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Bus Superstructure Reinforcement for Safety Improvement against Rollover Accidents

Sandro Mihradi, Andhika Dhaniswara, Satrio Wicaksono* & Andi Isra Mahyuddin

Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung,
Jalan Ganesa 10, Bandung 40132, Indonesia
*E-mail: satriowicaksono@ftmd.itb.ac.id

Highlights:

- Prior to reinforcement, the studied bus superstructure failed to fulfill the UNR66 residual space criterion.
- A simple methodology is introduced to quantify the rollover performance by using the horizontal intrusion distance to the residual space.
- Rollover performance comparison of several types of bus superstructure reinforcements was conducted.

Abstract. Bus rollover is considered the most dangerous road accident. To ensure bus safety against rollover accidents, the bus superstructure must conform to safety standards, one of which is UNR66. Unfortunately, in Indonesia, the increase in the number of buses has not been followed by bus safety improvement. In this paper, a numerical study on superstructure reinforcement to improve bus safety against rollover is presented. To reduce computational time, a simplified bus superstructure model comprising only three middle bays was used instead of a full bus model. Several superstructure reinforcements were implemented and their effectiveness in improving bus safety against rollover accidents was investigated. Among all reinforcements that were investigated, the most effective one was enhanced reinforcement by adding a connection between the seat structures and the side pillars. This modification yielded excellent results, as the modified superstructure showed a very significant improvement over a superstructure without reinforcement and it met the UNR66 residual space safety criterion.

Keywords: *finite element analysis; Indonesian bus; superstructure reinforcement; rollover safety; UNR66.*

1 Introduction

The number of buses in Indonesia keeps growing every year, as it is one of the leading transportation modes in the country. The increase in the number of buses, unfortunately, has been followed by a rise in the number of accidents involving buses [1]. Among the various types of accidents involving buses, the most lethal one is rollover, as 61% of fatalities in bus accidents may be attributed to rollover

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[2]. Thus, the importance of ensuring bus safety, especially against rollover, is apparent. Bus safety against rollover regarding the strength of its superstructure is regulated in United Nations Regulation 66 (UNR66), which requires a rollover test to be performed on a specific bus model to ensure its safety against rollover [3]. Unfortunately, rollover testing on bus superstructures is costly. Another method, which is allowed by UNR66, and much more economical, is computer simulation [3]. The finite element method is a computer simulation method that is relatively cheap and accurate, yet easy to implement.

The finite element method has been commonly used in bus crashworthiness analysis for various collision types, such as frontal collision [4,5], side collision [6,7], and rear collision [7]. In bus rollover analysis, Satrijo, *et al.* [8] tried to model a rollover accident of an electrical bus by simplifying the impact due to rollover as static load and constraining the bottom part of the superstructure. This analysis has several weaknesses, as converting the rollover impact energy to a static load may lead to a massive discrepancy in the results. In addition, over-constraining the bottom part of the superstructure may lead to overestimation in the deformation results. In a previous study, a finite element rollover analysis of one of the most common Indonesian intercity buses was performed by modeling the whole bus superstructure under rollover impact condition [9] as stated in UNR66. The result showed that the studied bus model was not safe against rollover accidents, as it did not comply with UNR66 [9]. This result raises enormous concern about the rollover safety of other bus models, especially in Indonesia, where UNR66 is not yet being enforced. Thus, finite element rollover analysis of other bus models, especially in Indonesia, is critical, as well as, if necessary, modification of the original bus design to reinforce the superstructure. The full bus model used in the previous study was unfortunately computationally very expensive. Bai, *et al.* [10] tried to reduce the computational cost in bus rollover analysis by simplifying the frame in the bus superstructure as a combination of beam elements and plastic joints. Although the result was quite good, with only slight underestimation in the results of the total energy absorbed, the model was too complicated, as it needed cautious remodeling of the bus superstructure and prior calculation of the geometric properties of the beam elements and the plastic joint properties.

In the current study, bus superstructure reinforcement was performed to a simplified model, which consisted of only three middle bays to avoid adding complexity in the simplification process. The model used in the current study was based on a full bus model made by a local bus manufacturer in Indonesia, which was developed in a previous study [11]. Based on the rollover response of the initial body section model, several different types of reinforcement were then evaluated to find the best reinforcement type to ensure conformity of the bus superstructure to UNR66.

2 Methodology

In the current study, the finite element method was used to find the best reinforcement type to improve bus safety against rollover. Several steps needed to be taken to achieve this goal. The first step was model simplification from a full bus model, which was developed in a previous study [11], followed by an initial simulation of the simplified model (bus section model) without reinforcement. The initial simulation results were the critical locations of the bus section based on the deformation and stress results. The next step was designing superstructure reinforcement at the critical locations, followed by simulation of the reinforced body section models. In the final step, rollover performance analysis was carried out to determine the best reinforcement type. Combining different reinforcement types was outside the scope of this study.

To compare the performance of each superstructure modification/reinforcement type, a value that quantifies the rollover performance was defined. As UNR66 states that the residual space must not be intruded by the bus structure during rollover [3]. Based on previous results, where most of the residual space got intruded at the top corner near to the impacted area [9], in the current study the rollover performance was quantified by the horizontal distance (*d*) between the corner of the residual space and the side pillars at the impacted side, as shown in Figure 1. A positive *d* value means the residual space is not intruded and a negative *d* value means the residual space is intruded.

