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Evaluating the Potential Weight Reduction of Truck Frames via Beam Element-Based FEA Models

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Abstract

Reducing the weight of truck frames using advanced materials and innovative designs is a critical pathway for improving energy efficiency. However, weight reduction must not adversely affect the frame rigidity to prevent excessive deflections and distortions. Integrating finite element analysis (FEA) into the development of truck frames allows designers to quantify the potential weight savings through alternative material substitutions without compromising the frame rigidity. This study has developed beam element-based FEA models for a baseline truck frame to evaluate the potential weight reduction through replacing mild steel with aluminum alloy. The torsional and bending stiffness of the frame has been maintained by appropriately modifying the thickness of the frame members. It is concluded that the aluminum alloy frame achieves a 17.45% weight reduction compared to the baseline steel design. The influence of lightweighting on the frame's natural frequencies and internal stress distributions is also evaluated.

Keywords

FEA, Truck Frame, Structural Rigidity, Weight Reduction

1. Introduction

The foundational ladder-type frame in most trucks is engineered to withstand an array of static and dynamic loads. The two primary side members are designed for high bending stiffness to avoid excessive vertical deflection. Simultaneously, the interconnecting cross members are critical for enhancing torsional stiffness, which is essential to avoid excessive twisting, ensure precise handling, and improve driving stability. FEA plays an important role in all stages of frame design and drives the design path at a much faster pace by evaluating the behaviors of a frame under operating conditions and identifying potential failures early in the preliminary design stages [1].

An integrated structure-material-performance framework was proposed for truck frame optimization [2]. Finite element modeling and experimental validation were conducted to evaluate the frame's static performance and fatigue life. It was concluded that the optimized frame could achieve a 13.46% mass reduction without compromising stiffness or strength. The static and dynamic behavior of a vehicle frame was studied under four typical operating conditions [3]. To address identified engine resonance risks, the frame was optimized using high-strength steel and a reconfigured crossbeam layout. This design modification achieved a 4.6% weight reduction while maintaining static strength and preventing resonance. Shape and size optimization of side rails of a large hybrid truck chassis was performed for weight reduction [4]. The front and rear suspensions and relevant truck components were integrated in the chassis FEA models. Vibration mode analysis and stress analysis for multiple load cases were performed on the entire model to evaluate the constraints in the optimization problem. It was concluded that a mass reduction of about 13.25% with respect to the baseline model was achieved. Shell element FEA models were used for investigating the potential lightweight design of a truck chassis [5]. Topological optimization was used in this study under different loading cases. It was concluded that a 20.97% weight reduction was achieved without compromising structural strength. Three-dimensional FEA modeling was conducted for a truck frame composed of two longitudinal beams and eight cross beams [6]. Through structural optimization, the frame's weight was reduced by 8.4% and maximum stress was lowered from 207.3 MPa to 177.86 MPa. It was concluded that the lightweighting goal was achieved without compromising strength requirements. As part of a research project to advance technology for efficient Class 8 trucks, a lightweight chassis was designed and built for a demonstrator vehicle. The new chassis design, which featured 6013-T6 aluminum side rails with tailored height and thickness, reportedly reduced the vehicle's weight by 720 pounds [7].

Finite element analysis of truck frames utilizing 1D beam, 2D shell, and 3D solid elements is widely documented across different design stages. The advantage of solid element models lies in the capability to capture complex geometries of frame structures, leading to accurate simulation results. However, modeling 3D geometries requires a massive degree of freedom, resulting in an extremely heavy computation cost. Instead of spatial discretization using either hexahedral or tetrahedral elements, beam elements simulate slender members by representing cross-sectional properties mathematically, resulting in 1D FEA models with extreme computational efficiency. In this paper, the previous study on the baseline truck frame is first discussed to illustrate the feasibility of simulating the frame structure with beam element-based FEA models. Secondly, torsional and bending stiffness analysis is performed on the baseline steel and modified aluminum frames to assess the weight savings achieved through material substitution. Thirdly, the impact of lightweighting on the frame's natural frequencies and internal stress distributions is evaluated. Finally, conclusions are drawn.

2. Developing Beam Element Models of the Truck Frame

Figure 1 plots the CAD model of the truck frame used for lightweight design in this study. A realistic truck frame has many small parts, such as the mounting brackets and attached nuts, that are used for manufacturing and assembly. However, these parts have negligible influence on the frame's stiffness and have been cleaned up in the following FEA models to reduce computational cost.

