Experimental Test and Computer Simulation Research on Rollover Impact of a Bus Structure

DAN ALEXANDRU MICU, MIHAIL DANIEL IOZSA, GHEORGHE FRĂȚILĂ
Automotive Engineering Department
University POLITEHNICA of Bucharest
313 Splaiul Independentei st., 6th Sector,
ROMANIA
dan.micu@upb.ro; daniel_iozsa@yahoo.com; ghe_fratila@yahoo.com

Abstract: - Bus structures are tested to ensure that no element enters the survival space during an rollover impact. In this paper an experimental of rollover test using body sections as an equivalent approval method is presented. The mass of the structure is bigger than the maximum acceptable one. Therefore, some elements of the structure enter the survival space for a little time during the impact, but in the last moments of the impact they are out of the survival space. The intrusion could be seen only using a video camera. These deformations were supposed to be obtained using a virtual simulation. Simulation results were very close to the experimental ones, but for the best fitting more parameters had to be modified. The deformation obtained using two different simulation models are compared with the experimental one.

Key-Words: - bus structure body sections Ansys rollover simulation

1 Introduction

There is a long-standing interest in rollover behavior of vehicles, especially of those designed and constructed for the carriage of more than 16 passengers. The safety problem of how to avoid the driver and the passengers being hurt during bus rollover collision has become the common concern for the bus industry of each country[1]. The Economic Commission for Europe enforced Regulation No. 66 (ECE R66) for the superstructure strength of buses to provide vehicle safety and protect passenger lives. Thus, design characteristics must satisfy ECE R66 under various load applications, without fail [2]. More and more simulation tests are made to analyse faster and cheaper the rollover impact behavior of buses. For a computer simulation, a number of tasks must be performed during model set up that can be somewhat repetitive and laborious, but also complex enough that they are easy to forget if one is not performing the rollover model setup task regularly[3]. Two model simulations using different parameters have different deformation results compared with the experimental result of a bus body section loaded more than its limit, but both of them validate the intrusion in the survival space.

A body section contains at least two bays (ring like structure of vertical pillars, roof stick and floor members) connected by representative structural members. In [4], the results obtained from body section rollover were compared with full vehicle rollover simulation and physical test of a full bus. Body section successfully passed the rollover simulation and it remained conservative compared to full bus rollover.

A methodology to analyse the bus structure during rollover using finite element method is presented in [5]. The used computational model of the entire structure provided comparable results to experimental measurements.

In [6] a FE modeling and model setup of the entire bus structure was carried out using HyperMesh and HyperCrash and simulation was carried out using RADIOSS explicit solver.

A physical single bay vehicle testing was paralleled via simulating the same scenario using an independently constructed RADIOSS FEA model of the test coupon in [3].

Authors of [1] present a case study on a typical bus body section rollover carried out using an algorithm, and the effectiveness of it is verified by comparing its results with LSDYNA and rollover test.

Section 2 presents the reference body section structure with a bigger mass than the maximum acceptable one. The physical test is provided in section 2.1, where the deformation phenomenon of "Rollover test using body sections as an equivalent approval method" of UNECE Regulation Number 66 is described. The Ansys simulation through "The pendulum method" according to the EU Directive No. 2001/85/EC models are presented in section 2.2 and the comparisons between the resulted deformations are given in section 3.

2 Model development

The vehicle is designed and constructed for the carriage of 23 passengers, except the driver. Seat positions are distributed on two rows (one with single seat and one with double seats) and two seats in the cabin. Curb weight is 4310 kg and the total weight is 6150 kg.

Figure 1 shows the weight distribution frames in a view of the single seats side. The number of bays assigned to the right side (1D-6D) and their masses (bay/m) are indicated at the top of the figure.

Fig.1. Mass distribution of bays for the total weight of the autovehicle.

Superstructure strength was fixed to the base and was made of rectangular profile type 304 stainless steel with the following features:
- modulus of elasticity \( E = 193 \text{ GPa} \);
- Poisson's ratio, \( \nu = 0.31 \);
- density, \( \rho = 8000 \text{ kg/m}^3 \);
- tension yield strength, \( \sigma_c = 210 \text{ MPa} \);
- failure stress, \( \sigma_f = 520 \text{ MPa} \);
- minimum breaking elongation \( A = 45\% \).

The section of the structure that will be rollover tested consists of frames 3, 4 and 5, as it is highlighted by the red background color in Figure 1. The most disadvantaged section, that includes the front pillar of the rear door plus two other pillars in the forward direction, was chosen for the test. The section is placed above the rear axle.

