MULTIBODY ANALYSIS OF M3 BUS ROLLOVER: STRUCTURAL BEHAVIOUR AND PASSENGER INJURY RISK

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ABSTRACT

In this work the multibody (MB) approach has been used to study the structural behaviour of a M3 bus in a rollover accident, to evaluate the structure resistance and passenger injury risks. This research is part of the ECBOS project (Enhanced Coach and Bus Occupant Safety), granted by the European Union.
The interest was focused on the effect of a rollover accident over the structure and the passengers.
For what concerns the rollover of a bus, in Europe the regulation for safety approval is the ECE Regulation 66 [1]. This regulation prescribes a test to be chosen between four of different kind: a complete bus rollover test, a bay section rollover test, a pendulum test and a numerical simulation of a rollover. The choice between these tests is completely up to the coach manufacturer. It is important to underline that in all these tests the presence of passengers is not considered.
The effect of the mass of the occupants over the superstructure and the injury risk for passengers in a rollover accident was evaluated considering different configurations. Only a bay section has been modelled: in a rollover event, with rotation axis parallel to the longitudinal bus axis, the behaviour of the bay section is well representative of the whole structure. To generate the virtual model of the bay section, the plastic hinge concept has been adopted by using generalized spring elements to represent the constitutive characteristics of localized plastic deformations. The program chosen to carry out the simulations is MADYMO, a MB-FE software developed by TNO, which has a complete library of virtual dummies.
The numerical analysis has given prominence to the inadequacy of the actual European regulation (ECE66), concerning passive safety. The mass increment due to presence of the passengers affects significantly the deformation of the superstructure and the absence of any prescription of restrain systems does not permit to protect the passengers against very serious or fatal injuries.

INTRODUCTION

In the last years the interest in the study of the plastic collapse behaviour of mechanical structures has constantly increased. The continuous development of innovative structures and materials, particularly in the automotive field, brought many new design problems concerning the reliability and safety. The large diffusion of individual and collective transport means increased the accident risks in automotive, aeronautical and railway fields.
The manufacturers are investing a lot of energy in researches to reduce the number of accidents and to limit their consequences. Nowadays the designers must respect strict safety regulations, which impose a hard verification of design and technological choices. All new car models must pass certain safety tests before they can be sold.
Buses are transport means for which in Europe the regulation is not at the moment so hard as for cars. The high cost of the single vehicle makes the manufacturers unwilling to perform full vehicle tests like car crash-tests.
Every year in the EC approximately 20.000 buses are involved in accidents. The statistics report about 300.000 injured and 150 fatalities per year due to these accidents [2].
These data show that the bus is one of the safest vehicles, safer than the aeroplane, safer than the train and the car. Nevertheless the few accidents are often so disastrous to capture the attention of the public opinion. In particular in a rollover event serious consequences for the occupants are nearly inevitable.

THE MULTIBODY APPROACH IN CRASH ANALYSIS

The use of a prototype to verify the various design steps is often unsuitable because of the high costs and execution time. As a consequence, the numerical simulation is taking an ever-growing importance, even though this technique is complementary and not alternative to the prototype.
The modelling of mechanical structure behaviour is usually performed by means of finite elements (FE) codes. This kind of approach allows an accurate description of the stress and strain field, even in highly non linear situation, like the ones which occur in impact analysis.
However in an early stage of the design process, the FE method has some undeniable drawbacks, like the laborious building of the mathematical model and the remarkable computation time required for the analysis, while some details of the structure are not yet fixed.

For these reasons, in a preliminary phase, it is advisable to employ some numerical techniques that, starting from a simplified analysis of the phenomenon allows the designer to obtain some useful indications in a reasonable amount of time and with good accuracy. These indications can be used for a first choice among different alternative solutions [3,4].

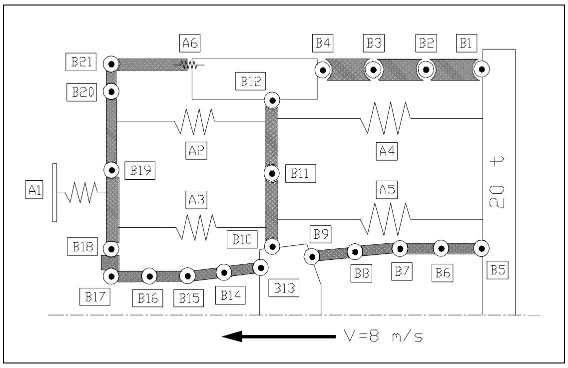

Figure 1. Example of MB approach.

The multi-body approach (figure 1 shows, as an example, the model of the front structure of a rail vehicle and figure 2 shows a curved box beam columns model) to crash analysis is based on a discretisation of continuous structures by means of an assembly of rigid parts joined by non-linear cinematic joints that are intended to model parts of the structure in which local plastic collapse takes place. This simplification is justified by the experimental evidence: deformations experienced by a structure as a consequence of an impact are localised in several narrow zones of each component, leaving the other zones relatively unaffected by the impulsive load.

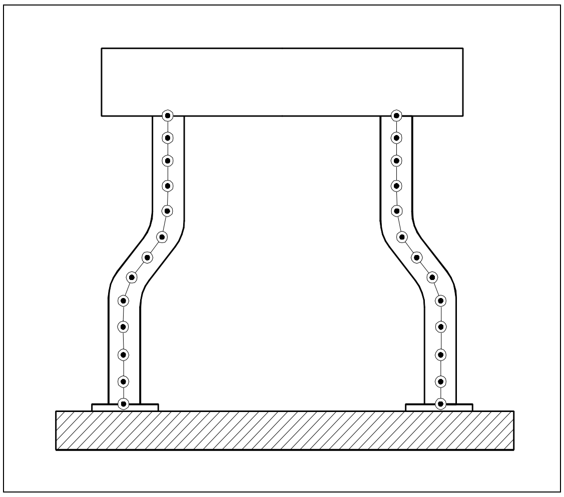

Figure 2. Example of a MB problem.

Obviously coarser discretisation of the structure leads to less accurate results with respect to those obtained by a full FE analysis. Moreover the mechanical joints that model plastic hinges [5] of the real structure are positioned by the analyst at his choice, although with some criteria, and this has the effect of restricting the cinematic degrees of freedom of the whole system. Therefore in the design phase it is important to evaluate the correct position of the plastic hinges.

