ENHANCEMENT OF THE STRUCTURAL PERFORMANCE OF MONOCOQUE BUS FRAMES TO IMPROVE ROLLOVER SAFETY

Nguyen Thanh Tam[1], Dao Ngoc Quoc Khanh[1,2]*, Nguyen Van Sy[3], Le Minh Xuan[4], Le Viet Trung[4]

[1]*Quy Nhon University, Vietnam*
[2]*Master's student in Automotive Engineering, Industrial University of Ho Chi Minh City, Vietnam*
[3]*Industrial University of Ho Chi Minh City, Vietnam*
[4]*Dong A University, Vietnam*

*Corresponding author: daongocquockhanh@qnu.edu.vn

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Abstract - The monocoque bus frame plays a critical role in ensuring structural integrity and passenger safety in public transportation. While prior studies have explored aluminum reinforcements to improve rollover crashworthiness, challenges such as high cost and material degradation over time remain. This study introduces an alternative optimization method by integrating lightweight I-shaped aluminum stiffeners into the bus frame structure. Finite Element Analysis (FEA) simulations using LS-DYNA were conducted to assess structural performance under rollover conditions in accordance with ECE R66 standards. The results confirm that the improved frame fully preserves the residual safety space and exhibits a 21.5% increase in flexural stiffness compared to the original configuration, with a negligible 0.06% increase in overall vehicle weight. This lightweight reinforcement solution significantly reduces plastic deformation in critical areas and meets all safety requirements, making it a cost-effective and manufacturable approach for sustainable public transport vehicle design.

Key words - Monocoque Bus Frame; LS-DYNA; Finite Element Analysis (FEA); Rollover Safety; Aluminum I-stiffeners

1. Introduction

Buses serve as a fundamental component of urban and intercity transportation networks worldwide. Among the various structural configurations, monocoque bus frames-characterized by an integrated load-bearing body-have becomes a focal point of research and development in Vietnam in recent years. The structural optimization of monocoque frames plays a pivotal role in achieving multiple objectives: enhancing fuel efficiency through weight reduction, lowering emissions for environmental sustainability, and ensuring occupant safety during rollover accidents, in line with international regulatory standards such as ECE R66 [1-2].

Recent literature has proposed several structural enhancement strategies to improve rollover crashworthiness. For instance, He Hanqiao et al. suggested increasing the wall thickness or cross-sectional area of steel tubes to enhance rigidity; Tomas et al. reinforced critical deformation zones to improve stiffness distribution; Friedman et al. implemented fiber-reinforced polymers in the roof section; and Salvador et al. filled hollow tubes with structural foam to mitigate collapse during rollover. However, these solutions resulted in increased overall vehicle weight, higher production costs, or complex manufacturing processes. Alam et al. explored multi-material frames combining aluminum and steel, achieving weight reduction while meeting safety regulations; Mikulski and Lavayen-Farfán demonstrated that using carbon fiber composites significantly improved rollover resistance and structural stiffness [3-9]. While promising, these approaches remain constrained by material costs, recyclability, and production feasibility, particularly in the context of localized manufacturing.

Tam et al. explored a tube-filling reinforcement strategy using composite materials at structural joints, which met ECE R66 requirements. However, the variability in mechanical properties due to environmental exposure-notably resulted in long-term performance degradation [10-11]. These limitations highlight the need for a more durable, cost-efficient, and manufacturable reinforcement method suitable for large-scale implementation.

Building upon these insights, this study introduces an innovative structural enhancement approach using I-shaped aluminum stiffeners as internal reinforcements in the monocoque frame. Aluminum offers advantages in manufacturability, material consistency, and cost-efficiency, while maintaining adequate mechanical strength. Finite Element Analysis (FEA) simulations using Hypermesh and the LS-DYNA solver were conducted to evaluate the mechanical performance of the optimized frame under rollover conditions defined by ECE R66. The results indicate a 21.5% improvement in global flexural stiffness, with only a 0.06% increase in overall frame mass. Additionally, the residual safety requires a critical requirement of ECE R66, remaining entirely intact post-rollover simulation. These findings support the use of aluminum stiffeners as a technically viable and economically scalable solution, contributing to the advancement of safe, lightweight, and sustainable public transportation vehicles in both domestic and international markets.

2. Safety Standards and Rollover Test

The Economic Commission for Europe Regulation No. 66 (ECE R66) outlines the structural integrity requirements for large single-deck buses that carry more than 22 passengers. The regulation mandates that, in the event of a rollover accident, the bus frame must possess sufficient strength and rigidity to prevent collapse and ensure passenger protection. Specifically, it emphasizes the importance of preserving a designated residual safety space, which must remain free from intrusion throughout and after the rollover event.

