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Design, Analysis & Weight Reduction of Disc Rotor for all Terrain Vehicle Using Topology Optimization

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KEYWORDS
ATV, Disc Rotor, Topology Optimization, OEM, SS410.

ABSTRACT:
This research paper presents a comprehensive study on the design, analysis, and weight reduction of a disc rotor for an All Terrain Vehicle (ATV) through the application of topology optimization techniques. In the context of modern engineering and vehicle design, the demand for enhanced performance, fuel efficiency, and overall sustainability has necessitated the development of lightweight yet structurally robust components. The disc rotor, a critical component in the ATV's braking system, is a prime candidate for optimization to achieve these objectives. The study begins by providing an overview of the challenges and requirements associated with disc rotor design for ATVs, emphasizing the need for enhanced performance and weight reduction. To address these challenges, topology optimization, a cutting-edge design methodology, is employed. This approach leverages advanced computer-aided design and finite element analysis tools to systematically explore and redefine the component's internal structure while ensuring it retains its mechanical integrity and braking efficiency. The methodology involves creating a finite element model of the disc rotor, specifying the loads and boundary conditions, and utilizing mathematical algorithms to iteratively remove material from non-critical areas, thereby reducing weight while preserving structural integrity. The study evaluates the disc rotor's performance in terms of stress distribution, heat dissipation, and overall efficiency, comparing it to conventional designs to highlight the benefits of the proposed topology-optimized rotor. The findings of this research are expected to contribute significantly to the field of ATV design and automotive engineering, offering insights into the application of topology optimization for weight reduction and improved performance of critical components. The optimized disc rotor design showcased in this study can potentially lead to reduced fuel consumption, enhanced braking capabilities, and increased vehicle manoeuvrability while maintaining safety standards. Furthermore, this research demonstrates the feasibility and advantages of utilizing topology optimization techniques in the development of lightweight and structurally efficient components for a wide range of applications beyond ATVs, thus promoting sustainable engineering practices.

CHAPTER 1: INTRODUCTION

1.1 Overview

Two cutting-edge engineering techniques that have transformed disc brake design and analysis are topology optimization and finite element analysis (FEA). These technologies have greatly improved the efficiency, performance, and safety of these vital automobile parts. Topology optimization is a computer approach that optimizes the interior material distribution within a given design area, frequently with the objective of lowering weight while increasing structural performance. This technology, when used to disc brakes, entails the meticulous reshaping of the brake's internal structure, ensuring that material is assigned precisely where it is required to withstand the pressures and stresses during braking. The result is a lighter, more efficient disc brake with structural integrity.

1.2 Background and Context of the Study

All-terrain vehicles (ATVs) have gained significant prominence in various industrial and recreational applications due to their ability to traverse challenging terrains with relative ease. The effective operation of ATVs relies heavily on the robustness and performance of their components, particularly the disc rotors, which are critical for ensuring reliable braking systems and overall safety. Traditionally, disc rotors have been designed using conventional manufacturing techniques and materials, often resulting in suboptimal performance and excessive weight, thereby impacting the vehicle's agility and fuel efficiency. The evolution of engineering design has led to the exploration of advanced methodologies such as topology optimization, which allows for the creation of structures with enhanced mechanical properties and reduced weight. By leveraging the principles of topology optimization, it becomes possible to systematically analyze and refine the structural configuration of disc rotors, thereby enabling the development of lightweight components that exhibit superior strength and durability. Furthermore, the growing emphasis on sustainable practices and fuel efficiency has driven the need for innovative solutions that can mitigate energy consumption and enhance overall vehicle performance. Integrating topology optimization in the design and analysis of disc rotors presents a significant opportunity to not only reduce the environmental impact of ATVs but also improve their overall operational efficiency and longevity. This study aims to contribute to the existing body of knowledge by exploring the application of topology optimization in the design, analysis, and weight reduction of disc rotors for all-terrain vehicles. By addressing the limitations of conventional design approaches and materials, the research endeavours to offer insights into the development of optimized disc rotor designs that can significantly enhance the performance, reliability, and sustainability of all-terrain vehicles in various operating conditions and environments.

1.3 Topology Optimization

Density-based topology optimization is a widely used technique that focuses on altering the material density distribution within a given design domain to obtain an optimal structural configuration. This method involves representing the design space as a grid of elements and adjusting the density of each element to achieve the desired structural performance while minimizing the overall mass of the structure. The optimization process typically follows an iterative approach, where the material is added or removed in different regions based on predefined objectives and constraints. The key features of density-based topology optimization include its ability to generate structures with complex geometries and smooth boundaries, enabling the creation of innovative designs that maximize performance while minimizing material usage. By controlling the material density distribution, engineers can identify the most efficient load-bearing paths and remove unnecessary material, resulting in lightweight and high-strength structures. Furthermore, density-based topology optimization allows for the consideration of multiple constraints, such as stress, displacement, and manufacturability, during the optimization process. By incorporating these constraints, engineers can ensure that the resulting designs not only meet the required structural performance criteria but also adhere to practical manufacturing limitations. Overall, density-based topology optimization serves as a powerful tool for engineers to develop optimized designs that are structurally efficient, lightweight, and cost-effective. By leveraging this method, engineers can achieve significant advancements in product design, leading to the creation of high-performance structures that meet stringent industry standards and customer expectations.

1.4 Significance of the Study

The significance of the study lies in its potential to revolutionize the design and manufacturing processes of disc rotors for all-terrain vehicles (ATVs) through the application of topology optimization. By addressing the limitations of conventional design methods, the study aims to achieve the following key contributions:

1. **Enhanced Performance**: The optimized disc rotor design can significantly improve the braking efficiency and overall performance of all-terrain vehicles, ensuring superior handling and safety in various challenging terrains and operating conditions.
2. **Weight Reduction**: Through the implementation of topology optimization, the study seeks to reduce the weight of the disc rotor without compromising its structural integrity, thereby contributing to the overall weight reduction of the ATV. This reduction can lead to improved fuel efficiency and manoeuvrability, consequently enhancing the vehicle's sustainability and operational costs.
3. **Innovative Design Solutions**: By exploring advanced design methodologies, the study intends to introduce innovative design solutions that can withstand dynamic loading conditions and promote efficient heat dissipation, thereby extending the lifespan of the disc rotor and ensuring long-term durability in demanding environments.
4. **Sustainable Engineering Practices**: The integration of topology optimization not only aims to enhance the performance of the disc rotor but also aligns with the principles of sustainable engineering. By minimizing material usage and optimizing structural configurations, the study contributes to the reduction of material waste and energy consumption, fostering a more environmentally friendly approach to vehicle design and manufacturing.
5. **Industry Advancements**: The findings of this study are expected to have implications for the wider

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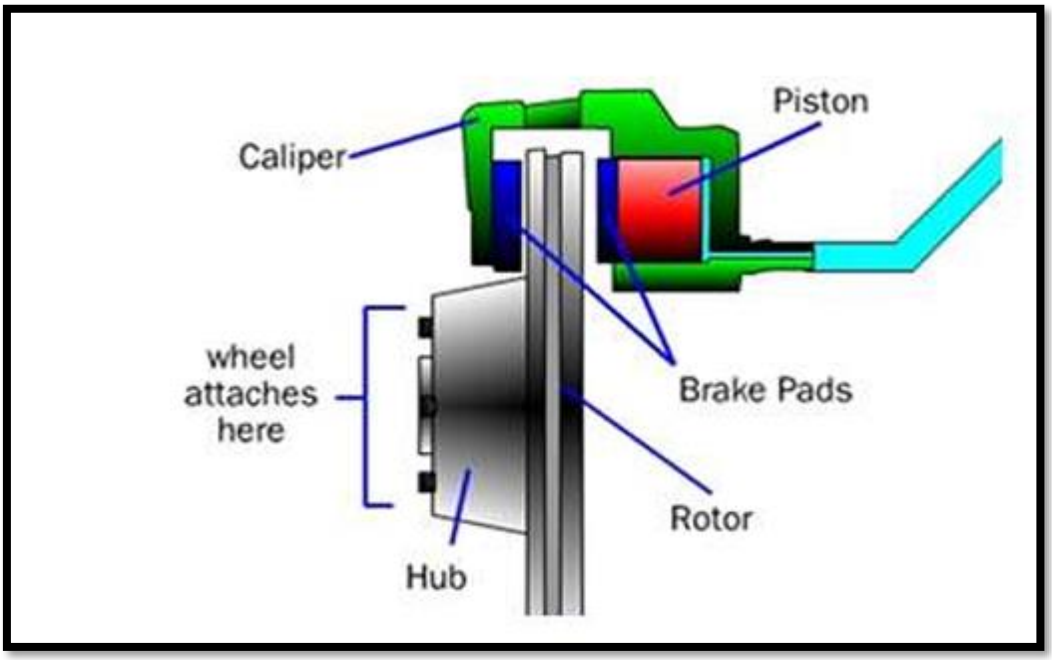
automotive and manufacturing industries, providing valuable insights into the potential applications of topology optimization in the development of lightweight, high-performance components. The research outcomes can inform future engineering practices, leading to the adoption of more efficient and sustainable manufacturing processes in the automotive sector.

By emphasizing these critical aspects, the study aims to demonstrate the significant implications of topology optimization in the design, analysis, and weight reduction of disc rotors for all-terrain vehicles, thereby contributing to the advancement of sustainable and high-performance automotive engineering practices.

***Figure 1** Representation of a disc brake system*



CHAPTER 2: LITERATURE REVIEW

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Industry Advancements: The findings of this study are expected to have implications for the wider automotive and manufacturing industries, providing valuable insights into the potential applications of topology optimization in the development of lightweight, high-performance components. The research outcomes can inform future engineering practices, leading to the adoption of more efficient and sustainable manufacturing processes in the automotive sector.

By emphasizing these critical aspects, the study aims to demonstrate the significant implications of topology optimization in the design, analysis, and weight reduction of disc rotors for all-terrain vehicles, thereby contributing to the advancement of sustainable and high-performance automotive engineering practices.

- In the context of disc brakes, the integration of topology optimization and Finite Element Analysis (FEA) has substantially enhanced the area of automobile engineering. This review of the literature gives an overview of major research and advancements in the application of these approaches for disc brake design optimization.
- Topology optimization is being used more and more to improve disc brake performance. Song et al. (2017) discovered the possibility of lowering disc brake weight while preserving or even increasing structural integrity. Such improvements are critical for lightweight vehicle design and increased fuel economy.
- FEA is critical in verifying and fine-tuning optimal designs. Leng et al. (2019) demonstrated how FEA may be used to study stress distribution, heat effects, and disc brake deformation in real-world settings. The use of FEA in conjunction with topology optimization guarantees that the improved design stays safe and efficient.
- Furthermore, FEA includes research into disc brake material behaviour and heat analysis. According to Abdulhay et al. (2020), it is critical to address thermal effects in disc brake design since these systems are subjected to significant temperatures during braking. FEA aids in the evaluation of thermal management techniques and their influence on overall performance.
- Zhou et al. (2018) work emphasized the need to include contact mechanics and friction analysis in FEA for disc brakes. This is important for understanding how different brake pad materials interact with the disc and the consequences on performance and wear.

