

Structural design and CAE simulation analysis of the strength performance of a light truck cargo box

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Abstract. Light trucks are the primary vehicles used for urban logistics, with the cargo box accounting for approximately 15%–30% of the vehicle's curb weight. This study investigates the structural optimization and Computer-Aided Engineering (CAE) simulation analysis of the cargo box for a light truck model. First, considering both the regulatory dimensional limits for blue-license light trucks and the operational requirements for logistics pallets, a cargo box with internal dimensions of 4,200 mm × 2,100 mm × 2,100 mm was selected as the research object. High-strength steel was adopted to replace conventional steel as the primary structural material, and an ultra-thin 0.6 mm panel design was employed, achieving an approximately 40% reduction in panel weight. Subsequently, a finite element model was established to evaluate the load-bearing performance of the cargo box under eight representative operating conditions, including static full-load, braking, cornering, and torsion. The maximum stresses of all critical components under each loading condition were found to be lower than the yield strength of the material.

Keywords: light truck cargo box, lightweight design, structural design, simulation analysis

1. Introduction

Light trucks are the dominant vehicles used in urban logistics. The cargo box accounts for approximately 15%–30% of the vehicle's curb weight. Previous studies have shown that a 10% reduction in vehicle weight can reduce fuel consumption by 6%–8% and correspondingly decrease pollutant emissions by 4%–10% [1]. With the continued implementation of national energy conservation and emission reduction strategies, together with increasingly stringent fuel economy regulations, lightweight vehicle design has become a major research focus in the transportation sector. In terms of lightweight materials and structural design, Wang et al. [2] applied basalt fiber composites to the body structure of a dump truck. Through mechanical performance testing and durability verification, they significantly reduced the cargo box weight while satisfying the required strength and stiffness, thereby supporting the concept of green and low-carbon development. Zheng [3] replaced conventional thick mild-steel plates with thin high-strength steel sheets and combined this approach with iterative finite element optimization, achieving a 48.7% reduction in cargo box weight while successfully validating the design under actual mining operating conditions. Regarding structural optimization methods and performance evaluation, Li et al. [4] optimized the thickness of body components through frontal crash testing, reducing the peak acceleration by 18% after optimization. Wang et al. [5] optimized the roof

crossbeam by adjusting its layout and cross-sectional geometry using a shape optimization method, reducing the roof weight by 37% while simultaneously improving its resistance to snow loads. Luan et al. [6] conducted comprehensive optimization of corrugated cargo box panels, achieving a structural weight reduction of more than 15% and increasing the first-order natural frequency by 25 Hz, thereby effectively enhancing the dynamic performance of the cargo box. Numanoy et al. [7] proposed a closed-loop validation framework that integrates non-destructive modal testing with finite element simulation to investigate the vibration characteristics of commercial truck cargo box frames. This method accurately identified the natural frequencies and mode shapes, thereby avoiding resonance during vehicle operation and significantly improving both fatigue life and ride comfort. Wei and Zhu [8], based on an existing cab platform, adopted a lightweight strategy emphasizing "material-driven lightweighting with comprehensive consideration of cost and weight." Through topology-guided optimization under multiple loading conditions, they integrated lightweight alloys and multi-material body structures, effectively balancing the three objectives of structural performance, manufacturing cost, and vehicle weight.

At present, the payload utilization coefficient of freight vehicles in China ranges from 1.3 to 1.5, whereas the corresponding value in Europe and the United States has reached approximately 1.6–1.8, indicating considerable room for further improvement in domestic vehicle lightweighting technologies [9]. From the user's perspective, reducing vehicle weight improves driving performance, lowers vibration and noise levels, and enhances driving safety. From the manufacturer's perspective, lightweight design reduces material consumption, lowers production costs, and strengthens market competitiveness. Among light trucks, van-type cargo boxes have become the mainstream configuration for urban logistics because of their advantages in safety and environmental protection. As the principal load-bearing component of a van truck, the cargo box accounts for approximately 15%–30% of the vehicle's curb weight [10]. Therefore, research on the structural design and optimization of light truck cargo boxes is of considerable significance for reducing vehicle energy consumption and enhancing product competitiveness.

2. Structural design of the light truck cargo box

2.1. Selection of internal dimensions for the cargo box

The selection of the internal dimensions of the cargo box must comprehensively consider regulatory requirements, industry standards, and practical operational needs. First, in accordance with the national regulations addressing the issue of "overloading with undersized registration" for light trucks, the maximum internal width of a cargo box for a blue-license light truck is limited to 2,100 mm. This regulation directly establishes the upper limit for the cargo box width. Second, the logistics industry widely adopts three standard pallet sizes: 1,000 mm × 1,200 mm, 1,100 mm × 1,100 mm, and 800 mm × 1,200 mm. Therefore, the cargo box should be capable of accommodating all three pallet specifications to facilitate efficient loading and unloading operations. Finally, a market survey showed that the internal length of mainstream light truck cargo boxes is generally concentrated within the range of 4,000–4,200 mm, while the internal height is typically around 2,100 mm. The internal dimensions of mainstream light truck cargo boxes are summarized in Table 1.

Based on the above regulatory requirements, industry standards, and market survey results, the internal dimensions of the cargo box selected in this study are 4,200 mm in length, 2,100 mm in width, and 2,100 mm in height. This dimensional configuration complies with the blue-license regulations, accommodates the mainstream pallet specifications, and remains competitive with current market offerings.

Table 1. Internal dimensions of mainstream light truck cargo boxes

Vehicle Model		Internal Length (mm)	Internal Width (mm)	Internal Height (mm)
Cargo box specification		4,200	2,100	2,100
JMC	Shunda Wide-body	4,080	2,100	2,100
	New Kaiyun	4,200	2,100	2,100
Foton	Aumark S1	4,140	2,100	2,100
	Speed	4,140	2,100	2,100
JAC	Junling V5	4,150	2,100	2,100
Dongfeng	Captain e-Star	4,100	2,100	2,100
Sinotruk	Hanjiang	4,150	2,100	2,100
FAW Jiefang	J6F	4,160	2,100	2,100
Qingling Isuzu	KV100	4,130	2,100	2,100
Jiangxi Isuzu	Yifang	4,200	2,100	2,100
Geely	H8E	4,140	2,080	2,100

2.2. Definition of lightweight design objectives for the cargo box

Lightweight design has become a major development trend in the commercial vehicle industry. Reducing the weight of the cargo box while maintaining adequate structural strength and stiffness not only decreases vehicle fuel consumption and exhaust emissions but also increases the vehicle's effective payload capacity. To establish the lightweight design objectives of this study, the weight of mainstream light truck cargo boxes currently available on the market was investigated and benchmarked. A competing manufacturer's lightweight cargo boxes were purchased and weighed experimentally. As shown in Table 2, the Jiangling steel-aluminum cargo box weighed approximately 611 kg, the Foton Suyun cargo box 671.5 kg, the Foton Aumark cargo box 691.7 kg, and the comparable cargo box manufactured by Keshite 624 kg. Based on the benchmarking analysis of these competing products, the lightweight design target of this study was established as a total cargo box weight not exceeding 600 kg.

Table 2. Measured weights of lightweight cargo boxes

Vehicle Model	Jiangling High-Strength Steel Cargo Box	Jiangling Steel-Aluminum Cargo Box	Foton Suyun	Foton Aumark	Keshite Cargo Box
Cargo box weight (kg) (Internal dimensions: 4,200 mm × 2,100 mm × 2,100 mm)	761	611	671.5	691.7	624

2.3. Selection of lightweight materials and joining methods

2.3.1. Material definition for the cargo box components

After selecting high-strength steel as the primary lightweight material, a differentiated material matching strategy was developed according to the loading characteristics and functional requirements of different cargo box components. Material selection for individual sheet-metal parts was based on the structural stress distribution. Under the premise of satisfying strength and stiffness requirements, an optimized material selection strategy was established to achieve the lightweight design objective.