2.1. Residual Space

The residual space represents a protected internal volume that must not be penetrated by any structural or internal components following a rollover. It serves as the minimum survivable volume necessary to safeguard passengers during such events. This space is geometrically defined by vertical and horizontal reference planes that are based on seat positions and clearances. For example, one of the key reference points lies 500mm above the seat base and between 150mm to 250mm from the side walls of the vehicle interior, depending on the configuration. Figure 1 illustrates the geometric boundaries of this protected region in accordance with ECE R66.

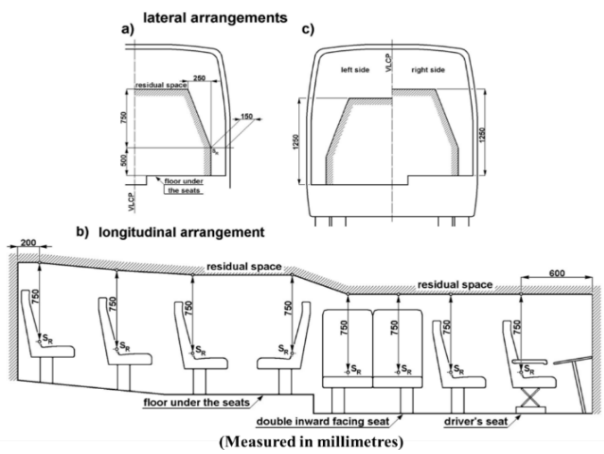

Figure 1. *Residual safety space specification according to ECER66 [13]*

2.2. Rollover Test Methodology

The rollover test defined by ECE R66 is structured to simulate a real-world overturning accident and evaluate the structural resilience of the bus frame. Its primary objective is to verify whether the superstructure can protect the residual safety space throughout the rollover process without permanent deformation or intrusion from structural components.

The test begins with the vehicle being loaded to simulate full occupancy including passengers, baggage, and onboard equipment being positioned on a tilting platform. To emulate a rigid body response, the suspension system is mechanically locked. The platform is then rotated slowly until the bus reaches the limit of static equilibrium, where the center of gravity extends beyond the rotation axis. At this critical tipping point, the vehicle is allowed to roll over freely under gravitational acceleration.

The bus impacts a concrete trench or trough with a nominal depth of 800mm, replicating the ground conditions in a rollover incident. The surface must be smooth, dry, and flat to ensure repeatability of results. The roll axis is assumed to lie along the contact line between the outer wheels and the platform edge.

To ensure conservative evaluation, the rollover is performed on the side determined to be most susceptible to residual space intrusion. This decision is based on multiple technical factors, such as: The asymmetrical distribution of mass within the vehicle (e.g., placement of batteries, air conditioners), the horizontal offset of the center of gravity,

The non-uniformity in frame stiffness due to localized reinforcements or cutouts, and the interior layout and support structure.

During the test or simulation, high-speed cameras, displacement sensors, and FEA post-processing tools are often employed to observe the deformation behavior and identify zones of critical strain or collapse.

Figure 2 schematically illustrates the rollover test setup. The diagram shows the bus positioned on a tilting platform, indicating the initial position (Stage A), the point of unstable equilibrium (Stage B), and the final impact into the concrete trench (Stage C). Key geometric references, such as the tilting angle, the roll axis, and the location of impact relative to the chassis, are clearly marked. This visual aids in understanding the vehicle dynamics during the rollover and the evaluation of how energy is dissipated upon contact.

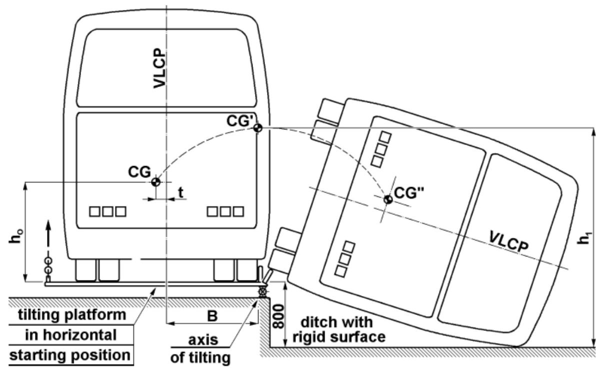

Figure 2. *Rollover test procedure [13]*

3. Finite Element Modeling

3.1. Monocoque Bus Model

To assess the structural response of a monocoque bus frame during a rollover event, a comprehensive finite element model of a 29-seat bus was developed in accordance with the ECE R66 regulation. The bus model represents a full-scale vehicle with a total length of 8.7 meters and width of 2.4 meters and was created in collaboration with a domestic manufacturer to ensure realistic geometry and production constraints.

The frame structure consists of six main subassemblies: front bulkhead, rear panel, roof module, left and right-side panels, and the underfloor chassis as shown in Figure 3. These parts collectively form a continuous load bearing monocoque shell in which the exterior contributes directly to the mechanical performance. Important geometric features such as door and window openings, joint intersections, and frame corners were retained to accurately reflect stress concentration zones.