Three variants of loading as required by Directive 2001/85 and Regulation 66 were considered to load the structure. The resulting loading of the structure section under the second method of R66, is approximately 93% higher than the mass determined by the requirements of Directive 2001/85, and 22% higher than the mass calculated by the first method [8].

Table 1 shows the weight values calculated according to the methods set out in regulations and the relative values reported to the mass determined by the second method of R66.

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Dir. 2001/85</th>
<th>R 66 Method 1</th>
<th>R 66 Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated mass</td>
<td>1400 kg</td>
<td>2200 kg</td>
<td>2700 kg</td>
</tr>
<tr>
<td>Relative mass</td>
<td>52%</td>
<td>81%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Testing the worst case was considered, so that the mass of the section was chose to exceed 5% of the maximum value specified in the Regulations.

The structure is completed with an additional mass of welded beams, observing an excess of about 130 kg of the value determined by Method 2, resulting a mass of 2830 kg. This additional mass is used to study the rollover behavior of the structure for overload vehicle with a mass greater than that specified by regulation.

A test platform that meets the dimensional requirements of R66 was built. Figure 2 shows a side view, from the sense of rollover, of the tested structure section.

Fig.2. Side view, from the sense of rollover, of the tested structure section.

Also, Figure 3 shows a front view of the section of the structure. The bodywork section, the fixed to ground structure designed to simulate the height of 800 mm as the regulations require, the survival space, tilting platform, axis of tilting, additional masses and the resulted center of gravity can be seen in both figures.
Fig. 3. Front view of the section of the structure. [7]

The tilting platform has two hinges weld to the fixed cylinder on the left side relative to the front view. Two metal profiles are fixed on the platform, in the area over the hinges. They have to support and protect the structure against slippage during its tilting. A lifting force is applied, using a forklift, on the right side, relative to the front view.

Figure 4 highlights the hinges and the supports and rod profile of the platform on which the lifting force is applied.

Fig. 4. Hinges and supports (a) and rod profile of the platform on which the lifting force is applied (b).

2.1 Physical Test

The "Rollover test using body sections as an equivalent approval method" of UNECE Regulation Number 66 was performed in an outdoor space with concrete surface by lifting with a forklift the tilting platform, where the structure was set. This raised platform at low speed up to the limit position of equilibrium of the structure. In Figure 5 two picture frames from the inclination of the platform can be seen: the moment of separation of the forklift element and the time preceding the impact with the ground.

Fig. 5. Separation of the forklift element and the moment preceding the impact with the ground.

Impact moments are captured with two cameras with views on both sides: the front and the back of the structure.

The total oscillation time of the structure’s elements is approximately 1s. The most significant deformations are observed in the first 0.200s.

Figure 6 shows four frames with back view from the first 0.370s of the impact.

Fig. 6. Frames with back view from the first 0.370s of the impact.

Principal moments sequence is shown in Table 2.
Table 2. Principal moments of the impact.

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Dynamic phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0</td>
<td>First contact of the structure with the soil and its detachment of tilting platform.</td>
</tr>
<tr>
<td>0,07</td>
<td>Roof beams start to sag and detach from the supports.</td>
</tr>
<tr>
<td>0,10</td>
<td>Structure reaches the limit of the survival space and translational moving with ground friction starts.</td>
</tr>
<tr>
<td>0,17</td>
<td>Maximum deflection of the structure and the first contact with the ground of the lower part of the structure.</td>
</tr>
<tr>
<td>0,20</td>
<td>Transverse displacement stops.</td>
</tr>
<tr>
<td>0,23</td>
<td>The first detachment between the lower part of structure and soil and structure’s passing out of the residual space.</td>
</tr>
<tr>
<td>0,47</td>
<td>The second contact of the lower part of the structure.</td>
</tr>
<tr>
<td>0,53</td>
<td>The second detachment between the lower part of structure and soil.</td>
</tr>
<tr>
<td>0,60</td>
<td>The third contact between the lower part of structure and soil.</td>
</tr>
<tr>
<td>0,73</td>
<td>The third detachment between the lower part of structure and soil.</td>
</tr>
<tr>
<td>0,83</td>
<td>Permanent contact with the ground of the lower part of the structure.</td>
</tr>
</tbody>
</table>

The total time of dynamic phenomenon following the first contact between the structure and the soil was 0.83 s. Maximum deflection amplitudes decrease sequentially from the first to the last impact. Structure deformation during the impact is an elastic-plastic nature, and at the end of the impact remains only plastic deformation. In the latter situation, the structure doesn’t intrude into the survival space, but that can be seen during the deformation process, from the moment 0.100s, structure enters the survival space, peaking at 0.170 s and gets out of this space at 0.230 s.

