EFFECTIVENESS OF SEAT BELT USAGE ON THE ROLLOVER CRASHWORTHINESS OF AN INTERCITY COACH

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ABSTRACT

Safety of vehicle occupants jeopardized during rollover accidents when necessary safety measures are not taken. Structural adequacy and protection of occupants are the two significant measures that can be implemented to minimize occupant injury risk during vehicular rollover events. The aim of this paper is to evaluate the structural resistance and passenger injury risks and compare the effectiveness of safety belt usage in occupant during a simulated rollover event of a 13 meter long TEMSA bus. A total of eight occupants were placed at the structurally weakest locations of the bus. Three different occupant protection cases were considered: i. no safety belt, ii. two-point safety belt and iii. three-point safety belt. A standard rollover procedure was simulated using non-linear finite element code LS-DYNA. Head injury criteria and neck forces were calculated and compared to evaluate the effectiveness of seat belt usage on occupant protection. Simulation results clearly illustrated that when occupants had no seat belt protection they suffered serious risk of injuries. Moreover, two and three point safety belts provided somewhat similar protection levels for most of the occupants. Based on the findings, use of two point safety belt in all of the seats of the TEMSA busses was recommended.

INTRODUCTION

The most typical collision configurations involving busses and coaches are side, rear, frontal and rollover. Although rollover crashes did not happen very often, when they did, the number of seriously injured occupants was high compared to other crash types [1]. According to Enhanced Coach and Bus Occupant Safety (ECBOS) project final report [1], granted by the European Union, in the EC, every year 20,000 buses are involved in accidents which results in approximately 300,000 injuries per year. Unfortunately, some 150 of these persons suffer fatal injuries.

In EC, there is a strong movement towards establishing new safety requirements for buses or coaches operated in Europe in order to reduce fatalities. These safety requirements are continuously visited to improve passenger safety in these busses or coaches.

Albertson et al. [2] conducted one of the most comprehensive studies on rollover crash injuries. They analyzed 128 injured in Sweden with regard to the injury outcome, mechanisms and possible injury reduction for occupants when using a safety belt. Other studies found out that when the bus or coach rolls 90º or more, occupants would have high risks of sustaining injuries [3,4]. In fact, Matolcsy [5] collected a rollover accident statistics over 300 accidents which showed that the average casualty rate was 25 casualties/accident.

In case of a rollover, passengers run the risk for being exposed to ejection, partial ejection, projection, or intrusion and thus exposed to a high fatality risk [5,6]. However the most dangerous one is the intrusion, when due to the large scale structural deformation structural parts intrude into the passenger, or compress them (lack of the strength of superstructure) [5].

The difference for a bus or coach passenger, with respect to biomechanics and space, as compared to those of lighter vehicle passenger becomes obvious in a rollover crash. During a bus or coach rollover, the occupant will have a larger distance from the center of rotation as compared to that of a car occupant. For this reason, European regulation "ECE R66" titled "Resistance of the Superstructure of Oversized Vehicles for Passenger Transportation" is

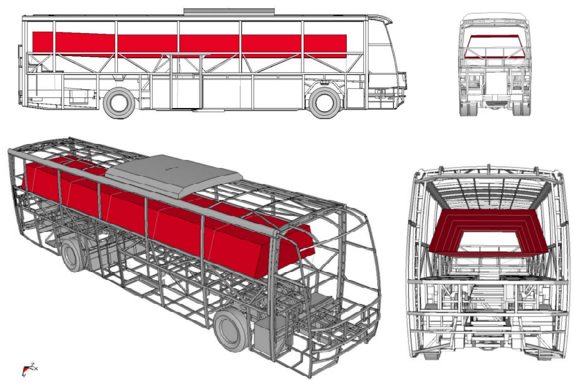


Figure 1. Placement of residual space in a bus.

in force to prevent catastrophic consequences of such rollover accidents thereby ensuring the safety of bus and coach passengers [7]. This regulation prescribes a test to be chosen between one of the following kinds

- A complete bus rollover test
- A bay section rollover test
- A pendulum test
- A numerical simulation of rollover.

The use of prototype to verify the design changes and doing real rollover, bay section or pendulum tests are often unsuitable because of the high costs and time. Therefore, among the alternatives, utilization of the numerical simulation is becoming more appealing to researchers. Friedman et al. [14] investigated using fiber-epoxy composite roof pillars under rollover (FEM). (FEM). In all of the above cases for the Regulation ECE R66 the effect of added mass of the passengers are not considered. The effect of passenger weight on the rollover crashworthiness is investigated by Guler et al. [15]. Results of that study shows that busses built with the current regulation does not comply if the passenger weight is considered. In another study by Belingardi et al. [16] FEM approach has been used to study the structural behavior of a M3 bus in a rollover accident and evaluate the structure resistance and passenger injury risks. In that study, only a bay section has been modeled with rotation axis parallel to the longitudinal bus axis. They also showed that the numerical analysis has given prominence to the inadequacy of the actual European regulation (ECE66), concerning passive safety.

