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Vehicle frame analysis and optimization using finite element analysis approach to improve rigidity and lightness

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Abstract

This study aims to analyze vehicle frame performance based on finite element analysis (FEA) simulations, evaluate stress distribution, deformation, and safety factors under static and dynamic load conditions, and optimize materials and geometry to reduce mass while maintaining rigidity and safety. The methods include a 3D frame model constructed in CAD software, import into FEA software, full-load bending, sudden braking, turning, and modal analysis simulations. Results show that alternative materials and geometric optimization can reduce mass by approximately 10-20% with stress increase tolerance and natural frequency reduction remaining within safe limits. Conclusion: Material optimization and geometric design are crucial for modern vehicle frames, especially electric vehicles or lightweight frames, to achieve a balance between strength, safety, and efficiency.

Keywords

Vehicle chassis, Stress, Finite element analysis, Displacement, Strain, Factor of safety

Introduction

The chassis is the main structure that supports all vehicle components, including the body, drive system, and driver. In addition to bearing static loads, the chassis also plays a role in transmitting dynamic forces that occur when the vehicle accelerates, brakes, or turns. Therefore, the chassis must be designed to be lightweight yet strong, so that it can withstand operational loads without structural failure and maintain vehicle energy efficiency. A lighter chassis weight can reduce the total mass of the vehicle, lower the engine workload, and improve energy efficiency, which is the main objective of the Energy-Efficient Car Contest (KMHE) [1]. In their previous design, the Pagaruyuang Team from Padang State University used AISI 304 stainless steel, which is known for its high tensile strength and excellent corrosion resistance [2]. However, AISI 304 has a high

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density of approximately 7.80–8.00 g/cm³, which is almost three times that of aluminum, resulting in a relatively heavy chassis weight [3]. This excess weight increases fuel consumption and reduces the vehicle's energy efficiency.

As an alternative, this study uses Aluminum Alloy 6061, which has a density of only 2.70 g/cm³, making it lighter than AISI 304 [3]. Despite its light weight, Aluminum 6061 still has adequate tensile strength, with an ultimate tensile strength of approximately 310 MPa under T6 conditions, as well as sufficient yield strength to withstand the operational loads of a vehicle [4]. The selection of Aluminum 6061 is also supported by its characteristics, which include a high strength-to-weight ratio, good corrosion resistance, and ease of fabrication [5]. However, the strength and rigidity of the chassis are not only determined by the type of material, but also by the shape of the profile used, such as hollow square pipes, hollow round pipes, or other shapes. The difference in profiles affects load distribution, stiffness against deformation, and resistance to dynamic forces [6]. To ensure a lightweight but strong chassis design, Finite Element Analysis (FEA) simulations are performed to determine important parameters such as stress, displacement, and strain. Stress analysis shows the distribution of forces on the chassis structure, deformation analysis describes changes in shape due to loads, while strain analysis shows how far the material can stretch before reaching its elastic limit [7]. In addition to material selection, the geometry of the structural profile also affects the stress distribution and stiffness of the frame [6]. Therefore, Finite Element Analysis (FEA) is widely used to evaluate structural behavior before the manufacturing process is carried out [7], [14].

And a Factor of Safety (FoS) analysis is needed to ensure the design's safety margin against material strength. The correct FoS ensures that the chassis can withstand normal and unexpected loads without adding excessive weight [8]. By comparing the simulation results of various profiles made of 6061 aluminum, an optimal chassis design can be obtained in terms of strength, rigidity, light weight, and safety. The novelty of this research lies in its integrated optimization approach, which combines material substitution and hollow profile variation with comprehensive numerical validation under identical loading conditions. This research contributes to the development of a numerically validated lightweight frame design model that can be used as a reference for the development of energy-efficient prototype vehicles [1].

