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Finite Element Analysis of Bus Rollover Test in Accordance with UN ECE R66 Standard

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Abstract. Bus transportation plays a significant role in short and long distance mass transportation in Indonesia. The number of buses in Indonesia shows significant growth every year. However, there is a lack of regulations regarding bus construction safety and the increasing number of bus accidents is also becoming a major concern. In this paper, a computer simulation of bus rollover is presented. The bus structure was modeled to represent the mass distribution in a real bus. Two conditions were tested: the bus when empty and when fully loaded. Both the empty bus and fully loaded bus simulation results show that the bus did not comply with the UN ECE R66 safety standard. The results were validated by making a comparison with other tests that have been conducted by other researchers.

Keywords: *finite element analysis; Indonesian bus; rollover; safety; UN ECE R66.*

1 Introduction

Transportation by bus is one of the main transportation modes in Indonesia because of its efficiency and flexibility. It can be seen from Table 1 that the total number of buses in Indonesia keeps increasing every year [1]. As the number of bus increases, the number of accidents also increases, which is followed by an increase in the total number of casualties [1]. Based on data from NHTSA (National Highway Traffic Safety Administration), the most frequent accident involving buses is rollover [2]. Rollover is also considered the most harmful accident [2].

There are 3 aspects affecting passenger safety against rollover: superstructure strength, seatbelts and seatbelt anchorage strength, seats and seat anchorage strength. Among these 3 aspects, the superstructure strength is the most important one. The superstructure is defined as the load-bearing components of the bodywork that play a role in the energy absorbing capability and strength of the bodywork as well as in maintaining residual space in rollover [3]. The definition of bays and superstructure can be seen in Figure 1. Superstructure safety testing against rollover is standardized, among others in the UN ECE-R66 standard (Uniform Technical Prescription Concerning The Approval of

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Large Passenger Vehicles With Regard to The Strength of Their Superstructure) [3]. This standard regulates rollover tests that must be performed as well as the criteria that must be fulfilled by a bus superstructure. The details of this standard will be discussed thoroughly in the next section.

Table 1 Data on accidents involving buses in Indonesia [1].

Year	Total number of vehicles	Total number of buses	Total number of accidents	Total number of casualties
2008	61,685,063	2,059,187	31,617	99,350
2009	67,290,816	2,160,973	31,981	106,384
2010	77,170,306	2,250,109	33,936	109,878
2011	85,601,351	2,254,406	37,538	176,763
2012	92,303,227	2,460,420	38,194	197,560

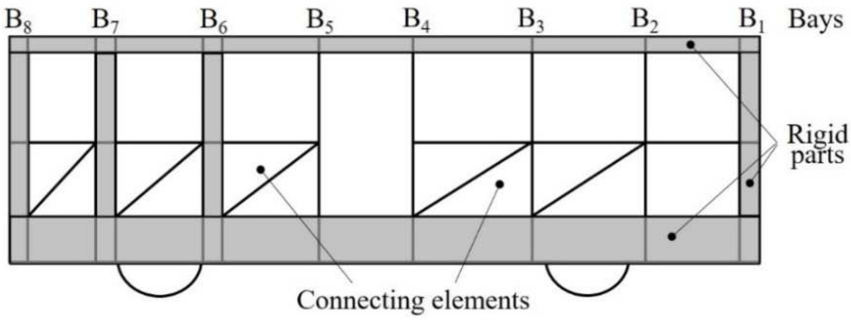

Figure 1 Bays and superstructure [3].

It is apparent that rollover testing is very important to ensure bus safety. Unfortunately, experimental testing of bus rollover is very expensive, thus an alternative testing method that is accurate yet easy and economic is needed. The finite element method is the most commonly used method, because it is accurate and relatively cheap to implement. Several researchers have done numerical simulations of bus rollover [4-6]. Sidhu [7] has performed an empty bus rollover simulation of an Indian bus model, but no one has attempted to perform a numerical simulation of rollover on an Indonesian bus model. To increase the awareness on bus safety in Indonesia, in this paper a computer simulation of bus rollover based on the UN ECE-R66 standard is presented. The chassis used was the R260 model, which is produced by PT. Rahayu Sentosa since 2010.