METHODOLOGY

In this paper, results of a numerical rollover investigation study involving TEMSA bus with occupants are presented. FEM was used to construct a 12.8 m long bus with stainless steel material and special reinforced roll bar structure in the front and in the most rear. The FEM of the bus is developed by the specialized pre-processing software ANSA 11.3.5. and calculations are made using a non-linear, explicit, three dimensional, dynamic finite element computer code LS-DYNA. To verify the accuracy of the bus FEM, a series of laboratory tests were performed on a breast knot of side-body and on a roof edge knot of the vehicle and compared with those obtained from subsequent numerical simulations. A high degree of theoretical and experimental correlation was obtained, which partially confirmed the validity of bus FEM. Once the component validation process completed, a complete vehicle rollover test simulation was carried out. The finite element model in this study consisted of a validated vehicle [15] and occupant models. LS-DYNA Hybrid III dummy models were used as occupant models and are seated in 4 double seats located in critical places by considering structurally weakest sections of the bus.

The rollover simulations performed are intended to determine the damage mechanics and potential injury risks of the dummies. Three different occupant protection cases were considered: i. no safety belt, ii. 2-point safety belt and iii. 3-point safety belt. In each case head and neck injury criteria were used to evaluate the effectiveness of seat belt usage on occupant protection.

The ECE R66 Regulation

The purpose of the ECE R66 analysis is to ensure that the superstructure of the vehicle has the sufficient strength that the residual space during and after the rollover test on complete vehicle is unharmed. That means no part of the vehicle which is outside the residual space at the start of the test (e.g. pillars, safety rings, luggage racks) are intruding into the residual space. As shown in Figure 1, the envelope of the vehicle's residual space is defined by creating a vertical transverse plane within the vehicle which has the periphery and moving this plane through the length of the vehicle.

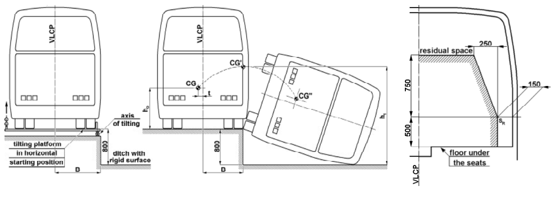


Figure 2. Details of rollover test according to ECE R66 [7]

The rollover test is carried out on that side of the vehicle which is more dangerous with respect to the residual space (see Figure 2). The decision is made by the competent Technical Service on the basis of the manufacturer's proposal, considering at least the following: i. the lateral eccentricity of the center of gravity and its effect on the potential energy in the unstable, starting position of the vehicle, ii. the asymmetry of the residual space, iii. the different, asymmetrical constructional features of the two sides of the vehicle, and iv. which side is stronger, better supported by partitions or inner boxes (e.g. wardrobe, toilet, and kitchenette).

