

Design-Space Exploration and Mechanical Response Optimization of Lightweight Ladder-Type Frames for Asymmetric Mobility Platforms

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To Cite this Article

N. V. S. Raju, Nunavath Chanti, Chiluka Shiva Prasad, Amara Raghava Vaishnav, Shaik Rashathali, "Design-Space Exploration and Mechanical Response Optimization of Lightweight Ladder-Type Frames for Asymmetric Mobility Platforms", *Journal of Science Engineering Technology and Management Science*, Vol. 03, Issue 06, June 2026, pp: 1234-1245, DOI: <http://doi.org/10.64771/jsetms.2026.v03.i06.pp1234-1245>

Submitted: 09-05-2026

Accepted: 18-06-2026

Published: 25-06-2026

Abstract

The structural framework of automotive vehicles has undergone significant evolution, transitioning from heavy, rigid steel constructions to optimized lightweight designs driven by advancements in computational engineering. In particular, three-wheeler vehicles, widely used for urban mobility, present unique challenges due to their asymmetric geometry and uneven load distribution. Historically, conventional chassis systems have relied on welded steel ladder frames, which, although robust, suffer from excessive weight, poor vibration characteristics, and inefficient stress distribution under dynamic loading conditions. These limitations often lead to increased fuel consumption, structural deformation, and reduced operational lifespan. The primary problem addressed in this study is the lack of an optimized chassis design that simultaneously ensures strength, stability, and reduced mass for three-wheeler configurations. Traditional design approaches are largely empirical and fail to adequately predict structural behaviour under real-world loading scenarios. Hence, there is a critical need for a simulation-driven methodology to enhance design reliability and performance. This work proposes an integrated computational framework combining Computer-Aided Design (CAD) and Finite Element Analysis (FEA) to develop and evaluate a ladder-type chassis structure. The model is created using SolidWorks and analysed in ANSYS under various loading and boundary conditions. Multiple materials, including Gray Cast Iron, Cast Iron, and Titanium Alloy, are investigated to determine optimal performance characteristics. The proposed system enables precise identification of stress concentration zones, deformation patterns, and vibration modes. The results demonstrate that material selection and structural optimization significantly improve the strength-to-weight ratio and dynamic stability. This study contributes to the development of safer, more efficient, and lightweight three-wheeler chassis designs, supporting advancements in sustainable and cost-effective urban transportation systems.

Keywords: Three-wheeler chassis, structural optimization, finite element analysis (FEA), computer-aided design (CAD), modal analysis, stress distribution, deformation analysis.

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1. Introduction

The chassis forms the fundamental structural backbone of any automobile, supporting all critical components such as the engine, transmission, suspension, and passenger body. Over the years, automotive chassis design has evolved significantly, shifting from heavy and rigid constructions to more efficient and lightweight configurations. This transformation has been largely driven by the need

to improve fuel efficiency, reduce emissions, and enhance vehicle performance. In the context of three-wheeler vehicles, which are widely used for urban transportation, chassis design becomes even more critical due to their unique geometric structure. Unlike four-wheeled vehicles, three-wheelers operate with asymmetric load distribution and a higher tendency for instability during cornering and braking. These conditions demand a chassis that is not only strong but also capable of maintaining stability under varying operational loads. Traditionally, auto rickshaw chassis have been fabricated using steel ladder-type frames due to their simplicity and strength. However, these conventional designs often suffer from drawbacks such as excessive weight, poor vibration control, and inefficient stress distribution. As a result, they may experience higher deformation, reduced durability, and increased fuel consumption over time. With advancements in computational tools, modern engineering approaches now allow designers to simulate and analyse structural behaviour before physical implementation, as shown in figure 1.

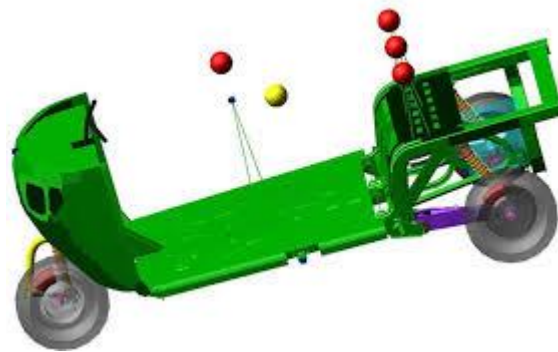


Figure. 1: Auto chassis frame.

