAVED DATA FILE: file0.esav

3.938 MB WRITTEN ON ASSEMBLED MATRIX FILE: file0.full

1.000 MB WRITTEN ON RESULTS FILE: file0.rst

Write FE CONNECTORS

WRITE OUT CONSTRAINT EQUATIONS TO FILE=

file.ce

GET _WALLASOL FROM ACTI ITEM=TIME WALL VALUE= 23.4061111

PRINTOUT RESUMED BY /GOP

FINISH SOLUTION PROCESSING

ROUTINE COMPLETED CP = 1.766

ANSYS - ENGINEERING ANALYSIS SYSTEM RELEASE

DISTRIBUTED ANSYS Mechanical Enterprise

VERSION=WINDOWS x64 23:24:22 DEC 11, 2021 CP= 1.781

test1--Static Structural (A5)

ANSYS RESULTS INTERPRETATION (POST1)
CP = 1.781 TIME= 23:24:22
Reading results into the database (SET command) will update the current
displacement and force boundary conditions in the database with the
values from the results file for that load set. Note that any
subsequent solutions will use these values unless action is taken to
either SAVE the current values or not overwrite them (/EXIT,NOSAVE).
Set Encoding of XML File to:ISO-8859-1
DATABASE WRITTEN ON
EXIT THE ANSYS POST1 DATABASE PROCESSOR
PRINTOUT RESUMED BY /GOP
GET _WALLDONE FROM ACTI ITEM=TIME WALL VALUE= 23.4061111
PARAMETER _PREPTIME = 1.000000000
PARAMETER _SOLVTIME = 1.000000000
PARAMETER _POSTTIME = 0.000000000
PARAMETER _TOTALTIM = 2.000000000
EXIT ANSYS WITHOUT SAVING DATABASE
NUMBER OF WARNING MESSAGES ENCOUNTERED= 2
NUMBER OF ERROR MESSAGES ENCOUNTERED= 0
Processor Model: Intel(R) Core(TM) i5-7200U CPU @ 2.50GHz
Total number of cores available : 4
Number of physical cores available : 2
Number of processes requested : 2
Number of threads per process requested : 1
Total number of cores requested : 2 (Distributed Memory Parallel)
MPI Type: INTELMPI
MPI Version: Intel(R) MPI Library 5.1.3 for Windows* OS
GPU Acceleration: Not Requested
Job Name: file0
Input File: dummy.dat
Latency time from master to core 1 = 1.873 microseconds
Communication speed from master to core 1 = 2888.60 MB/sec

Total CPU time for main thread	:	1.4 seconds
Total CPU time summed for all threads	:	1.8 seconds
Elapsed time spent pre-processing model (/PREP7)	:	0.2 seconds
Elapsed time spent solution - preprocessing	:	0.2 seconds
Elapsed time spent computing solution	:	0.8 seconds
Elapsed time spent solution - postprocessing	:	0.0 seconds
Elapsed time spent post-processing model (/POST1)	:	0.0 seconds
Equation solver used	:	Sparse (symmetric)
Equation solver computational rate	:	3078.0 Mflops
Maximum total memory used	:	267.0 MB
Maximum total memory allocated	:	3136.0 MB
Total physical memory available	:	8 GB”

Chapter 4 RESULTS AND DISCUSSION

This chapter examines the comparative analysis of several techniques, including topology optimization, lattice structure methodology, and generic mono leaf spring design, in order to identify various characteristics that are crucial for determining the optimal strength-to-weight ratio for an appropriate mono leaf spring design.

4.1 Validation of Numerical Results

I. **Agarwal *et al.* 2020** conducted finite element and taguchi response analysis of the application of Graphite Aluminium MMC in automotive leaf spring. Author use ANSYS software for static structural analysis along with appropriate boundary conditions.

II. The total number of elements generated was 474 and number of nodes generated was 3268.

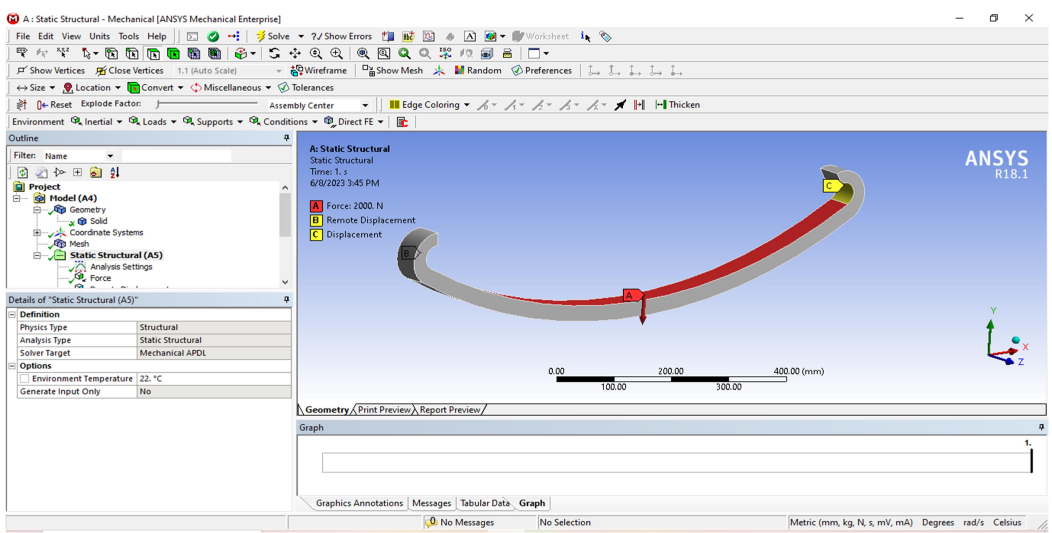

Figure. 4.1 Illustration of applied boundary condition

Table 4.1 Comparison of numerical results

Results	Result (**Arora *et al.***)	Numerical values	% Error
Equivalent stress	141.78	147.54	4.06
Total deformations	14.67	19.3	3.1

After validating previous research, we will perform the same procedure for finding different optimized designs for the same mono-leaf spring. Then mono leaf spring is also introduced to modal analysis for finding different mode shapes and natural frequencies.

The following parameters which are used to obtain the best strength-to-weight ratio are as follows-

(i) Equivalent stress

(ii) Principal stress

(iii) Total deformation

(iv) Strain Energy

(v) Factor of Safety

(vi) Mass

4.2 Generic Design Results

The generic leaf spring design is used for the FEA structural analysis. Plots are made to visualize the distribution of equivalent stress, main stress, total deformation, and strain energy. The region of the leaf spring's cylindrical support zone that exhibits a red coloration corresponds to the spot experiencing the highest level of equivalent stress. The upper limit of the equivalent stress present in this particular area is measured at 142 MPa.

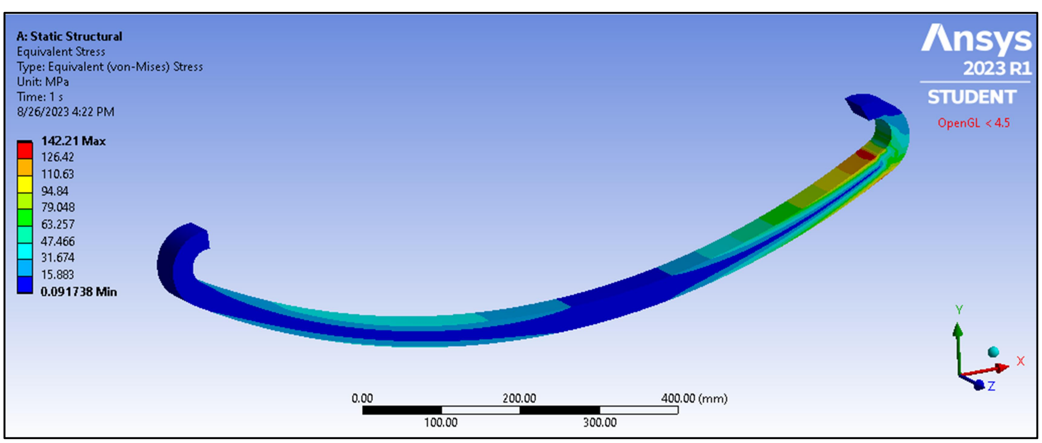

Figure 4.2 Generic design equivalent stress

The core zone of the leaf spring exhibits the minimum equivalent stress, characterized by tension values below 15.8 MPa. The stress distribution in the left support region, often referred to as the fixed support, exhibits its minimum value at this specific point, as shown by the dark blue color.

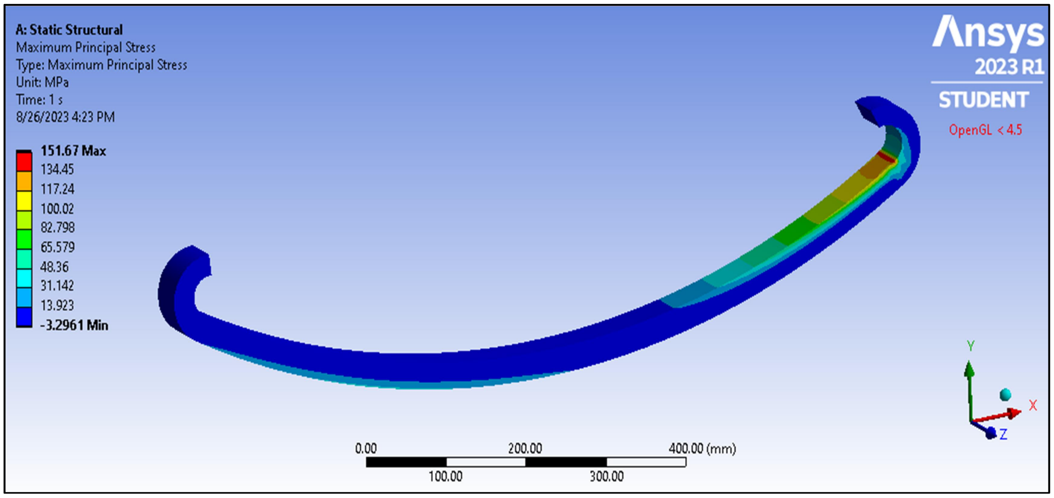

Figure 4.3 Generic design principal stress

Within the midsection, also known as the central zone, of the leaf spring, the principal stress reaches its minimum value, where it remains below the threshold of 13.92MPa. The stress distribution in the left support region, often referred to as the fixed support, exhibits its minimum value at this particular point, as shown by the dark blue shading.

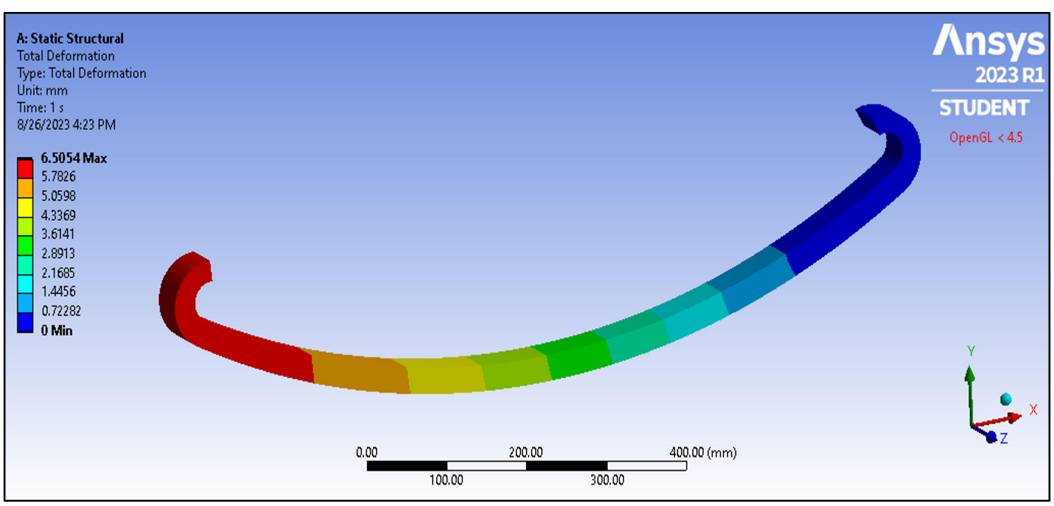

Figure 4.4 Generic design deformation

The deformation plot of a leaf spring with a generic design has been generated, as shown in the recently displayed figure (Figure 4.4). The region of permanent support located on the left side has the highest degree of distortion, measuring in excess of 6.5 millimeters. The leaf spring's rightmost end exhibits the least deformation, as shown by the hue of darkish blue.