Finally multi-body modelling requires the knowledge of the non-linear joint behaviour, usually expressed by non-linear generalised force vs. displacement laws. This information, which depends on the section geometry and material properties, can be obtained either by experimental tests, by FE simulations or by use of cinematic theoretical models.

STRUCTURAL BEHAVIOUR ANALYSIS

Numerical model

The fist purpose of this work is to build a simplified MB model for the numerical analysis of the rollover of a M3 class bus employed in suburban and tourism services. The applicability, the result approximation level and the advantages of the MB approach to a complex problem have been evaluated. The kind of problem that is now dealt with is certainly more complex than the ones analysed up to now [6,9].

The numerical model was developed starting from the bay section structure (figure 3) built and used by the Cranfield Impact Centre (CIC) for some experimental tests within the ECBOS project [10]. This structure was obtained following what is stated in the ECE66 regulation. Therefore, for what concerns this regulation, this structure is fully representative of the rollover behaviour of the complete bus from which it was obtained.

Figure 3. Bay section (courtesy of CIC).

Examining the structure, it is clear that the lower part is much more rigid than the upper one because of the presence of crossbars and stiffening elements. As shown in figure 4, in a rollover test performed on this structure, almost only the upper part undergoes large deformations, while the lower part is not submitted to significant deformations. Therefore, in the numerical model development, it is possible to assume that the lower part of the bay section behaves as infinitely rigid.

Figure 4. Deformed bay section (courtesy of CIC).

The bay section numerical model (figure 5) was built using MADYMO, software developed by TNO specifically for the crash simulations. In this model both rigid bodies and finite elements were employed [11]. The windows and the roof pillars were modelled using rigid bodies connected each other by revolute joints. The characteristics of these joints (figure 6) were obtained by the FE analysis of the bending collapse of the thin walled beams that constitute the pillars.

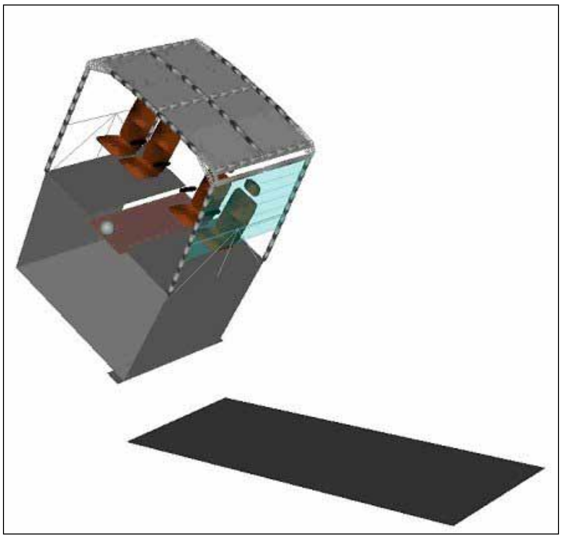

Figure 5. Bay section numerical model.

The lower part of the bay section was modelled using one rigid body. The model include also some parts modelled by FE, they were employed with the aim to avoid the problem of building closed chain structures, that are very difficult to be treated in MB software. The use of both FE and MB in the same model allowed a remarkable simplification in the assembly phase of the structure. Furthermore the introduction of finite elements made it possible to describe parts of the structure whose behaviour was not easily foreseeable.

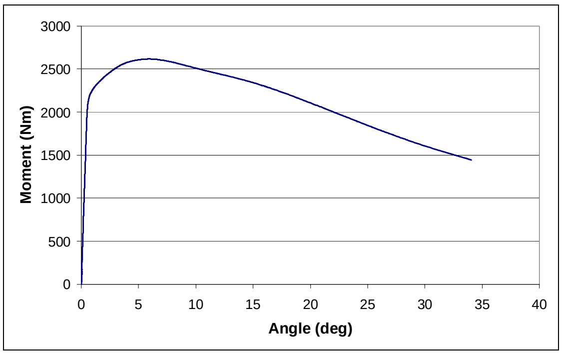

Figure 6. Window pillar strength characteristics.

Model validation

In order to validate the numerical model the simulations of two experimental tests performed by CIC were performed. The first experimental test was a standard ECE66 rollover test, while the second one was a rollover test but with four Hybrid III dummies onboard restrained with two-point belts. Four relative distances (figure 7 and figure 8) between a point of the window pillar and a point of the floor were measured both during the experimental tests and in the numerical simulations

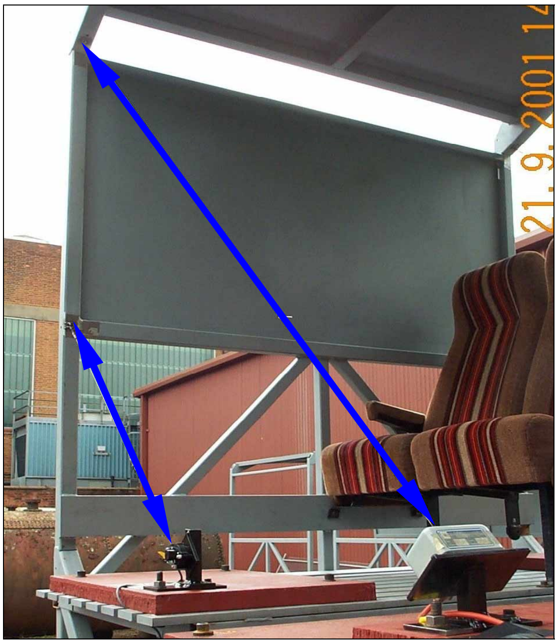

Figure 7. Front pillar: measurement points (courtesy of CIC).

Figure 8. Rear pillar: measurement points (courtesy of CIC).

The results are compared in figure 9 and in figure 10, where the time histories of the above mentioned relative distances are shown. As it is possible to see, the numerical results are in very good accordance with the experimental tests. Also the deformed shapes, experimental (figure 4) and numerical (figure 11), are very similar.

Therefore it is possible to say that the bay section numerical model simulates in a good way the behaviour of the bay section during a rollover.

