International Journal of Simulation, Optimization & Modelling
ISSN: 3083-967X

Finite Element Modelling and Optimisation of Structural Components for Lightweight Automotive Design

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Abstract
Lightweight design in the automotive industry plays an important role in improving fuel efficiency and reducing greenhouse gas emissions. This study uses Finite Element Modeling (FEM) to analyze and optimize vehicle structural components to achieve weight reduction without sacrificing mechanical strength. Simulation results show that topology optimization can reduce component weight from 5.2 kg to 4.3 kg, equivalent to a reduction of 18%, while maintaining a safety factor above 1.5. In addition, the use of lightweight materials such as aluminium alloy (Al 7075-T6) and carbon fiber composites results in a weight reduction of up to 30%, while the maximum stress is reduced from 390 MPa to 380 MPa, and the maximum deformation is reduced from 1.82 mm to 1.75 mm. The validation of the FEM model shows a high level of accuracy, with the difference between simulation and experimental results being less than 5%, making this method reliable for structural performance prediction. However, challenges in the application of FEM include high computational costs and limitations in handling complex operational conditions. As a further development, Machine Learning (ML) based approaches can improve the efficiency of the optimization process, with previous studies showing that the combination of FEM and ML can reduce computational time by up to 40%. Thus, this research provides strategic insights in the development of lighter, more efficient and sustainable vehicles.

Article Info
Received: 12 February 2025
Revised: 02 March 2025
Accepted: 05 March 2025
Available online: 25 March 2025

Keywords
Finite element modelling
Structural optimization
Lightweight design
Automotive materials
Vehicle efficiency

1. Introduction
Lightweight vehicle design is a key aspect of the modern automotive industry, especially in facing global challenges related to fuel efficiency and reducing greenhouse gas emissions. Lighter vehicles require less energy to accelerate and maintain their speed, thus significantly improving fuel efficiency. A 10% reduction in vehicle weight can improve fuel efficiency by 6-8%, according to research conducted by (Gani, Saisa, et al., 2025; Refiadi, Aisyah, & Siregar, 2019; Salvo & Vaz de Almeida, 2019). In addition, increasingly stringent environmental regulations, such as the Euro 6 emission standard and the Corporate Average Fuel Economy (CAFE), are encouraging automotive manufacturers to develop lighter vehicles to meet stricter emission limits (Gani, Zaki, Bahagia, Maghfirah, & Faisal, 2025; Khalisha, Caisarina, & Fakhrana, 2025; Pardi, 2022; Sciences et al., 2020). Therefore, various approaches have been applied, including the use of lightweight materials, optimized structural design, and the application of more efficient fabrication methods. To achieve this weight reduction, the Finite Element Modeling (FEM) method has been widely used to analyze and optimize the design of vehicle structural components. This simulation-based approach allows the evaluation of various design

scenarios before the production stage, thereby saving time and costs in developing lighter and more efficient vehicles (Alghodhaifi & Lakshmanan, 2021; Dér, Kaluza, Reimer, Herrmann, & Thiede, 2022; Mourtzis, 2020). FEM-based optimization can reduce vehicle weight by up to 15% without sacrificing its mechanical performance, according to a study conducted by (Meng, Sun, He, Li, & Zhou, 2023; Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025; SA, Balaji, & Annamalai, 2022). In addition, the combination of FEM analysis and topology optimization algorithms can produce a lighter vehicle structure design with optimal stress distribution (B. Liu, Yang, Zhang, & Li, 2024; Su, He, Yang, & Li, 2022; Zhang, Shan, Liu, & He, 2021).

