OTEKON 2014

7. Otomotiv Teknolojileri Kongresi

26 - 27 Mayıs 2014, BURSA

ROLLOVER CRASHWORTHINESS OF A MULTIPURPOSE COACH

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ABSTRACT

Bus rollover is one of the most serious types of accident as compared to other modes of bus accidents. In the European countries, the certification of sufficient deformation strength when overturning is compulsory for the approval of a coach according to the ECE 66-02 regulation. The certification is granted after positive results from computer simulations with full bus structure. The simulation specifies either overturning of the vehicle structure from tilting platform or the impact of a plate on the coach structure as it would correspond to the crash of the structure when falling onto the ground.

In this paper, the rollover analysis of the coach structure was performed nonlinear explicit dynamic FEM code RADIOSS software as a solver. FEA model of the rollover analysis was generated with HyperMesh and HyperCrash preprocessor softwares. According to the ECE 66-02 regulation, a passenger's survival space is defined in the coach model to check whether there is any intrusion into the survival space during the rollover. This ensures that the coach structure has sufficient strength to avoid intrusions into the survival space. The effect of passenger and luggage weights on energy absorbed by the coach structure during rollover is also discussed.

Keywords: ECE 66-02, Rollover crashworthiness, Explicit dynamics, FEM, RADIOSS

1. INTRODUCTION

1.1. Purpose

The purpose of the ECE 66-02 regulation is to ensure that the superstructure of the vehicles, which belonging to Categories M2 or M3, Classes II or III or Class B having more than 16 passengers, have the sufficient strength that the residual space during and after the rollover is unharmed.

1.2. ECE 66-02 Regulation

Bus rollover is one of the most serious types of accident as compared to other modes of bus accidents. Strengthening bus frames to maintain residual space (occupant space) and minimizing occupant injury are necessary. In the European countries, the certification of sufficient deformation strength when overturning is compulsory for the approval of a coach according to the ECE 66-02 regulation. The certification is granted after positive results from computer simulations with full bus structure. The ECE 66-02 regulation defines a survival space for the passengers, which must remain intact after the accident. The simulation specifies either overturning of the vehicle structure from tilting platform or the impact of a plate on the coach structure as it would correspond to the crash of the structure when falling onto the ground. Since such tests with real structure are costly and computer efficiency, on the other hand, is becoming increasingly better and cheaper, rollover simulations have been playing a more important role for the approval. The verification of calculation is a compulsory requirement of the regulation, as it is the technical service's responsibility to verify the assumptions used in the finite element analysis.

1.3. Requirements

No part of the vehicle, which is outside the residual space at the start of the test (e.g. pillars, safety rings, luggage racks) shall intrude into the residual space during the test. Any structural parts, which are originally in the residual space (e.g. vertical handholds, partitions, kitchenettes, toilets) shall be ignored when evaluating the intrusion into the residual space.

2. ROLLOVER ANALYSIS

2.1. Residual Space

Residual space means a space to be preserved in the passengers', crew and driver's compartment to provide better survival possibility for passengers, driver and crew in case of a rollover accident.

The definition of survival space is the statement in the regulation ECE 66-02 was used to form the basis of the survival space model. It was introduced 500 mm above the floor, under the passengers' feet, 300 mm away from the inside surface of the side of the vehicle, throughout the entire vehicle (trim lengths were also considered and added to these values). The model of the survival space consists in rigid beam frames in each section, rigidly mounted in the hard region under the floor. There is no stiffness connection these between these rigid beam frames as shell elements are modelled using "void material" for visual purposes only.