This study focuses on utilizing Computer-Aided Design (CAD) and Finite Element Analysis (FEA) to develop and evaluate an optimized chassis model. By examining different materials and analysing stress, deformation, and vibration characteristics, the research aims to enhance the strength-to-weight ratio and overall performance of three-wheeler chassis systems.

2. Literature Survey

He, et al. [1] proposed a combined size and topology optimization strategy for vehicle frames using a Kriging surrogate model and analytic hierarchy process to improve lightweight structural performance. The frame of an automatic loading and unloading mixer truck was modeled and evaluated under multiple representative operating conditions using finite element analysis. Sensitivity analysis was applied to identify dominant geometric variables influencing mass, stress, and modal characteristics. A surrogate-assisted multi-objective optimization framework was then used to reduce structural mass while maintaining stiffness and allowable stress limits. Topology optimization was subsequently integrated to refine material distribution after dimensional refinement. The optimized configuration achieved a notable reduction in mass while preserving structural integrity under all tested load cases. The optimization route also improved convergence efficiency compared with conventional single-stage approaches. The formulation demonstrated that coupling parametric and topology optimization improved design efficiency for load-bearing ladder-type structures. The methodology provided a strong baseline for lightweight ladder-frame design under multi-condition loading.

Cascino, et al. [2] presented a manufacturability-oriented lightweight optimization framework for a railway motor support subjected to severe structural loading. The structural member was redesigned using topology optimization with adaptive stress constraints and manufacturing-aware geometric restrictions. Finite element analysis was used to identify critical stress regions and guide material redistribution within the allowable design domain. The optimization process preserved mechanical strength while minimizing structural mass and respecting production feasibility.

Additive-manufacturing and conventional fabrication constraints were incorporated to avoid impractical geometries. Stress-adaptive material removal improved stiffness retention in highly loaded regions. The final configuration demonstrated significant weight reduction with acceptable stress margins and deformation response. The formulation showed how manufacturability constraints could be integrated with topology optimization for practical lightweight structural systems. The approach was directly relevant to ladder-type mobility frames where stiffness, weight, and manufacturability had to be balanced. Tomasi, et al. [3] investigated the use of composite materials for lightweight heavy-vehicle chassis structures to improve stiffness-to-weight performance. Carbon-fiber-reinforced polymer concepts were introduced into conventional chassis architecture to reduce structural mass while maintaining load-bearing capability. Numerical simulations were conducted to compare composite and steel chassis responses under realistic heavy-duty operating conditions. Mechanical response metrics included stress distribution, deformation, and stiffness retention. Composite integration reduced overall frame weight while preserving acceptable structural performance. Load path continuity and section stiffness were found to be critical for achieving stable chassis behavior. Material substitution also improved structural efficiency in regions with high bending demand. The analysis demonstrated that lightweight material strategies could complement geometric optimization in chassis development. The formulation was useful for extending ladder-frame optimization toward hybrid lightweight mobility platforms.

Zhang, et al. [4] proposed an integrated free-size and size optimization strategy for lightweight composite floor structures in automotive applications. The formulation linked conceptual and detailed design stages through a continuous structural optimization route. Composite laminate behavior was modeled using layered mechanics and finite element simulation. Free-size optimization was first used to determine material distribution and load-efficient laminate regions. Thickness optimization was then applied to refine local layer configurations while maintaining stiffness and strength constraints. Mechanical performance before and after optimization was validated through simulation under representative structural loading. The optimized composite configuration achieved substantial mass reduction without violating failure criteria. The strategy demonstrated how multi-stage structural optimization improved both weight efficiency and manufacturability. The formulation provided useful guidance for lightweight mobility structures with distributed load-bearing requirements. Upadhyaya [5] developed a topology optimization route for a steel ladder-frame truck chassis to improve stiffness-to-weight performance under heavy-duty loading. A three-dimensional chassis model was created and evaluated using finite element analysis under realistic static and distributed loading conditions. Topology optimization was then applied to identify non-critical material zones and improve structural efficiency. The formulation focused on manufacturable structural redesign rather than purely numerical mass reduction. Load-bearing rails and cross-members were examined for stiffness preservation during material removal. The optimized chassis retained structural integrity while reducing unnecessary mass in low-sensitivity regions. Stress redistribution and deformation control were maintained within acceptable limits after redesign. The numerical route demonstrated the practical value of topology optimization in steel ladder-frame chassis development. The formulation was directly applicable to lightweight ladder-type mobility platforms with asymmetric loading demands.