CHAPTER 3: GAPS IDENTIFICATION AND OBJECTIVES

3.1 Gaps Identification

Following the comprehensive literature review, several gaps were identified in the existing research pertaining to the application of topology optimization in the design and analysis of disc rotors for all-terrain vehicles (ATVs). These gaps include:-

Limited Application of Topology Optimization: Despite the advancements in topology optimization techniques, there is a lack of specific research focused on the application of these methods in the design and weight reduction of disc rotors for all-terrain vehicles, indicating a need for further exploration in this area.

Insufficient Integration of Material Considerations: Existing studies often overlook the integration of specific material properties and their impact on the performance and durability of disc rotors. A comprehensive understanding of material characteristics and their influence on the optimization process is crucial for achieving the desired structural integrity and thermal efficiency.

Inadequate Assessment of Real-World Operating Conditions: Some studies lack a comprehensive analysis of the disc rotor's performance under real-world operating conditions, including extreme temperatures, varied terrains, and dynamic loading scenarios commonly encountered by all-terrain vehicles. Incorporating a detailed evaluation of these factors is essential for ensuring the reliability and longevity of the optimized disc rotor designs.

3.2 Objective of the Study

To address these identified gaps, the primary objectives of the present study are as follows:-

- **To Develop an Advanced Topology Optimization Framework**: The study aims to develop an advanced topology optimization framework specifically tailored for the design and weight reduction of disc rotors for all-terrain vehicles. This framework will incorporate comprehensive material considerations and real-world operating conditions to ensure the practical applicability and reliability of the optimized designs.

- **To Optimize Material Distribution for Enhanced Performance**: The study seeks to optimize the material distribution within the disc rotor design to improve its overall performance, including braking efficiency, heat dissipation, and structural integrity. By leveraging advanced topology optimization techniques, the research aims to achieve a significant reduction in the disc rotor's weight without compromising its mechanical strength and thermal characteristics.

- **To Validate the Optimized Designs through Rigorous Analysis**: The study intends to validate the optimized disc rotor designs through rigorous finite element analysis (FEA) and real-world simulations, considering various operational scenarios and environmental conditions. By conducting comprehensive performance assessments, the research aims to demonstrate the reliability and effectiveness of the optimized disc rotor designs for all-terrain vehicles.

By addressing these objectives, the study aims to bridge the existing research gaps and contribute to the advancement of innovative and sustainable engineering practices in the design and manufacturing of high-performance disc rotors for all-terrain vehicles.

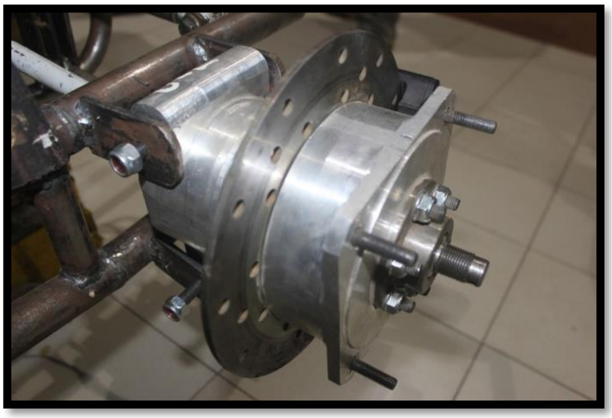

Figure 2 *Non-Optimized Disc Rotor*

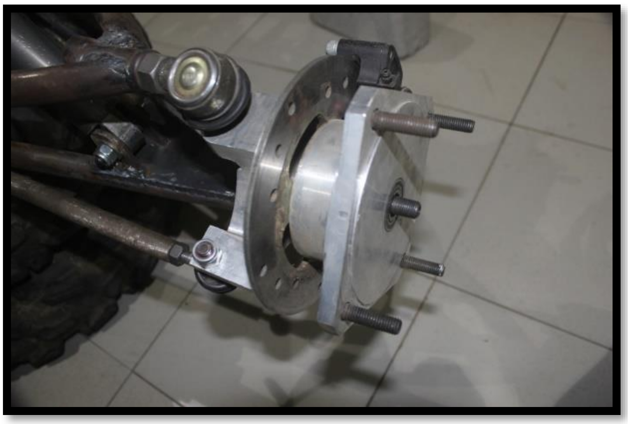

Figure 3 *Non-Optimized Disc Rotor*

CHAPTER 4: MATERIALS AND METHOD

4.1 Material Selection

The selection of suitable materials for the disc rotor design is crucial to ensure optimal performance, durability, and weight reduction. Considering the demanding operating conditions and performance requirements of all-terrain vehicles (ATVs), the material selection process should prioritize the following key factors:

Table 1 Value comparison table for different materials

VALUES COMPARISON TABLE	SS 304 AND 316	SS 410 AND 416
CORROSION RESISTANCE	Good	Moderate
MACHINABILITY	Poor/Gummy – will not hold bright finish	Good
WELDABILITY OF STEEL	Good	Moderate
SOUR SERVICE (SS) ENVIRONMENTS	Poor	Acceptable
WEAR RESISTANCE	Moderate	Good/Further hardening diminishes
MAGNETIC	No	Yes
SHOCK RESISTANCE	Excellent	Good
RETAINED STRESS	Poor / High degree of memory	Moderate / High degree of memory
LONG LENGTHS AVAILABLE	No	Yes
FINISH OPTIONS	Cold Drawn	Hot Roll
YIELD STRESS (TYP)	304L = 25,000 PSI 316L = 30,000 PSI	410 = 90,000 PSI 416 = 110,000 PSI
SERVICE TEMPERATURE RANGE	304L = 1100°F 316L = 1400°F	410 = 1100°F 416 = 1100°F
TENSILE STRESS (TYP)	304L = 70,000 PSI 316L = 75,000 PSI	410 = 120,000 PSI 416 = 124,000 PSI
THERMAL HARDENABILITY	No	Yes

Consequently, SS410 material was selected for the disc rotor design after careful consideration and comparison of the qualities of several materials.

4.2 Topology Optimization of a Disc Rotor

With the aid of topology optimization, engineers can create the best possible design in every way. Initially, the topology optimization method is used at the concept stage to produce an initial design that is subsequently further optimized while accounting for the manufacturing aspect. This helps to reduce the number of design iterations, which in turn lowers the overall cost. Frequently, the designs produced by topology optimization meet performance requirements, but they are difficult to produce. As a result, during the design phase, necessary changes are made to the design while taking manufacturing into account. To obtain the ideal arrangement, the subsequent actions were carried out. In Finite Element Analysis (FEA) for structural analysis, topology optimization generally entails optimizing the material layout within a particular design space to achieve certain performance objectives while adhering to different limitations. There are various types of topology optimization

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approaches that are often employed in the context of FEA.

1. **<u>Density-based topology optimization</u>**: One of the most frequent approaches is density-based topology optimization, which seeks to discover the ideal material distribution within a given design space. It generally begins with a homogenous density field and eliminates material from non-critical places repeatedly while maintaining stiffness or minimizing compliance.
2. **<u>Mixed density-based topology optimization</u>**: This method focuses on optimizing the design domain's shape. It entails adjusting the border shape to improve structural performance and is frequently utilized when structural boundaries may be modified.
3. **<u>Level set topology optimization</u>**: Unlike density-based optimization, material distribution optimization focuses on spreading different materials within the design space to obtain the required performance. This is especially significant in the design of composite materials.

In the present work, the density-based topology optimization method is used to minimize the weight of the disc brake of an automotive vehicle. Density-based optimization is a complex engineering process that focuses on optimizing the distribution of material inside a particular structure or design. The basic purpose of density-based optimization is to obtain a configuration in which material is distributed in such a way that it maximizes performance, minimizes weight, or optimizes some other key criterion. This method frequently involves the use of mathematical algorithms and computer approaches to modify the density distribution inside a component in order to improve its overall efficiency and effectiveness. Shape optimization design's main concept is to place material where it is necessary and reduce material in areas that aren't necessary for a precise function in order to create the best possible shape that satisfies all of the essential functional requirements, such as stiffness and strength-to-weight ratio. Density-based optimization is used in a variety of sectors, including aerospace, automotive, and civil engineering, to create lightweight yet durable structures, increase energy efficiency, and improve the overall performance of diverse products and systems. This optimization approach contributes to attaining a balance between structural integrity and resource utilization, resulting in more sustainable and cost-effective designs by carefully regulating material distribution. The table below shows the demerits of all three methods.

Table 2 Comparison of different types of Topology Optimization

	Element Type	**Not Supported**			
		Features	Model analysis Limitations	Static Structural Limitations	Steady State Thermal Analysis
Density Based Topology	Solid, Shell, Plane	• Imported Composite plies • A creak in fractured object • No strain-based result	• Damping • Unsymmetrical or optimality criteria solvers • Pre-stressed model analysis	• B/C of joint Load, Fsi, or EM Transducer • Large deflection effects • Nonlinear contacts	• RSM Usage • Thermal + static structural linkage
Level Set Topology	3D Elements	Use uniform mesh			
Shape Optimization	3D Tetrahedral Elements				

Applying topology optimization choosing density as the objective function. Both surfaces are chosen as the optimized region whereas the lower inner edge, holes and outer edge are selected as a region for exclusion. Response constraint is selected as 65% mass reduction

4.2 Methodology

In ANSYS, topology optimisation involves a set of techniques to discover the best material distribution within a given design area. Here is a general approach to topology optimisation with ANSYS:

• **<u>Preparing the Geometry</u>:**
Begin by importing or building a 3D CAD model of the structure or component to be optimised into ANSYS 2021 R1. Define and build the finite element mesh, making sure it is finely tuned to represent the geometry's intricacies.

• **<u>Material Characteristics and Constraints</u>:**
Define the original design's material attributes. Specify the boundary conditions and loads that will be applied to the structure. Constraints (fixed or prescribed displacements) and applied loads (forces, pressures, etc.) are examples of this.

• **<u>First Design Space</u>:**
Define the initial design space in which the optimisation will take place. This might entail establishing areas where stuff can be present.

• **<u>Goals and constraints</u>:**

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Define the optimisation target, which might be based on goals such as minimising compliance, reducing weight, increasing stiffness, or achieving specified performance standards. Set limitations for the optimised design, such as maximum stress, displacement, or mode shapes.

- **Configuration of Topology Optimisation:**

In ANSYS, start the topology optimisation tool. Set optimisation parameters such as the design space, objectives, constraints, and solver choices.

- **Execution of Solver:**

Use the topology optimisation solver to solve the problem. To determine the best design, ANSYS will repeatedly change the material distribution. The SIMP (Solid Isotropic Material with Penalization) approach is frequently used by the solver.

- **Examining and Post-Processing:**

When the optimisation is finished, go over the findings to determine the best material distribution.

Analyse the performance of the optimised structure using ANSYS post-processing tools such as stress analysis, deformation analysis, and other relevant data.

- **Validation and Improvement:**

Validating the optimised design is critical to ensuring that it satisfies the specified objectives and restrictions. Make any required design changes based on the results, or re-run the optimisation procedure with new parameters.

- **Export the Improved Design:**

Once you're happy with the optimised design, save it as a CAD model or other appropriate file for further examination or manufacture.

Topology optimisation in ANSYS may be a useful tool for enhancing engineering design performance and efficiency. The procedure may differ based on the version of ANSYS software and modules you are using, but the fundamental methods provided here should serve as a basis for executing topology optimisation projects.