Structure has not remained in the survival space defined by metal profiles. The distance between the pillars of the structure and the limit areas of the survival space is bigger than 43 mm.

Maximum strain is recorded in overlap form and compared to the initial dimensions of the structure in Figure 7.

Fig.7. The overlap of the maximum deformed frame and the initial one.

2.2 Simulation test
2.2.1 Simulation model
A virtual model of the structure section was built with ANSYS [9] and the rollover behavior was analyzed using different ways. The pendulum method [7] according to the EU Directive No. 2001/85/EC of 20 November 2001, entitled “Strength of superstructure” was used.

The geometric modeling is a copy of profiles beams and of their join method. The pendulum is represented by a parallelepiped a and the survival space is represented by a body, as it was attached to the experimental model. This way it is easier to see if the structure enters the residual space during or after the rollover.

The structure is made of rolled bars of a rectangular, square or L-shaped profile. The entire geometrical model was composed of surfaces. Figure 8 shows the meshed model views of the bodies.

Fig.8. Pendulum (a), survival space (b) and bus body section (c).
Geometric elements meshing was performed with different densities depending on their role. The resulting model has 17,446 elements.

### 2.2.2. Simulation settings

The simulation time is established at 0.17 s. The structure is constrained in the bottom part through some fixed support applied on faces of longitudinal and transversal elements (Figure 9).

![Fixed support applied on faces of longitudinal and transversal elements.](image)

Fig.9. Fixed support applied on faces of longitudinal and transversal elements.

Also, at this stage it was necessary to define the impact speed of pendulum using the total energy that needs to be equal to the initial potential energy of the structure. The total energy of impact is determined by Equation (1):

\[ E = 0.75Mg\Delta h \]  

where:
- \( E \) – the total impact energy;
- \( M \) – the structure mass, \( M = 2830 \text{ kg} \);
- \( g \) – acceleration of gravity, \( g = 9.8 \text{ m/s}^2 \);
- \( \Delta h \) – distance from the position of the center of gravity of the structure when it is subjected to the test bench to its final position after overturning or vertical displacement of the center of gravity during rollover, \( \Delta h = 0.558 \text{ m} \).

Energy determined by relation (1) is 11,606.68 J. Determination of the center of gravity displacement was achieved [7] by the graphical method specified in Directive 2001/85/EC.

Angle of the pendulum at the moment of collision was also graphically determined. It is equal to the angle between the surface overturning structure and its vertical longitudinal central plane. The value of this angle, determined graphically, is 20°.

By equating the total energy of the pendulum with the potential one, equality (1) becomes:

\[ 0.75Mg\Delta h = \frac{m \cdot v^2}{2} \]  

where:
- \( m \) – pendulum mass, density and volume determined as follows:
\[ m = \rho \cdot V = \rho \cdot L_p \cdot l_p \cdot h_p \]  

- \( \rho \) – density of the steel used for the pendulum, \( \rho_p = 7850 \text{ kg/m}^3 \);
- \( L_p, l_p, h_p \) – dimensions (length, width, height) defining pendulum (3.075x0.8x0.1 m);
- \( v \) – impact velocity of the block, [m/s];

Pendulum mass resulted with (3) is \( m = 1931.1 \text{ kg} \). Substituting (3) into (2) the speed of the pendulum is given by:

\[ v = \sqrt{\frac{1.5Mg\Delta h}{m}} = \sqrt{\frac{1.5Mg\Delta h}{\rho_p L_p l_p h_p}} = 3.47 \text{ m/s} \]  

Energy of the pendulum is transmitted to the structure by 3D contact elements that define the contact area. For energy conservation, the contact algorithm uses the "Penalty" [9]. Contact was considered frictionless, so that there will be no loss on the transfer of energy from the pendulum to the superstructure.

Figure 10 shows a front view and one side of the system consists of body structure, survival space and pendulum velocity vector assigned.

![Front and side views of the system consists of body structure, survival space and pendulum velocity vector.](image)

Fig.10. Front and side views of the system consists of body structure, survival space and pendulum velocity vector.

The speed of the pendulum has been directed in a transverse plane of the structure, at 70° to the longitudinal vertical plane of the structure, corresponding to a tilt angle of 20° between the block and the vertical central longitudinal vertical plane of the structure.

