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# VERIFICATION OF THE COMPUTER MODEL OF THE BUS ROLLOVER ACCORDING TO ANNEX 9 UNECE R66

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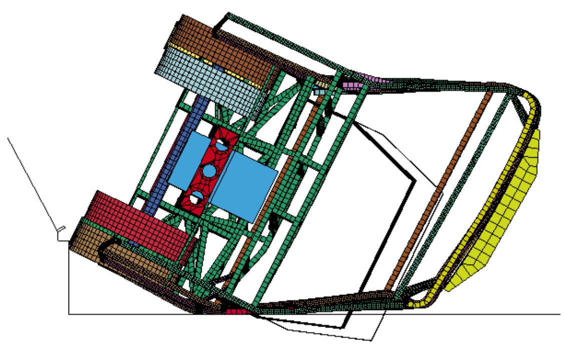
**Graphical abstract**



**Abstract**

An increased use of simulation models to solve problems and assist in decision making has led to a doubt on how to access the confidence of the simulation and modelling. Thus, the simulation models are in dire to be verified. Verification is a process of checking the accuracy of the simulation model by comparing with the known solutions. In this study, the computer model of the bus rollover according to Annex 9 UNECE R66 is verified using two methods which is mesh convergence analysis and through the energy balance and ratio. In mesh convergence analysis, it is important to choose the suitable size of the element of the bus superstructure to be used in the simulation to ensure that the bus structure is not too soft or too rigid. Three elements across the ring pillars of 50x50mm square hollow section (SHS) is chosen based on the intrusion into residual space and the amount of the internal energy absorbed. Energy ratio is the ratio of input energy to output which is total energy and must be in the range of 1.00+/- 0.07. The energy ratio obtained is between 0.963 to 1.0148 in this study.

*Keywords*: Bus rollover, Annex 9 UNECE R66, verification, mesh convergence, energy ratio



## 1.0 INTRODUCTION

Buses have always been a favorable choice to travel whether for short or long distances due to their availability, large carrying capacity and affordability other than trains and airplanes. The history of buses is believed to begin in 1662 when a French philosopher, Blaise Pascal created the public transportation system in Paris. Travelling by buses is safer compared to cars and almost safe as trains and airplanes [1, 2, 3].

However, if the accident happened, many passengers would be affected as buses usually carry 44 passengers once fully occupied or more if the buses are overloaded. For instance, in Malaysia, a deadly bus crash happened in Genting Highlands in 2013 which killed 37 passengers on the scene while another 16 passengers were injured when the bus skidded and rammed the divider before plunging 60 meters into the ravine [4].

Investigation has revealed that almost all the severe bus crashes that occurred are rollover accidents [5]. In addition, from more than 300 bus rollover accidents' statistics recorded by Matolcsy, the casualties' rate is 25/ accidents making it as the most dangerous bus type accident [6]. A rollover is an event when the vehicle is leaned over onto its side or roof. It is considered as a two times impact collision as in rollover the bus must be knocked on something first, before losing its balance, tipped, and rolled. In rollover accident, the occupants in the bus will be further distance from the center of rotation compared to the occupants in the car thus enhancing the possibility of ejection, partial ejection, or intrusion with higher velocity.

Consequently, due to the severity of the bus rollover accidents, the regulations have been legislated focusing on the strength of superstructure to preserve the residual space for the occupants in the rollover event. The area of the passengers and driver in the bus that must be protected to increase safety during the rollover is called residual space. The familiar standard that is used in more than 50 countries is the United Nation Economic Commission for Europe Regulation No. 66 (UNECE R66) [7], the Automotive Industry Standard (AIS)-031 which is used in India, and Australian Design Rules (ADRs) 59/00 in Australia which is imposed in addition to the present international standard UNECE R66. In the United States, the standard number 220 of the American Federal Motor Vehicle Safety Standards (FMVSS 220) is a standard designed for the school bus rollover protection that may be adapted for motor coaches.

Besides having the complete full-scale bus to be tested experimentally, the regulation also authorises the testing by computer simulation. Through finite element analysis (FEA) software, more designs of the bus with combination of parameters including materials, dimension, designs and so on can be configured rapidly without having to build the expensive prototype. However, there is an uncertainty on how to ensure that the computer model is accurate. Thus, the simulation models urgently need to be verified and validated [8]. Verification is a process of checking the accuracy of the simulation model by comparing with the known solutions [9]. In other words, verification is the method of determining that the computer model is precisely signifies the mathematical or conceptual model as in figure 1.