4.3 Fork Flow in Ansys

Figure 4 shows the ANSYS fork flow for the topology-optimized process of disk brake. Initially, the FEA analysis of the disc brake outer diameter of 584.2 mm is conducted using a steady-state structural analysis module. The geometry is created using spaceclaim 2021 R1 CAD software as shown in figure 4 and figure 6.

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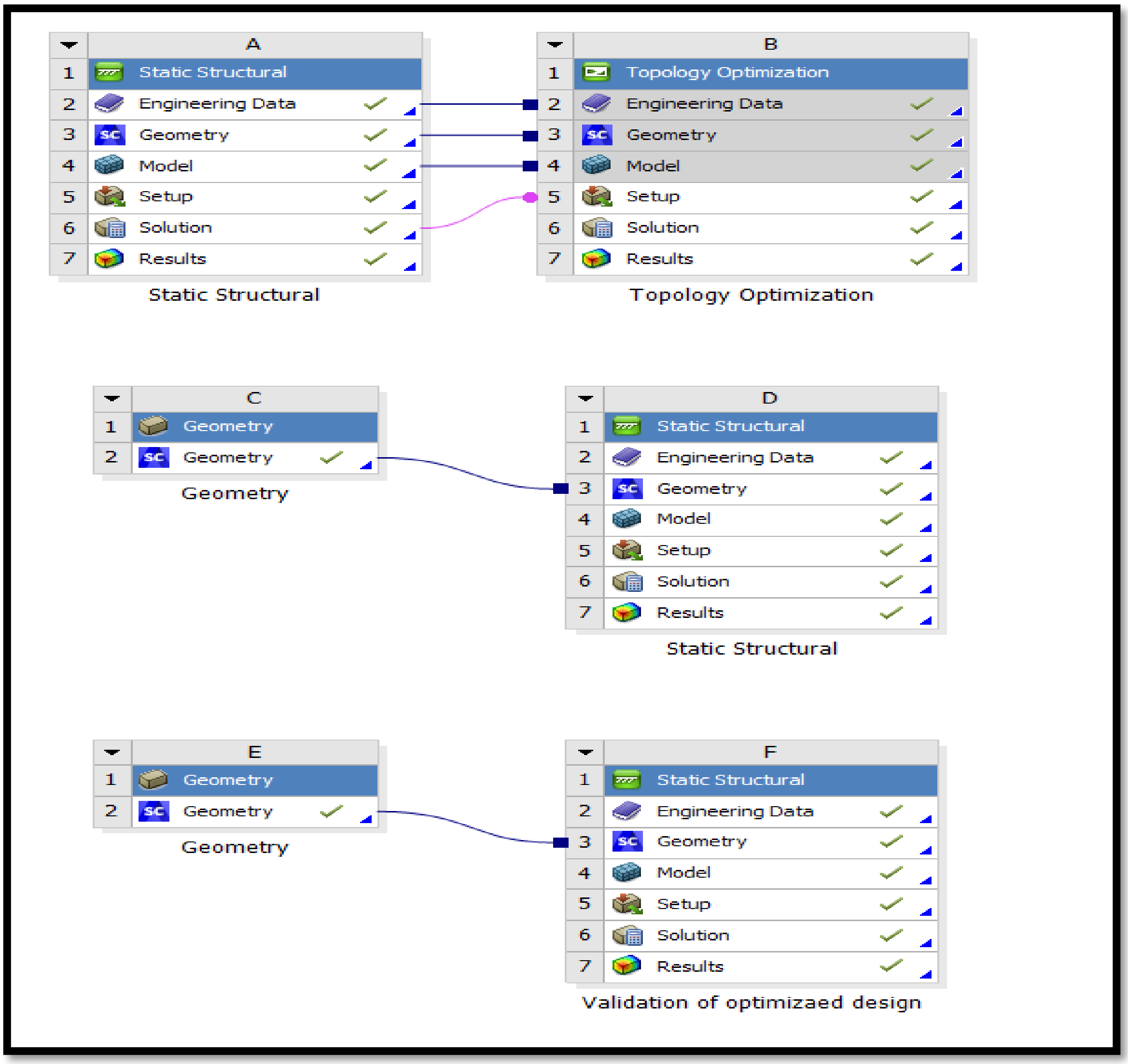

Figure 4*Fork flow analysis in ANSYS*

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CHAPTER 5: NON-OPTIMIZED DISC ROTOR MODEL & ANALYSIS

5.1 CAD Modeling of Non-Optimized Disc Rotor Model

CAD modelling SpaceClaim is a dynamic process that enables engineers and designers to generate, alter, and optimise 3D models with unprecedented speed and flexibility. Ansys spaceclaim is used to develop the 3D model of a disc rotor of diameter 584.2 mm. SpaceClaim's direct modelling technique enables users to edit and alter geometry from diverse CAD sources without the need for costly pre-processing. The 3D model is shown in the figure.5 & 6 Four holes of 20mm diameter are created for tightening the screws for mounting it to the drum.

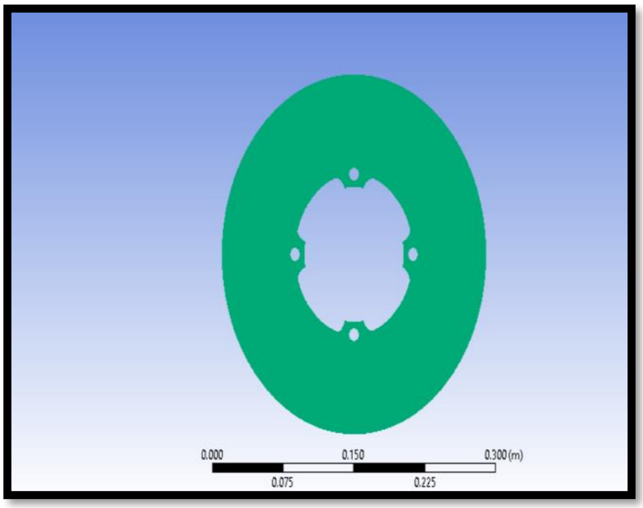

Figure 5 *3D-Model of Non-Optimized Disc Rotor*

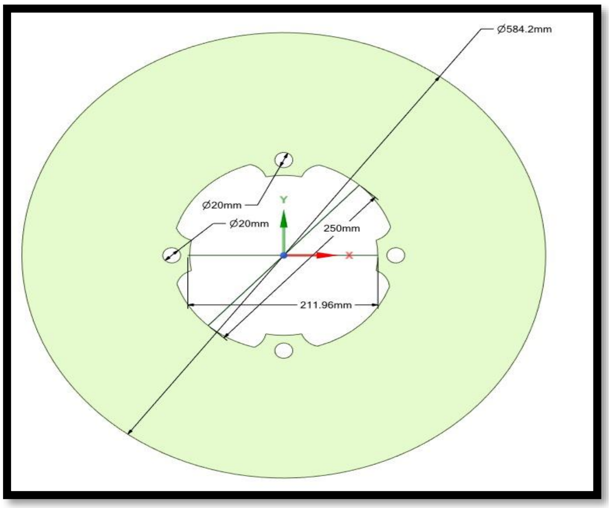

Figure 6 *3D-Model of Non-Optimized Disc Rotor with Dimension*

5.1 CAD Model Meshing

Proper disc brake meshing is crucial for generating trustworthy and accurate results in FEA simulations, especially in applications where stress, deformation, and heat dissipation are critical, as in disc brake analysis. The mesh size, element type, and boundary conditions should all be chosen with the analysis's unique goals in mind.

- Tetrahedral and hexahedra mesh is used to discretize the geometry for FEA analysis.
- The tetrahedral mesh contains a total of 31487 nodes and 16609 elements whereas the hexahedral
- The grid dependence test is conducted to estimate the total average displacement and approximate difference in both meshes is less than 0.4%.

The tetrahedral mesh shows a larger number of elements which finally consume more computational time. Hence therefore the optimum number of elements obtained for the hexahedral mesh is utilised under this study.

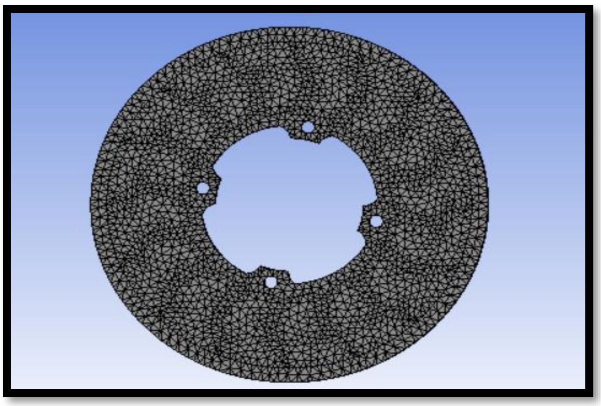

Figure 7 *Tetrahedral Mesh of non-optimized disc rotor*

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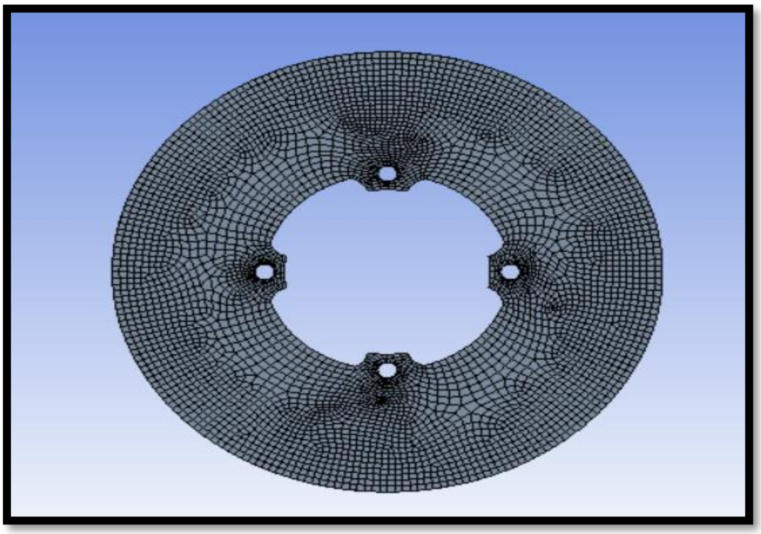

Figure 8 *Hexahedral Mesh of non-optimized disc rotor*

5.2 Boundary Conditions
Pressure 4.6 N/mm^2 pressure is applied in 10 steps at both surfaces of the disc as shown in the figure. Pressure applied to both sides, often from brake pads, is critical in turning kinetic energy into thermal energy, allowing a vehicle to decelerate. This pressure distribution throughout the brake surface has been meticulously designed to provide effective heat dissipation and even wear, hence optimising braking performance and safety. At the same time, permanent supports, generally at the hub or axle, are required to secure the disc brake, allowing it to withstand the opposing forces created during braking. These permanent supports help to stabilise the system, eliminating unwanted displacements and ensuring that the braking system works predictably and dependably.