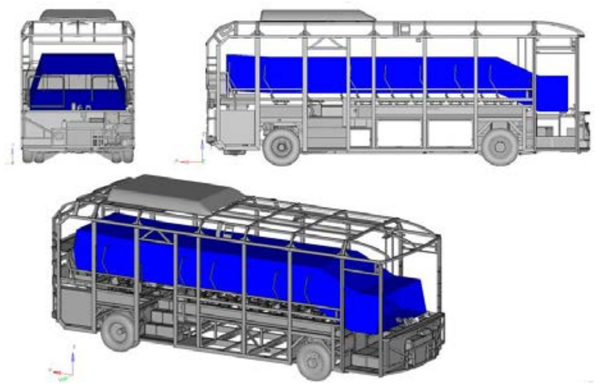

Figure 1. Finite element model of the vehicle and residual space

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 Figure 1, and moving this plane through the length of the vehicle.

2.2. Specification Of Rollover Test On A Complete Vehicle

The full scale vehicle is standing stationary and is tilted slowly to its unstable equilibrium position. The rollover test starts in this unstable vehicle position with zero angular velocity and the axis of rotation runs through the wheel-ground contact points. At this moment, the vehicle is characterized by the reference energy. The vehicle tips over into ditch, having a horizontal, dry and smooth concrete ground surface with a nominal depth of 800 mm.

The position of the vehicle in unstable equilibrium at point of rollover, and the position at first contact with the ground is specified at Figure 2. The simulation is started at the point of first contact with the ground. The initial conditions at the point of first contact with the ground are defined using the change of potential energy from the unstable equilibrium position.

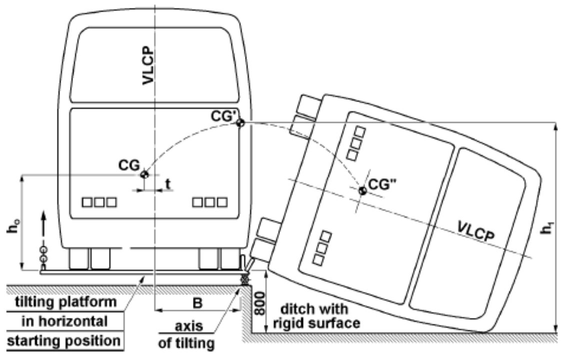

Figure 2. Rotation of the vehicle to the point of first contact with the ground

The total energy according to formula indicated in the ECE 66-02 regulation:

$$E^* = 0.75\ M\ g\ \Delta h$$

where M is the unladen kerb mass of the vehicle structure and %50 of the total occupant mass, g is the gravitational acceleration and $\Delta h = h_{CG\ I} - h_{CG\ II}$.

The "Center of Gravity" of the vehicle was measured in Hexagon Studio. After the measurement of CG value, mass balancing was done with ADMAS elements in finite element model as possible.

2.3. Material Properties

In accordance with ECE 66-02 regulation; materials, which are used on the actual vehicle structure, were performed tensile strength test at ITU Laboratory of Strength of Materials and Biomechanics, in order to determine mechanical properties such as stress-strain curve, yield strength, ultimate tensile strength, Young modulus, toughness and cross-sectional narrowing at specimens.

The specimens, which used in the tensile strength tests, are presented at Figure 3. Specimen head are used for clamping to applying force. Narrow region of the specimen is expected to deform and break when load is applied. As a result, Load - Displacement curve is obtained from tensile strength test.