PT. Rahayu Sentosa is one of the biggest bus assembly companies in Indonesia. The bus superstructure was modeled to represent the mass distribution in the real bus for two different conditions: when empty and when fully loaded.

2 Bus Rollover Standard (UN ECE R66)

The standard used in this bus rollover research was UN ECE R66. This standard states that a rollover test must follow the path as shown in Figure 2. At the beginning, the vehicle stands on a tilting platform, after which it is tilted over slowly until it reaches unstable equilibrium. The test starts at this position with the wheel-ground contact points as the axis of rotation and with zero angular velocity [3].

The bus's superstructure is required to have sufficient strength to ensure that the residual space during and after the rollover test is unharmed, which means: no part of the vehicle outside of the residual space at the start of the test shall intrude into the residual space during the test and no part of the residual space shall project outside the contour of the deformed structure. The residual space is a space to be preserved in order to ensure better chance of survival for the passengers, driver and crew in the case of a rollover accident [3].

The envelope of the bus's residual space is defined by drawing a vertical transverse plane as illustrated in Figure 3. The plane is then shifted through the length of the vehicle as shown in Figure 4.

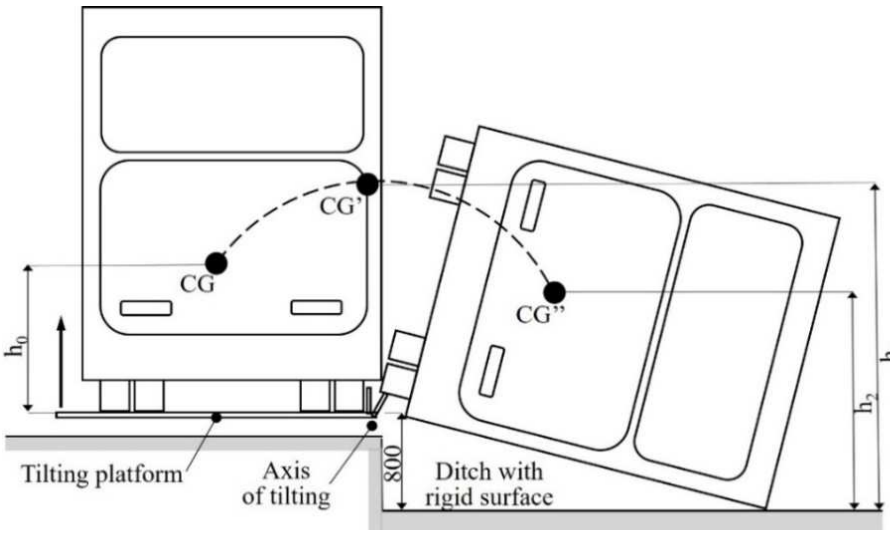

Figure 2 Specification of the rollover test showing the path of the center of gravity through the starting position (unstable equilibrium) [3].

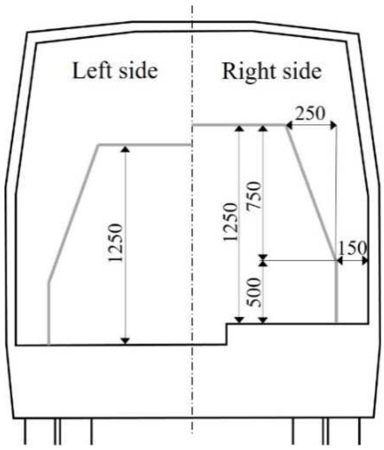

Figure 3 Specification of residual space in lateral arrangement [3].