To represent non-structural components such as passenger seats; engine; heating, ventilation, and air conditioning (HVAC) systems; luggage and battery modules..., CONM2 point mass elements were used. Their positions and magnitudes correspond to realistic full-load conditions of the vehicle, as shown in Table 1.

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Table 1. *Weight Distribution of Bus Components (Internal Combustion Engine Configuration*

No.	Component	Weight (kg)
1	Front panel	48
2	Rear panel	41
3	Main side frame	127
4	Auxiliary side frame	110
5	Roof frame	151
6	Roof cover	200
7	Chassis	506
8	Body cover	80
9	Front axle	470
10	Rear axle	730
11	Front load distribution	1195
12	Rear load distribution	868
13	Fuel tank	240
14	Transmission system	280
15	Air conditioner	150
16	Starter battery	40
17	Passengers	1885
18	Seats	320
19	Diesel engine	480
20	Windshield glass	175
21	Others	359
	Total (ICE configuration)	7765

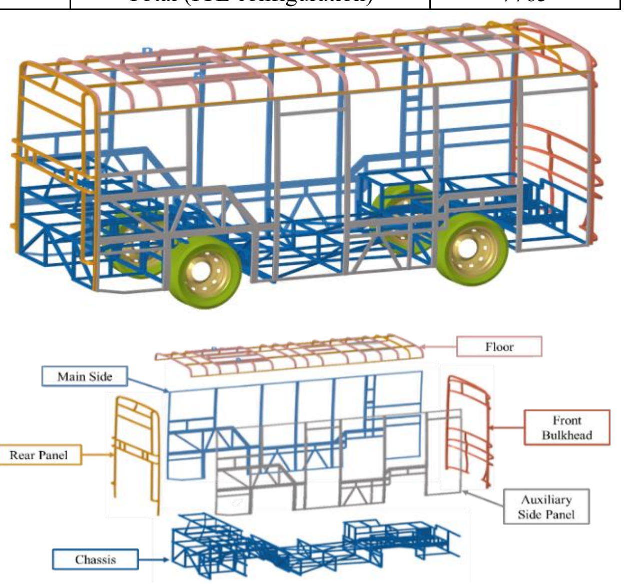

Figure 3. *3D model of the 29-seat bus and main structural components*

In the process of developing the finite element model, the choice of element type for each specific application is crucial, as it directly impacts the accuracy of the simulation results when compared to real-world data. In this study, the six main sections of the bus frame were modeled using MATL 24 *MAT_PIECEWISE_LINEAR_PLASTICITY (for steel materials requiring deformation analysis), with a mesh size of 10, along with the properties outlined in Table 1. The impact zone was modeled using MATL 20 *MAT_RIGID (completely rigid) with a mesh size of 100.

Additionally, to represent components with mass such as passengers, seats, luggage, engine, battery, HVAC systems, and windows, CONM2 point mass elements were applied. At the connection points between the beams and to simulate joint behaviors, RBE2 rigid body elements were used. RBE3 elements were also employed for linking mass elements.

The gravitational acceleration was set to $g = 9.806$ m/s², and the center of gravity (CG) for the full-loaded bus was determined using LS-DYNA software, as shown in Figure 4. This calculation indicates that the vehicle's rollover direction is towards the auxiliary side, as the center of gravity is tilted towards the main side [4].

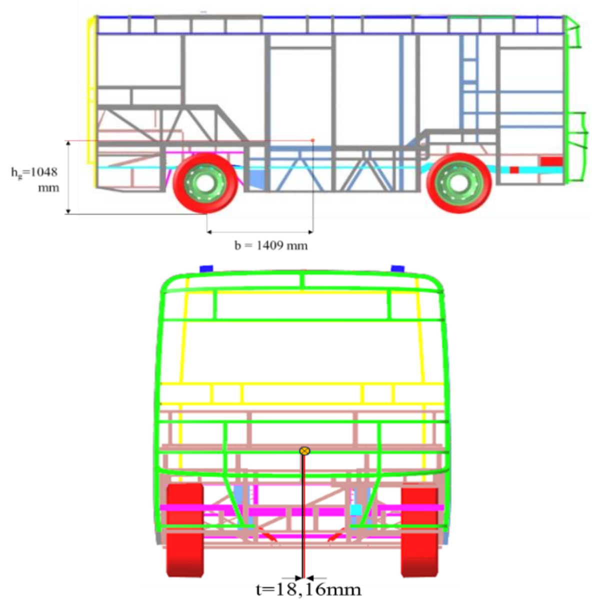

Figure 4. *Center of gravity coordinates*

The geometry was created in CAD software and imported into HyperMesh for meshing. A combination of beam elements (1D) was used for tubular members, and shell elements (2D) were applied to thin-walled panels. Local mesh refinement was introduced at joints, corners, and other expected deformation zones to improve solution accuracy.

