BODY SECTION ANALYSIS IN BUS ROLLOVER SIMULATION

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Abstract: Bus rollover crashes have claimed many lives and injured even more victims. The rare occurrence of the crash as compared to other crash configurations such as full frontal and side impact has underrepresented the fatality caused in rollover crash. In Malaysia, there have been several fatal high profile cases involving bus rollover. Adopted in 2007, ECE R66 is in force in Malaysia to prevent disastrous consequences as a result of a bus rollover crash. The paper describes the methodology of performing a rollover simulation to a bus, albeit only to selected body section. Commercially available software was used to develop a finite element model based on the manufacturer’s 2D drawing. With close reference to the ECE R66 regulation, simulation was conducted and results were presented in the form of structural deformation overview and energy vs. time history.

Key Words: Rollover, ECE R66, superstructure, LS-DYNA, finite element analysis

1. INTRODUCTION

Rollover is the worst possible crash scenario as the resultant damage to the vehicle and the injury to passengers could be extreme. In a rollover crash, the lack of sufficient roof strength and structural integrity in providing protection to occupants is likely to cause severe or fatal injuries as highlighted in Matolcsy (2007), Friedman (2001) and Young (2007). Occupant protection in rollover crashes is still poor and often results in severe injuries, especially when a bus is involved. In comparison, injury severity in more common crash types such as frontal collision...
has been significantly reduced over the years. The reduction is largely attributed to the advancement in technology and research performed on crash occupant protection (Chang, 2006).

Most rollover crashes fall under the trip-over category. A trip-over occurs when the tyre is in contact with a tripping object, stopping the lateral motion of the vehicle and flipping it around the object (Aqbal, 2009). Contact with ground structure such as curbs, ramps, and rocks is the main cause of trip-overs (more than 90%) (Parenteau et al., 2003). After examining the injury factor in many bus rollover crashes, it is apparent that the intrusion by the edge of the roof into occupant space poses the most severe injury risk to bus occupants (Conroy et al., 2006).

In Europe, 150 fatalities are recorded in bus related crashes every year. Moreover, some 30,000 occupants also suffer injuries in those crashes (ECBOS, 2003). Although the number of bus-related accidents in Malaysia is low, the fatality rate due to the crash is overrepresented. According to a Malaysian accident database; MROADS, there are 5.78 fatalities per 10,000 buses in 2008, which is 75% higher as compared to Malaysian road fatality indicator of 3.32 fatalities per 10,000 vehicles. Furthermore, 1/3 of those fatalities are from rollover cases.

ECE R66 is regulated in many countries with the aim of reducing injury severity resulting from bus rollover crashes. The regulation focuses on the strength of bus superstructure to prevent occupant space from intrusion during a bus rollover. There are several methods accepted as equivalent approval for the physical test, including computer simulation of a complete bus (United Nations agreement, 2006). During the initial phase of the computational method, critical bus structural components in rollover crash were identified so as to understand their energy absorption capability.

This paper describes the methodology of performing a rollover simulation on a body section of a single deck bus. A FEA model was developed from CAD data according to the manufacturer’s geometrical drawing. The development of the tilting platform model and the residual space as well as the location of the center of gravity (CG) determination was carried out according to the UNECE R66 procedure. Boundary conditions for rotational motion and gravity loading were specified to simulate physical rollover test conditions. Non-linear, explicit and dynamic solver, LS-DYNA was utilized for computational calculation and LS-Prepost was used as post-processing software. Energy absorption capability of the structure was analyzed and critical structural components were identified from said analysis.

2. BUS ROLLOVER ACCIDENTS IN MALAYSIA

Interstate express bus operators in Malaysia invest large capital to increase their overall productivity. The recent trend in express bus industry of switching from single-decker (SD) to high-decker (HD) coaches is increasing. Among the reason for this trend is to increase the total capacity, improve marketing image and enhance passenger comfort (Hemily, 2008).

Although it does not appear to pose any significant safety concern (Calgary, 2002), the operation of HD in Malaysia has initiated mixed reactions by the public and relevant agencies following several high-profile bus crashes. Since 2007, a number of bus rollover crashes have occurred and claimed many lives. The public and the authority are concerned about the construction of high
deckers whereby the CG factor appears to be neglected. To them, rollover crashes are caused by the instability of buses which they relate to high deckers. Contrary to this belief, rollover crashes actually have involved both single and high decker buses. Moreover, the CG factor remains crucial in high decker design and bus constructors need to prove to the authority that this factor is handled accordingly in order for their design to be approved.