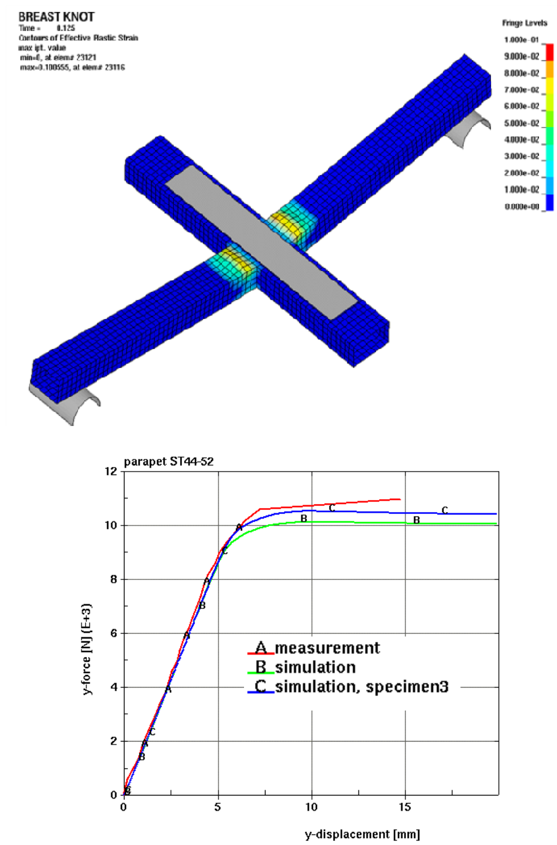


Figure 3. LS-DYNA simulation results for breast knot subassemblies

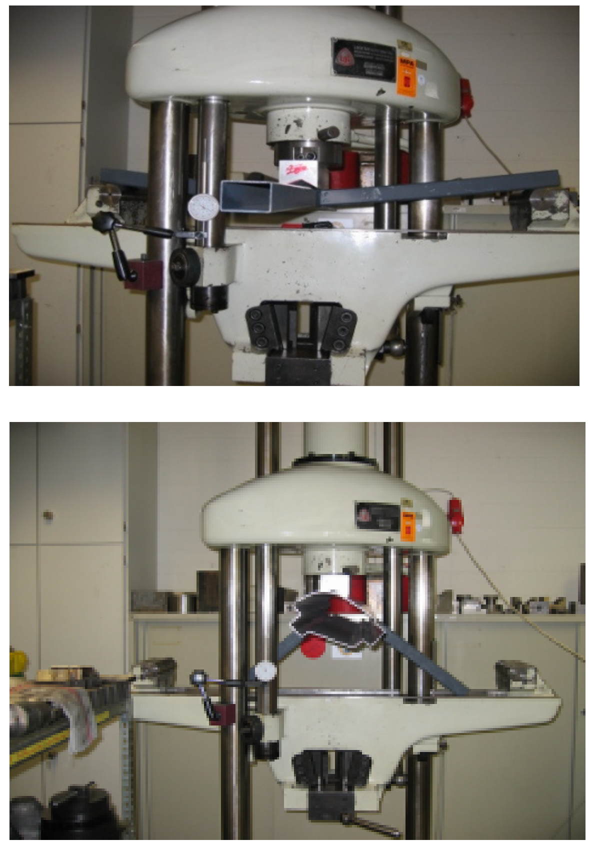


Figure 4. Test arrangements for breast knot and special roof profile subassemblies

Verification of Calculation

Before starting the ECE R66 simulation and certification process, a verification of calculation procedure set forth by the regulation ECE R66 was performed. Two separate specimens (breast knot and roof edge knot extracted from the vehicle) were prepared and sent to TÜV Automotive for experimental investigations. These parts were subjected to certain boundary conditions and quasi-static loads at TÜV's testing facility [17]. The same subassemblies were also modeled and simulated using LS-DYNA. Force-deflection curves obtained from both the experiments and simulations were compared and a good correlation between experiment and simulation results was obtained (see Figure 3 and Figure 4).

Description of the Computational Model

FEA model of the full vehicle (with seats) was comprised of 770,404 number of nodes, 785,940 first order explicit shell elements, 153 beam and 51,460

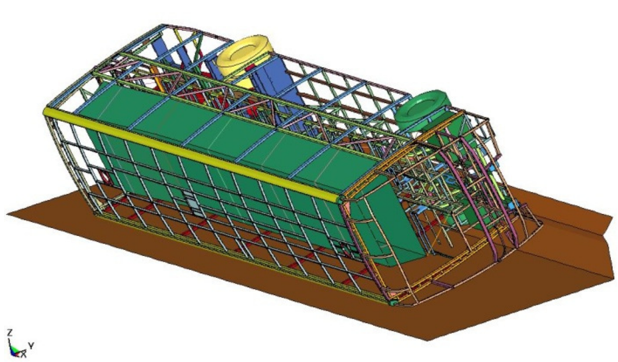


Figure 5. Finite Element Model of the whole bus rotated about the ground contact position

mass elements (see Figure 5). Element length is assigned to be 10 mm in the critical regions (A verified assumption coming from the verification of calculation) and for the regions under the floor (lower structure-chassis) element length up to 40 mm was used. The number of elements per profile width is at least 3 for the upper structure whereas the number of elements per width is 4 for side wall pillars which are significant for rollover deformation.

All deformable parts were modeled with the 4-node Belytschko-Tsay shell elements with three integration points through the shell thickness [18]. The shell element formulation is based on Belytschko-Lin-Tsay formulation with reduced integration available in LS-DYNA [19]. This element is generally considered as computationally efficient and accurate. The shell element that has been, and still remains to be, the basis of all crashworthiness simulations is the 4-noded Belytschko and Tsay shell. Upon completion of mesh generation of bare structure, masses were imposed according to a certain methodology. First, a list of masses of the 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 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. Further details on bus FEM can be obtained from the study by Guler et al. [15].

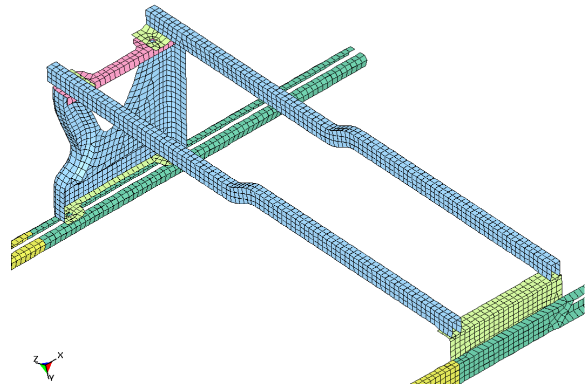


Figure 6. FEA Model of the seat structure

To model the seat structure, the geometry of the seat base was constructed using shell elements. The seat structure was connected to the floor elements located below using spotweld option in LS-DYNA. This option represented the closest approximation to an actual bolted connection due to its properties, such as bolt failure. A detailed representation of the spotwelds and finite element mesh of the seat structure is shown in Figure 6.

The Center of Gravity (C.G.) 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 finite element model of the bus. To exactly match the measured and calculated C.G.'s, the C.G.'s of engine, gearbox and the axles were fine tuned in the model.

For obtaining the material data, tension tests were applied on several specimens 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" [20]. This is an elastic plastic material model which uses the Young's 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.