The model incorporated three types of structural steel commonly used in bus frame manufacturing: D135, D159, and D357. Their mechanical properties were defined based on standardized test data, as shown in Table 2. These steels provide a balance between structural stiffness, crash energy absorption, and manufacturability.

A full-scale rollover test was numerically simulated to replicate realistic crash conditions. The simulation setup included a full-scale 3D model of the bus, and a tilting platform configured to mimic the procedure defined in ECE

R66. The virtual bus was designed to fall from a height of 800 mm, consistent with the standard's impact criteria [4].

During the simulation, the tilting platform was rotated at an angular velocity of 0.087 radians per second, gradually bringing the vehicle to an unstable equilibrium state. At this critical point, the calculated initial angular velocity applied to the model was 3.815×10^{-3} radians per millisecond, enabling the simulation to realistically replicate the moment of loss of stability and free-fall rollover.

The total loaded mass of the bus model, including structural components and internal loads (passengers, equipment, etc.), was set at 7765 kg. Figure 5 illustrates the initial tipping configuration, and the direction of rotation used in the simulation.

$$\omega = \sqrt{\frac{2.m.g.(h_1 - h_2)}{J}} = \sqrt{\frac{2.7765.0,009806.366}{3,82.10^9}} \qquad (1)$$

$$\approx 3,815.10^{-3} \text{(rad/ ms)}$$

In Equation (1), m (kg) denotes the total mass of the vehicle, g is the gravitational acceleration, J is the moment of inertia, and $(h_1 - h_2)$ represents the vertical distance between the vehicle's center of gravity in the upright position (h_1) and its position at the rollover impact moment (h_2).

Table 2. *Mechanical Properties of Materials Used in the Frame and Reinforcements*

Steel	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Srength (MPa)
D357	7760	196	0.27	470
D135	7840	199	0.26	341
D159	7660	196	0.28	382

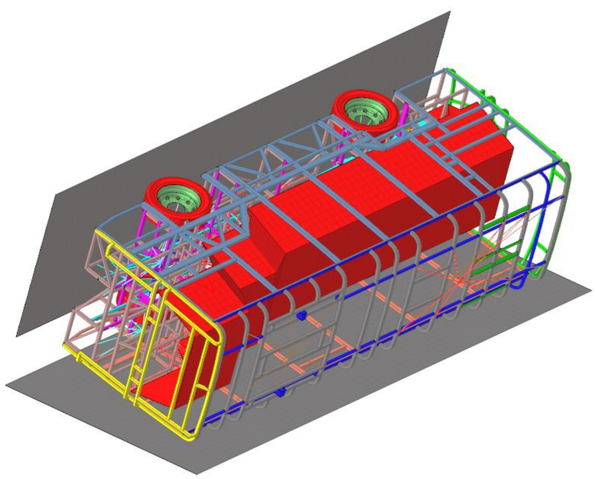

Figure 5. *Finite element model of the bus under ECE R66 rollover conditions*

4. Simulation Results of the Initial Frame Design.

The initial simulation of the baseline monocoque bus frame without reinforcement was conducted to assess its rollover resistance under ECE R66 conditions. The results revealed that the original structure was unable to preserve the residual safety space, which is a critical requirement of the regulation.

As shown in Figure 6, significant plastic deformation occurred at several key locations, including the main and auxiliary sidewalls, the roof edge, and the upper corner joints. These regions experienced high strain concentrations due to impact energy transfer, resulting in permanent distortion and collapse of load-bearing members.

The deformation exceeded the boundaries of the defined residual space, leading to partial intrusion into the passenger zone. Figure 7 highlights the areas with the most severe structural failure, especially at the joint between the side frame and the roof rail on the impact side.

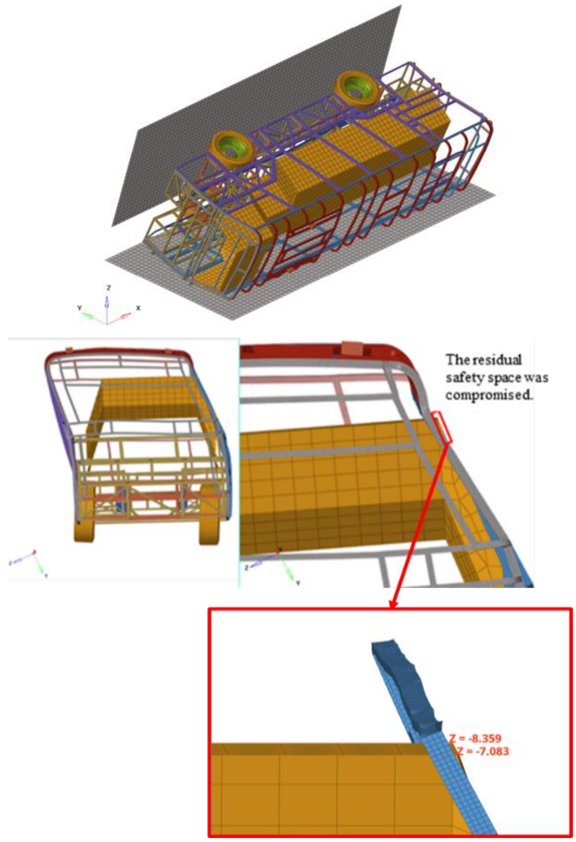

Figure 6. *Deformation results of the initial frame design during rollover simulation*