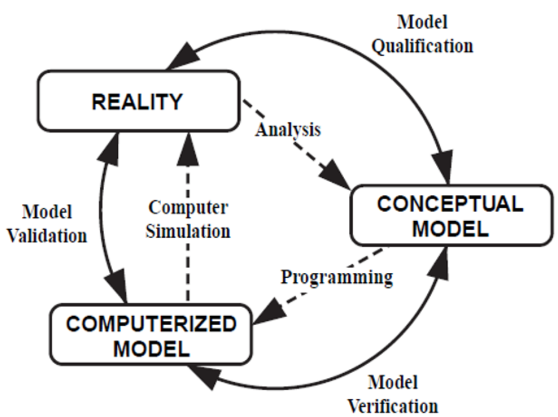



**Figure 1** The processes involved between three elements of reality, conceptual model, and computerized model [10]

Verification can be categorized into two which are code verification and calculation verification. Code verification is performed by comparing the output of the coding to the existing analytical solutions to determine the programming errors. Meanwhile, the calculation verification can be done by checking the convergence of the model towards the solution through discretization error. For example, by comparing two or more different sizes of mesh or element. When the solution reaches the convergence point using a certain size of element or mesh, it is said that the model has been verified [11, 12]. This method is referred to as mesh refinement study, mesh convergence analysis or mesh sensitivity analysis.

To develop certainty in the result of complex numerical analysis, The American Society of Mechanical Engineers (ASME) has published the guide on Verification and Validation in Computational Solid Mechanics in July 2006 [13]. Earlier, in 1998, a similar guideline entitled Guide for the Verification and Validation of Computational Fluid Dynamics Simulation has been approved by Computational Fluid Dynamics Committee of the American Institute of Aeronautics and Astronautics (AIAA) [14].

According to Dominik, mesh convergence analyses for vehicles crashworthiness including bus rollover are rarely found in the publications due to the complexity of the model [15]. As an alternative, another method is widely used which is through energy balance analysis and energy ratio of the simulation. Schwer has emphasized that by ignoring the discretization error in the simulation, the researchers are often not sure if they got the converged output or not [16]. Nonetheless, the analysis of the energy balance and ratio is still a beneficial method to notice the error of the input or the calculation in the simulation. The simulation model is accepted if its energy balance is perfect following the law of conservation of energy where the total energy remains the same all the time with the spurious energies like hourglass and damping are kept at minimum value. Also, the model is approved when the ratio is 1.0. Many researchers have checked on the energy balance of their simulation model of bus rollover [17, 18, 19, 20, 21, 22].

As mentioned earlier, due to the time consuming, cost and complexity of the FE model of the bus, the mesh refinement method is not performed on the whole bus. Instead, mesh refinement study is performed using a three- point bending test of the square hollow section tube. For example, Guler performed the three- point bending test on the breast knot and roof edge knot which is extracted from the bus and compared the force-deflection curve for both simulation and experiment by adjusting up the mesh size in simulation [23]. Also, Mahathir in his research, performed the three- point bending quasi static load test on the waist trail knot of the bus structure and later compared with the simulation by LS Dyna using different sizes of element. As a result, the simulation using element size of 8 and 10 mm showed a good agreement with the experimental result as in figure 2. The element size of 10mm is chosen to be used in the entire simulation [24]. Instead of using the knot of the bus parts, they also performed a simple three point bending test on a tube and adjusting the mesh size. For example, the setup for the simulation of the three-point bending test on a tube with two elements across the tube as in figure 2 [15].

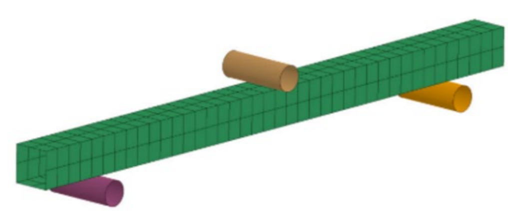


**Figure 2** The setup of the simulation of three- point bending test on a tube with two elements across [15].

## 2.0 METHODOLOGY

In this study, the simulation of the bus rollover is performed based on the setup in UNECE R66 using computer simulation as in Annex 9. The FEA software used is LS Dyna.

The bus model used in this study is a typical single decker bus. The length, width and height of the bus is 11525mm, 2450mm and 3840mm. All the dimensions are within the allowable range provided by Pusat Pemeriksaan Berkomputer or Malaysian computerized vehicle inspection company

(Puspakom) which is the length, the width, the height, and the distance of floor from the surface of road. The structures are constructed using square hollow section (SHS) sized 50mm x 50mm, rectangle hollow section (RHS) sized 25mm x 50mm and 50mm x 75mm with various thickness. The bus used in this simulation is having Unladen Kerb Mass with the weight of 12303 kg. The bus for testing does not need to be fully finished or in complete condition to operate provided that the center of gravity and the total mass of the bus are same.