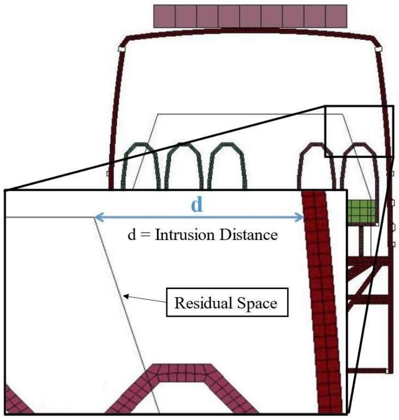


Figure 1 Illustration of reinforcement performance quantification (d).

3 Initial Finite Element Modeling

A finite element model was built to mimic the rollover testing in UNR66. As previously stated, the model used in the current research was a simplification of the model that was developed in the previous study [11]. The simplification was performed by taking only three middle bays from the previous model, as shown in Figure 2. These three middle bays were chosen because the three middle bays were considered sufficient to represent the whole superstructure and possessed lower bending stiffness than the front and rear bays. Thus, if the middle bays fulfill the residual space criterion, the front and rear bays as well as the whole superstructure will also certainly fulfill the residual space criterion. The body section model consisting of three middle bays is shown in Figure 3.

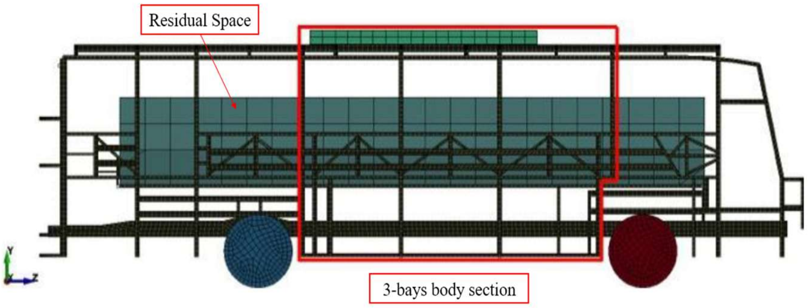


Figure 2 Bus section considered in the simplified model.

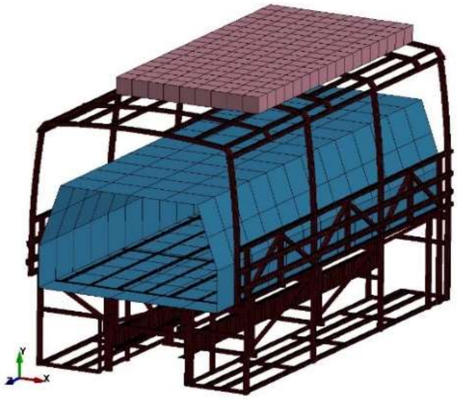


Figure 3 Bus body section model.

To model the seat arrangement and the passenger mass, model of the seats was added based on the seat arrangement from the bus manufacturer. Then, a lumped mass representing a passenger was added to each seat, as shown in Figure 4. The final body section model with all chairs and masses representing the passengers is shown in Figure 5. Additionally, the material used for the superstructure and seat structure was STKM 13B with mechanical properties as shown in Table 1.

Table 1 STKM 13B mechanical properties [11].

Material Properties	Values
Density	7,830 kg/m^3
Young's modulus	200 GPa
Poisson's ratio	0.3
Yield strength	309 MPa
Ultimate tensile strength	667 MPa

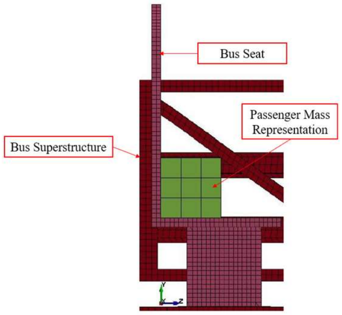


Figure 4 Passenger mass representation on the chair model.

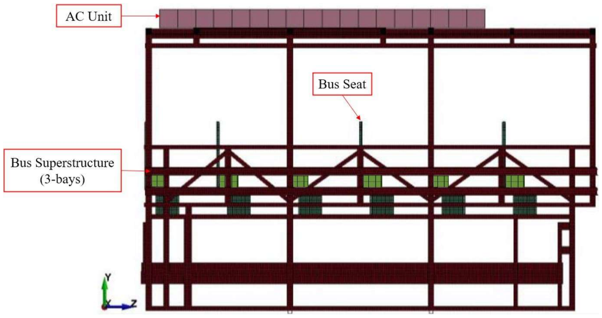
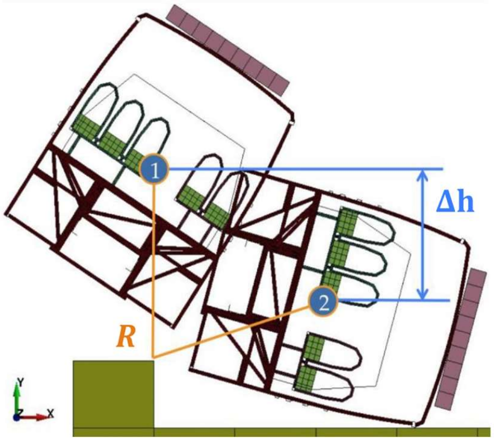


Figure 5 Final body section model with chairs and passenger masses.