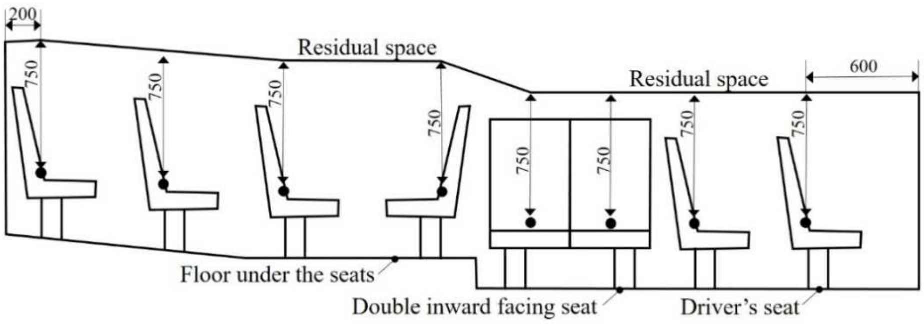

Figure 4 Specification of residual space in longitudinal arrangement [3].

3 Finite Element Modeling

Finite element analysis was done in LS-DYNA based on the R260 chassis model. The bus superstructure was modeled to represent the mass distribution of the real bus.

The superstructure of the bus is made of JIS G3113 SAPH400 structural steel with 2.6 mm thickness. The properties of this material are shown in Table 2. To ensure the validity of the model, a convergence test was performed, which resulted in the final chosen model consisting of 93,830 deformable triangular shell elements, with 3% relative error. Additionally, to represent the real mass distribution of the bus, the other parts, such as air conditioner (AC), fuel tank, wheels, engine and transmission, were modeled using a solid rigid body because the stress distribution and deformation in these parts were not the main interest of this study.

The weight of each bus component and the total weight of the bus when empty are shown in Table 3. To simplify the model, contact was defined only between the side structure and the floor, with a friction coefficient of 0.4. Furthermore, to reduce the computational time, the simulation was started just before the superstructure made contact with the floor. The angular velocity of the empty bus model was defined to be 2.077 rad/s, which was found by converting all bus potential energy to the rotational kinetic energy. The final finite element model of the empty bus is shown in Figure 5.

In fully loaded condition, the total weight of passengers, seats and seatbelts needs to be added. The bus was assumed to be an executive class bus with 36 passengers (at 69 kg) and 18 sets of seats and seatbelts (at 31 kg). The total additional weight was 3042 kg, which made the weight of a fully loaded bus add up to 9233.5 kg. The additional weight caused a raise in the bus's center of gravity (CoG) from 977 mm to 1283 mm from the ground and increased its potential energy, resulting in an angular velocity of 2.199 rad/s. The final model of the fully loaded bus is shown in Figure 6. Simulations of both the empty and the fully loaded bus were run using LS-DYNA with 5-millisecond time increments.

Table 2 JIS G3113 SAPH400 material properties.

Properties	**Value**
Density	7.850e-006 kg/mm^3
Yield stress	255 MPa
Yield strain	0.125%
Ultimate stress	402 MPa
Poison ratio	0.3
Ultimate strain	20%
Modulus Young	210 GPa

Table 3 Weight of bus components.

Component	**Weight (kg)**
Frame	1683.5
Fuel tank	228.0
AC	160.6
Engine	403.3
Transmission	30.7
Front axle (including tires)	437.2
Rear axle (including tires)	1593.5
Chassis and other components	1654.7
Total	**6191.5**

