

# COMPUTER MODELING OF ENERGY ABSORBING CAPABILITY OF BUS SUPERSTRUCTURE FOR ROLLOVER SAFETY

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## **Abstract**

*This paper describes further investigations that have been carried out to make the proposed procedure [5] becomes more reliable to be practically applied as a requirement in bus type approval. One important aspect highlighted in this paper is an effort to improve the accuracy of the FEA model by taking into account detailed construction of bus superstructure. It worth to note that, based on survey carried out on several bus manufacturers, the detailed construction may vary from manufacturer to manufacturer. As a case study, a bus superstructure from a prominent manufacturer was chosen as a sample. Energy absorbing capacity of a bus superstructure section consisting of four bays including rear entrance door, emergency door and rear end was investigated through elastic-plastic finite element model. Incremental quasi static load according to ECE R66 was applied, subsequently to the right and left cantrail to obtain load deflection curve. Then the energy absorbing capacity of the structure when residual space limit was reached was evaluated through derived energy deflection curve. Essential components of the bus superstructure governing its energy absorbing capacity will be discussed. Modeling strategy in dealing with elastic-plastic analysis for such a rather complex structure is also highlighted.*

**Keywords:** *ECE R66, bus superstructure, rollover test, residual space, FEA, quasi-static incremental loading, elastic-plastic*

## **1. Introduction**

Bus transportation plays a very significant role for short and long distance mass transport in Indonesia. Long distance transportation by buses, for economical reason, is still very competitive, despite the availability of other modes of transportation such as trains and airlines which offer advantages such as comfort and shorter travel time.

The importance of bus crashworthiness against rollover accident in Indonesia can be emphasized by looking at Fig. 1, which reveals recorded accident data throughout the year of 2008 to 2010. It shows that the percentage of rollover accidents is quite high as compared with other modes of accident, such as frontal collision accidents and collision with train. Among many factors which are prone to rollover accidents is the fact that much intercity highway in Indonesia is passing through mountaineous country sides. In that particular area it is easy to find highway pavement that is higher than the terrain. Other typical situation is a narrow road on a mountain slope with poor guard rail. The latest may become worse if the ground over which the road was constructed is unstable. Despite the fact that rollover accidents are responsible for half of all highway accidents, unfortunately, there has been no much attention paid by concerned parties to address such accidents in the form of research.

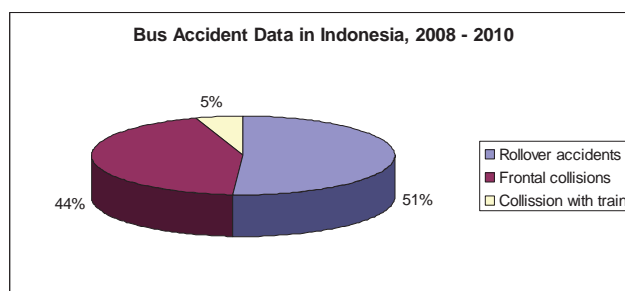


Fig. 1. Bus accidents data in Indonesia, 2008 – 2010 [7]

The strength of bus superstructure in rollover accident can be represented as its capacity in absorbing the associated impact energy. In connection with that, and taking into consideration the condition of domestic bus manufacturing in Indonesia, a preliminary study on computer based procedure for quantitative assessment of bus superstructure crashworthiness has been carried out and presented in KONES 2010 [5]. At this moment there is no standard applicable for bus superstructure crashworthiness in Indonesia. For example, in the bus type approval, there is no quantitative measure that concerns with superstructure crashworthiness evaluation. Approval on this particular aspect is merely judged on empirical field experiences.

Considering that ECE R66 (Regulation No. 66 of the Economic Commission for Europe of the United Nations) may be the most widely adopted in many countries in the future, therefore it was decided that the study was based on such a regulation. As stated in ECE R66, energy absorbing capacity of bus superstructure in rollover can be determined by using a bus superstructure section as a test structure under quasi-static load. As powerful computing machines become cheaper and more common place, the use of digital simulation becomes more attractive to be utilized for quantitative evaluation of bus superstructure crashworthiness [1, 2]. So, to substitute structural testing with quasi-static load, computer simulation is proposed in order to obtain a more affordable technique to most bus manufacturers.