To further reduce the computational time, the rollover simulation was started at the state when the body section was just about to touch the floor (position 2) instead of when the body section was in an unbalanced position (position 1), as illustrated in Figure 6. The body section angular velocity at the time of impact can be calculated using Eq. (1).

$$\omega = \sqrt{\frac{2mg(\Delta h)}{I_o + mR^2}} \quad (1)$$

where m is the total mass of the body section, Δh is the rollover height difference as illustrated in Figure 6, I_o is the body section mass moment of inertia through its center of gravity, R is the distance between the center of gravity and the rollover center of rotation, and $I_o + mR^2$ is the mass moment of inertia through the rollover center of rotation.



R = Distance between bus center of gravity to center of rotation

Δh = Height difference between the center of gravity at position 1 and 2

Figure 6 Illustration of the body section model movement.

As mentioned above, the body section model was divided into several parts: the body section frame with a mass of 732 kg, the seat structures with a total mass of 218 kg, the air conditioner system with a mass of 160 kg, and the passengers with a total mass of 1020 kg. Thus, in total, the mass of the body section model was 2,130 kg. The calculated value of the mass moment of inertia (I_o) was 2.547 x 10^9 kg.mm^2. Furthermore, with R and Δh values of 2,324 mm and 1,618 mm, respectively, the angular velocity of the body section at the time of impact was calculated using Eq. (1) with the result of 2.193 rad/s.

A convergence test was performed to ensure the validity of the body section model. Three different total numbers of elements were attempted: 48,930, 94,982, and 118,276 elements. The body section model with 118,276 elements was chosen as the final model, as it gave an acceptable relative error of 1.2%.

Although the convergence test had already been performed, the validity of the body section simulation in terms of energy still needed to be confirmed. Three different things need to be verified to confirm the validity of a model in terms of energy. Firstly, the actual initial kinetic energy is supposed to be the same as the theoretical potential energy of the bus body section in an unbalanced position (position 1 shown in Figure 6). The theoretical potential energy was calculated analytically based on the model mass and dimension, with the result of 33,827 Joule. As shown in Figure 7, the actual initial kinetic energy had a value of 33,872 Joule, which is very close to the body section theoretical potential energy with an error of 0.133%. The next thing that needed to be confirmed was the gradient of the sliding energy, which should not give a negative value for the whole simulation. This model fulfilled this condition because the simulated sliding energy, as shown in Figure 7, had no negative gradient. The last thing to be checked was the ratio between the total energy and the sum of external work and initial value of total energy, which is supposed to have a value close to 1. The ratio was calculated from the values shown in Figure 7, which gave a maximum ratio of 1.0017, which is equal to a maximum error of 0.17%. Thus, the validity of the body section simulation was confirmed, as all three above conditions were fulfilled. Additionally, a previous study conducted by Wicaksono *et al.* [9] yielded a similar energy curve to the one obtained in this study, which strengthens the validity of the current body section simulation.

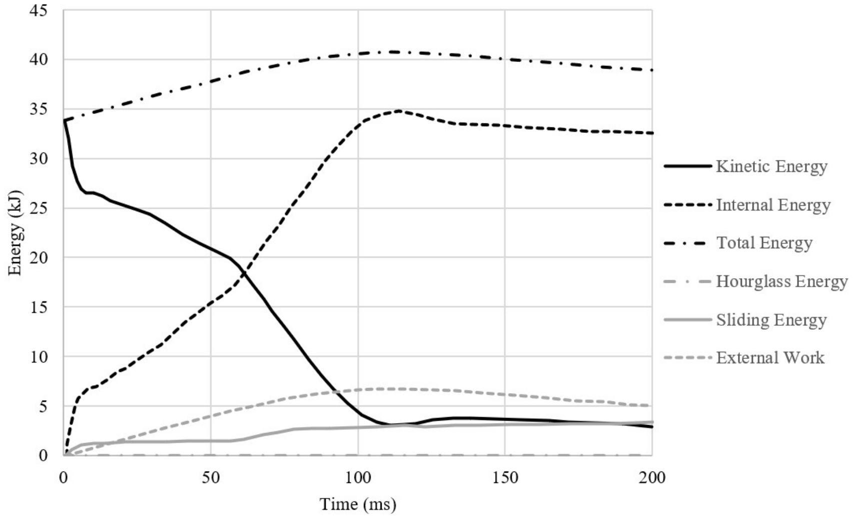


Figure 7 Energy curve of the initial model simulation.

4 Initial Result and Superstructure Reinforcement

The initial result of the body section model without reinforcement is shown in Figure 8. It can be seen that the bus superstructure was not safe, as parts of the side pillar intruded the residual space with a *d* value of -95.1 mm, as shown in Figure 9. Therefore, it could be deduced that the superstructure of the bus model was not safe based on UNR66. Thus, superstructure reinforcement needed to be performed for this particular bus model.