The case that caught the attention of the Malaysian public and authority is the Bukit Gantang crash on North-South Expressway on 13 August 2007 (Figure 1). The high decker coach skidded and ramped over the roadside guardrails, underwent a quarter roll down a concrete drain, fell into a culvert and came to rest after hitting a large rock. 22 perished in the crash which was attributed to the weak structure and poor roof-pillar joints.

In December 2008, another bus crash occurred and shook the country again. An express bus tripped over a roadside drain, hit some trees and overturned (quarter roll) resulting in 10 deaths on the North-South Expressway near Tangkak. Following these two crashes, immediate countermeasures were imposed and few recommendations such as the implementation of UNECE R66 were made to the government.

A recent crash on 10 October 2010 on the southbound lane of KM 233 of the North-South expressway has sparked public interest in the issue of bus superstructure yet again. The crash which occurred near Simpang Ampat, claimed 13 lives and 35 were severely injured in the crash. Among the deceased, 11 fatalities were the occupants of the bus. Investigation on the vehicle revealed that UNECE R66 verification procedure was not carried out to the superstructure during its design process in 2006. This is due to the fact that the regulation was only enforced starting from 2007.

Since April 2006, Malaysia has become a signatory member WP29 of UNECE (Wong, 2009). The Malaysian Cabinet has incorporated UNECE R66 as part of the approval requirements effective November 2007 following the horrendous Bukit Gantang crash. The Road Transport Department (JPJ); as the agency in-charge of vehicle type approval (VTA) is responsible in spearheading a committee to implement this regulation. However, the procedure for type approval and rollover simulation validity conducted by the technical service providers is still unclear.
3. MODELLING ACCORDING TO ECE R66

A rollover crash is by far the worst possible crash for a vehicle to undergo because the resulting damage could be more severe as compared to other type of crash such as head-on and side collisions. Due to the nature of rollover crashes, bus occupants face higher possibility of undergoing serious or fatal injuries when the vehicle topples. At that instance of time, the roof of the structure is vulnerable to intrusion and projection.

A rollover test on a complete vehicle as part of the basic approval method specifies that the test must be conducted using a test platform (United Nations, 2006). The test; which is also known as the lateral tilting test, requires that the platform be tilted slowly with the vehicle on top until it reaches an unstable equilibrium position. There are two test options regarding the occupant restraining method:

- The vehicle is tested at unladen kerb mass for a vehicle not fitted with seatbelts.
- The vehicle is tested at total effective vehicle mass for a vehicle fitted with seatbelts.

Once the vehicle reaches an unstable position, the rollover test starts with zero angular velocity rotation along the wheel-platform contact point, as the axis of rotation. The regulation also specifies that the vehicle be tipped over from an 800 mm-high edge into a ditch of horizontal, dry and smooth concrete ground.

The direction of the rollover rotation follows the weaker side of the vehicle, upon the manufacturer’s proposal, while considering at least the following conditions:

- The lateral eccentricity of the center of gravity and its effects on the reference energy in the unstable, starting position of the vehicle.
- The asymmetry of the residual space.
- The different, asymmetrical constructional features of the two sides of the vehicle, and the support given by partitions or inner boxes (e.g. wardrobe, toilet, kitchenette)

3.1 Residual space specifications

ECE R66 concentrates on the ability of a vehicle to sustain its residual space in a rollover crash. The residual space is not expected to be intruded by structural deformations resulting from a rollover crash, for regulation approval. The specifications for the residual space (Figure 2), viewed as wireframe trapezoid, from cross section were as follows:

- The lower edge line shall be at 500 mm above the floor under the seat.
- The lower edge point shall be at 150 mm from the inside surface of the wall.
- The upper edge line shall be at 750 mm from the lower edge line.
- The upper edge point shall be at 250 mm from the line perpendicular to the lower edge point.
For the body section model, the width from wall-to-wall was measured as 2268 mm. Taking into account the above specifications, residual space above the seat was designed with the dimension specified below:

<table>
<thead>
<tr>
<th>Description</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lower edge length</strong></td>
<td>2268 mm – (2 x 150 mm)</td>
</tr>
<tr>
<td><strong>Upper edge length</strong></td>
<td>2268 mm – (2 x 400 mm)</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>As specified in ECE R66</td>
</tr>
<tr>
<td><strong>Longitudinal length</strong></td>
<td>According to body section length</td>
</tr>
</tbody>
</table>

Thin rigid beam frames were used for modeling the residual space, which were mounted on rigid part under the floor. Null material was assigned to the residual space, thus the stiffness connection between these frames was voided.

### 3.2 Tilting platform specifications

Tilting platform was modelled horizontally at a vertical height of 800 mm from the ground. It rotated at a maximum 5 degree/sec angular velocity with its axis of rotation located 100 mm below the platform and 100 mm from the vertical wall of the ditch.

A stopper was introduced to provide support for the wheel so that the bus would tip over from the platform without moving along its longitudinal axis, and to keep the side of the wheel at a maximum distance of 100 mm from the axis of rotation. The stopper was 500 mm and 20 mm in length and width respectively (Figure 3).
3.3 Location of Center of Gravity (CG)

The location of the center of gravity (CG) is essential in determining the reference and the total energy to be absorbed in the rollover test. The CG location of the body section in Table 2 was determined using a software function by means of structural dimension and its kerb mass, which was derived from material properties.

<table>
<thead>
<tr>
<th>Section</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>The front edge from the CG</td>
<td>1015 mm</td>
</tr>
<tr>
<td>The rear edge from the CG</td>
<td>931.2 mm</td>
</tr>
<tr>
<td>The CG from the VLCP</td>
<td>4.708 mm</td>
</tr>
<tr>
<td>Height of the CG</td>
<td>1540 mm</td>
</tr>
</tbody>
</table>

The rollover simulation only started after the body section roll passed the angle of stability in an unstable equilibrium position to save cost and processing time. Moreover, mass scaling and deformable-to-rigid switching functions in LS-DYNA were utilized for the same purpose. The location of CG was used to determine the unstable equilibrium angle ($39^\circ$) given by the equation below:

$$\Theta = \arccos\left(\frac{h}{r + \frac{h}{\cos(39^\circ)}}\right)$$
whereby \( h \) is the height of CG, \( B \) is the perpendicular distance of the vehicle’s vertical longitudinal center plane (VLCP) to the axis of rotation, and \( t \) is the perpendicular distance of the CG from VLCP.

4. DEVELOPMENT OF FINITE ELEMENT MODEL

A 3D model of the body section was developed from geometrical data provided by the manufacturer. Although geometrical drawings of every section of the bus is available, additional information especially regarding joint technology was also gathered in developing a more realistic bus model. Data used as input parameters are presented in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unladen kerb mass of model</td>
<td>565.22 kg</td>
</tr>
<tr>
<td>Overall width of the model</td>
<td>2355 mm</td>
</tr>
<tr>
<td>Height of the model</td>
<td>3326 mm</td>
</tr>
</tbody>
</table>

A finite element model (FEM) of the body section was created from the geometry data involving tasks such as model discretization, element and material properties assignment, and contact and initial velocity condition definition. This simulation was conducted to the model to generate predictions of structural deformation in a rollover crash. The finite element model of the body section (Figure 4) comprised 141,557 shell elements; 139,975 of those were quadrilateral, 1,582 were triangular beams. An element length of 10mm was assigned to upper body section and 20mm for lower body section for finest analysis result. All deformable parts were modeled with the 4-noded Belytschko-Tsay shell elements with three integration points through the shell thickness (Livermore, 2009).

The structural model of body section was majorly represented by deformable bodies which include window pillars, the roof structure and beams. Components such as seats and joints were modelled and integrated into the FEM as rigid bodies. For a realistic analysis, stress-strain curves of the body section material were obtained from the manufacturer. MAT Type 24, “Piecewise Linear Isotropic Plasticity model” was used to represent deformable bodies and rigid bodies were modeled with “Rigid Material, MAT Type 20”.