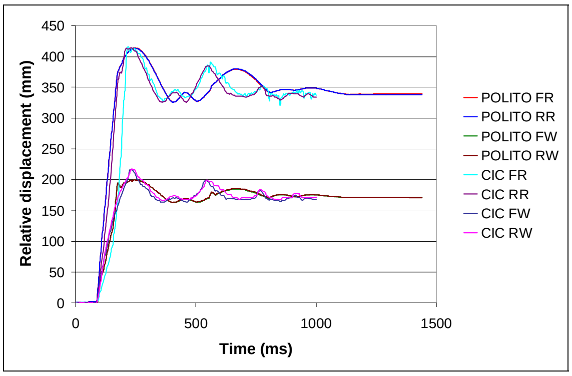

Figure 9. Results comparison first test.

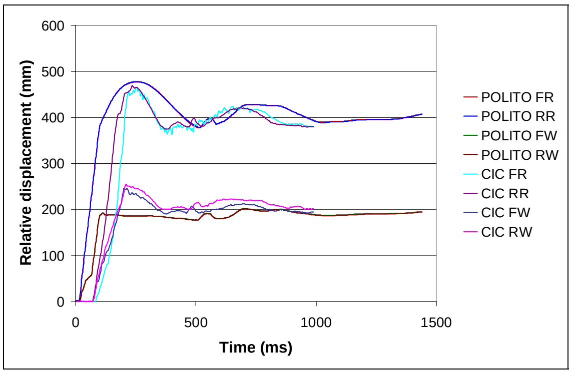

Figure 10. Results comparison second test.

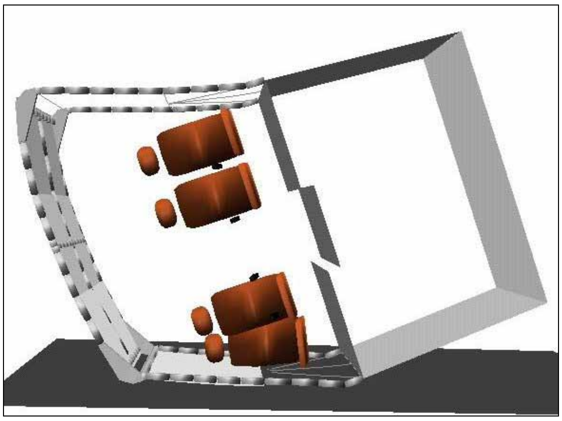

Figure 11. Deformed bay section.

Effect of the passengers onboard

In order to obtain the approval the superstructure of a vehicle must be of sufficient strength to ensure that during and after the test no displaced part of the vehicle intrudes into the residual space (figure 12) and no part of the residual space projects outside the deformed structure.

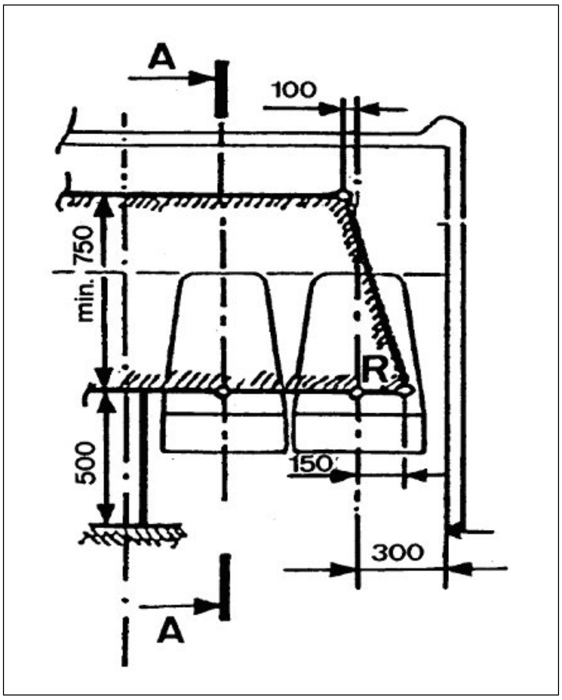

Figure 12. Residual space.

As already put in evidence in the previous paragraphs, the presence of the passengers is not considered for tests performed according to the ECE66 regulation. However it was considered of relevance to compare (figure 13) the results of the two tests in order to understand how the presence of passengers affects the structural behaviour of the bay section. As mentioned above the first test was a standard ECE66 rollover test while the second one was a rollover test but with four Hybrid III dummies onboard restrained with two-point belts.

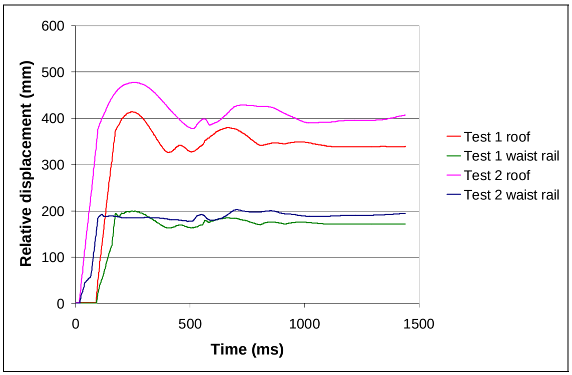

Figure 13. Comparison of the two tests.

The mass increment due to the presence of the passengers is in this case about the 16% of the empty bay section mass. Furthermore the presence of the dummies, in addition to a mass increment, moves to a higher position the structure centre of gravity changing the crash dynamics. It is therefore obvious to expect a different behaviour of the structure between the two tests. As shown in figure 13, the increment of deformation due to the presence of the passengers onboard is not negligible.

PASSENGER INJURY RISK ANALYSIS

Numerical model

In order to evaluate the injury risk for passengers, the numerical model of a EuroSID dummy was positioned inside the bay section numerical model. The EuroSID dummy was employed as it is has been designed to represent a 50th percentile adult male subject during lateral impact conditions, that is the crashing condition most similar, although not fully consistent, to the rollover event to be studied. The numerical model of the EuroSID dummy consists of 80 bodies linked by joints or restraints. Ellipsoids are assigned to the bodies to provide the interaction with the environment. The virtual instrumentation assigned to the dummy permits to extract all the necessary information to evaluate the injury risk for passengers according to the existing regulations. Six different accelerometers give the measure of the head, clavicle, thorax, rib and pubic symphysis acceleration histories. Furthermore it is possible to extract the time histories of the forces acting on abdomen, lumbar spine, neck, femurs, shoulders and pubic symphysis.