The material used for this bus superstructure in this study is standard mild steel having yield strength of 270 MPa and ultimate tensile strength of 400-500 MPa. Figure 3 shows the bus superstructure with the parts including the residual space. Pillar 1 to pillar 7 refers to the ring pillars.

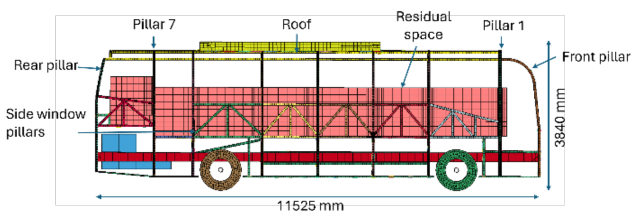



**Figure 3** The bus model with the parts.

Figure 4 describes the flow of the finite element analysis for this paper. In this research, a finite element analysis software, LS Dyna, is used to simulate real rollover of the bus. It involves three stages which are pre-processing or preparation, processing or solution, and post-processing or evaluation phase. In the pre-processing, the 3D model of the bus is converted into FE model by meshing the parts into small elements. It can be made using software such as hypermesh. The size of the element is important as it can affect the accuracy of the result, hence, the mesh convergence analysis needs to be done. Also, the material is determined, define all the keywords, set the boundary conditions and so on. Next, the simulation is run to get the result in the processing or analysis stage (Solver). The final stage is evaluating the output (LS-PrePost).

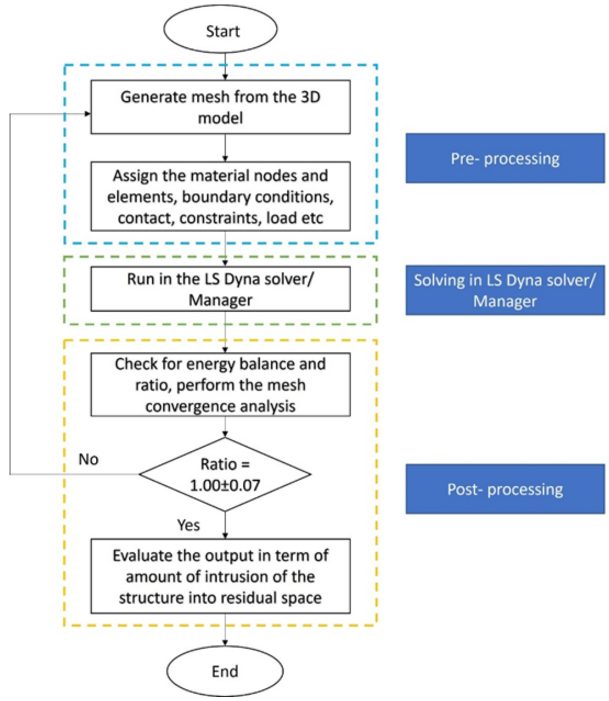



**Figure 4** The stages of Finite Element Analysis

In this work, most parts are assigned to MAT 20 RIGID or MAT 24 PIECEWISE LINEAR PLASTICITY. MAT 020 is used for the rigid parts that are the components of the bus where the deformation or energy absorbing ability is not remarkable during the rollover such as the chassis, axles, wheels, tilting platform and residual space. MAT 024 is used for all the structures of the bus other than rigid parts.

In UNECE R66, the setup of the bus rollover is as shown in figure 5. The distance between the rigid wall or floor with the tilting platform is 800 ±20 mm. To reduce the computational time, the platform is tilted until the bus is in the unstable equilibrium position where the center of gravity (CoG) of the bus is at the highest and the bus will fall with gravity. In this study, based on calculation, it happened when the platform is tilted at the angle of 55.1 degrees.