Hybrid III 50th percentile dummy was used to represent passengers riding in the bus during a rollover accident. Dummy is a completely deformable finite element model (see Figure 7) and detailed information about the dummy can be found

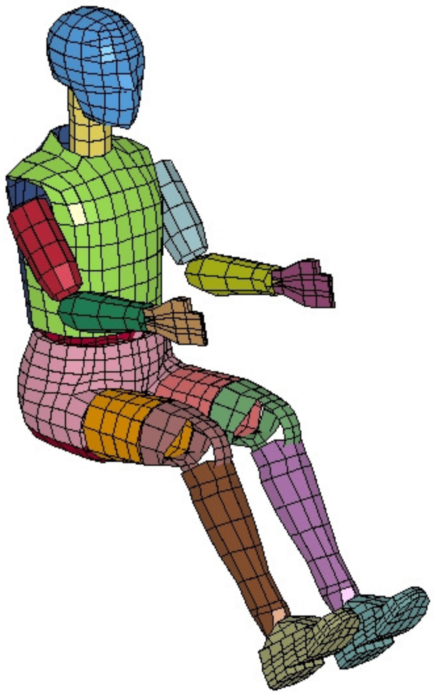


Figure 7. Hybrid III Dummy

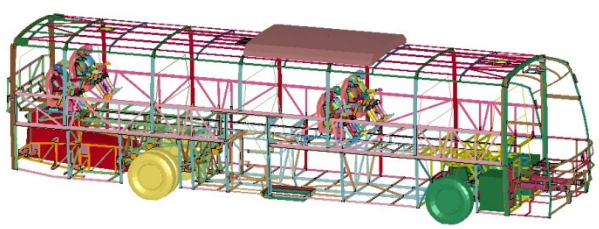
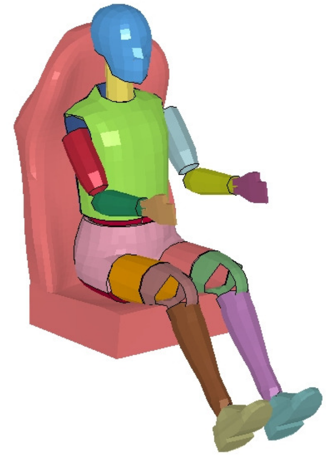


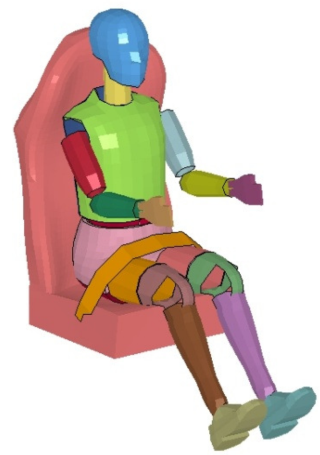
Figure 8. Positioning of Dummies in the bus structure

in [21]. A total of eight dummies were used in the rollover analysis. The dummies were placed in the weakest sections of the bus as shown in Figure 8. These locations were determined from the past experiences of the rollover study. The dummy positioning into the seats was done automatically using LS-DYNA.

Two types of seat belts evaluated in this study are: two point or lap belt and three point or shoulder belt (see Figure 9). The top end of the seat belt near the shoulders of the dummy was positioned so that it fits the contours of the chest and the upper body of the dummy whereas the lap belts positioned to fit the contours of the thigh.



(a)



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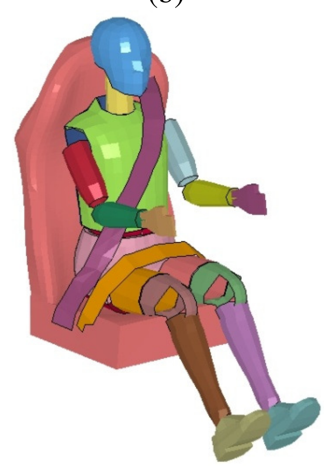

(c)

Figure 9. Finite Element Model of the dummy, seat and seat belt; (a) No seat belt; (b) two–point or lap seat belt; (c) three–point seat belt

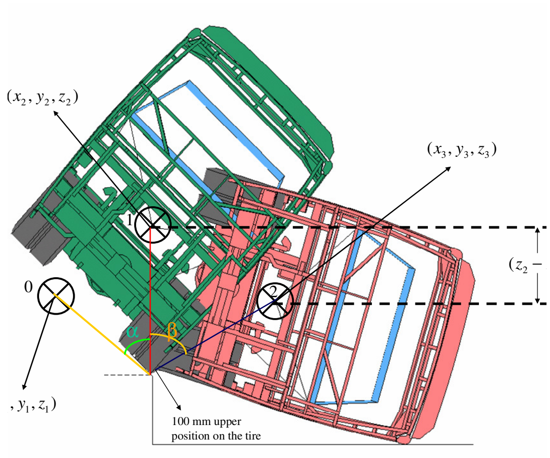

Figure 10. Rotation of the bus to the ground contact position

LS-DYNA Solution procedure

The solution procedure in general is described as follows: The total energy according to the formula indicated in the ECE R66 regulation:

$$E = 0.75Mgh \tag{1}$$

where, E is the total energy, M is the unloaded curb mass of the bus structure, g is the gravitational acceleration and $h = \Delta z = z_2 - z_3$ as shown in Figure 10. This energy is applied to the structure by applying a rotational velocity to all of the deformable and rigid parts of the vehicle. *h* is the vertical distance between the C.G. of the vehicle at free fall position (z_2) and the C.G. of the vehicle which is kinematically rotated up to the ground contact position (z_3).