Injury parameters

In order to evaluate the injury risk for passengers the following injury parameters were calculated:

- Head injury Criterion (HIC)
- Thoracic Trauma Index (TTI)
- Viscous Injury Response (VC)
- Rib Deflection
- Pubic Symphysis Peak Force

As there isn't a regulation that fixes limit values of the previous injury parameters for a bus or a bus rollover accident, the limit values established by the directive 96/27/EC for a motorcar side impact were considered [12]. Therefore the following limit values were taken into account

- Head injury Criterion (HIC): 1000
- Thoracic Trauma Index (TTI): 90 g
- Viscous Injury Response (VC): 1 m/s
- Rib Deflection: 42 mm
- Pubic Symphysis Peak Force: 6000 N

It is important to underline that these limit values have to be intended as the values at which 80% of the corresponding human being does not suffer fatal injuries. If the index value results to be larger than this limit value the fatality or injury risk groves dramatically.

Base configuration results

For each sitting position inside the bay section (figure 14), a simulation of a rollover test with one EuroSID dummy onboard, restrained with two-point belts, was performed.

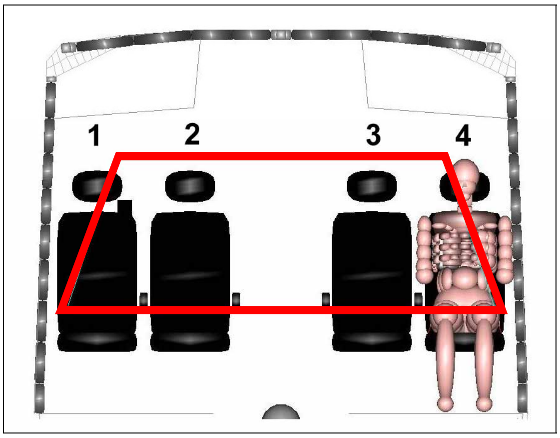

Figure 14. Position inside the bay section.

In all the simulations the maximum rib deflection (upper, middle and lower), the TTI(d) and the VC (upper, middle and lower) values are below the limits stated by the directive 96/27/EC.
For what concerns the HIC values, the results for the dummies seated in position one and two are well below the limit, while for the dummies seated in position three and four they are over the limit. Finally, the load on the pubic symphysis is over the limit for the dummies seated in position one, two and four.

Parametric study

Starting from the base configuration some important parameters were submitted to quite large modifications of their value, one by one, in order to evaluate their influence on the injury risk for passengers [13]. The considered parameters are the following:

Structure strength: five different strength characteristics of the joints of the window pillars were considered (figure 15). These characteristics are obtained by changing the thickness and/or the material properties of the thin walled beam that constitute the pillar.

Characteristic n° 1: Base resistant moment – rotation angle curve (unmodified)
Characteristic n° 2: 20% decrease of the thickness of the thin walled beam
Characteristic n° 3: 20% increase of the thickness of the thin walled beam
Characteristic n° 4: 20% decrease of the thickness and 20% decrease of the stress in the stress-strain curve of the material of the thin walled beam
Characteristic n° 5: 20% increase of the thickness and 20% increase of the stress in the stress-strain curve of the material of the thin walled beam

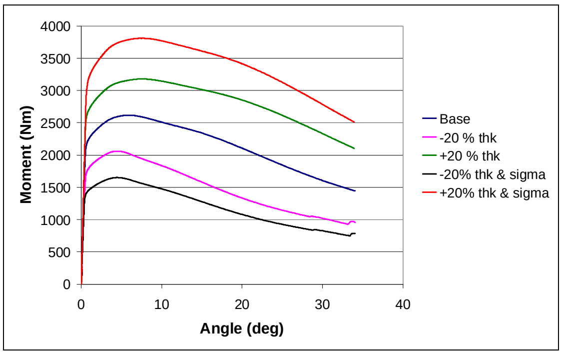

Figure 15. Window pillar strength characteristics.

Occupant size: three different occupant sizes were examined:

1. 5th Female occupant
2. 50th Male occupant
3. 95th Male occupant

Restrain system: three different configurations were examined:

1. Unbelted
2. Two-point belt
3. Three-point belt

Therefore for each sitting position inside the bay section, ten different configurations were analysed:

BASCON – 50th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 1 of the joints of the window pillar

LESTF_1 – 50th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 2 of the joints of the window pillar

LESTF_2 – 50th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 4 of the joints of the window pillar

MOSTF_1 – 50th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 3 of the joints of the window pillar

MOSTF_2 – 50th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 5 of the joints of the window pillar

UNBELT – 50th male EuroSID dummy unbelted and strength characteristic n° 1 of the joints of the window pillar

RGT3PB – 50th male EuroSID dummy restrained to the seat by a three-point belt with the third point over the right shoulder of the dummy and strength characteristic n° 1 of the joints of the window pillar

LFT3PB – 50th male EuroSID dummy restrained to the seat by a three-point belt with the third point over the left shoulder of the dummy and strength characteristic n° 1 of the joints of the window pillar

5THFDU – 5th female EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 1 of the joints of the window pillar

95THMDU – 95th male EuroSID dummy restrained to the seat by a two-point belt and strength characteristic n° 1 of the joints of the window pillar

In all the simulations three ballast masses corresponding each to the weight of a 50th male EuroSID (about 72 kilos) were added to the mass of each seat in order to consider a full occupied bay section.
In order to represent the interaction between the passenger and the internal parts of the bus (seats, side windows, pillars, etc.) some contact characteristics obtained from experimental tests performed by TNO and CIC within the ECBOS project were included in the models [14,15].

