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Research Paper

Integrated Finite Element and Topology Optimization Approach for Next-Generation Lightweight Automotive Chassis Design

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ABSTRACT

The automotive industry is increasingly focused on developing lightweight vehicle structures to enhance fuel efficiency, improve performance, and reduce environmental impact. Among various structural components, the chassis plays a critical role in determining vehicle strength, stability, and overall weight. Conventional chassis designs often employ uniform material distribution, leading to excessive mass and inefficient utilization of resources. This study presents a comprehensive investigation of lightweight automotive chassis design through topology optimization and advanced material removal algorithms. A comparative analysis was conducted on four engineering materials—Structural Steel, Magnesium Alloy, Aluminum Alloy, and Titanium Alloy such as to evaluate their structural behavior under identical loading conditions. The chassis geometry was developed using SolidWorks and subsequently analyzed in ANSYS through Finite Element Analysis (FEA) to assess deformation, equivalent stress, and strain characteristics. The research adopts an optimization-driven approach in which low-stress regions are identified and selectively removed to achieve significant weight reduction while maintaining structural integrity. The primary challenge addressed is the balance between minimizing chassis mass and preserving adequate stiffness and strength. Results indicate that lightweight materials such as magnesium and aluminum offer substantial weight savings, whereas structural steel provides superior strength. Titanium Alloy demonstrated the most favorable performance when subjected to topology optimization, exhibiting considerable potential for material reduction without compromising safety or mechanical reliability. The proposed methodology establishes a validated framework for material selection and structural optimization, contributing to the development of next-generation automotive chassis systems that meet modern sustainability goals while ensuring high levels of structural performance, durability, and efficiency.

Keywords: Topology Optimization, Automotive Chassis, Finite Element Analysis, Lightweight Structures, Multi-Material Design

1. INTRODUCTION

The automotive industry has witnessed remarkable advancements over the past few decades, driven by the growing demand for safer, more efficient, and environmentally sustainable vehicles. Automotive design is a comprehensive process that involves the development of both the visual appearance and functional characteristics of motor vehicles, including passenger cars, commercial vehicles, buses, motorcycles, and utility vehicles.

Modern vehicle development requires the collaboration of professionals from various disciplines such as mechanical engineering, manufacturing engineering, industrial design, materials science, and ergonomics as shown in fig 1. The primary objective of automotive design is to create vehicles that not only possess an attractive appearance but also deliver superior performance, safety, durability, and user comfort. As global regulations become increasingly stringent regarding fuel

consumption and emissions, automotive manufacturers are placing greater emphasis on innovative design approaches that enhance vehicle efficiency without compromising structural integrity.

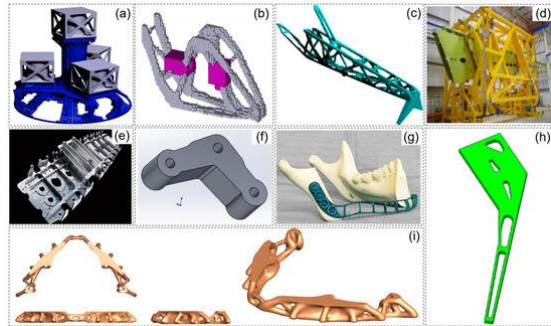


Fig 1. Topology optimization structural designs

A key aspect of automotive design is the integration of exterior styling, interior ergonomics, color and trim selection, and advanced graphical elements into a unified vehicle concept. Exterior design focuses on developing the proportions, shape, aerodynamic characteristics, and surface details of the vehicle, while interior design emphasizes passenger comfort, accessibility, visibility, and human-machine interaction. Designers carefully consider the placement of instrument panels, seating arrangements, controls, and infotainment systems to create an intuitive and comfortable driving environment. In addition, color and trim design plays an important role in enhancing the visual appeal and perceived quality of the vehicle through the strategic use of materials, textures, fabrics, plastics, and surface finishes. These design elements are continuously refined through market research, consumer feedback, and trend analysis to ensure that the final product meets both customer expectations and industry standards. The advancement of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and simulation technologies has significantly transformed the automotive design process. Initial concepts are developed through sketches and digital renderings, which are subsequently converted into detailed three-dimensional models for engineering evaluation and optimization. These digital models undergo

extensive analysis to assess structural strength, durability, manufacturability, and performance under various operating conditions. Modern design methodologies also incorporate topology optimization and finite element analysis techniques to identify inefficient material regions and improve structural efficiency. Such approaches are particularly important in chassis design, where reducing vehicle weight while maintaining stiffness and safety is a critical engineering challenge. By leveraging advanced computational tools and optimization algorithms, automotive engineers can develop lightweight, high-performance chassis structures that contribute to improved fuel economy, reduced emissions, enhanced vehicle dynamics, and greater overall sustainability.