First, the model is rotated around *x* axis until the mass center of the whole vehicle reaches its highest position. At this point the coordinate of the C.G. in the *z* direction is recorded. Then, the bus is rotated around the 100 mm obstacle until the vehicle contacts the ground (an offset is left considering the shell thickness of the ground and the corresponding vehicle structural part). The *z* coordinate of the C.G. at this position is recorded as well. Then, as shown in Figure 10, the vertical distance between these two points is determined and recorded as *h*.

Initial velocity generation is done with `*INITIAL_VELOCITY_GENERATION` card in LS-DYNA. `*CONTACT_AUTOMATIC_NODES_TO_SURFACE` was used to establish contact between the vehicle super-structure (body-in-white) and the ground. On the other hand, `*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE` was used between the seat structure and the seat rails on the side-wall and on the sill(see Figure 6). 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 of the surfaces in contact. Shell thickness change option in *CONTROL_SHELL is enabled assuming that membrane straining causes thickness change during the deformation. Mass scaling was applied to the smallest 100 elements which resulted in negligible change in overall mass. This provided a significant computational time savings.

The solutions are performed with SMP version of LS-DYNA. The analyses run approximately 12 hours for belted dummies and 20 hours for unbelted dummies on an AIX IBM P5+ series work-station with four P5 processors. Simulations lasted until dummies become stationary. Simulation time was 500 ms for unbelted dummies and 300 ms for belted dummies with results output required after every 5000 time steps..

Head Injury Criteria

The Head Injury Criteria (HIC) is used to assess the risk of injury to the head of bus occupants. This criteria is first introduced by Versace [22] and later modified by modified by The National Highway Traffic Safety Administration's NHTSA. HIC is a commonly used injury criterion for the assessment of the level of head injury risk in frontal collisions. A HIC of 1000 is conventionally accepted as the threshold where linear skull fractures will begin to appear, but NHTSA changed this value to 700 in March 2000 [23]. HIC is calculated as:

$$\mathrm{HIC}_{t_2-t_1} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,dt \right]^{2.5} (t_2 - t_1) \tag{2}$$

where $a(t)$ is the resultant linear acceleration at the center of gravity of the head and t_1, t_2 are arbitrary instants of time when head experiences acceleration of deceleration. The HIC was analyzed using 36 ms time interval in this study.

It should be noted that in this study, neck injury criteria was not used. Instead, neck forces obtained from simulation was compared with limit values to assess the severity of neck injury during rollover event.

DISCUSSION OF RESULTS

In order to check the accuracy of the simulation results, the first thing to check is whether the total energy remains constant during the simulation time period. The graph showing various energy distributions obtained from the rollover simulation of the bus structure is given in Figure 11. As shown in this figure, the total energy remains 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 + sliding energy) over the time and the hourglass energy remains negligible.

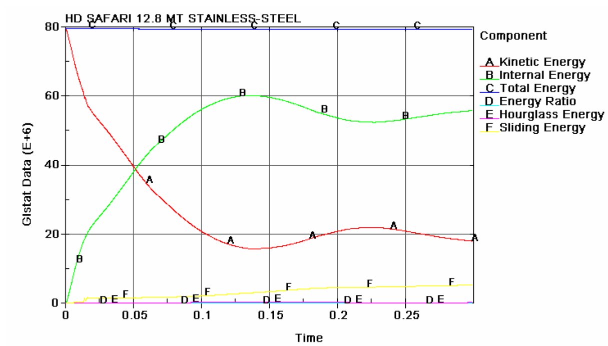

Figure 11. Energy distribution versus time

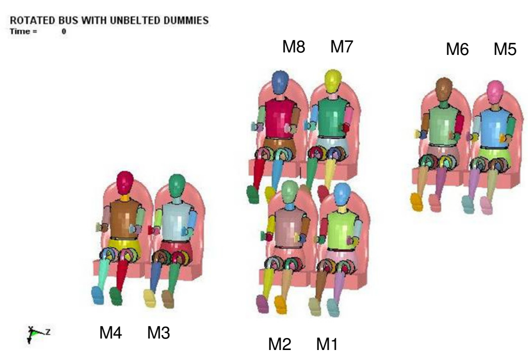

Figure 12. The arrangement of dummies

To clarify the dummy referencing, labels shown in Figure 12 were used**.** So, the dummies seated in the bus model were labeled from M1 to M8. According to the arrangements, dummies M1 to M4 and M5 to M8 are sitting near the front and back of the bus, respectively.