Norouzi, et al. [6] proposed a topology and modular size optimization strategy for a small electric vehicle frame based on cross-section contribution analysis. The formulation evaluated sectional load contribution to identify inefficient structural regions within the frame architecture. Topology optimization was first used to determine optimal material distribution under static loading constraints. Modular size optimization was then introduced to refine local cross-sectional dimensions and improve structural efficiency. The combined strategy reduced mass while

preserving bending stiffness and torsional rigidity. Structural contribution mapping improved the interpretability of material redistribution decisions. The optimized electric vehicle frame achieved improved lightweight performance with acceptable deformation response. The formulation showed that modular sectional refinement improved practicality after topology-driven material removal. The strategy was highly relevant to compact asymmetric mobility frames requiring efficient load redistribution. Tyburec, et al. [7] presented a global weight optimization framework for frame structures under free-vibration eigenvalue constraints. The formulation minimized structural mass while preserving dynamic stiffness through eigenfrequency-based constraints. A semidefinite programming representation was introduced to address the nonconvex nature of frame topology optimization. The approach generated lower and upper bounds for globally optimal structural configurations. Dynamic stability was preserved by constraining vibration-sensitive structural modes during mass reduction. The optimization route improved the reliability of lightweight frame design under modal performance requirements. Numerical validation demonstrated convergence across representative structural configurations. The formulation established a rigorous basis for integrating dynamic constraints into lightweight frame optimization. The methodology was valuable for ladder-type mobility frames where vibration response and lightweighting had to be balanced simultaneously.

Agarwal and Mthembu [8] examined the structural optimization of heavy vehicle frames through finite element-guided lightweight redesign. Static load conditions representative of heavy-duty service was used to assess stress concentration, bending deformation, and structural compliance. Parametric and topology-based refinements were introduced to reduce structural mass while preserving load-carrying capability. Cross-member placement and side-rail stiffness were identified as dominant factors affecting frame response. Structural refinement improved weight efficiency without compromising primary load paths. The optimized configuration demonstrated improved stiffness-to-weight ratio and reduced localized stress peaks. The numerical results confirmed that frame optimization could significantly improve structural efficiency in heavy transport systems. The formulation supported the use of finite element-driven design-space exploration in ladder-frame development. The approach was relevant to asymmetric mobility platforms with uneven load distribution and torsional demand. Agbii and Okorochoa [9] investigated finite element and optimization-driven weight reduction strategies for heavy vehicle chassis systems. Structural load cases involving distributed payload and localized support conditions were used to evaluate frame behavior. Stress-sensitive zones were identified through finite element simulation and used to guide geometric refinement. Optimization was applied to improve mass efficiency while maintaining stiffness and structural safety. Cross-member and rail redesign reduced excess material in low-utilization regions. The refined chassis exhibited lower mass and improved stress uniformity across the frame span. Deformation remained within acceptable structural limits after material redistribution. The formulation demonstrated the effectiveness of integrated simulation and optimization in ladder-frame development. The numerical route was useful for lightweight chassis concepts subjected to asymmetric operational loading.