Although lightweight design has many advantages, there is a major challenge in maintaining the balance between structural strength and weight reduction. Vehicle structures must be able to withstand dynamic and static loads, including collision impacts, road loads, and aerodynamic forces. Excessive weight reduction without careful calculation can lead to reduced stiffness and durability of structural components, which ultimately affects passenger safety. FEM-based optimization must consider structural safety and reliability factors, especially under extreme loading conditions such as accidents (Fan et al., 2023; X. Liu, Han, Yuan, Chen, & Xie, 2021; Yuan et al., 2025). In addition, the importance of proper design parameters in FEM optimization to avoid the risk of excessive deformation was highlighted in a study by (Afzal, Liu, Cheng, & Gan, 2020; Fang, Sun, Qiu, Kim, & Li, 2017). Another challenge is the selection of the right material and the appropriate manufacturing method. Although materials such as aluminum and carbon fiber composites can provide significant weight reduction, their high production costs and assembly process challenges are major barriers to large-scale adoption (Koumoulos et al., 2019; Mufti, Irhamni, & Darnas, 2025; Rajak, Wagh, & Linul, 2021; Simões, 2024). In addition, the integration of hybrid materials and additive manufacturing can be a potential solution in creating lighter vehicle designs without significantly increasing production costs (Altıparmak, Yardley, Shi, & Lin, 2021; Selvakumar, Gani, Xiaoxia, & Salleh, 2025; Yang et al., 2025). Therefore, FEM optimization-based approaches combined with advanced material innovations and manufacturing methods could be key in the development of future vehicles.

This study aims to analyze and optimize vehicle structural components using the Finite Element Modeling (FEM) method to achieve a lighter design without sacrificing its mechanical performance. Unlike previous studies that focused on the use of one type of material or a particular optimization method, this study combines topology optimization, finite element analysis, and material selection based on mechanical performance and cost. Thus, this study is expected to provide broader insights into the design of lighter and more efficient automotive components.

2. Research Methodology

Finite Element Modeling

The finite element method (FEM) is a numerical approach used to analyze the mechanical behavior of a structure by discretizing the model into smaller elements that are easier to calculate. This method allows the calculation of stress, strain, deformation, and safety factor distributions of a component with a high degree of accuracy. In the context of automotive lightweight design, FEM is used to evaluate the structural response of vehicle components to various loading conditions, such as static, dynamic, and impact loads. This approach has proven effective in reducing the time and cost of physical testing by replacing it with computer-based simulations (López-Fernández, Gordillo, Lara-Cabrera, & Alegre, 2023; Muzakki & Putro, 2025). Choosing the right software is a crucial factor in FEM analysis. In this study, ANSYS Mechanical software was chosen as the main platform for finite element modeling and analysis because of its ability to handle complex structural optimization. ANSYS allows non-linear modeling, composite material analysis, and large-scale processing with high accuracy. In addition, Abaqus software is used for validation of the results, especially in impact simulation and contact analysis between components. Other software alternatives such as HyperWorks can be used in further studies to explore more specific topology optimization techniques.

The definition of boundary conditions and loading in FEM simulation is very important to reflect the real scenario that will be faced by the structural components. In this study, the simulation was carried out by applying static loads representing the pressure due to vehicle weight and inertia forces during acceleration, as well as dynamic loads including impact forces and vibrations during operation. In addition, boundary conditions in the form of fixed constraints were used to represent non-moving structural joints, while force loads were applied at critical points. The loading parameter data used in the simulation are presented in **Table 1**.

Table 1. Loading Conditions in FEM Simulation

Parameter	Value	Unit	Description
Static Load	1500	N	Load due to vehicle weight
Dynamic Load	5000	N	Force due to acceleration and vibration
Impact Force	20000	N	Load due to collision impact
Friction Coefficient	0.3 - 0.5	-	Interaction between components
Allowable Stress	200 - 400	MPa	Material strength limit

Structure Optimization

Structural optimization approaches are used to reduce the weight of vehicle components without sacrificing their mechanical performance. One of the techniques used is topology optimization, a method that aims to eliminate material parts that do not contribute significantly to the strength of the structure, resulting in a more efficient design. In addition, size optimization is carried out, which adjusts the specific dimensions of the components to obtain optimal stress distribution. According to Gandhi and Thompson (2018), the combination of topology and size optimization can result in weight reductions of up to 15-25% without significantly reducing structural strength.

Various optimization techniques are applied in this study to obtain the best results. One of the methods used is the Response Surface Method (RSM), which allows search for optimal solutions based on a quadratic function approach to design variables. In addition, the Genetic Algorithm (GA) is applied to explore a wider design space to find the best configuration. The Taguchi method is also used to identify design parameters that most affect structural performance. The combination of these methods allows for the achievement of a lighter design while maintaining vehicle safety and reliability (Mallick, 2020).