Method

The design method is a research approach that combines the design and development processes to produce products in the form of systems, models, or devices that are ready to be tested and used. In the context of this research, the design method is used to design a lightweight, strong, and safe energy-efficient vehicle chassis using CAD (Computer-Aided Design) software and Finite Element Analysis (FEA)-based analysis shown in Figure 1. The design method is a research method that aims to produce a specific product and test its effectiveness through a series of structured stages, starting from problem identification, planning, design development, testing, to implementation [9]. In this study, the researchers carried out several stages, namely: 1. Problem identification, 2. Literature study and material selection, 3. Initial design using CAD, 4. Simulation using the finite element method, 5. Prototype creation and testing, and 6. Design evaluation and revision.

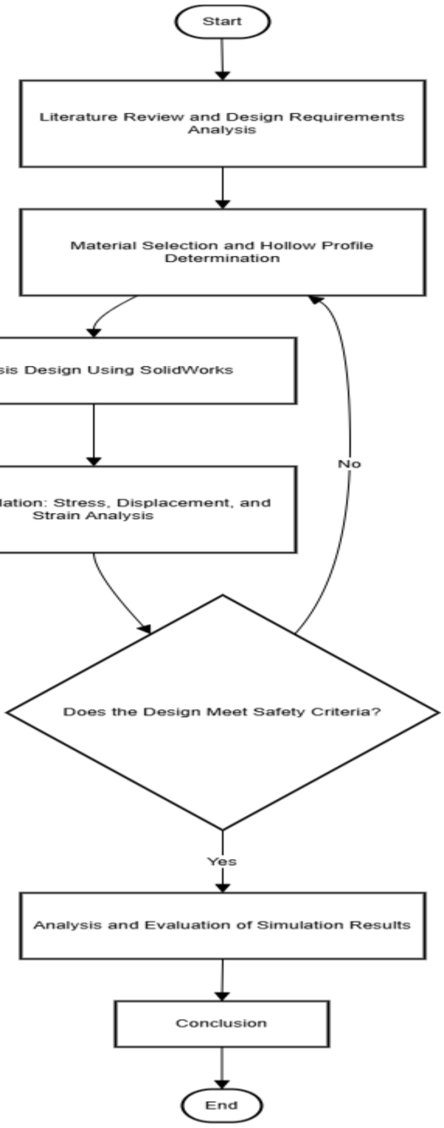

Figure 1. Research scheme

The problem identification stage is the initial stage of determining problems to ensure compliance with regulations and desired performance targets [10]. Literature studies and material selection aim to select materials that comply with regulations, where the selected materials are lightweight for the chassis to reduce the engine's workload [11]. Material selection plays an important role in vehicle frame optimization because it affects energy efficiency and safety [12]. Preliminary design using CAD plays an important role in the initial chassis design stage to minimize manufacturing errors and facilitate the evaluation process [13]. The simulation stage using the finite element method (FEA) can predict critical points in the vehicle frame before physical testing is carried out [14]. Physical manufacturing and testing are used to validate the FEA simulation predictions on the vehicle structure and as proof of concept as well as design evaluation material [12], [13]. Finally, the evaluation and revision of this design aims to compare the simulation and experiment. If there are significant differences, design revisions can be made [15]. The following is the chassis design that will be made is presents in Figure 2. Mechanical properties of materials used in simulation shows on Table 1.