Bendsoe and Kikuchi [10] introduced a homogenization-based topology optimization framework for continuum structural design. Material distribution within a prescribed design space was optimized to maximize stiffness under defined loading and constraint conditions. The formulation established the theoretical basis for modern topology optimization in structural mechanics. Continuum material redistribution was represented using density-like design variables to enable numerical optimization. The method enabled systematic identification of efficient load paths in structural systems. Stiffness-driven material placement significantly improved structural efficiency compared with conventional intuitive design routes. The formulation became foundational for

lightweight mechanical and vehicle frame optimization. The approach established the theoretical basis for topology-guided ladder-frame redesign. The methodology remained essential for structural material distribution problems in mobility platform development. Bendsoe [11] introduced the Solid Isotropic Material with Penalization formulation to improve density-based topology optimization for structural design. The formulation represented material distribution using continuous density variables penalized to favor solid-void solutions. This strategy improved the physical interpretability and manufacturability of topology optimization outcomes. The numerical route enabled efficient finite element-based optimization for stiffness-driven lightweight design. Intermediate material densities were discouraged to generate structurally meaningful solutions. The formulation became one of the most widely used approaches in structural topology optimization. It significantly improved the practical applicability of topology optimization in engineering design. The strategy was especially useful for frame structures where efficient material placement governed stiffness and mass performance. The formulation remained central to ladder-type frame optimization under constrained structural loading.

Xie and Steven [12] proposed the evolutionary structural optimization method for stiffness-driven material removal in continuum structures. The formulation progressively eliminated inefficient material from low-stress regions while preserving the primary load path. Structural evolution was guided by finite element stress response and iterative sensitivity ranking. The method enabled intuitive and computationally efficient structural refinement. Material removal proceeded incrementally to maintain structural continuity during optimization. The approach produced lightweight designs with improved stiffness efficiency under defined loading conditions. The method became widely adopted in structural and mechanical optimization problems due to its simplicity and practical relevance. The formulation was highly suitable for ladder-type frame refinement where gradual structural simplification was preferred. The strategy provided a practical route for lightweight frame evolution under asymmetric mechanical loading. Sosnovik and Oseledets [13] proposed a neural-network-assisted topology optimization approach to accelerate structural material distribution analysis. A data-driven surrogate was used to approximate optimal material layouts and reduce iterative computational cost. The formulation significantly reduced optimization time compared with conventional iterative solvers. Structural layouts predicted by the neural model preserved the main load-bearing paths and stiffness trends. The surrogate-assisted strategy improved optimization efficiency for large structural systems. The approach was particularly useful for computationally intensive design-space exploration problems. The formulation demonstrated that data-driven acceleration could support rapid lightweight structural development. The strategy was highly relevant to iterative frame optimization where repeated finite element evaluations increased design cost. The approach provided an efficient computational direction for lightweight ladder-type mobility frame optimization.

3. Proposed Methodology

The proposed methodology presents a systematic computational framework for analyzing and optimizing the structural and vibration performance of a three-wheeler chassis using engineering simulation techniques. The analytical workflow begins with chassis design and geometric modeling, followed by material assignment and finite element discretization. The developed model is then subjected to static structural and modal analysis to evaluate deformation, stress distribution, and natural frequency behavior under realistic operating conditions.