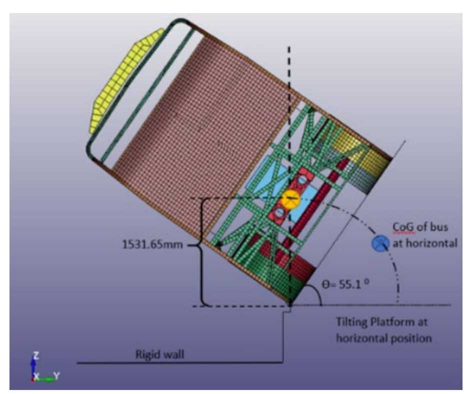



**Figure 5** CoG at unstable equilibrium position

Residual space is an imaginary space in the bus simulation rollover to illustrate the safety area for the passengers and driver. The bus is said to pass the R66 if there is no intrusion of the parts into it. Since it is not there in the real event, it is set to be rigid or not deform. Thus, a type of material MAT RIGID 020 is used. The weight is set to be very small as it is negligible throughout the simulation. The movement of the residual space follows the chassis through the CONSTRAINED RIGID BODIES. The rigid chassis acts as master while residual space is the slave. There are no constrained nodal rigid bodies (CNRB) need to be attached between the residual space and chassis.

Also, to show the correct intrusion into it, it must be made to penetrate the floor or rigid wall. To do so, all nodes in residual space are excluded in RIGID WALL PLANAR FINITE. All the nodes of it are grouped as set nodes and put under NSIDEX box. By doing this, the residual space will go through the rigid wall as the bus falls into the rigid wall. The difference between included and excluded residual space onto rigid wall is shown in figures 5 and 6. In Figure 6, the residual space is set to hit the floor. Since the residual space is rigid, it cannot deform. Thus, the bus will bounce. It causes the structure to look stronger too as the structure cannot bend furthermore as it is prevented by the rigid residual space. While in figure 7, residual space is set to penetrate the rigidwall.

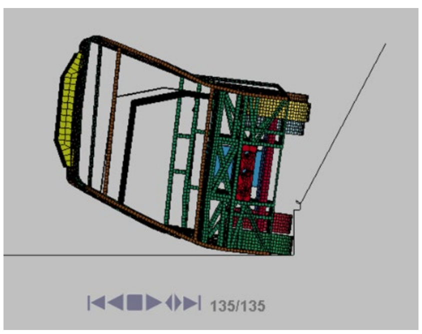



**Figure 6** The condition when residual space is set to hit the rigidwall

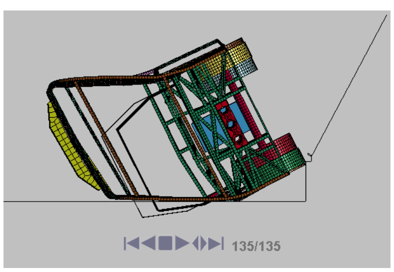



**Figure 7** The condition when the residual space is set to penetrate the rigidwall.

There are 27 types of element formulation for shell in LS Dyna and the selection is based on the time consumption, types of material and simulation whether it is implicit or explicit simulation. In this work, the default Belytschko-Tsay, EQ. 2 is recommended and used as it is the most economical.

Under the card section shell, there is an option of NLOC. It is used to offset the thickness whether to protrude outwards, inwards, or half inwards and half outwards from the element surface. The difference between three NLOC= 0, 1 and -1 can be seen in figure 8. There are no changes in the weight, however the amount of intrusion is different as shown in figure 9. Figure 9 shows the difference in intrusion of the bus for NLOC 0, 1 and -1. In this work, NLOC 1 is chosen to be used because the dimension of the pillar will remain same as thickness changes as the thickness will protrude inwards. This is parallel with the dimension of the pillar in the market as the outer dimension remains the same no matter what thicknesses are. For example, for 50 x 50 mm SHS with thickness 2.0, 3.0, 4.0 and so on, the outer dimension remains 50 x 50mm.