## 2. Survey on bus superstructure design

Most buses and coaches in Indonesia are of body over frame type, where the body is constructed on chassis frame imported through authorized distributors. Despite the availability of national rules determining overall bus dimension and its configuration, there is no further regulation that governs the detail of superstructure design. Therefore, most manufacturers rely on their empirical experience, examples and technical guidance from chassis makers as well as from government bodies in designing their product [4].

Structural testing, analysis and calculation may have been regarded as unimportant since there is no fundamental need for doing it and no criterion to fulfil. Hence, structural members are arranged and joined based on consideration toward efficient fabrication and exterior appearance. The effect of such arrangements on the structural strength may be secondary or beyond consideration. To illustrate such a condition, compare two side wall frameworks fabricated by two different manufacturers for buses of the same size, as shown in Fig. 2. By careful observation one can conclude that those two bear different structural principles that may yield different structural advantages and disadvantages. Fig. 2 left depicts a side wall framework with longitudinal members designed as the main structure. In this type of side frame the pillars are not in the form of continuous steel beams. Lower end of window pillars are welded to waistrail. The Fig. 2 (right) shows a side frame structure where the pillars are chosen as a base structure. The pillars are made of curved continuous steel beam connecting the roof frame and the floor frame. Waistrails are built from continuous steel beams, welded on the outer side of the pillars through gusset plates.

Another important issue to be discussed is the joint between roof bows and pillars. These joints dictate plastic deformation of the bay structure in case of rollover accidents. There are three

structural members meet at this joint, namely roof bow, pillar and cantrail. So, the cantrail is an integral part of the joint. The placement of the cantrail in the joint will significantly affect the strength of the joint. Fig. 3 represents samples obtained from two different manufacturers that show interesting structural solutions. In the left figure, roof bows and pillars are welded on the cantrail, where cantrail act as the joint centre. In the right figure the weld joints are partially interrupted by cant rails since cantrail axis is offset to joint centre line. Therefore, there is some segment of roof bow ends that welded to pillars.

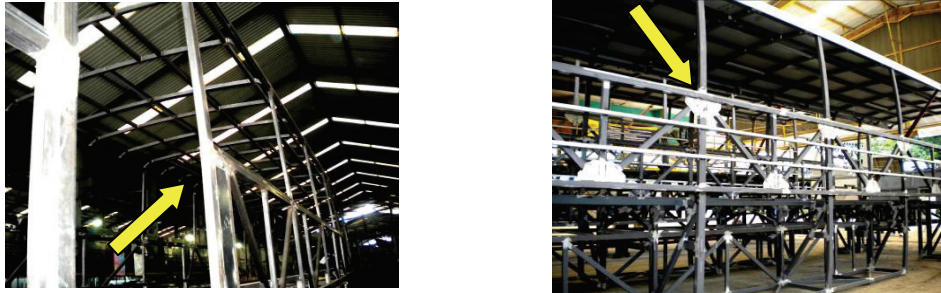


Fig. 2. Side wall frameworks fabricated by two different manufacturers



Fig. 3. Pillar and roof bow joint details from two different manufacturers

Figure 4 shows samples of floor framework and side wall framework joint, obtained from two different manufacturers. Both share the same principle, where pillars of side wall frame are welded to cross members of floor frame.

### 3. Digital simulation model

#### 3.1. Physical Model and CAD Model Description

The case study discussed in this section is an initial step to find a computer simulation procedure that can be reliably utilized as a substitute to the quasi static load test. Autodesk Inventor was chosen for geometrical modelling, while ANSYS was chosen for finite element analysis. Firstly, a CAD model of bus superstructure was built using Autodesk Inventor, software that can be easily utilized to create geometrical model of the structure with high accuracy.