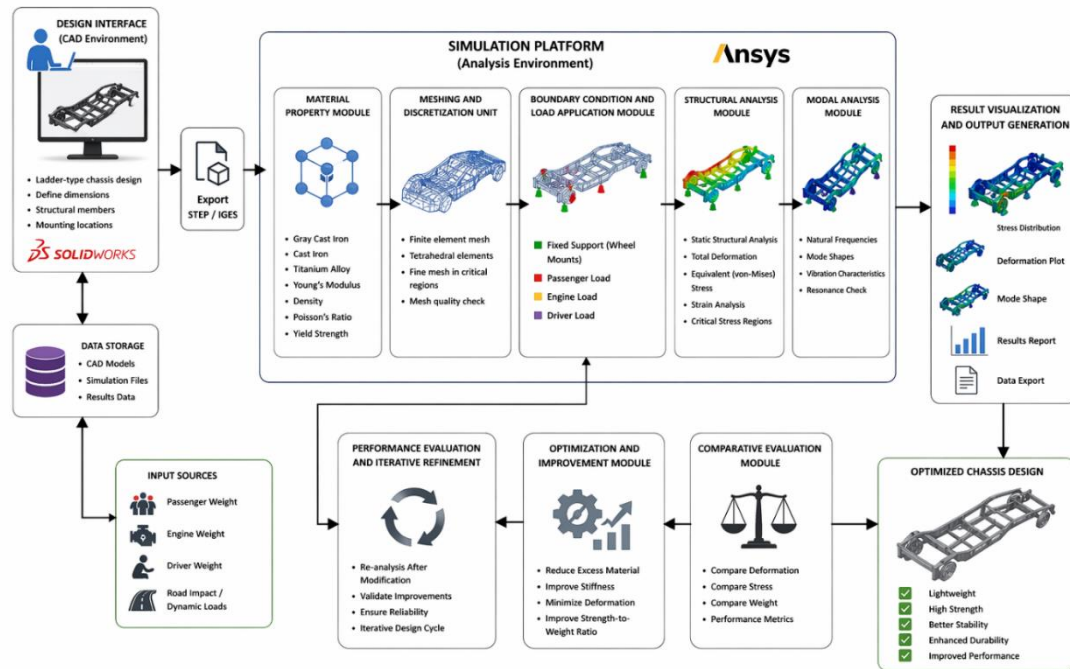


Figure. 2: System architecture.

Design Interface (CAD Environment)

- The design process begins with a graphical modelling environment used to create the chassis structure.
- A ladder-type chassis configuration is developed using parametric design tools.
- The interface allows defining dimensions, structural members, and mounting locations.
- The completed 3D model is exported in standard formats for simulation purposes.

Simulation Platform (Analysis Environment)

- The simulation environment acts as the central processing system for structural evaluation.
- It receives the CAD model and prepares it for analysis.
- The platform manages preprocessing, solving, and post-processing operations.
- It ensures accurate computation of mechanical responses under applied conditions.

Material Property Module

- Different materials are assigned to the chassis model for comparative analysis.
- Material properties such as Young's modulus, density, and Poisson's ratio are defined.
- The module enables evaluation of strength-to-weight performance.
- Each material is tested under identical conditions to ensure fair comparison.

Meshing and Discretization Unit

- The chassis model is divided into small finite elements for numerical analysis.
- Fine meshing is applied in regions prone to stress concentration.
- Tetrahedral elements are used to represent complex geometry.
- Mesh quality is verified to ensure accurate simulation results.

Boundary Condition and Load Application Module

- Real-world operating conditions are simulated by applying constraints and loads.
- Fixed supports are applied at wheel mounting locations.
- Loads representing passengers, engine, and driver are applied at respective points.
- These conditions replicate actual working scenarios of the chassis.

Structural Analysis Module

- Static structural analysis is performed to evaluate deformation and stress.
- The system calculates total deformation, equivalent stress, and strain values.
- Critical regions with high stress concentration are identified.
- The results help in assessing structural strength and safety.

Modal Analysis Module

- Modal analysis is carried out to determine natural frequencies and mode shapes.
- The system identifies vibration characteristics of the chassis.
- It helps detect potential resonance conditions.
- This improves vibration performance and structural reliability.

Result Visualization and Output Generation

- Simulation results are displayed through graphical plots and contour diagrams.
- Deformation, stress, and strain distributions are visualized clearly.
- The output enables easy identification of weak regions in the design.
- Comparative results for different materials are also presented.

Comparative Evaluation Module

- The performance of each material is compared based on key parameters.
- Metrics include deformation, stress, and overall weight.
- The best-performing material is selected based on optimized results.
- This ensures improved efficiency and durability of the chassis.

Optimization and Improvement Module

- Design improvements are made based on simulation outcomes.
- Excess material is reduced to minimize weight.
- Structural stiffness is enhanced to reduce deformation.
- The final optimized design achieves better strength-to-weight ratio.

Performance Evaluation and Iterative Refinement

- The system supports repeated analysis for improved accuracy.
- Design modifications can be re-evaluated through simulation.
- Continuous refinement enhances structural performance.
- This iterative process ensures reliable and optimized results.

4. Result and Discussion

The results obtained from the structural and modal analysis provide a comprehensive understanding of the mechanical behavior of the chassis under realistic operating conditions. The simulation outputs are analyzed to evaluate key parameters such as deformation, stress distribution, and vibration characteristics. By comparing the performance of different materials, it becomes possible to identify variations in strength, stiffness, and weight efficiency. The discussion focuses on interpreting these results to highlight critical stress regions and potential failure points within the structure. Special attention is given to how material selection influences overall chassis stability and durability. Furthermore, the findings are used to assess the effectiveness of the design in achieving an improved strength-to-weight ratio. This section ultimately connects the analytical outcomes with practical design improvements for enhanced performance.

