Finite Element Modeling of Bus Rollover

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ABSTRACT

There are many reports on an accident involving bus rollover that includes fatal crash cases. Thus, the implementation of Regulation 66 on the new design of bus is a must or requirement for every bus/coach builder prior to it being mass produced. The preferred method to produce this test is by having a simulation on the bus superstructure having a rollover following Annex 5 of the Regulation 66. This is due to the fact that running the real test is very expensive and it means sacrificing a new bus for the test. However, there are many factors need to be addressed in the simulation model to mimic accurately the real test conditions, for instance, the total mass and location of the center of gravity. Therefore, this paper deals with the methodology to perform a finite element simulation of a bus having a rollover accident in accordance to Annex 5, Regulation 66. As a result, the deformation for the critical beam has been recorded and it appears to have an optimum deformation of 92 mm and does not intrude into the passenger survival area.

Keywords: *Bus rollover, accident, superstructure, UNECE R66, finite element model*

1.0 INTRODUCTION

Bus rollover is the most critical accident based on the number of fatalities and severe injuries that it may cause. Previous study found that an average of 25 casualties per number of accidents [1]. Figure 1 shows the distribution of percentage of fatal accidents due to bus rollover in the USA (Source from the Fatality Analysis Reporting System (FARS) in the USA) [2]:

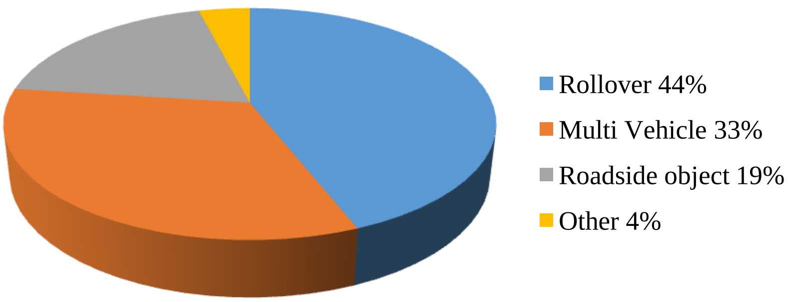

Figure 1: Motorcoach fatal accidents (FARS 1999-2008) [2]

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According to the chart, 44% of fatal events involving motor coach had been contributed by rollover accident. This show that the rollover case is likely to occur in vehicle accident especially for a large vehicle. This had been reported based on the market in the United State of America. Meanwhile, Malaysia similarly had experienced a dramatic growth in the number of fatalities in bus rollover accident cases. In 2007, one histrionic bus rollover crash involving a fatality of 22 passengers that took place near Bukit Berapit, Bukit Gantang had occurred [3]. In addition, six years later, severe rollover crash occurred which involved 37 casualties happened in Genting Highland where the bus is plunged into 60 m ravine [4]. Since then, most of Malaysian considerably more concern of bus superstructure safety. This accident shows that bus superstructure needs to be strong enough to withstand rollover impact and provide better survival space for occupants. Adequate design and sufficient strength of bus superstructure can reduce the number of injuries and fatalities.

According to the United Nation Economic Commission of Europe Regulation 66 (UNECE R66), the bus superstructure needs to withstand the load during and after the rollover [5]. In addition, the structure must not intrude into the survival area. A pioneer research on the bus rollover had been described by Kecman and Tidbury [6] for calculating the different parameters for the certification of rollover related issues. In addition, the effect of several factors including mass, beam profile size also been addressed by previous study [7, 8]. Thus, in this study, the methodology to perform a simulation of bus rollover following Annex 5 in the Regulation 66 are described.