### 3 The Results

Several tests with various energy parameters, geometry or material have been carried out in order to achieve a virtual model to simulate as well and as efficiently as experimental tests. Here, only the most significant test cases are presented, each of them...
being assigned with a capital letter associated with the name "Model" (eg "Model X").

The influence of pendulum speed on the structure behavior has been studied (models A and B). Increasing the structure mass or the height of center of gravity would change the impact energy. These changes require a study on the impact velocity of the pendulum.

a) Model A – the pendulum kinetic energy equivalent to the energy of the impact

A first simulation was done with the pendulum speed corresponding to the impact energy, as determined by relation 4.

The final strain obtained is shown in Figure 11, being illustrated in comparison with the initial shape of the structure.

Fig.11. The obtained deformation of the model A.

In Ansys, the corresponding deformation results are expressed by the relative movements of the finite elements to the global reference system. For this reason, it is observed that the pendulum is shown in red, corresponding to the greatest strain, despite the fact that it has assigned a specific rigid behavior. The maximum total displacement of the roof and the pendulum is 353 mm.

The deformation resulted in the intrusion of the structure in the residual space, as in the case of the experimental test. Intrusion into the residual space for model A is shown in Figure 12.

Fig.12. The Intrusion into the residual space for model A.

b) Model B – the kinetic energy of the pendulum three times greater than the energy of an impact

Many scenarios, distinguished by the increase of the kinetic energy of the pendulum, have been studied in order to obtain the same deformation as
the experimental test structure. By assigning a speed of 6 m/s instead of 3.46 m/s, the mass corresponding to the resulted energy of the bus structure is about three times higher than the original. The relation used for determining the mass of structure associated with speed resulted from equation (3), becomes:

\[ M = \frac{m \cdot v^2}{1.5g \Delta h} \]  

where:
- \( M \) – mass of the bus structure, [kg];
- \( m \) – mass of pendulum, [kg];
- \( v \) – velocity of pendulum, [m/s];
- \( g \) – acceleration of gravity, [m/s^2];
- \( \Delta h \) – vertical displacement of the center of mass, [m].

Figure 15 shows the moment when the structure comes into contact with the residual space. The corresponding time is 0.075s, with 25 ms earlier than the experimental testing. Pendulum speed when entering the residual space is 4.8 m/s.

In this case, the computer program was set to not consider the existence of contact between the structure and the residual space.

The deformation shape is very similar to the shape determined by experimental testing, as shown in Figure 17.

![Fig.15. Entry of the structure in contact with the residual space for model B.](image)

![Fig.16. Intrusion into the residual space of the model B.](image)

The program was set to perform calculations for a period of 0.1 seconds. However, calculations were off, without giving an error at 0.091s. The strain determined in this situation is shown in Figure 16, where it can be seen that the structure enters the residual space.

![Fig.16. Intrusion into the residual space of the model B.](image)

![Modification of the survival space speed](image)

![The same deformations of pillars](image)

![Deformation shape is very similar to the shape determined by experimental testing](image)

Fig.17. Comparison between deformations of model B and experimental model.

Major differences between model B and the experimental model are: the simulated equivalent mass is considered 8475 kg and the real structure has 2830 kg, and appropriate time deformations shown in Figure 17 is 0.09 s for the virtual model and 0.17 for the experimental model.

The times corresponding to the moment of intrusion in the residual space is 0.15 for model A, and 0.075 for model B (Figure 18).

![Fig.18. The times corresponding to the moment of intrusion in the residual space for all three models](image)

Deformations obtained for model B were also compared with deformations obtained for model A. Figure 19 presents the deformations resulted with pendulum method for model A (Fig. 19.a.) and model B (Fig. 19.b) in the moment when the structure enters the residual space.
Fig.19. Comparison of structural deformations of the model A with model B, in the moment when structure enters the residual space.

4 Conclusion

There is a long-standing interest in rollover behavior of vehicles designed and constructed for the carriage of more than 16 passengers.

In physical test the worst case was considered, so that the mass of the section was chose to exceed 5% of the maximum value specified in the Regulations. During the deformation process, from the moment 0.100s, structure enters the survival space, peaking at 0.170 s and gets out of this space at 0.230 s. Structure has not remained in the survival space defined by metal profiles.

The deformation mode for the simulation with the pendulum speed corresponding to the impact energy is slightly different to the experimental test.

The deformation shape for the model with the energy of the bus structure three times higher than the original is very similar to the shape determined by experimental testing.

References:

[8] Regulation 66-UNECE.