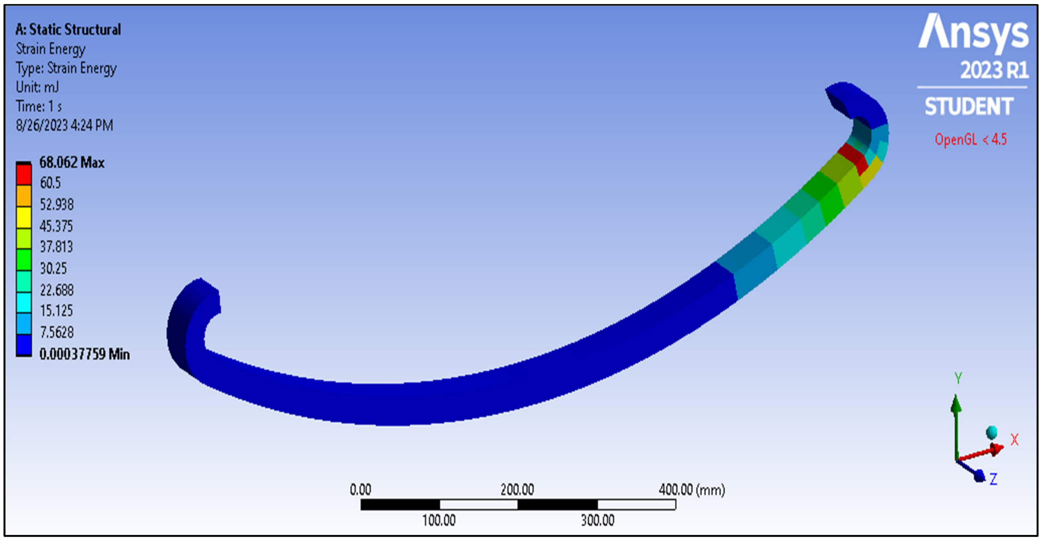

Figure 4.5 Generic design strain energy

The plot illustrating the strain energy for a leaf spring is shown in Fig 4.5. The region of a leaf spring often referred to as the fixed support area exhibits the highest level of strain energy, surpassing a magnitude of 60.5 milli joule. The regions corresponding to the center and left side of the leaf spring exhibit the lowest levels of strain energy, since their respective deformations do not exceed 7.56mJ in either of these regions.

4.3 Topology Optimized Design Results

After the topological optimization of the leaf spring design, as seen in Fig 4.6, a subsequent design iteration will be produced with a reduced mass density compared to the prior design. The middle portion of the leaf spring, as well as the region immediately below the support area on both sides, have a reduced mass density compared to the other sections of the spring.

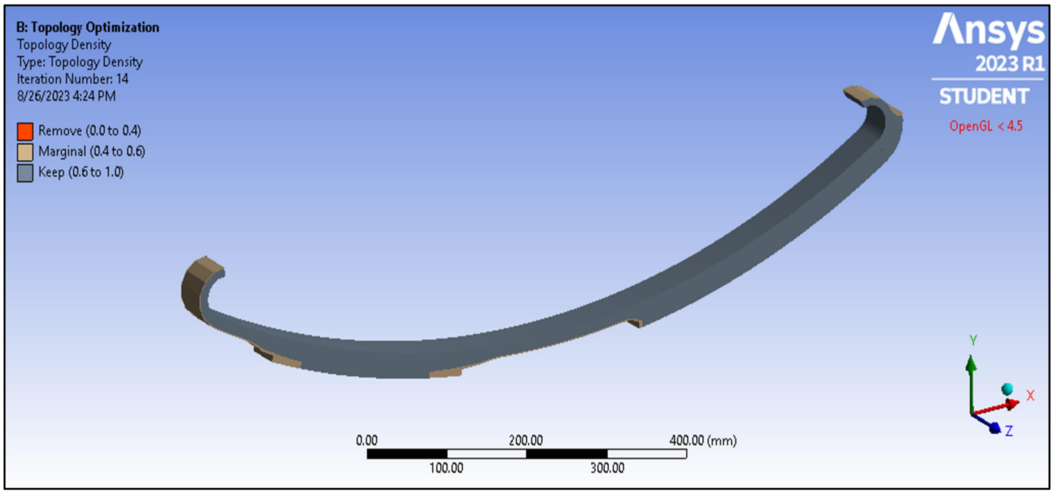

Figure 4.6 Leaf spring topologically optimized design

A stress plot is constructed for a leaf spring developed with topology optimization in consideration, exhibiting similarities. The region of the leaf spring's cylindrical support zone that exhibits a red coloration represents the spot characterized by the highest level of similar stress. The highest measured equivalent stress at this location is 242.59 Megapascals (MPa).

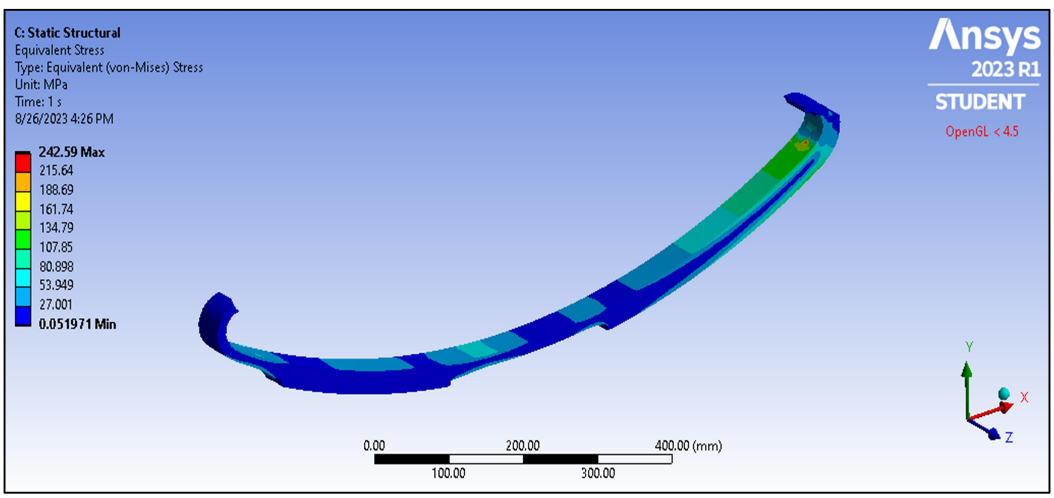

Figure 4.7 Topology optimized design equivalent stress

The primary focal point of stress concentration occurs inside the core region of the leaf spring, where the stress level is seen to be below 40.2 MPa. The stress distribution in the left support region, often referred to as the fixed support, exhibits its minimum value at this specific point, as seen by the dark blue shade. The cylindrical support component of the leaf spring experiences the highest magnitude of stress, at 381.61MPa.

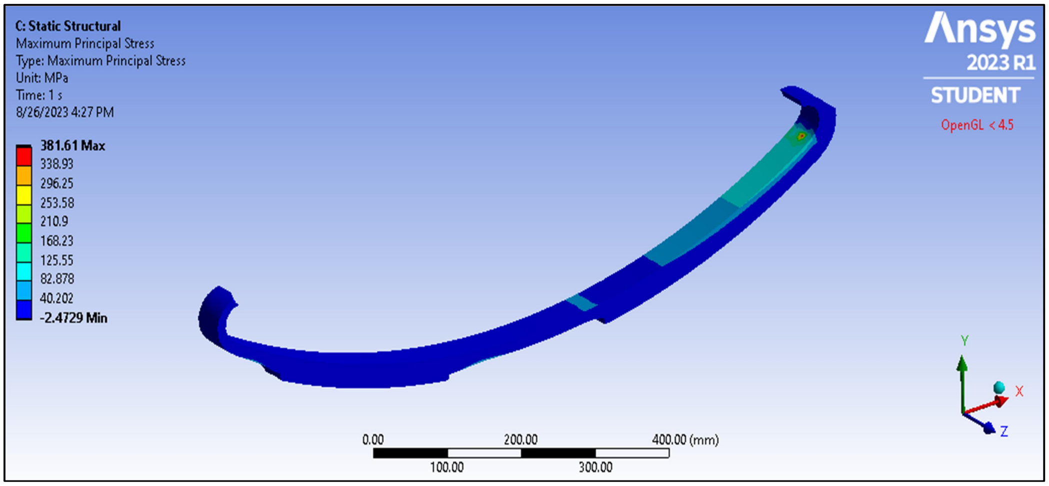

Figure 4.8 Topology optimized design principal stress

The deformation curve shown in Figure 4.9 illustrates the topologically optimal design of the leaf spring. The zone of the fixed support on the left-hand side has the most significant deformation, surpassing a magnitude of 6.85 millimeters. The leaf spring's rightmost end exhibits the least deformation, as seen by the hue of dark blue.

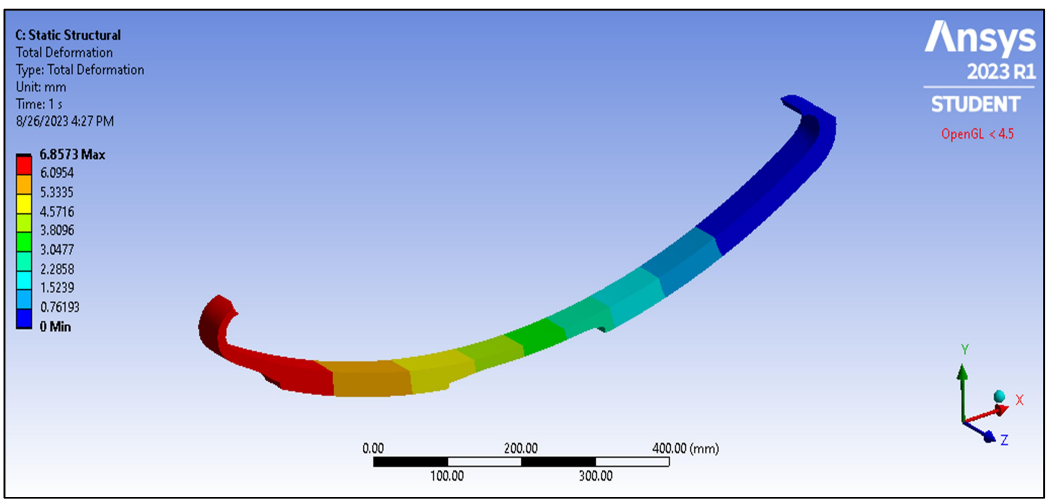

Figure 4.9 Topology optimized design deformation

The strain energy distribution for the leaf spring design that has undergone topological optimization is shown in Figure 4.10. The cylindrical component of the leaf spring exhibits a strain energy that surpasses the overall strain energy at any other site by about 18.604 millijoules. The regions of the leaf spring's central and left sections, whereby the magnitude of deformation is below 4.13 mJ, exhibit the lowest level of strain energy.

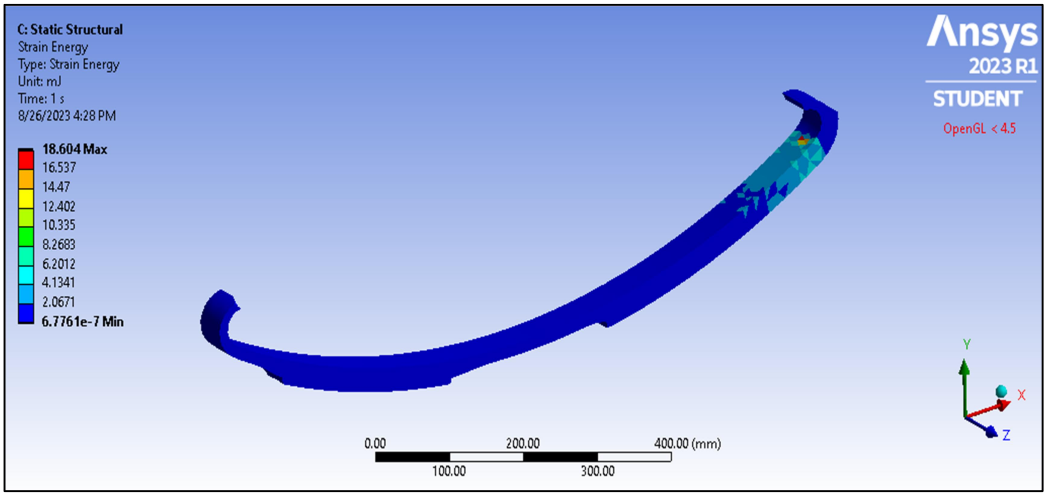

Figure 4.10 Topology optimized design strain energy

4.4 Square Lattice Structure Design

The figure shown in Figure 4.11 illustrates the integration of a leaf spring design with the framework of a square lattice, resulting in a novel design characterized by a decreased mass density. The phenomenon of mass density decrease is seen to be uniformly distributed over the whole leaf spring structure.