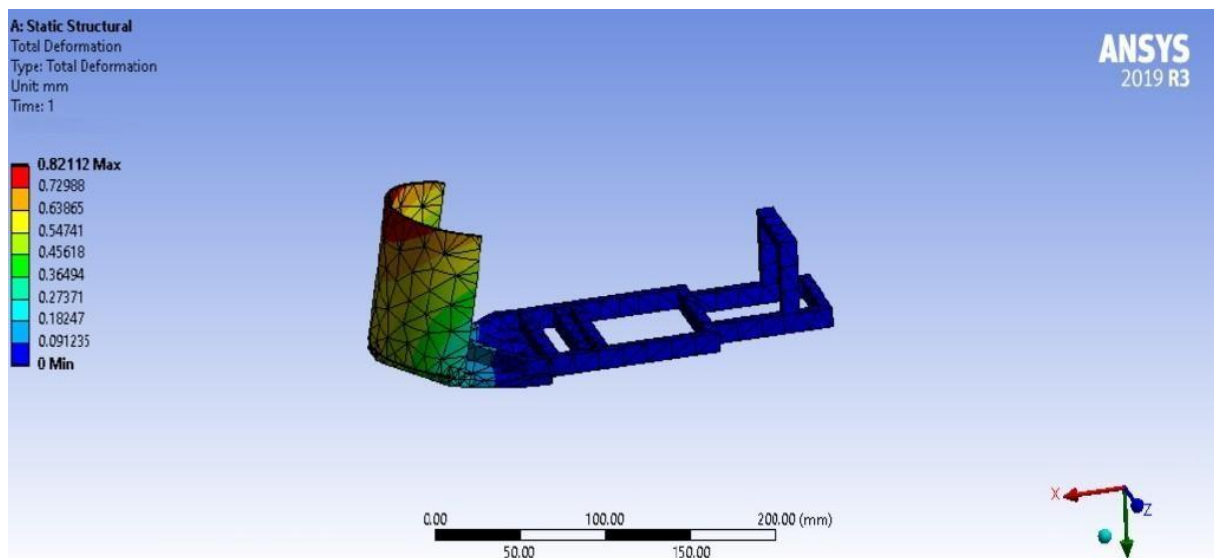


Figure. 3: Total deformation of chassis using gray cast iron

Figure 3 illustrates the total deformation behaviour of the chassis model fabricated with Gray Cast Iron under applied loading and boundary conditions. The contour distribution highlights the variation in displacement across the structure, indicating that maximum deformation occurs at the front curved section where load concentration and geometric discontinuity are prominent. The deformation gradually decreases along the longitudinal members, demonstrating improved stiffness in the central and rear regions of the chassis. The results reveal that the material exhibits moderate resistance to bending, but localized deformation suggests potential areas susceptible to structural weakening under continuous loading. The deformation pattern also reflects the influence of load transfer from the front mounting region to the supporting frame.

● Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	0.82112	mm	1.
Equivalent Elastic Strain	1.9366e-013	1.1612e-003	mm/mm	1.
Equivalent Stress	6.0264e-009	122.22	MPa	1.

Figure 4 illustrates the summarized results obtained from the structural analysis of the chassis model using Gray Cast Iron material. The tabulated data presents key performance parameters, including total deformation and equivalent elastic strain, along with their respective minimum and maximum values. The results indicate that the structure experiences a measurable level of deformation under applied loading conditions, while the corresponding strain values remain within a controlled range. The variation between minimum and maximum values highlights the non-uniform distribution of mechanical response across the chassis. These results provide a quantitative understanding of the structural behaviour and material performance under simulated conditions.