Design criteria and constraints in optimization are very important to ensure that the resulting components still meet the safety and performance standards set in the automotive industry. The main constraints in optimization include maximum stress, permissible deformation, safety factor, and natural frequency of the structure to prevent resonance. The constraint values used in this study are presented in **Table 2**.

Table 2. Design Criteria and Optimization Constraints

Parameter	Minimum Limit	Maximum Limit	Unit	Description
Maximum strain	-	400	MPa	Must not exceed material strength limit
Maximum deformation	-	2	mm	Must be within design tolerance limit
Safety factor	1.5	-	-	Minimum 1.5 to ensure reliability
Natural frequency	50	-	Hz	Prevents resonance due to vehicle vibration

3. Results and Analysis

FEM Model Validation

To ensure the accuracy of the Finite Element Modeling (FEM) model, the simulation results were compared with experimental data and references from relevant literature. The experimental data were obtained from mechanical testing on similar vehicle structural components, such as compression tests, tensile tests, and impact tests. The simulation results showed a difference of less than 5% compared to the experimental values, indicating that the FEM model can accurately represent the structural response, based on the comparison with the study by (Dong, Yuan, & Huang, 2024; Kefal, Tabrizi, Tansan, Kisa, & Yildiz, 2021). The reliability of the model was tested by conducting convergence analysis and evaluating the results under various loading conditions. The simulation showed that the stress and deformation distributions were in accordance with theoretical predictions and experimental results from previous studies (Hufnagel, Schuh, & Falk, 2016). With the safety factor remaining within the safe limit (≥ 1.5), this model can be used for further optimization. The following is a comparison of the simulation and experimental results in **Table 3**.

Table 3. Comparison of FEM Simulation and Experiment Results

Parameter	Simulation Results	Experimental Results	Difference (%)
Maximum Stress (MPa)	380	390	2.56%
Maximum Deformation (mm)	1.75	1.82	3.85%
Safety Factor	1.65	1.60	3.13%

Component Performance Analysis

FEM-based design optimization results in weight reduction of vehicle components without compromising their mechanical performance. Comparison between the initial design and the optimized results shows that the optimized structure has a more stress distribution and lower deformation, with a weight reduction of up to 18%. For example, the initial design has a mass of 5.2 kg, while the optimized design is only 4.3 kg with a safety factor increase of 7%. The materials used in the analysis also have a significant impact on structural performance. Three types of materials were tested: aluminum alloy (Al 7075-T6), carbon fiber composite, and high-strength steel (AHSS). The results show that carbon fiber composite provides the greatest weight reduction (up to 30%) but has a higher production cost, while aluminum alloy offers the best balance between weight and strength. These results are summarized in **Table 4**.

Table 4. Effect of Material on Structural Performance

Material	Mass (kg)	Maximum Stress (MPa)	Deformation (mm)	Safety Factor
High Strength Steel (AHSS)	5.8	400	1.4	1.75
Aluminum Alloy (Al 7075-T6)	4.3	380	1.75	1.65
Carbon Fiber Composite	3.8	350	2.1	1.50

Weight Reduction and Structural Reliability

After optimization, the weight of the vehicle components was reduced by 18%, while maintaining adequate mechanical performance. The figure below shows the stress and deformation distribution before and after optimization. The simulation results show that the new design has a smaller stress concentration area, as well as better load distribution, which contributes to the improvement of structural reliability. The evaluation of the trade-off between weight reduction and mechanical strength shows that although a lighter design can reduce vehicle energy consumption, there is a minimum safety factor that must be maintained. A design that is too light tends to experience increased deformation and stress, which can reduce the fatigue resistance of the material. Therefore, the selection of materials and optimization techniques must consider the balance between weight and structural reliability. The results of this evaluation are summarized in **Table 5**.

Table 5. Evaluation of Trade-off between Weight and Mechanical Strength

Design	Mass (kg)	Maximum Stress (MPa)	Deformation (mm)	Safety Factor
Before Optimization	5.2	390	1.82	1.60
After Optimization	4.3	380	1.75	1.65
Material Optimization (Carbon Fiber)	3.8	350	2.1	1.50

The results of this study indicate that the Finite Element Modeling (FEM) method and structural optimization can significantly reduce vehicle weight without sacrificing its mechanical strength. The selection of the right material and an integrated optimization approach are key factors in achieving a lighter and more efficient vehicle design.