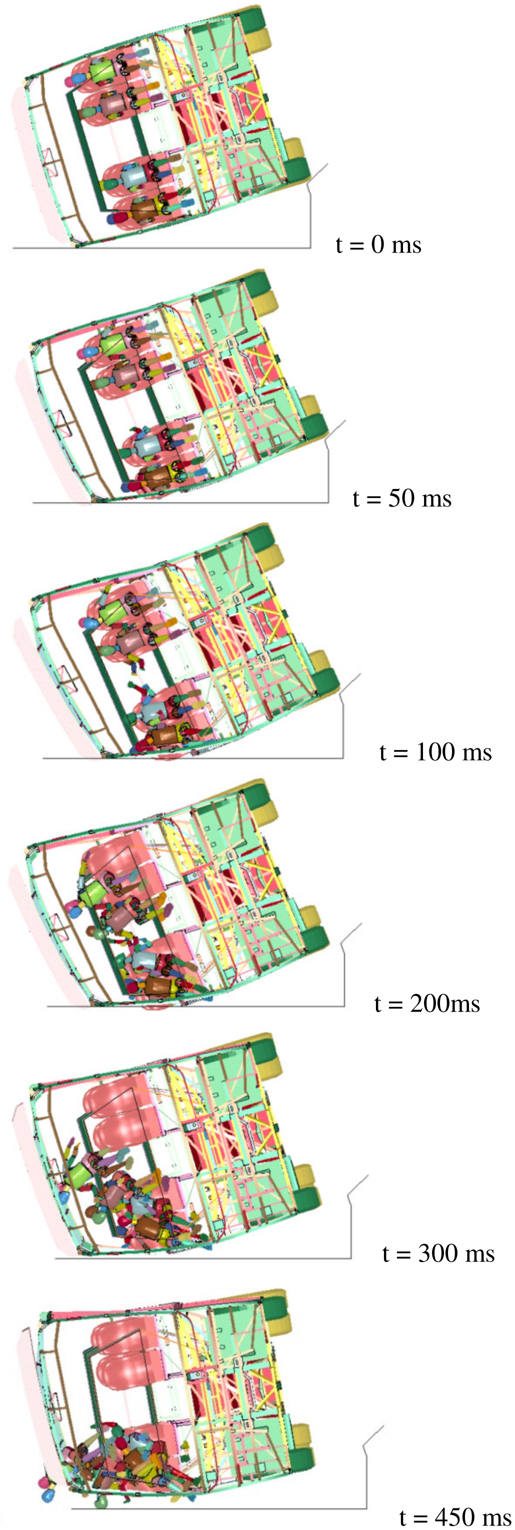

Figure 13 Sequential pictures showing behavior of unbelted dummies during ECE R66 test simulation.

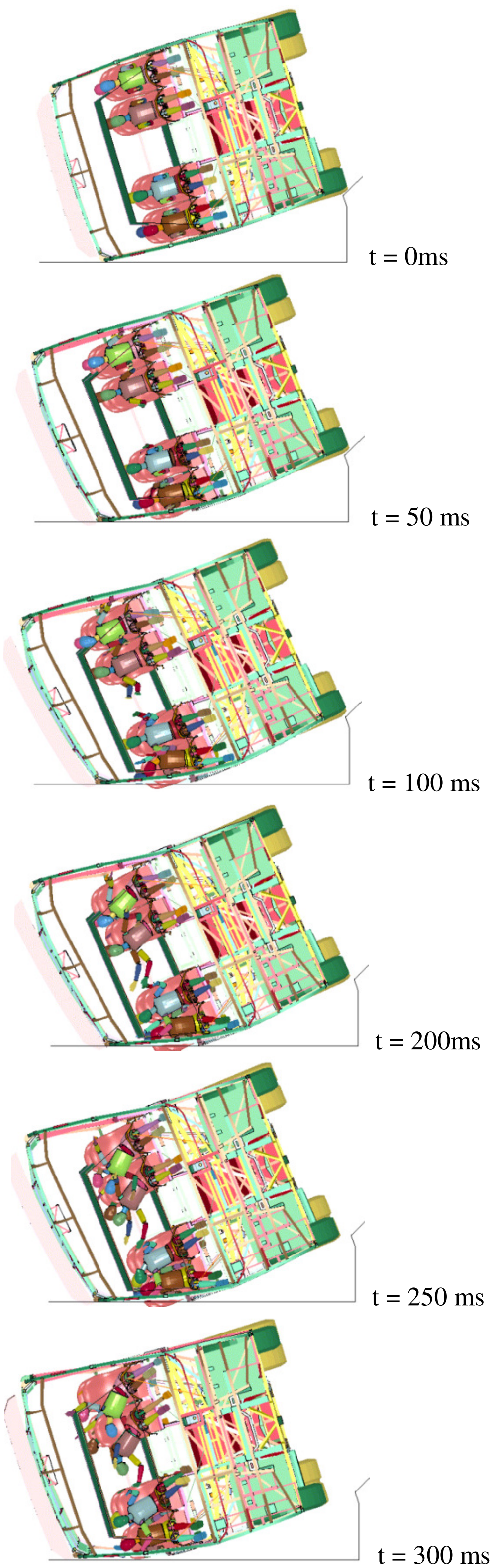

Figure 14 Sequential pictures showing behavior of lap-belted dummies during ECE R66 test simulation.