2. LITERATURE SURVEY

2.1 Lightweight Materials for Automotive Applications

The increasing demand for fuel-efficient and environmentally sustainable vehicles has encouraged extensive research into lightweight materials for automotive structures. Becker [1] discussed the emerging role of aluminum in downstream automotive applications, highlighting its excellent strength-to-weight ratio and corrosion resistance. Clark [2] emphasized the importance of techno-economic considerations in material selection, demonstrating that lightweight materials can significantly improve vehicle efficiency while balancing manufacturing costs. Hoegh [3] further investigated the economic feasibility of aluminum sheet applications in automotive body structures and concluded that aluminum offers substantial weight reduction benefits compared to conventional steel components.

Katrak et al. [4] presented a comparative analysis of steel, aluminum, and polymer materials for automotive body applications, identifying aluminum as a promising alternative due to its lower density and acceptable structural performance. Similarly, Kelkar [5] analyzed the strategic implications of aluminum adoption in automobile body designs and reported notable improvements in

vehicle lightweighting and fuel economy. Kelkar et al. [6] extended this work by evaluating the cost implications associated with the development of aluminum autobody designs, demonstrating that learning-based manufacturing improvements can significantly reduce production costs over time. Ostermann [8] provided a comprehensive overview of aluminum material technologies and their applications in modern automotive engineering, reinforcing aluminum's importance in lightweight vehicle development.

2.2 Cost Modeling and Manufacturing Considerations in Vehicle Design

Material selection for automotive structures is influenced not only by mechanical performance but also by economic and manufacturing factors. Marti [7] developed a cost-modeling methodology for automotive body-in-white assembly processes using relational databases, providing valuable insights into manufacturing efficiency and production economics. The study demonstrated that accurate cost estimation techniques are essential for evaluating alternative materials and design configurations during vehicle development.

2.3 Finite Element Analysis in Automotive Structural Design

Finite Element Analysis (FEA) has become one of the most widely used computational techniques for evaluating the structural behavior of automotive components. Bathe [9] provided the theoretical foundation for modern finite element procedures, presenting methodologies for analyzing deformation, stress distribution, strain behavior, and structural stability under various loading conditions. The work serves as a fundamental reference for implementing numerical simulations in engineering design and optimization.

The application of FEA enables engineers to accurately predict the mechanical response of vehicle structures before physical prototyping, thereby reducing development costs and improving design reliability. In automotive chassis design, FEA is extensively used to identify critical stress regions, evaluate material

performance, and assess structural safety under operational loads. The methodologies proposed by M. P. Bendsoe [12] form the basis for the ANSYS simulations employed in this research for comparative material analysis and topology optimization.

2.4 Structural Optimization and Chassis Design

Structural optimization has emerged as a critical technique for achieving lightweight yet robust automotive structures. Rajan [11] investigated the structural analysis and optimization of automotive chassis systems, demonstrating that optimized designs can significantly reduce vehicle weight while maintaining required stiffness and safety standards. The study emphasized the importance of integrating numerical simulation tools with optimization algorithms to improve structural efficiency.

The research highlighted the trade-off between mass reduction and structural integrity, a challenge that remains central to modern automotive engineering. By employing optimization methodologies during the design stage, engineers can identify redundant material regions and improve overall chassis performance without compromising durability or load-carrying capability.

2.5 Topology Optimization and Advanced Material Removal Techniques

Topology optimization has become a powerful design methodology for developing lightweight engineering structures. Bendsoe and Sigmund [10] introduced the theoretical foundations, mathematical formulations, and practical applications of topology optimization, establishing it as one of the most effective approaches for material distribution and structural weight reduction. Their work demonstrated how low-stress regions within a structure can be systematically identified and removed while preserving mechanical performance requirements.