First, the floor frame members, including the cross-members and longitudinal beams, primarily withstand bending and shear loads induced by the self-weight of the cargo box and the payload. Significant stress concentrations occur in the floor frame, particularly at the intersections of the longitudinal and cross-members. Therefore, both strength and stiffness must be maintained to prevent local buckling caused by excessive thickness reduction. In addition, by retaining the original cross-sectional dimensions of the floor longitudinal and cross-members, the existing roll-forming tooling can be reused, thereby reducing tooling investment and development costs. Accordingly, HC700LA (yield strength ≥ 700 MPa) is recommended for the floor longitudinal beams, while HC550LA (yield strength ≥ 550 MPa) is recommended for the floor cross-members and front side beams. Second, the side-frame pillars serve as the primary load-transferring members for both vertical and lateral loads. These components connect the roof to the floor frame and are mainly subjected to combined compression and bending, resulting in relatively moderate stress levels. Therefore, HC420LA (yield strength ≥ 420 MPa) is recommended for these structural members. Finally, the front panel, side panels, and rear door panels are mainly subjected to uniformly distributed wind pressure and lateral loads from the cargo. Stress concentrations generally occur near the frame pillars, hinge mounting locations, and locking mechanisms, whereas the remaining panel regions experience relatively low stress levels. Since the roof functions as a non-primary load-bearing component, it mainly carries its own weight and snow loads, which can be further distributed through appropriately designed stiffening ribs. To simplify raw material procurement and improve manufacturing efficiency, HC420LA (yield strength ≥ 420 MPa) is recommended as the standard material for these components.

The initial sheet thickness of each cargo box component can be estimated using the simplified relationship given in Equation (1) [2]:

$$t_0 \times \frac{\sigma_0}{\sigma_x} \leq t_x \leq t_0 \times \sqrt{\frac{\sigma_0}{\sigma_x}} \quad (1)$$

where: t_x = thickness of the high-strength steel; t_0 = thickness of the conventional steel; σ_0 = yield strength of the conventional steel; σ_x = yield strength of the high-strength steel.

Taking the side panel skin as an illustrative example, and applying formula (1), the substitution of HC700LA (700 MPa) for DC01 (180 MPa) enables the theoretical thickness to be reduced to half of its original value, with an appropriate safety margin being reserved. Accordingly, the side panel skin material is provisionally specified as HC700LA with a thickness of 0.6 mm. By the same reasoning, the material specifications for the main components of the cargo container are preliminarily established, as presented in Table 3.

Table 3. Material selection scheme for major cargo box components

Vehicle Model		Production Models		Material Selection Recommendations	
		Material Grade	Thickness (mm)	Material Grade	Thickness (mm)
1	Longitudinal Beam	Q235	3	HC700LA	2
2	Cross-member	Q235	2	HC550LA	1.5
3	Floor Assembly	Floor Panel	DC01	HC420LA	0.7
4	Front Side Beam	DC01	1.5	HC550LA	1.5
5	Rear Side Beam	DC01	1.5	HC420LA	1.8

Table 3. Continued

6	Front Panel Assembly	Front Panel Skin	DC01	1	HC700LA	0.6
7		Upper Front Beam	DC01	1.5	HC420LA	1.4
8		Pillar	DC01	2	HC420LA	1.4
9	Left/Right Side Panel Assembly	Left/Right Side Beam	DC01	2	HC420LA	1.4
10		Side Panel Skin	DC01	1	HC700LA	0.6
11		Upper Side Beam	DC01	1.5	HC420LA	1.2
12	Cargo Box Door	Door Panel	DC01	0.8	HC420LA	0.7
13	Roof Assembly	Roof Panel Skin	DC01	0.7	HC420LA	0.7

2.3.2. Selection of connection methods for the cargo container

The selection of connection methods has a significant impact on the structural integrity, manufacturing efficiency, and lightweight effect of the cargo container. The commonly used connection methods include welding, riveting, bolting, and adhesive bonding, each of which possesses distinct technical characteristics and applicable scopes.

Welding is the predominant connection method for steel cargo containers, offering advantages such as high connection strength, good sealing performance, and suitability for automated production. Resistance spot welding is applicable to the lap joint of thin sheets and serves as the primary joining process for panel assemblies such as side panels and roof panels. CO₂ gas-shielded welding is suitable for corner joints and butt joints of the frame structure, characterized by deep penetration and strong adaptability. Riveting is primarily employed for connections between dissimilar materials (e.g., steel-aluminum hybrid structures) and for locations where welding is not feasible. The advantages of riveted connections lie in the absence of heat input during the process, which avoids microstructural changes and thermal deformation of the materials; however, the disadvantages include lower connection strength compared to welding and the requirement for pre-drilled holes. Bolted connections are mainly used for the assembly connection between the cargo container and the chassis frame, as well as for components requiring detachable maintenance, such as door locks, hinges, and other accessories. Bolted connections offer the advantages of convenient disassembly and reusability, but they increase the number of components and the overall mass. Adhesive bonding achieves connection through structural adhesives, featuring uniform stress distribution, good sealing performance, and no thermal effects. Nevertheless, it demands high surface preparation, requires prolonged curing time, and its aging resistance needs to be verified. To ensure compatibility with the existing production line of the carriage manufacturer, it is recommended to maintain the current connection methods adopted by the manufacturer: resistance spot welding combined with CO₂ gas-shielded welding for the main structure, and bolted connections for the few locations that require maintenance and disassembly.

2.4. Design of key structural parameters of the cargo box

2.4.1. Optimization of the floor frame layout and cross-sectional parameters of the longitudinal and cross-members

The floor frame is the core load-bearing structure of the cargo box, responsible for transferring cargo loads to the vehicle chassis. It consists of longitudinal and cross-members arranged orthogonally at specified intervals to form a grid-like supporting structure. The longitudinal beams, positioned along the longitudinal direction of the cargo box, serve as the primary load-bearing members. To maximize the reuse of the existing manufacturing platform and roll-forming tooling, longitudinal beams with a 100 mm × 60 mm × 2 mm hat-

shaped section fabricated from HC700LA steel were adopted. Two longitudinal beams are evenly distributed across the width of the cargo box, and both ends are bolted to the front panel and the rear door frame pillars.

The cross-members are arranged transversely, perpendicular to the longitudinal beams, and primarily resist bending loads generated by the cargo while maintaining the in-plane stiffness of the floor. Based on the existing production platform, Ω -shaped sections measuring $51 \text{ mm} \times 48 \text{ mm} \times 1.5 \text{ mm}$, manufactured from HC550LA steel, were selected. The cross-members are spaced at approximately 400 mm intervals along the longitudinal direction, as illustrated in Figure 1. The intersections between the longitudinal and cross-members are connected by bolted joints to ensure the integrity and dimensional stability of the grid structure.

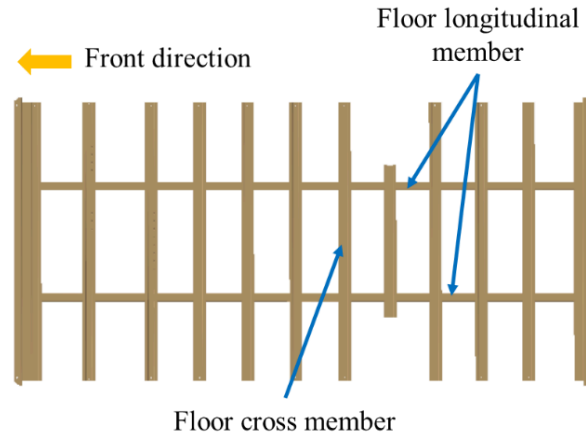


Figure 1. Floor frame structure

Table 4. Cross-Sectional parameters of floor frames used by benchmark vehicles

Vehicle Model	Longitudinal Beam		Cross-Member		Quantity
	Cross-section (mm)	Illustration	Cross-section (mm)	Illustration	
Recommended design	Hat-shaped $100 \times 60 \times 2$		Ω -shaped $51 \times 48 \times 1.5$		12
Jiangling High-Strength Steel	Hat-shaped $100 \times 60 \times 2.5$		Ω -shaped $51 \times 48 \times 1.5$		12
Jiangling Steel-Aluminum	Hat-shaped $100 \times 60 \times 4.3$		Ω -shaped $51 \times 48 \times 1.5$		10
Foton Suyun	Hat-shaped $80 \times 50 \times 2.5$		C-shaped $70 \times 40 \times 1.5$		11
JAC Junling	C-shaped $100 \times 50 \times 2.5$		C-shaped $95 \times 43 \times 2.5$		11
Foton Aoling TS	C-shaped $100 \times 45 \times 5.3$		C-shaped $60 \times 30 \times 2.5$		11
Foton Aumark	C-shaped $100 \times 50 \times 3.0$		C-shaped $60 \times 40 \times 2.0$		12
Keshite Cargo Box	C-shaped $100 \times 60 \times 2.0$		C-shaped $60 \times 30 \times 1.5$		14

A benchmarking analysis of the floor frame structures used in major competing products indicates that the proposed design adopts a comparable number of longitudinal beams and similar cross-member spacing to mainstream products, while achieving additional weight reduction through optimized cross-sectional dimensions. The comparison results are presented in Table 4.