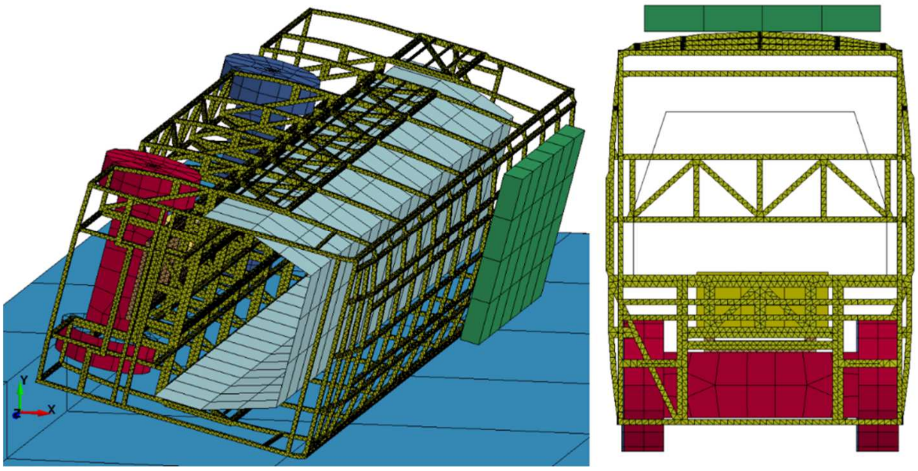

Figure 5 Empty full bus finite element model.

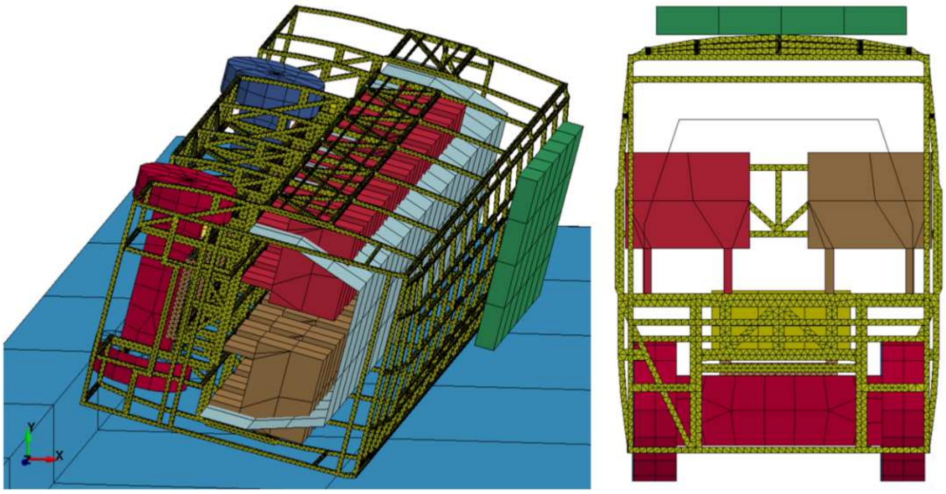

Figure 6 Finite element model of fully loaded bus.

4 Results and Discussion

The finite element model of the empty bus resulted in several different time steps as shown in Figure 7. Additionally, Figure 8 shows a comparison between the empty bus residual space envelope before and after rollover, as well as two different residual space envelopes that were considered: the envelope with consideration of the overhead compartment (pink line) and without consideration of the overhead compartment (yellow line). It was shown that even in empty condition and using the smaller residual space envelope (without consideration of the overhead compartment), the safety criterion is not fulfilled. Further observation shows that the front and rear frames have higher stiffness than the middle frame. This is because the left and right sides of the front and rear frames are connected by a steel structure. The highest deformation and stress happened on the cantrail (longitudinal structural part of the frame above the side windows) and the connection between the side frame and the floor, as shown in Figure 9.