Zhang and Xu [13] applied topology optimization techniques to titanium alloy components used in aerospace and automotive applications. Their findings indicated that

titanium alloys exhibit excellent potential for material removal due to their superior strength-to-weight characteristics. The optimized designs achieved substantial mass reduction without compromising structural safety or performance. These studies provide the theoretical and practical basis for implementing topology optimization in automotive chassis structures and support the material removal algorithms utilized in the present work.

3. PROPOSED SYSTEM

SolidWorks is a widely used Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software developed by Dassault Systèmes for creating, modeling, simulating, and analyzing three-dimensional engineering designs. It provides an integrated platform that enables engineers and designers to efficiently develop complex mechanical components and assemblies with high precision and accuracy. Known for its user-friendly interface and powerful modeling capabilities, SolidWorks supports various design activities, including part modeling, assembly design, sheet metal design, simulation, motion analysis, and product data management. The software is extensively utilized across industries such as automotive, aerospace, manufacturing, and product development to reduce design time, improve productivity, and enhance product quality. Its compatibility with advanced simulation and analysis tools allows engineers to evaluate structural performance and optimize designs before physical manufacturing, making it an essential tool for modern engineering design and development processes.

The proposed automotive chassis model was developed using SolidWorks as the primary CAD platform to serve as the structural foundation of the vehicle. The chassis features a lightweight frame configuration with strategically designed cross-members, mounting points, and reinforced sections to ensure adequate load-bearing capacity and structural rigidity. The geometry incorporates multiple cut-outs and optimized structural regions to reduce unnecessary material usage while maintaining strength and durability under

operational loads. The design provides suitable support for major vehicle subsystems such as the powertrain, suspension, and body structure, while also facilitating efficient load distribution throughout the frame. This chassis model serves as the baseline structure for subsequent finite element analysis (FEA) and topology optimization studies aimed at evaluating deformation, stress, strain, and weight reduction performance using different engineering materials.

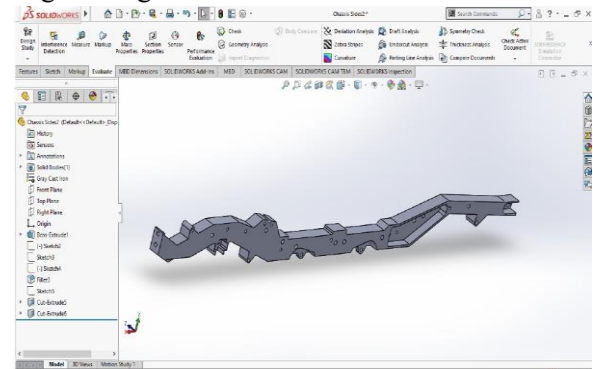


Fig 2. SolidWorks 3D Model of the Automotive Chassis Frame.

The chassis consists of interconnected longitudinal members, mounting brackets, and reinforced sections that contribute to load-bearing capacity and structural stability. Various cut-outs and attachment points are incorporated to accommodate vehicle components while minimizing unnecessary material usage. The design emphasizes an optimal balance between strength, stiffness, and weight reduction, making it suitable for lightweight vehicle applications. The detailed CAD model serves as the foundation for finite element analysis and topology optimization, enabling the evaluation of stress distribution, deformation behavior, and potential material removal regions for improved structural efficiency.

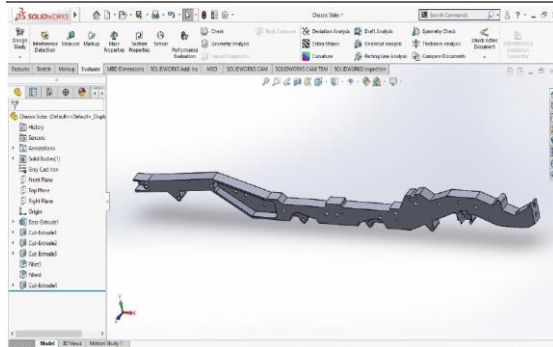


Fig 3. Opposite Side View of the Automotive Chassis Model

The SolidWorks interface is designed as a native Windows-based environment, allowing users to interact with it in a manner similar to other Windows applications. It provides a comprehensive menu system that offers access to all available commands, where arrow symbols indicate the presence of sub-menus and ellipses (...) signify additional dialog boxes containing further options or information. The software also includes customizable toolbars that provide quick access to frequently used commands, enhancing productivity and ease of use. On the left side of the graphics window, the Feature Manager Design Tree displays the complete chronological history of part, assembly, and drawing creation, enabling users to view, manage, and edit model features efficiently throughout the design process.

