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Aluminium-based Light-weight Bus Superstructure Design to Comply to Global Rollover Regulations

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Abstract – *The number of vehicle accidents in Indonesia has an upward trend as a consequence of the yearly increasing number of motor vehicles. Rollover accidents, especially those involving bus, have the highest number of fatality due to the limited strength of bus superstructure. Common bus superstructure is constructed by using a standard medium strength steel. This makes the bus has heavy mass with high center of gravity which influences its rollover propensity. Hence, an improvement of bus superstructure with light-weight concept and higher rollover resistance is needed. In this study, a bus superstructure is redesigned by changing its material from steel to aluminium 6061-T6. The new superstructure is redesigned by adding the extruded-roof-edge and by thickening parts that function as energy absorbers during accident. Rollover simulations of the bus with modified superstructure are then carried out using finite element analysis and the superstructure is evaluated by using regulations related to roof crush resistance i.e. FMVSS 216 which uses force method and UN R66 which uses energy method. The results show that the new design of aluminium-based bus superstructure fulfils the FMVSS 216 and UN R66. The results also indicate that by using aluminium material the empty weight of the bus is reduced by 40%, which will improve its rollover stability and fuel efficiency.*

Keywords: Overweight, rollover accident, reinforcement, light-weight bus superstructure, FMVSS 216, UN R66

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1.0 INTRODUCTION

Indonesia is a state with a high population growth rate and mobility (Kata Data, 2017). The number of vehicles in the country, namely passenger cars, busses, freight cars and motorcycles, is growing as shown in Figure 1 (Badan Pusat Statistik, 2017b). The increasing number of vehicles should be followed by the increasing of appropriate infrastructure. However, based on the collected data for 2000–2016 (Badan Pusat Statistik, 2017a), the number of vehicles has increased 13%, while the road length increases only 3% in average every year, as shown in Figure 2. This growth discrepancy causes the roads are loaded more frequently and damaged sooner than expected (Yudaningrum, 2017).

The increasing number of vehicles is also followed by the increasing number of vehicle accidents on the highways as shown in Figure 3 (Badan Pusat Statistik, 2017c). Based on data from National Transportation Safety Committee (NTSC) about the fatality of car vehicle accidents from 2007–2016, a high portion of fatality is due to rollover as shown in Figure 4 (Komite Nasional Keselamatan Transportasi, 2018). Figure 5 illustrates the after-crash condition of a bus rollover accident in Indonesia (Jawa Pos, 2014). The roof and vertical pillars of bus structure intruded into the passenger's safe space and injured them.

Those reasons urge to improve bus design in Indonesia such that it has lower weight yet sufficient rolling resistance. Reducing bus superstructure weight which is constructed mostly from a standard medium strength steel is the most obvious way to carry out this improvement. Reducing superstructure weight also will lower bus center of gravity which influences its rollover propensity. This paper presents the development of light-weight bus superstructure design using Aluminium 6061 T6 material that has lower density and sufficient strength to replace the existing steel superstructure which is commonly used. It is expected that the new design will improve bus rolling resistance and reduce weight that will reduce road damage.

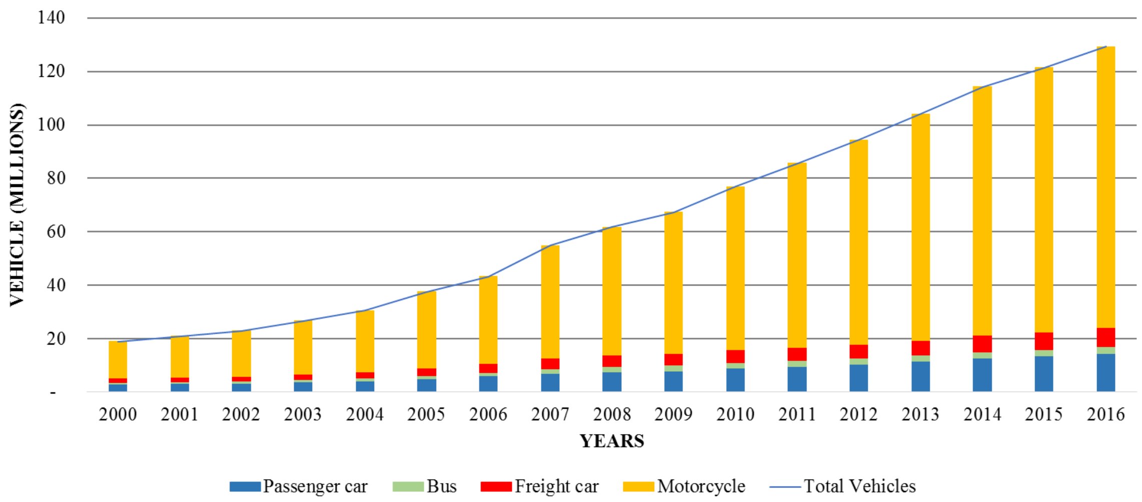


Figure 1: Motor vehicle growth curve in Indonesia in 2000-2016 (Badan Pusat Statistik, 2017b)