It should be born in mind though, besides maintaining geometrical accuracy, the decision in geometrical modelling will affects next modelling in ANSYS. For example, an option of creating surface bodies was not utilized to avoid difficulties in defining thickness when the model imported and edited in ANSYS. In simple models, surface bodies might be easy to handle and obtained results might be more accurate. However, in complicated geometry such as bus body structure, defining thickness of all structural member profiles is not an easy task. Every contact edge between structural members needs to be made as smooth as possible. Otherwise, many obstacles will be encountered in meshing process. In this case study, the majority of superstructure was constructed from thick wall hollow beams. So the application of solid model representing the

hollow beam was appropriate for CAD model, whereas the cross sections bus structural members were changed from filleted corner to sharp corner to reduce problems in meshing. The whole superstructure was modelled by assembly technique where face-contact acted for several connections between parts of structures.



Fig. 4. Side frame and floor frame joint detail from two different manufacturers

Figure 5 left shows a CAD model of bus superstructure used in this study, representing typical intercity buses of 28 seating capacity. For the first trial it was decided that computer simulation would involve a body section according to ECE R66. This decision was made in order to anticipate the multitude of problems that could be encountered during the beginning period of the research and to avoid acquiring computer with high computing capacity. The shaded part in Fig. 5 left is a rear body section comprising of four bays, chosen to be analyzed as the test model.

As shown in Fig. 5 right, the rear body section included entrance door on the left side, emergency exit on the right side and rear end framework. This was the type bus superstructure that utilized continuous steel beam pillars with joint details as described by Figs. 2 right, 3 right and 4 right. All principal structural members were of closed section steel beams. To simplify the modelling the steel sheet skin was omitted from the model since the effect of the skin in the direction of deformation was assumed very small. A 3D residual space envelope was also included in the drawing to indicate the limit of structural deformation in rollover test. Bus structure deformation must remain outside the envelope to provide better survivability for passengers, crews and driver. To take into account the effect of overhead luggage rack as part of bus interior, the original residual space (Fig. 6 left) was then modified to become 280 mm higher (Fig. 6 right).

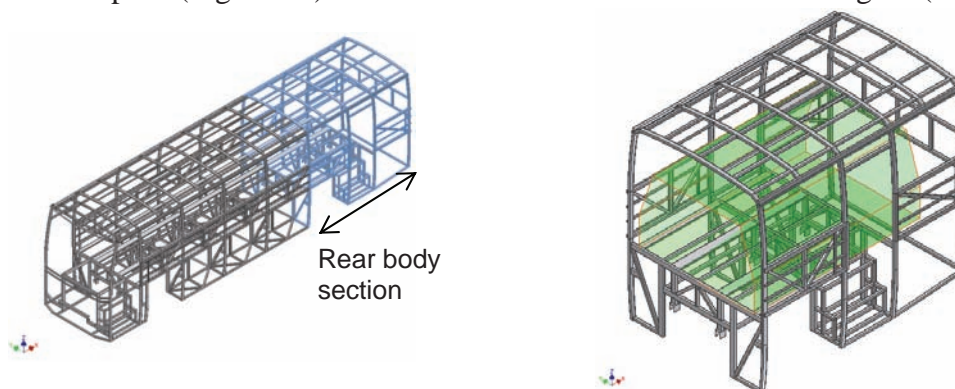


Fig. 5. Bus superstructure design under investigation (left) and CAD model of rear bus body section with 3D residual space (right)

### 3.2. Finite Element Model

In this work, tetrahedron elements were applied to all structural members by arranging higher density around joints. A combination of sharp corner cross sections and face-contact between members gave some significant simplification to connectivity problems during generating mesh arrangement.

To obtain elastic plastic response of the finite element model to quasi-static load imposed on it material model as shown in Fig. 7 left was used, representing mechanical properties of the SAPH 41 steel (according to JIS G 3113), a typical steel used in bus body manufacturing. This particular steel has yield strength of 255 MPa (at 0.1275 % yield strain), tensile strength of 402 MPa (at 20% ultimate strain), modulus of elasticity of 200 GPa, Poisson’s ratio of 0.3 and tangent modulus of 740 MPa. Then the properties were modelled in the ANSYS Workbench as a bilinear isotropic hardening model, as shown in Fig. 7 right. In the finite element model the weld joints were assumed to be perfect.

By importing the CAD model in Fig. 5 right to ANSYS Workbench, a finite element model then was generated as depicted in Fig. 8 left. The finite element model consisted of 144836 tetrahedron elements with 280723 total number of nodes.

