COMPUTATIONAL METODOLOGIES FOR VEHICLE ROOF STRENGTH ASSESSMENT TO PREVENT OCCUPANTS INJURY IN ROLLOVER CRASHES

Anderson de Lima, andersonkaipers.lima@gm.com
Rogério José Marczak, rato@mecanica.ufrgs.br
Mechanical Engeneering Dept. – Federal University of Rio Grande do Sul

Abstract. *Among all types of vehicle crashes, rollover is the most complex and yet least understood. During the last decades, a constant increase in the studies involving rollover crashes and injuries associated with it can be observed. Although the rollover is not the most frequent type of accident, it is of the greatest significance with respect to injury and trauma caused to the vehicle occupants. The existing standards and procedures to test rollover crashworthiness are still not suitable to computer simulation because of the huge computational effort required, and the need of faithful/overly complex representation of the aspects involved in real crashes. The objective of the present work is the development of computational models particularly adapted to simulate different standards and procedures used to evaluate the vehicles' roof strength. The models are compared with other approaches, and their advantages/disadvantages are discussed*

Keywords*: crashworthiness, vehicle simulation, rollover, roof strength.*

1. INTRODUCTION

Nowadays, the automotive engineers and the industry has been challenged to develop safer vehicles, although it is also needed to reduce the design cycle time. Physical crash tests are extremely expensive, therefore computer simulations has been playing a key role in assisting and analyzing new vehicle designs.

Global numbers of cars are growing year by year; thereafter the number of occupants injured and deaths due to vehicular crashes are increasing as well. Vehicular accidents are among major causes of deaths in the United States according to the National Center for Health Statistics, 2005. Table 1 shows the rate of deaths per 100,000 standard population, where it can be verified that and vehicular accidents have a significant participation.

Table 1. Causes of deaths per 100.000 U.S. standard population according to Centers for Disease Control and Prevention (2005).

Causes	**2005**	**2004**
Diseases of heart	210,3	217,0
Malignant neoplasms	183,8	185,8
Cerebrovascular diseases	46,6	50,0
Diabetes mellitus	24,5	24,5
Alzheimer's disease	22,9	21,8
Vehicular accidents (1)	**14,7**	**14,6**
Septicemia	11,2	11,2
Intentional self-harm (suicide)	10,6	10,9
Chronic liver disease and cirrhosis	8,9	9,0
Assault (homicide)	5,9	5,9

(1): source NHTSA, 2005

Rollovers are dangerous incidents and have a higher fatality rate than other kinds of crashes. Of all types the vehicle crashes only 3.3% are involved in rollover. Meanwhile, rollover is responsible for more than 20% of total passenger deaths in vehicular accidents (see Fig.1).

During the last decades a steady increase in studies of vehicular accidents and occupants injuries involving rollovers has been observed. Rollover is defined as a maneuver in which the vehicle rotates 90 degrees or more around its longitudinal axis (Gillespie, 1992).

There are several studies in the literature showing the effects of the vehicle's roof crushing on the occupants due to rollover. Initial works demonstrated that there were no correlation between roof crushing and the occupant injuries

(Moffat, 1975). After reviewing some real cases of rollover crashes researchers found out that the severity of injury was associated with the intrusion of the roof on the occupant survival space (Grzebieta *et al.*, 2007a).