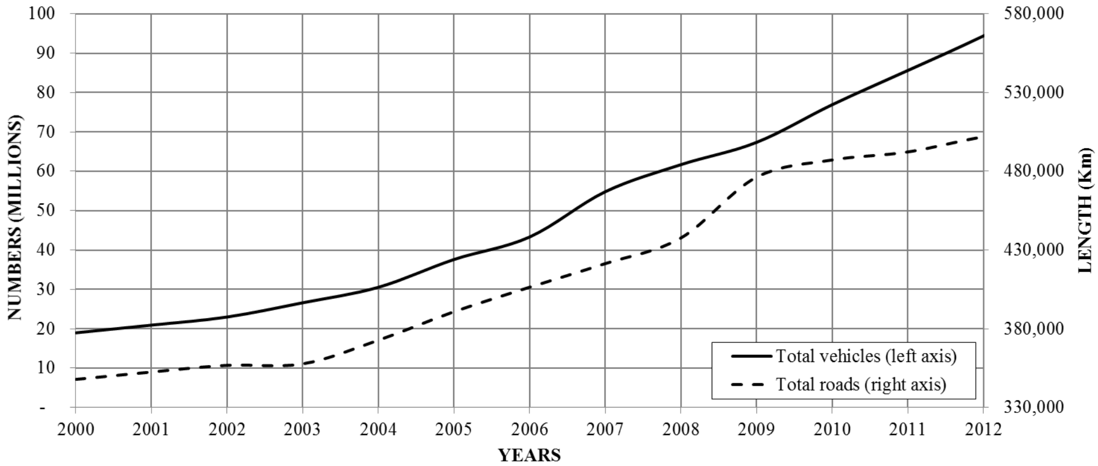


Figure 2: Vehicle and road growth curve in Indonesia in 2000-2016 (Badan Pusat Statistik, 2017a)

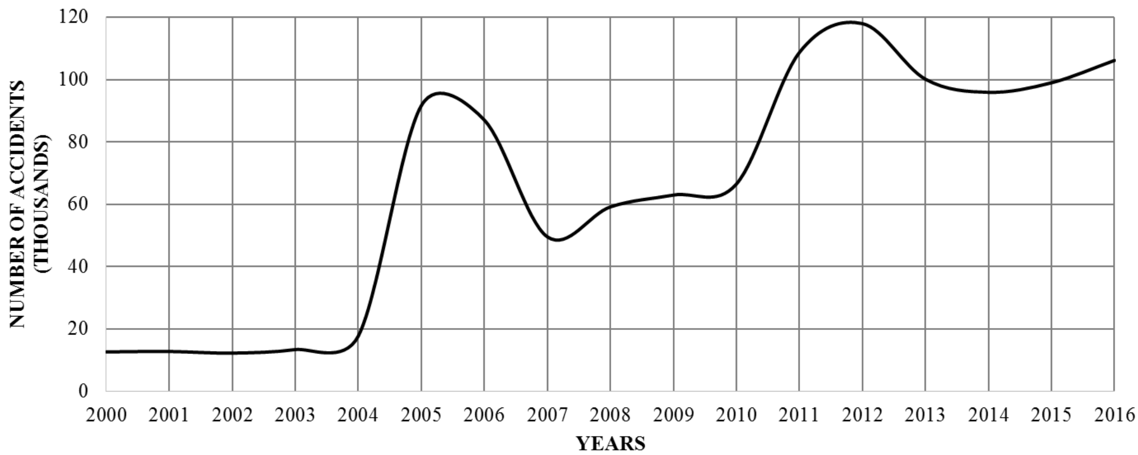


Figure 3: Accidents occurrences growth curve in Indonesia in 2012-2016 (Badan Pusat Statistik, 2017c)

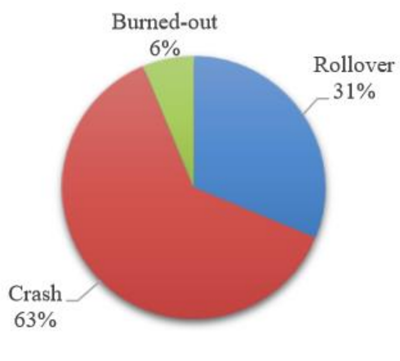


Figure 4: Fatality in each car accident in Indonesia in 2007-2016 (Komite Nasional Keselamatan Transportasi, 2018)

Figure 5: Rollover bus (Jawa Pos, 2014)

2.0 REGULATIONS

Bus structure strength during rollover accident is evaluated by using Federal Motor Vehicle Safety Standards (FMVSS) 216 and United Nations Economic Commissions for Europe (UNECE) R66 standards – previously shortened as UNECE R66, and presently referred to as UN R66 (Wahab et al., 2017). FMVSS 216 is based on the evolution of the crushing force, while UN R66 on the structure capability to absorb energy.

2.1 FMVSS 216

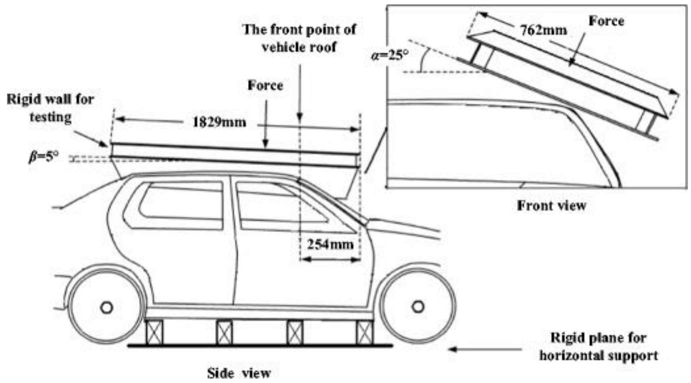


Figure 6: FMVSS 216 test section (US Department of Transportation, 2012)