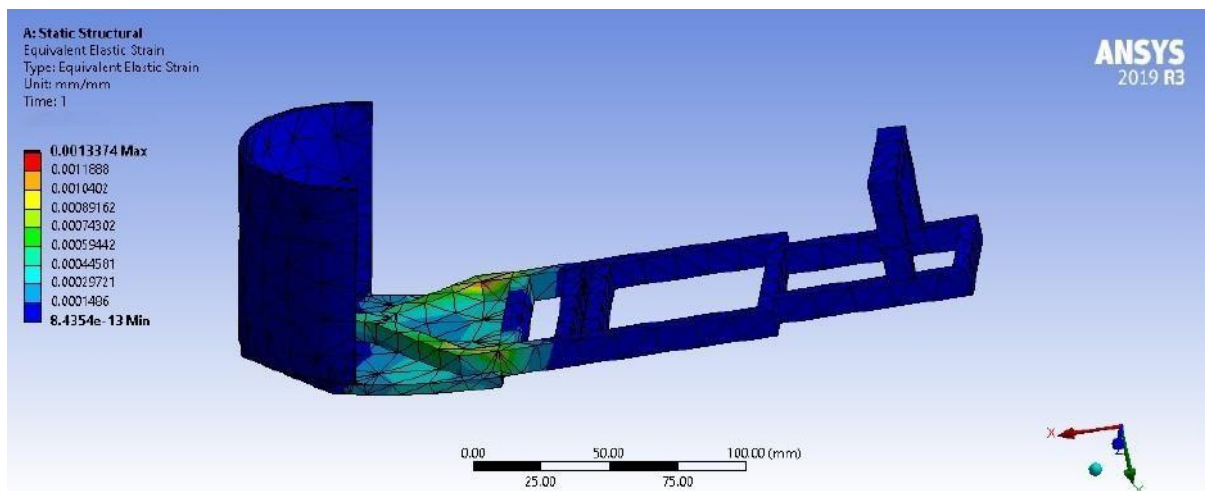


Figure. 5: Equivalent elastic strain distribution of chassis using titanium alloy

Figure 5 depicts the equivalent elastic strain distribution of the chassis structure fabricated with Titanium Alloy under applied loading conditions. The contour pattern indicates that the maximum strain is concentrated near the front curved region and joint interfaces, where load transfer and geometric transitions occur. The strain gradually reduces along the longitudinal members, reflecting effective load distribution and higher stiffness across the remaining structure. The overall strain levels are relatively low, demonstrating the superior mechanical properties and deformation resistance of Titanium Alloy. The distribution also highlights that critical regions are localized rather than widespread, indicating structural stability under operational loads. These results confirm that the material provides enhanced performance in terms of strain control, contributing to improved durability and reduced risk of failure in the chassis system.

Figure 6 illustrates the summarized simulation results of the chassis model using Titanium Alloy under applied loading conditions. The table presents key structural parameters, including total deformation, equivalent elastic strain, and equivalent stress, along with their respective minimum and maximum values. The results indicate that the deformation remains within an acceptable range, while the strain values are relatively low, reflecting the material's high stiffness and resistance to deformation. The equivalent stress values demonstrate that the structure can sustain the applied loads without exceeding critical limits. The variation between minimum and maximum values highlights the non-uniform distribution of mechanical response across different regions of the chassis.

● Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	0.94649	mm	1.
Equivalent Elastic Strain	8.4354e-013	1.3374e-003	mm/mm	1.
Equivalent Stress	2.2698e-008	123.1	MPa	1.

Figure. 6: Result summary of deformation, strain, and stress for titanium alloy

Figure 7 depicts the equivalent (Von-Mises) stress distribution of the chassis structure when Cast Iron is used as the material under applied loading conditions. The stress contours indicate that the maximum stress is concentrated near the front curved section and joint

regions, where load transfer and geometric discontinuities are prominent. The stress intensity gradually decreases along the longitudinal members, showing effective distribution of loads across the frame. The overall stress values remain within acceptable limits, suggesting that the material can sustain operational loads without immediate failure. However, the localized stress concentration highlights critical regions that may require reinforcement to prevent long-term fatigue issues. The distribution pattern reflects the material's capability to handle compressive loads while indicating areas sensitive to structural loading. These results provide valuable insight into the stress behavior and structural reliability of the chassis using Cast Iron.