2.0 METHODOLOGY

The full bus superstructure had been modeled using finite element software. In this study, *SIMULIA Abaqus 6.12-1* was used as a tool for running the simulation. At first, the computer-aided drawing (CAD) of the superstructure was acquired from bus coach builder. The drawings were in 2-D drawing format and need to be converted into the 3-D format. The 3-D drawing then checked by technical inspection company to ensure that the dimension, beam profile and the material are accurately assigned and identical with real bus superstructure. The details of the methodology for instance geometry of the model, material properties used and loadings and boundary conditions are described in the subsequent child sections.

2.1 Geometry Model

All members of the superstructure including the chassis were modeled using beam elements. The cross-sectional areas for all members were specified during the development of the finite element model, based on the descriptions provided by the bus builder. All the beam elements were discretized into several smaller elements to ensure reasonable precision of the simulation results. The model geometry of the bus superstructure complete with chassis is shown in Figure 2.

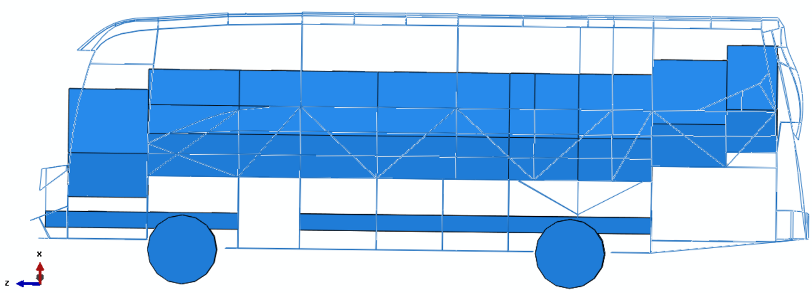


Figure 2: Model geometry of the bus superstructure

The residual space of the superstructure is illustrated in Figure 3. By definition, this is a space to be reserved for the passengers', crew and driver's compartment(s) to provide better survival possibility for passengers, driver and crew in case of a rollover accident.

For approval, no members of the superstructure should protrude into this space, as the superstructure experiences deformation upon impact with the rigid floor.

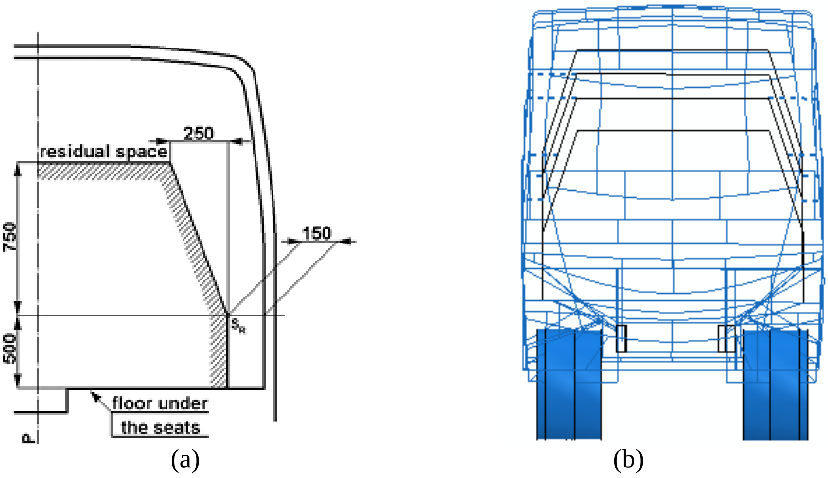


Figure 3: Residual space definition (a) by Regulation 66 and (b) in the FE model

2.2 Material Properties

All materials used were based on the specifications provided by the manufacturer and assumed to behave in an elastic-plastic manner. The material used was mild steel with *Young's* modulus of 210 GPa and the density of 7800 kg/m^3. The *Poisson* ratio and the yield stress used are 0.3 and 381 MPa respectively. The strain rates recoded from the simulation is happen to be 10 s^{-1} and it is advisable to use the existing model that can capture the strain rate effect such as *Johnson-Cook* constitutive model [9]. The moderate speed of strain rates is due to the fact that this rollover is based on the gravitational force only. Tires and chassis were assumed as rigid bodies due to the fact that the deformation of both parts is not the main concern. All the dead loads including engine, transmission, fuel tank, battery unit and air conditioning unit were considered as point mass assign in the model. All welded and bolted joints were assumed to be perfectly bonded. The engineering stress-strain curve is depicted in Figure 4.