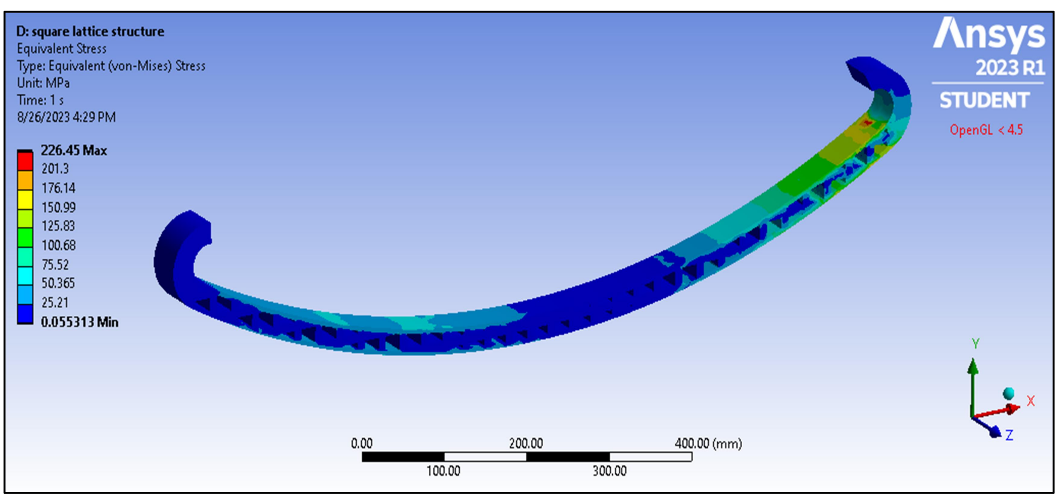

Figure 4.11 Square lattice design equivalent stress

A stress map of equal magnitude is produced for the construction of a leaf spring using a square lattice. The region of the leaf spring's cylindrical support zone that exhibits a red coloration represents the spot where the highest level of comparable stress is seen. The magnitude of the greatest equivalent stress in this location is recorded as 226.45 MPa.

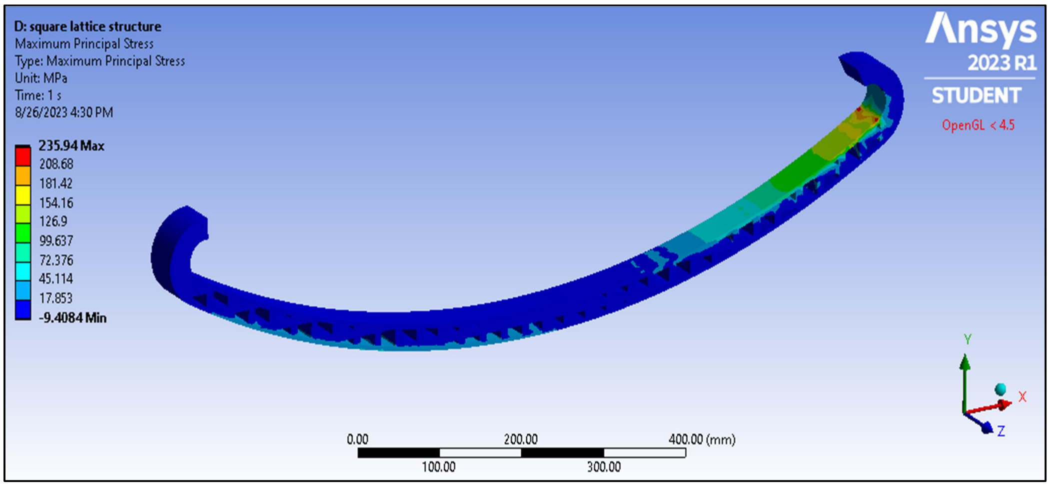

Figure 4.12 Square lattice design principal stress

The stress in the mid section of a leaf spring is below 45.114 MPa, which corresponds to the region with the lowest main stress, the minor stress likewise reaches its minimum value. The stress distribution in the left support region, referred to as the fixed support, exhibits its minimum value at this specific point, as shown by the dark blue shading. The cylindrical support component of the leaf spring experiences the highest level of primary stress, with a magnitude of 235.94 MPa.

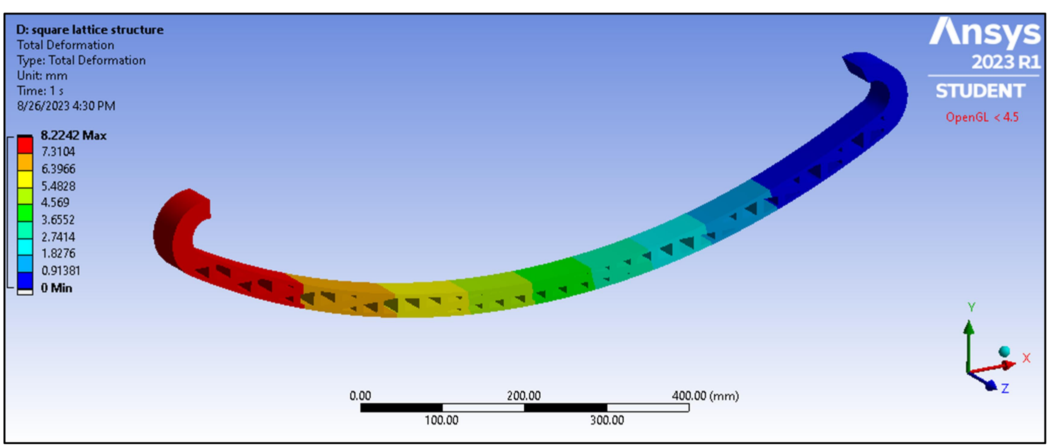

Figure 4.13 Square lattice deformation

Figure 4.13 displays the deformation plot of a leaf spring using a square lattice structure. The region of the permanent support on the left-hand side exhibits the highest level of deformation, surpassing a magnitude of 8.22mm. The leaf spring's rightmost end exhibits the least deformation, as shown by the hue of dark blue.

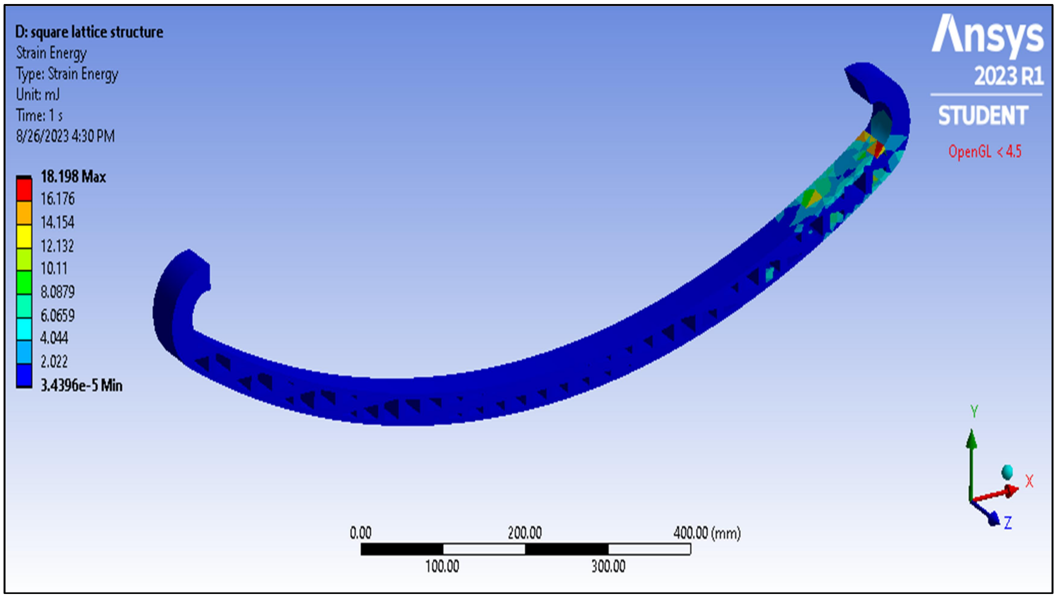

Figure 4.14 Square lattice design strain energy

Figure 4.14 displays the strain energy curve pertaining to the square lattice configuration of the leaf spring. The cylindrical support of the leaf spring is the primary site exhibiting the highest level of strain energy, surpassing 18.198 milli Joules. The regions of the leaf spring's central and left sections, where the magnitude of deformation is below 4.04mJ, exhibit the lowest level of strain energy.

4.5 Triangular Lattice Structure Design

The figure shown in Figure 4.15 showcases the integration of a leaf spring design with the framework of a triangular lattice, resulting in a novel design characterized by a reduced mass density contrasted with the original design. The phenomenon of mass density decrease is uniformly distributed over the whole leaf spring.

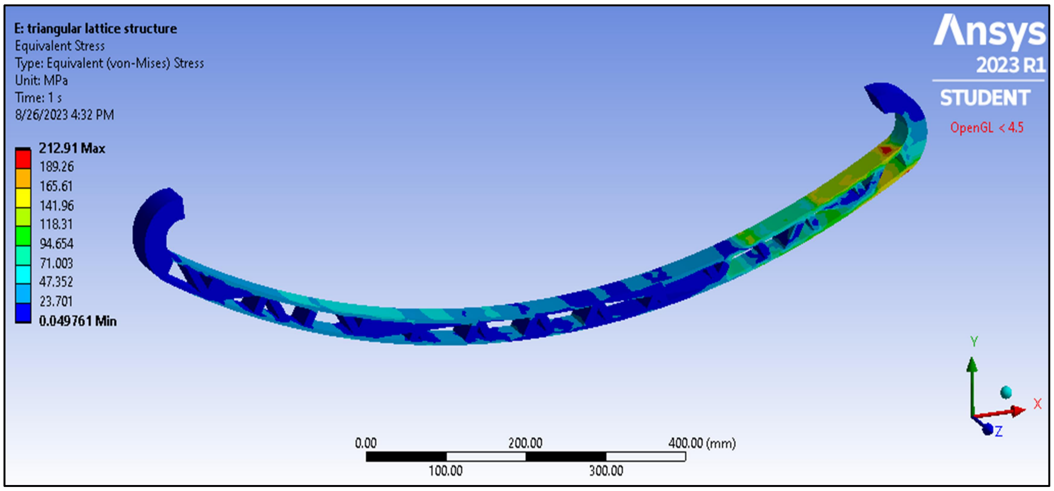

Figure 4.15 Triangular lattice design equivalent stress

A stress plot is constructed for a leaf spring built in the shape of a triangular lattice, which exhibits similarities. The region of the leaf spring's cylindrical support zone that exhibits a red coloration represents the spot characterized by the highest level of similar stress. The magnitude of the greatest equivalent stress in this location is 212.91 MPa.

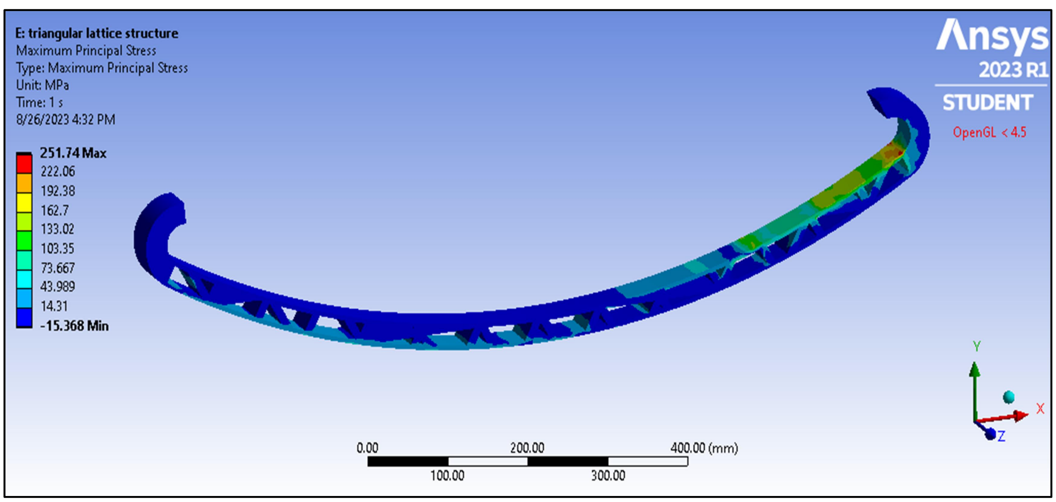

Figure 4.16 Triangular lattice design principal stress

In the core zone of a leaf spring, when the stress level is below 43.989 MPa, both the main stress and the minor stress reach their minimum values. The stress distribution in the left support region, often referred to as the fixed support, exhibits its minimum value at this specific point, as shown by the dark blue color. The cylindrical support component of the leaf spring experiences the highest principal stress, at 251.74 MPa.