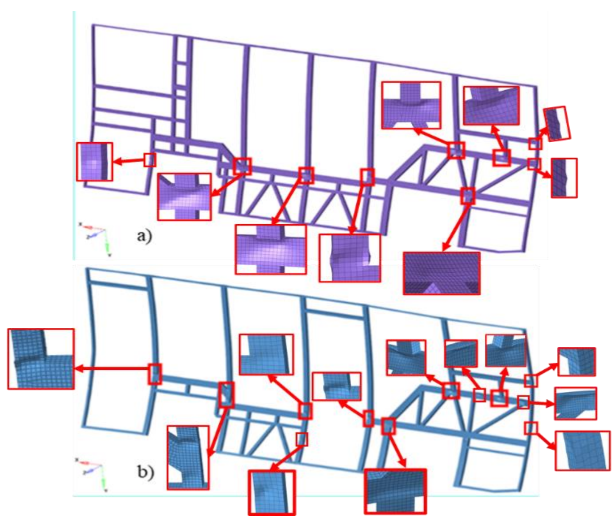

Figure 7. *a. Severe deformation on the main side structure; b. structural collapse on the auxiliary side frame*

Stress analysis further indicated that several structural components reached their yield point and entered the plastic regime, particularly at connections and weld lines. This compromised the frame's ability to absorb energy and maintain geometric stability during the rollover event.

Overall, the initial design failed to meet ECE R66 compliance criteria. These findings confirmed the necessity of structural optimization, particularly through reinforcement strategies targeting the most vulnerable regions. To illustrate the performance of the proposed DP-FBI-FCM algorithm in custom segmentation, wholesale customer data collected in UCI machine learning repository is used for analysis [27]. This dataset presents the yearly spending in monetary units (m.u.) on several product categories. There are eight features with a total of 440 data instances in this dataset. These features describe the annual spending on fresh products, milk products, groceries, frozen foods, detergent and paper products, delicatessen products, retail channels, and regions.

5. Improvement Method and Experiment.

To strengthen the rollover resistance of the monocoque bus frame without significantly increasing structural mass, this study proposes an enhancement approach that incorporates I-section aluminum stiffeners made from AA6060T4 alloy. This strategy was developed based on the failure analysis of the initial design, where high-stress regions such as roof-sidewall junctions and corner intersections were identified as critical zones for reinforcement.

The selected material, AA6060T4, belongs to the Al-Mg-Si heat-treatable alloy group. It offers an excellent compromise between mechanical strength, lightweight characteristics, corrosion resistance, and ease of extrusion, making it highly suitable for applications in both transportation and structural engineering. The alloy's favorable mechanical response under medium loading conditions further supports its selection for energy-absorbing components.

The approach employed I-shaped thin-walled stiffeners (as shown in Figure 8a) to enhance structural stiffness without significantly increasing the overall weight. They were distributed along structurally sensitive paths within the frame and connected using rigid body elements (RBE2) to simulate the physical behavior of welded or bolted joints as shown in Figure 8b. This ensured a realistic transfer of loads during the rollover event.

The mechanical properties assigned to the AA6060T4 alloy in the simulation are summarized in Table 3 [12].

Table 3. *AA6060T4 Mechanical Properties*

Property	Value
Density (kg/m^3)	2700
Young's Modulus (GPa)	68.2
Yield Strength (MPa)	80
Poisson's Ratio	0.3

The aluminum material was modeled and analyzed using a finite element model within the LS-DYNA software, employing the MAT_024 PIECEWISE_LINEAR_PLASTICITY material model. This model accurately captures the elastic-plastic behavior of the AA6060T4T4 alloy under loading conditions relevant to rollover scenarios.

Subsequently, a three-point bending test simulation was conducted to evaluate the flexural stiffness of steel tubes reinforced with the I-shaped aluminum stiffeners. This test setup enables quantification of the stiffeners' effectiveness in enhancing the bending resistance and overall load-bearing capacity of the bus frame structure.