The above result is consistent with the full bus model result from the previous work [11]. As shown in Figure 10, there was an identical deformation of the bus superstructure compared to Figure 8. However, the intrusion of the side pillar into the residual space in the previous work was only 15.3 mm (*d* = -15.3 mm) [11]. This result is understandable, since the three middle bays simulated in the present work represent the weakest section of the whole bus in terms of bending stiffness. Additionally, a comparison with experimental results from the literature was also performed. The deformation in the present work was similar to that in the body section rollover experiment performed by Gürsel, *et al.* [12]. Most of the body section deformation occurred above the bus floor up to the roof, while the rest of the structure sustained minimal deformation.

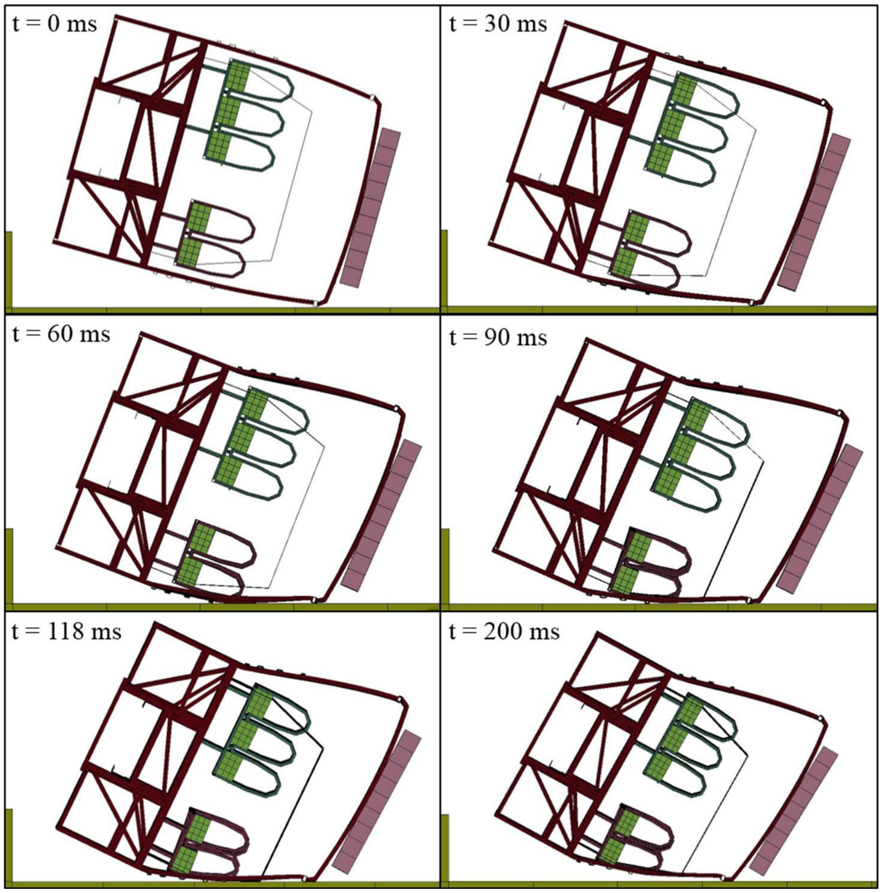


Figure 8 The test results of the body section model without reinforcement at several time steps.

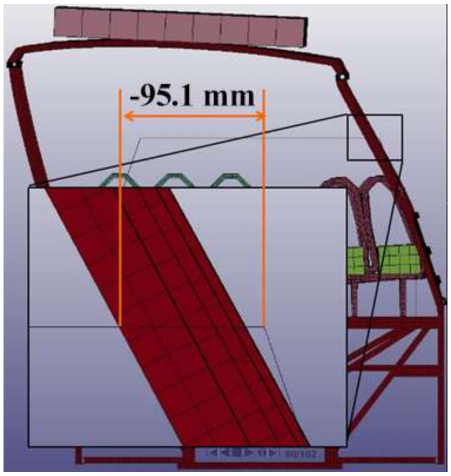


Figure 9 The *d* value of the body section model without reinforcement.

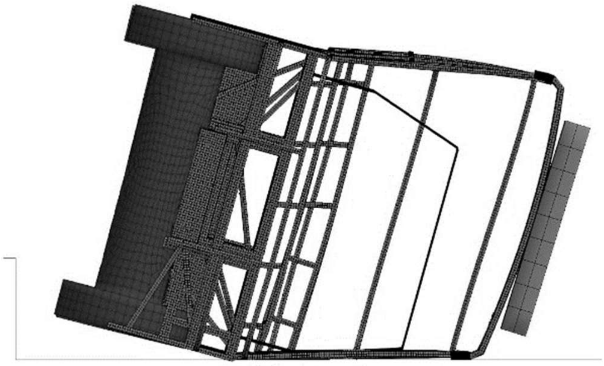


Figure 10 The simulation results of the full bus model without reinforcement from the previous work [11].