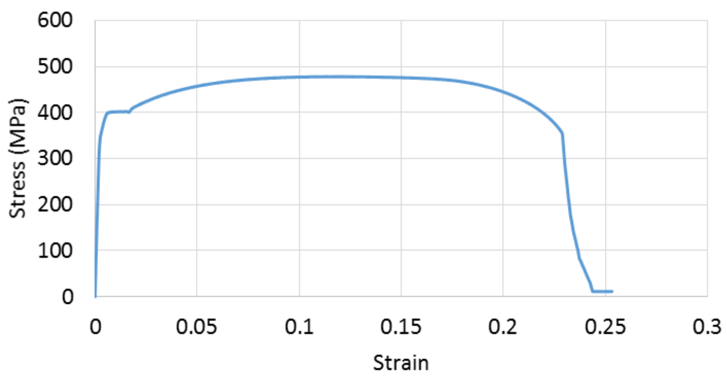


Figure 4: Engineering stress-strain curve for mild steel

2.3 Loadings and Boundary Conditions

The finite element simulation of the rollover test was performed using the dynamic explicit solver of the commercial finite element software. The bus superstructure was tilted at an inclination angle such that the structure starts to roll freely. The initial tilting angle is 62.5° at which it is the position of unstable equilibrium of the bus. The height of the platform is 800 mm according to the regulation. This is illustrated as in Figure 5.