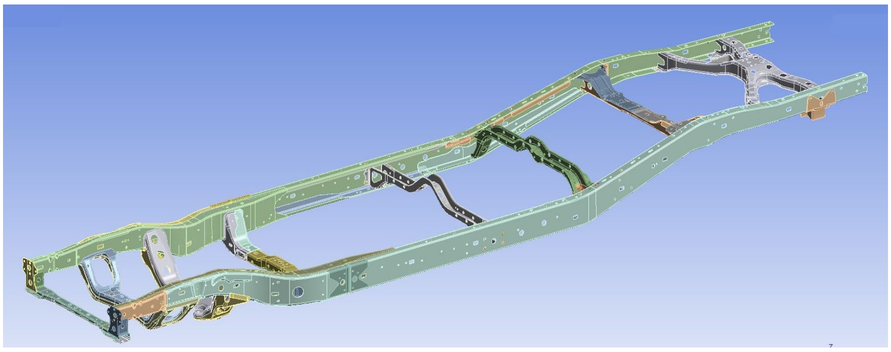
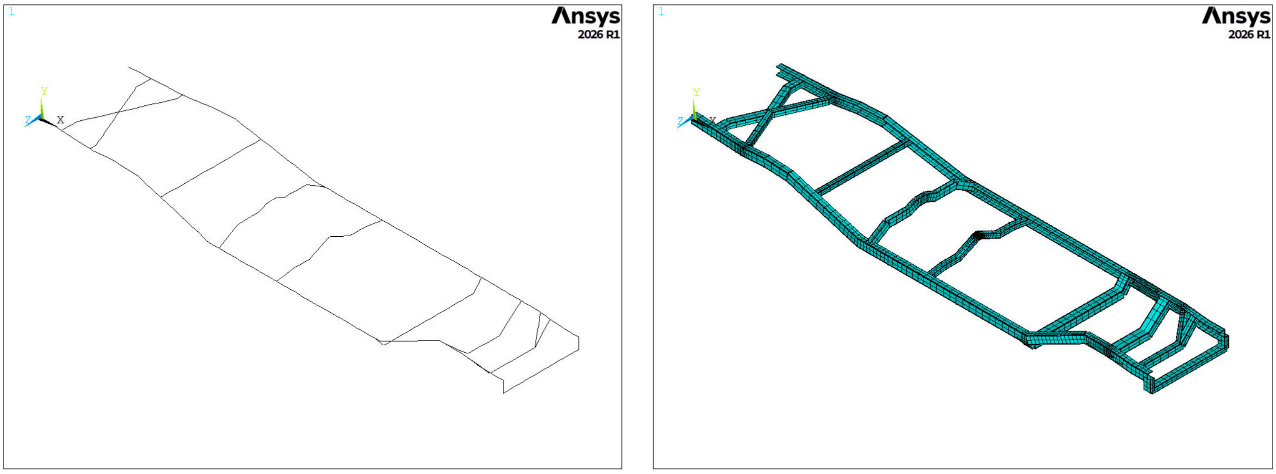


Figure 1. CAD model of the truck frame for lightweight design.

Beam elements are highly suitable for modeling structures composed of slender members, such as the frame structure in this study. Also, beam elements can transfer forces along the lateral direction, bending moments about the neutral axis, and torsional moments along the longitudinal direction, which is in line with the loading conditions of the truck frame in this study. In addition, compared to solid elements, which have at least four or eight nodes for each tetrahedral or hexahedral element, a beam element has two or three nodes, resulting in a significant reduction in model size and computation cost. The beam element models of the frame were developed in ANSYS APDL, as shown in **Figure 2**. BEAM188 elements were utilized to mesh the side rails and transverse cross members. These elements accommodated the different cross-sectional shapes, sizes, and orientations as derived from the CAD model. The developed model consisted of 447 beam elements and 822 nodes. Connections between structural members were idealized as rigid to represent the bolted, riveted, and welded joints standard in frame manufacturing. We validated the cross-sectional properties of each member, such as the area and moment of inertia, using the Beam Tool in Mechanical APDL before solving. Mechanical properties of steel are presented below: Young's modulus E = 200 GPa, Poisson's ratio $\nu = 0.29$, yielding stress $\sigma_y = 250$ MPa, and material density $\rho = 7850$ kg/m^3.