Further analysis of the body section model without reinforcement showed that the most substantial deformation and stress occurred at the connection between the roof structure and the side frame, as well as at the connection between the floor structure and the side frame. Thus, reinforcements in those areas might significantly improve the superstructure performance against rollover. Moreover, in the simulation it was also observed that the seat structures, especially the one nearest to the impacted side, also helped to withstand the deformation and the impact load. The stress distribution result of the seat structure is shown in Figure 11. It was clear that some critical areas of the seat structure experienced relatively high stresses.

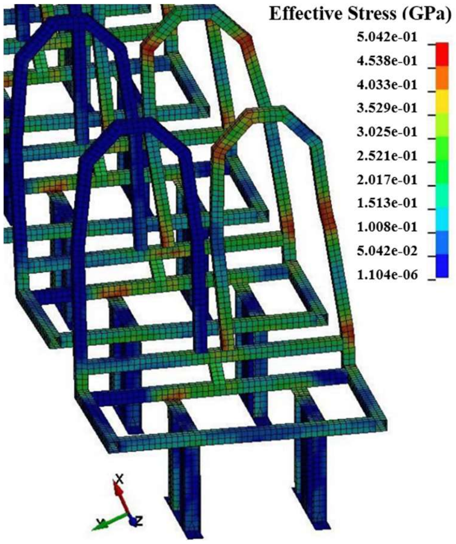


Figure 11 Seat structure stress distribution.

Based on the deformation and stress distribution results of the body section's main structure, several different reinforcements were designed to improve these critical areas. The first reinforcement design added lower gussets at the connection between the floor structures and the side pillars, as shown in Figure 12. The following design added upper gussets to improve the stiffness at the connection between the roof structure and the side pillars, as shown in Figure 13. Figure 14 shows the next reinforcement type by adding side pillars.

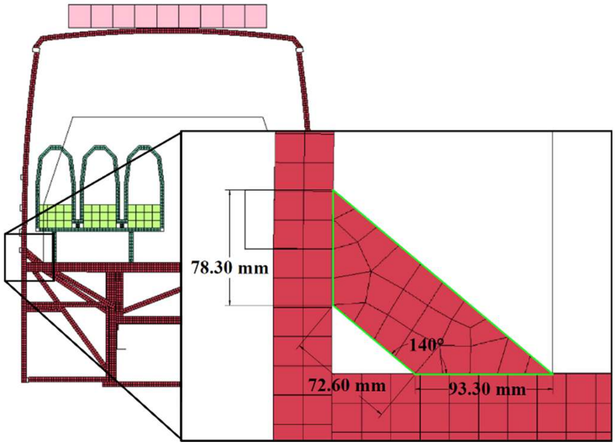


Figure 12 Illustration of lower gusset structure reinforcement.

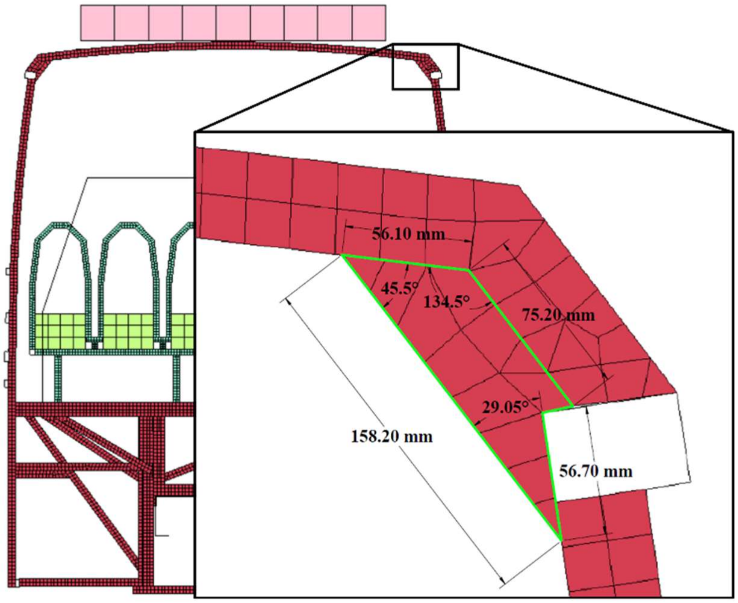


Figure 13 Illustration of upper gusset structure reinforcement.

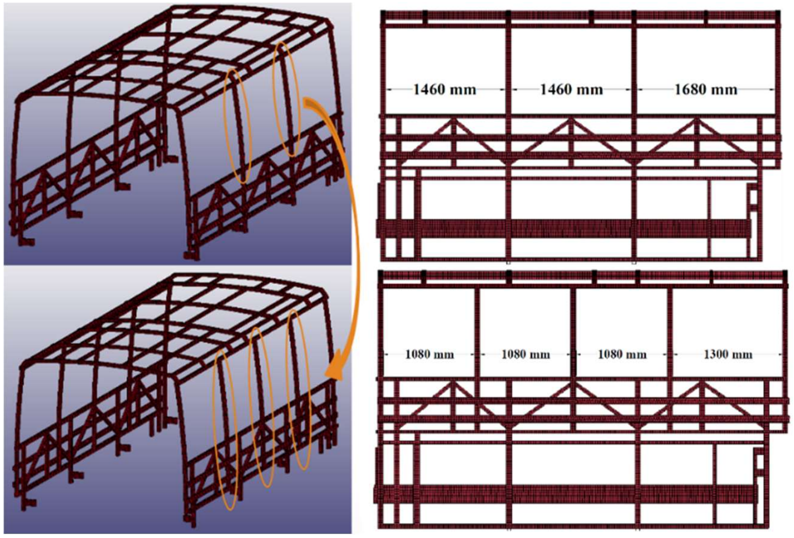


Figure 14 Illustration of structure reinforcement by adding side pillars.