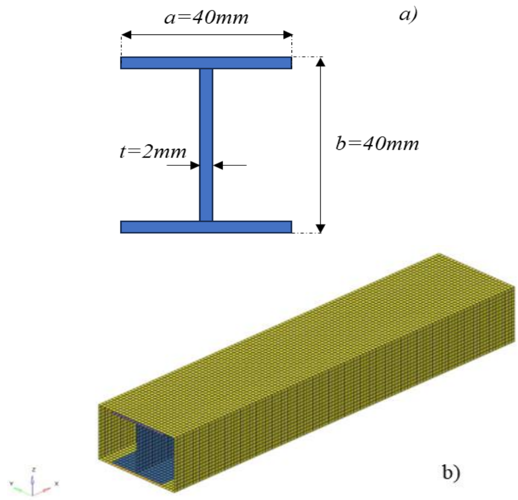

Figure 8. *a. Aluminum stiffener shape;*
b. Installation of the stiffener into the steel tube

5.1. Three Point Bending Test

The three-point bending test model was developed based on the experimental setup described in reference [16], as illustrated in Figure 9. The test was conducted on specimens made of D159 steel tubes with dimensions of height b = 40mm, width a = 40mm, and length L = 270mm. The radii of both the supports and the loading punch were set to R = 12mm, with a span distance between the supports of S=180mm.

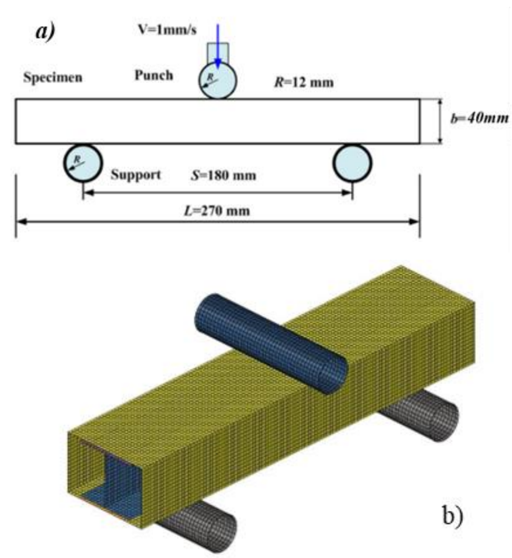

Figure 9. *a. Three-point bending test setup [16];*
b. Three-point bending model in Ls Dyna

A finite element model was created with a structured mesh of square elements having a mesh size of 2.5mm. This bending test was performed to investigate the deformation behavior and load-bearing capacity of the specimens under static loading conditions.

The test results, compared to the original steel tube without reinforcement, are presented in Figure 10. The force-displacement curve indicates that the steel tube reinforced with the aluminum stiffeners exhibited an increase in flexural stiffness of up to 21.5% relative to the unreinforced tube of identical dimensions.

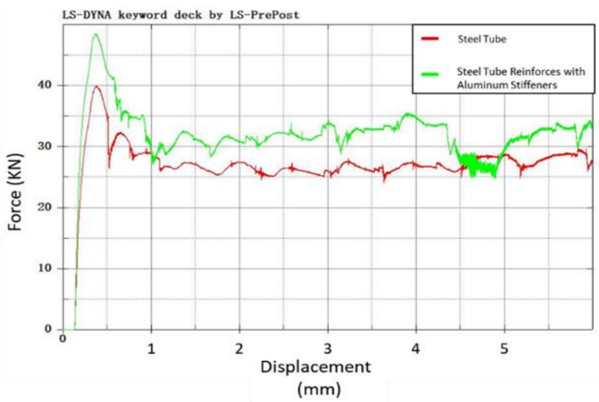

Figure 10. *Force-Displacement curve of the original 40×60×2 mm steel tube and the same tube reinforced with AA6060T4 aluminum stiffeners*

5.2. Improment method

Aluminum stiffeners were strategically placed at structurally critical regions of the bus frame identified as highly susceptible to significant deformation during rollover events. The reinforcement configuration adheres to the schematic layout depicted in Figure 11.

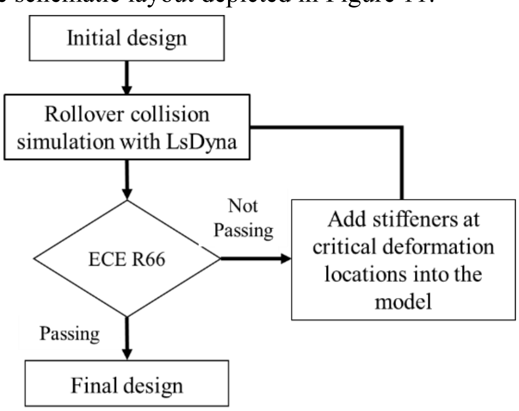

Figure 11. *Schematic diagram of the aluminum stiffener reinforcement layout on the bus frame*

These stiffeners were systematically installed in zones exhibiting elevated tensile stresses and concentrated strains, which are prone to structural instability or failure under extreme loading scenarios. In particular, the side panels and the rear sections adjoining the side frames were highlighted as especially vulnerable areas necessitating prioritized reinforcement.