(a) (b)

Figure 2. Beam element model of the truck frame. (a) Excluding cross-sectional size and shape of beams; (b) Showing cross-sectional size and shape of beams.

To validate the feasibility of the developed beam element models for the truck's stiffness analysis and subsequent lightweight design, a solid element-based FEA model was built as the benchmark for the validation study [8]. All frame members were meshed automatically by either eight-node hexahedral elements or four-node tetrahedral elements in the benchmark model. Both the beam element model and solid element model were identically constrained at the four suspension mounting points. Two concentrated forces of equal magnitude were applied downward at the midpoints of the two side members. Frame stiffness was calculated as the ratio of the net applied force to the average deflection at the application points. Results from the beam element model demonstrated close agreement with the benchmark model, showing a discrepancy of less than 3.5%.

3. Quantifying Potential Weight Reduction of the Truck Frame

Subsequent lightweight design is conducted using the developed beam element models. First, the torsional stiffness of the baseline steel frame is evaluated. The frame is fully constrained at the rear suspension mounts, while two equal and opposite vertical forces are applied to the front suspension mounts to generate a twisting moment. The FEA model, including the boundary conditions and applied loads, is illustrated in **Figure 3**. The torsional stiffness is calculated by dividing the torsional moment by the resulting angular deformation of a reference line connecting the front mounting points. A vertical load of 1200 N is applied to each side rail in this study, yielding a torsional load of 1.03 kNm. Under the specified load, the baseline frame undergoes an angular deformation of 0.0261 rad., which corresponds to a torsional stiffness of 39.42 kNm/rad.

Secondly, using the FEA model illustrated in **Figure 3**, we investigated the potential for weight reduction through low-density material substitution. This study employs 6061-T6 aluminum alloy as the substitute material, and its mechanical properties are presented below: Young's modulus E = 68.9 GPa, Poisson's ratio $\nu = 0.33$, yielding stress σ_y = 276 MPa, and material density ρ = 2700 kg/m^3. To maintain structural integrity when replacing steel with aluminum alloys, member thickness is increased to compensate for the lower elastic modulus of the aluminum alloy. The cross-sectional centerlines of the frame members are preserved while the material is substituted from steel to aluminum alloy. The thickness of all beam segments is then scaled uniformly based on a defined modification factor. For instance, the baseline steel frame has a side rail thickness of 6.4 mm, applying a scaling factor of 1.5 would result in a new thickness of 9.6 mm. The torsional stiffness of the modified aluminum alloy frame is subsequently evaluated under various thickness scaling factors. The results indicate that by scaling the member thickness to 2.4 times that of the baseline steel frame, the aluminum frame achieves a torsional stiffness of 38.73 kNm/rad, closely matching the baseline frame performance.

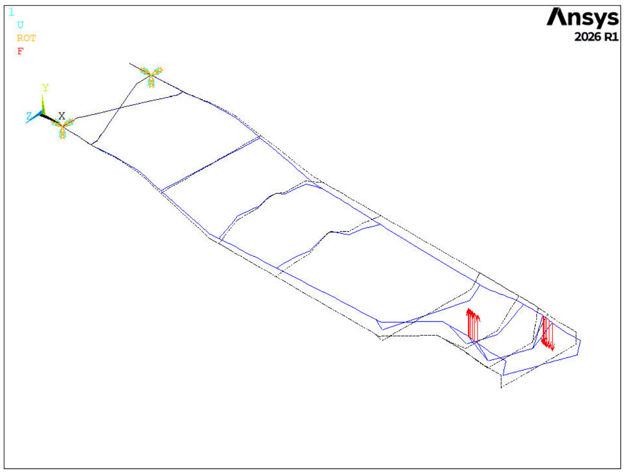


Figure 3. Torsional deformation of the baseline steel frame.

The total weight of the frame, whether the original steel or lightweight aluminum design, is determined by summing the weights of its longitudinal and transverse members, calculated as the product of each member's length, cross-sectional area, and material density. The baseline frame is made of steel with a material density of 7850 kg/m^3, while the lightweight frame is made of aluminum alloy with a material density of 2700 kg/m^3. Results from the baseline steel frame and the lightweight aluminum alloy frame are compared in **Table 1**. It is concluded that the lightweight design achieves a 17.45% weight reduction while maintaining near-equivalent structural performance, with torsional stiffness decreasing by a negligible 1.75%.