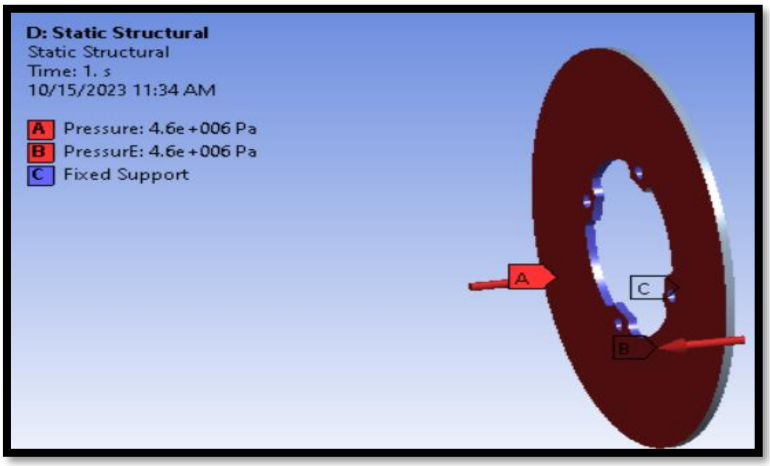

Figure 9 *Pressure Applied on surface of non-optimized disc*

5.2 Analysis of Non-Optimized Disc Rotor
The FEA results for disc brakes, which include displacement, stress, and strain, give essential insight into the structural performance and safety of these critical vehicle components. These numerical models provide a complete picture of how disc brakes react to different operating situations, such as braking forces and heat loads. The displacement analysis exposes how the brake components bend under load, ensuring that they remain within safe clearance limits. Figure J shows the average displacement of the disc rotor

computed for the given boundary condition is 0.0017mm. The disc is mounted at the holes, hence there is less chance of deformation, however, the region away from the holes is subjected to higher deformation.

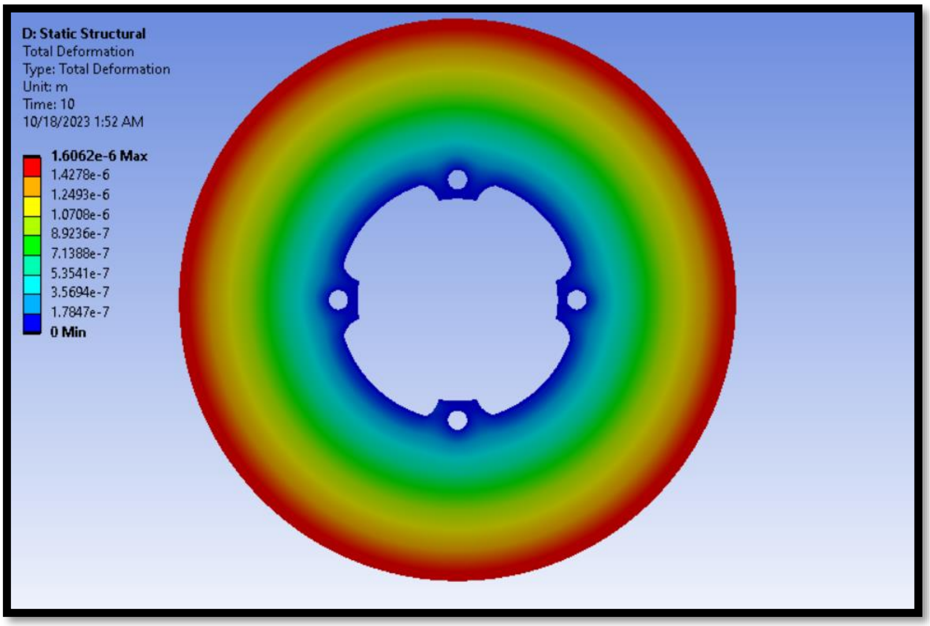

***Figure 10** Total Deformation Analysis of Non-Optimized Disc Rotor*

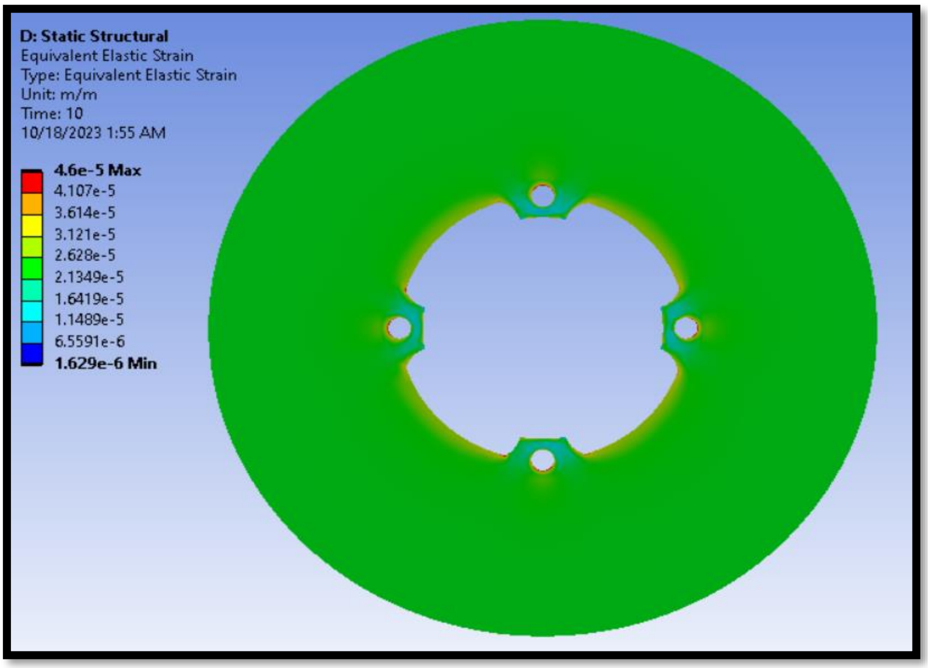

***Figure 11** Equivalent Stress Analysis of Non-Optimised Disc Rotor*

The equivalent stress is a representation of the combined effect of all internal stresses within the material and is often used to assess the potential for mechanical failure or deformation in critical regions of the disc rotor. By evaluating the maximum equivalent stress, engineers can identify areas that are prone to high-stress concentrations and make informed decisions regarding material selection, design modifications, or structural reinforcements to ensure

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the rotor's reliability and durability under operating conditions.

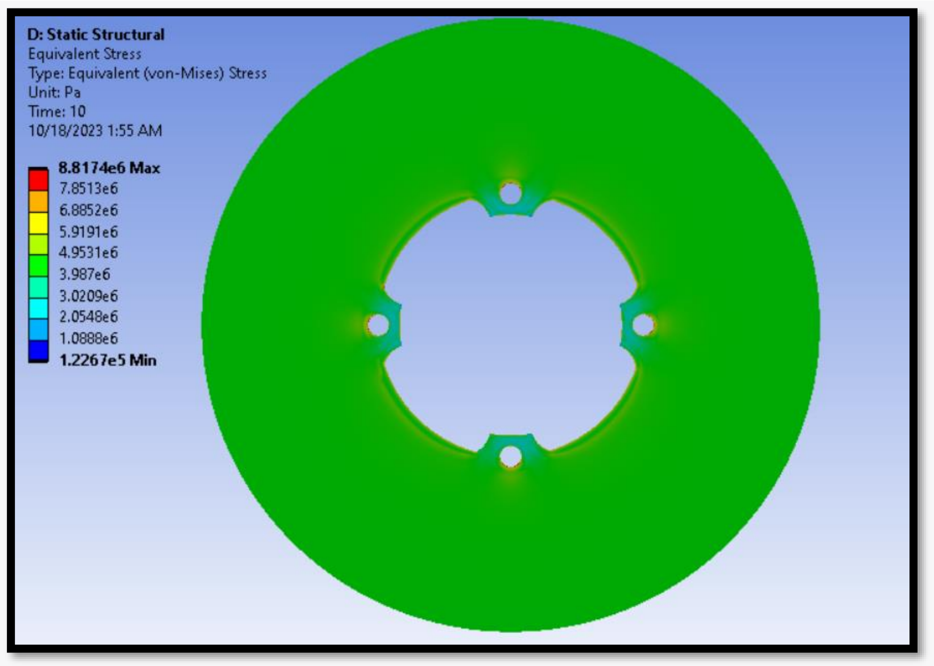

***Figure 12** Equivalent Elastic Strain Analysis of Non-Optimized Disc Rotor*

The equivalent elastic strain values serve as indicators of the level of deformation and stress experienced by the disc rotor's material, allowing engineers to assess its structural integrity and potential for fatigue or failure over time. By examining the maximum elastic strain values, engineers can pinpoint critical areas where the material is subjected to excessive deformation and determine whether design modifications or material enhancements are necessary to improve the rotor's mechanical performance and longevity.

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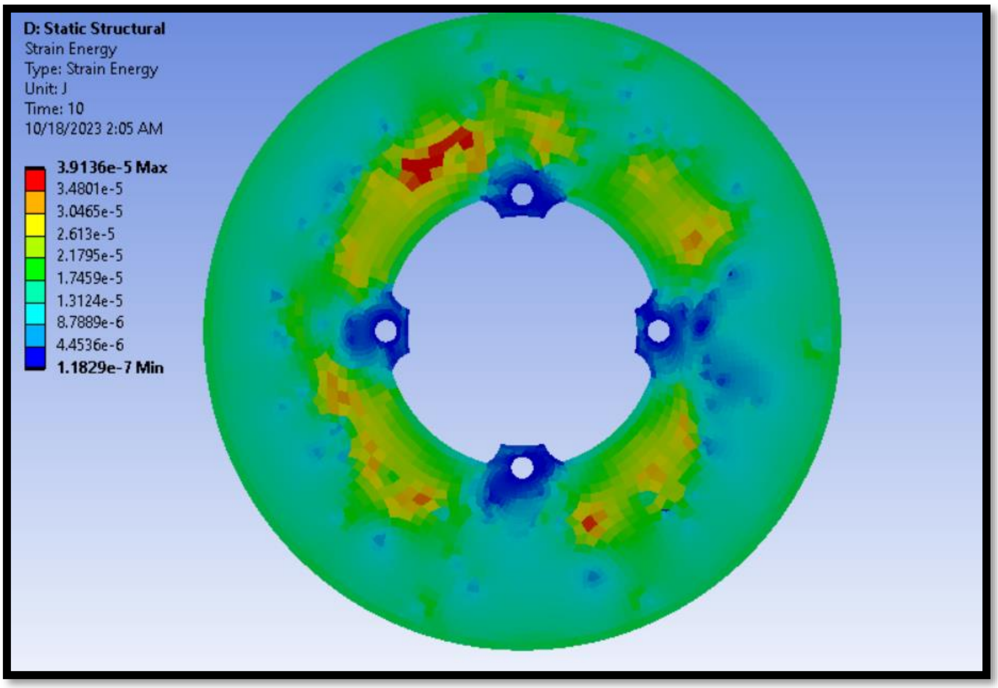

Figure 13 *Strain Energy Analysis of Non-Optimized Disc Rotor*

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Strain energy analysis is an important element of FEA findings for disc rotor, which include displacement, stress, and strain data. Strain energy is a measure of a material's ability to absorb and retain mechanical energy when subjected to loading circumstances. Understanding the distribution of strain energy in the context of disc brakes is critical in determining how well these components manage the energy created during braking. The maximum strain is reported in the region near the fixed support which is $3.14e^{-5}$Joules. The figure shows the strain energy distribution over the disc brake surface.