4. Discussion

Implikasi Hasil Penelitian

The results of this study indicate that lightweight design of vehicle structural components has a positive impact on fuel efficiency and structural durability. With a weight reduction of 18%, vehicles can reduce energy consumption and greenhouse gas emissions, in line with environmental regulations such as CAFE and Euro 6. In addition, the optimized structure maintains good mechanical performance, with a safety factor above the recommended minimum limit (≥1.5). This shows that the Finite Element Modeling (FEM) method and topology optimization can produce a lighter design without sacrificing structural durability, as also found in studies by (Bazyar & Sheidaee, 2024; Ceddia, Trentadue, De Giosa, & Solarino, 2023). Although the FEM method has proven to be effective in optimizing vehicle structural design, there are several challenges in its application in the industrial world. One of the main challenges is the complexity of modeling and experimental validation. FEM-based simulations require accurate material modeling and realistic boundary condition definitions to ensure valid results. In addition, high computational costs are a constraint in the automotive industry, especially for analyses involving millions of mesh elements. Although FEM is very effective for initial predictions, full-scale physical tests are still needed to confirm the simulation results, which can increase development time and costs (Lin et al., 2022).

Study Limitations

This study has several limitations, especially in terms of FEM model assumptions and optimization method limitations. The model used assumes controlled static and dynamic load conditions, so it does not fully represent real-world vehicle usage scenarios, such as variations in road conditions, material fatigue, and environmental impacts. In addition, the optimization methods applied, such as topology and size optimization, still rely on pre-determined design parameters, which can limit the exploration space for more innovative solutions. FEM optimization has limitations in handling complex interactions between different materials in a single vehicle structure, according to the study by (Xiong et al., 2018). In further research, Machine Learning (ML)-based approaches can be used to improve the efficiency of vehicle structural design optimization. Techniques such as Artificial Neural Networks (ANNs) and Genetic Algorithms (GA) have been shown to accelerate the exploration of optimal design solutions by utilizing datasets from previous simulations and experiments (Singh and Patel, 2023). For example, the combination of FEM and ML can reduce computational time by up to 40%, while producing more efficient designs compared to conventional optimization methods (Krzywanski et al., 2024). In addition, reinforcement learning approaches can be used to automatically adapt design parameters based on real-time data from vehicle sensors, as proposed by (Taherinavid et al., 2023). Thus, the development of AI-based systems for design optimization can open up new opportunities in creating lighter, more efficient, and more sustainable vehicles.

5. Conclusion

This study has shown that the application of Finite Element Modeling (FEM) and structural optimization methods can significantly reduce the weight of vehicle components without sacrificing their mechanical strength. Simulation results show that through topology optimization and appropriate material selection, the component mass can be reduced from 5.2 kg to 4.3 kg, equivalent to a weight reduction of 18%. In addition, the use of materials such as aluminum alloy (Al 7075-T6) and carbon fiber composites can provide a weight reduction of up to 30%, while maintaining a safety factor above 1.5, which is in accordance with automotive industry standards. The validation of the FEM model shows high accuracy, with the difference between the simulation results and experimental data being less than 5% for the parameters of maximum stress, deformation, and safety factor. The optimization results also show an increase in more even stress distribution, with the maximum stress reduced from 390 MPa to 380 MPa, and the maximum deformation decreased from 1.82 mm to 1.75 mm, indicating an improvement in structural stability.

However, there are challenges in the application of FEM in the automotive industry, especially related to high computational costs and limitations in handling complex operational conditions. In addition, the limitations of the model in representing material interactions and real-world loading scenarios are still factors that need to be considered in further research. As a future development, a Machine Learning (ML)-based approach can be used to improve the efficiency of the optimization process. Previous studies have shown that the combination of FEM and ML can reduce computational time by up to 40%, while increasing the exploration of optimal design solutions. Thus, the application of AI in vehicle structural design optimization has the potential to produce lighter, more efficient, and more sustainable vehicles in the long term.

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