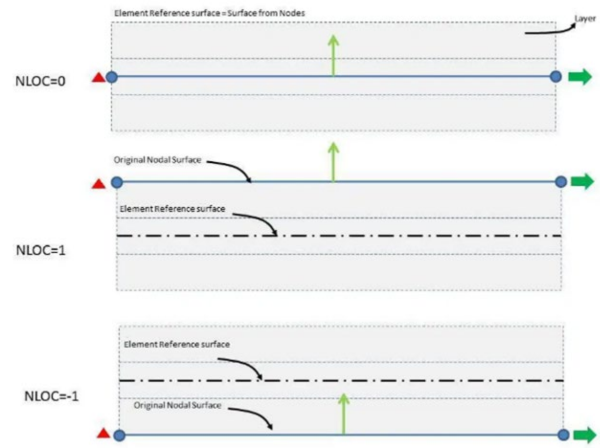



**Figure 8** Condition of NLOC

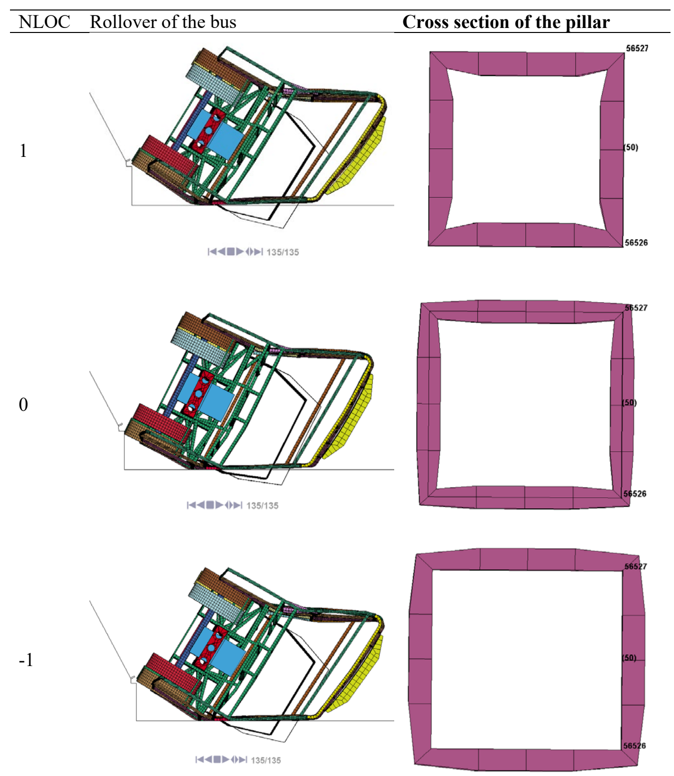



**Figure 9** The effect of different NLOC to the rollover.

## 2.1 Mesh Convergence Study

Theoretically, the smaller the mesh size, the more precise the solution is. However, the downside is, more elements require more time. As mentioned before, there is no mesh refinement or convergence on the bus rollover is found. Here, in this work, a simulation of bus rollover of the full-scale bus is performed. To find the best size of elements which balance between the accuracy and time consumption, mesh convergence study is conducted by comparing the internal energy absorbed and intrusion into residual space. As there are a lot of parts in the bus, it is not necessary to mesh all the parts with the same size. In this work, only the most critical part, which is the ring pillars, are considered. A few numbers of elements horizontally of the pillar are determined and the bus is rolled towards the ground. The number of elements selected are 2, 3, 4, 5 and 6 across the horizontal for 50mm square hollow section ring pillar as shown in figure 10.

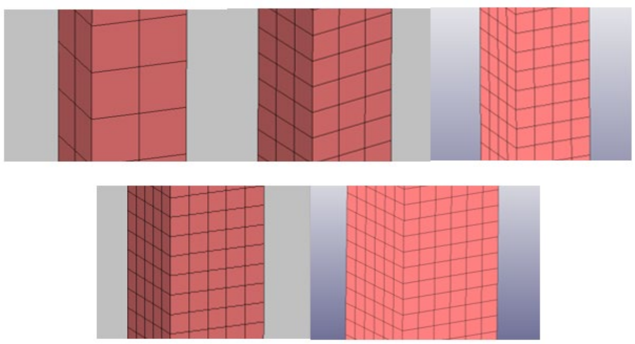


**Figure 10** The number of elements in horizontal for 50mm square hollow section tubes.

### 2.2 Energy Balance and Ratio

Matolcsky and Molnar proposed that for bus rollovers, verification of computational model and simulations are made by the values of energy balance, deformations, and other components [25]. In this simulation of the bus rollover, the numerical error is checked through the energy balance. According to Bojanowski, energy components must abide the laws of conservation of energy and all the non-physical energy are reserved at minimum [26]. The energy data in Ls Dyna are beneficial in the analysis. The subsequent equation should always be retained during analysis.

$$E_{total} = E_{kin} + E_{int} + E_{si} + E_{rw} + E_{damp} + E_{hg} = E^0_{total} + W_{ext} \quad \text{Eq.1}$$

$$E^0_{total} = E^0_{kin} + E^0_{int} \quad \text{Eq.2}$$

Where,

$E_{kin}$ = current kinetic energy
$E_{int}$ = current internal energy
$E_{si}$ = current sliding interface energy
$E_{rw}$ = current rigid wall energy
$E_{damp}$ = current damping energy
$E_{hg}$ = current hourglass energy
$E^0_{kin}$ = initial kinetic energy
$E^0_{int}$ = initial internal energy
$W_{ext}$ = external work
$E^0_{total}$ = initial total energy