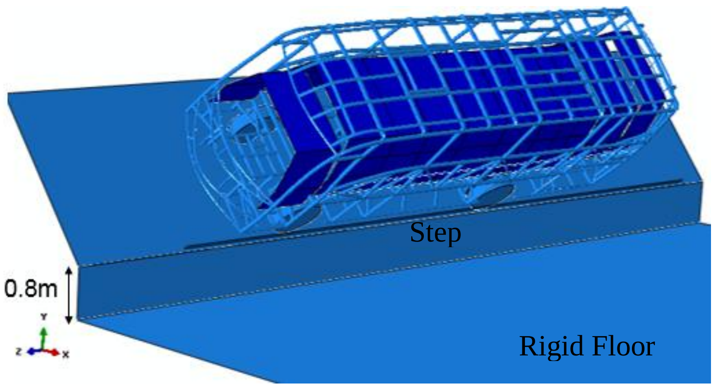


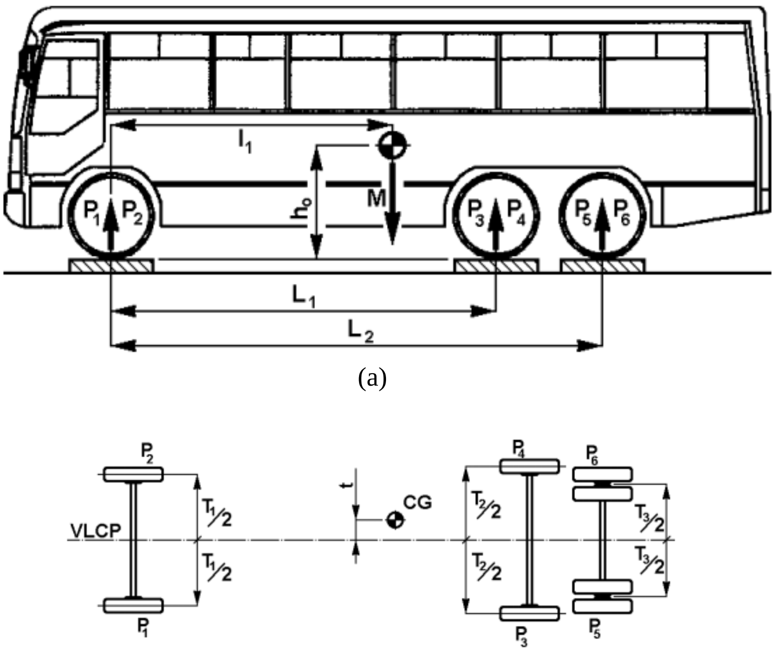
Figure 5: Rollover simulation setup

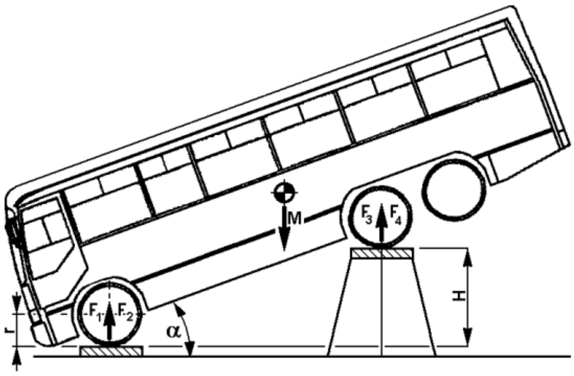
The following boundary conditions were imposed on the finite element model:

a) Gravitational acceleration of 9.81 m/s^2 is prescribed for the entire model of the bus superstructure.
b) The friction coefficient of 0.45 between steel and concrete surface is prescribed.
c) Fixed (zero) displacements are prescribed at the base of the rigid floor.

2.4 Total Mass and Center of Gravity

It is compulsory that the model for rollover simulation have identical mass and center of gravity (CoG) position with the real bus superstructure. The total mass recorded from this model is 6565 kg. The measured longitudinal distance, transverse distance and the height of CoG is 2.36 m, 0.0137 m and 0.3599 m respectively. The transverse distance is measured from the center of the bus and it is located to the left side of the superstructure. The details figure for the determination of CoG location are depict as in figure 6.