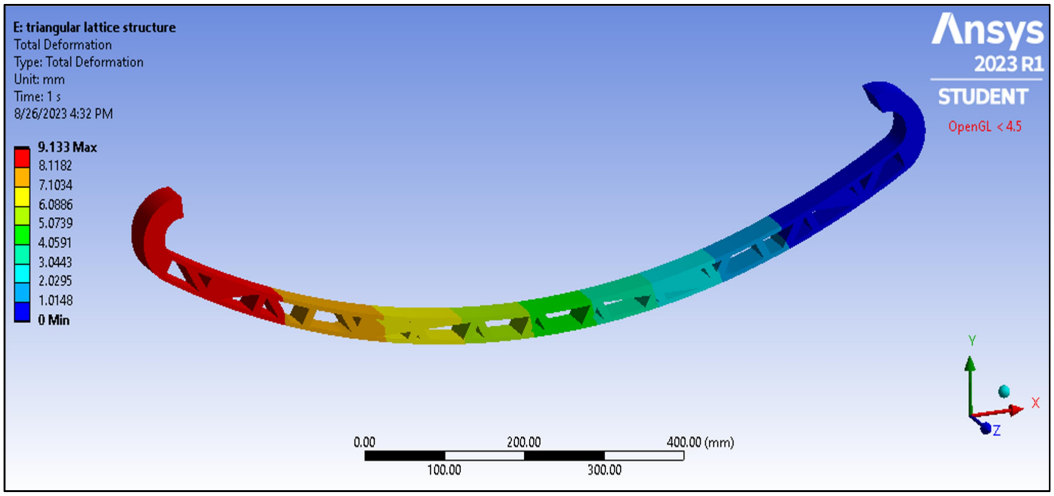

Figure 4.17 Triangular lattice design deformation

The deformation plot for the design of the triangular lattice leaf spring is shown in Figure 4.17. The zone of the fixed support on the left-hand side has the most significant deformation, exceeding a magnitude of 9.13 millimeters. The leaf spring's rightmost end exhibits the least deformation, as shown by the hue of dark blue.

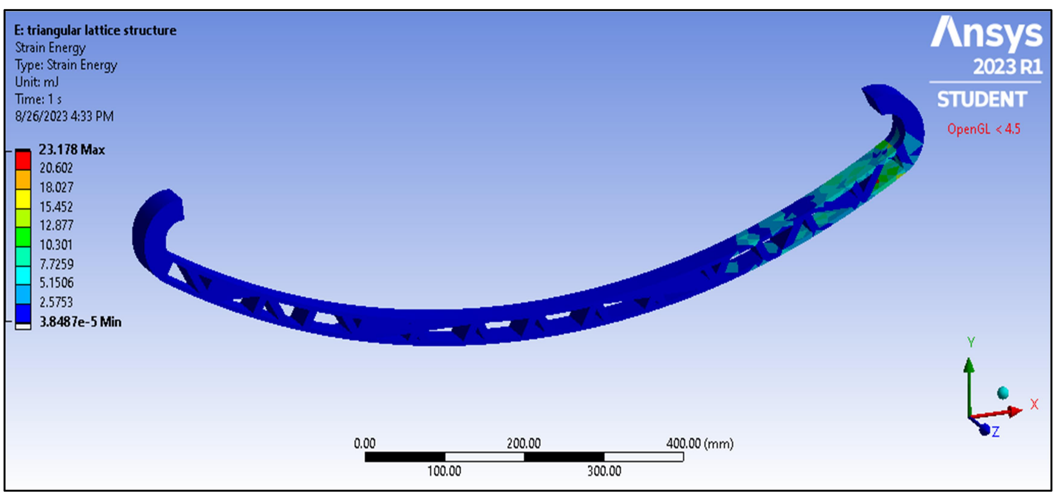

Figure 4.18 Triangular lattice design strain energy

Figure 4.18 displays the strain energy curve pertaining to the triangular lattice configuration of the leaf spring design. The cylindrical support of the leaf spring is identified as the primary site where the highest level of strain energy is seen, measuring in excess of 23.178 millijoules. The regions of the leaf spring's central and left sections, where the magnitude of deformation is below 5.15 mJ, exhibit the lowest level of strain energy.

Table 4.2 Comparative study chart

Design Type	**Generic Design**	**Topology Optimization Design**	**Square Lattice Design**	**Triangular Lattice Design**
Equivalent stress (MPa)	142.21	242.59	226.45	212.91
Principal stress (MPa)	151.67	381.61	235.94	251.74
Total deformation (mm)	6.505	6.857	8.2242	9.133
Strain energy (mJ)	68.062	18.604	18.198	23.178
Mass(kg)	12.767	10.123	9.72	8.429

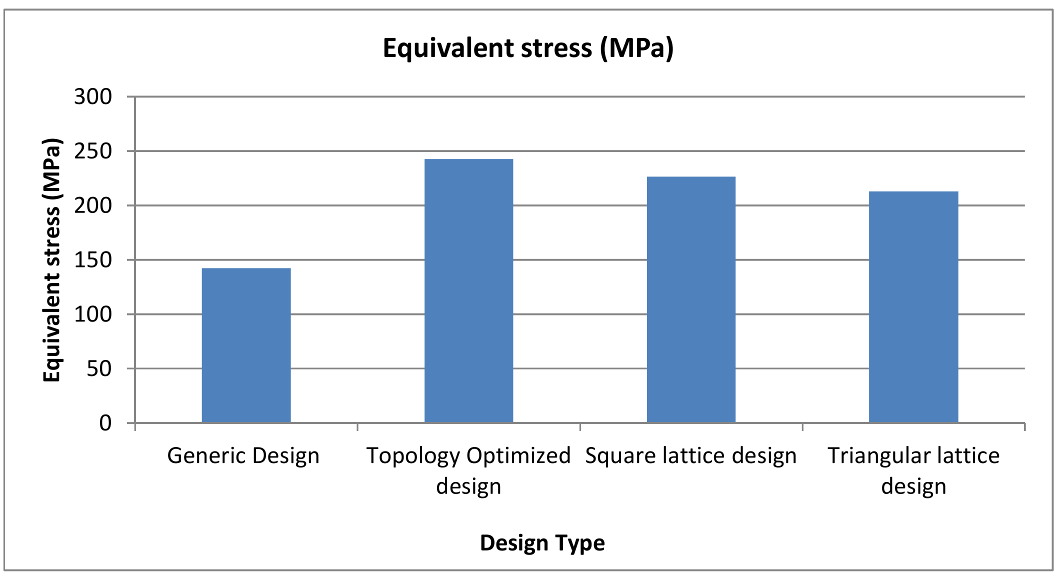

Figure 4.19 Comparison of equivalent stresses for various leaf spring designs

A comparative stress analysis plot is generated for each distinct leaf spring design, as seen in the preceding figure 4.19. The generic design aims to minimize the equivalent stress, whereas the topologically optimal design of a leaf spring maximizes the equivalent stress. When compared to other perfect configurations, it can be shown that the triangular lattice structure exhibits the lowest level of equivalent stress.

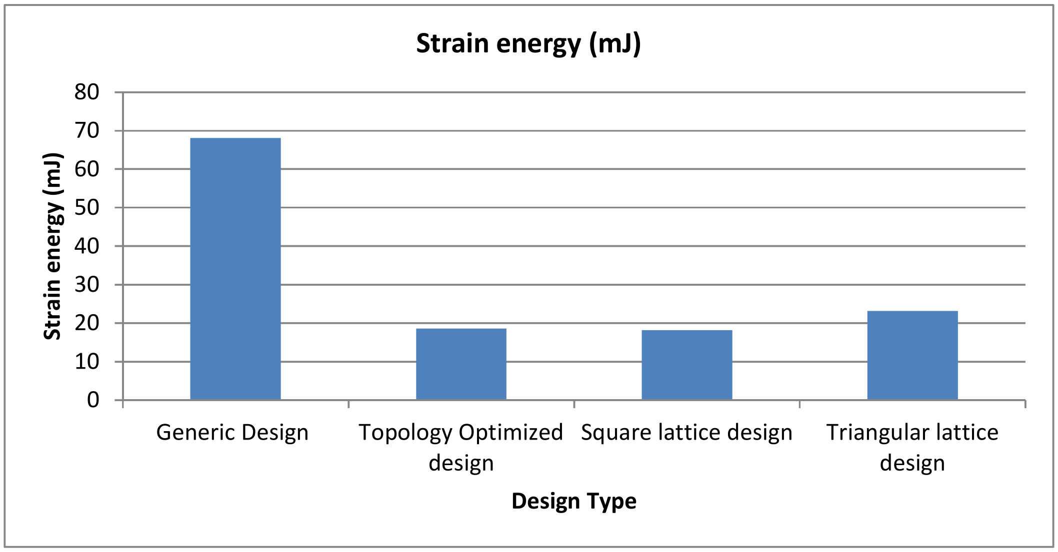

Figure 4.20 Comparison of strain energy for various leaf spring designs

The strain energy comparison plot has been generated to analyze various leaf spring designs, as seen in Figure 4.20, which has been recently presented. The graphical representation illustrates that a conventional leaf spring configuration has a higher capacity for strain and energy absorption, while topologically optimized leaf spring designs have a comparatively lower capacity for strain and energy absorption.

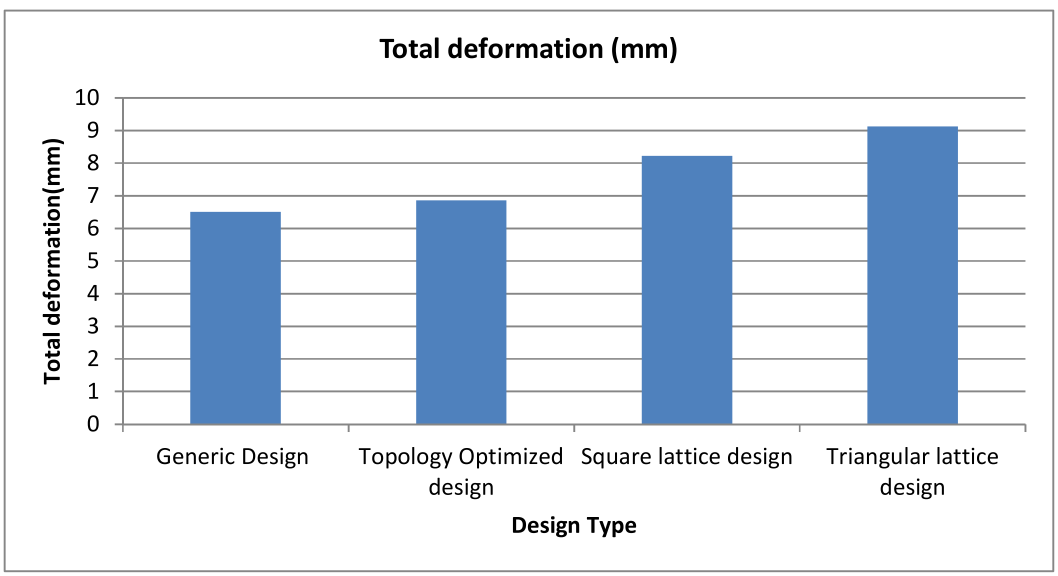

Figure 4.21 Comparison of total deformation for various leaf spring designs

The comparison plot depicting the overall deformation is shown in Figure 4.21, illustrating various leaf spring designs. Typically, the configuration of a leaf spring is associated with little deformation, whereas the arrangement of a triangular lattice structure is linked to significant distortion. The leaf spring exhibits little distortion, but the triangular lattice structure has the maximum total deformation, measuring 9.133mm.