However, the total energy in LS Dyna does not represent the exact total energy for the whole simulation which defines the law of conservation of energy. The total energy should remain flat from the start to the end to indicate the energy is conserved throughout the simulation. To obtain the real total energy, the potential energy must be calculated first and added to the total energy of LS Dyna. The potential energy is calculated from the general equation which is;

$$E_{pot} = Mg\Delta h \quad \text{Eq. 3}$$

Where,

$E_{pot}$ = Potential energy
$M$ = Total mass of the bus (tonne)
$g$ = Gravitational acceleration (mm/s$^2$)
$\Delta h$ = Vertical distance in CG from unstable to final position (mm)

The energy ratio,

$$e_{ratio} = \frac{E_{total}}{E^0_{total} + W_{ext}} \quad \text{Eq. 4}$$

## 3.0 RESULTS AND DISCUSSION

### 3.1 Mesh Convergence Study

The intrusion, internal energy and total element of the bus is recorded in table 1 for each size of the element used.

**Table 1** Outputs for mesh convergence analysis

| Number of elements in horizontal | Intrusion (mm) | Internal Energy (kJ) | Total element of the bus |
|---|---|---|---|
| 2 | 578.086 | 98.31 | 78072 |
| 3 | 657.255 | 99.92 | 108670 |
| 4 | 674.844 | 99.90 | 135376 |
| 5 | 735.284 | 100.70 | 178251 |
| 6 | 773.928 | 102.50 | 257119 |

From the results, in figure 11, the number of elements of 3 and 4 showed similarities in amount of energy absorbed indicating the convergence is achieved. As for five and six number elements, the internal energy is continuing to increase. Since internal energy related to the deformation or intrusion into residual space, the result for intrusion exhibited a similar pattern as shown in figure 12. Thus, three elements across the pillar are used for further analysis. The more elements will cause the parts to be softer while less elements enhance the rigidity.

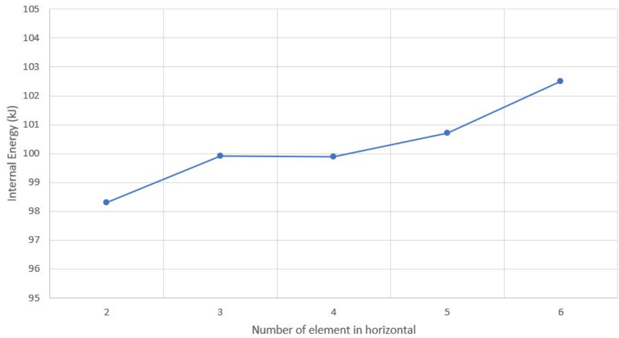



**Figure 11** Internal Energy absorbed compared to the number of elements.

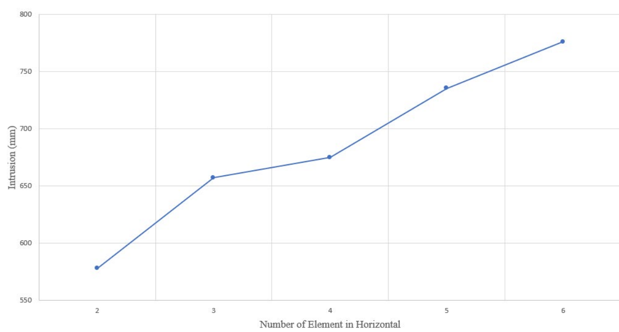



**Figure 12** The intrusion into residual space for different number of elements.

In figure 13, the bending condition of the pillar for the different size of mesh is compared. When using two elements across the horizontal of the pillar, the pillar will bend in a coarser way than when using more elements. Therefore, mesh convergence analysis is important to perform before running more analysis. For other parts of the bus, the coarser elements are used because they are indirectly involved in the rollover impact.

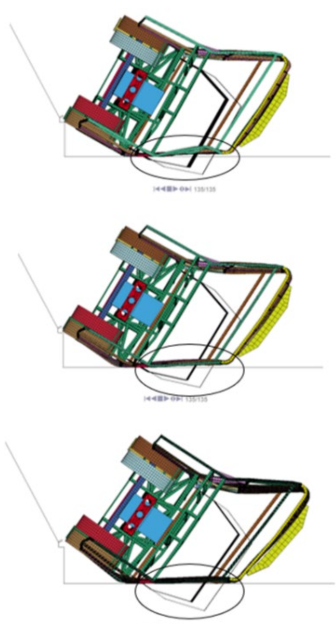


**Figure 13** The comparison of bending in ring pillar for 2, 3 and 6 elements.

### 3.2 Energy Balance and Ratio

The formula for energy conservation and energy ratio are mentioned in section 2.2. Figure 14 shows the vertical distance between the starting and final position of the CoG which is 905.35 mm. Using Equation 3 in section 2.2, the potential energy at the beginning of simulation is

$$12.3109 \text{ x } 9810 \text{ x } 905.35 = 109339055.2\ tonne.mm^2.s^{-2}$$
$$= 109.3390552\ kJ$$