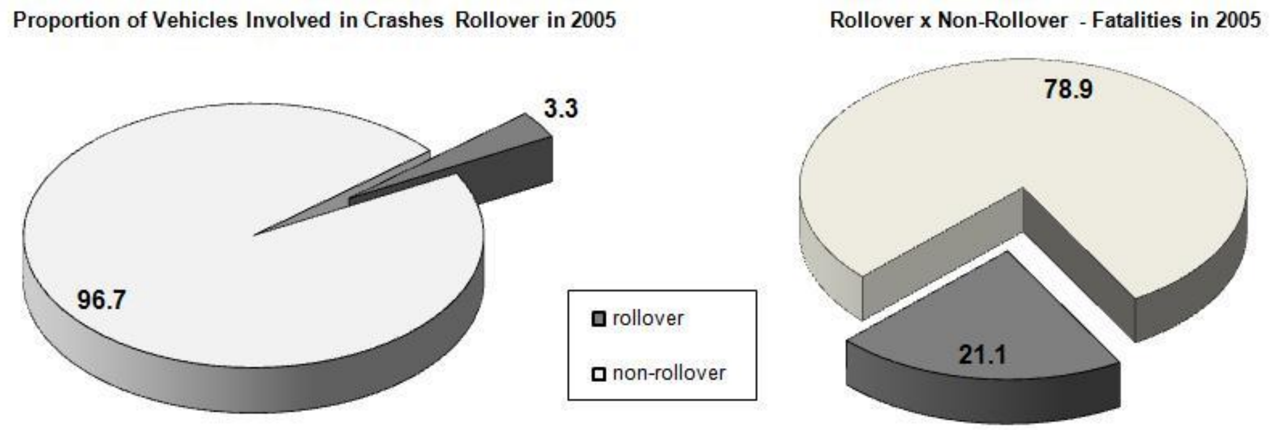

Figure 1. Proportion of vehicles involved in rollover crashes and fatalities, source NHTSA (2006)

The roof strength clearly affects the likelihood of head and neck injuries in occupants during rollover incidents, (Friedman and Nash, 2001). Significant roof crushing occurs in more severe vehicular accidents and therefore the occupant has greater risk of injury. Even after several published studies on this field during the last two decades, the role of roof crushing and the associated injury caused in vehicle's occupant is still an area of intense research. It is also possible to identify various points of view regarding the mechanisms which cause the injuries and, accordingly, there has been considerable debate about the role of roof deformation in this context. One of the major difficulties in analyzing rollover crashes and designing countermeasures is the lack of a widely accepted standard measure of crash severity.

2. STANDARDS AND PROCEDURES

2.1. Roof Crush Resistance – FMVSS 216 (NHTSA, 2005)

This standard requires that a passenger car roof withstand a load of 1.5 times the vehicle's weight in kilograms multiplied by 9.8 or 22.240 N (whichever is the smaller), applied on each side of vehicle's roof and producing no more 127 mm of crush. This standard has been criticized for being a static test which does not represent the real-world rollover events, i.e. it actually refers to a quasi-static test (Grzebieta *et al.*, 2007b).

The load is applied by an rigid rectangular plate 762 mm by 1829 mm. The direction of load is 5 degrees from the longitudinal axis, applied at the front header, and 25 degrees from lateral axis, applied at the side roof rails (Fig.2).

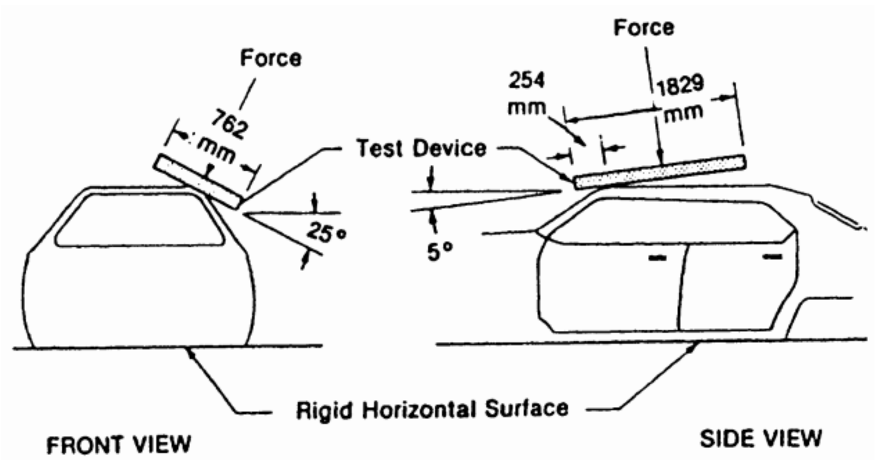

Figure 2. FMVSS 216 test illustration.

2.2. Inverted Drop Test (SAE J996, 1967)

The inverted drop test procedure is devised to evaluate the structural integrity of roofs under loadings similar to those seen in real world rollovers. This procedure presents some advantages: the lateral or slip velocity between the vehicle and pavement is taken into account, so that the real dynamics of the roof crush and the geometry of the roof is considered in the evaluation of occupant's injuries.