Results comparison

The results of the simulations are shown in the following figures and tables. In the figures the reference limit value is also shown to make easy the diagram interpretation. To better evaluate the effect of each parameter on the injury risk for passengers the results were grouped in three sections:

- Structure strength effects
- Restrain system effects
- Occupant size effect

Structure stiffness effects

In all the examined configurations, differing each other for the structure stiffness, the maximum rib deflection (upper, middle and lower), the TTI(d) and the VC (upper, middle and lower) values are below the limits stated by the directive 96/27/EC.

For what concerns the HIC values, in every case the results about the dummies seated in position three and four are over the limit value (1000), while the HIC values for dummies seated in position one and two are always below the limit. Furthermore it is possible to notice that the HIC values for dummies in position three and four increase as the structure strength is increased.

Finally it is possible to see that the maximum load on the pubic symphysis is always below the limit for the dummy seated in position three, while it is always over the limit for the dummies in all the other positions. This is due to the impact of the lower part of the torso with the armrest. For position number one and two it is possible to notice a slight decrement of the maximum value of the pubic symphysis

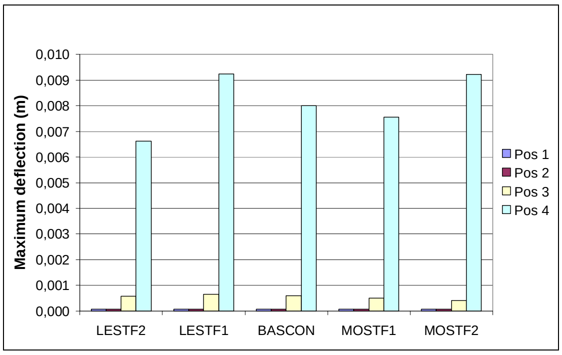

Figure 16. Upper rib deflection.

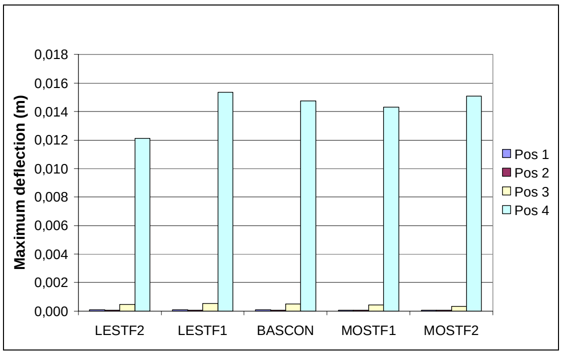

Figure 17. Middle rib deflection.

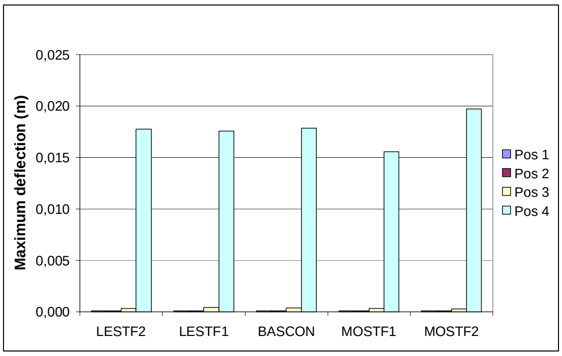

Figure 18. Lower rib deflection.

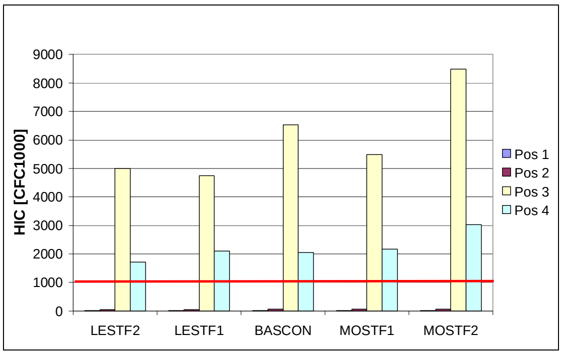

Figure 19. Head Injury Criterion (HIC).

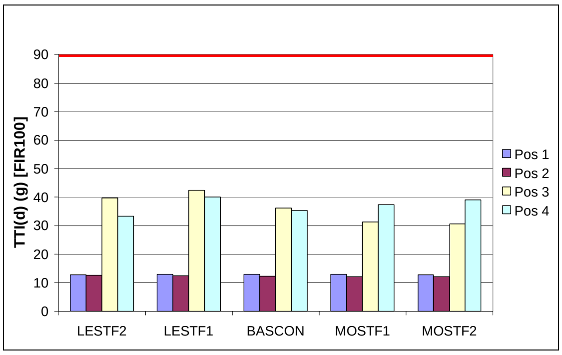

Figure 20. Thorax Trauma Index (TTI).

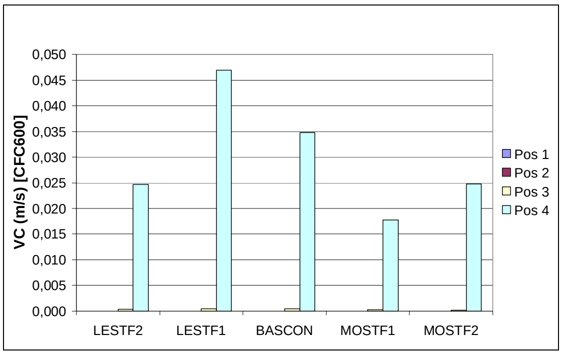

Figure 21. Upper rib Viscous Criterion (VC).

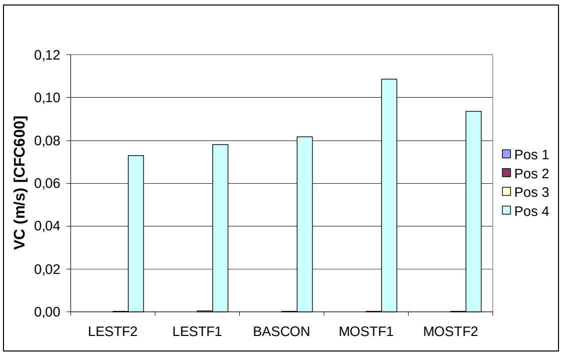

Figure 22. Middle rib Viscous Criterion (VC).