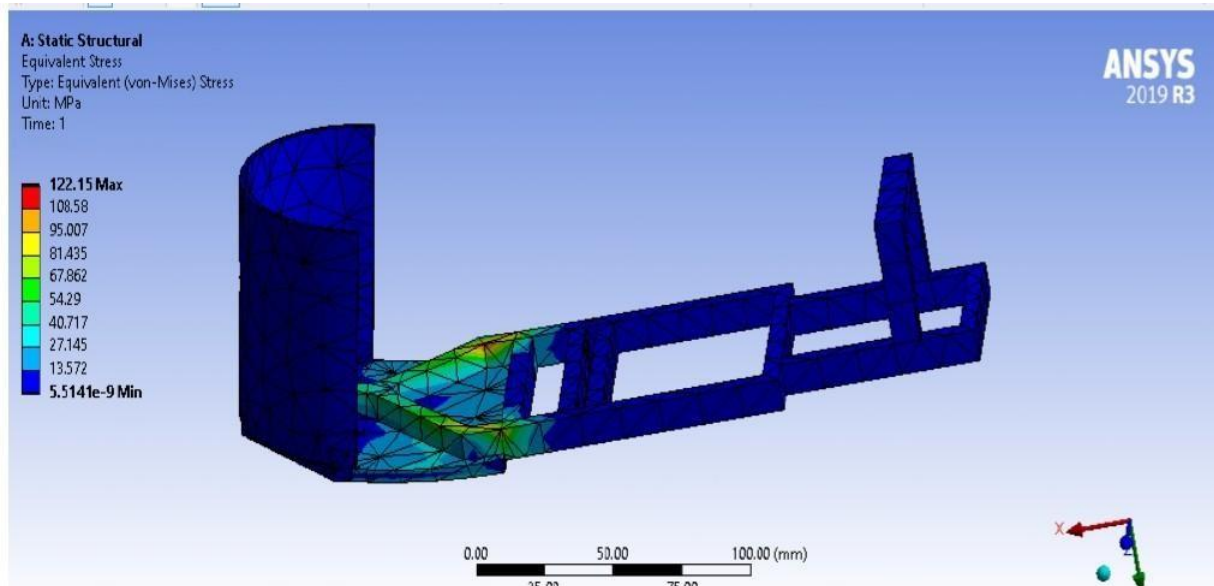


Figure. 7: Equivalent (Von-Mises) stress distribution of chassis using cast iron

● Result Summary

Results	Minimum	Maximum	Units	Time (s)
Total Deformation	0.	0.5279	mm	1.
Equivalent Elastic Strain	1.2793e-013	7.4663e-004	mm/mm	1.
Equivalent Stress	5.5141e-009	122.15	MPa	1.

Figure. 8: Result Summary of Deformation, Strain, and Stress for Cast Iron

Figure 8 illustrates the summarized results obtained from the structural analysis of the chassis model using Cast Iron material under applied loading conditions. The table presents key parameters such as total deformation, equivalent elastic strain, and equivalent stress, along with their corresponding minimum and maximum values. The results indicate that the deformation is comparatively moderate, while the strain values remain within a controlled range, reflecting stable structural behaviour. The equivalent stress values suggest that the material is capable of withstanding the applied loads without exceeding critical limits. The variation between minimum and maximum values highlights the distribution of mechanical response across different regions of the chassis.

Conclusion

The study successfully demonstrates the effectiveness of a simulation-driven approach for improving the structural performance of a three-wheeler chassis. By integrating CAD modeling with finite element analysis, the structural behavior under realistic loading conditions was accurately evaluated.

The results indicate that stress concentration primarily occurs at the front mounting and joint regions, while deformation is distributed along the longitudinal members. Comparative analysis of materials shows that Titanium Alloy offers superior performance in terms of strength-to-weight ratio, reduced deformation, and improved vibration resistance. Cast Iron and Gray Cast Iron provide adequate strength but contribute to higher overall weight and comparatively higher deformation. The optimized design reduces unnecessary material usage while maintaining structural integrity and stability. Modal analysis further confirms improved vibration characteristics, minimizing the risk of resonance. The study achieves significant performance improvements in terms of reduced weight, enhanced stiffness, better load distribution, and increased durability. These improvements contribute to safer, more efficient, and reliable chassis design for three-wheeler applications.

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