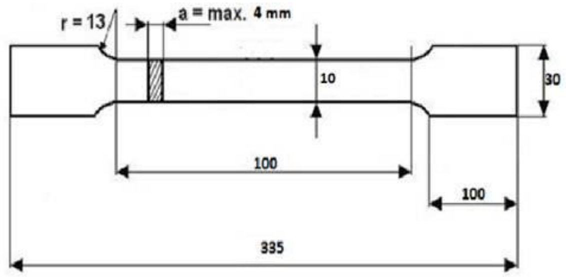

Figure 3. Test specimen for tensile strength tests

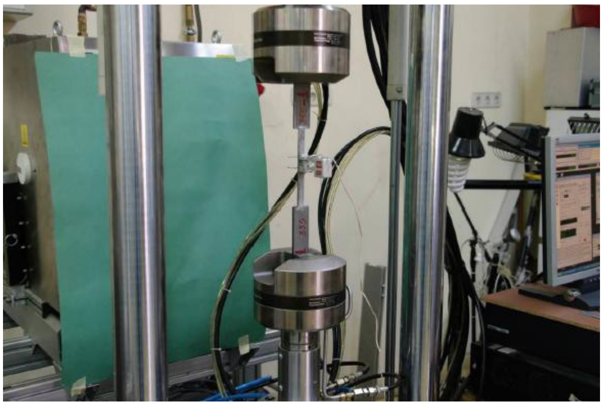

Figure 4. Picture of tensile strength test system

The tensile strength were tests made with MTS Minibionix Model 858-II Dynamic Universal Test Machine *(Model Number: 359.XX, Part Number: 100-146-714, Serial Number : 10189576, Manufacture Date: 07.20.2005, MTS System Corporation, 14000 Technology Drive, Eden Prairie, MN USA, 55344, Capacity: 25 kN Axial Load – 200 Nm Torsion)*. The tests were made in the laboratory environment. Pulling speed at the tests was set to 10 mm/minute. Visuals about the tests are presented at Figure 2 and Figure 3.

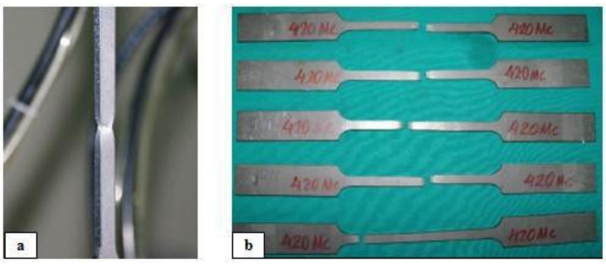

Figure 5. The specimens for tensile strength tests
a) During test, b) After test

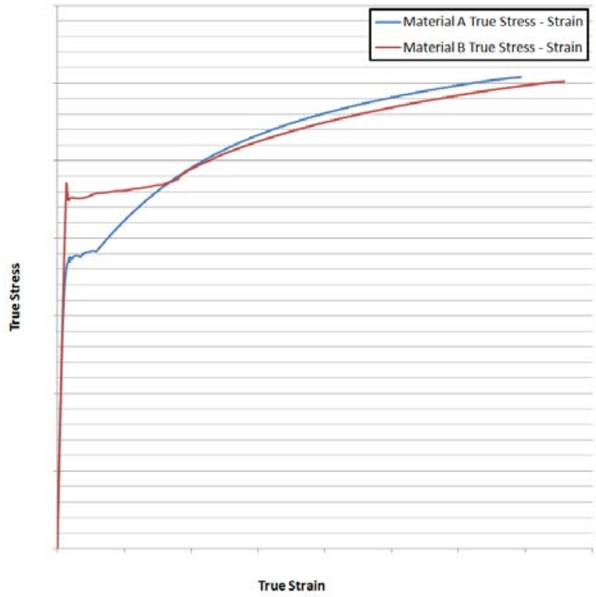

Figure 6. True stress-strain curves of “Material A” and “Material B”

For obtaining the material data, tensile strength tests were applied on several specimens at ITU Laboratory of Strength of Materials and Biomechanics. The True Stress – Plastic Strain curve was imposed in RADIOSS accordingly. The material model for the deformable structure in RADIOSS is called “Elastic Plastic Piecewise Linear Material (LAW36). This is an elasto-plastic material model, which uses the Young’s Modulus if stresses are below the yield strength and the measured stress-strain curve if the stresses are above the yield strength. Moreover, failure criteria were defined at material model based on the tensile strength tests. Thus, elements were deleted if stresses are above the ultimate tensile strength.