2.4.2. Optimization of the layout and cross-sectional parameters of the side frame pillars

The side frame pillars are the key structural members connecting the side panels, front panel, and floor assembly, playing an essential role in resisting lateral cargo impacts and maintaining the overall stiffness of the cargo box. The pillars are arranged vertically along the height of the cargo box, with their lower ends welded to the floor frame and their upper ends connected to the roof frame, as shown in Figure 2.

The cross-sectional design of the side frame pillars must satisfy two principal requirements. First, sufficient overall structural stiffness must be provided to prevent excessive outward bulging of the side panels under lateral cargo loads. Second, the pillars must provide an adequate flat surface for mounting side and rear retro-reflective markings. According to GB 7258-2017 *Safety Specifications for Power-Driven Vehicles Operating on Roads*, trucks and trailers must be equipped with side retro-reflective markings having a minimum attachment width of 50 mm. Therefore, the external flat surface of the frame pillar is recommended to be at least 53 mm wide to satisfy this regulatory requirement. A C-shaped section was selected for the side frame pillars to reduce material consumption while remaining compatible with optional rectangular closed sections required for heavy-duty applications. The upper frame adopts a rectangular closed section, which provides nearly identical bending stiffness in both principal directions and effectively resists deformation transmitted from the floor, front panel, and side panels, thereby improving the rigidity of the roof frame. The lower frame adopts a C-shaped section to facilitate welding with the floor assembly. For the two rear door frame pillars, local reinforcement is introduced around the hinge mounting locations to ensure reliable door operation while satisfying the stiffness and corner strength requirements of the door frame.

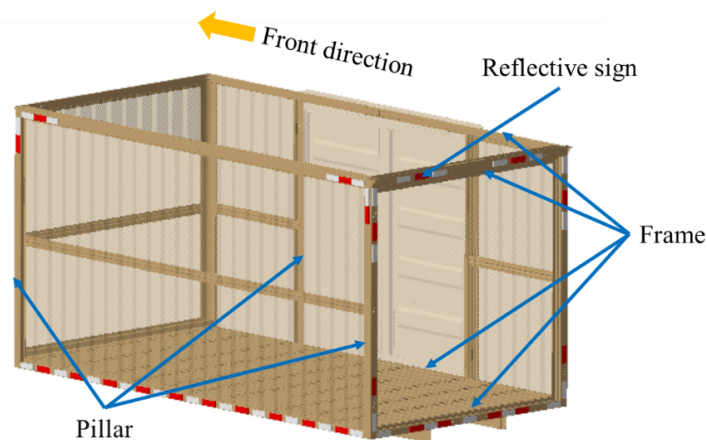


Figure 2. Side frame pillars

2.4.3. Optimization of the layout and cross-sectional parameters of the front and side panels

The side panel is the largest exterior body panel of the cargo box, and its stiffness and deformation resistance directly influence the structural performance and service life of the entire cargo box. The side panel assembly consists of the outer panel, side frame pillars, and internal reinforcing beams. The outer panel provides sealing and load-bearing functions, while the internal reinforcing beams increase panel stiffness and buckling resistance. To reduce tooling investment, the front panel and side panel generally adopt identical corrugated

cross-sectional profiles, allowing the same forming dies to be used. Consequently, the front panel assembly shares a structure similar to that of the side panel assembly.

During vehicle operation, particularly under cornering and braking conditions, cargo may exert substantial pressure on the front or side panels, resulting in permanent deformation. Similarly, impacts during loading and unloading are unavoidable and may cause localized bulging failure of the front and side panels, commonly referred to as panel bulging, as illustrated in Figure 3. To improve resistance to plastic deformation, HC700LA high-strength steel was selected for both the front and side panel skins. In addition, the corrugated profiles of competing cargo boxes were benchmarked, as summarized in Table 5. The corrugation depth (H) ranges from 19 mm to 30 mm, while the corrugation width (L) ranges from 82 mm to 100 mm. Increasing the corrugation depth improves deformation resistance but also increases material consumption, which is unfavorable for lightweight design. Conversely, for a constant corrugation depth, increasing the corrugation width reduces material usage and therefore contributes to weight reduction. Based on the benchmarking results and overall lightweight objectives, a corrugation depth of 25 mm and a corrugation width of 111 mm were selected.



Figure 3. Deformation of the side panel

Table 5. Cross-sectional parameters of benchmark front and side panels

Vehicle Model	Corrugation Depth H (mm)	Corrugation Width L (mm)	Illustration
Recommended design	25	111	
Jiangxi Shenghang	30	100	
CIMC	23	103	
Aoling Suyun	20	82	
Junling V6	20	88	
Geely H8E	19	93	
Jiangling Kaiyun	17	94	

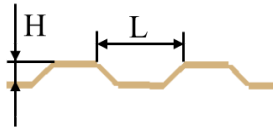
2.4.4. Optimization of roof reinforcement layout and cross-sectional parameters

The primary function of the cargo box roof is to seal the upper compartment, preventing rainwater ingress and cargo loss. Although the roof is subjected to relatively small cargo loads, it must possess sufficient bending stiffness to prevent sagging that could lead to water accumulation. Furthermore, during vehicle operation, adequate stiffness is required to prevent resonance between the roof and road-induced vibrations, thereby avoiding abnormal noise or fatigue cracking. To ensure effective waterproof sealing, the roof panel is

continuously welded to the upper frame of the cargo box, and structural sealant is applied along all overlapping joints.

The reinforcing ribs of roof panels from competing products were benchmarked, as summarized in Table 6. Most reinforcement ribs are arranged primarily in the X-direction, with rib depths ranging from 8 mm to 25 mm, rib widths from 44 mm to 216 mm, and the number of ribs varying between 9 and 23. Greater rib depth enhances stiffness but increases material consumption and complicates sheet-metal forming. For a constant rib depth, a larger rib width reduces material usage and is therefore more favorable for lightweight design. Considering the benchmark data and overall weight reduction objectives, the proposed roof adopts Y-direction reinforcing ribs with a rib depth of 23 mm, a rib width of 220 mm, and 18 reinforcing ribs. This roof configuration has already been successfully applied in multiple light truck cargo boxes and has demonstrated excellent manufacturing maturity and structural reliability.

Table 6. Benchmark parameters of roof reinforcing ribs

Vehicle Model	Rib Direction	Depth H (mm)	Width L (mm)	Number of Ribs	Illustration
Recommended design	Y-direction	23	220	18	
Dongfeng Captain	Y-direction	11	170	23	
Foton Aumark	Y-direction	24	200	20	
Foton Aoling	Y-direction	24	216	18	
Foton External Cargo Box	Y-direction	25	180	23	
Jiangling Kaiyun	X-direction	8	44	9	

2.4.5. Optimization of rear door height, thickness, and reinforcement layout

The rear doors constitute an important functional component of the cargo box. In addition to providing enclosure, they also serve as the mounting platform for hardware such as locking bars and related accessories. Light truck cargo boxes generally adopt a double-door configuration with an opening angle of approximately 270° , allowing personnel and forklifts to load and unload cargo efficiently from the rear. This configuration has become the mainstream design for urban logistics vehicles. First, the operating handle of the locking bar was optimized and combined with rubber vulcanization to improve the user experience during door opening and closing. The reinforcement layout of the door panel was also redesigned by replacing the original Z-direction ribs with Y-direction ribs, and the rib arrangement was optimized to simultaneously enhance dent resistance and provide sufficient mounting surfaces for the locking mechanism. Second, the door frame structure was strengthened by applying full-perimeter welding at all four corner joints, thereby improving the torsional stiffness of the rear doors and reducing deformation caused by cargo impact or compression. Finally, considering the superior rigidity and wear resistance of cast hinges, the existing cast-hinge design was retained to ensure adequate structural strength, durability, and long-term operational reliability.