The stiffeners were incorporated into the steel frame using rigid body elements (RBE2) to realistically simulate welded or mechanically fastened joints, ensuring efficient load transfer and structural continuity. The reinforcement layout was symmetrically designed along the vehicle's longitudinal axis to preserve dynamic equilibrium and prevent lateral mass imbalance, which could adversely affect rollover dynamics.

The reinforcement procedure for the bus frame was executed following the methodologies illustrated in Figure 11, with a careful selection of material and optimal placement of stiffeners to maximize structural performance. The aluminum stiffeners were specifically designed to enhance stiffness and energy absorption capacity during rollover events, ensuring the residual space remains uncompromised in accordance with ECE R66 standards.

Figure 12 provides a detailed illustration of the optimized stiffener locations. These reinforcements are arranged symmetrically along both sidewalls, with a particular concentration at the rear section of the vehicle - identified as the zone of highest concentration during lateral rollover.

Simulation results, as discussed in Section 6, demonstrate that this strategic configuration not only significantly reduces localized deformation but also substantially improves the overall stiffness of the bus frame. Consequently, this enhances occupant protection during rollover accidents by maintaining structural integrity and preserving critical safety zones.

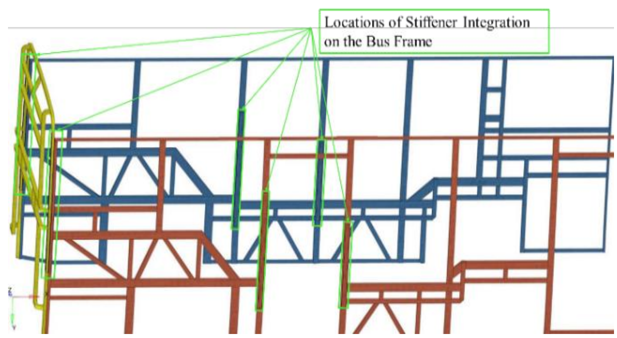

Figure 12. *Detailed illustration of the improved aluminum stiffener locations on the bus frame*

6. Post-Improvement Results

The reinforcement method for the monocoque bus frame using aluminum stiffeners was validated through rollover simulation tests conforming to the ECE R66 standard. The simulation outcomes demonstrated that the improved bus frame fully satisfies safety requirements, particularly in maintaining the integrity of the residual safety space during rollover accidents. This confirms the effectiveness of the reinforcement in enhancing structural stiffness, improving load-bearing capacity, and safeguarding passengers from injury risks during severe collisions.

Prior to improvement, the baseline bus frame model exhibited significant plastic deformation at critical locations such as the main sidewalls, auxiliary sidewalls, and rear sections, as illustrated in Figures 6 and 7. These areas experienced an intrusion into the residual safety space, the occupant protection zone, posing a direct threat to passenger safety. Specifically, structural components showed bending and distortion beyond material yield limits, leading to substantial degradation of strength and rollover resistance. This failure to contain deformation was the primary cause of non-compliance with the ECE R66 standard.

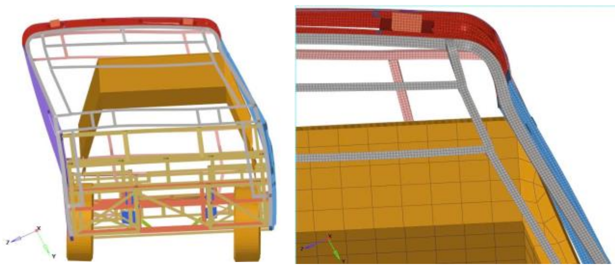

Figure 13. *Simulation outcomes of the bus frame following structural enhancement under rollover conditions*

After reinforcement with aluminum stiffeners, the bus frame model successfully maintained the residual safety space throughout the rollover simulation, as illustrated in Figure 13. The aluminum stiffeners were strategically placed in high-stress areas and critical structural joints, such as the intersections between the main beams and vertical pillars, the corners between the roof and side panels, the areas around the door openings, and the rear section where it connects with the two side panels. Installing the aluminum stiffeners at these locations significantly reduced plastic deformation and facilitated a more uniform stress distribution across the entire frame, thereby preventing intrusion into the residual space.

The symmetrical arrangement of the stiffeners also reduced the risk of localized failure in high-stress regions, especially at the rear of the vehicle - a zone that typically experiences the highest stress concentrations during rollover events (see Figure 12). This symmetrical configuration ensures balanced load distribution, minimizes uneven deformation, and enhances the overall load-bearing capacity of the frame, particularly under complex loading conditions. Since the stiffeners are designed symmetrically, they do not affect the rollover direction specified in the ECE R66 standard, while ensuring passenger protection regardless of rollover onto either the main or auxiliary side.