5.3 Thermal Analysis of Non-Optimized Disc Rotor

The FEA results for disc rotors, which include displacement, stress, and strain, give essential insight into the structural performance and safety of these critical vehicle components. These numerical models provide a complete picture of how disc rotors react to different operating situations, such as braking forces and heat loads. The displacement analysis exposes how the brake components bend under load, ensuring that they remain within safe clearance limits. Figure 10 shows the average displacement of the disc brake computed for the given boundary condition is 0.0017mm. The disc is mounted at the holes, hence there is less chance of deformation, however, the region away from the holes is subjected to higher deformation.

Thermal analysis of the disc rotor with ANSYS is an important part of braking system design and performance evaluation. Disc rotors are essential in contemporary automobiles, and their ability to properly disperse heat is critical for safety and lifespan. An overview of how ANSYS is used for thermal analysis in the context of disc brakes follows:

Mesh and Geometry Creation:-

Begin by importing or building an ANSYS 3D model of the disc rotor.

Create a finite element mesh that reflects the geometry properly. The mesh should be fine enough to capture details while remaining computationally efficient.

Material Characteristics:-

Define the brake disc's material parameters, such as thermal conductivity and specific heat capacity.

Conditions of Limitation:-

Define the boundary conditions, including beginning temperature, convective heat transfer coefficients at the disc's surface, and any contact interfaces with other components, such as brake pads.

Thermal loads include:-

Use thermal loads to replicate the heat produced during braking. This can be accomplished by introducing warmth or heat flux to the surface of the brake disc.

Analysis (Transient or Steady-State):-

Depending on whether you want to analyze temperature change over time or the ultimate, equilibrium temperature distribution, choose between transient and steady-state thermal analysis.

Run the analysis:-

Use ANSYS to run the thermal analysis, which will solve the heat conduction equations based on the provided geometry, material characteristics, boundary conditions, and loads.

Visualization of Results:-

Analyze the findings, which should include temperature distribution over the disc, temperature gradients, and probable hotspots. ANSYS' visualization tools assist you in understanding the heat dissipation characteristics.

ANSYS thermal analysis of disc rotor supports the creation of efficient and dependable braking systems by ensuring that the brake discs can properly disperse heat during braking, lowering the danger of overheating and assuring safer and more durable performance on the road.

Disc rotor thermal analysis is an important part of their design and performance evaluation. During braking, disc rotors are subjected to strong thermal stresses, and their capacity to properly dissipate heat is critical to guaranteeing safety and dependability. Engineers use methods like Finite Element Analysis (FEA) to model and analyze the heat distribution throughout the brake components in this analysis. The study takes into account elements such as the disc's starting temperature, heat transmission coefficients at the surface, and heat generated during braking. This information is utilized to visualize and evaluate the temperature distribution over the disk, ensuring that it stays within acceptable limits. Thermal analysis also considers the effect of high temperatures on the structural integrity of brake components, looking for possible deformations or thermal strains.

Figure 14 shows the boundary condition applied to the disc rotor. The flux of 25000 W/m^2 is applied to both surfaces in contact with the break shoe. The convection of 25 W/m^2-C is applied to all the surfaces and the radiation at the ambient temperature is defined. The solution is computed and the results are described in the below section.

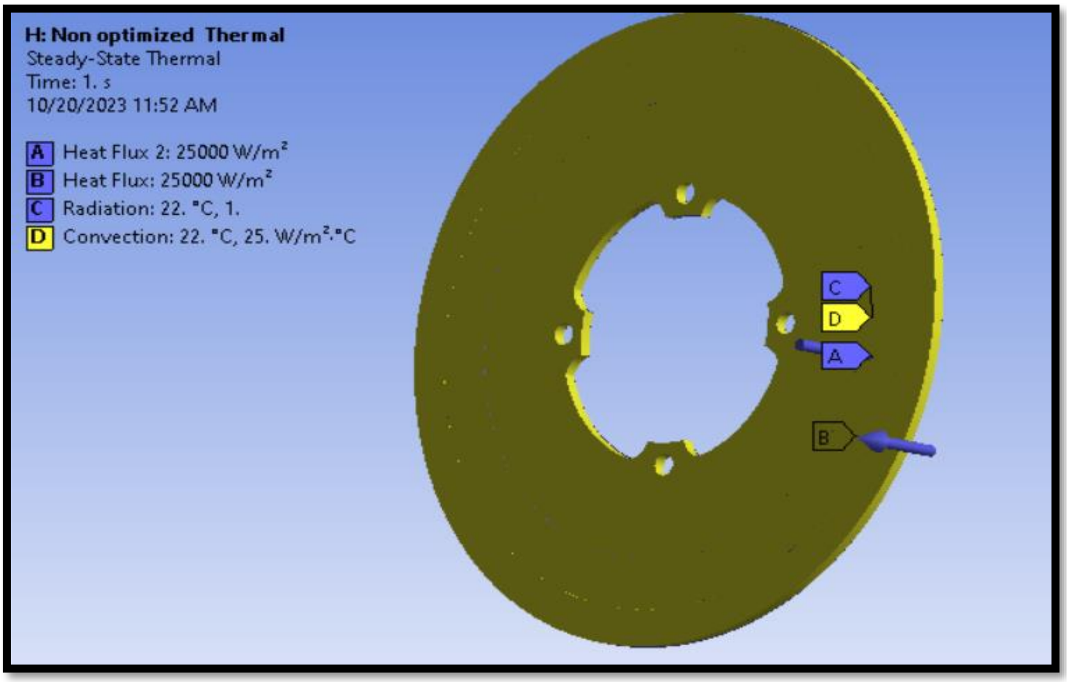

***Figure 14** The boundary condition applied to the non-optimized disc rotor*

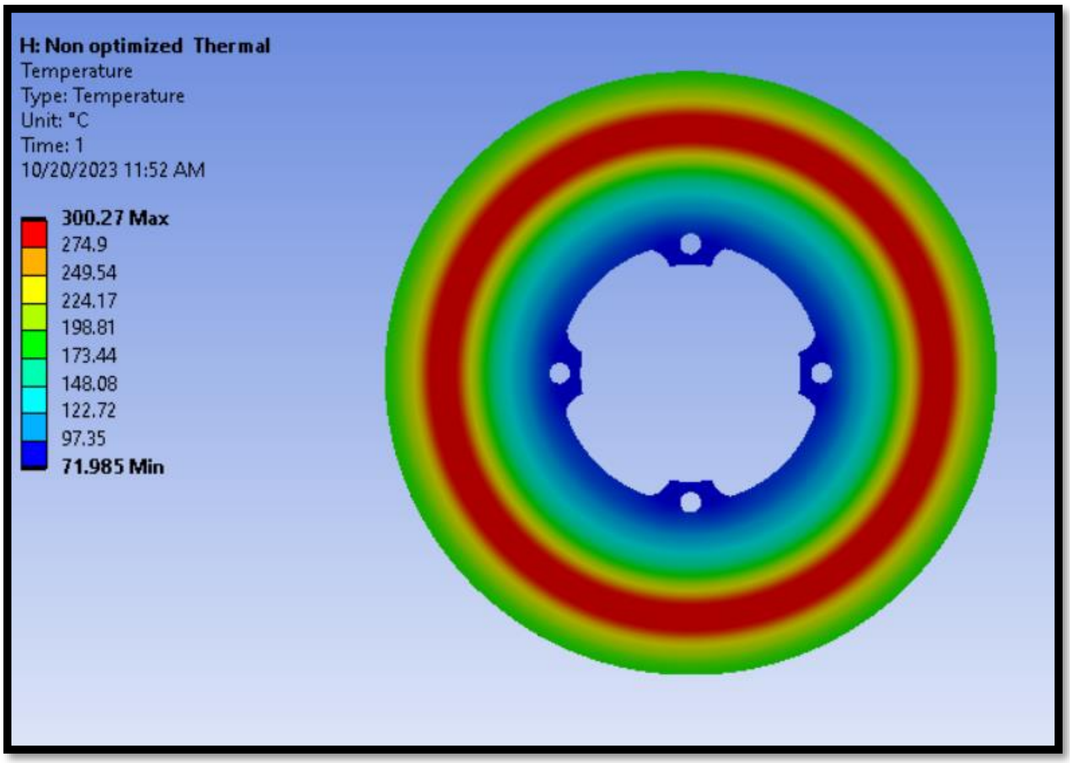

***Figure 15** The temperature distribution on the disc surface of non-optimized disc rotor*

Figure 15 shows the temperature distribution on the disc surface. The heat is generated due to the friction between the break shoe and disc hence the maximum temperature is at the surface in contact with the brake shoe. The temperature is uniformly distributed over the surface and the maximum value is 300.27 ºC. The minimum value of temperature is 71.98ºC at the innermost area mounted on the brake drum. The average temperature over the surface of the disc rotor is 224ºC

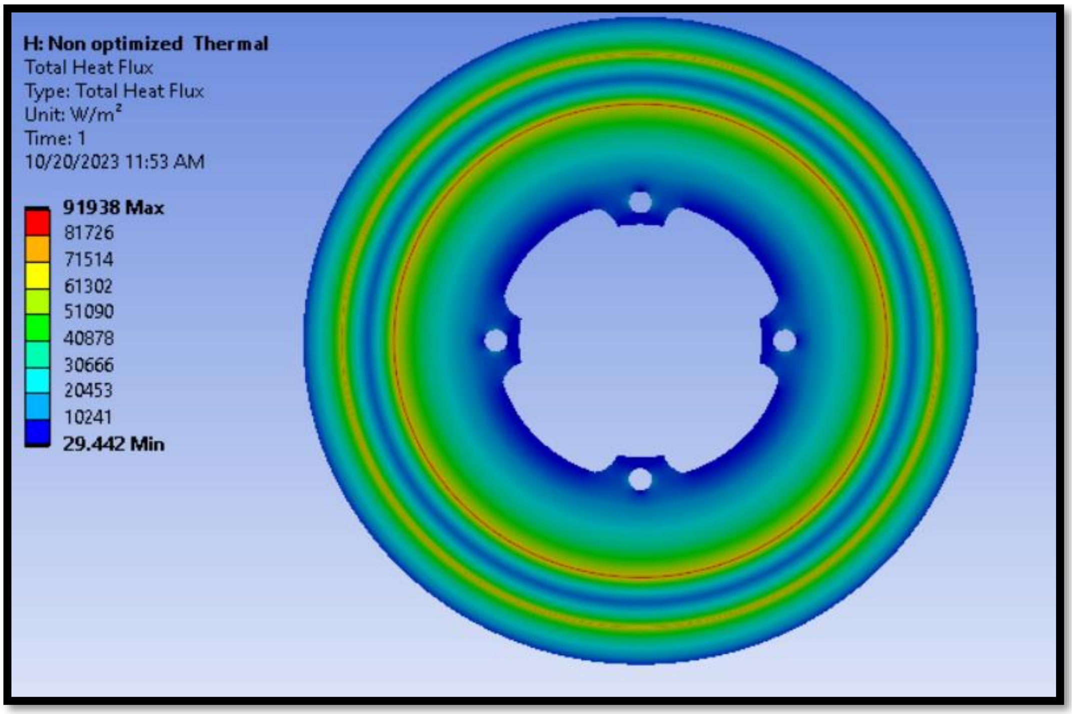

Figure 16 *the total heat flux is maximum at the point of contact of the breaking shoe with the disc*

Figure 17 shows directional heat flux along the direction of heat flux is maximum at the point of contact of brake shoe and disc which is 89688 W/m^2 and minimum away from the surface of contact which is 9955.5 W/m^2. The average value of heat flux in the x direction is 49822 W/m^2.