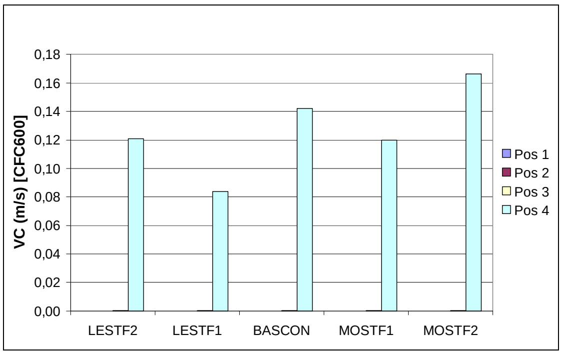

Figure 23. Lower rib Viscous Criterion (VC).

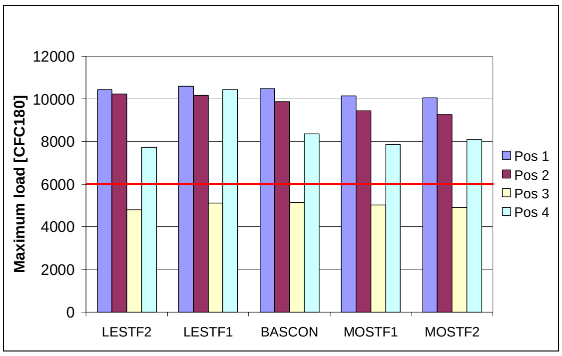

Figure 24. Pubic symphysis load.

<u>Restrain system effects</u>

In all the examined configurations, differing each other for the restrain system, the maximum rib deflection (upper, middle and lower), the TTI(d) and the VC (upper, middle and lower) values are below the limits stated by the directive 96/27/EC. Furthermore it is possible to notice that the maximum deflection (middle and lower ribs), the VC (middle and lower ribs) and the TTI(d) values increase changing from two-point belts to three-point belts because with this kind of belt the upper torso of the dummy is more constrained to the seat and, as a consequence, during the impact the forces applied from the structure to the ribs and the lumbar spine are greater, and so, obviously, the accelerations.

For what concerns the HIC values, the results about the dummy seated in position three are very interesting. As it is possible to see, the HIC values for this position are still over the limit (1000) even with two-point belts. Actually this kind of belt, in the considered event, is completely ineffective because it can't prevent the impact between the head of the dummy and the side window. Instead three-point belt prevents the impact and, as a consequence, in the considered event, the HIC values drop below the limit. The dummy seated in position four doesn't benefit from the use of any kind of belts (two or three point belts) as they can't prevent the impact of the head with the side window. For the dummies seated in position one and two, the HIC values are always below the limit. But for these passengers the most important advantage of the use of belts (two or three point belts) is that they prevent the dummies from flying into the structure or against the other passengers.

Finally it is possible to see that the maximum load on the pubic symphysis is almost always over the limit. This is due to the impact of the lower part of the torso with the armrest.

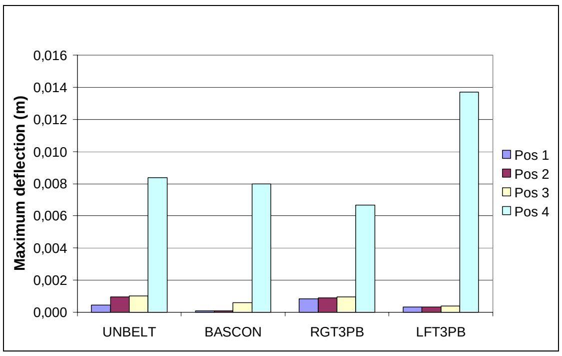

Figure 25. Upper rib deflection.

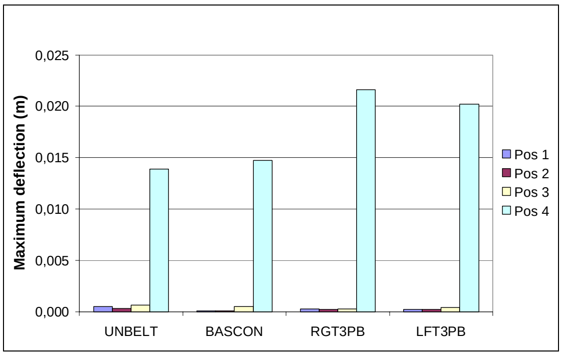

Figure 26. Middle rib deflection.

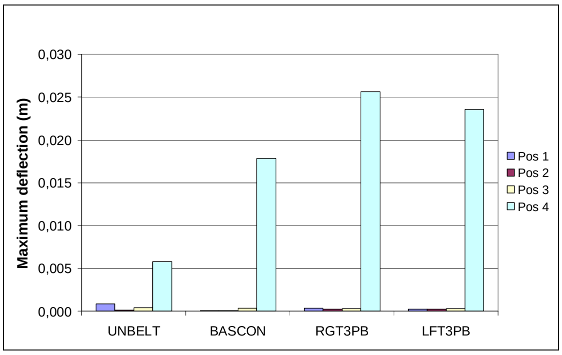

Figure 27. Lower rib deflection.

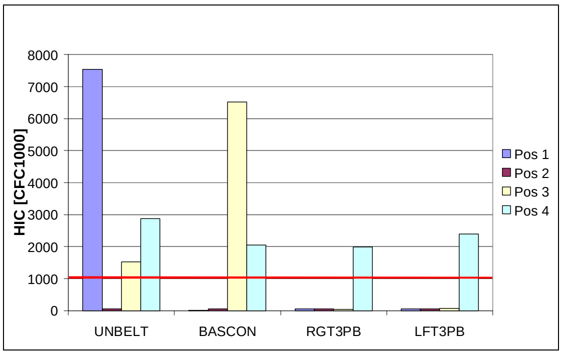

Figure 28. Head Injury Criterion (HIC).

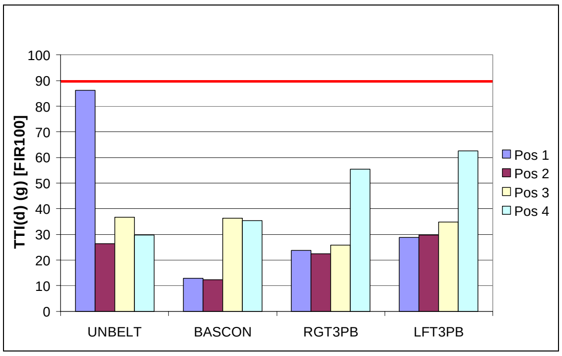

Figure 29. Thorax Trauma Index (TTI).