2.4. Description Of Finite Element Model

The finite element model of the vehicle was performed by the specialized pre-processor software HYPERMESH and HYPERCRASH. The vehicle was modelled with the quad QEPH (formulation with physical hourglass stabilization for general use) elements with five integration points through the shell thickness and the model contains triad elements less than % 5 of the vehicle model. The QEPH formulation provides a good precision/cost ratio. QEPH elements do not have hourglass energy. QEPH shells will give better results if the mesh is fine enough. QEPH formulation is recommended for isotropic materials because the stabilization forces are computed based on isotropic assumptions. During the simulation, thickness change at the shell elements was taken into account because of the membrane strain. Plasticity calculation was proceeded with iterative projection with three

Newton iterations. Weld connections in the finite element model of knots are modeled with rigid elements (RBE2).

All contacts in simulations were defined as sliding contact with Interface Type 7. Interface Type 7 is a general purpose interface and can simulate all types of impact between a set of nodes and a master surface, especially buckling during a high speed crash. The search for the closest segment is done via a direct search algorithm; therefore, there are no search limitations and all possible contacts are found. The energy jumps induced by a node impacting from the shell edges are removed by the use of a cylindrical gap around the edges. The main advantage of interface type 7 is that the stiffness is not constant and increases with the penetration preventing the node from going through the shell mid-surface. This solves many bad contact treatments. Cloumb friction law was used as a friction formulation. This formulation provides accurate results in crash analysis. The friction coefficient between all parts was set to 0.2.

2.5. Verification And Validation Of Computational Calculation

The technical service requires tests to be carried out on the actual vehicle structure to prove the validity of the mathematical model and to verify the assumptions made in the model. Load – Displacement curves both for the experiments and the simulations should be compared and it should be seen that there is a consistent correlation between the experiments and the simulations results.

The model shall be capable of describing the real physical behavior of the bending tests. The mathematical model shall be constructed, and assumptions prescribed, in such a way that the calculation gives conservative results.

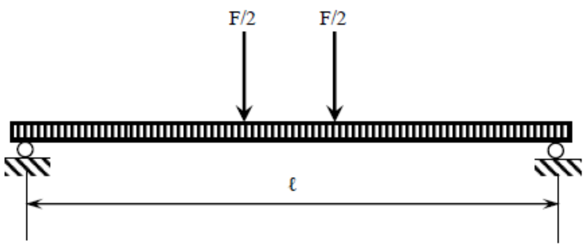

Figure 7. Four point bending approach for breast knot

Verification and validation process is based on multi-scale laboratory testing including: material characterization, wall panel and connection tests, and testing of the entire bus. Validated FE models are subsequently used to provide a comprehensive safety assessment of the entire vehicle. The validation has the goal of assessing the predictive capability of the model for a given simulated event. It is performed by comparison of predicted results from FE simulations to experimental results from the same physical test. It is essential to select validation tests that are closely related to the event for which model is intended.