An impact surface was created to represent the impact ground and RIGIDWALL_PLANAR was defined as the contact point of the vehicle and the ground. AUTOMATIC_SINGLE_SURFACE contact was specified for interaction between the vehicle superstructure as the contact is more rigorous in the treatment of interior sharp corners within the finite element mesh and in the handling of triangular contact segments. AUTOMATIC_SURFACE_TO_SURFACE was used between vehicle superstructure and tilting table. This contact type is established when a surface of one body penetrates the surface of another body. AUTOMATIC_NODE_TO_SURFACE was used between the vehicle tyre and the tilting table. It is a contact type which is established when a contacting node penetrates a target surface.
Simulation analysis commenced after the finite element model was developed in which elements were formulated, meshing and spotweld was applied, materials were specified, and contacts were defined. To reduce CPU cost and improve analysis performance, deformable to rigid switching and mass scaling technique was applied. Deformable elements were switched to rigid at the beginning of the simulation time and were switched back to deformable, a few milliseconds before the initial impact occurred. Small time step size was achieved for time step is usually small to maintain the numerical stability. To prevent the inefficiency, mass scaling was applied whereby nonphysical mass was added to a structure in order to achieve a large explicit time step, increasing the time step size in each simulation cycle.
5. DISCUSSION OF RESULTS

A typical bus design comprises three areas; front, middle and rear as illustrated in Figure 5. The middle area usually consists of more than one body section while the front and the rear are composed of only one section each. For that reason, the middle area was more appropriate for analysis since there were four similar body sections in that area in which most passenger seats were located at. Finally, the particular body section (the dotted box) was selected for the rollover analysis because the longitudinal CG of the complete bus was also located at that particular section.

The residual space of the superstructure for the selected time step was observed as illustrated in Figure 6. At $t = 1.81$ sec, the body section hit the ground at roof knot area. The roof knot started to deform but the upper structure was able to absorb most of the impact force, leaving the residual space unharmed. At $t = 1.86$ sec, the impact force was distributed to the middle frame, causing the window knot to bend. The deformation caused the side frame to move closer to the residual space. Finally, the critical time for maximum deformation occurred at $t = 1.94$ sec. Impact energy transferred to the lower frame and caused floor knot deformation. The side frame bended, distorted and subsequently moved even closer to the residual space without enough force to intrude it. At this moment, the distance between the side frame and the residual space was only 100.1 mm. This indicated that the model did satisfy the condition set by the regulation for a physical body section rollover test.
The structural deformation on the right frame of the body section was observed in Figure 7. Upon impacting the ground at $t = 1.81$ second, the roof knot of the frame touched the ground first. The impact force was distributed to the entire side structure especially to the roof knot. Figure 7A shows a close-up look of the deformed roof knot edge after absorbing a certain amount of impact force.
Further structural deformation could be seen distributed to the middle structure. At this point, the impact energy was transferred to the middle right frame i.e. the window knot. The middle structure also absorbed impact energy and at $t = 1.86$ sec, the impact force caused the window knot to bend and deform (Figure 7B).

The impact energy was further distributed to the lower right frame as the upper frame reached its material strength limit. The floor was also under slight material stress level as shown by the color contour in the figure. Finally at $t = 1.94$ sec, the floor knot experienced the maximum stress (Figure 7C) indicating that the impact force was mostly distributed to the lower structure.

Based on the residual space intrusion and structural deformation overview against time, it could be inferred that roof knots and window knots were the critical components in containing residual space from intrusion by the structural frame. Those two joints were observed to have lower yield point in absorbing impact energy and were prone to structural failures upon impact with the ground. Window knots benefitted from vertical continuous beams as opposed to lateral hollow beams, enabling the knots to distribute impact stress to joining members. It also had additional supporting beams attached to the joint which improved the joint strength.
Figure 8 shows that the total energy and kinetic energy increased after the body section started rolling down the platform, passing the unstable equilibrium position. After the roof knot hit the ground at 1.81 sec, kinetic energy decreased while internal energy increased, indicating that the energy was completely transformed into another form, although there were also slight hourglass and sliding energy present. The applied energy when the roof knot hit the ground at 1.81 sec, when obtained from the energy vs. time history was $7.1 \times 10^6$ N mm.