Simulation results further indicate that the severe deformation zones identified in the initial design were substantially controlled after reinforcement. As shown in Figure 14, plastic deformation of the frame was markedly reduced, particularly around the auxiliary sidewalls, the rear section where it interfaces with both side panels, and the roof junction. This demonstrates that the aluminum stiffener reinforcement not only improves load-bearing capacity but also maintains the structural integrity of the bus frame throughout the impact events.

Another crucial factor assessed is the impact of reinforcement on vehicle weight. The simulation results indicate that the addition of aluminum stiffeners increased the bus weight from 7765 kg to 7770 kg, representing a minimal increase of approximately 0.06% (as shown in Table 4). This increase is negligible compared to traditional reinforcement techniques, such as increasing the thickness of the steel beams. As a result, the bus continues to maintain optimal performance while reducing fuel consumption, thereby meeting both economic and environmental sustainability goals.

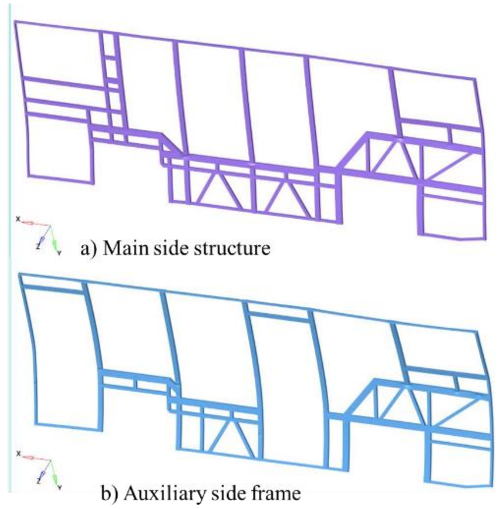

Figure 14. *Significant reduction of plastic deformation observed throughout the bus frame*

Table 4. *Comparison of simulation results before and after reinforcing the bus frame*

Criteria	Before Improvement	After Improvement
Residual Safety Space	Not achieved	Achieved
Plastic Deformation	High	Significantly reduced
Vehicle Weight (Full Load)	7765 kg	7770 kg

A comparison between the initial and improved designs, summarized in Table 4, clearly highlights the significant enhancement in the bus frame's crashworthiness. Before the reinforcement, the frame failed to meet the required residual safety space, with significant plastic deformation occurring at several critical locations. After the incorporation of aluminum stiffeners, these issues were largely mitigated, ensuring that the safety space remained intact and minimizing the potential for structural failure during rollover accidents.

The simulation results affirm that the method of reinforcing the bus frame with AA6060T4 aluminum stiffeners provides an effective solution for enhancing load resistance and passenger safety in compliance with the ECE R66 standard. The strategically placed stiffeners effectively reduce localized deformation, distribute stress more uniformly across the frame, and maintain the structural integrity during rollover events. Particularly, the symmetrical placement of the aluminum stiffeners ensures that the frame retains its protective function regardless of the rollover direction, fully meeting the test requirements specified in the ECE R66 standard. This reinforcement strategy also demonstrates economic viability, with only a slight increase in vehicle weight, thereby maintaining fuel efficiency and operational performance. The findings from this study indicate that the aluminum stiffener reinforcement method is an optimal solution, enhancing passenger safety and contributing to the development of sustainable and environmentally friendly public transportation systems.

7. Conclusion

This study proposes a reinforcement method for the monocoque bus frame using aluminum stiffeners made from AA6060T4 alloy, designed to improve load-bearing capacity and ensure safety during rollover scenarios, fully complying with ECE R66 standards. Finite element analysis results demonstrate that this reinforcement approach significantly reduces plastic deformation in critical areas, ensuring that the frame maintains the residual safety space throughout the entire rollover simulation.

Notably, the symmetrical placement of the aluminum stiffeners on the frame ensures that load-bearing capacity is unaffected by the rollover direction in the test. This design allows the bus frame to maintain effective passenger protection in both rollover directions, in line with the requirements of the ECE R66 standard. The symmetric configuration also helps to evenly distribute stresses and reduce the risk of localized failure in vulnerable areas, such as the auxiliary sidewall, main sidewall, and rear section.

A prominent advantage of this reinforcement method is that the vehicle weight increases by only 0.06% after optimization, ensuring that the bus retains its operational efficiency and minimizes fuel consumption. Compared to traditional reinforcement methods, such as increasing material thickness, the use of aluminum stiffeners offers a lighter, more cost-effective solution with superior load-bearing performance. Additionally, the ease of installation, reusability, and high economic efficiency of aluminum stiffeners make them an attractive option for large-scale manufacturing.

The results of this study indicate that applying aluminum stiffeners to the bus frame is a feasible solution that enhances the safety of public transportation vehicles, while contributing to the development of sustainable and environmentally friendly transportation solutions. This research paves the way for future advancements in bus frame design in Vietnam and sets the stage for broader applications of aluminum stiffeners in the global bus manufacturing industry.

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