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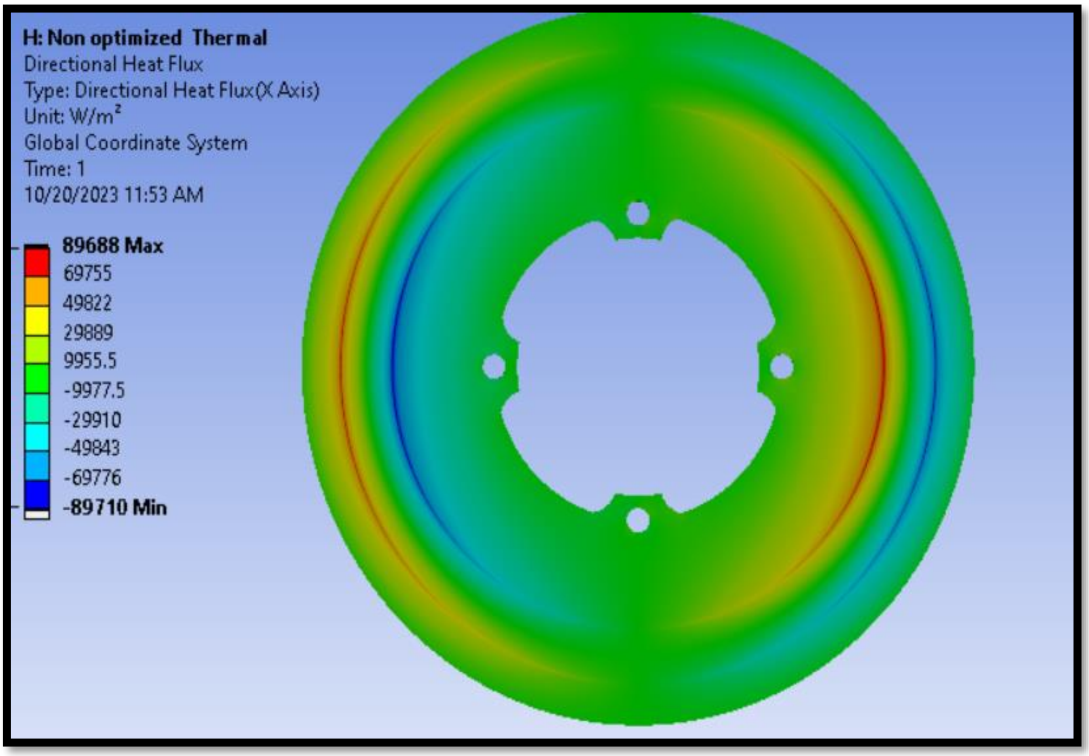

***Figure 17** Shows directional heat flux in non-optimised disc rotor*

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Topology Optimization Results

Density-based topology optimisation is used to find the most economical material layout that minimises weight and maximises structural integrity while adhering to performance restrictions. Displacement, stress, and strain evaluations are critical components in determining how these optimised systems behave to real-world loads, ensuring that the brake system remains safe and dependable while benefiting from weight reduction and better performance.

Mass as compliance is set as a parameter for topology optimization with minimization as the objective function. The constraint for the given objective is set as a 65% reduction in mass. Figure 18 shows the results of the geometry of topology-optimized density and topology-optimized elemental density of the disc rotor. The SS410 material is assigned to the disk brake the Table below reports the physical properties of the material used for this analysis.

Table 3 Physical Properties of the Material Used for this Analysis

Physical properties	**Metric**	**English**
Tensile Strength, Ultimate	510 MPa	74000psi
Tensile strength, yield	290 MPa @ Strain 0.20%	42000 psi @strain 0.20%
Elongation at Break	34%	34%
Modulus of elasticity	200GPa	29.0 x 106 psi

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Topology optimisation within FEA findings for disc rotors, using displacement, stress, and strain data, is a transformational technique in engineering design. It focuses on optimising internal material distribution, which enables the development of novel, lightweight, and high-performance brake components. Figure 18 shows the average displacement of topology optimized disc rotor which is 0.0097 mm.

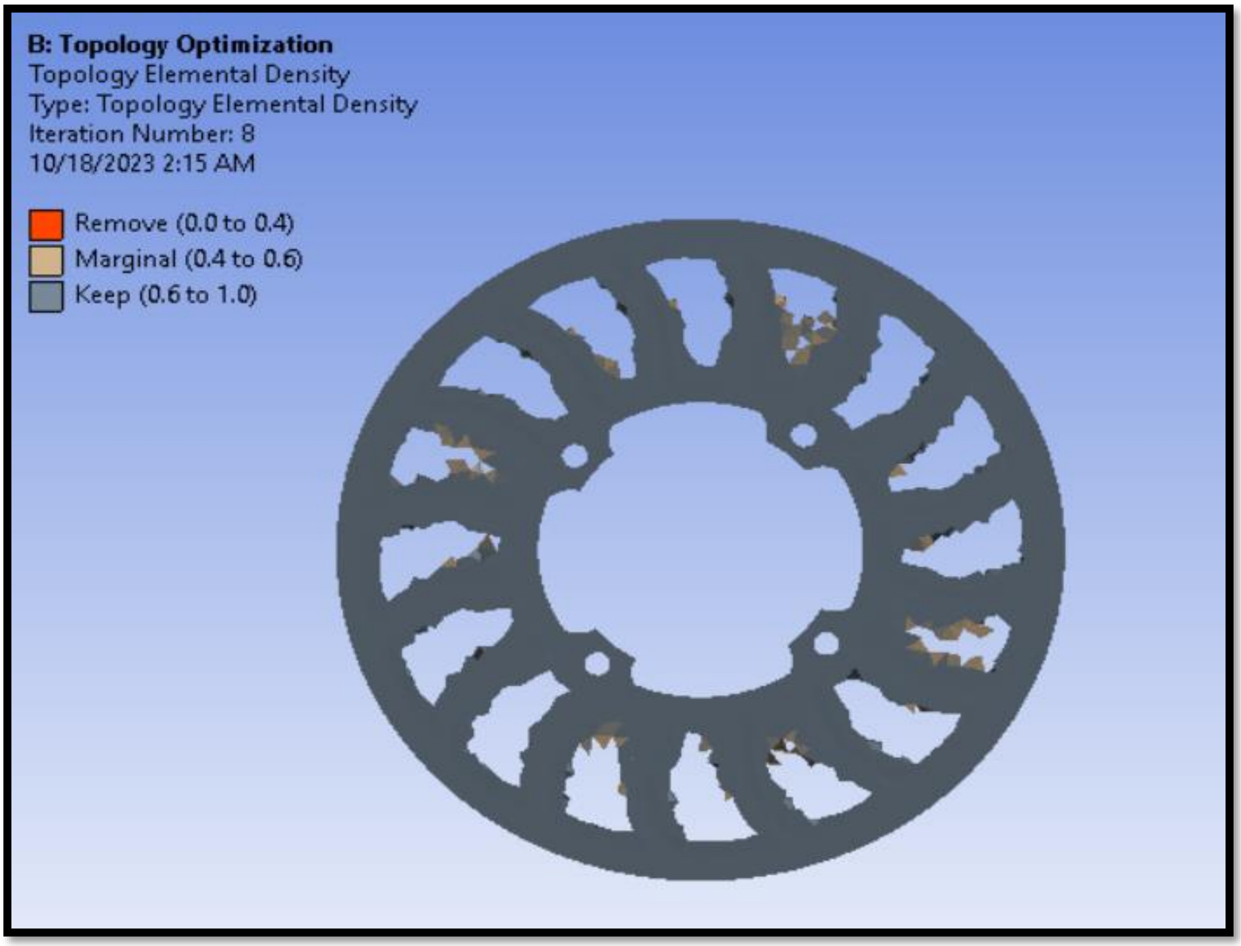

Figure 18 *The average displacement of topology optimized disc rotor*

6.2 Analysis of Optimised Disc Rotor

The FEA results for disc rotors, which include displacement, stress, and strain, give essential insight into the structural performance and safety of these critical vehicle components. These numerical models provide a complete picture of how disc rotors react to different operating situations, such as braking forces and heat loads. The displacement analysis exposes how the brake components bend under load, ensuring that they remain within safe clearance limits. Figure W shows the average displacement of the disc rotor computed for the given boundary condition is 0.00057mm. The disc is mounted at the holes, so there is less chance of deformation, however, the region away from the holes is subjected to higher deformation.

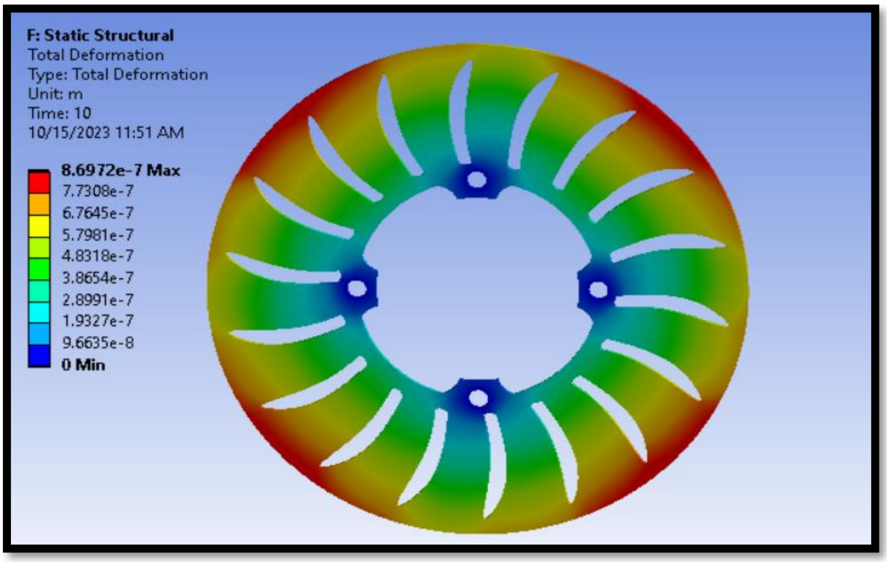

Figure 19 *Total Deformation Analysis of Optimized Disc Rotor*

Furthermore, FEA stress and strain data give critical information about the material's reaction to applied forces, assisting engineers in identifying regions of possible fatigue or failure. Examining these facts allows designers to optimise disc rotor designs to improve longevity, heat dissipation, and overall performance, resulting in safer and more economical braking systems.