FMVSS 216 is issued by Federal Motor Vehicle Safety Standards in the United States (US Department of Transportation, 2012). Figure 6 illustrates the test configuration during the evaluation by using the FMVSS 216 regulation. The car is placed on a rigid support system so that the sill or chassis of the car is in pinched or fixed position. Rollover accident is simulated by slowly moving an impactor in the form of a rigid plate that is oriented at certain α and β angles in the direction normal to its contact surface to crush the roof edge (cant rail) until its displacement reaches 127 mm or until the crushing force equals to 150% empty bus weight. The structure will comply the regulation if the crushing force reaches at least 150% of its empty weight just before the impactor moves 127 mm:

$$F = 1.5\,M\,g \tag{1}$$

where, F : crushing force (N)
M : mass of vehicle without passenger and baggage (kg)
g : gravity acceleration (m/s^2).

2.2 UN R66

UN R66 is issued by United Nations Economic Commissions for Europe (UNECE) in Europe (UNECE, 2006). Figure 7 illustrates the test configuration during the evaluation by using UN R 66. The bus is set on the horizontal support system and a residual space is defined in the superstructure. The residual space represents a safe space for passengers and driver inside the bus where it should not be intruded by any structure during a rollover accident. Rollover accident is simulated by loading the structure using rigid plate or impactor with quasi-static motion. The load configuration of the load system in UN R66 is shown in Figure 8 and its direction is stated in Equation 2.

$$\alpha = 90° - \arcsin(\frac{800}{H_c}) \tag{2}$$

Where, α : impactor angle (degrees),
H_c : roof edge height (m).

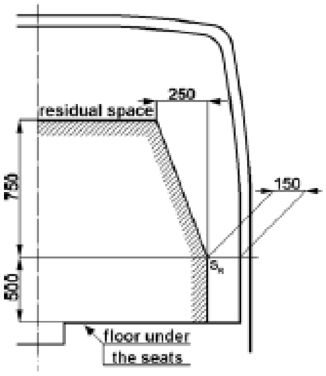


Figure 7: Residual space definition according to (UNECE, 2006)

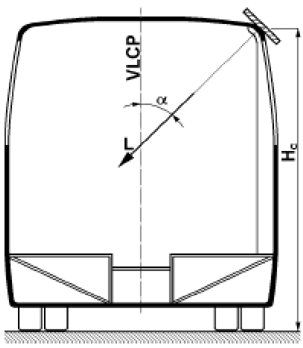


Figure 8: Rigid plate from regulation (UNECE, 2006)

The rigid plate is moved to crush the roof edge or can't rail until the ultimate deformation (*du*) is reached, i.e. when a part of bus structure starts to intrude into the residual space. The structure design will comply the regulation if the absorbed energy during the crush, in the form of increased internal energy (absorbed energy) E_T, at least equals to 75% of the change of the potential energy of the bus during roll over. The criteria are formulated as follows:

$$E_T = 0{,}75\ M\ g\ \Delta H \tag{3}$$

$$M = M_k + 0.5\ M_m \tag{4}$$

Where, E_T : internal energy (absorbed energy) (Joule),
M : effective mass (kg),
g : gravity acceleration (m/s^2),
ΔH : bus CG displacement during roll over (m)
M_k : empty mass (kg),
M_m : total passengers mass (kg).

ΔH is obtained from the difference of CG height at the highest position and that at the position when one part of the bus structure right touch the land or road, as illustrated in Figure 9.

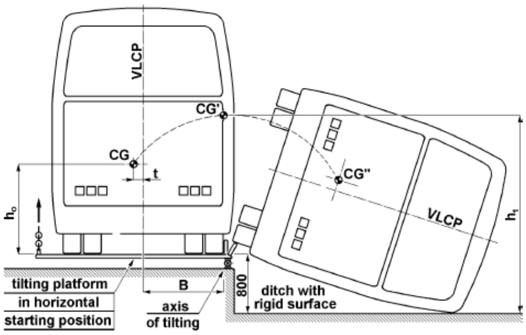


Figure 8: Center of gravity displacement from regulation (UNECE, 2006)

3.0 RESEARCH METHODOLOGY

The redesigned bus is an Indonesia's big bus and the rollover simulation is conducted based on explicit finite element method using LS-DYNA software. First the existing steel superstructure is redesigned using aluminium AL 6061 T6. Then structure weight calculation, finite element modelling and analysis are carried out. The design is then verified by using FMVVS 216 and UN R66. The design improvement, weight calculation, and finite element analysis were carried out iteratively until the best design and configuration that complies both regulations were obtained. The workflow is illustrated in Figure 10.