2.5. Lightweight structural design and evaluation of the cargo box

The structural design of the cargo box directly affects the vehicle's load-bearing stiffness, manufacturability, and lightweight performance. Based on the material selection strategy and the structural configurations of the key components described above, a three-dimensional cargo box model was established in CATIA to support

subsequent CAE analysis, CFD simulation, manufacturing process evaluation, and vehicle packaging assessment, while verifying whether the lightweight design objectives had been achieved.

2.5.1. Cargo box structural modeling and weight reduction evaluation

Based on the structural configurations determined for the major components, a preliminary three-dimensional model was developed. Design reviews were then conducted jointly with packaging and manufacturing engineers to refine the proposed scheme and complete the final CAD model. Subsequently, material properties and densities were assigned to all components to estimate the total mass of the optimized high-strength steel cargo box. The calculated total weight was approximately 590 kg. As summarized in Table 7, compared with the original conventional steel cargo box, which weighed approximately 870 kg, the optimized lightweight design achieved a weight reduction of approximately 280 kg, corresponding to a 32.2% decrease in overall mass. The weight reduction was mainly attributed to two factors. First, the application of high-strength steel enabled substantial reductions in sheet thickness. For example, the floor longitudinal beams were reduced from 3.0 mm to 2.0 mm, the floor cross-members and several frame pillars from 2.0 mm to 1.5 mm, and the front and side panel skins from 1.0 mm to below 0.7 mm, resulting in an average thickness reduction of approximately 30% for these components. Second, optimization of the reinforcement layout and structural configuration of the front panel, side panels, rear doors, and roof panel reduced the number of internal reinforcing members required while maintaining sufficient structural stiffness, thereby further exploiting the lightweight potential.

Table 7. Summary of cargo box weight reduction

No.	Subassembly	Conventional Steel Cargo Box (kg)	Optimized Design (kg)	Weight Reduction (kg)	Reduction Ratio
1	Floor assembly	256	170	86	33.6%
2	Left side panel assembly	125	80	45	36.0%
3	Right side panel assembly	109	66	43	39.4%
4	Front panel assembly	68	32	36	52.9%
5	Roof assembly	97	67	30	30.9%
6	Rear door/Side door assembly	151	129	22	14.6%
7	Accessories	64	46	18	28.1%
	Total	870	590	280	32.2%

2.5.2. Comprehensive evaluation of the proposed design

The optimized high-strength steel cargo box satisfies the predefined objectives in terms of both lightweight performance and key structural design parameters. From the perspective of lightweight design, the estimated total mass of 590 kg is below the target value of 600 kg, representing a 32.2% reduction compared with the original design. Moreover, it demonstrates a clear competitive advantage over mainstream products currently available on the market, whose cargo box weights generally range from 611 kg to 692 kg. Regarding structural stiffness, the cross-sectional geometry and reinforcement layouts of the front panel, side panels, roof panel, and rear doors were developed through comprehensive benchmarking against competing products. Consequently, the proposed design is expected to provide structural stiffness comparable to that of leading commercial cargo boxes.

From the perspectives of manufacturability and production cost, the optimized design offers several notable advantages. First, the use of high-strength steel provides a cost-effective solution that achieves an optimal balance among lightweight performance, load-bearing capacity, and economic efficiency, thereby meeting both market demand and the manufacturer's competitiveness objectives. Second, the proposed welding processes are fully compatible with the existing production line, eliminating the need for extensive equipment upgrades. Third, key manufacturing technologies—including 0.6 mm thin-sheet roll forming and resistance spot welding of high-strength steel—have already been successfully implemented in industrial production, indicating that the associated technical risks are well controlled.

3. Structural performance analysis of the light truck cargo box

3.1. Fundamentals of static structural analysis

Static structural analysis is employed to determine the displacement, stress, and strain responses of a structure subjected to constant external loads. Under static loading conditions, the calculated stresses, strains, and displacements remain time-independent. Structural static analysis can generally be classified into linear and nonlinear analyses. In linear analysis, nonlinear effects have a negligible influence on the structural response and are therefore ignored. However, when the structure exhibits large deformations, contact behavior, or hyperelastic material characteristics, nonlinear analysis becomes necessary. The general equation of motion for structural analysis is expressed as Equation (2):

$$[M]\{\ddot{s}\} + [C]\{\dot{s}\} + [K]\{s\} = \{F(t)\} \quad (2)$$

where: $[M]$ denotes the mass matrix; $\{\ddot{s}\}$ is the acceleration vector; $[C]$ denotes the damping matrix; $\{\dot{s}\}$ is the velocity vector; $[K]$ denotes the stiffness matrix; $\{s\}$ is the displacement vector; and $\{F(t)\}$ represents the external force vector.

When the effects of inertia and damping are neglected, the governing equation of motion can be simplified. Under time-independent loading conditions, both inertial and damping forces may be ignored, yielding the static equilibrium equation shown in Equation (3):

$$[K]\{s\} = \{F(t)\} \quad (3)$$

where K is the stiffness matrix. When K is constant, Equation (3) represents linear static analysis, in which the material exhibits linear elastic behavior and the structural deformation remains sufficiently small. When K varies with deformation, Equation (3) represents nonlinear static analysis.

3.2. Establishment of the finite element analysis model for the cargo box

The accuracy of the finite element model of the cargo container is directly related to the reliability of the subsequent analysis results, and thus exerts a significant influence on the structural performance evaluation and optimization improvement of the container. In this study, the actual service conditions of the cargo container are fully taken into consideration. The container is assembled with the matching light-duty truck chassis frame to establish a finite element analysis model under the full-vehicle environment, thereby enhancing the precision of the computational results.

3.2.1. Finite element meshing of the cargo box

The components of the cargo container assembly are predominantly sheet metal parts, whose dimensions in the thickness direction are considerably smaller than those in the length and width directions, thereby conforming to the thin-shell theory. These components can be modeled using three-dimensional quadrilateral

or triangular shell elements, with the proportion of quadrilateral elements controlled above 95%. Considering the structural dimensions and analysis accuracy comprehensively, the global element size for the shell elements is set to 8–10 mm, with local refinement applied to the critical load-bearing regions.

The three-dimensional digital model of the cargo container assembly created in CATIA is saved as an IGES-format file and subsequently imported into HyperMesh, where the solver environment is switched to ABAQUS. During the pre-processing stage, the geometric processing module embedded in HyperMesh is employed to extract the mid-surfaces of each sheet metal part using the MidSurface function, and the surface contours and feature lines of the parts are cleaned and simplified to enhance the quality of the subsequent mesh generation. Upon completion of the geometric repair, the automatic shell element meshing tool AutoMesh is invoked to discretize the sheet metal components, ultimately establishing the shell element finite element model for each component of the cargo container.

3.22. Assembly of the cargo box and chassis frame in the analytical model

When conducting finite element analysis under the full-vehicle environment, the construction of an accurate analytical model is the core prerequisite for ensuring that the simulation data possess engineering reference value. Among all the modeling procedures, the treatment of connection relationships between the cargo container and the chassis frame constitutes one of the key aspects in the full-vehicle integrated modeling. The cargo container investigated in this study is designed based on a light commercial vehicle platform. During actual user operation, the container is not rigidly fixed to the main chassis frame; instead, it is elastically clamped by means of several sets of U-bolts. Meanwhile, as the mounting carrier for various vehicle assemblies—including the powertrain, transmission mechanism, and cab—the chassis frame plays a dual role in the overall load transmission path: it serves as the primary load-bearing component that receives road excitation transmitted upward through the suspension system, and also acts as the intermediate medium that transfers the mass loads of each component downward to the suspension. When the cargo container is assembled onto the chassis frame via the connecting elements, the longitudinal load-bearing beams and transverse reinforcing beams of the two structures form a stacked arrangement in space. This configuration enables the upper and lower beam systems to undergo coordinated deformation under bending, torsion, and combined load cases, jointly providing the required flexural section modulus and torsional stiffness for the entire vehicle.