The direction of the applied load (shown in Fig. 8 right) was determined as follows:

$$\alpha = 90^\circ - \arcsin\left(\frac{800}{H_c}\right),$$

$$H_c = 3325\text{mm},$$

$$\alpha = 76.07^\circ \approx 76^\circ.$$

Incremental loads were applied on the cantrail of body section until the residual space was intruded by the vehicle deformed structure.

Boundary conditions were formulated as fixed restraints at the attachment points connecting the superstructure and the ladder frame.

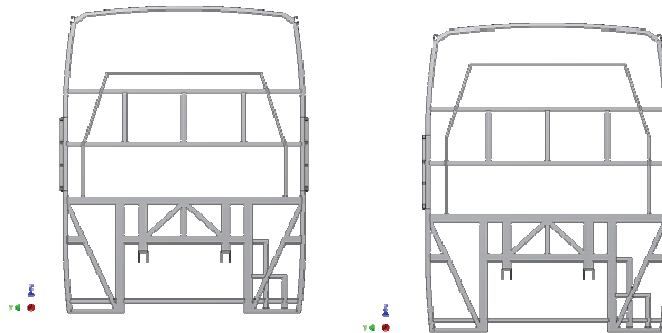


Fig. 6. Original residual space (left) and modified residual space (right)

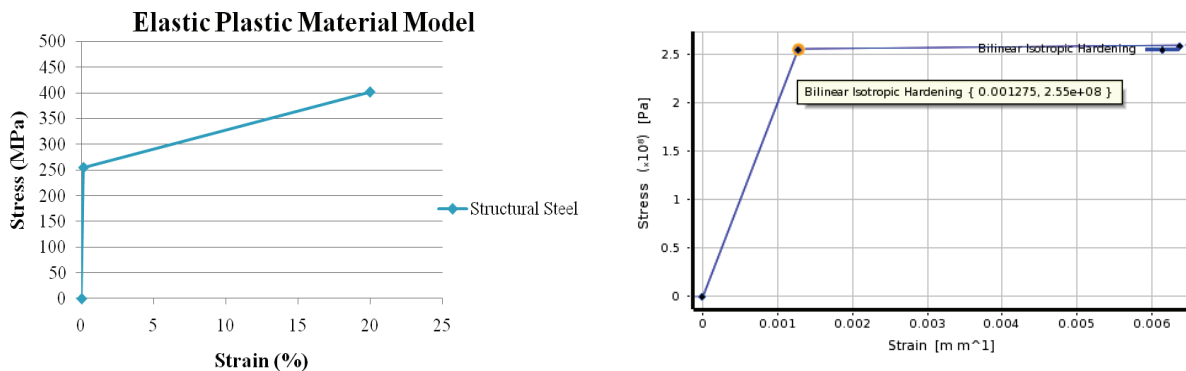


Fig. 7. Bilinear material model (left) and its representation in ANSYS (right)

### 3.3 Calculation of Absorbing Energy Capability $E_{BS}$

Figure 9 shows deformed structure that just reached residual space after a force of 55,500 Newton's magnitude imposed on the cantrail, with corresponding load-deformation and energy-deformation curves shown in Fig. 10. In this case deformation was measured in the same direction of applied force. A trial and error scheme for determining the load magnitude was used in obtaining such a structure deformation that just intruded the residual space.

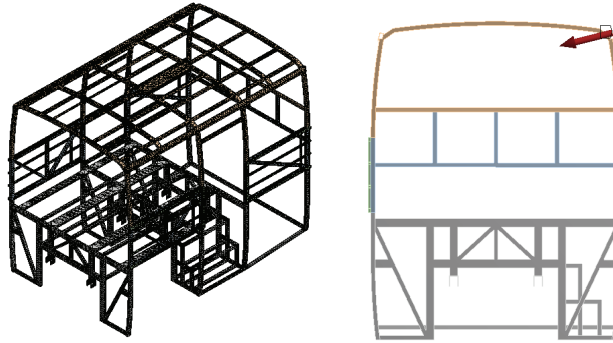


Fig. 8. Finite element mesh (left) and load model (right)