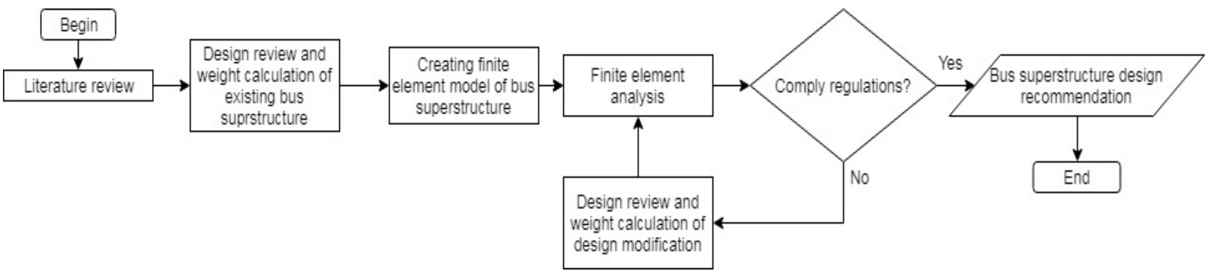


Figure 9: Flow chart of the methodology

3.1 Bus Specification

The bus used in this research has a capacity of 59 passengers, length of 12 m, width of 2.5 m, and height of 3.4 m (Laksana, 2017). The weight of the bus with its heaviest configuration is 13,481 kg, with location of CG at 1.382 m in Z direction and -0.019 m in Y direction. The superstructure is made of STK13B steel with weight of 1,637 kg (Hakim, 2018). Figure 7 shows the bus dimension and the locations of its components' CG, while Table 1 shows the detailed weight distribution of the bus and the overall weight and CG of the bus. The number of components at Table 1 corresponds to number that are shown in Figure 11.

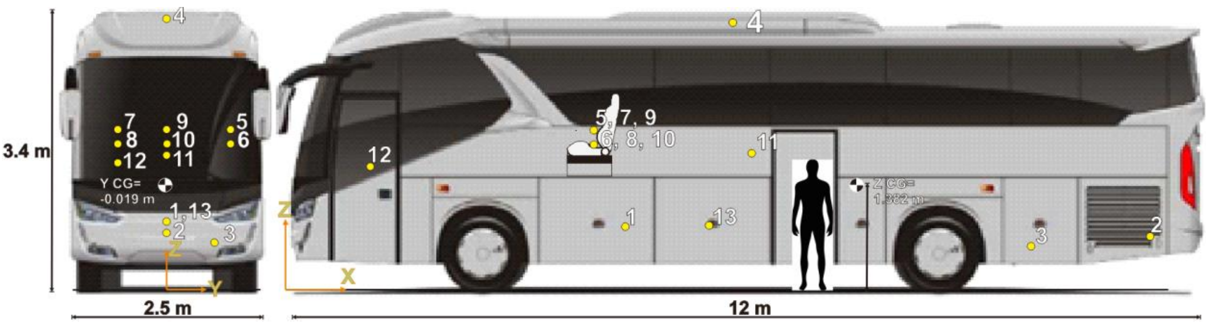


Figure 10: Front view and side view of bus and the location of bus components (Hakim, 2018)

Table 1: Weight distribution

No.	Components	Mass (kg)	Center of Gravity (CG)	
			Z (m)	Y (m)
1	Superstructure [a] (STK13B steel)	1,637	0.883	0
2	Chassis	4,820	0.750	0
3	Fuel	200	0.621	0.632
4	Air conditioner	160	3.580	0
5	Left seat (20)	190	1.927	0.844
6	Right seat (33)	314	1.927	-0.644
7	Rear seat (6)	57	1.927	0
8	Closure, Exterior dan Interior	1,426	1.850	0
9	Driver	75	1.677	-0.644
10	Left passenger (20)	1,360	2.117	0.844
11	Right passenger (33)	2,244	2.117	-0.644
12	Rear passenger (6)	408	2.117	0
13	Baggage	590	0.899	0
	Total	**13,481**	**1.382**	**-0.019**

[a] Superstructure weight and CG is updated for each improved design

3.2 Aluminium AL 6061 T6 Properties

STK12B steel that form bus superstructure is replaced with aluminium Al 6061 T6 due to its good strength to weight ratio, good corrosion resistance, good manufacturability, cost effectivity and wide availability in Indonesia. Table 2 shows the static material properties of Al 6061 T6 and Figure 12 shows the plastic region of the material.

Table 2: AL 6061 T6 Material Properties (ASM Matweb, 2009).

Mass density, ρ	2.69 x 10^{-6}	kg/mm^3
Young modulus, E	68.9	GPa
Poisson ratio, v	0.33	-
Yield strength, σ_y	0.276	GPa

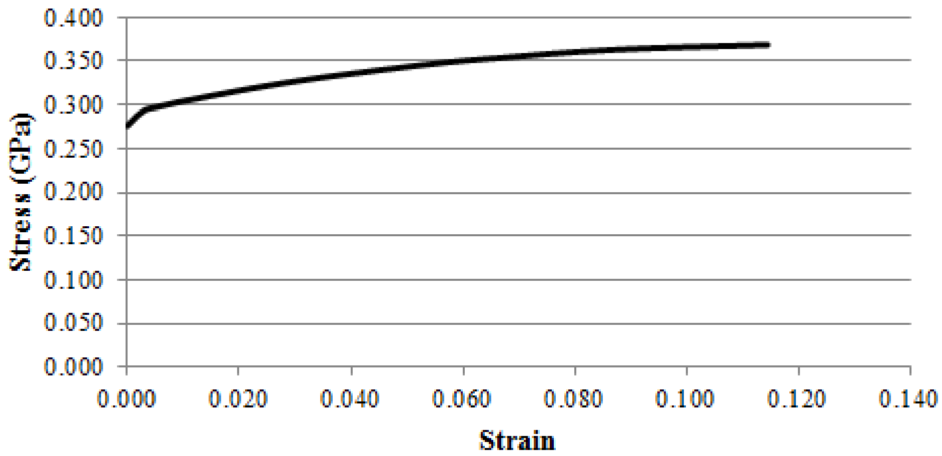


Figure 11: AL 6061 T6 plasticity curve (Brutt, 2015)