To prevent stress concentration or abnormal wear caused by direct contact between the container longitudinal beams and the frame longitudinal beams, and to attenuate high-frequency vibrations transmitted from the road surface to a certain extent, a cushioning and vibration-isolating medium—typically made of fine-textured wood or rubber pads with moderate elasticity—is interposed between the container longitudinal beams and the frame longitudinal beams. The width of this pad is kept consistent with the flange width of the frame longitudinal beams, and its thickness is generally 20–40 mm (20 mm is adopted in this study). The solid geometric modeling of the main container body, chassis frame, cushioning pads, U-bolts, and other components is illustrated in Figure 4.

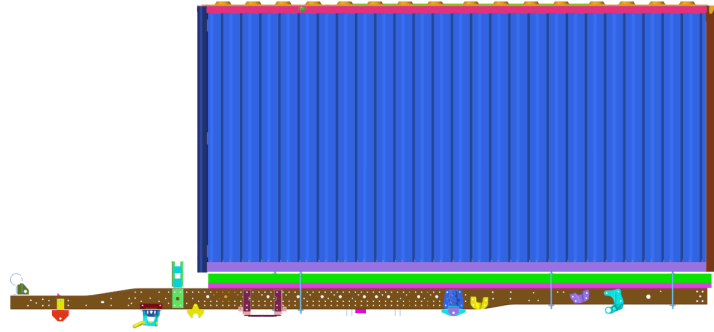


Figure 4. Assembly model of the cargo box and chassis

3.2.3. Material parameter configuration for the cargo container analysis model

Three types of materials are primarily adopted for the cargo container components, namely HC700LA, HC550LA, and HC420LA, whose corresponding mechanical property parameters are detailed in Table 8. In HyperMesh software, the Materials definition module is accessed to establish the respective material property cards according to the material grades, with each card identified directly by the corresponding material grade designation. For each material card, two categories of key parameters are required to be defined: the first category comprises the linear elastic parameters, including the elastic modulus and Poisson's ratio; the second category comprises the plastic parameters, i.e., the stress-strain curve data of the material.

Table 8. Material parameters of cargo container components

Material grade	Density (kg/m ³)	Yield strength (MPa)	Elastic modulus (GPa)	Poisson's ratio
HC700LA	7850	700	210	0.3
HC550LA	7850	550	210	0.3
HC420LA	7850	420	210	0.3

3.3. Structural strength analysis of the cargo box

The objective of the structural strength analysis is to verify that the cargo box possesses sufficient load-carrying capacity under representative operating conditions. Specifically, the stresses developed in all structural components must remain within the allowable limits of the constituent materials to prevent plastic deformation or structural failure.

3.3.1. Strength evaluation criteria

The cargo box is primarily constructed from high-strength steel sheets, whose predominant failure mode is plastic yielding. Accordingly, the structural strength in this study was evaluated based on the fourth strength theory (von Mises yield criterion). According to this criterion, when the equivalent stress at a given point within the structure reaches or exceeds the material's yield strength, plastic yielding occurs at that location. The equivalent stress is calculated using Equation (4):

$$\sigma_r = \sqrt{\frac{1}{2} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]} \quad (4)$$

where σ_r denotes the equivalent (von Mises) stress.

In engineering design, a factor of safety is generally introduced to account for uncertainties arising from load estimation, material variability, and manufacturing imperfections. The allowable material stress is defined

3.3.3. Structural strength analysis and results

Finite element strength analyses were performed for the cargo box assembly under the eight representative loading conditions described above. The simulation results indicate that under all loading scenarios—including the static full-load condition, emergency braking, cornering, and the remaining representative operating conditions—the stresses developed throughout the cargo box remained below the allowable material stresses. No structural component exceeded its yield limit, and all critical regions satisfied the prescribed design requirements. Therefore, the overall structural strength of the cargo box meets the specified engineering performance targets. A summary of the maximum stress values obtained under each loading condition is presented in Table 10, while the detailed results for each individual case are discussed in the following sections.

Table 10. Summary of maximum von mises stress under various operating conditions (MPa)

Component (MPa)	CASE1	CASE2	CASE3	CASE4	CASE5	CASE6	CASE7	CASE8	Acceptance Criterion
Straight longitudinal beam	170.5	315.4	398.1	484.4	408.4	306.1	380.0	324.3	< 700 MPa
U-shaped member	143.6	226.5	212.4	287.9	309.2	271.1	328.3	315.4	< 420Mpa
Cross-member	148.7	168.4	170.1	158.8	277.5	256.7	340.3	317.2	< 420Mpa
Floor panel	130.4	186.2	157.4	200.2	162.8	162.3	232.2	245.6	< 420Mpa
Side frame	113.2	146.5	112.4	139.1	150.3	144.0	193.2	163.6	< 420Mpa

3.3.3.1. CASE1 – static full-load condition

The stress contour for the static full-load condition is presented in Figure 6. The maximum stress in the cargo box floor is 170.5 MPa, which is substantially lower than the yield strength of the corresponding material. This indicates that the risk of structural failure in the floor under this loading condition is negligible and that the design satisfies the required performance criteria. Furthermore, the stress contours show that the U-shaped members, cross-members, floor panel, and side frame also experience relatively low stress levels, which is consistent with the expectation that the static full-load condition represents the least demanding case among all strength evaluation scenarios.

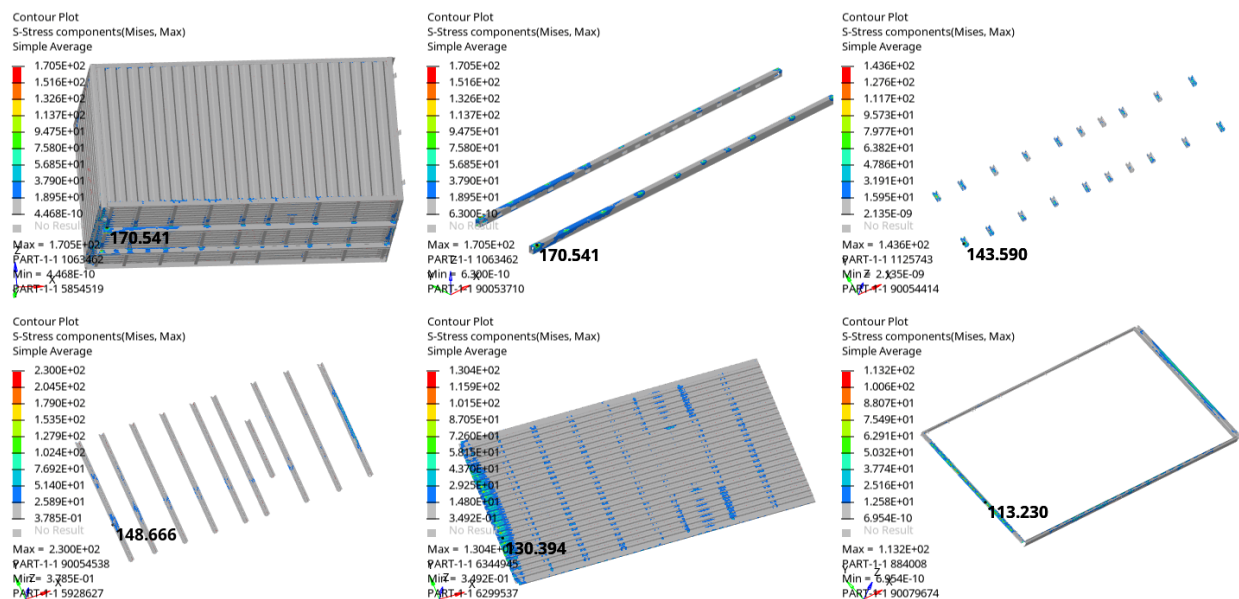


Figure 6. Stress contour of the cargo box under the static full-load condition

3.3.3.2. CASE2 – braking condition

The stress distribution under the braking condition is shown in Figure 7. The stress concentration is primarily located at the front portion of the cargo box, with the maximum stress of 315.4 MPa occurring at the connection between the longitudinal beam and the U-shaped member. This value remains below the material yield strength and therefore satisfies the design criterion. From the stress distribution, it can be observed that the longitudinal inertial force generated during braking acts along the vehicle's longitudinal (X) direction, causing the front section of the cargo box to experience the highest loading. The stress concentrations at the beam-to-U-member connections are therefore consistent with the expected load transfer path. Moreover, the stress levels on the left and right longitudinal beams and U-shaped members are nearly identical, reflecting the structural symmetry of the vehicle under the braking condition.