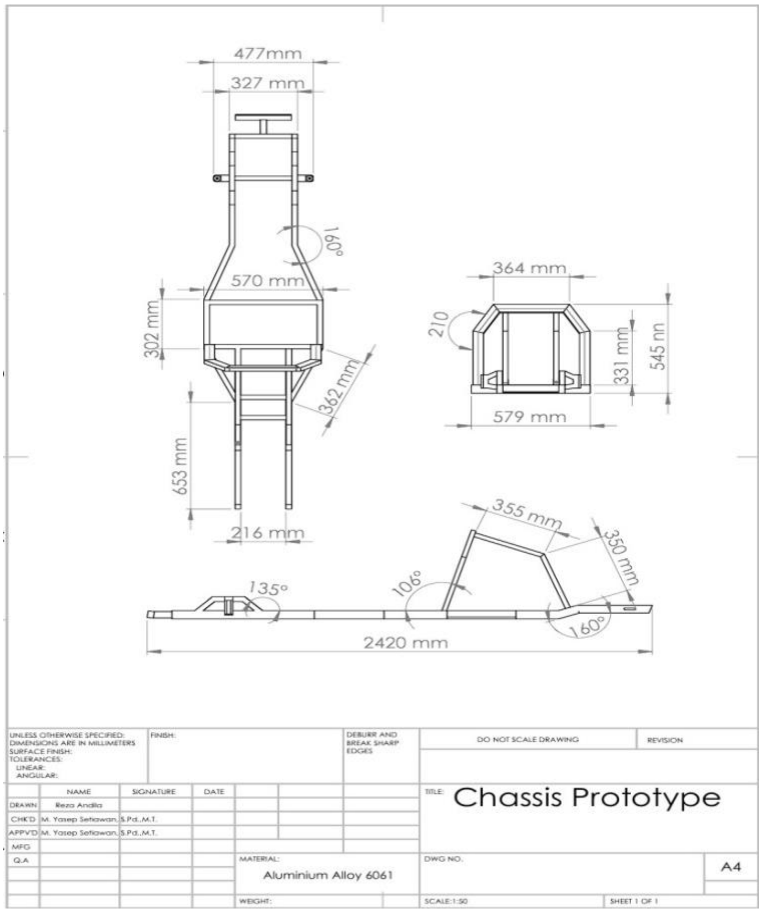

Figure 2. Technical drawing

Table 2. Mechanical properties of materials used in simulation

Property	AISI 304	Aluminum Alloy 6061
Density (kg/m³)	8000	2700
Young's Modulus (GPa)	193	69
Shear Modulus (GPa)	77	26
Poisson's Ratio	0.29	0.33
Yield Strength (MPa)	215	55.1
Ultimate Tensile Strength (MPa)	505	310

These material properties were input into the FEA software to ensure accurate stress and deformation prediction under identical loading conditions. The chassis model was discretized using tetrahedral solid elements. A medium-to-fine mesh configuration was applied to ensure convergence accuracy. The mesh parameters were:

1. Element type: Tetrahedral
2. Average element size: 5 mm
3. Total elements: ± 185,000

4. Total nodes: ± 320,000
5. Mesh quality: > 0.75

Mesh convergence testing was performed to ensure that further mesh refinement did not significantly change maximum stress results (variation < 5%).

Results

Stress

The simulation results show in Figure 3 that the maximum stress occurs at the joint area and suspension mounting points.

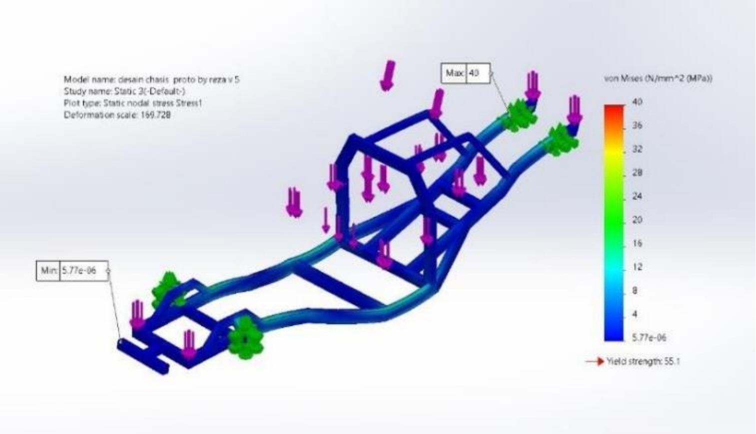

Figure 3. Von Mises Stress Contour on 6061 Aluminum Frame

The maximum stress value of 40 MPa is still below the yield strength of Aluminum 6061 (55.1 MPa), so the structure works in the elastic range. The relatively even stress distribution indicates that the hollow profile design is capable of effectively distributing the load and reducing excessive stress concentration. Critical locations need to be considered as potential areas for local reinforcement if the vehicle experiences dynamic loading greater than the static simulation conditions.