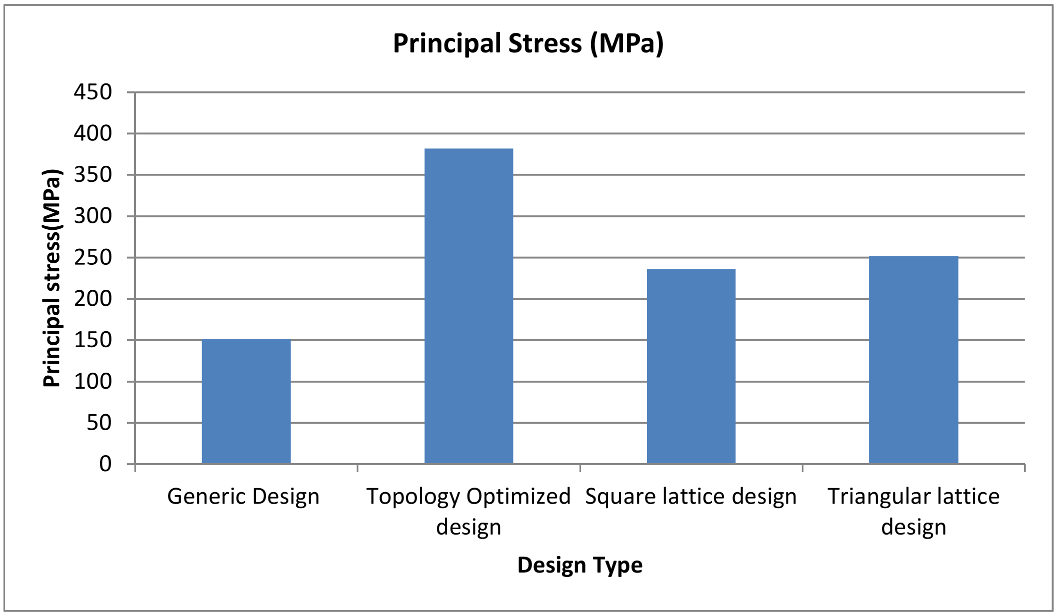

Figure 4.22 Comparison of the principal stresses for various leaf spring designs

The primary focus of this study is to analyze and compare the stress levels across various leaf spring designs, as seen in the previous Figure 4.22. When endeavoring to create a leaf spring with a topologically optimized configuration, the objective is to achieve the maximum principal stress while concurrently minimizing the minimum principal stress. On the contrary, a design that lacks specificity has the potential to reach a minimum principal stress of 151.67 MPa, but a design that is topologically optimized has the capability to reach a maximum principal stress of 381.61 MPa.

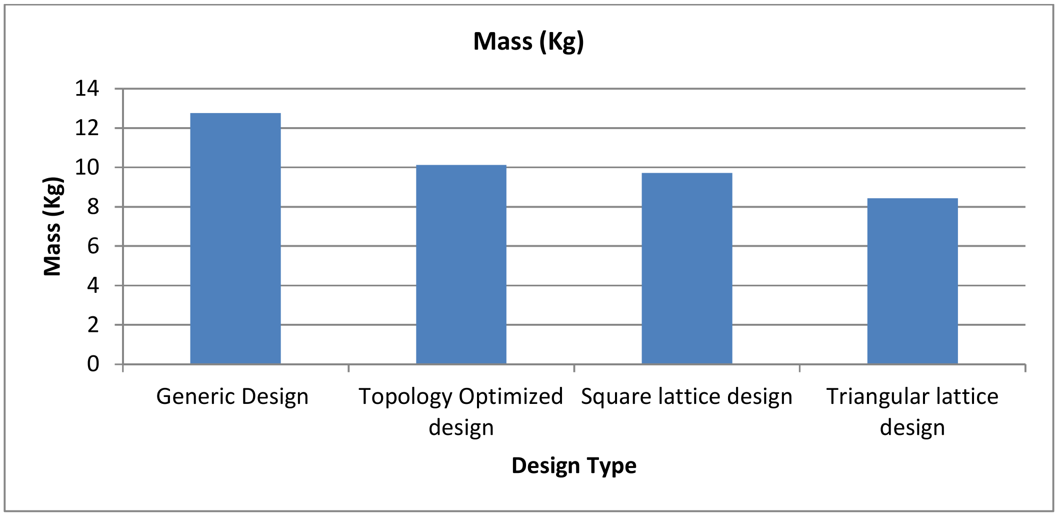

Figure 4.23 Comparison of the mass of different leaf spring designs

The mass comparison chart has been developed to analyze various leaf spring designs, as seen in figure 4.23, presented above. In comparison to the conventional structure of a leaf spring, the topologically optimized design exhibits a reduction in mass of 2.64 kg. The use of a triangular lattice structure in the design of a leaf spring leads to the achievement of a minimal mass of 8.429 kg.

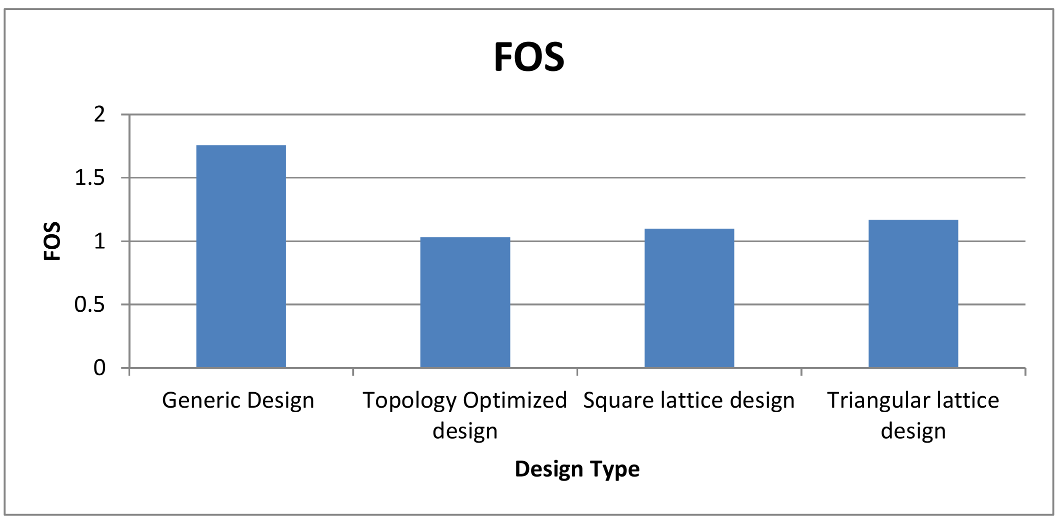

Figure. 4.24- Comparison chart of FOS for various design types

Fig 4.24 shows the comparison chart of FOS for various design types. The factor of safety (fos) can be calculated as ratio of yield strength to the equivalent stress. The yield strength of selected material of leaf spring is 250 MPa.

Table 4.3 FOS comparison table

Design Type	Generic Design	Topology Optimized Design	Square Lattice Design	Triangular Lattice Design
FOS	1.757	1.03	1.1	1.17

4.6 Modal Analysis Results

From the modal analysis, the natural frequency and mode shapes are determined for each design type. The natural frequency enables to determine the frequency at which the resonance occurs.

4.6.1 Generic Design Results

The remote displacement face, where the magnitude is 14.2mm, exhibits greater deformation at the first natural frequency of the leaf spring. The first natural frequency obtained is 28.195Hz.

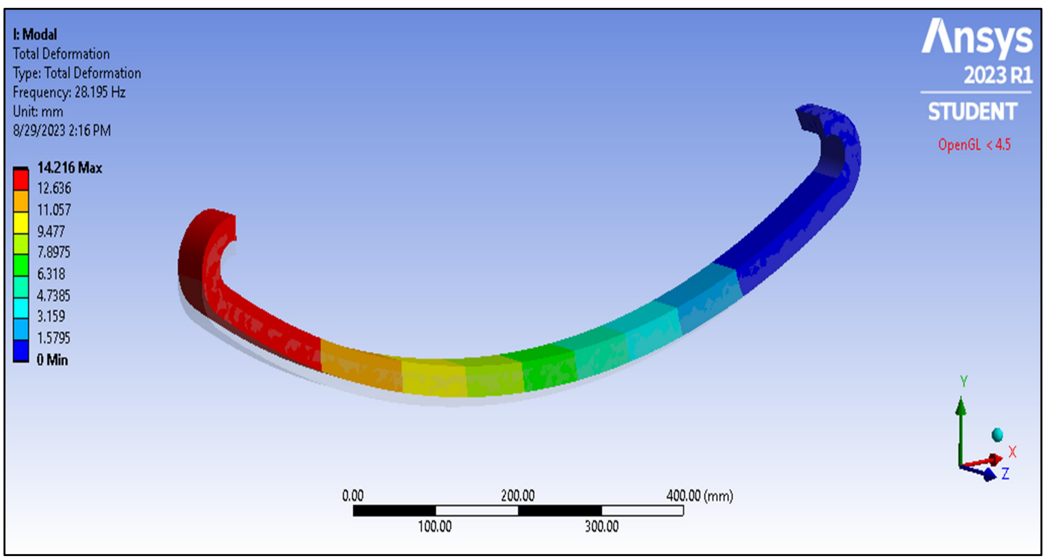

Figure 4.25 First natural frequency of generic design

The midsection of the second natural frequency of the leaf spring exhibits greater deformation, with a magnitude of 14.991mm. The second natural frequency obtained is 103.97Hz.

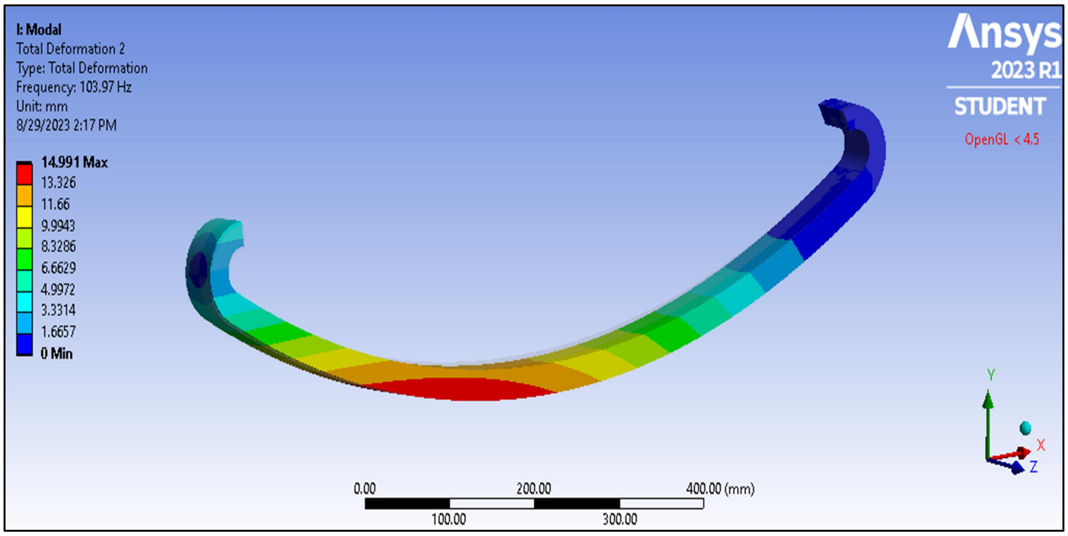

Figure 4.26 Second natural frequency of generic design

The third natural frequency of leaf spring shows higher deformation at the zone shown in red color wherein the magnitude is 14.672mm. The third natural frequency obtained is 14.672Hz.

