Regulatory Bus Roll-Over Crash Analysis Using LS-DYNA

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Introduction

A roll-over event is one of the most crucial hazards for the safety of passengers and the crew riding in a bus. In the past years it was observed after the accidents that the deforming body structure seriously threatens the lives of the passengers and the rollover strength has become an important issue for bus- and coach manufacturers.
Introduction

Today the European regulation “ECE R66” is in force to prevent catastrophic consequences of such roll-over accidents thereby ensuring the safety of bus and coach passengers.

Introduction

According to the said regulation the certification can be gained either by full-scale vehicle testing, or by calculation techniques based on advanced numerical methods (i.e. non-linear explicit dynamic finite element analysis). The quantity of interest at the end is the bending deformation enabling engineers to investigate whether there is any intrusion in the passenger survival space (residual space) along the entire vehicle.
Accidents and Rollover

- 42% of “severe injury or passenger fatality” real-world coach crashes are Rollovers.
- Usually, 19% of the occupants were killed in the real-world crashes.

Accidents and Rollover

- There is a 30% rate of KSI (killed or seriously injured) in rollovers with a fixed barrier and 14% KSI without a fixed barrier.
- 80% of KSI is located in the upper section of the coach if the coach had an upper and a lower compartment.
Accidents and Rollover

- The most severe injuries generally occur during sliding over the outside ground after the rollover.
- Overall rollover frequency is 4% in all coach accidents with a 5 times greater risk of fatalities than any other coach accidents (Spanish Data).

Accidents and Rollover

- Among 48 touring coach crashes occurred in Germany, eight of them were rollover/overturn crashes. These eight crashes accounted for 50% of all severe injuries and 90% of all fatalities.
Risks in Rollover

- Most common dangers waiting for a bus or coach occupant in rollovers are being exposed to:
  
  i. Ejection
  ii. Half Ejection
  iii. Intrusion

- In summary, during a bus or coach rollover, the occupant will have a larger distance from the centre of rotation as compared to that of a car occupant. This what makes a rollover accident extremely fatal and explains the previous statistics.

Project

- ECE R66 calculation procedure performed for a TEMSA bus named “HD SAFARI”
- HD SAFARI is a 12.8 meters bus with special reinforced roll-bar structure in the front and at the most rear.
- FEA modeling is done by the specialized pre-processing software ANSA 11.3.5
- Calculations are made by means of a non-linear, explicit, 3-D, dynamic FE computer code LS-DYNA.
The calculation technique has been checked by verification of calculation tests applied on a breast knot of side-body and on a roof edge knot of the vehicle and subsequent numerical simulations were performed. A high degree of theoretical and experimental correlation is obtained, which confirms its validity.

Once the method was assessed, a complete vehicle rollover test simulation was carried out, and observing the deformation results with respect to the residual space it is inferred that the structure of the bus is able to pass the required regulations.
The purpose of the ECE R66 analysis is to ensure that the superstructure of the vehicle have the sufficient strength that the residual space during and after the rollover test on complete vehicle is unharmed.

The envelope of the vehicle’s residual space is defined by creating a vertical transverse plane within the vehicle which has the periphery described in the next figure, and moving this plane through the length of the vehicle.
The rollover test shall be carried out on that side of the vehicle which is more dangerous with respect to the residual space. The decision is made considering at least the following:

1. The lateral eccentricity of the centre of gravity and its effect on the potential energy in the unstable, starting position of the vehicle
2. The asymmetry of the residual space,
3. Different, asymmetrical constructional features of the two sides of the vehicle,
4. Which side is stronger, better supported by partitions or inner boxes (e.g. wardrobe, toilet, kitchenette).
Verification of Calculation

- The Breast Knot and Roof Edge Knot of the bus were subjected to certain boundary conditions and quasi-static loads at TÜV Automotive’s testing facility. The same test scenarios were simulated by using LS DYNA. Force-deflection curves both for the experiment and simulation were compared and it was seen that there is a good correlation between experiment and simulation results.
Verification of Calculation

Finite Element Model

- **Elements**:
  1. 750,000 4 noded Belytschko-Tsay Elements
  2. 103 Beam Elements
  3. 450,000 Mass Elements

- **Element length is assigned to be**:
  - 10 mm in the critical regions,
  - 40 mm for the regions under the floor (lower structure-chassis)
  - Number of elements per profile width is at least 3 for the upper structure.
  - Number of elements per width is 4 for side-wall pillars (significant regions for rollover deformation).
Upon completion of mesh generation of bare structure, masses were imposed according to a certain methodology. First, a list of masses of HD SAFARI 12.8m vehicle was prepared. The engine, gearbox, air conditioner and fuel tank were roughly 3D modeled as rigid parts, the inertias were calculated analytically and mass and the inertia was imposed on a representative node (On the approximate center of gravity points for the relevant part) of these parts.