Additionally, three different reinforcement designs were generated based on the deformation and stress distributions of the seat structure. The first design was added connections between the seat structures and the side pillars, as shown in Figures 15 and 16. Furthermore, the last two reinforcements were performed by adding a seat gusset and horizontal seat bar, as shown in Figures 17 and 18, respectively. Finally, different body section finite element models were built for each reinforcement design, after which the simulation was run.

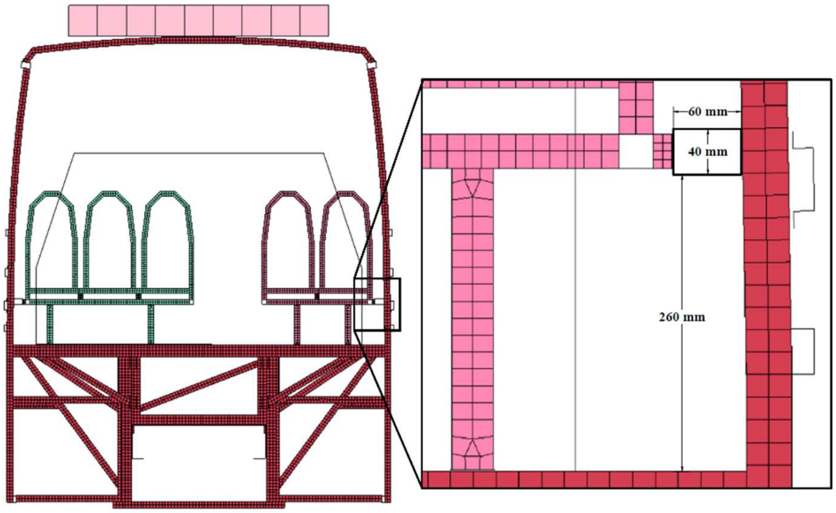


Figure 15 Illustration of seat structure to side pillar connection reinforcement.

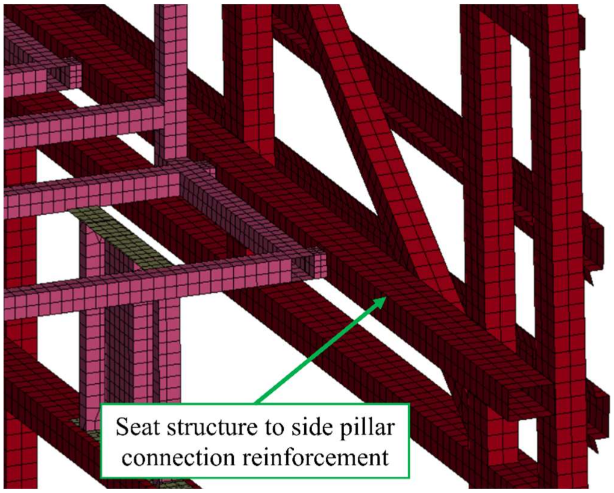


Figure 16 Isometric view of the seat structure to side pillar connection reinforcement.

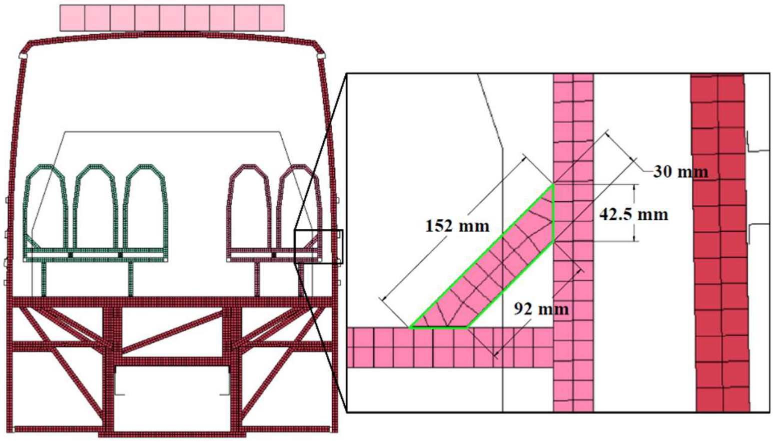


Figure 17 Illustration of seat gusset reinforcement.