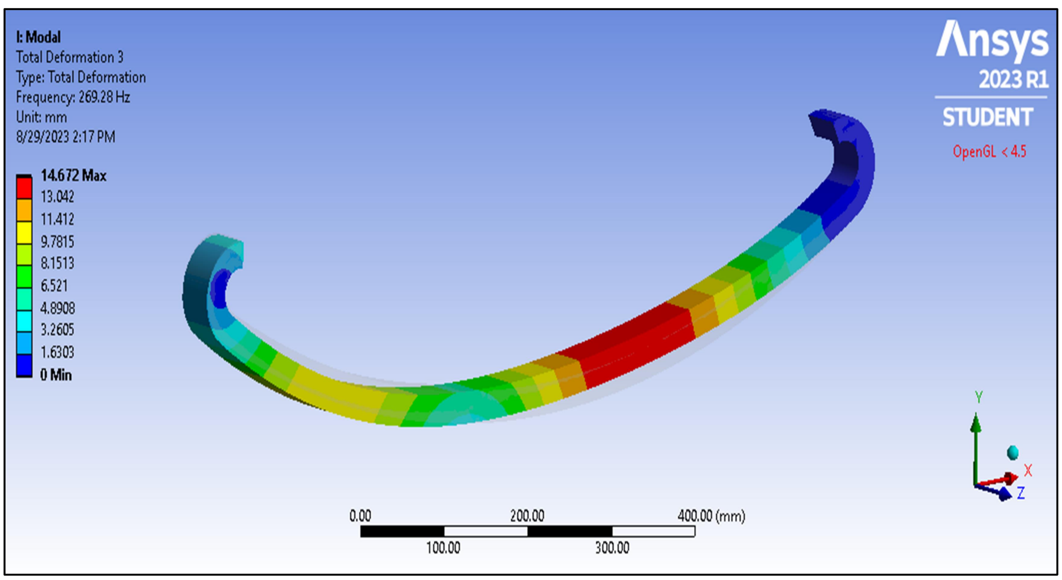

Figure 4.27 Third natural frequency of generic design

4.6.2 Topology Optimized Design Results

The remote displacement face, where the magnitude is 16.595mm, exhibits greater deformation at the topology-optimized leaf spring's first natural frequency. The first natural frequency obtained is 32.5Hz.

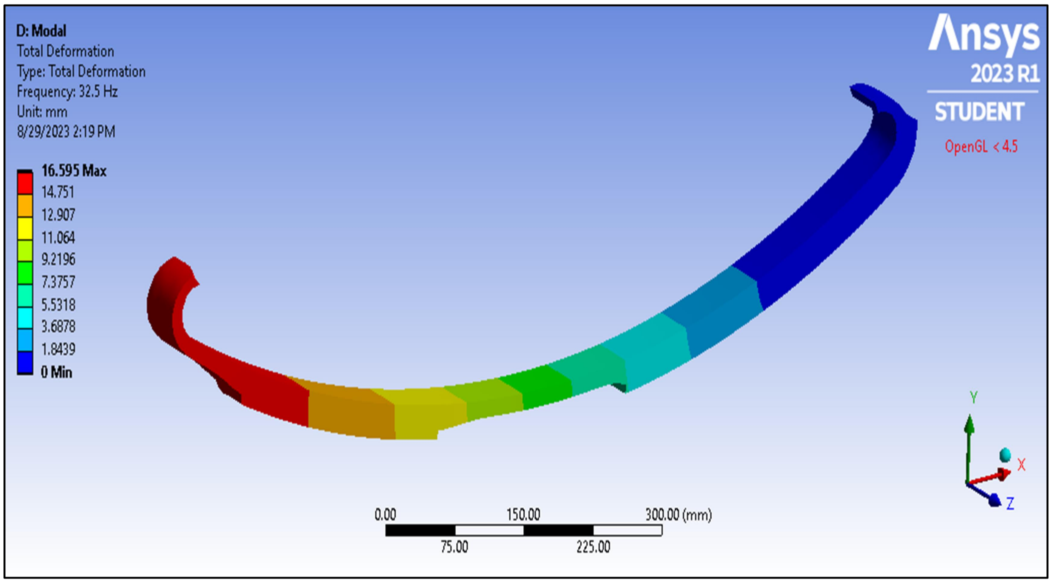

Figure 4.28 First natural frequency of topologically optimized design

The midsection of a leaf spring having topological optimization's second natural frequency exhibits greater deformation, having a magnitude of 18.104mm. The second natural frequency obtained is 97.766Hz.

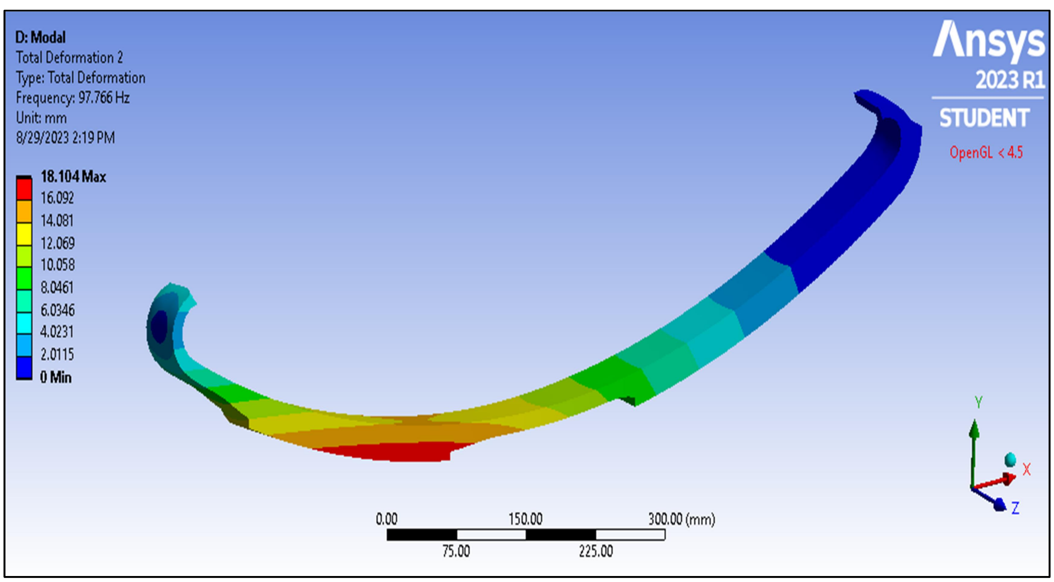

Figure 4.29 Second natural frequency of topologically optimized design

The topologically optimized leaf spring's third natural frequency exhibits greater deformation at the zone highlighted in red, where the magnitude is 19.07mm. The third natural frequency obtained is 221.7Hz.

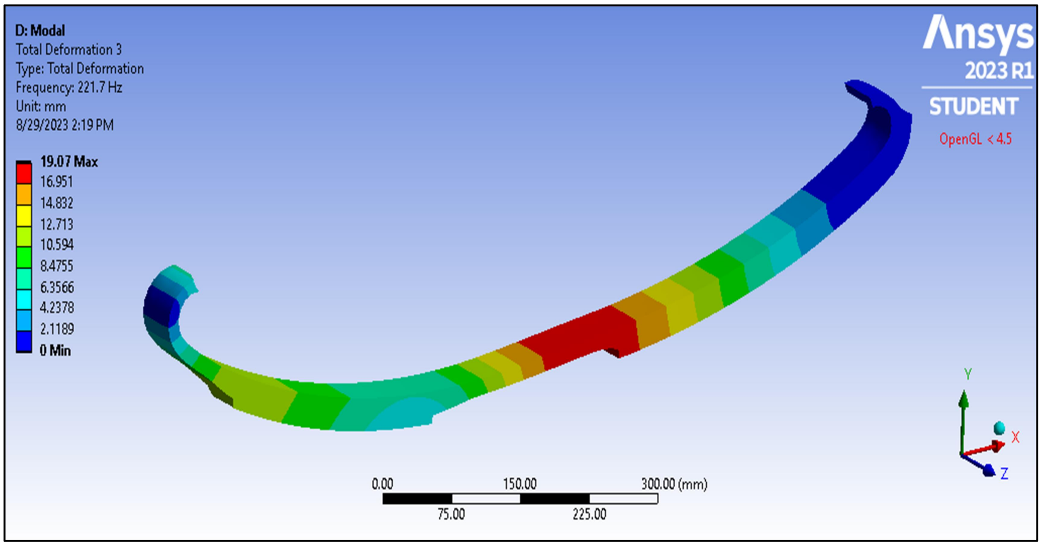

Figure 4.30 Third natural frequency of topologically optimized design

4.6.3 Square Lattice Design Results

At the remote displacement face, where the magnitude is 16.206mm, the first natural frequency of a square lattice leaf spring exhibits greater deformation. The first natural frequency obtained is 28.582Hz.

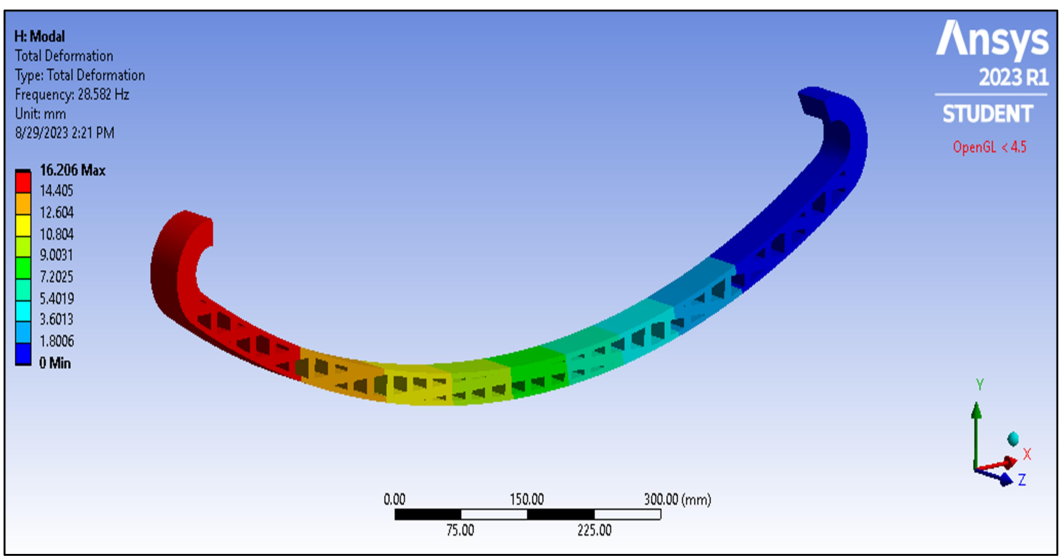

Figure 4.31 First natural frequency of square lattice design

The square leaf spring's second natural frequency exhibits greater deformation in the midpoint, where the magnitude is 17.684mm. The second natural frequency obtained is 84.207Hz.

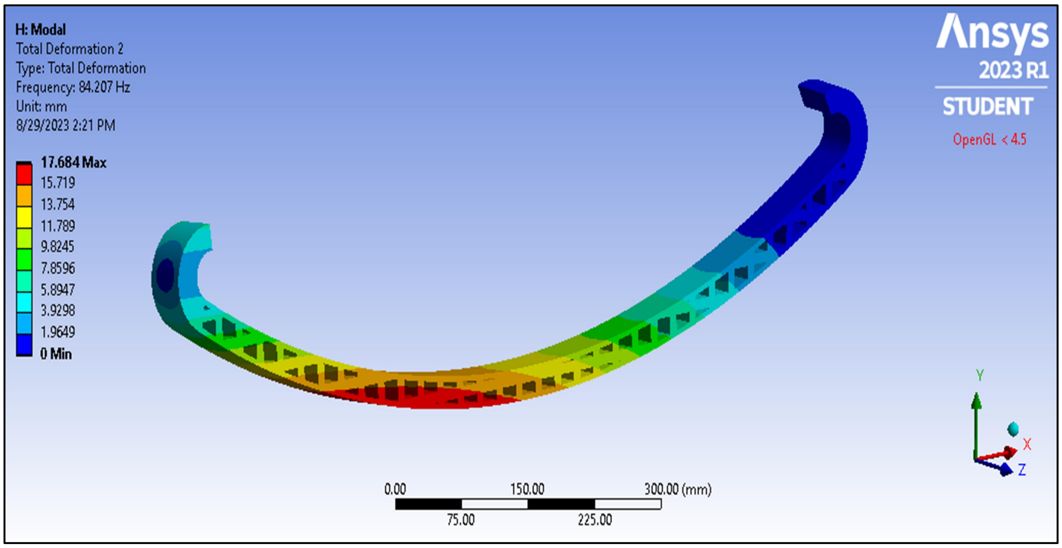

Figure 4.32 Second natural frequency of square lattice design

The third natural frequency of square lattice design shows higher deformation at the zone shown in red color wherein the magnitude is 17.229mm. The third natural frequency obtained is 277.96Hz.