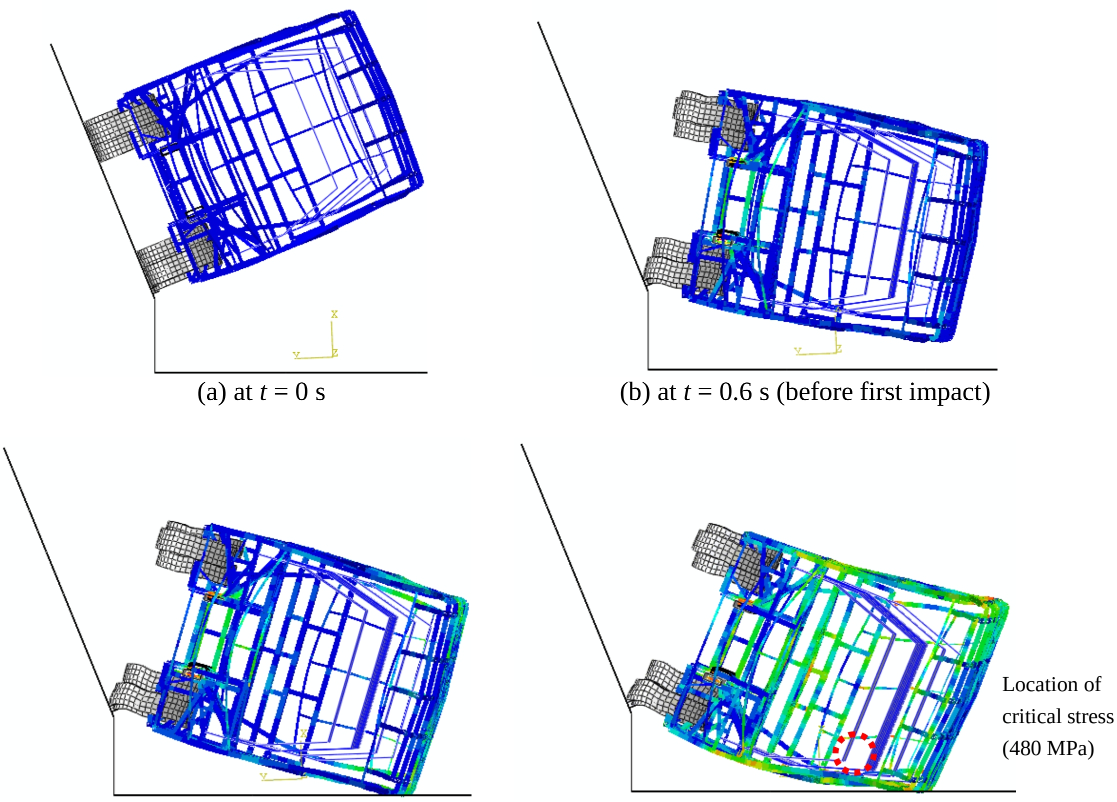


(c)

Figure 6: (a) Longitudinal position, L (b) transverse position, t and (c) height of the center of gravity, H [5]

3.0 RESULTS AND DISCUSSION

The sequence of the rollover simulation is shown in Figures 7(a) to (f). The critical deformation occurs at 0.75 s at which the measured stress is 480 MPa. After the first impact at t = 0.65 s, severe deformation occurs due to the elastic deformation and at the next frame, there are some elastic recovery take place and the deformation is lesser than the first impact. This deformation is known as plastic deformation. Based on this images of the bus during the rollover, it is found that the structure does not intrude into the residual space as mention in the Regulation 66. However, to quantify the minimum distance between the critical structure and the residual space, a criterion based on equivalence plastic strain was used and described in the next section.

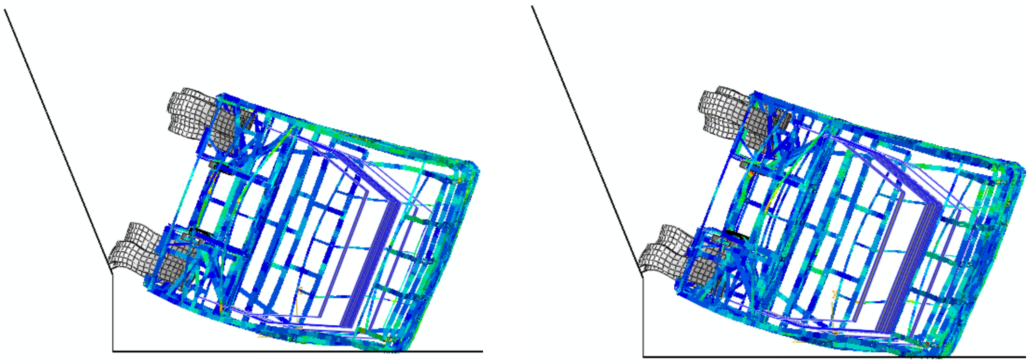


(a) at t = 0 s

(b) at t = 0.6 s (before first impact)

(c) at t = 0.65 s (first impact)

(d) at t = 0.75 s (severe deformation)