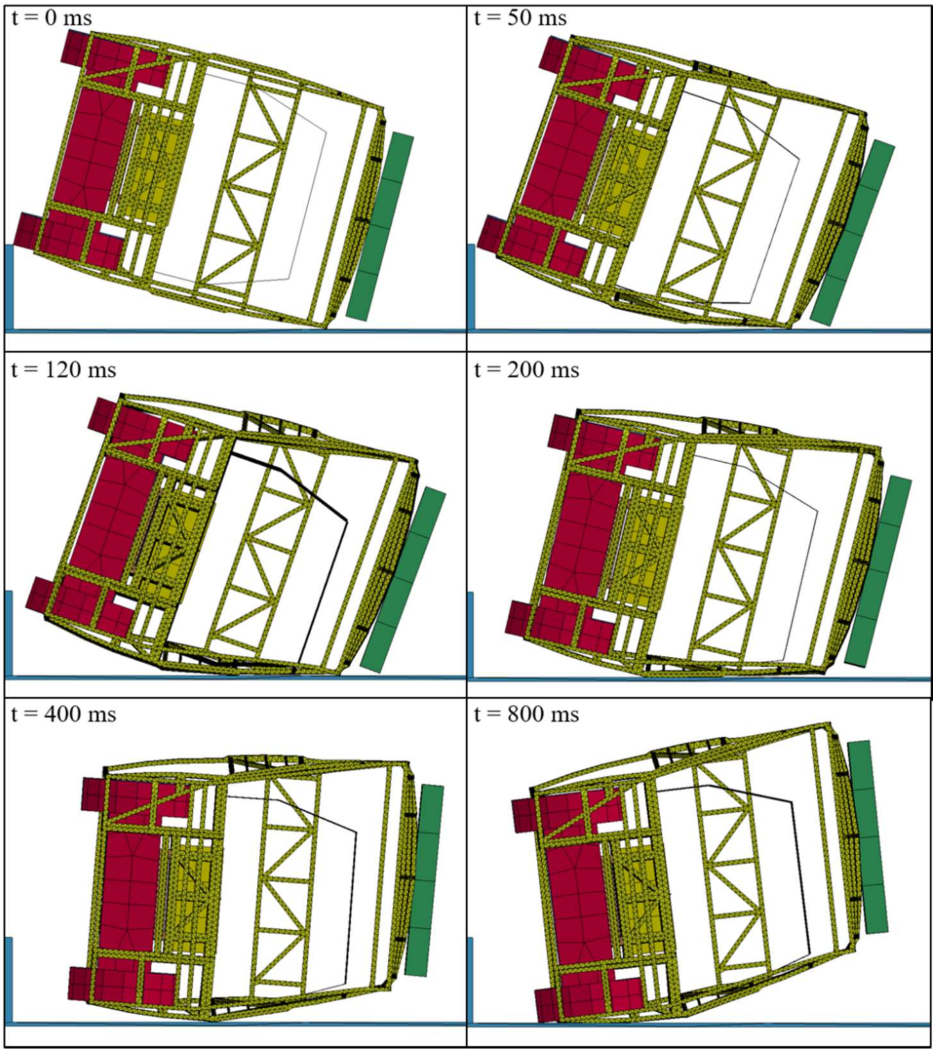

Figure 7 Empty bus rollover test results at several time steps.

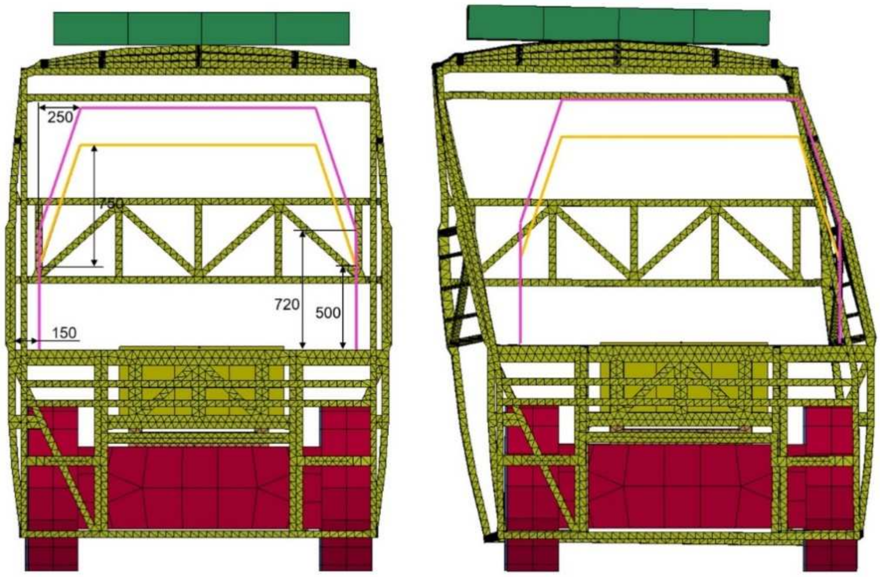

Figure 8 Empty bus residual space envelope before and after rollover test.