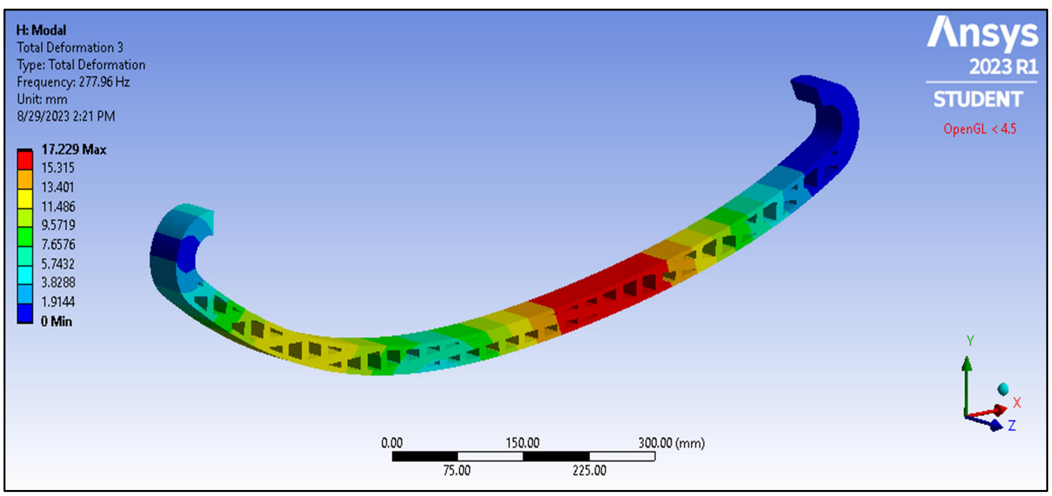

Figure 4.33 Third natural frequency of square lattice design

4.6.4 Triangular Lattice Design Results

The remote displacement face of a triangular lattice leaf spring's first natural frequency exhibits greater deformation, with a magnitude of 17.31mm. The first natural frequency obtained is 28.953Hz.

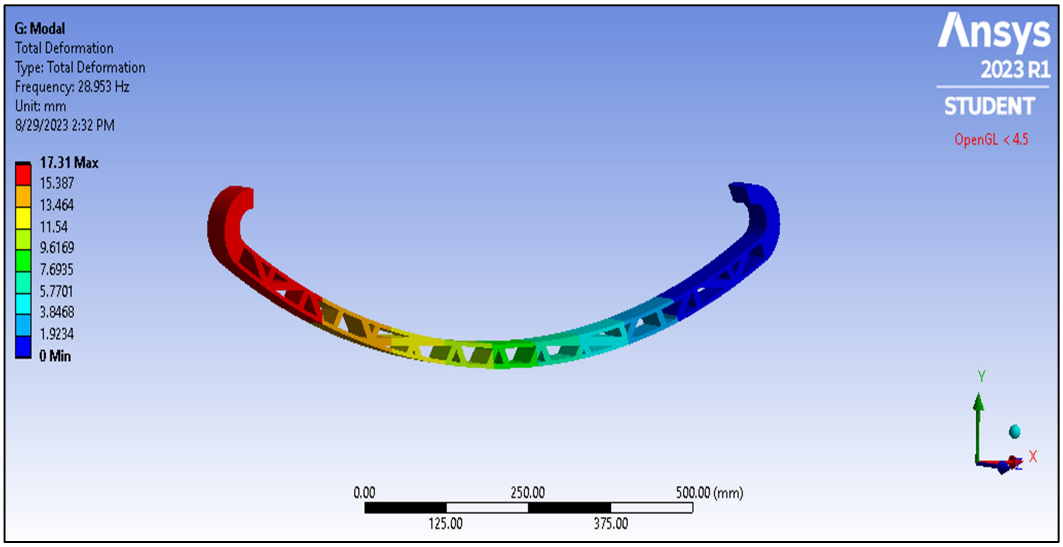

Figure 4.34 First natural frequency of triangular lattice design

The triangular lattice leaf spring's second natural frequency exhibits greater deformation around the midpoint, where the magnitude is 19.633mm. The second natural frequency obtained is 79.478Hz.

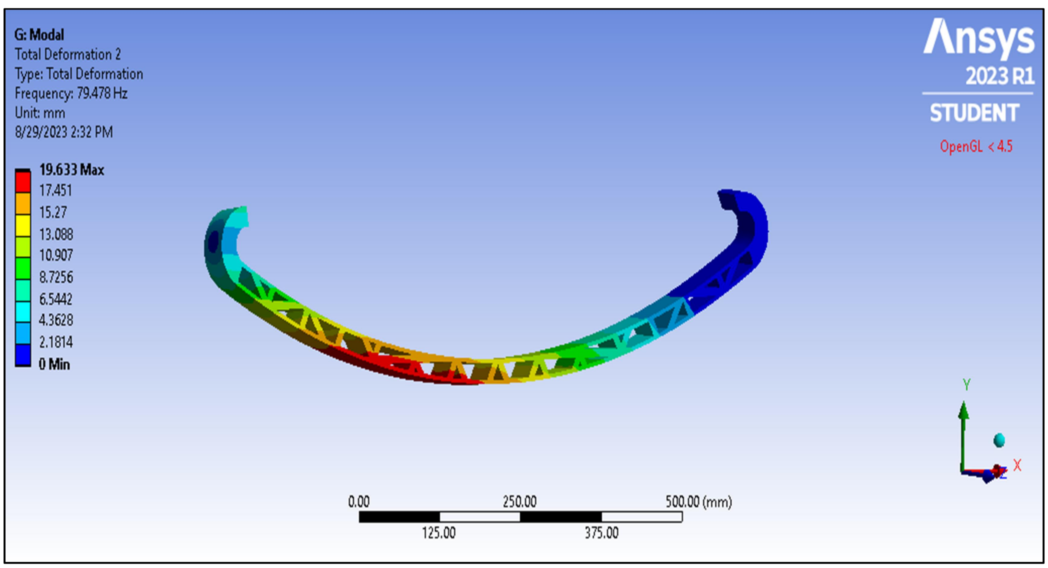

Figure 4.35 Second natural frequency of triangular lattice design

Higher deformation is visible at the zone highlighted in red on the third natural frequency of the triangular lattice design, where the magnitude is 22.522mm. The third natural frequency obtained is 267.72Hz.

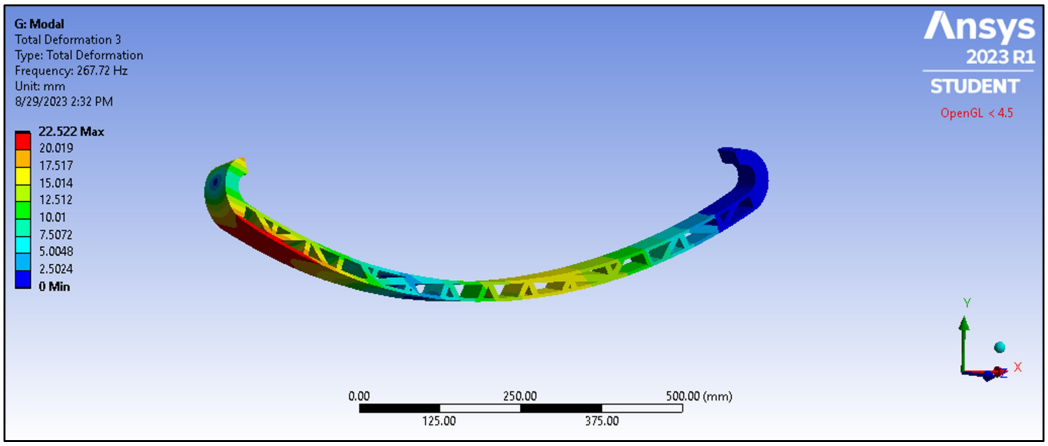

Figure 4.36 Third natural frequency of triangular lattice design

Table 4.4 Natural frequency comparison

Design Type	Generic Design	Topology Optimized Design	Square Lattice Design	Triangular Lattice Design
First Natural Frequency (Hz)	28.195	32.5	28.582	28.953
Second Natural Frequency (Hz)	103.97	97.76	84.207	79.478
Third Natural Frequency (Hz)	269.28	221.7	277.96	267.72

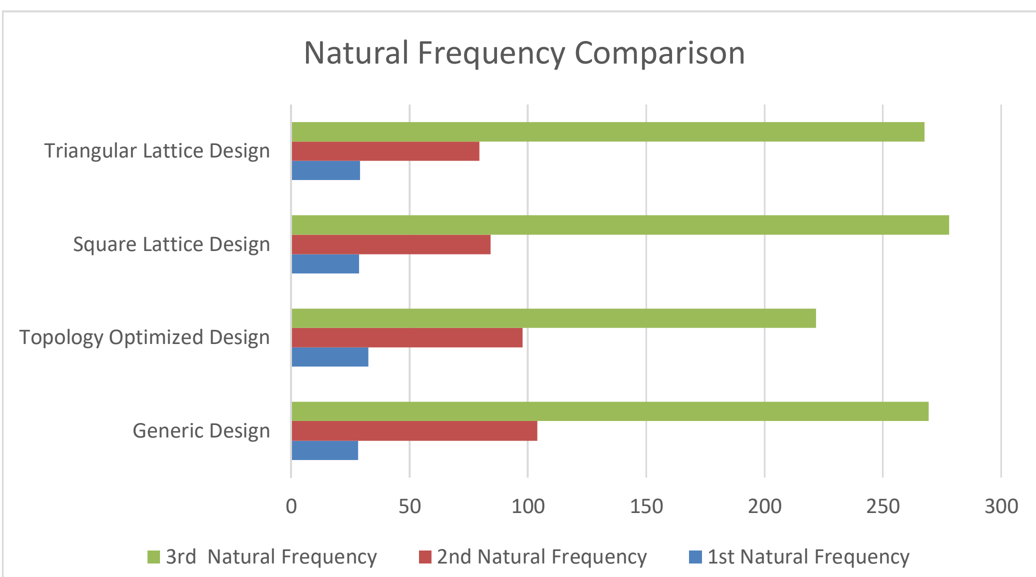

Figure 4.37 Natural frequency comparison chart

For all design types, the natural frequency comparison chart is produced, as seen in figure 4.37 above. The chart displays a higher natural frequency for the design using a square lattice and a minimum frequency for the design using topological optimization.

Table 4.5 Natural frequency deformation comparison

Design Type	Generic Design	Topology Optimized Design	Square Lattice Design	Triangular Lattice Design
First Frequency deformation (mm)	14.2	16.59	16.206	17.31
Second Frequency deformation (mm)	14.991	18.104	17.684	19.633
Third Natural Frequency (mm)	14.672	19.07	17.229	22.522

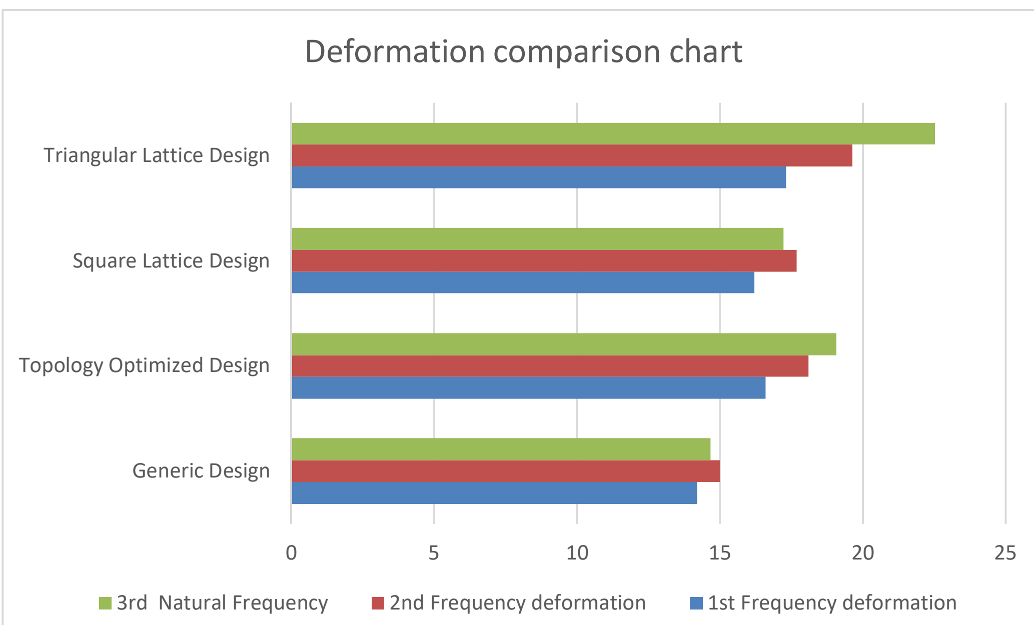

Figure 4.38 Deformation comparison chart

The deformation comparison chart is generated for different designs of leaf spring as shown in figure 4.38. According to the comparative chart, the triangular lattice design results in the most deformation while the generic design results in the least distortion. For the third natural frequency, a maximum deformation of 22.52mm is obtained.