In addition to torsional stiffness, frame bending stiffness is critical for resisting vertical deflection under loads. A frame with higher bending stiffness undergoes less deflection under the same applied load, improving ride comfort and handling precision. Consequently, it is necessary to verify that the proposed torsional stiffness-based lightweight design does not compromise the frame's overall bending resistance. Figure 4 shows the bending loads and constraints for both the baseline steel frame and the lightweight aluminum alloy frame. Two distributed forces with the same magnitude of 1200 N are applied downward at the middle of the two side rails, while sufficient constraints are applied at the front and rear suspension locations. Bending stiffness is calculated by dividing the total applied forces by the average deflection along the vertical direction in the loaded regions. Under the specified load, the baseline frame undergoes an average deflection of 1.2267 mm, which corresponds to a bending stiffness of 1956.47 kN/m. Subject to identical loading conditions, the lightweight aluminum alloy frame experiences an average deflection of 1.2021 mm, yielding a bending stiffness of 1996.59 kN/m. This stiffness is 2.01% higher than the baseline steel frame, confirming that the material substitution does not compromise the structural bending resistance.

Table 1. Comparison of changes in the cross-sectional area and mass of each frame member (The cross members are numbered sequentially from the rear to the front).

		Side Rails		Cross Members								
		Left Rail	Right Rail	#1	#2	#3	#4	#5	#6	#7	#8	#9
Length (mm)	Baseline Frame	5222.8	5222.8	1136.5	1079.7	1144.4	1202.5	1204.7	1182.4	854.3	1242.4	1071.1
	Lightweight Frame	5222.8	5222.8	1136.5	1079.7	1144.4	1202.5	1204.7	1182.4	854.3	1242.4	1071.1
Cross-Sectional Area (mm^2)	Baseline Frame	1241.6	1241.6	676.5	792.3	1046.1	852.6	633.5	1906.1	1836.3	1128.4	931.2
	Lightweight Frame	2979.8	2979.8	1623.5	1901.5	2510.4	2046.3	1520.4	4574.7	4407.1	2708.2	2334.9
Mass (kg)	Baseline Frame	50.90	50.90	6.04	6.72	9.40	8.05	5.99	17.69	12.31	11.00	7.83
	Lightweight Frame	42.02	42.02	4.98	5.54	7.76	6.64	4.95	14.60	10.16	9.08	6.46