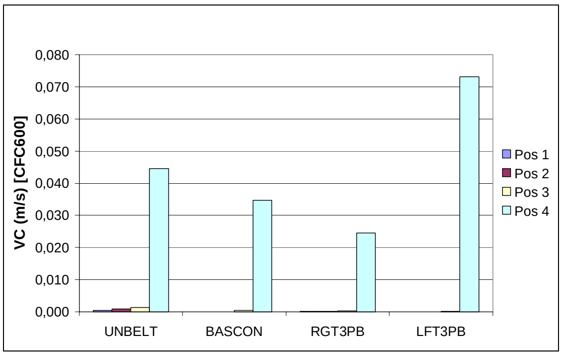

Figure 30. Upper rib Viscous Criterion (VC).

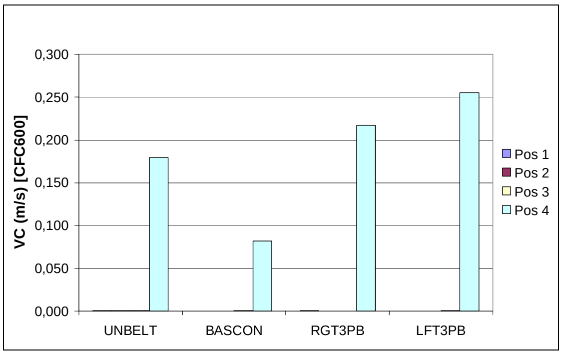

Figure 31. Middle rib Viscous Criterion (VC).

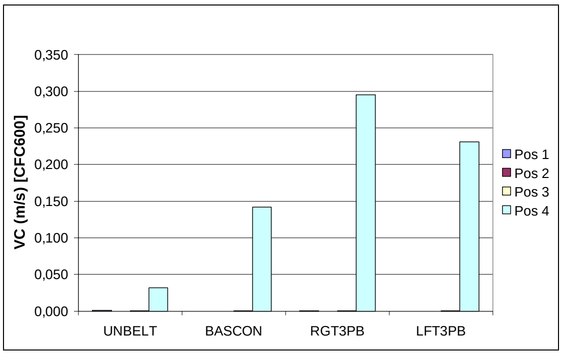

Figure 32. Lower rib Viscous Criterion (VC).

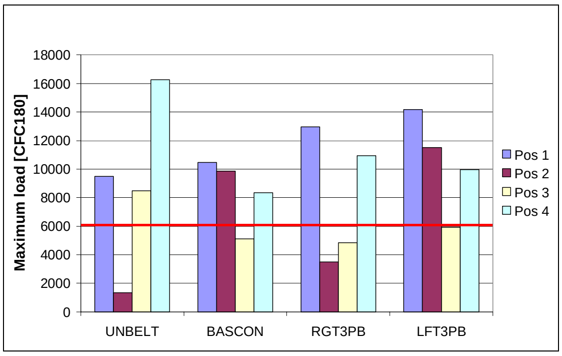

Figure 33. Pubic symphysis load.

Occupant size effect

In all the examined configurations, differing each other for the occupant size, the maximum rib deflection (upper, middle and lower) values are higher for the 05th female dummies. This behaviour is caused by the impact of the ribs into the armrest due to the small size of the dummy. The TTI(d) and the VC (upper, middle and lower) values are always below the limits stated by the directive 96/27/EC. For the VC it is possible to notice that the maximum values for the dummy seated in position four (upper, middle and lower ribs), increase as the occupant size is increased.

For what concerns the HIC values, in every case the results about the dummies seated in position three and four are over the limit value (1000), while the HIC values for dummies seated in position one and two are always below the limit. Furthermore it is possible to notice that the HIC values for dummies in position three and four decrease as the occupant size is increased.

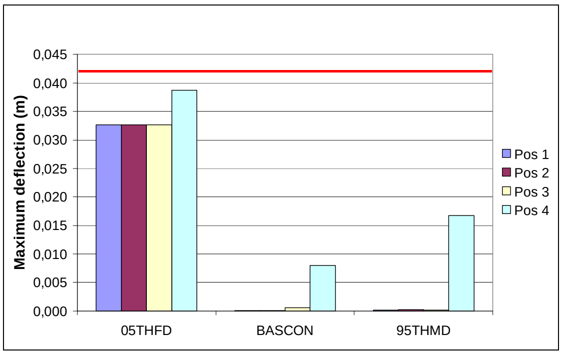

Figure 34. Upper rib deflection.

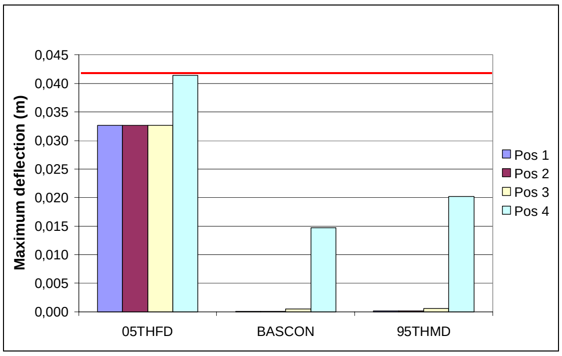

Figure 35. Middle rib deflection.

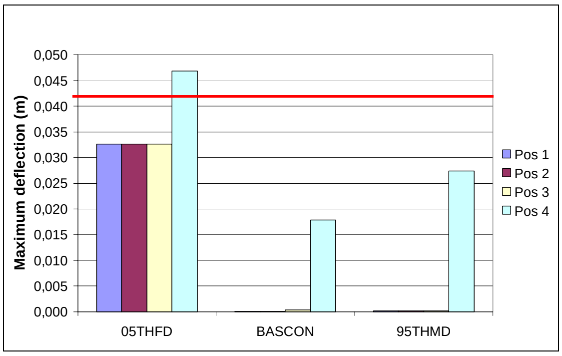

Figure 36. Lower rib deflection.