4. RESULT ANALYSIS

Fig 4 shows the automotive chassis model imported from SolidWorks into the ANSYS Mechanical environment for structural analysis. The imported geometry serves as the foundation for finite element simulations, enabling the evaluation of deformation, stress, and strain under applied loading conditions. The chassis model is assigned Structural Steel material properties, and the analysis setup includes meshing, boundary conditions, and external force applications to replicate real-world operating conditions. This integration between SolidWorks and ANSYS facilitates accurate structural assessment and provides a reliable platform for comparing material performance and performing topology optimization to achieve a lightweight and structurally efficient chassis design.

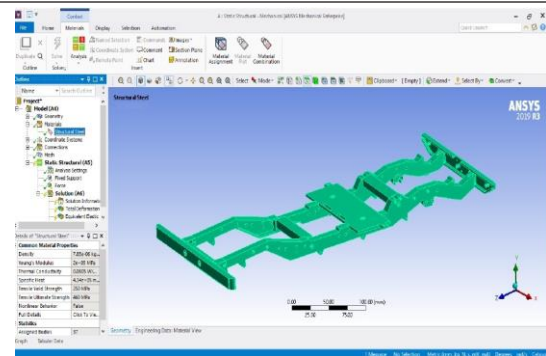


Fig 4. Import of Automotive Chassis Model into ANSYS for Structural Analysis

Fig 5 presents the thermal, electrical, and magnetic material properties of Structural Steel defined within the ANSYS Engineering Data module. These properties include isotropic thermal conductivity, specific heat capacity, electrical resistivity, and relative magnetic permeability, which are essential for accurately representing the material behavior during simulation. The assigned material parameters enable ANSYS to model the physical characteristics of the chassis material with greater precision, ensuring reliable structural and multiphysics analysis. Defining these properties is a crucial step in the preprocessing stage, as it establishes the material database required for evaluating the performance of the automotive chassis under various operating and loading conditions.

Thermal	
Isotropic Thermal Conductivity	0.0605 W/mm-°C
Specific Heat Constant Pressure	4.34e+05 ml/kg-°C
Electric	
Isotropic Resistivity	0.00017 ohm-mm
Magnetic	
Isotropic Relative Permeability	10000

Fig 5. Thermal, Electrical, and Magnetic Properties of Structural Steel in ANSYS

Fig 6 illustrates the total deformation distribution of the automotive chassis fabricated with Magnesium Alloy under the applied loading and boundary conditions in ANSYS. The contour plot indicates the variation of deformation across the chassis structure, with blue regions representing minimum deformation and red regions indicating maximum deformation. The maximum deformation observed is 5.5471×10^{-2} mm, occurring at the free end of the

chassis, while the fixed regions experience negligible displacement. Due to its low density and relatively lower stiffness compared to structural steel, Magnesium Alloy exhibits higher deformation under identical loading conditions. However, its lightweight characteristics make it an attractive material for automotive applications where weight reduction is a primary objective. The results demonstrate that although Magnesium Alloy significantly reduces vehicle mass, additional design optimization or reinforcement may be required in critical load-bearing regions to maintain adequate structural rigidity and performance.

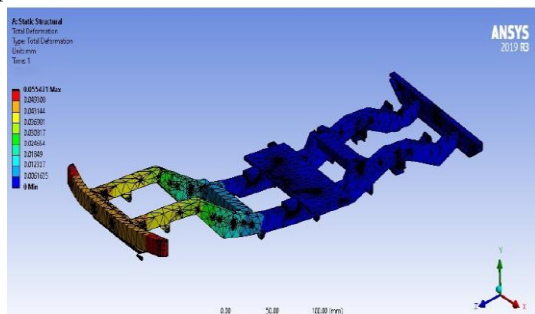


Fig 6. Total Deformation Analysis of Automotive Chassis Using Magnesium Alloy

Fig 7 presents the summary of static structural analysis results obtained for the automotive chassis using Magnesium Alloy in ANSYS. The analysis reports a maximum total deformation of 5.5471×10^{-2} mm, a maximum equivalent elastic strain of 1.8647×10^{-4} mm/mm, and a maximum equivalent stress of 8.3913 MPa under the applied loading conditions. The results indicate that the chassis experiences relatively higher deformation and strain due to the lower stiffness of Magnesium Alloy compared to conventional structural materials. However, the stress value remains within acceptable limits, demonstrating the material's capability to withstand the applied load. These findings highlight the lightweight advantages of Magnesium Alloy while emphasizing the need for careful structural optimization to ensure adequate rigidity and durability in automotive chassis applications.

Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	5.5471e-002	mm	1.
Equivalent Elastic Strain	0.	1.8647e-004	mm/mm	1.
Equivalent Stress	0.	8.3913	MPa	1.

Fig 7. Result Summary of Magnesium Alloy Chassis Analysis

Fig 8 presents the summary of static structural analysis results obtained for the automotive chassis using Titanium Alloy in ANSYS. The simulation results indicate a maximum total deformation of 2.5957×10^{-2} mm, a maximum equivalent elastic strain of 8.7004×10^{-5} mm/mm, and a maximum equivalent stress of 8.3524 MPa under the specified loading conditions. Compared to Magnesium Alloy, Titanium Alloy exhibits significantly lower deformation and strain, demonstrating its superior stiffness and structural stability while maintaining a relatively lightweight profile. The stress distribution remains within acceptable limits, indicating that the material can safely withstand the applied loads. These results highlight the effectiveness of Titanium Alloy in automotive chassis applications, where achieving a balance between weight reduction, strength, and durability is essential. Furthermore, its favorable mechanical performance makes it an ideal candidate for topology optimization, enabling substantial material removal while preserving structural integrity and safety requirements.

Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	2.5957e-002	mm	1.
Equivalent Elastic Strain	0.	8.7004e-005	mm/mm	1.
Equivalent Stress	0.	8.3524	MPa	1.

Fig 8. Result summary of Titanium Alloy Chassis Analysis



Fig 9. Topology Optimization Result Showing Elemental Density Distribution for Titanium Alloy Chassis

Fig 9 illustrates the topology optimization result of the Titanium Alloy automotive chassis based on elemental density distribution obtained in ANSYS. The optimization process identifies regions of the chassis that contribute significantly to structural performance and distinguishes them from low-stress areas where material can be removed. The density scale categorizes elements into removal regions (0.0–0.4), marginal regions (0.4–0.6), and retained regions (0.6–1.0). Elements with higher density values represent critical load-bearing sections that must be preserved to maintain structural integrity, whereas lower-density regions indicate non-essential material suitable for removal. The optimized design demonstrates that a considerable amount of material can be eliminated without adversely affecting the chassis strength and stiffness. This elemental density distribution provides valuable guidance for developing a lightweight chassis configuration, leading to improved strength-to-weight ratio, enhanced fuel efficiency, reduced material consumption, and better overall vehicle performance while satisfying structural safety requirements.

5. CONCLUSION

The research successfully investigates the structural performance and topology optimization of an automotive chassis using different engineering materials, namely Structural Steel, Magnesium Alloy, and Titanium Alloy. Finite Element Analysis was conducted to evaluate deformation, stress, and strain characteristics under identical loading

conditions. The results revealed significant variations in material behavior, demonstrating the importance of material selection in chassis design. Structural Steel exhibited the lowest deformation value of 1.2556×10^{-2} mm and the lowest strain value of 4.2934×10^{-5} , confirming its superior stiffness and ability to maintain structural integrity under applied loads. Although Magnesium Alloy offers substantial weight reduction advantages, it recorded the highest deformation and strain values, indicating reduced rigidity and the potential need for additional reinforcement in critical load-bearing regions. Titanium Alloy demonstrated a balanced combination of strength, stiffness, and lightweight characteristics, making it a highly suitable material for advanced automotive applications. Furthermore, topology optimization performed on the Titanium Alloy chassis produced an optimal material retention range of 0.4–0.6, indicating that approximately 40–60% of non-critical material can be removed without compromising structural safety or performance requirements. This optimized design approach significantly improves the strength-to-weight ratio while reducing overall chassis mass. The findings confirm that combining appropriate material selection with topology optimization techniques can lead to highly efficient and lightweight chassis structures. Overall, the study establishes a reliable framework for developing next-generation automotive chassis systems that achieve enhanced structural performance, reduced weight, improved fuel efficiency, and greater sustainability while maintaining the safety and durability standards required in modern vehicle engineering.

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