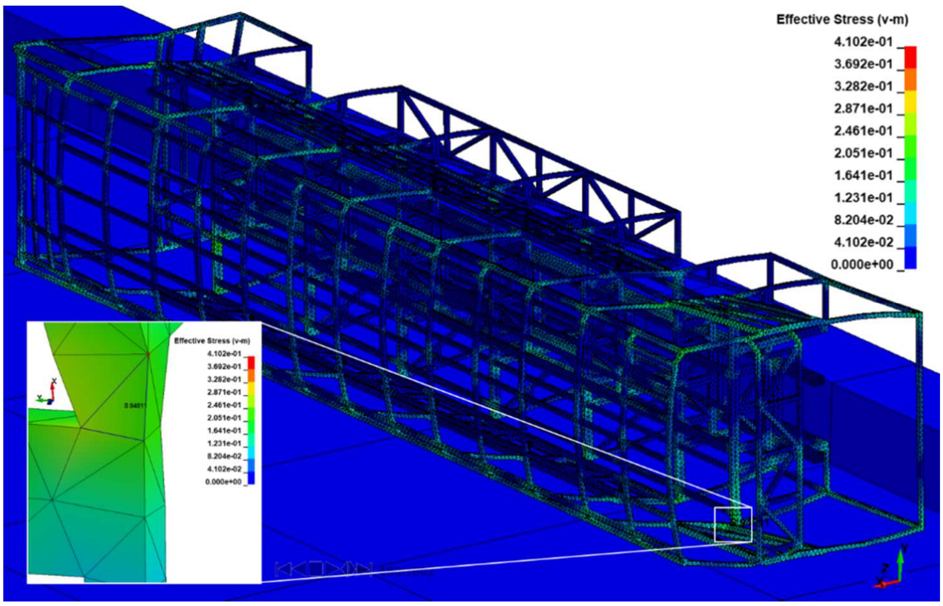

Figure 9 Von Misses stress distribution for empty bus (in GPa).

As shown in Figure 10, the kinetic energy reached its maximum value of 43 kJ at the beginning of the test, just before the bus structure hit the ground.

Subsequently, this kinetic energy was absorbed by the structure and became internal energy. The total energy is the sum of the initial kinetic energy and the external work (because of gravity). The internal energy reached its highest value at the end of the simulation, after the kinetic energy was absorbed completely by the structure.

The current bus deformation result shown in Figure 8 is consistent with Sidhu's empty bus result [7]. However, the model tested by Sidhu, which is an actual Indian bus model, successfully fulfilled the residual space criterion, as no part of the superstructure intruded into the residual space [7]. Based on this comparison, it is clear that further strengthening or remodeling of PT. Rahayu Sentosa's R260 model needs to be performed to improve passenger safety against rollover accidents.

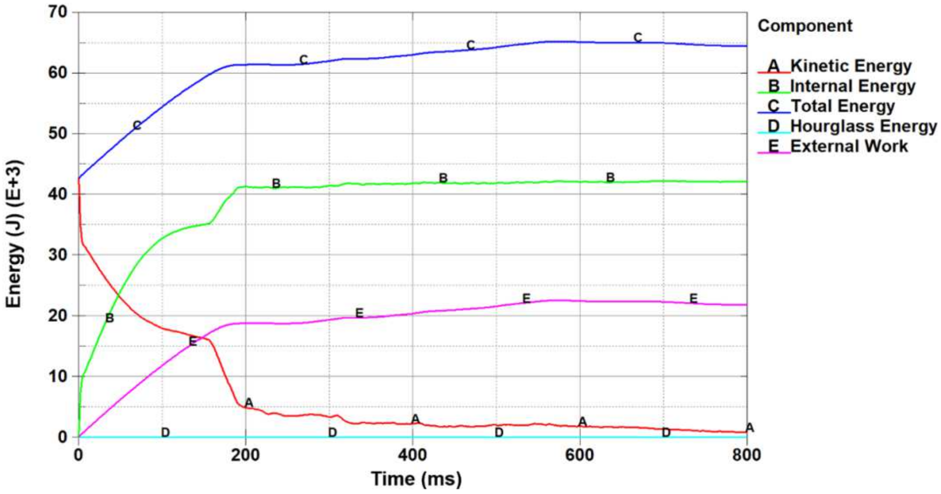

Figure 10 Energy level of empty bus rollover against time.