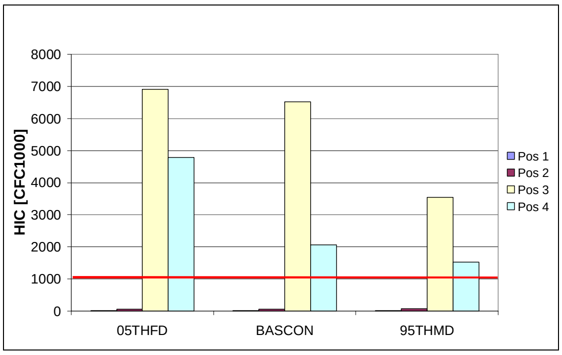

Figure 37. Head Injury Criterion (HIC).

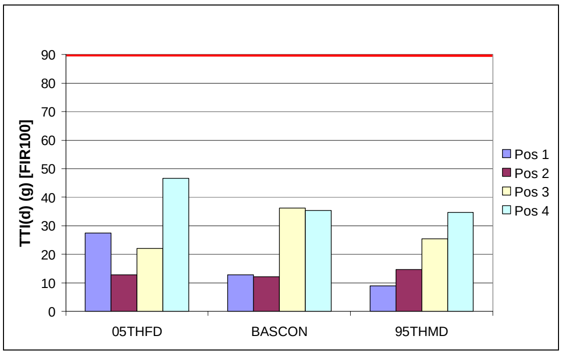

Figure 38. Thorax Trauma Index (TTI).

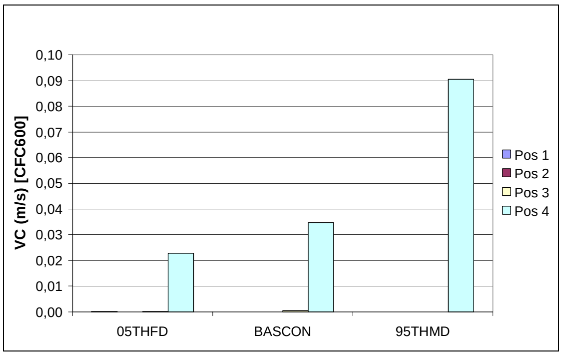

Figure 39. Upper rib Viscous Criterion (VC).

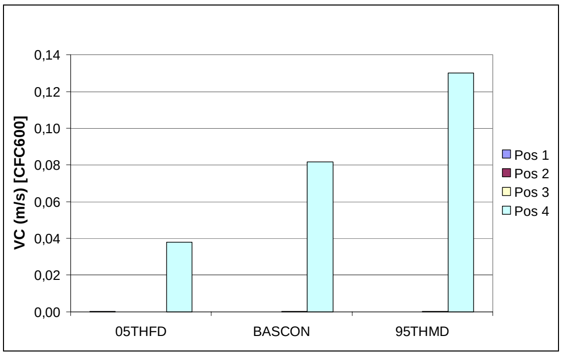

Figure 40. Middle rib Viscous Criterion (VC).

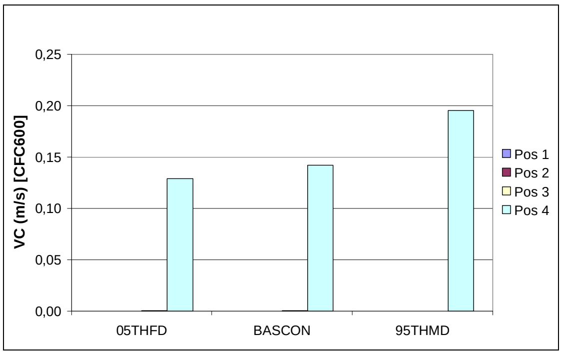

Figure 41. Lower rib Viscous Criterion (VC).

CONCLUSIONS

The numerical simulation of the bus rollover accident has been performed based on the current provisions about bus homologation (ECE66). This regulation is based on the definition of a bus internal volume, called residual space, which must not be penetrated by the structure during the homologation tests. Such volume was determined according to measures and references imposed by the regulation itself. It is possible to notice (figure 14) that the head and a portion of the torax of the passengers near the side walls are already outside the residual space before starting the test.

The numerical model has been built using a mixed MB and FE approach. The CIC bay section was chosen as reference and its numerical model has been validated against the CIC experimental test results.

For what concerns the structural behaviour the performed simulations show the influence of the passengers mass on the energy amount the structure must absorb during the rollover. As consequence a structure that had successfully passed the ECE66 test (no residual space intrusion) could not pass a similar test in which the presence of the passengers on board was considered (survival space intrusion). Then the study has been developed with the aim of evaluating the effect of some design parameters on the passenger injury risk. In all the examined configurations the VC (upper, middle and lower) values are below the limits stated by the directive 96/27/EC. The maximum value of lower rib deflection is over the limit only for the 5th female dummy in position four. For all the other configurations the maximum values of the rib deflection (upper, middle and lower rib) are below the limit. The results of the HIC for the dummy seated in position three are very interesting. The HIC values for this position are still over the limit (1000) even with two-point belts. Actually this kind of belt, in the considered event, is completely ineffective because it can't prevent the impact between the head of the dummy and the side window. Instead three-point belt prevents the impact and, as a consequence, in the considered event, the HIC values drop below the limit. The dummy seated in position four doesn't benefit from the use of any kind of belts (two or three point belts) as they can't prevent the impact of the head with the side window. For the dummies seated in position one and two, the HIC values are always below the limit. But for these passengers the most important advantage of the use of belts (two or three point belts) is that they prevent the dummies from flying into the structure or against the other passengers. Looking to the risk of injury for the thorax, in all the cases the TTI(d) values are below the limit. Nevertheless with three-point belts the TTI(d) values are higher because with this kind of belt the upper torso of the dummy is more constrained to the seat and, as a consequence, during the impact the forces from the structure to the ribs and the lumbar spine are greater, and so, obviously, the accelerations. Finally it is possible to say that the maximum load on the pubic symphysis is almost always over the limit. This is due to the impact of the lower part of the torso with the armrest.

Final conclusions of the research work are the following recommendations for ECE regulation modification:

- include the presence of passengers mass during the rollover test
- prescribe the use of safety belts for all the passengers

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