(e) at t = 1.5 s (f) at t = 2 s

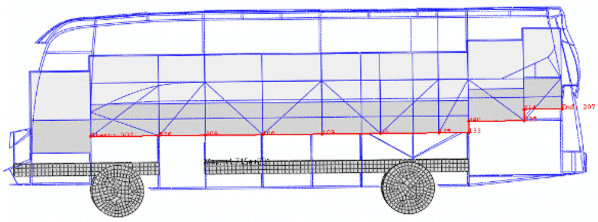
Figure 7: Bus rollover sequence

3.1 Severe Deformation

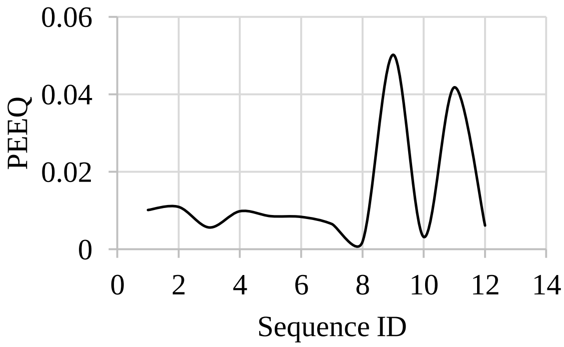
The method of identifying the critical pillar is listed as follows:

1. Determining the location of the critical pillar by employing equivalence inelastic strain (PEEQ) criterion plotting across a particular path
2. Measuring the distance between structure beam and residual space on maximum PEEQ points as determined using method above at critical frame of rollover

At first, the path along beam on impact side has been plotted as in Figure 8(a). Then, the value of PEEQ were plotted against the path for critical deformation stage (at 0.75 s) of the simulation. The sequence ID is referring to the query node list starting from left to right across the path. Afterward, the critical point (located at ID: 9 with reference to Figure 8 (a)) for each path was analyzed and the distance between maximum deformation on critical beam and its periphery residual space measured. Figure 8 (b) shows the graph of distance between the structure and residual space on particular rollover stages. Based on the graph plotted, the closest distance recorded was 92 mm. Figure 9 shows a graph of the distance versus time for the critical node at Path-1 with reference to Figure 6.



(a)



(b)

Figure 8: (a) Path plot (red line) on bus superstructure (Path-1) and (b) Graph of PEEQ versus Sequence ID on Path-1

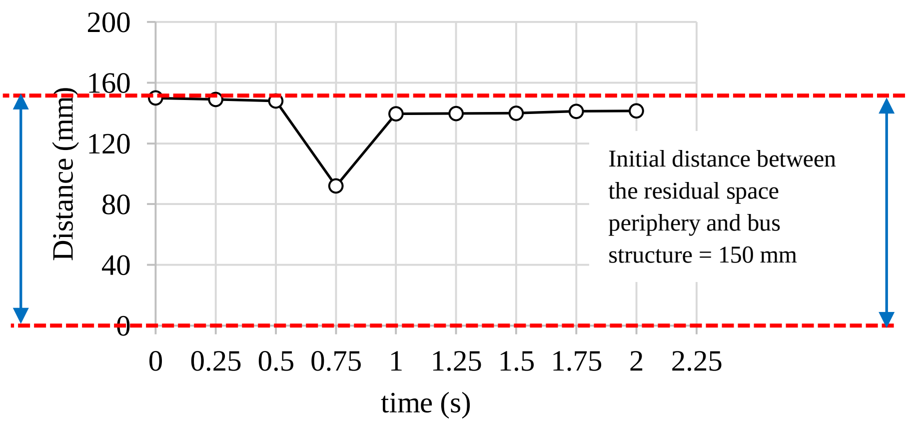


Figure 9: Distance vs time for the critical node at Path-1 (refer to Figure 8 (a))

4.0 CONCLUSION

The procedure to perform bus rollover simulation according to Annex 5 Regulation 66 has been described and presented. The bus superstructure was modeled and a rollover simulation was performed using the finite element simulation software. Results of the rollover simulation show that:

- The bus superstructure undergoes an acceptable amount of permanent deformation due to the impact with the rigid floor. The closest distance recorded was 92 mm (refer to Figure 8).
- The structure during the deformation due to the first impact does not protrude beyond the limit set by regulation (residual area) and the stress level during the first impact is calculated and the recorded value is 480 MPa which occurred at 0.75 s (refer to Figure 6).
- The superstructure of this vehicle has sufficient strength to ensure that the residual space during and after the rollover test on the complete vehicle is unharmed.

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