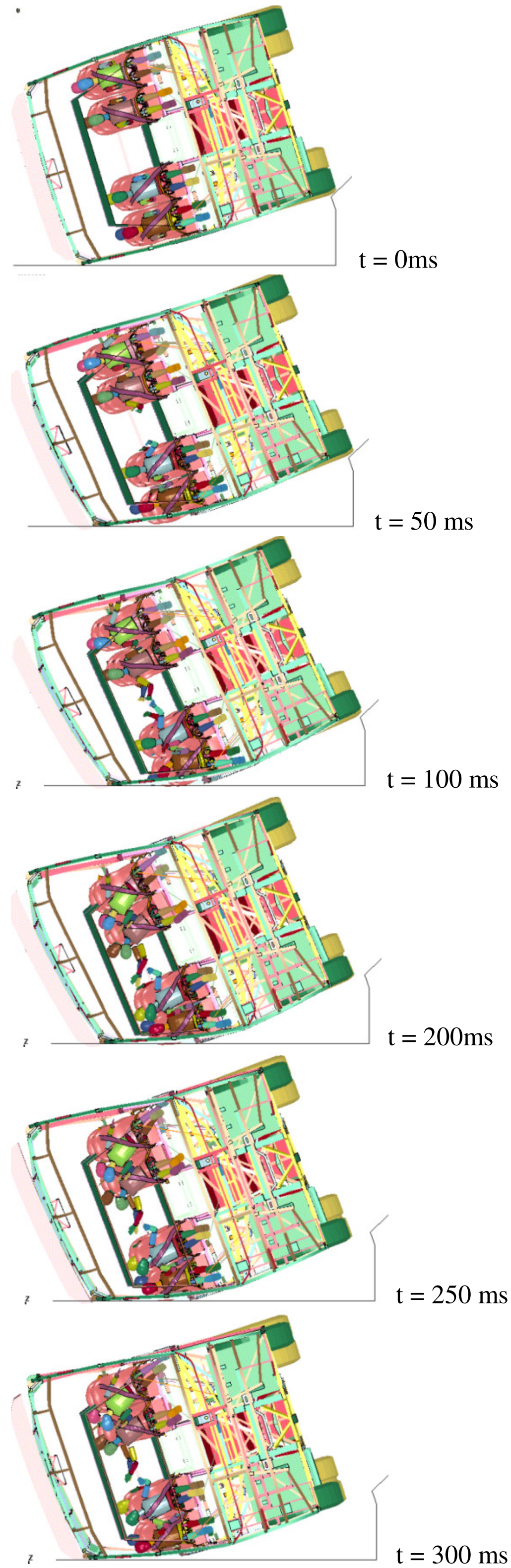

Figure 15 Sequential pictures showing behavior of three-point-belted dummies during ECE R66 test simulation.

Time histories for selected time steps are illustrated are presented in Figure 13 for the unbelted dummies. The rollover behavior is typical such that bus first comes into contact with the ground and then starts absorbing energy by elasto-plastic deformation through bending at the plastic hinge zones. After sufficient deformation occurs the bus starts sliding. Since the dummies are not belted, it is obvious that the dummies M1, M2, M5 and M6 would fly in the space and quite possibly hit either the dummies sitting on the rollover side (Dummies M3, M4, M7 and M8) or hit the luggage compartment or sealing of the bus structure. In reality, a full ejection or partial ejection of passengers occurs which is very common in the rollover traffic accidents. As it can be seen from Figure 14, Dummy M3 first collides with M4 at 150 milliseconds and after that M2 falls down to M3 at 295 milliseconds. The situation is similar for the dummies sitting at the back of the bus. In this case dummy M8 is hit by M7 at 145 milliseconds and M6 falls down to M7 at 290 milliseconds.

Sequential pictures for the two-point or lap belted dummies rollover simulation are given in Figure 14. During the rollover event, the passengers seating near the window from the rollover side (in our case dummy M4 and dummy M8) typically hit their head to the window or side pillars of the bus. As shown in Figure 14, seat belt usage clearly showed positive effect on protecting the passengers. In fact, simulation results showed that passengers seating across the rollover side were prevented from partial or full ejection due to the employment of two-point seat belt.

Finally, time histories of the rollover simulation for three-point belted dummies are presented in Figure 15. In this case neither partial nor full ejection of dummies are observed.

For the standpoint of injury criteria, HIC and neck forces observed during the rollover simulation for the unbelted dummies case are given in Table 1. All of the dummies HIC values are greater than 1000 and neck forces are greater than 4000 N except dummy M3 and dummy M7 indicating series injury of all of the passengers. Dummy M3 is coming into contact with dummy M4 in 150 ms and with dummy M2 in 295 ms. Also Dummy M7 is coming into contact with dummy M8 in 145 ms and with dummy M6 in 290 ms.

For the two-point or lap belted dummies the HIC and neck forces are given in Table 2. Observe that only dummy M8 has a HIC value higher than 1000 due to the fact that it comes into contact with the ground in 105 ms and dummy M7 is colliding with dummy M8 in 185 ms. Neck forces are in allowable range for the belted dummies.

For three-point belted dummies, HIC and neck forces are given in Table 3. As shown in this table, all of the HIC values and neck forces are within the acceptable limits. The highest HIC value is observed in the dummy M4 due to the fact that it collides with side pillars at 125 ms.