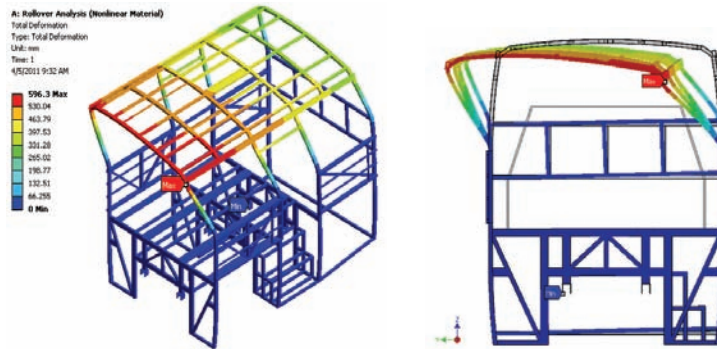


Fig. 9. Deformed structure just touched residual space

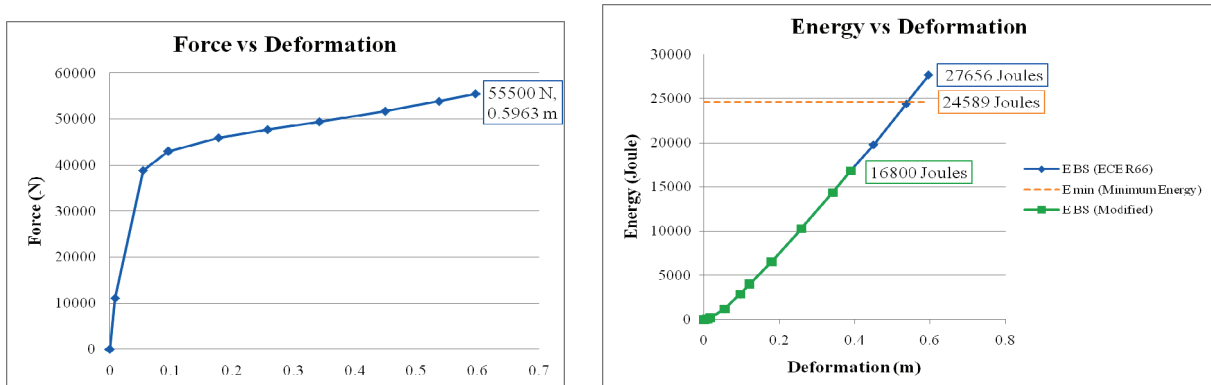


Fig. 10. Load vs. deformation (left) and energy vs. deformation curves (right)

One of important findings from the simulation was about parts of the structure that contribute to the strength against rollover accident. Finite element analysis results showed that, the deformation mainly occurred at the parts of the structure above waistrail (plastic hinges near waistrail). Structural parts below the waistrail were practically intact. Hence, it can be presumed that the truss structure had a significant role in providing the strength of side wall frame. To verify this presumption, further investigation was performed by eliminating outer members of side wall frameworks from the finite element model. This particular model showed that the structure deformed with plastic hinges located at lower ends of pillars joining floor frame cross members, Fig. 11 left. Fig. 11 right shows deformed bus section structure when cross members at rear end framework were omitted. This is an evident that the deformation shape of the pillars was not dictated by the existence of rear end cross members.

Energy absorbed by the structure when deformation reached the residual space was calculated to be  $E_{BS} = 27656$  Joules. In the case of modified residual space was used to limit the structural deformation, the absorbed energy reduced to  $E_{BSm} = 16800$  Joules. Finite element simulation with

the same loading scheme applied on the opposite cantrail was performed. This was due to the fact that there were differences between right side and left side frameworks of the test structure. The results showed that there was no significant different between energy absorbing capacity when the bus section rolled over either to the left or to the right.