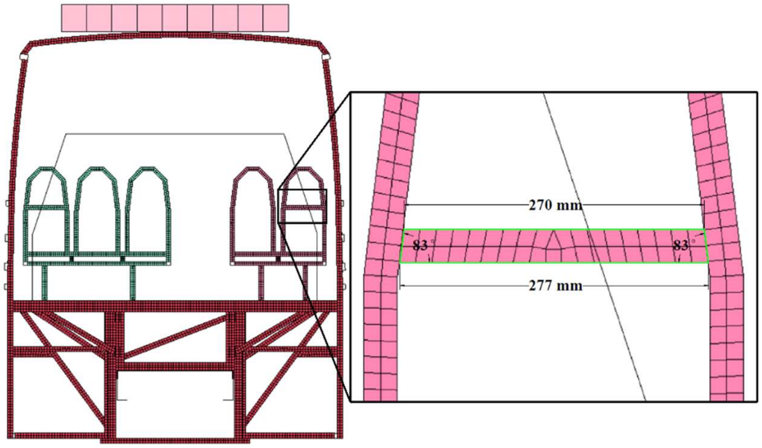
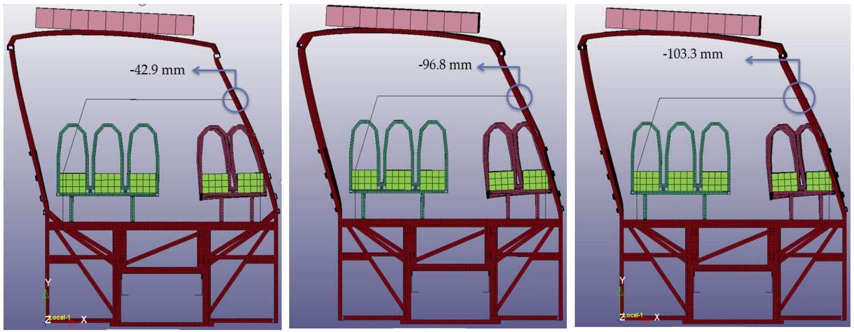


Figure 18 Illustration of seat reinforcement by adding a horizontal bar.

5 Results and Discussion

The simulation results of the main structure reinforcements and the seat structure reinforcements are shown in Figure 19 and Figure 20, respectively, with all *d* values and *Δd* values (relative *d* value over the body section without reinforcement) listed in Table 2. The lower gusset reinforcement gave a *d* value of -42.9 mm, as shown in Figure 19a, which was still not safe based on UNR66, but showed significant improvement (*Δd* = 52.5 mm) in comparison to the initial body section model. This result indicated that the lower gusset significantly strengthened the connection between the floor structure and the side pillars and significantly improved the bending stiffness of the body section. Reinforcement using the upper gusset, on the other hand, did not show a significant change in comparison to the body section without reinforcement, as can be seen in Figure 19b. Most certainly this was caused by the dimension of the upper gusset, which was too small and did not cover the critical area. Thus, it would not provide a significant additional reinforcement to the body section. An interesting result was discovered in the case of the side pillar reinforcement. As shown in Figure 19c, the side pillar reinforcement performed worse than the body section without reinforcement. The reason behind this was that the side pillars were not aligned with the lateral roof structure, as shown in Figure 14. Thus, the bending stiffness was smaller than that of the original configuration, where the pillars were all aligned with the lateral roof structure. It is interesting to note the importance of preserving the alignment of the superstructure from the side to the roof of the bus, as it increases the bending stiffness of the superstructure.



(a) (b) (c)

Figure 19 The *d* value of the primary structure reinforcements: (a) lower gusset, (b) upper gusset, and (c) side pillar addition.

The seat gusset and horizontal seat bar reinforcements yielded *d* values of -62.1 mm and -67.9 mm, respectively, as shown in Figures 20b and 20c, which were decent improvements over the body section without reinforcement. The addition of a seat gusset and horizontal seat bar improved the stiffness of the seat structure, thus reducing the deformation due to rollover. It should be noted that when deformation takes place, the waist rail, the longitudinal structural part of the bodywork below the side windows, presses against the seat structure. This phenomenon helps to reduce the bending of the side pillars.

The addition of a connection between the seat structure and the side pillar, on the other hand, resulted in a *d* value of 23.1 mm, which was a 118.2 mm improvement over the body section without reinforcement. This improvement was the best among all investigated reinforcement types. The additional connections made the seat structure perform similarly to a massive lower gusset connecting the side pillars and the floor structure. Due to the size of the seat structure, which is considerably larger than the lower gusset used in the previous reinforcement, the improvement of the body section's bending stiffness was massive. Thus, the deformation due to rollover was much smaller than the body section with lower gusset reinforcement. However, the current reinforcements in the body section model were able to be applied since the seat structure positions in this model were perfectly aligned with the side pillars. For other models, some adjustments need to be applied. For example, instead of connecting directly to the side pillar, the seat structure could be connected to the waist rail, which will transfer the force from the side pillars in the course of bending due to rollover.

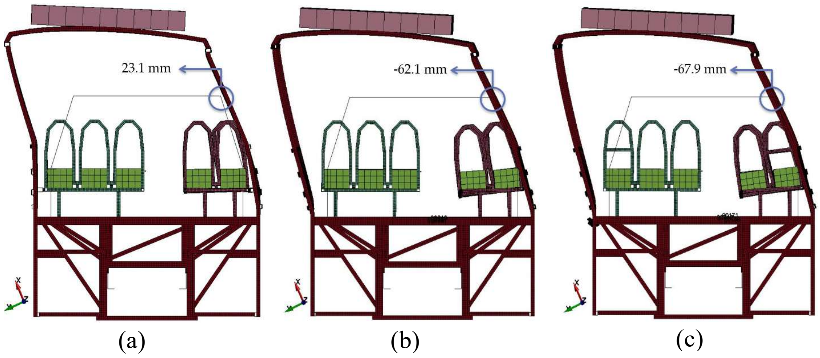


Figure 20 The *d* value of the seat structure reinforcement: (a) seat structure to side pillar connection, (b) seat gusset, and (c) horizontal seat bar.