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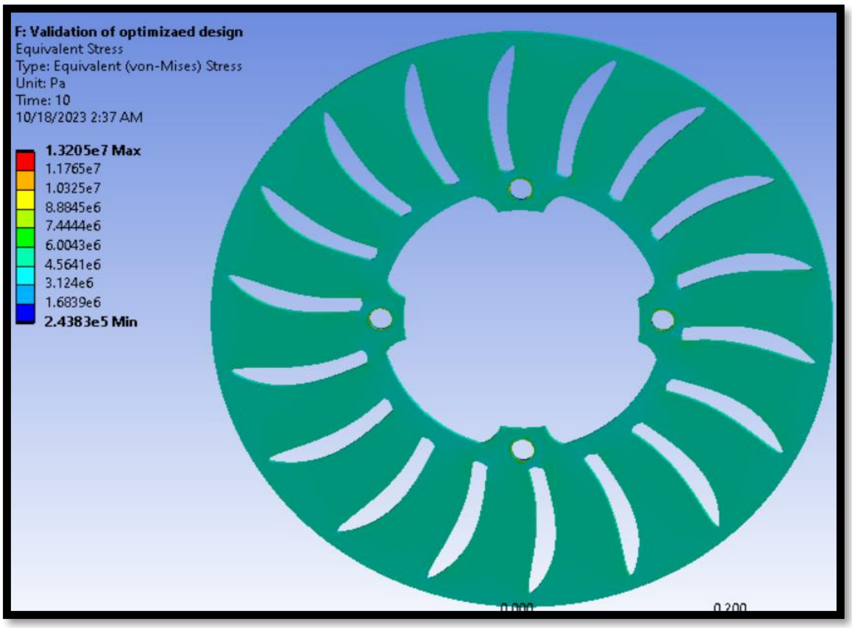

Figure 20 *Equivalent Stress Analysis of Optimized Disc Rotor*

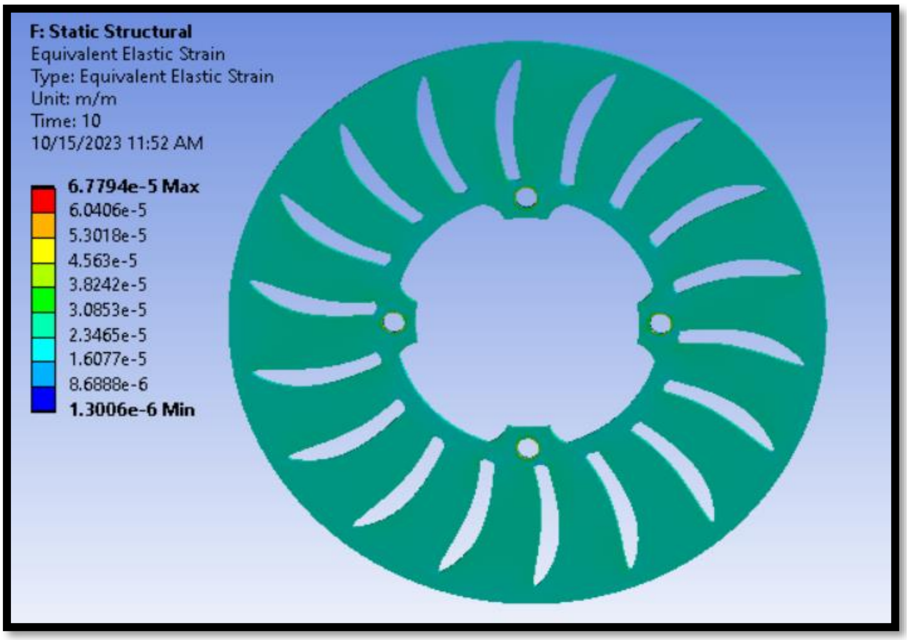

Figure 21 *Equivalent Elastic Strain Analysis of Optimized Disc Rotor*

Evaluate the disc rotor's performance based on the results of the equivalent elastic strain analysis, comparing the observed strain levels with predefined performance criteria and industry standards. Assess the effectiveness of the topology optimization in reducing strain concentrations and improving the structural integrity of the disc rotor, and consider further design refinements or optimization iterations if necessary.

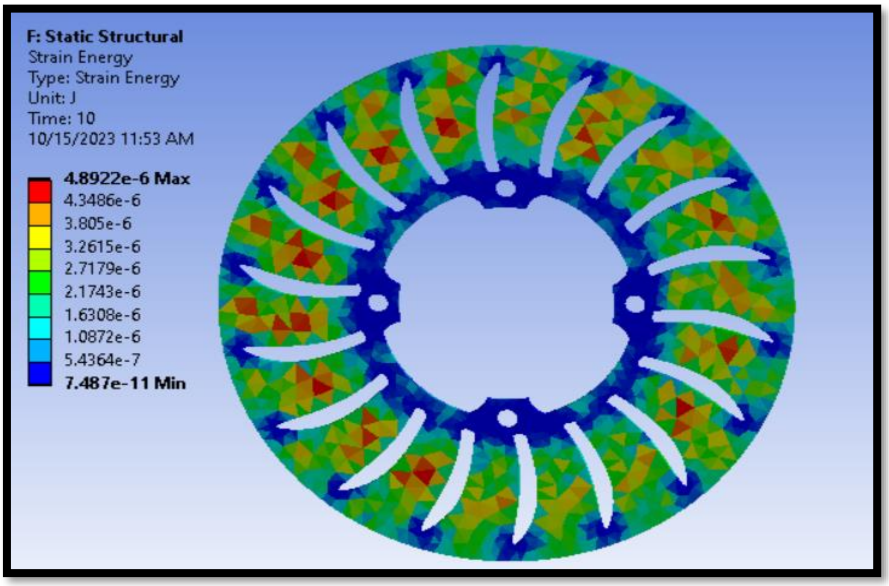

***Figure 22** Strain Energy Analysis of Optimized Disc Rotor*

Strain energy analysis is an important element of FEA findings for disc rotors, which include displacement, stress, and strain data. Strain energy is a measure of a material's ability to absorb and retain mechanical energy when subjected to loading circumstances. Understanding the distribution of strain energy in the context of the disc rotor is critical in determining how well these components manage the energy created during braking. The maximum strain is reported in the region near the fixed support which is 1.29 e^{-5} Joules.

The figure shows the strain energy distribution over the disc rotor surface.

6.2 Thermal Analysis of Optimised Disc Rotor

Figure 23 shows the boundary condition applied to the disc rotor. The flux of 25000 W/m2 is applied to both surfaces in contact with the break shoe. The convection of 25 W/m2-C is applied to all the surfaces and the radiation at the ambient temperature is defined. The solution is computed and the results are described in the below section.

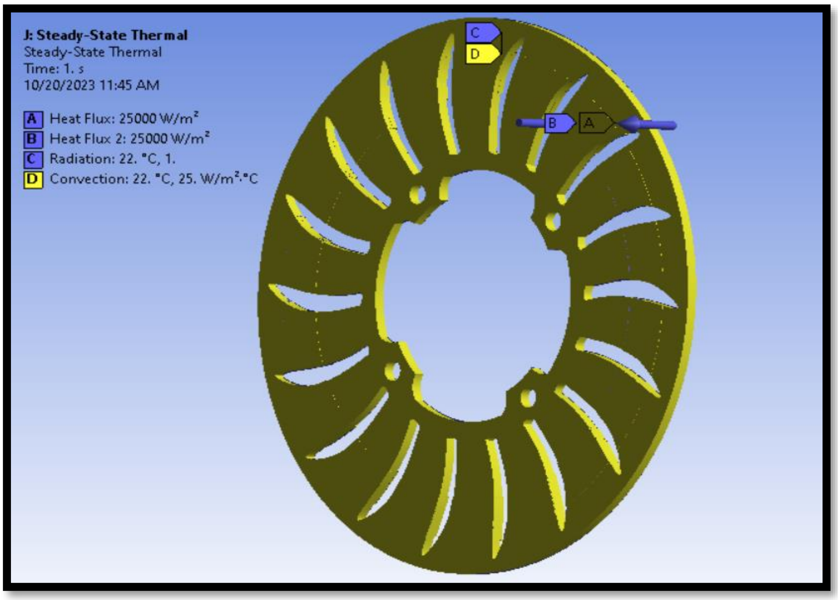

***Figure 23** The boundary condition applied to the optimised disc rotor*

Figure 24 shows the temperature distribution on the disc surface. The heat is generated due to the friction between the break shoe and disc hence the maximum temperature is at the surface in contact with the bread shoe. The temperature is uniformly distributed over the surface and the maximum value is 206ºC. The minimum value of temperature is 121.65ºC at the innermost area mounted on the brake drum. The average temperature over the surface of the disc brake is 178ºC. The average value of temperature is 21% less in the optimized disc due to less heat flux generated because less friction is generated.

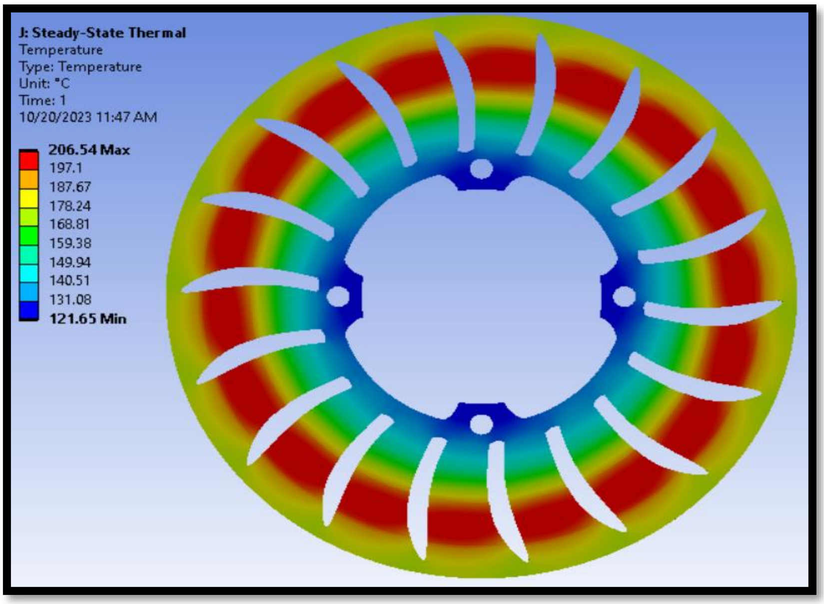

Figure 24 *The temperature distribution on the disc surface of optimised disc rotor*

The total heat flux is maximum at the point of contact of the breaking shoe with the disc. The maximum value of heat flux is 82585 W/m^2 where the minimum is away from the contact surface which is 12652 W/m^2. The average value of heat flux is 52274 W/m^2. The average value of total heat flux is 14% less than in the case of the optimized case.