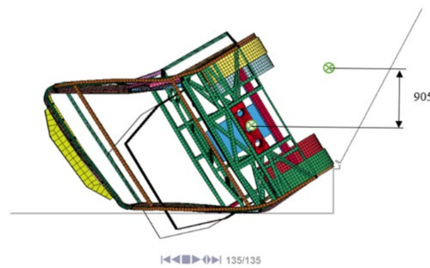



**Figure 14** The vertical distance of CoG between starting and final position.

At the start of the simulation, the only energy that exists is potential energy. However, it is not shown directly from the result unlike the external work. According to Ls Dyna, external work is the work done by the applied forces, pressures, velocity, displacement, or acceleration boundary conditions. In this simulation of rollover, the external work is the change in potential energy as the bus rotates. Thus, both curves of potential energy and external work should be symmetrical as illustrated in figure 15. It can be used to check for the hand calculation of the potential energy as well.

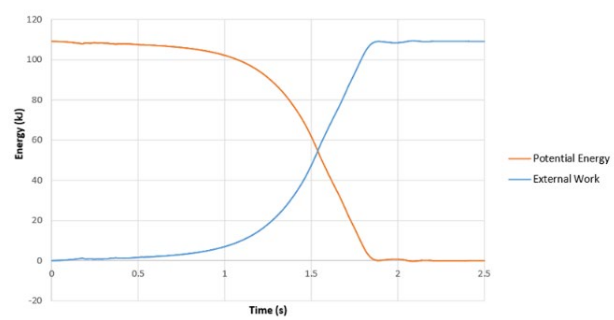



**Figure 15** The graph of potential energy and external work in symmetrical pattern.

From Ls Dyna, the total energy is equal to the summation of initial kinetic and internal energy as well as external work. Since at time, t= 0, at the beginning of simulation, there is no velocity, thus kinetic energy is zero. Also, the deformation which is related to the internal energy is absent at the start of simulation, hence zero initial internal energy is recorded too. The only energy exists at the start of simulation which is at the unstable equilibrium position is the potential energy. Thus, the total energy obtained from Ls Dyna is supposedly equal to the external work. The difference between total energy and external work indicates the existence of non-physical or spurious energies in the simulation where these should be kept minimum to achieve the perfect energy ratio. In figure 16, the spurious energies appear after the impact which is after 1.54s.

There is a small amount of positive contact energy which is less than 5 percent of the total energy. Another energy sources such as hourglass energy are also within the range of less than 10 percent of the total energy too. The energy absorbed or internal energy also satisfies the equation in the R66 which is 87.5 percent from the total energy. The requirement is at least 75 percent. Hence the energy ratio can be found by dividing the output energy which is the real total energy to the input energy which is potential energy and external work. Figure 17 shows the graph of ratio vs time(s) and the ratio is between 1.0148 and 0.963. It is in the permissible range of 1.00+/- 0.07, therefore no adjustment to the model is needed. Thus, the simulation is verified to be used in further analysis.

According to the energy distribution plot, the kinetic energy starts picking up as the bus falls due to the gravity. Referring to figure 16, the energy conservation graph of bus rollover, at 1.54s, the bus starts to touch the ground. Kinetic energy drops and is absorbed by the internal energy. The kinetic energy continues to be transferred into internal energy making the rise in internal energy and decline in kinetic energy. At 1.85s, the bus is completely rest on the ground until the termination time stops at 2.5s. The maximum stress recorded from the model summary is 442.26 Mpa. That is beyond the stress that the mild steel can bear which is 440 MPa, thus there may be fractured in the structure.