Table 2 Results of horizontal distance to residual space.

Reinforcement type	*d* (mm)	*Δd* (mm)
No reinforcement	-95.1	0
Lower gusset	-42.9	52.2
Upper gusset	-96.8	-1.7
Side pillar addition	-103.3	-8.2
Seat structure and side pillar connection	23.1	118.2
Seat gusset	-62.1	33
Horizontal seat bar	-67.9	27.2

As shown in Table 2, the only reinforcement type that fulfilled the UNR66 residual space criterion was the seat structure and side pillar connection. Although the present results were achieved on the current bus section model, the idea could also be implemented in other bus models. The resulted reinforcement may significantly improve bus rollover performance in general when implemented in the future.

6 Conclusions

Rollover numerical analysis of a bus superstructure model made by a local bus manufacturer in Indonesia was presented. The superstructure without reinforcement failed to fulfill the UNR66 residual space criterion. Several different modifications and reinforcements were then performed to the bus body section model based on the deformation and stress results of the initial body section model. Six reinforcement types were investigated: lower gusset, upper gusset, side pillar addition, connection between seat structure and side structure, seat gusset, and horizontal seat bar. Based on the simulation results, the best reinforcement type was the connection between seat structure and side structure, which resulted in a 118.2 mm improvement in the horizontal distance to the residual space compared to the body section without reinforcement. This type of reinforcement can be implemented in new bus production to improve the safety against rollover accidents, especially in Indonesia.

This work is considered a giant leap in improving bus safety in Indonesia. In the near future, experimental tests will be performed to validate the current results. Additionally, the effect of the superstructure modification on the injuries of passengers will also be studied.

Acknowledgments

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References

[1] Transportation Ministry Secretariat General, *Transportation Statistics 2015*, Transportation Ministry Secretariat General – Data and Information Center, Jakarta, 2016. (Text in Indonesian)
[2] US Department of Transportation, *Motorcoach Safety Action Plan*, Federal Motor Carrier Safety Administration, 2012.
[3] United Nations, *Uniform Technical Prescriptions Concerning the Approval of Large Passenger Vehicles with regard to the Strength of Their Passenger Vehicles with regard to the Strength of Their Superstructure (Revision 1)*, Regulation No. 66 of the Economic Commission for Europe of the United Nations, 2006.

[4] Jongpradist, P., Senawat, S. & Muangto, B., *Improvement of Crashworthiness of Bus Structure under Frontal Impact*, The 2015 World Congress on Advances in Structural Engineering and Mechanics (ASEM15), 2015.

[5] Meira, A.D. Jr., Iturrioz, I., Walber, M. & Goedel, F., *Numerical Analysis of an Intercity Bus Structure: A Simple Unifilar Model Proposal to Assess Frontal and Semifrontal Crash Scenarios*, Latin American Journal of Solids and Structures, **13**(9), pp. 1616-1640, Sept. 2016.

[6] Li, H., Nimbalkar, R., Kwasniewski, L. & Wekezer, J., *Finite Element Analysis of a Transit Bus*, Structures Under Shock and Impact VIII, Jones, N. & Brebbia, C. A., eds., WIT Press, pp. 397-406, 2004.

[7] Tanov, R., Brueggert, M. & Yang, S., *Finite Element Modeling and Crash Analysis of a School Bus*. SAE Technical Paper 2003-01-3425, 2003.

[8] Satrijo, D., Kurdi, O., Haryanto, I., Yob, M.S., Riyantiarno, N., Taufiqurrahman, I., *Rollover Performance Analysis of Electric Bus Superstructure Frame with Alternative Material Using Finite Element Method*, AIP Conference Proceedings, 2217, 030153, 2020.

[9] Wicaksono, S., Rahman, M.R.F., Mihradi, S. & Nurhadi, I., *Finite Element Analysis of Bus Rollover Test in Accordance with UN ECE R66 Standard*, Journal of Engineering and Technological Sciences, **49**(6), pp. 799-810, Dec. 2017.

[10] Bai, J., Meng, G. & Zuo, W., *Rollover Crashworthiness Analysis and Optimization of Bus Frame for Conceptual Design*, Journal of Mechanical Science and Technology, **33**(7), pp. 3363-3373, April 2019.

[11] Abdiwijaya, C.Z., *Rollover Safety Analysis of Indonesian Passenger's Bus Structure and Related Regulation Proposal*, Master Thesis, Institut Teknologi Bandung, Bandung, Indonesia, 2017. (Text in Indonesian)

[12] Gürsel, K.T. & Gürseslí, S., *Analysis of the Superstructure of a Designed Bus in Accordance with Regulations ECE R 66*, Gazi University Journal of Science, **23**(1), pp. 71-79, January 2010.