Strain

The maximum strain recorded was 0.475×10^{-3}, which is still within the elastic limit of the material. In the chassis design using 6061 aluminum alloy which design shown in Figure 4, the maximum stress obtained was 40 MPa, while the yield strength of the material was 55.1 MPa. Thus, the factor of safety (FOS) value is:

$$\mathbf{FOS} = \frac{\boldsymbol{Yield\ Strenght}}{\boldsymbol{Maximum\ Stress}} = \frac{\mathbf{55,1}}{\mathbf{40,0}} = \mathbf{1,37}$$

The Factor of Safety distribution shows a minimum value of 1.37 located in the structural joint area. A FoS value > 1 indicates that the design still meets structural safety criteria for static loading conditions. However, for real vehicle applications, additional analyses such as dynamic loading and fatigue testing are recommended to improve design reliability.

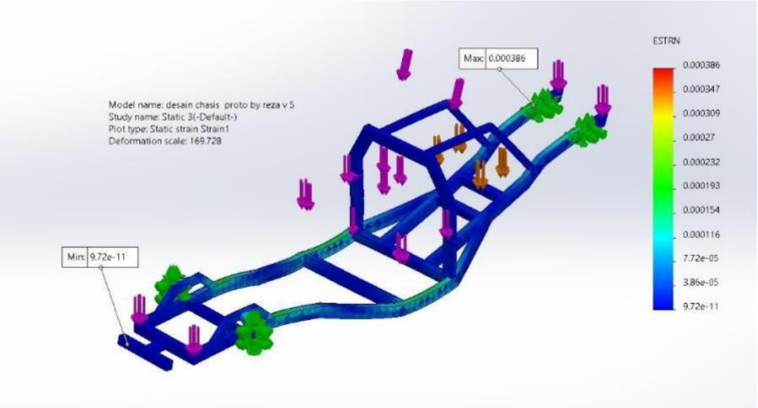

Figure 4. Strain distribution

Displacement chassis

The maximum displacement that occurred was 1.43 mm and was localized in the middle of the frame span. This value is still within the design tolerance limits for light vehicles. The low deformation indicates that the structure has adequate global stiffness despite a 50% reduction in mass compared to the previous design. The relationship between the elastic modulus and the geometry of the hollow profile plays an important role in maintaining the stiffness of the structure against vertical loading. Total frame contour displacement shown in Figure 5.

The selection of the final shape of the hollow profile in the prototype chassis design considers several important aspects, namely weight efficiency, stiffness against dynamic loads, ease of fabrication, and material availability in the market. Based on the results of simulations and technical analysis shown in Table 2, the hollow rail profile was selected as the most optimal design because it provides the best combination of structural strength and weight efficiency.

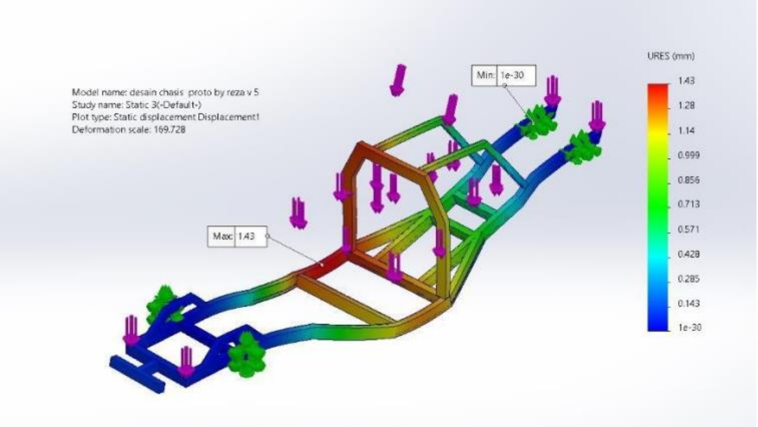

Figure 5. Total frame contour displacement

Table 3. Simulation results for 6061 aluminum hollow profile

Hollow Size (mm)	Maximum Stress (MPa)	Strain ($\times10^{-3}$)	Displacement (mm)	FOS	Description
Hollow rail profil	32.7	0.475	0.0197	>1.68	Selected
Hollow 39mm x 27 mm	34.3	0.315	0.0105	>1.60	Safe
Hollow 49 mm x 27 mm	34.2	0.328	0.0121	>1.61	Safe