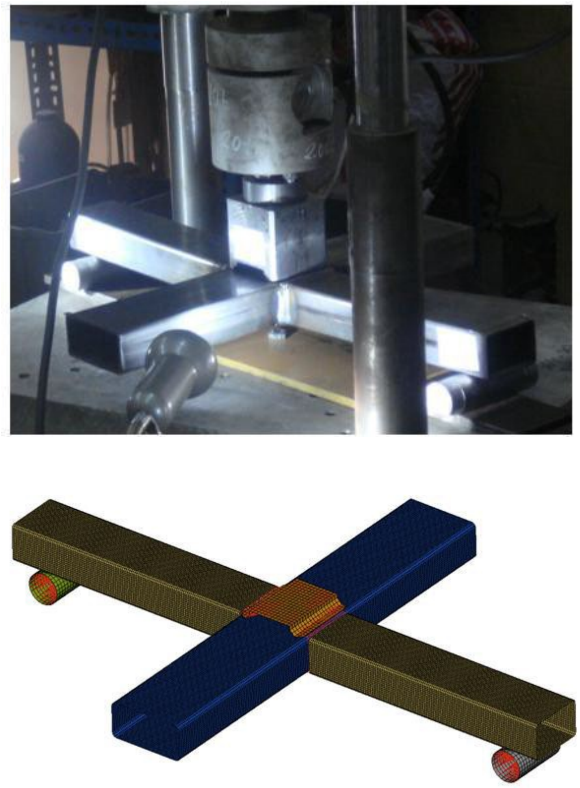

Figure 8. Breast knot similarity between test setup and finite element model

The specimens were subjected to certain boundary conditions and quasi-static loads at ITU Laboratory of Strength of Materials and Biomechanics. The same test scenarios were simulated by using RADIOSS explicit finite element method solver. Load – Displacement curves both for the experiments and the simulations were compared and it was seen that there is a consistent correlation between the experiments and the simulations results.

Two different knot specimens (Breast Knot and Roof Edge Knot) were used for the bending tests. At bending tests; four point bending test was performed to Breast Knot and three point bending test was performed to Roof Edge Knot. One of the correlation tests and its result are presented figures below.

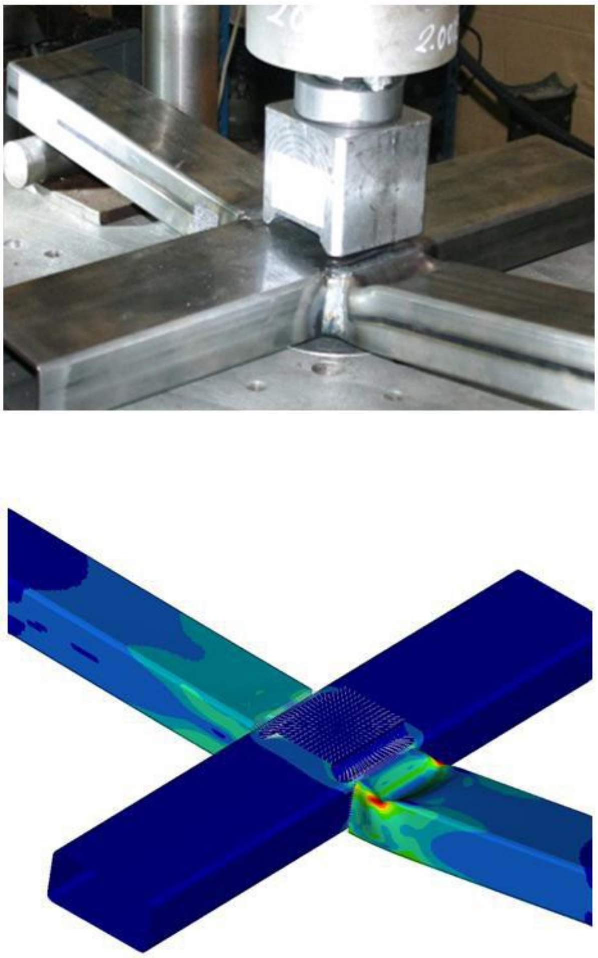

Figure 9. Breast knot test visual and finite element analysis visuals

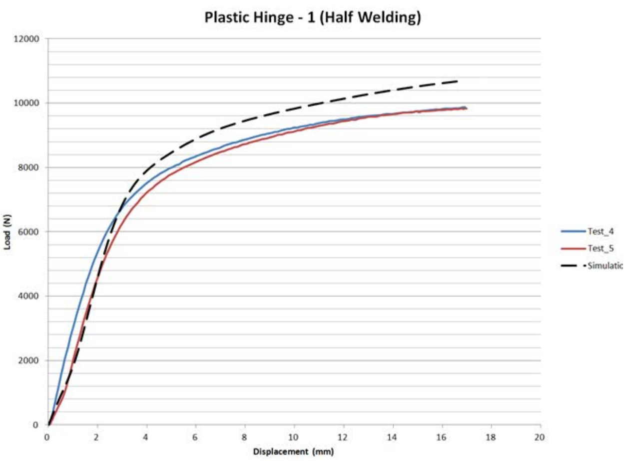

Figure 10. Load – displacement curves of breast knot's test and finite element simulation results

Load - Displacement curves both for the experiments and the simulations were compared and it was seen that there are similar characterized curves and consistent correlation between the experiments and the simulations results. Factor of Correlation between the experiments and the simulations is determined with respect to maximum loads.