3.3 Superstructure Design Strategy

Superstructure of the bus comprises main frame superstructure, vertical pillars, roof, horizontal pillars, and roof edge, as shown in Figure 13 and Table 2. The superstructure design is modified by replacing all of the parts with aluminium materials and adjusting the thickness. Every part has its own function to resists the load during rollover, so the stiffness of each part must be different each other depending on the load type. Basically, the heavier weight of the part the greater is its stiffness with uniform thickening, so that the thickening must be controlled, so the weight will be lighter but still has a good stiffness. Thickening is done on parts that absorb significant energy.

From first numerical simulation, the part that absorbs most crash energy during rollover are vertical pillars by the bending deformation, so the cross-sectional inertia of vertical pillars should be high. Based on Hakim (2018)**,** the cross-sectional inertia needed is 3.98x10^{-7} m^4 and the thickness is adjusted to produce cross-sectional moment of inertia at least 3.98x10^{-7} m^4.

For roof edge parts, the structure is replaced with aluminium extruded beams, as shown in Figure 14. Ideas of extruded roof edge are to use one of the benefits of aluminium that is easy to do extrusion with certain cross-section design. Other than that, extruded roof edge with perfect design will give perfect energy absorption.

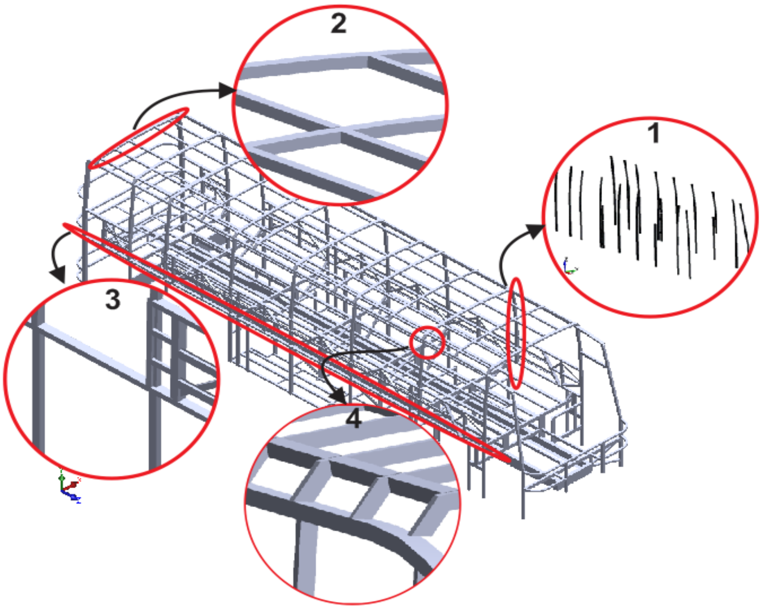
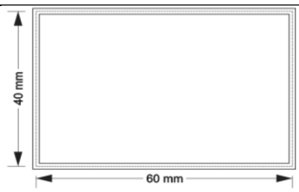
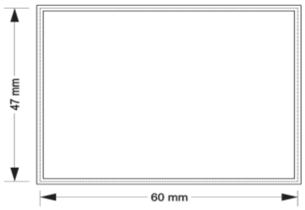
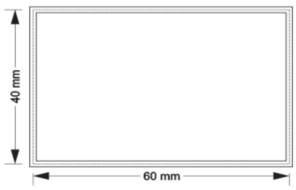
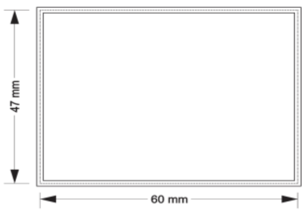


Figure 12: 2D bus model

Table 3: Part's profile description

No.	Parts	Cross-section	Thickness (mm)
1	Vertical Pillar		3.5
2	Roof		3.5
3	Horizontal Pillar		3.5
4	Roof Edge		2
5	Main frame superstructure (All of the others four parts above)	Varies	2

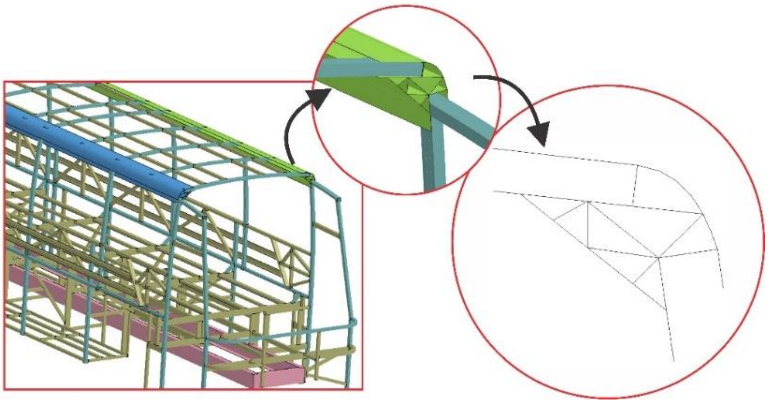


Figure 13: Extruded roof edge design

3.4 Finite Element Modelling (FEM)

This simulation with FMVSS 216 and UN R66 regulations only using superstructure component as the finite element model (FEM) for simulation. The other components such as engine, closure, exterior, interior, seat, passenger and baggage are not modelled and only used its mass as the load calculation requirement. The superstructure is the component that surrounding and protecting all other components, so the superstructure must be strong enough to protect all of the passengers inside.