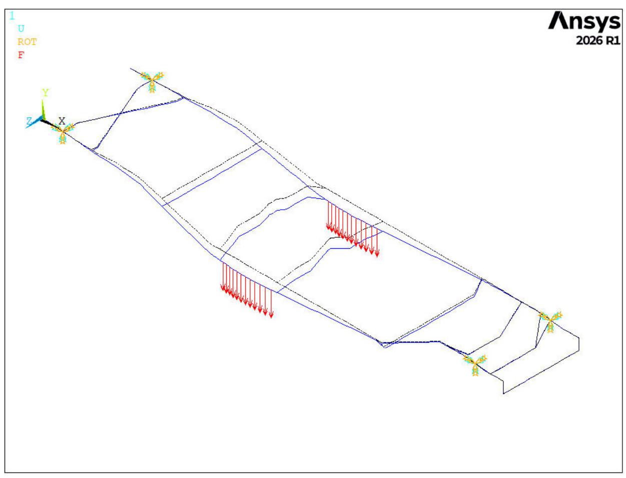


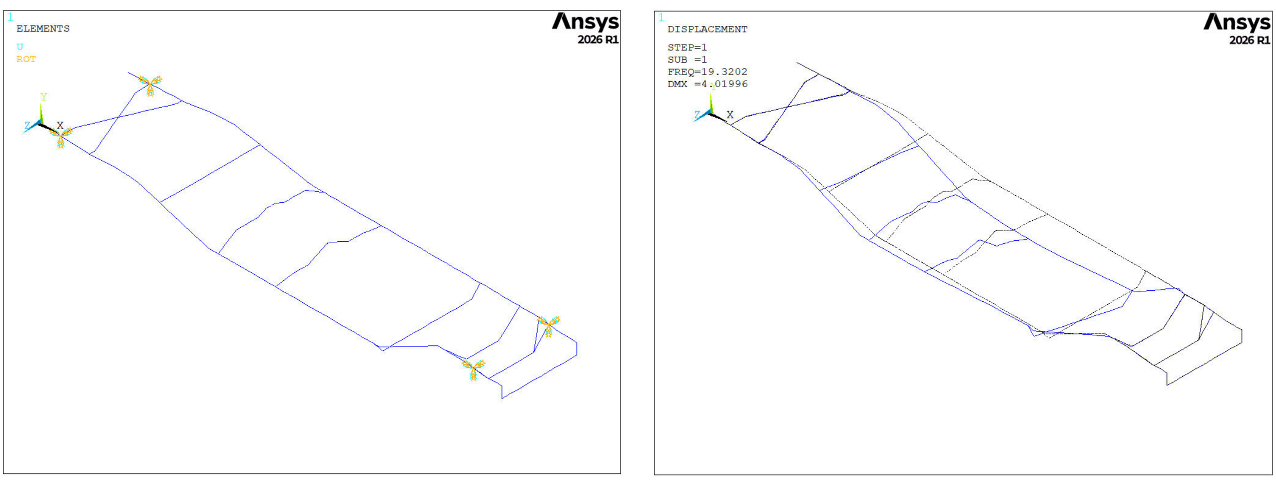
Figure 4. Bending deformation of the baseline steel frame.

Stress analysis identifies internal stress distributions and is critical in frame designs to prevent failures. Under the applied torsional and bending loads shown in **Figure 3** and **Figure 4**, the maximum von Mises stress is determined for both the baseline steel frame and lightweight aluminum alloy frame. As detailed in **Table 2**, the maximum von Mises stress in the lightweight aluminum frame is substantially below the material's yield strength, thus satisfying the maximum distortion energy criterion and preventing failure.

Table 2. Comparison of the maximum von Mises stress for the baseline frame and lightweight frame under torsional and bending loads.

	Maximum von Mises Stress, MPa	
	Torsional Load	Bending Load
Baseline Frame	86.12	23.21
Lightweight Frame	23.63	9.08

Modal analysis is conducted to evaluate the impact of lightweight design on the frame's natural frequencies. To ensure a direct comparison, both the baseline steel frame and the lightweight aluminum alloy frame are constrained with identical boundary conditions. As illustrated in **Figure 5(a)**, sufficient constraints are applied at the front and rear suspension mounting points. The continuous distributed mass of each structural member is determined by the product of its length, cross-sectional area, and respective material density. Modal analysis is performed to extract the first five mode shapes and natural frequencies, which are shown for the steel frame in **Figures 5(b)-(f)**. Subsequently, a similar modal analysis is performed on the aluminum alloy frame. The results indicate that the lightweight design increases these frequencies, thereby enhancing the frame's dynamic performance. A comparison of the first five natural frequencies for both the baseline and lightweight frames is presented in **Table 3**.



(a) (b)