3. RESULTS

In Figure 12, sequential pictures from the simulation results for selected time steps are illustrated. Firstly, the vehicle comes into contact with ground, then starts absorbing energy by elasto-plastic deformation, and bends at the plastic hinge zones. After sufficient deformation occurs, the vehicle starts sliding and springback occurs at pillars.

Figure 13 and 14 show the peaks dynamic deformed shape front and rear section of the vehicle structure. During the simulation, it was observed that the vehicle side structure does not intrude into residual space envelope. It was also observed that considerable amount of elastic energy is stored in elastic deformations of the structure and later released after sliding of the vehicle on the ground.

As seen in the graphics, the nearest pillars to the residual space are which are surrounding the doors. Deformation increases in the door area, which is because of no continuity of the cross connections between pillars.

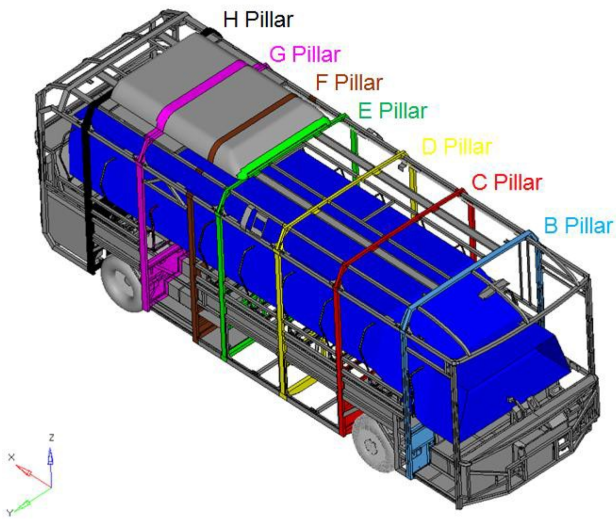

Figure 11. Bay Sections of the Bus Structure

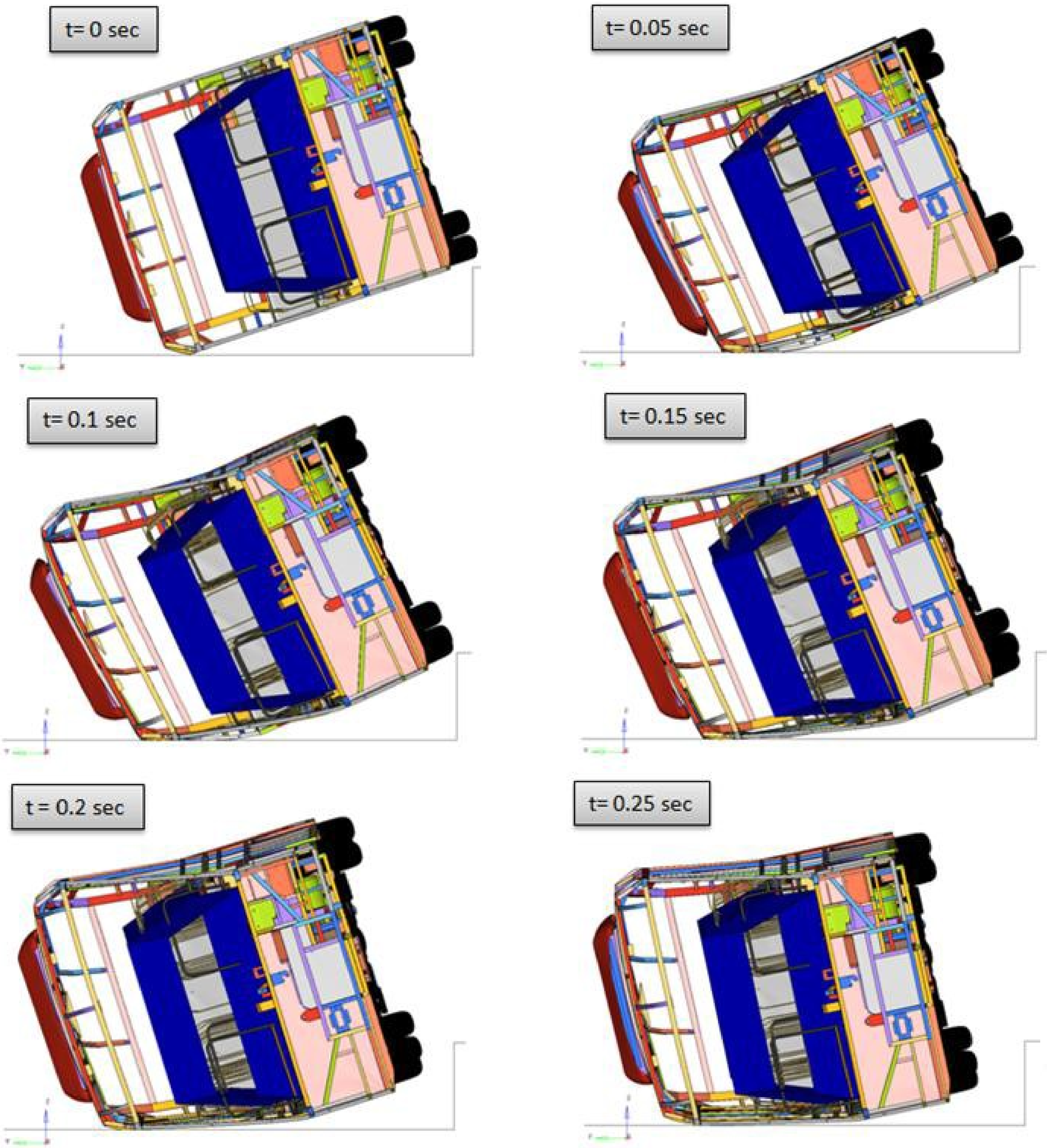

Figure 12. Sequential pictures showing behavior of deformation of the vehicle through the time step

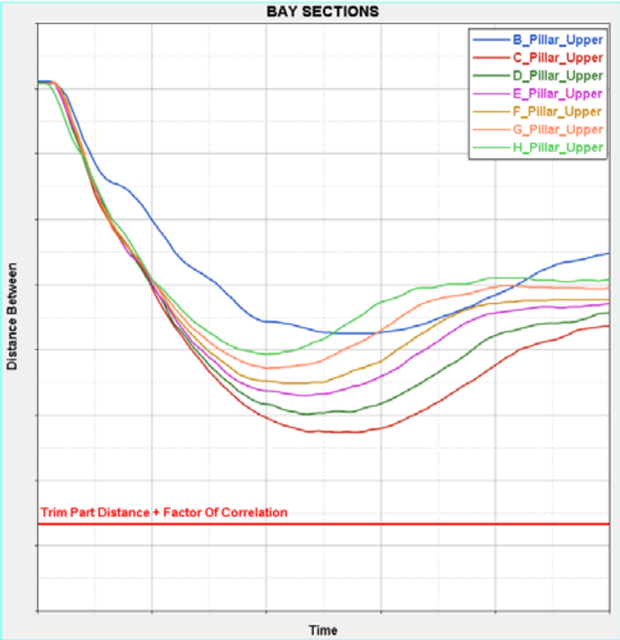

Figure 13. Distance between upper edge of the residual space and pillars of the vehicle