The FEM mesh type that is used is shell element for all superstructure component parts, the average size is 20 mm. All part's material using Aluminum 6061 T6 as shown in Table 2 and Figure 12, except the impactor using rigid body material. The boundary conditions are 1 m/s constant velocity of impactor perpendicular to its surface and fixed displacement from floor below to simplify the model because the deformation is too small based on Satyo (2015).

Superstructure mass that changes according to geometry and element properties such as thickness in design step is obtained from automatic calculations by LS-PrePost. Superstructure mass is checked to make its value remains small enough compared to that of the steel superstructure to maximize the weight reduction.

3.4.1 Setting of FMVSS 216

Figure 15 shows the FEM model for roof crush testing based on FMVSS 216 regulation and the setting of impactor. The impactor's angle is 5^o in side view and 25^o in front view as shown in Figure 6 on 2.1.1 FMVSS sub-chapter.

The impactor moves 1 m/s perpendicular to its surface until its displacement reaches 127 mm or the crushing force equals the crushing force criteria based on Equation 1. Crushing force is obtained from contact force between the impactor and the superstructure parts.

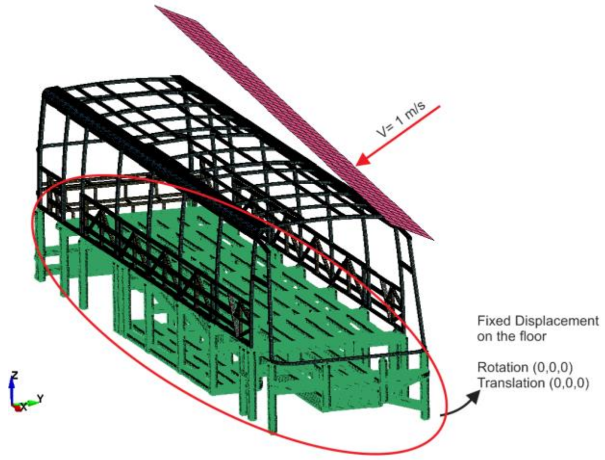


Figure 14: Roof crush testing in FEM with its boundary conditions

3.4.2 Setting of UN R66

Figure 16 shows the residual space and impactor setting in FEM based UN R66. By using Equation 2, the impactor angle is 76.39°. The impactor moves 1 m/s perpendicular to its surface until there is any superstructure part contacts or intrusions to the residual space and it is monitored by visual. LS-DYNA will read the energy absorption by its superstructure parts. If the absorbed energy is same or more than that absorbed energy criteria by Equation 3 then the superstructure will comply the regulation.

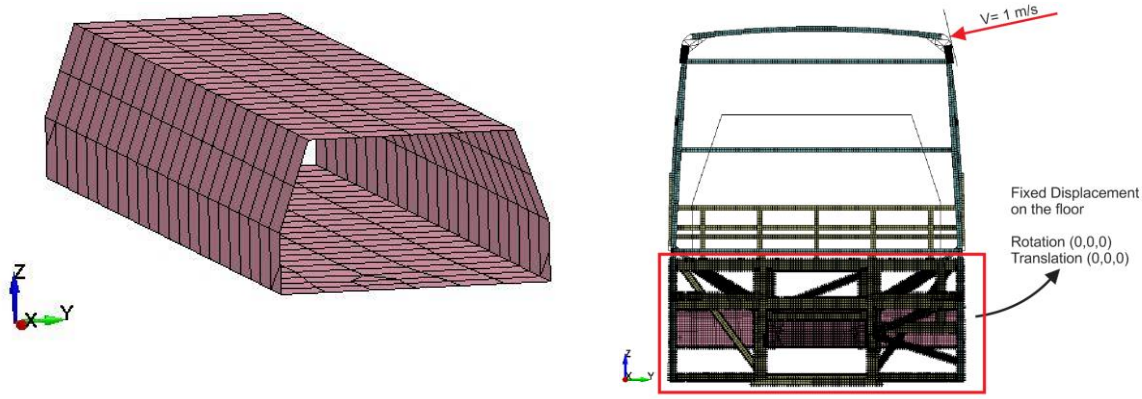


Figure 15: Residual space FEM (left) and FEM settings with boundary conditions (right)

4.0 RESULT AND DISCUSSION

After the design iteration using LS-DYNA, the final dimension of the aluminium superstructure components is obtained, as shown in Table 4 and explanation in Figure 17. Cross section inertia of vertical pillars is 5.66×10^{-7} m^4. The value that far enough from the reference because of the design will more concentrate the strength in vertical pillars. Therefore, the other parts will have a smaller thickness than vertical pillars, so that the weight will reduce.