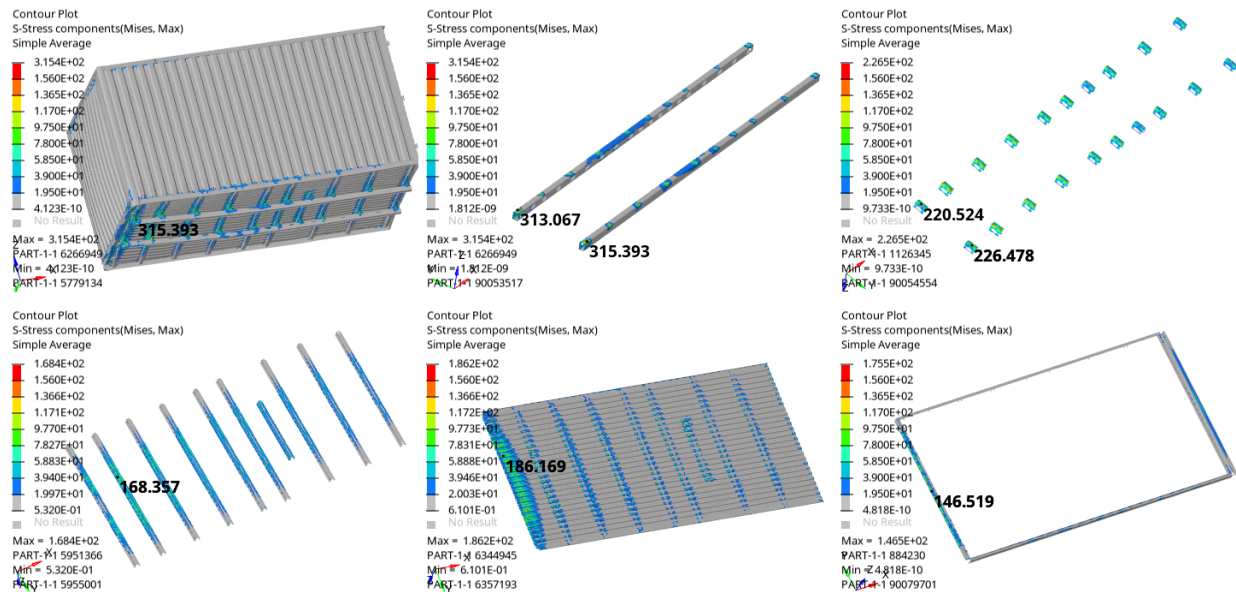


Figure 7. Stress contour of the cargo box under the braking condition

3.3.3.3. CASE3 – cornering condition

The stress contour for the cornering condition is illustrated in Figure 8. In this case, the vehicle is assumed to execute a left-hand turn. The maximum stress reaches 398.1 MPa at the connection between the longitudinal beam and the U-shaped member, remaining below the corresponding material yield strength. During a left turn, the vehicle experiences centripetal acceleration toward the left, while the inertia of the cargo generates an outward centrifugal force toward the right. Consequently, the right-hand side of the cargo box is subjected to higher loading. The finite element results confirm this behavior, as the maximum stresses in the longitudinal beams, U-shaped members, cross-members, floor panel, and side frame are all located on the right-hand side, demonstrating excellent agreement with the prescribed loading condition.

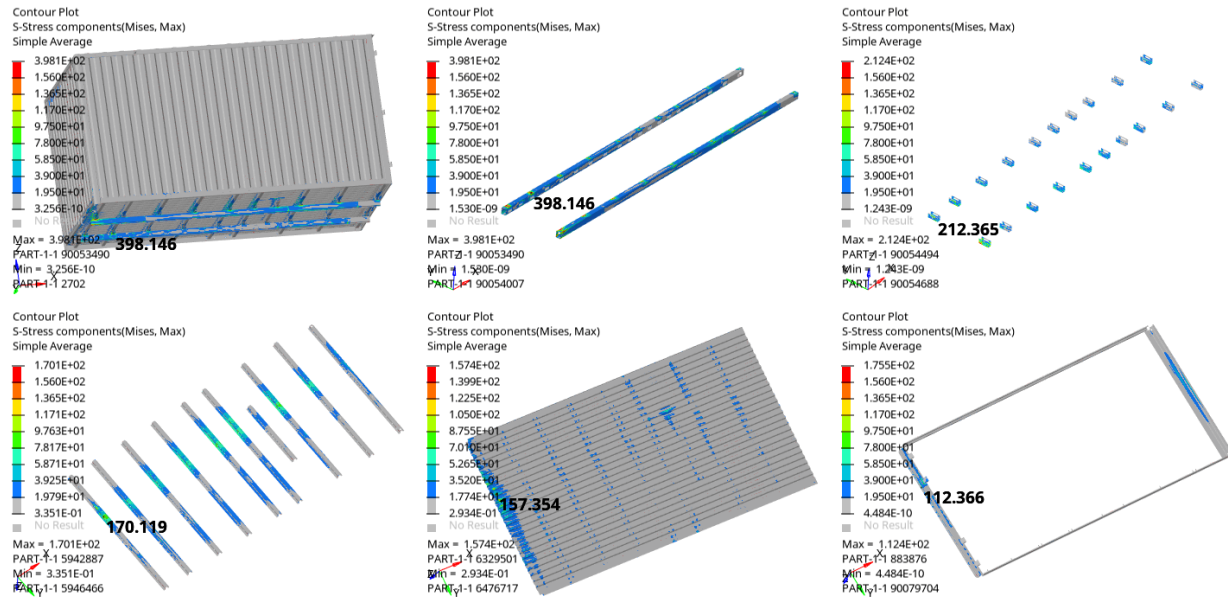


Figure 8. Stress contour of the cargo box under the cornering condition

3.3.3.4. CASE4 – combined braking and cornering condition

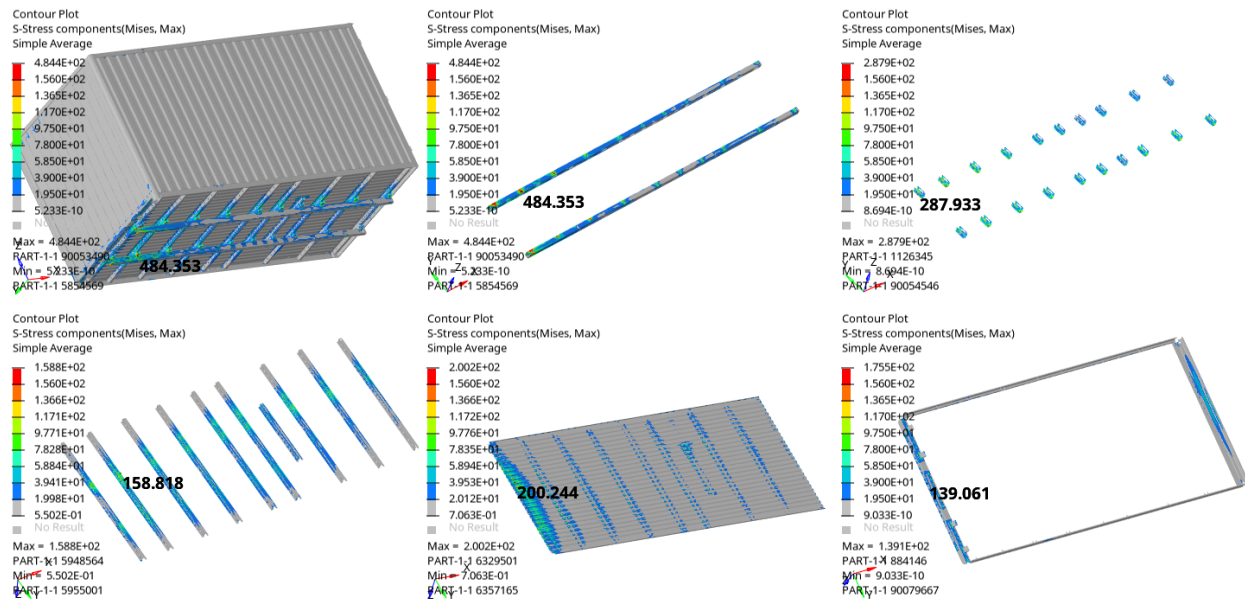


Figure 9. Stress contour of the cargo box under the combined braking and cornering condition

The stress contour corresponding to simultaneous left-hand cornering and braking is presented in Figure 9. The maximum stress is 484.4 MPa, occurring at the connection between the longitudinal beam and the second U-shaped member on the right-hand side. This value remains below the yield strength of the material and therefore satisfies the structural strength requirement. Under this combined loading condition, the longitudinal inertial force generated by braking is superimposed on the lateral inertial force caused by cornering. Although the longitudinal loading increases, the right-hand side continues to experience the highest stress because of the lateral centrifugal effect. The stress distributions in the longitudinal beams, U-shaped members, cross-

members, floor panel, and side frame consistently show higher stresses on the right-hand side, matching the prescribed loading scenario.