Although it has a slightly higher deformation value than other profiles, the maximum stress produced is lower (32.7 MPa), with a strain value of 0.475×10^{-3} and a displacement of 0.0197 mm, and remains within the elastic limit of 6061 aluminum material, which has a yield strength of ±55.1 MPa. Additionally, the Safety Factor (SF) value exceeding 1.68 indicates that this design is safe and effective for use. With smaller dimensions, this profile is also lighter and more practical for manual fabrication, making it highly suitable for prototype vehicles prioritizing energy efficiency and a strong yet lightweight structure.

Discussion

The previous chassis design using AISI 304 exhibited a high safety factor due to its high yield strength; however, it resulted in excessive structural mass. In contrast, the optimized Aluminum 6061 design significantly reduced weight by 50% while maintaining structural integrity under identical loading conditions. The maximum stress of 40 MPa remains below the yield strength of 55.1 MPa, confirming elastic behavior. Although the safety factor decreased to 1.37, it remains within acceptable engineering standards for lightweight vehicle applications. The comparison of old and new chassis presents in Table 3.

Table 4. Comparison of old and new chassis

Aspect	Old	New
Material Realization	AISI 304 (ρ ≈ 8 g/cm³).	Aluminium Alloy 6061 (ρ ≈ 2,70 g/cm³).
Yield Strength	215 MPa.	55,1 MPa.
Simulation Load	700 N	700 N
Maximum Stress Result	139 Mpa	40 MPa
Total Chassis Weight	12 Kg	6 Kg
Maximum Stress	139 MPa	40 MPa
Displacement	15,388 mm	1,43 mm
FoS	5,38	1,37

The results confirm that material substitution combined with geometric optimization effectively improves stiffness-to-weight ratio, which is essential for energy-efficient vehicles.

Conclusion

Based on the entire series of designs, simulations, and analyses that have been carried out, it can be concluded that the prototype chassis design that has been developed has met the research objectives, namely to produce a strong, lightweight, and efficient frame for energy-efficient vehicles. The design process began with identifying requirements based on competition regulations, selecting component dimensions and positions, and conducting Finite Element Analysis (FEA) using SolidWorks. Aluminum Alloy 6061 was chosen as the main material because it has low density (2.70 g/cm³), adequate tensile strength, corrosion resistance, is easy to work with, and is available in the local market. A comparison with the previous chassis material, AISI 304, shows that the use of Aluminum 6061 reduces the chassis weight by up to 50% (from 12 kg to 6 kg), thereby significantly improving the vehicle's energy efficiency. Although AISI 304 has higher tensile strength, its much greater weight makes it less efficient for energy-efficient vehicle applications. With a better power-to-weight ratio, Aluminum 6061 provides more optimal acceleration and mileage performance in competition conditions.

Various shapes and sizes of hollow profiles were tested to determine the optimal design. Simulation results show that the hollow rail profile provides the best combination of strength and weight efficiency, with a maximum stress of 32.7 MPa, displacement of 0.0197 mm, strain of 0.000475, and a Safety Factor (FoS) > 1.68 in single element testing. Full chassis structure simulations showed a maximum stress of 40 MPa, displacement of 1.43 mm, and an overall FoS of 1.37, which is still safe within the material's elastic limit. Thus, the designed chassis is suitable for use in KMHE prototype vehicles and similar competitions, meeting the aspects of safety, stiffness, weight efficiency, and ease of production. The simulation-based approach has proven effective in predicting structural behavior, making it a reference for further development of lighter and stronger chassis designs in the future.

Acknowledgments

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