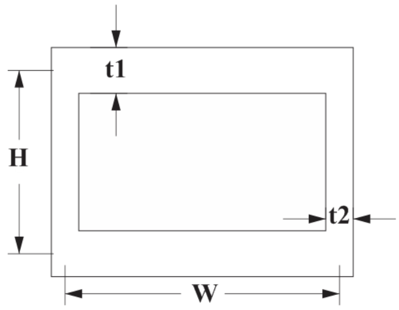


Figure 16: Detail of superstructure component cross-section

Table 4: Thickness Details

Parts	Width, W (mm)	Height, H (mm)	Thickness, t1 (mm)	Thickness, t2 (mm)
Vertical pillars	60	40	10	6
Roof	60	47	5	2
Horizontal pillars	60	40	3	3
Main frame superstructure	Varies	Varies	2	2
Extruded roof edge	200 (overall)	200 (overall)	1.8	1.8

The mass of the new design of bus superstructure become 865 kg with the total weight is 12,705 kg. While, the CG location in Z direction is 1.412 m and Y direction is -0.021 m. So that, superstructure material substitution from steel to aluminium 6061 T6 reduces the weight from 1,637 kg to 862 kg (40%), while the total empty weight of the bus reduces from 8,878 kg to 8,103 kg (8.7%).

4.1 Results of FMVSS 216

For the final configuration, the contact force between the roof edge and the rigid plate required by FMVSS 216 is 119,238 N, calculated with Equation 1. With the impactor constant velocity of 1 m/s, the simulation shows that when the impactor displacement reaches 127 mm, the contact force is 124,000 N (larger than 119,238 N). When the contact force value reaches 119,238 N, the displacement is 124 mm (less than 127 mm), as shown by Figure 18 and Figure 19. This result indicates that the aluminium bus superstructure complies the FMVSS 216.

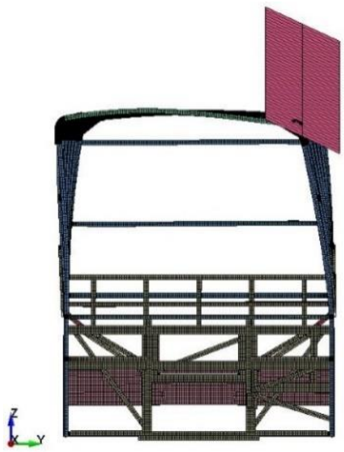


Figure 17: FMVSS 216 simulation

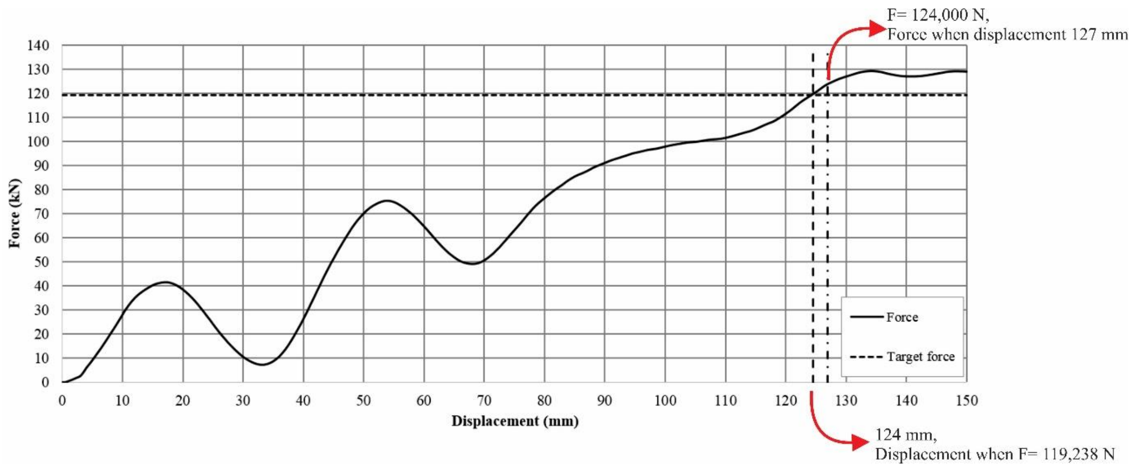


Figure 18: Force curve

4.2 Results of UN R66

The CG displacement of the bus final design during rollover is 1.031 m as shown in Figure 20, so that, the energy that must be absorbed is 78,922 J based on Equation 3 and Equation 4. Figure 21 shows bus superstructure crushed by the impactor just before the residual space is intruded. The superstructure pillar just touch the residual space is at displacement of 483 mm. Figure 22 shows the internal energy that is absorbed by the structure to the impactor displacements which shows that the absorbed energy 79,626 J. This is larger than the energy required by the regulation, 78,922 J. Hence this indicates that the bus with aluminium superstructure complies the UN R66.

Figure 23 shows the energy that is absorbed by each part of superstructure. It is evident that the vertical pillars are the dominant energy absorbers by absorbing 51% of the total deformation energy.