3.3.3.5. CASE5–CASE6 – single-wheel lift (150 mm)

CASE5 and CASE6 simulate the deformation experienced when one wheel passes over a raised obstacle. Under these conditions, the vehicle body tilts toward one side, causing significant deformation of both the chassis and the cargo box. Since the suspension travel reaches its limit, the structural rigidity of the chassis and cargo box becomes the primary mechanism resisting deformation, making sufficient structural strength essential.

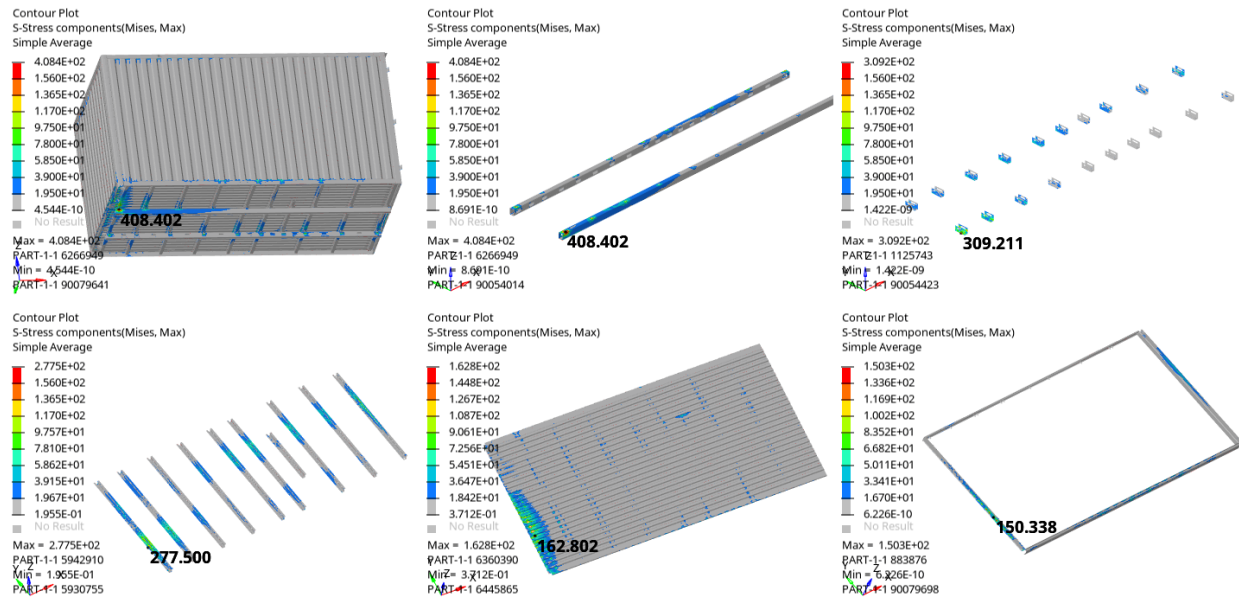


Figure 10. Stress contour with the left front wheel raised by 150 mm

The stress contour for the left front wheel raised by 150 mm is shown in Figure 10. The maximum stress in the cargo box is 408.4 MPa, occurring at the connection between the left front longitudinal beam and the U-shaped member. This stress remains below the material yield strength, indicating satisfactory structural performance. As expected, the highest stress is concentrated at the left front corner of the cargo box, consistent with the applied loading condition.

The stress contour for the right front wheel raised by 150 mm is presented in Figure 11. The maximum stress is 306.1 MPa, occurring at the connection between the right front longitudinal beam and the U-shaped member. This value also remains below the material yield strength and satisfies the evaluation criterion. The stress concentration occurs primarily in the right front region of the cargo box, which is consistent with the prescribed loading condition.

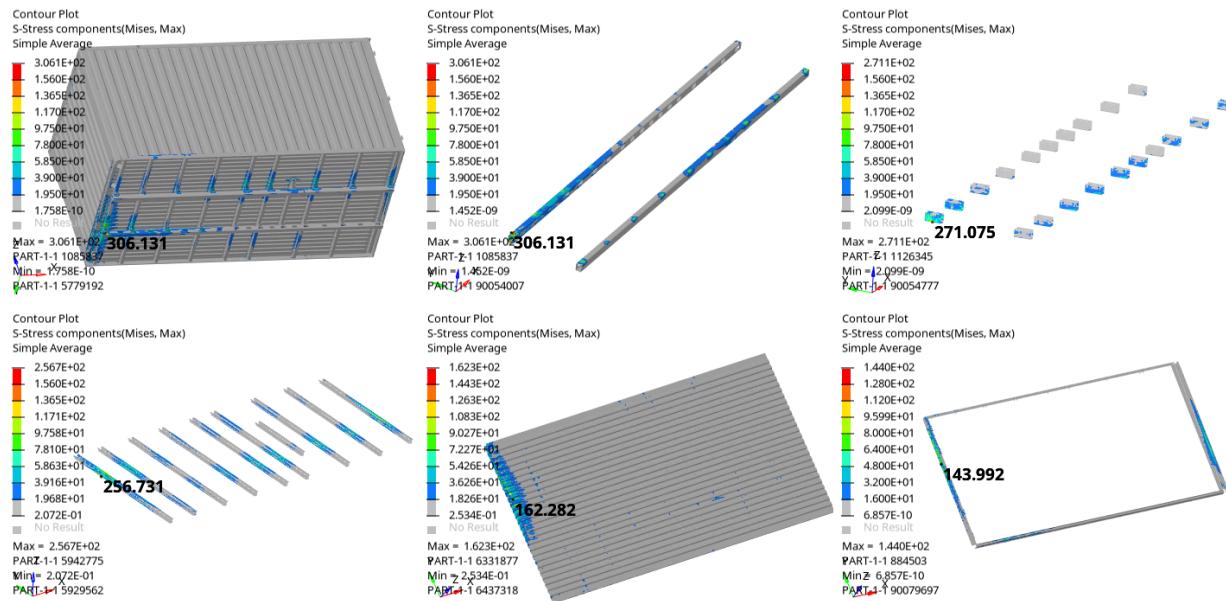


Figure 11. Stress contour with the right front wheel raised by 150 mm

3.3.3.6. CASE7 and CASE8 – diagonal wheel lift

CASE7 and CASE8 simulate vehicle operation on a twisted road surface, where diagonally opposite front and rear wheels simultaneously pass over raised obstacles, producing a diagonal support configuration. Under these conditions, loads are simultaneously transmitted through the front and rear suspension attachment points, causing the chassis and cargo box to undergo diagonal bending and torsional deformation.

The stress contour for the left front and right rear wheels raised is shown in Figure 12. The maximum stress in the cargo box is 380.0 MPa, occurring at the connection between the left front longitudinal beam and the U-shaped member. This stress is below the material yield strength and therefore satisfies the evaluation criterion. The stress distribution indicates that the highest stresses are concentrated at the left front corner of the cargo box and at the right rear suspension connection, which agrees well with the prescribed loading condition.