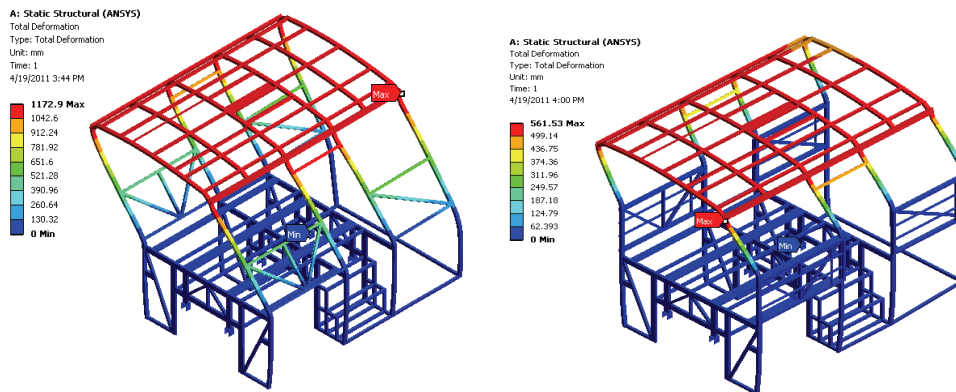


Fig. 11. Deformation of body section structure without outer side wall members of (left) and without cross member structure on the rear end wall (right)

### 3.4. Calculation of energy to be absorbed by a body section $E_{min}$

Total energy to be absorbed by superstructure in a rollover test can be calculated as  $E_T = 0.75Mg\Delta h$ , where M is unladen kerb mass of the vehicle, g is gravity and  $\Delta h$  is the vertical movement of vehicle centre of gravity [6].

With vehicle data as follows;  $M = 10250$  kg and  $\Delta h = 2.742 - 1.570 = 1.172$  meters then total energy was calculated as  $E_T = (0.75)(10250 \text{ kg})(9.81 \text{ m/sec}^2)(1.172 \text{ m}) = 88386$  Joules.

Since only a body section is considered, then the corresponding energy to be absorbed can be calculated as  $E_{min} = \sum E_i = E_T \frac{\sum m_i}{M}$ , where  $E_i$  is energy to be absorbed by the  $i^{th}$  bay and  $m_i$  is mass of the  $i^{th}$  bay.  $\sum m_i$  is mass of body section includes rear section of ladder frame, and everything attached to it such as engine, rear axle, drive train, wheels, etc. According to the formula, the calculation can be preceded as every of component acts individually to the superstructure. However, taking into consideration that most components are attached to the ladder frame which is much more rigid than the superstructure, then their effects in rollover can be approximated as uniformly distributed mass. Therefore the term  $\frac{\sum m_i}{M}$  was approximated by the ratio of defined body section mass to the total mass of the superstructure. Using this approach, with mass of body section of 615.58 kg and mass of superstructure of 2212.7 kg, then the energy to be absorbed by body section under investigation was determined to be  $E_{min} = 24589$  Joules. As depicted in Fig. 10 right, the value of energy to be absorbed by body section,  $E_{min}$ , is lower than the value of energy absorbing capability of body section  $E_{BS}$ , when original residual space is used, while  $E_{min}$  is greater than the value of energy absorbing capability of body section  $E_{BS}$ , when modified residual space is used.

A word of caution is in order. The influence of overhead luggage rack in modifying residual space has to be carefully formulated. Other wise, the structure of the bus has to be made unnecessarily much stronger. The validity of the approximation in calculating  $E_{min}$  to corresponding ECE R66 rule needs to be verified in the future work.

### 4. Closure

Deeper study on the computer modelling of energy absorbing capability of bus superstructure using Autodesk Inventor and ANSYS was performed. There are findings from the study that can

be regarded as valuable steps toward the ultimate objectives, highlighted as follow.

1. Preliminary procedure to determine energy absorbing capability of a bus body section in rollover as reported in [5] has been further developed.
2. Strategy in geometrical modelling using Autodesk Inventor and finite element modelling using ANSYS have been work out.
3. Parts of bus superstructure contributing to its crashworthiness in rollover have been identified.
4. The effects of overhead luggage rack in modifying residual space have to be carefully formulated.

Further work is still required to make the proposed procedure appropriate to be practically applied in type approval. A study is going on to include change of material properties due to welding (HAZ) in the finite element model. The effects of different structural joint designs on the strength of the superstructure will be studied in the future work. Inaccuracy due to omitting steel skin in the modelling body section will be investigated.

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