The simulation results at several different time steps for the fully loaded bus are shown in Figure 11. It is apparent that the bus when fully loaded deformed more than the empty bus (Figure 12) because additional weight from passengers, seats and seatbelts causes an increase in the potential energy. As a result, it is expected that a fully loaded bus suffers greater damage than an empty bus, as the total kinetic energy to be absorbed by the structure is larger (Figure 13). The fully loaded bus simulation result further urges the strengthening of PT. Rahayu Sentosa's R260 bus superstructure to improve passenger safety against rollover accidents.

Please note that the fully loaded bus deformation result may be slightly overestimated in this analysis, as the contact between the chair structures and the side structures were not defined. In most cases, the contact between the chair structure and the side structure will increase the whole structure's rigidity and will result in a reduction of total structure deformation.

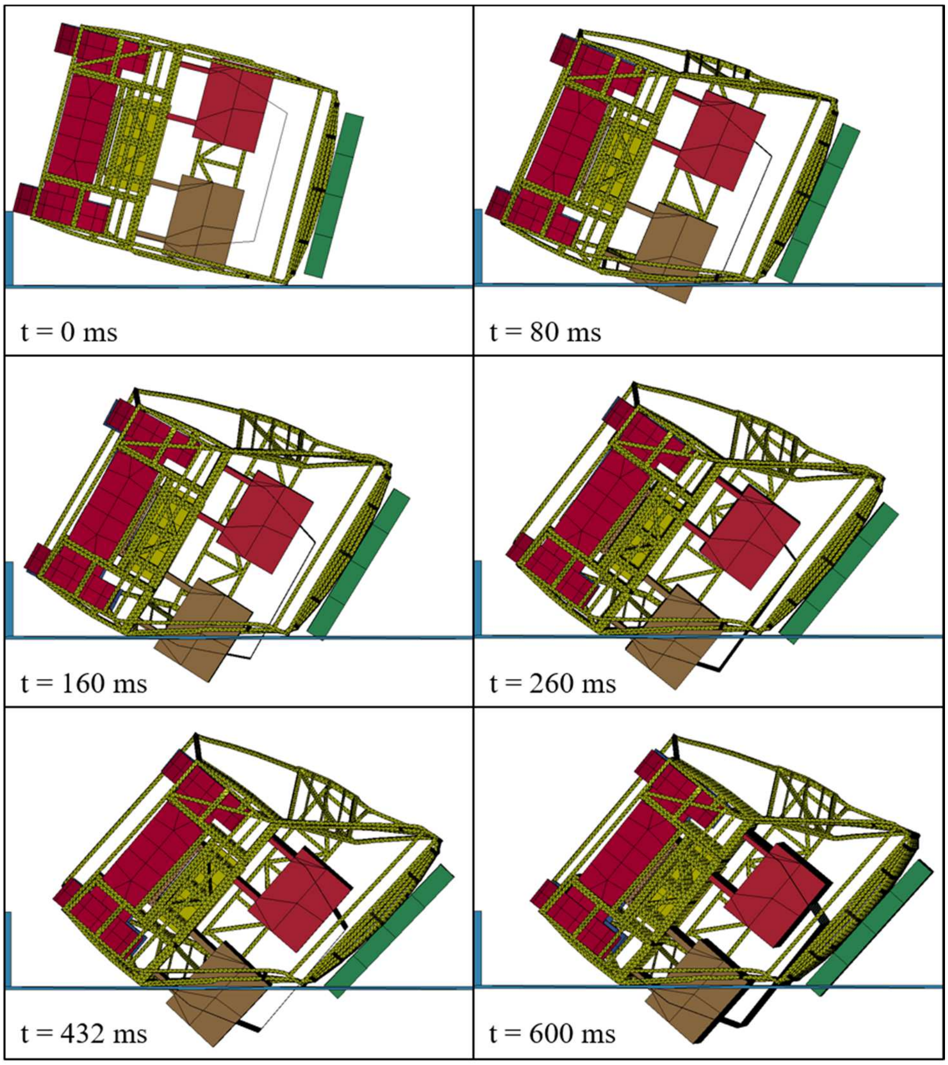

Figure 11 Fully loaded bus rollover test results at several time steps.

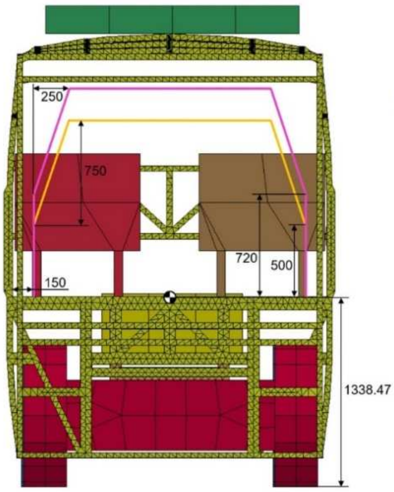

Figure 12 Fully loaded bus residual space envelope before and after rollover test.

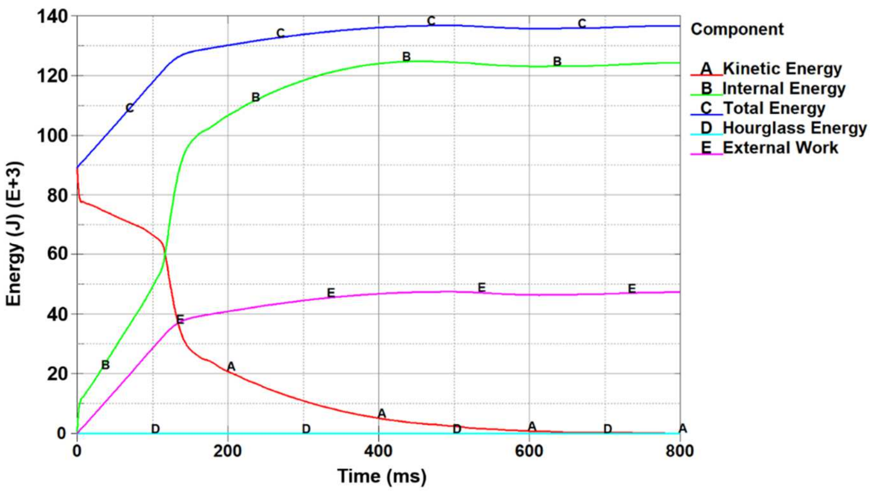

Figure 13 Energy absorption of fully loaded bus rollover against time.

5 Conclusions

A numerical simulation of bus rollover was presented and discussed. Investigation of the bus in empty and fully loaded condition showed that the superstructure of the bus is not strong enough, as the residual space safety criterion was violated. The most critical parts of the bus's superstructure are the cantrail and the connection between frame and floor. In fully loaded condition it shows more damage than in empty condition, mainly because of the additional weight from passengers, seats and seatbelts increasing the potential energy of the structure, which also increases the kinetic energy to be absorbed by the structure. Further strengthening or remodeling of PT. Rahayu Sentosa's R260 bus model needs to be performed. To improve the safety of passengers against rollover accidents in Indonesia, the same simulation should be performed on all bus models used in Indonesia.

The current work is only an initial step towards advancement in bus rollover prediction in Indonesia. In the near future, the contact between the chair structure and the side structure will be modeled in order to provide more realistic deformation results. Additionally, the current bus superstructure will be modified with the aim of fulfilling the residual space safety criterion against rollover accidents. Bus rollover model simplification will be done as well to reduce the computational time without sacrificing the accuracy of the prediction.

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