Chapter 5 SUMMARY AND CONCLUSIONS

This chapter summarizes the work followed by the result as discussed in the previous chapters. Finally it provides some recommendations for the future scopes in the weight reduction techniques for mono leaf spring of an automobile.

5.1 Summary

In summary, the thesis explores the integration of topology optimization and lattice structure techniques to enhance the design of a mono leaf spring. The objective is to create a more efficient and reliable spring structure by optimizing its material distribution while ensuring its dynamic behavior meets design requirements. The current thesis primarily focused on most suitable design of mono leaf spring for achieving best strength-weight ratio. This types of innovative technique helps weight reduction of mono leaf spring for same strength, due to which cost of automobile will also decrease. This weight reduction will also leads to increases the millage as well as efficiency of an automobile.

5.2 Conclusions

The finite element analysis is a helpful tool for determining the strength of the mono leaf spring when subjected to static loading conditions. The new design of the leaf spring is less in weight yet having a stronger construction. The analysis provides the output parameters for structural analysis, which include the equivalent stress, main stress, safety factor, and deformation output parameters. The following are the particular findings reached:

1. Critical zones with high levels of main stress are identified. The main stress is measured to be at its maximum just next to the cylindrical support zone of the mono leaf spring. This is a characteristic shared by both generic and topologically optimum design approaches.
2. By using FEA analysis, high equivalent stress zones are located and mapped out. Regardless of the kind of design (either a generic design or a topologically

optimized design), the critical zones that have significant equivalent stress may almost always be located in close proximity to the zones that provide support.

3. The design of a leaf spring that utilizes a triangular lattice structure results in a minimum mass of 8.429 kg, which is 4.338 kg less than the mass produced by the generic design. The results of the research showed a weight loss percentage of 33.97 percent.
4. The topological optimized leaf spring design has a weight of just 10.123 kilograms, which is 2.644 kilograms less than the weight of the generic design. The results of the research showed a weight loss percentage of 20.70 percent.
5. The design of the leaf spring square lattice structure weighs in at 9.72 kilograms, which is 3.047 kilograms lighter than the usual design. The results of the research showed a weight loss percentage of 23.94 percent.
6. The FOS is compared to each of the designs, and the one that is the safest is picked. The design of the triangular lattice structure is the ideal one for the greatest amount of safety among them.
7. From the modal analysis, the higher natural frequency is obtained for square lattice design and minimum frequency is obtained for topologically optimized design.
8. From the modal analysis, the maximum deformation is obtained for triangular lattice design and minimum deformation is obtained for generic design.

The overall result is that triangular lattice-structure type leaf springs are preferable to generic (solid) type leaf springs in vehicles that are frequently used primarily for transportation reasons and where comfort is not a top priority. Because designing a triangular lattice structure maximizes weight minimization and also as per safety concerns, the design of the triangular lattice structure is the ideal one for the greatest amount of safety among them.

5.3 Scope of future work

The process of analyzing topologically ideal designs is difficult. However, it is essential to examine leaf springs that are subjected to dynamic loading conditions due to the diverse road conditions. Other leaf spring materials, such as lightweight composites, can also be evaluated. It is feasible for one to experiment with using carbon composites or metal matrix composites.

LITERATURE CITED

Abdi, M., Ashcroft, I. and Wildman, R., 2018. Design optimisation for an additively manufactured automotive component. *Inter. J. Powertrains*, 7(1/2/3): 142.

Agarwal, A., Seretse, O. M. and Pumwa, J. 2020. Finite element and Taguchi response analysis of the application of graphite aluminium mmc in automotive leaf spring. *Int. J. Mech.Contin. Math. Sci.,* 15: 168-79.

Arora, V., Aggarwal, M. L. and Bhushan, G. 2011. A comparative study of CAE and experimental results of leaf springs in automotive vehicles. *Int. J. Eng. Sci. Technol*., 3(9): 6856-6866.

Bendsøe, M. and Kikuchi, N., 1988. Generating optimal topologies in structural design using a homogenization method. *Comput Methods Appl Mech Eng.*, 71(2): 197-224.

Charde, R. B. and Bhope, D. V. 2012. Investigation of stresses in master leaf of leaf spring by FEM and its experimental verification. *Int. J. Eng. Sci. Technol*., 4(2): 633-640.

Chen, W., Zheng, X. and Liu, S., 2018. Finite-Element-Mesh Based Method for Modeling and Optimization of Lattice Structures for Additive Manufacturing. *Materials*, 11(11): 2073.

Dubey, D. N. and Mahakalkar, S. G.2013. Stress analysis of a mono-parabolic leaf spring–a review. *Int. J. Mod. Eng. Res.*, 3(2):769-772.

Gaynor, A. and Guest, J., 2016. Topology optimization considering overhang constraints: Eliminating sacrificial support material in additive manufacturing through design. *Struct Multidiscipl Optim*, 54(5): 1157-1172.

Gebremeskel, S. A. 2012. Design, simulation, and prototyping of single composite leaf spring for light weight vehicle. *Glob. J. Res. Eng. Mech.*, 12(7): 21-30.

Langelaar, M., 2018. Combined optimization of part topology, support structure layout and build orientation for additive manufacturing. *Struct Multidiscipl Optim* , 57(5): 1985-2004.

Liu, L., Yan, J. and Cheng, G., 2008. Optimum structure with homogeneous optimum truss-like material. *Comp. & Struct.*, 86(13-14): 1417-1425.

Liu, S., Li, Q., Liu, J., Chen, W. and Zhang, Y., 2018. A Realization Method for Transforming a Topology Optimization Design into Additive Manufacturing Structures. *Engg.*, 4(2): 277-285.

Mehul, S., Shah, D. B. and Bhojawala, V. 2012. Analysis of composite leaf spring using FEA for light vehicle mini truck. *J. Inf. Knowl. Res. Mech. Eng*., 2(2): 424-428.

Mouleeswaran, S. 2012. Design, Manufacturing and Testing of Polymer Composite Multi Leaf Spring for Light Passenger Automobiles-A Review. *Mater. Sci. Technol.*, pp 59-74.

Nabaki, K., Shen, J. and Huang, X., 2019. Evolutionary topology optimization of continuum structures considering fatigue failure. *Mater. Des.*, 166: 107586.

Panesar, A., Abdi, M., Hickman, D. and Ashcroft, I., 2018. Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing. *Addit. Manuf.*, 19: 81-94.

Patunkar, M. M. and Dolas, D. R. 2011. Modelling and analysis of composite leaf spring under the static load condition by using FEA. *Int. J. Mech. Ind. Eng*., 1(1): 1-4.

Qian, X., 2017. Undercut and overhang angle control in topology optimization: A density gradient based integral approach. *Inter. J. Num. Meth. in Engg.*, 111(3): 247-272.

Rodrigues, H., Guedes, J. and Bendsoe, M., 2002. Hierarchical optimization of material and structure. *Struct Multidiscipl Optim*, 24(1): 1-10.

Satpute, A. A. and Chavan, S. S. 2013. Mono composite leaf spring-design and testing. *Indian J. Appl. Res.,* 3(7): 282-284.

Song, G., Jing, S., Zhao, F., Wang, Y., Xing, H. and Zhou, J., 2017. Design Optimization of Irregular Cellular Structure for Additive Manufacturing. *Chin. J. Mech. Engg.*, 30(5): 1184-1192.

Tadesse, B. A. and Fatoba, O. 2022. Design optimization and numerical analyses of composite leaf spring in a heavy-duty truck vehicle. *Mater. Today*, 62: 2814-2821

Tang, Y., Kurtz, A. and Zhao, Y., 2015. Bidirectional Evolutionary Structural Optimization (BESO) based design method for lattice structure to be fabricated by additive manufacturing. *Comput Aided Des*, 69: 91-101.

Team, I., 2021. *Topology Optimization for Additive Manufacturing - 3DIncredible*. [online] 3DIncredible. Available at: <https://3dincredible.com/topology-optimization-for-additive-manufacturing/> [Accessed 27 December 2021].

Wang, B., Tian, K., Zhou, C., Hao, P., Zheng, Y., Ma, Y. and Wang, J., 2017. Grid-pattern optimization framework of novel hierarchical stiffened shells allowing for imperfection sensitivity. *Aerosp Sci Technol*, 62: 114-121.

Wang, C., Gu, X., Zhu, J., Zhou, H., Li, S. and Zhang, W., 2020. Concurrent design of hierarchical structures with three-dimensional parameterized lattice microstructures for additive manufacturing. *Struct Multidiscipl Optim* , 61(3): 869-894.

Zhang, P., Toman, J., Yu, Y., Biyikli, E., Kirca, M., Chmielus, M. and To, A., 2015. Efficient Design-Optimization of Variable-Density Hexagonal Cellular Structure by Additive Manufacturing: Theory and Validation. *J. Manuf. Sci. and Engg.*, 137(2).

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2	B.Tech (Mechanical Engg.)	Bipin Tripathi Kamoun Institue of Technology, Dwarahat, Uttarakhand	2018	67.76
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ABSTRACT

In today's world, automobiles have become an integrated part of our lives, but in reality, we also want the operation of automobiles to be budget-friendly. This can only be possible by cutting down on the extra cost of automobile operation and maintenance. This cost cutting can be done in various ways, but in the present work, this can be done by removing extra, unnecessary material, which leads to the weight minimization of the automobile. The aim of the present work is to reduce the weight of the mono-leaf spring without compromising its strength. A finite element analysis of different designs of mono-leaf springs, like generic design, topology optimized design, and lattice structure design (square lattice structure, triangular lattice structure), is conducted. Then, for all such designs, modal analysis is also conducted. At last, final comparative results on the basis of deformation, stress, factor of safety, and natural frequency are concluded. On the basis of the present analysis, the triangular lattice structure design type of mono leaf spring achieves a maximum weight reduction of 33.97% with respect to the generic design type without comparing strength to weight ratio. Then we can easily say that a triangular lattice-type design of a mono-leaf spring is an economical option.

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शोध का शीर्षक		**"परिमित तत्व विधि का उपयोग करते हुए मोनो लीफ स्प्रिंग का टोपोलॉजी अनुकूलन और मॉडल विश्लेषण "**			
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सारांश

आज की दुनिया में ऑटोमोबाइल हमारे जीवन का एक अभिन्न हिस्सा बन गया है, लेकिन वास्तव में, हम यह भी चाहते हैं कि ऑटोमोबाइल का संचालन बजट के अनुकूल हो। यह केवल ऑटोमोबाइल संचालन और रखरखाव की अतिरिक्त लागत में कटौती करके ही संभव हो सकता है। यह लागत कटौती विभिन्न तरीकों से की जा सकती है, लेकिन वर्तमान कार्य में, यह अतिरिक्त, अनावश्यक सामग्री को हटाकर किया जा सकता है, जिससे ऑटोमोबाइल का वजन कम हो जाता है। वर्तमान कार्य का उद्देश्य मोनो-लीफ स्प्रिंग की ताकत से समझौता किए बिना उसका वजन कम करना है। मोनो-लीफ स्प्रिंग्स के विभिन्न डिज़ाइनों, जैसे सामान्य डिज़ाइन, टोपोलॉजी अनुकूलित डिज़ाइन और जाली संरचना डिज़ाइन (वर्ग जाली संरचना, त्रिकोणीय जाली संरचना) का एक सीमित तत्व विश्लेषण किया जाता है। फिर, ऐसे सभी डिज़ाइनों के लिए, मोडल विश्लेषण भी किया जाता है। अंत में विकृति, तनाव, सुरक्षा के कारक और प्राकृतिक आवृत्ति के आधार पर अंतिम तुलनात्मक परिणाम निकाले जाते हैं। वर्तमान विश्लेषण के आधार पर, मोनो लीफ स्प्रिंग का त्रिकोणीय जाली संरचना डिजाइन प्रकार वजन अनुपात की ताकत की तुलना किए बिना सामान्य डिजाइन प्रकार के संबंध में 33.97% की अधिकतम वजन में कमी प्राप्त करता है। तब हम आसानी से कह सकते हैं कि मोनो-लीफ स्प्रिंग का त्रिकोणीय जाली-प्रकार का डिज़ाइन एक किफायती विकल्प है।

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