Analysis results showed that the three-point belt usage provided the best occupant protection since it results in the lowest values in terms of HIC. However, as it can be seen from the Tables 2 and 3, wearing the three-point belt generally increases the neck forces during a rollover accident. Since the values of HIC values are in acceptable range for two-point seat belts, wearing two-point seat belts seems to be a good alternative to more complex three-point seat belts.

SUMMARY AND CONCLUSIONS

A state-of-the-art computational nonlinear explicit dynamic analysis was employed to assess the behavior of bus occupants during a rollover event. Vehicle model was partially validated using subassamblage experimental data which proved the accuracy of the bus model used in the rollover simulation study according to ECE R66 regulation.

As predicted by the rollover analysis presented in this paper, unbelted bus passengers are in a great risk of partial or full ejection resulting in serious injuries. Simulation results showed that passengers wearing two-point or lap belts are very likely to remain seated during rollover which prevents passengers flying in vehicle and consequently hitting the windows or pillars of the bus structure or other passengers.

Three-point belt usage resulted in the lowest values in terms of HIC. However, three-point belt usage increased the neck forces during a rollover. Since the HIC values obtained from two-point belt simulations are in acceptable range, it is recommended to use two-point seat belts rather than three-point seat belts to achieve improved passenger protection. It should be added also that incorporation of two point belt system into busses are easier and more cost-effective for bus manufacturers. This aspect should also be considered during the manufacturing phase.

Table 1 HIC values and Neck Forces for unbelted dummies

Dummy	HIC36	Neck Forces (N)	Description
M1	2390 @ 0.450 s	6400 @ 0.450 s	Collision with ground @ 450 ms
M2	2170 @ 0.435 s	4800 @ 0.435 s	Collision with ground @ 435 ms
M3	695 @ 0.295 s	2390 @ 0.150 s	Contact with Dummy M4 @ 150 ms and with Dummy M2 @ 295 ms
M4	1280 @ 0.075 s	1070 @ 0.335 s	Contact with side pillar @ 75 ms
M5	2530 @ 0.490 s	5700 @ 0.490 s	Collision with ground @ 490 ms
M6	3200 @ 0.375 s	5200 @ 0.450 s	Contact with side pillar @ 375 ms
M7	460 @ 0.290 s	3200 @ 0.145 s	Contact with Dummy M8 @ 145 ms and with Dummy M6 @ 290 ms
M8	1350 @ 0.095 s	2370 @ 0.235 s	Collision with ground @ 95 ms

Table 2 HIC values and Neck Forces for two-point or lap belted dummies

Dummy	HIC36	Neck Forces (N)	Description
M1	308 @ 0.230 s	1400 @ 0.280 s	No contact
M2	160 @ 0.210 s	1600 @ 0.270 s	No contact
M3	175 @ 0.120 s	1950 @ 0.215 s	No contact
M4	255 @ 0.110 s	2840 @ 0.100 s	Collision of hand with side pillar @ 110 ms
M5	295 @ 0.230 s	1450 @ 0.280 s	No contact
M6	155 @ 0.210 s	1570 @ 0.270 s	No contact
M7	640 @ 0.185 s	2700 @ 0.245 s	Contact with Dummy M8 @ 185 ms
M8	1130 @ 0.105 s	1210 @ 0.135 s	Contact with ground @ 105 ms

Table 3 HIC values and Neck Forces for three-point belted dummies

Dummy	HIC36	Neck Forces (N)	Description
M1	290 @ 0.220 s	1400 @ 0.270 s	No contact
M2	160 @ 0.210 s	1600 @ 0.280 s	No contact
M3	175 @ 0.120 s	2300 @ 0.210 s	No contact
M4	750 @ 0.125 s	3400 @ 0.100 s	Contact with side pillar @ 125 ms
M5	205 @ 0.225 s	1050 @ 0.192 s	No contact
M6	155 @ 0.216 s	970 @ 0.200 s	No contact
M7	225 @ 0.200 s	1750 @ 0.185 s	No contact
M8	345 @ 0. 112 s	2450 @ 0.112 s	Belt contacts with the neck of the dummy @ 112 ms

It should be noted that the FEM used in this study did not include the trim parts of the interior of the bus structure. Since the presence of trim parts would have an effect on the HIC values its inclusion in a future study is strongly recommended. Also increasing the number of dummies in the vehicle and using more sophisticated dummies would result more accurate analysis results. Finally, improvements on seatbelts FEM is recommended for further studies.

The influence of the belted occupants must be considered by adding a percentage of the whole passenger mass to the vehicle mass. That percentage depends on the type of belt system and is 70% for passengers wearing 2-point belts and 90% for passengers wearing 3-point belts [24]. In authors' earlier study [15], it was shown that adding passenger weight to the bus structure significantly changes the rollover crash scenario increasing the initial kinetic energy of the whole system and causing much more damage than expected to the structure of the bus. Hence for further studies it is recommended that a full passenger's weight must be added to the bus structure or dummies equal to the passenger number must added to the finite element model and authors believe that this should be adapted in the ECE R66 regulation.

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