The axles too were modeled with rigid truss elements and the mass and the inertias were imposed using the same method. The masses particularly located were imposed by using mass elements. The distributed masses were imposed by changing the density of the related region.
 Finite Element Model

Finite Element Model - CoG

- The “Center of Gravity (CoG)” of the vehicle was measured using a test platform in TEMSA. The measured values were in a good agreement with the ones coming from the FEA model. To exactly match the measured and calculated CoGs, the CoGs of engine, gearbox and the axles were fine tuned in the FEA model.
When it came to the definition of survival space in LS-PRE the statement in the regulation ECE R66 was forming the basis of the survival space model. Through the whole vehicle, it was introduced to be 500 mm above the floor under the passengers' feet, 300 mm from the inside surface of the side of the vehicle. The model of the survival space consists of rigid beam frames in each section (10 sections), rigidly mounted in the stiff region under the floor. There is no stiffness connection between these rigid beam frames because these shell elements are modeled with “Null material” for visualization only.

For obtaining the material data, tension tests were applied on several specimen at TÜV Automotive facilities. The true stress-strain curves were obtained and imposed in LS DYNA accordingly. The material model for the deformable structure in LS DYNA is the so called “MAT Type 24, Piecewise Linear Isotropic Plasticity model”. This is an elastic plastic material model which uses the Youngs modulus if stresses are below the yield stress and the measured stress-strain-curve if the stresses are above the yield stress. Rigid parts (engine, gear box, fuel tank, axles, etc) are modeled with the so called “Rigid Material, MAT Type 20”. For the definition of the survival space (residual space) “MAT Type 9, Null Material” is used.
The total energy according to the formula indicated in the ECE R66 regulation:

\[ E^* = 0.75Mgh \]

where \( M \) is the unladen kerb mass of the bus structure, \( g \) is the gravitational acceleration and \( h = z_2 - z_3 \) (see next slide for \( z_2 \) and \( z_3 \))
The “h” is the vertical distance between the CoG of the vehicle at free fall position \((z_2)\) and the CoG of the vehicle which is kinematically rotated up to the ground contact position \((z_3)\).

“h” is determined by rotating the model around its axis until the mass center of the whole vehicle reaches its highest position. At this point the coordinate of the CoG in the direction is recorded. Then the bus is rotated around the 100mm obstacle until the vehicle contacts the ground. The coordinate of the CoG at this position is recorded as well. Then the vertical distance between these 2 points is determined \((h)\).

The total energy which is given by the previous formula is applied to the structure by applying a rotational velocity to all of the parts of the vehicle.

This initial velocity generation is done with LS-DYNA keyword *INITIAL VELOCITY GENERATION. Figure on the next slide shows the energy calculation for initial velocity generation.
LS-Dyna Solution

\[ \alpha = \tan^{-1} \frac{\Delta y}{\Delta z} \]

\[ (x_1, y_1, z_1) \]

\[ (x_2, y_2, z_2) \]

\[ (x_3, y_3, z_3) \]

800 mm

100 mm

The platform is translated in shell normal direction to contact the tires

LS-Dyna Solution - Contact

- All surfaces of the model were defined as one contact group, thus, effectively accounting for multiple self-contacting regimes during computational impact analyses. The static friction coefficient between all parts was set to 0.1 and the dynamic friction coefficient was set to default which assumes that it is dependent on the relative velocity \( v_{rel} \) of the surfaces in contact.
Mass scaling was applied to the smallest 100 element which resulted in negligible change in overall mass and a good time saving in the total elapsed time.

Objective Stress Update (OSU) option which is generally applied in explicit calculations for only those parts undergoing large rotations is turned on.

Shell thickness change option in *CONTROL_SHELL* is enabled assuming that membrane straining causes thickness change during the deformation.

The solutions are performed with SMP (Shared Memory Parallel) version of LS-DYNA. The analysis time interval was set to 300 ms, with results output required after every 5000 time-steps. The analyses run ≈20–22 h on an AIX IBM P5+ series workstation with 4 P5 processors depending on the complexity of the individual model.
Results

After each analysis the deformation behavior (at time step when it reaches the maximum deformation amount) is investigated for the each section through the vehicle. The shortest distance between the pillar and the survival space in the corresponding section is observed and recorded. The shortest distance between the survival space and the pillar at section 2 is found to be 75 mm at time 152 msec which comfortably satisfies the requirement of ECE-R66 (see next slide).
In the next slide a general overview of the simulation results for selected time steps are illustrated. The bus first comes into contact with the ground and then starts absorbing energy by elasto-plastic deformation and bends at the plastic hinge zones. After sufficient deformation occurs the bus starts sliding.
Results - Results overview through the time steps

$t = 0$

$t = 0.04$

$t = 0.09$

$t = 0.14$

$t = 0.19$

$t = 0.24$

Results
Results

- Next slide tracks the structural energies. The total energy remains to be constant which is one of the indications for correct analysis results. It can be observed that the kinetic energy drops and transforms into internal energy (Strain energy) over the time and the hourglass energy remains negligible.

Results - Energy distribution versus time
Conclusions

- Computational nonlinear explicit dynamic analysis was employed for evaluation of the roll-over deformation behavior under test vehicle impact conditions.
- The used computational model provided comparable results to experimental measurements and can thus be used for computational evaluation of other type of bus & coach vehicles in order to avoid numerous expensive full-scale crash tests.

Conclusions

- The tests have also shown that the new safety roll-bar structure assures controllable crash energy absorption which in turn increases the safety of vehicle occupants.
Thanks.