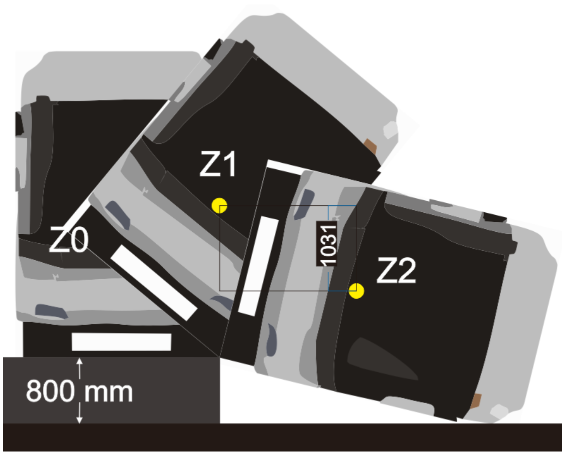


Figure 19: Center of gravity displacement

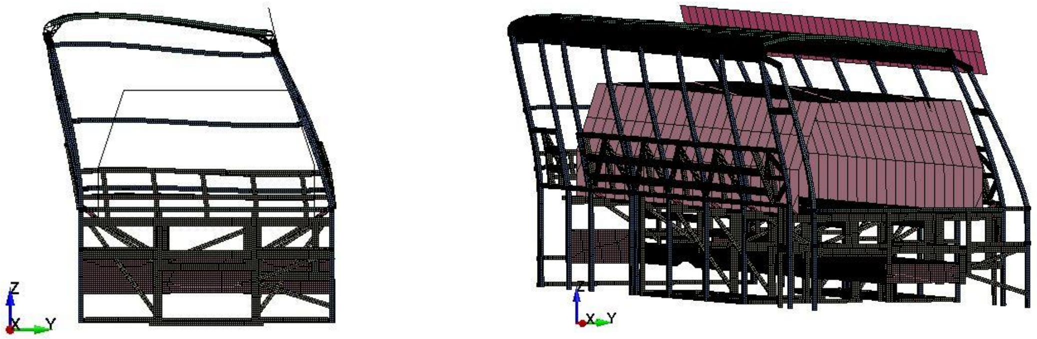


Figure 20: UN R66 simulation – front view (left), isometric view (right)

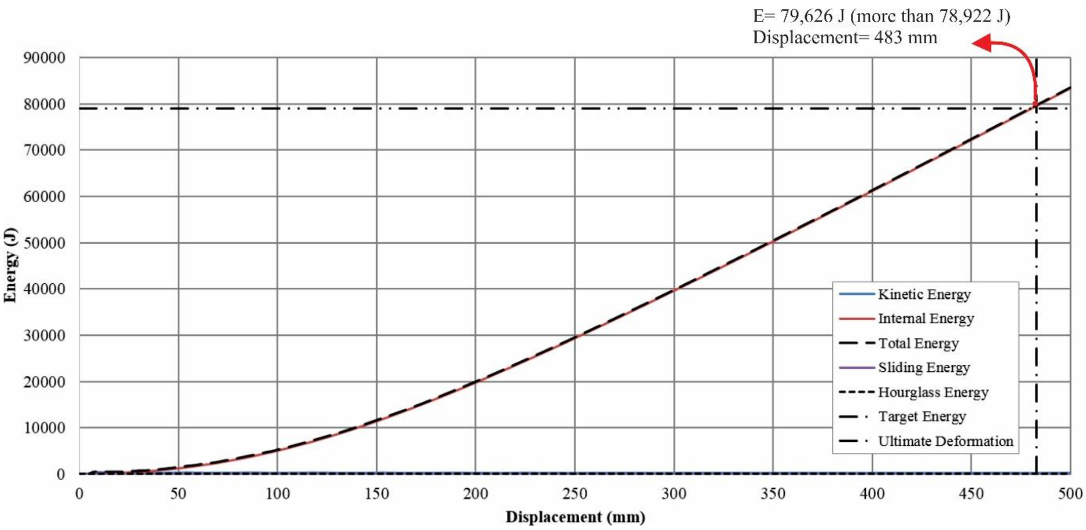


Figure 21: Energy curve validation

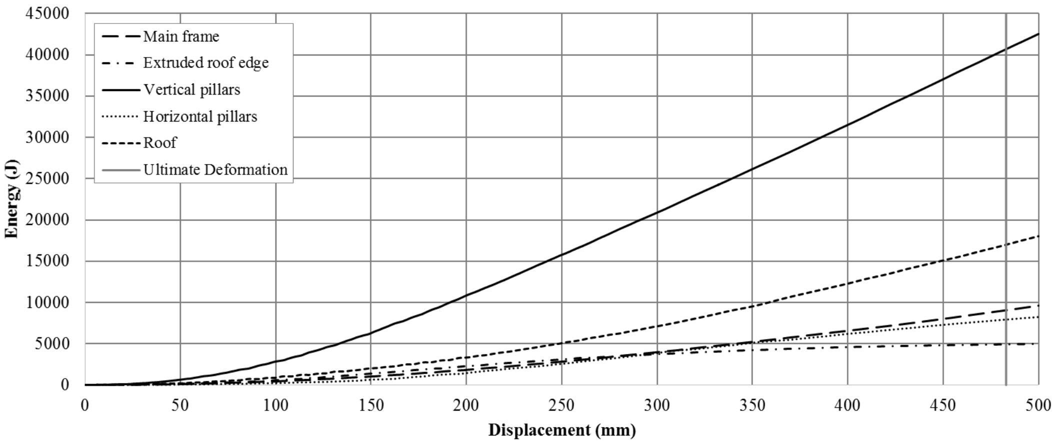


Figure 22: Energy absorbed in each part

4.0 CONCLUSION

In this paper, an iteration method is done to find the best design of aluminium-based bus superstructure that complies FMVSS 216 and UN R66 and is 40% lighter than that of the existing design with steel superstructure. The bus with aluminium superstructure will keep the safety of the passengers from fatality when rollover accident happens and due to its lightweight will reduce the damage rate of the road, consumes less energy, and produces less pollution.

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