The stress contour for the right front and left rear wheels raised is presented in Figure 13. The maximum stress is 324.3 MPa, occurring at the connection between the right front longitudinal beam and the U-shaped member. This value also remains below the material yield strength. The stress concentration appears primarily at the right front corner and the left rear suspension connection, consistent with the expected structural response under diagonal wheel lift.

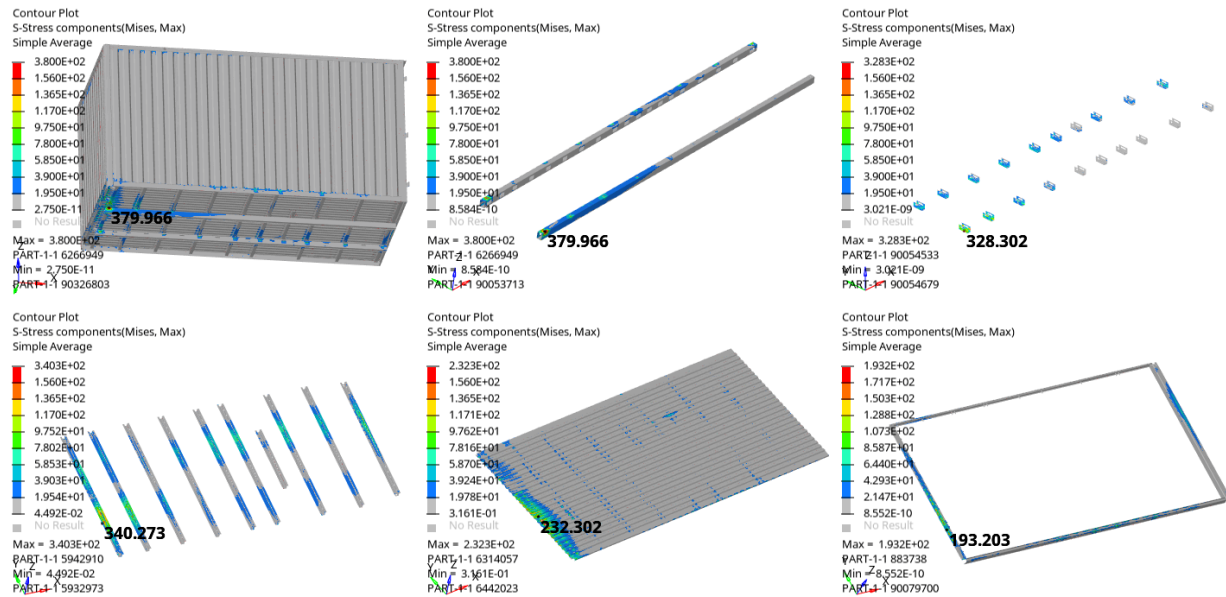


Figure 12. Stress contour with the left front and right rear wheels raised

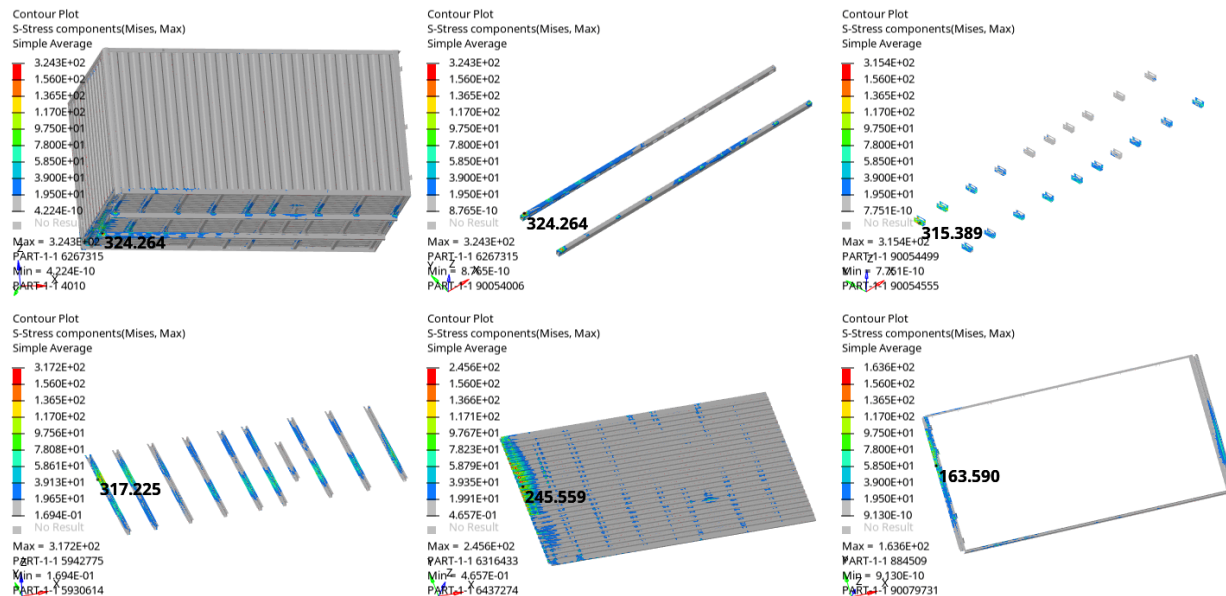


Figure 13. Stress contour with the right front and left rear wheels raised

Considering all loading conditions, it is evident that the connection between the front end of the longitudinal beam and the U-shaped member is the location where stress concentrations most frequently occur. This behavior arises because the region constitutes the primary load-transfer section of the cargo box structure. Since multiple floor support members are arranged longitudinally, the foremost beam is invariably the first structural member to receive and transmit external loads and impact forces. Consequently, it forms a natural bottleneck within the structural load path. To ensure adequate strength at this critical location, HC700LA high-strength steel was selected for the longitudinal beams. Under all eight loading conditions, the maximum

computed stresses remained below the yield strength of HC700LA, demonstrating that the proposed design satisfies the prescribed structural strength requirements.

4. Conclusions

This study conducted the lightweight design, structural design, and structural performance analysis of a light truck cargo box. The main conclusions are as follows.

(1) The internal dimensions of the cargo box were determined to be 4,200 mm × 2,100 mm × 2,100 mm, satisfying both the regulatory requirements for blue-plate light trucks and the dimensional requirements for standard logistics pallets. High-strength steels (HC700LA, HC550LA, and HC420LA) were selected to replace conventional steels. The adoption of 0.6 mm ultra-thin front and side panels achieved an approximately 40% reduction in panel weight. A joining strategy based primarily on welding, supplemented by bolted connections, was adopted, making the proposed design fully compatible with the manufacturer's existing production capabilities. The structural parameters of the key cargo box components were optimized, including the dimensions and layout of the floor longitudinal beams (100 mm × 60 mm box section) and cross-members (51 mm × 48 mm Ω -section), the cross-sectional configuration and spacing of the side-frame pillars, and the stiffener profiles and layouts of the front panel, side panels, roof panel, and door panels. The optimized cargo box has an estimated total mass of approximately 590 kg, representing a 32.2% reduction compared with the original design (870 kg), thereby successfully achieving the lightweight design target.

(2) Based on the corporate specifications, a comprehensive finite element model of the cargo box was established. The load-bearing performance of the cargo box was evaluated under eight typical operating conditions, including static loading, braking, cornering, left-front wheel lift of 150 mm (both sides), and diagonal wheel lift of 100 mm. The results indicate that the maximum stresses in the longitudinal beams, U-section members, cross members, floor panel, and side frames remain below the yield strength of the respective materials under all conditions, thereby satisfying all prescribed evaluation criteria. Furthermore, stress concentration zones are consistently observed at the junctions between the front ends of the longitudinal beams and the U-section members, as well as in the front and rear cross-member regions. This phenomenon is attributed to the structural configuration of the floor assembly, where multiple cross members are arranged longitudinally and connected to the longitudinal beams. Since all loads are transmitted from the cargo box to the chassis frame through the longitudinal beams, the front and rear cross-member areas resist the torsional deformation induced by external loads through their own stiffness. Consequently, it is recommended that materials with superior mechanical properties be preferentially selected for the longitudinal beams, with particular attention paid to the structural stresses in both the front and rear cross-member zones.

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