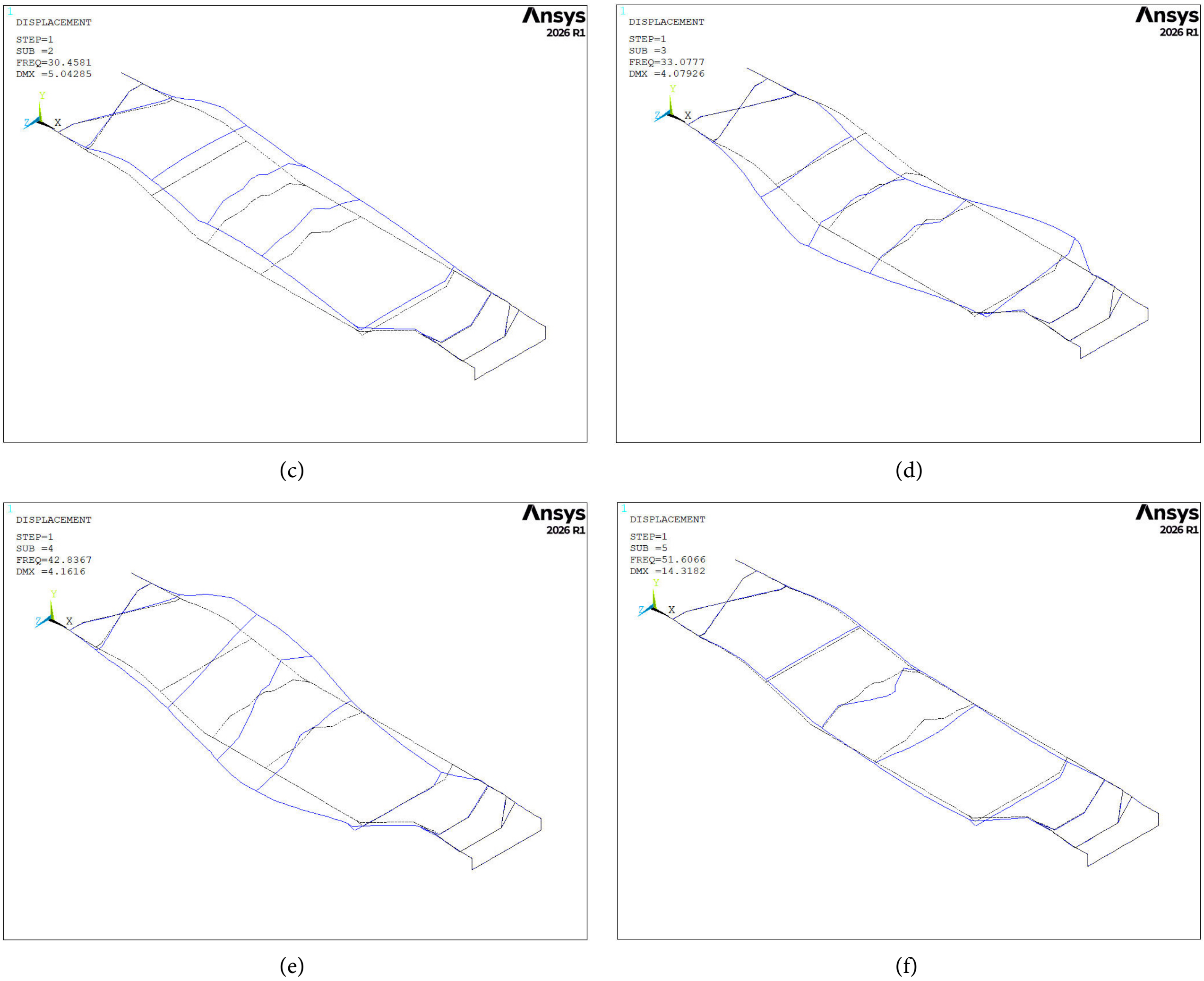


Figure 5. FEA model with applied boundary conditions for modal analysis and the first five mode shapes with their natural frequencies. (a) Boundary conditions for both frames; (b) First-order mode shape and corresponding natural frequency; (c) Second-order mode shape and corresponding natural frequency; (d) Third-order mode shape and corresponding natural frequency; (e) Fourth-order mode shape and corresponding natural frequency; (f) Fifth-order mode shape and corresponding natural frequency.

Table 3. Improvement of the frame's natural frequencies from lightweight design.

	Natural Frequencies, Hz				
	1St order	2nd order	3rd order	4th order	5th order
Baseline Frame	19.32	30.45	33.08	42.84	51.60
Lightweight Frame	24.72	32.53	39.05	52.08	60.41

4. Conclusion

In this study, 1D beam element-based FEA models are developed to facilitate the lightweight design of a truck frame. Validation results demonstrate that while the beam element models are exceptionally computationally efficient, they maintain high accuracy comparable to high-fidelity 3D solid element models. Lightweighting of the truck frame is achieved by substituting conventional steel with a low-density aluminum alloy. To compensate for the lower modulus of elasticity of aluminum alloy, the thickness of the frame members is systematically increased to satisfy equivalent stiffness constraints. The optimized lightweight design achieves a 17.45% reduction in frame weight, while maintaining structural performance with only a marginal 1.75% decrease in torsional stiffness and a 2.01% increase in bending stiffness. Additionally, this lightweight design improves truck frame performance by yielding higher natural frequencies and lower internal von Mises stress distributions.

Author Contributions

All authors contributed to all aspects of this manuscript, including literature review, CAD modeling, FEA analysis, manuscript draft and revision.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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