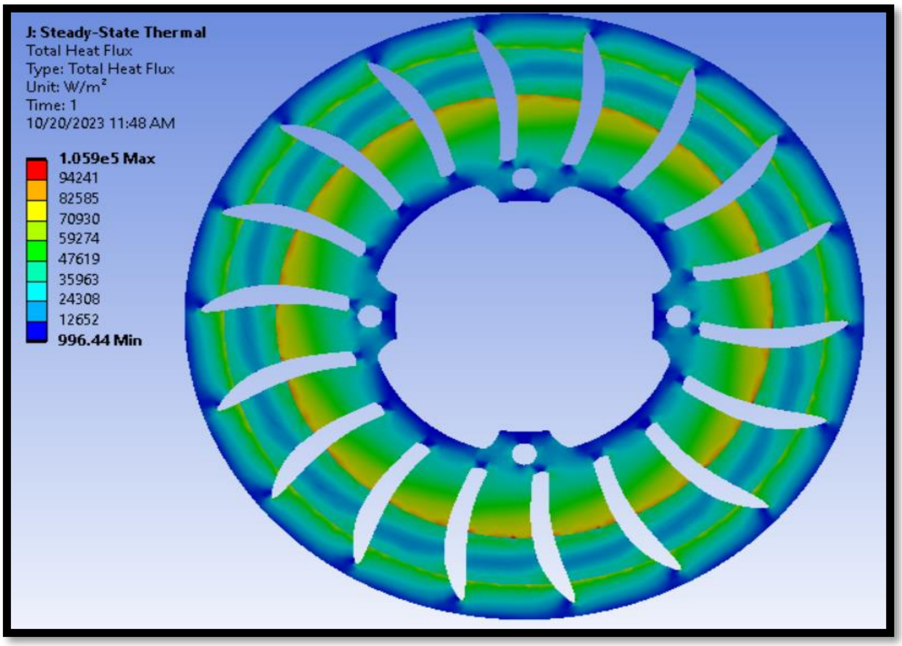

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Figure 25 *The total heat flux analysis of optimized disc rotor*

Directional heat flux along the direction of heat flux is maximum at the point of contact of break shoe and disc which is 83780 W/m2 and minimum at the away from the surface of contact which is 8250 W/m2. The average value of heat flux in the x direction is 36015 W/m2. The directional heat flux value is 27 % less in the optimized disc rotor

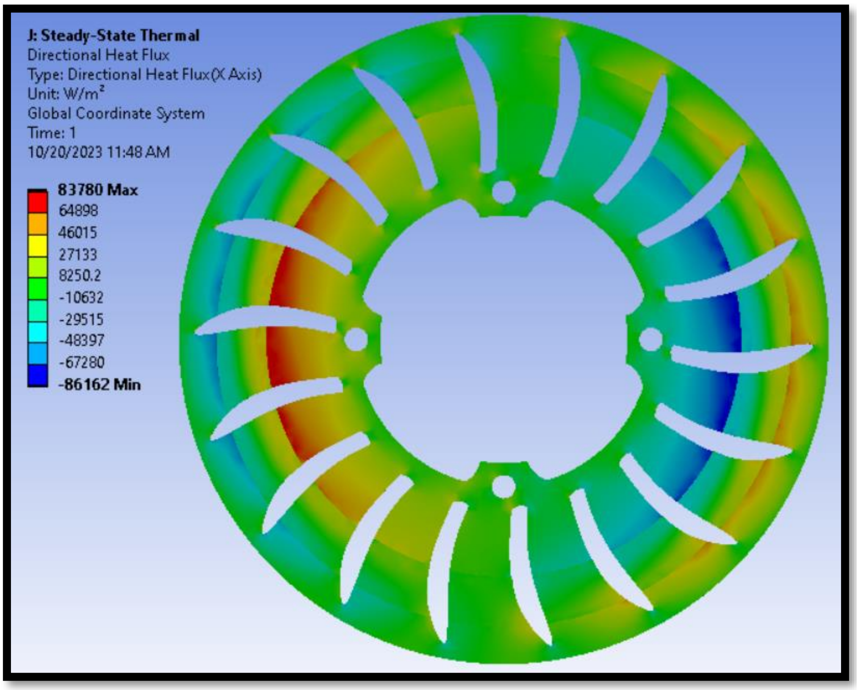

Figure 26 *The directional heat flux analysis of optimized disc rotor*

Efficient thermal analysis aids in the optimization of disc rotor design by enabling engineers to make essential changes such as implementing cooling methods such as ventilation channels, optimizing materials, or altering geometry to improve heat dissipation. Finally, thermal analysis helps to build safer and more dependable braking systems by lowering the danger of overheating and assuring consistent performance under a variety of operating circumstances.

6.3 Results

As a result of this procedure, a disc rotor that is not only much lighter but also physically strong, ensuring dependable performance under different loads, is produced. The FEA study confirms that the optimised design successfully regulates displacement, stress, and strain, while topology optimisation ensures that materials are used optimally. This breakthrough in automotive engineering and vehicle safety opens the path for safer and more efficient braking systems.

The following factors are taken into consideration when designing the new rotor design.:-

- Optimal Heat Dissipation.
- Reduced Weight.
- Rotor Size according to our ideal needs.
- Thickness to meet our highest standards.
- Less space is needed for packaging.

The graph between the objective, iteration number, and mass constraint shows the convergence iteration curve

to achieve the combined defined objective which is achieved at $1.2e^{-2}$ in the 8^{th} iteration number. Mass constraint which is defined to reduce up to 65% is achieved in 8^{th} iterations. The compliance mass to reduce to 65% is satisfied under 10 steps of pressure applied on the disc.

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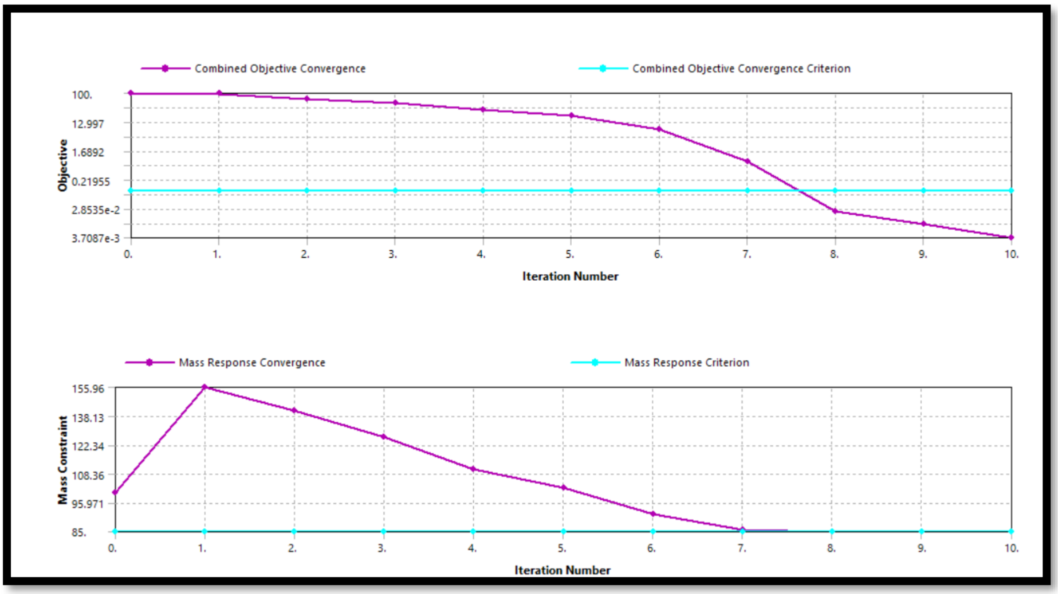

Figure 27 *The Graph between objective, iteration number, mass constraint is obtained*

Table 4 The summary of FEA analysis of the initial disc rotor, topology-optimized disc rotor and new disc rotor

Parameter	**FEA Results**	**Topology optimized results**	**Topology Optimized geometry results**
Displacement Units (mm)	0.0017	0.0097	0.0057
Stress (pa)	4.96E+06	9.60E+06	9.80E+06
Strain (mm/mm)	2.62E-06	7.80E-06	7.70E-06
Strain energy (J)	2.17E-05	3.32E-05	3.29E-05
Mass (kg)	3.001	2.009	1.8
Volume (m^3)	2.40E-04	1.50E-04	9.80E-05

The table shows the summary of FEA analysis of the initial disc rotor, topology-optimized disc rotor and new disc rotor. The total average displacement results in an 82 % total increase and a 70% increase in the topology optimized and new proposed disc rotor design due to a reduction in 33% and 40% of the mass respectively. Conscetuviely the principal stress value increases to 48 % and 49% in the topology optimized and new proposed design due to reduction in the surface area due to removal of mass. The strain value results in a 35 % and 34% increase compared to the initial disc. The average strain energy of the topology optimized and proposed new design shows a 33% and 40% increase respectively as compared to the initial disc. The measured stress and deformation value are under the range of the ultimate strength value of SS410 material which is 510 MPa.

Table 5 Weight comparison table between Non-optimized and Optimized disc rotor

	OEM Disc Rotor	**Optimized Disc Rotor**
Weight	967.84g	338.744g

The optimized disc rotor demonstrates a significant reduction in weight, achieved through the implementation of topology optimization techniques and highlighting the potential for weight reduction without compromising the structural integrity and performance of the disc rotor.

CHAPTER 7: CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

- Finally, the findings of the Finite Element Analysis (FEA) and disc rotor topology optimization constitute a significant step forward in the evolution of vehicle safety and performance. FEA has offered vital insights into the behaviour of disc rotors under real-world settings, allowing for a thorough understanding of variables such as displacement, stress, and strain. This understanding is required to ensure the structural integrity and safety of these crucial components. We can draw the conclusion that the rotor with the above

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design produces an output that is more optimised for rough terrain. The disc rotor underwent topology optimisation by identifying design constraints and pertinent boundary conditions to limit its weight. Comparing the new disc rotor to the old OEM disc rotor, the former is 65% lighter. With this understanding of topology optimisation, a high strength-to-weight ratio disc rotor design can be created quickly.

- Furthermore, the use of topology optimization has ushered in a new age of brake design, resulting in lightweight yet durable constructions with improved efficiency and performance. Engineers found the optimal balance between weight reduction and structural strength by optimizing internal material distribution, decreasing failure risk and enhancing safety.
- In conclusion, the combined power of FEA and topology optimization not only refines disc rotor engineering but also adds to the larger objective of building safer, more efficient, and more sustainable automotive systems. These findings demonstrate the relentless pursuit of perfection in the search for new and dependable braking solutions.

7.2 Future Scope of the Study

Some potential areas for further exploration and the future scope of this study include:-

Multi-Objective Optimization: Extending the research to incorporate multi-objective optimization techniques, considering additional parameters such as cost-effectiveness, manufacturability, and environmental sustainability. Implementing a holistic approach that simultaneously addresses various design considerations can lead to the development of highly efficient and cost-effective disc rotor designs for all-terrain vehicles.

Advanced Material Integration: Investigating the integration of advanced composite materials and hybrid material systems into the disc rotor design to further enhance the structural performance, durability, and weight reduction potential. Exploring the use of nanomaterials and smart materials could offer new opportunities for improving the overall efficiency and functional capabilities of the disc rotor in demanding operating environments.

Durability and Fatigue Analysis: Conducting comprehensive durability and fatigue analysis to assess the long-term performance and reliability of the optimized disc rotor under prolonged and rigorous operating conditions. Investigating the disc rotor's resistance to wear, corrosion, and thermal degradation can provide insights into its lifecycle behaviour and facilitate the development of maintenance strategies to ensure sustained performance over extended periods of use.

Integration of Additive Manufacturing: Exploring the integration of additive manufacturing processes, such as 3D printing, in the production of optimized disc rotors. Investigating the feasibility of utilizing additive manufacturing techniques to create complex geometries, internal lattice structures, and customized designs can streamline the manufacturing process, reduce material waste, and facilitate the production of highly customized and lightweight disc rotor components.

Real-World Testing and Validation: Conduct extensive real-world testing and validation of the optimized disc rotor designs under diverse terrain conditions and varying operating environments. Performing field tests, durability trials, and performance evaluations on all-terrain vehicles equipped with the optimized disc rotors can provide practical insights into their real-world applicability, performance, and long-term reliability, further confirming the effectiveness of the topology optimization approach.

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