![Figure 8 Energy vs. time history](image)

5.1 The Effect of Passenger Loading

In the case in which seatbelts are part of the vehicle seat, UNECE R66 regulation prescribes that a mass of 68 kg shall be attached to each seat. Considering that fastening a two-point seatbelt to a passenger is effective in restraining the passenger from crash impact, 68 kg mass was imposed in the model by means of placing concentrated element mass of 68 kg at 100 mm above and 100 mm to the front of manufacturer’s reference point for each seat.

The addition of four concentrated element mass of 68 kg each changed the kerb mass of the body section to 844.11 kg. Furthermore, the CG height shifted up to 1626.9 mm from the floor and the unstable equilibrium angle also changed to 37 degree. To further inspect the impact of a rollover to the superstructure, distances between the residual space and structural beam were measured at three nodes; bottom, middle and top represented by node 1, node 2 and node 3 respectively in Figure 10.
Table 4 presented the displacement of structural beam after the impact for the unladen body section and the body section with passenger loading. In both cases, the time for maximum deformation was different as a result of the change in overall weight. For the unladen body section, the critical time for maximum deformation was at $t = 1.936$ sec and the closest distance before residual space intrusion was 100.1 mm at front pillar. The addition of passenger loading had shortened the critical time for maximum deformation to $t = 1.824$ sec. Corresponding closest distance from residual space to side frame was recorded 38.1 mm at front pillar. Although the introduction of passenger loading imposed greater consequence in displacement of side frame, this laden body section was proven to comply with UNECE R66 regulation via simulation analysis.

Table 4: Displacement of side frame at the critical time for laden and unladen body section

<table>
<thead>
<tr>
<th>Pillar</th>
<th>Node</th>
<th>Original distance (mm)</th>
<th>After impact distance (mm)</th>
<th>Displacement (mm)</th>
<th>Residual space R66</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without passenger loading</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>1</td>
<td>149.3</td>
<td>119.9</td>
<td>29.4</td>
<td>All meet requirement</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>274.3</td>
<td>147.4</td>
<td>126.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>399.3</td>
<td>100.1</td>
<td>299.2</td>
<td></td>
</tr>
<tr>
<td>Rear</td>
<td>1</td>
<td>149.3</td>
<td>119.5</td>
<td>29.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>274.3</td>
<td>159.2</td>
<td>115.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>399.3</td>
<td>115.5</td>
<td>283.8</td>
<td></td>
</tr>
<tr>
<td><strong>With passenger loading</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>1</td>
<td>149.3</td>
<td>91.6</td>
<td>57.7</td>
<td>All meet requirement</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>274.3</td>
<td>97.7</td>
<td>176.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>399.3</td>
<td>38.1</td>
<td>361.2</td>
<td></td>
</tr>
<tr>
<td>Rear</td>
<td>1</td>
<td>149.3</td>
<td>93.5</td>
<td>55.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>274.3</td>
<td>111.7</td>
<td>162.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>399.3</td>
<td>52.5</td>
<td>346.8</td>
<td></td>
</tr>
</tbody>
</table>
6. CONCLUSION

The study explored the computational method of rollover simulation test on a body section of a single deck bus. While the body section analysis is not sufficient as an equivalent approval for ECE R66, this study served as a platform to discover the best practice in rollover simulations. Cost-saving approach to the CPU time and the computational method acquired shall be applied in future analyses, which will involve a complete bus finite element model.

Via body section simulation, structural frame components that were critical to the rigidity of superstructure in a rollover crash were identified. Additionally, structural joints that experience the most stress upon impact with the ground were also identified in the simulation. The information is valuable for bus constructors in the sense that the structural frame needs to be designed and fabricated with the failure criteria of critical beams and joints under consideration. To comply with UNECE R66, constructors need to emphasize on aspects of superstructure strength in bus construction for improving passenger protection during a rollover crash.

In the next phase of the project, further works need to be done in fabricating the critical components, namely roof knot and window knot. Tensile and compression tests shall be conducted to obtain the material properties of the structural beams and the failure characteristics of joint welding. The properties shall be used as input to the model for better analysis accuracy. Ultimately, the simulation shall be conducted on a whole bus using the same approach and the result shall be compared with experimental result. In addition to the constant total energy in the energy vs. time plot, close replication of experimental test results is an even better indication of the validity of the model.

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