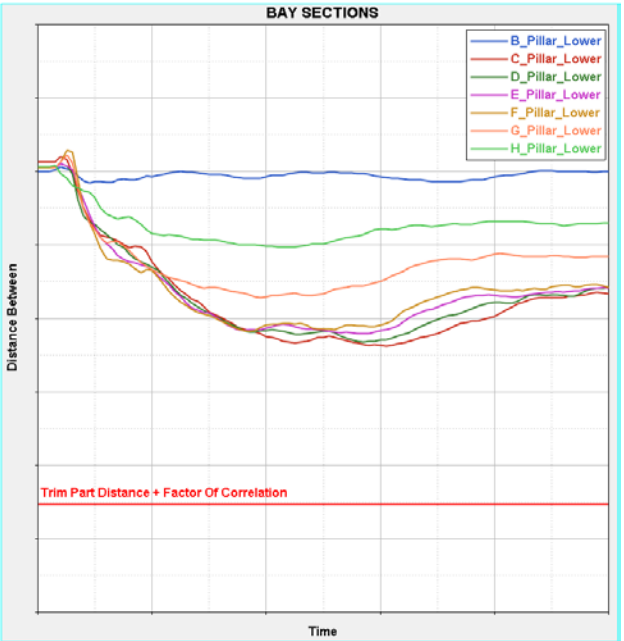

Figure 14. Distance between lower edge of the residual space and pillars of the vehicle

In order to check the accuracy of simulation results, it was verified whether the total energy remained constant during the simulation time. A graph showing various energy distributions from the rollover simulation of the vehicle structure (Figure 15). The figure shows that energy distribution did remain constant, indicating that analysis results were accurate. It could be observed that kinetic energy drops and transforms into internal energy (strain energy + sliding energy) over time and hourglass energy remains negligible.

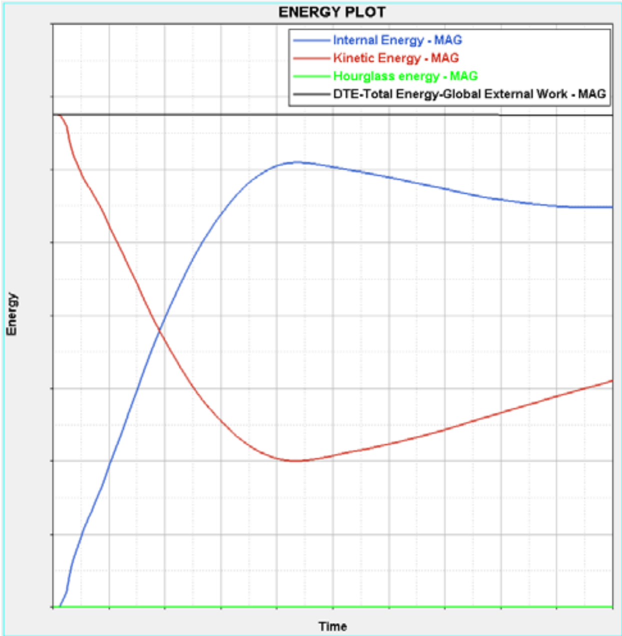

Figure 15. Energy distribution of the simulation versus time

4. CONCLUSION

A rollover event is one of the most crucial hazards for the safety of passengers and bus drivers. In past years, it was observed that the deforming body structure seriously threatened passengers' lives. Today, European regulation "ECE 66-02" is in force to prevent the catastrophic consequences of such rollover accidents from occurring and thereby ensuring passenger safety for buses and coaches. According to said regulations, certification can be obtained by numerical simulation. The bending deformation enables engineers to investigate whether there is any intrusion in the passenger residual space along the entire vehicle.

Verification and validation methodology for the Finite Element simulations of standardized rollover test are introduced. Computational mechanics analyses were verified by the energy balance tracking. The numerical results were compared to the results from the experiments on different levels of the validation hierarchy. Consistent correlation of results was obtained for each case. Based on that validation study, Factor Of Correlation was taken in computational simulation's results evaluation. Final design was confidently implemented with taking into consideration factor of correlation.

It was observed that the vehicle side structure does not intrude into residual space envelope. For the baseline vehicle, it can be seen that the shortest distance between the residual space and pillar at "C Pillar", which comfortably satisfies the requirements of ECE 66-02.

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