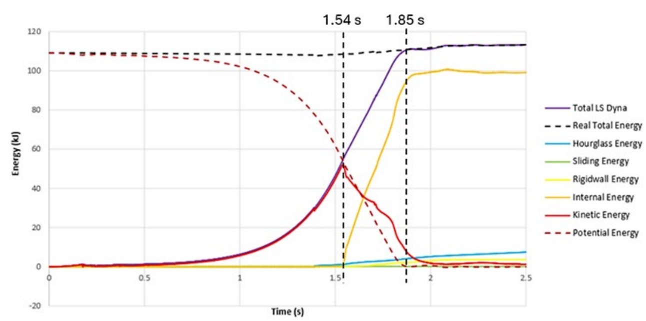



**Figure 16** The energy balance of the bus rollover.

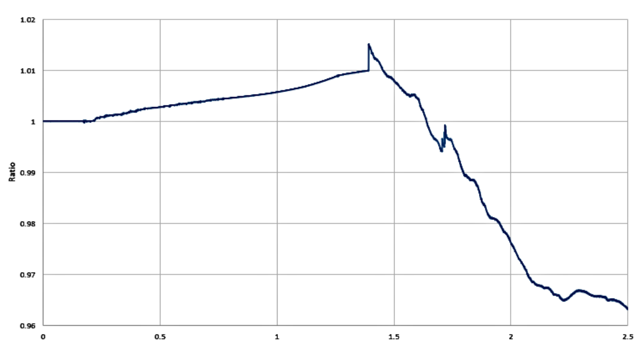



**Figure 17** The energy ratio of the bus rollover.

The sequences of the bus rollover from the 0 to 2.5s time as shown in figure 18. The bus is placed on the tilting platform at the unstable position with the highest CoG. The bus starts to touch the ground at 1.54s. Kinetic energy drops and is absorbed by the internal energy. The impact of the rollover has caused the pillars to be bent and the residual space be violated. Further intrusion of the residual space is seen as the time goes by.

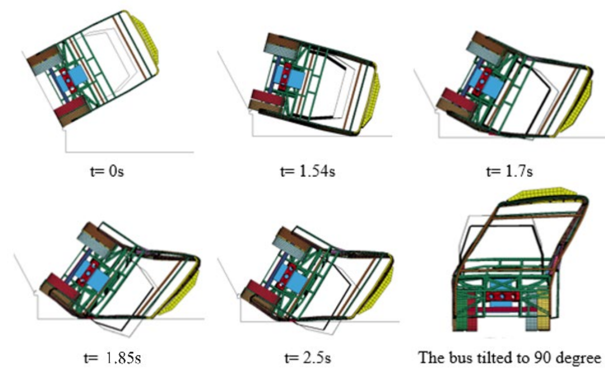



**Figure 18** Sequences of bus rollover from unstable position to the resting point.

As comparison from the previous study, here is the figure of energy balance and energy ratio for the bus rollover by Liu from the moment the bus touched the ground until it is at rest [27]. The total energy is the sum of the kinetic, internal and hourglass energy. The ratio is in the range of 0.998 to 1. It is said that the energy is balanced throughout the simulation. The pattern for both energy balance and energy ratio similar to the result in this research as in figure 17. Figure 19 shows the energy balance and ratio of their bus rollover analysis.

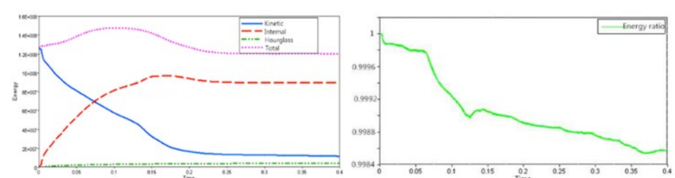



**Figure 19** The energy balance and energy ratio of the bus superstructure [27]

## 4.0 CONCLUSION

This paper focuses on the methods to verify the computer simulation of the bus rollover. The suitable sizes of the element or mesh used must be determined to ensure that the simulation of the bus rollover can signify the real rollover of the bus. However, due to the cost and extensive computational time to perform the mesh refinement analyses of the whole bus superstructure, it is rare to find it in the publications on numerical calculations of the bus rollover. To overcome this problem, researchers use the energy balance and ratio of the simulation model as a tool to ensure the simulation is free from errors. In this study, a method of mesh convergence analysis of the bus superstructure is introduced by differentiating the sizes of the mesh of the ring pillars, and compared the result using two parameters which are internal energy and intrusion into residual space. The simulations of the bus rollover are performed a few times and adjusting the size of the mesh of the ring pillars. Convergence is achieved when using three and four elements across the pillar. To reduce computational times, three elements across the ring pillars are selected. Besides that, the computer model of the bus rollover simulation has been verified using the energy balance and energy ratio too. The simulation analysis is said to be effective and stable since the finite element model energy conservation meets the R66 requirements and the ratio meets the engineering demands. It is hoped that the study of the mesh convergence in bus rollover can help to gain confidence that the simulation model is close to the real rollover.

## Acknowledgement

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## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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