According to this procedure the vehicle is hanged upside down in a 25º roll angle and 5º pitch angle attitude and then dropped (Fig.3). This orientation is the same as the FMVSS 216. The suggested drop heights are 304,8 mm and 457,2 mm.

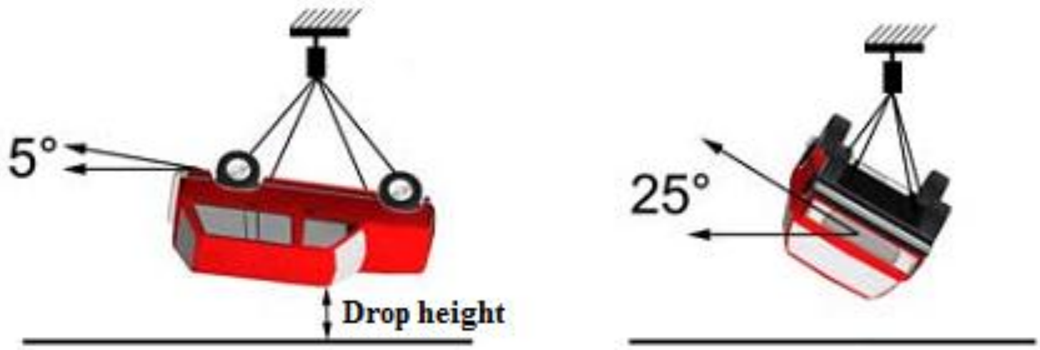

Figure 3. Inverted drop test setup.

2.3. Dolly Rollover Test (SAE J2114, 1999)

The SAE J2114 rollover test procedure is shown in Fig.4. The test vehicle is placed on a device inclined by 23º from the horizontal plane, hold in position by a flange 102 mm high touching the tires of the test vehicle. The distance of the inner corner of the flange and the concrete roll surface is 229 mm.

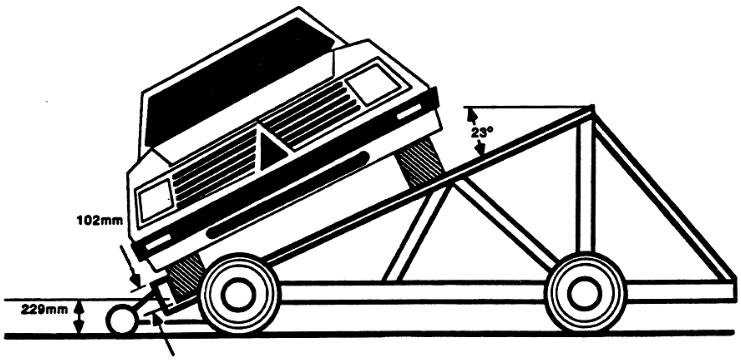

Figure 4. Dolly rollover test setup.

The vehicle and device are accelerated to a constant velocity of 48 km/h, and the device is then stopped in a distance of no more than 914 mm without transverse or rotational movement. The device deceleration cycle must reach at least 20 g during a minimum time of 40 ms.

3. NUMERICAL SIMULATIONS RESULTS

All three tests described in section 2 were modeled in a commercial finite element software for a particular car model, including the passenger dummies to take into account the inertial contribution of the occupants and verify possible contact between occupants and the vehicle structures. The simulations followed in detail the standards for each test, in order to reproduce as faithfully as possible the conditions of the testing (Lima, 2009).

3.1. Roof Crush Resistance – FMVSS 216

The roof strength is extremely important to reduce the injury to vehicle occupants during the rollover phenomenon. FMVSS 216 states that the maximum allowed intrusion of the roof is 127 mm, under a load of 1.5 times the weight of the vehicle (the vehicle's mass considered in this work is 991 kg).

Figure 5 shows a displacement vs. normal force plot of roof intrusion of the vehicle. Two finite element models were used: one considering the additional stiffness provided by the vehicle windows and another devoid of windows. Even in the later case, it is evident that the maximum roof displacement is much lower than the allowable value. It is worth to note that the suggested load of 1.5 times the weight of the vehicle seems to be too small for a realistic analysis.

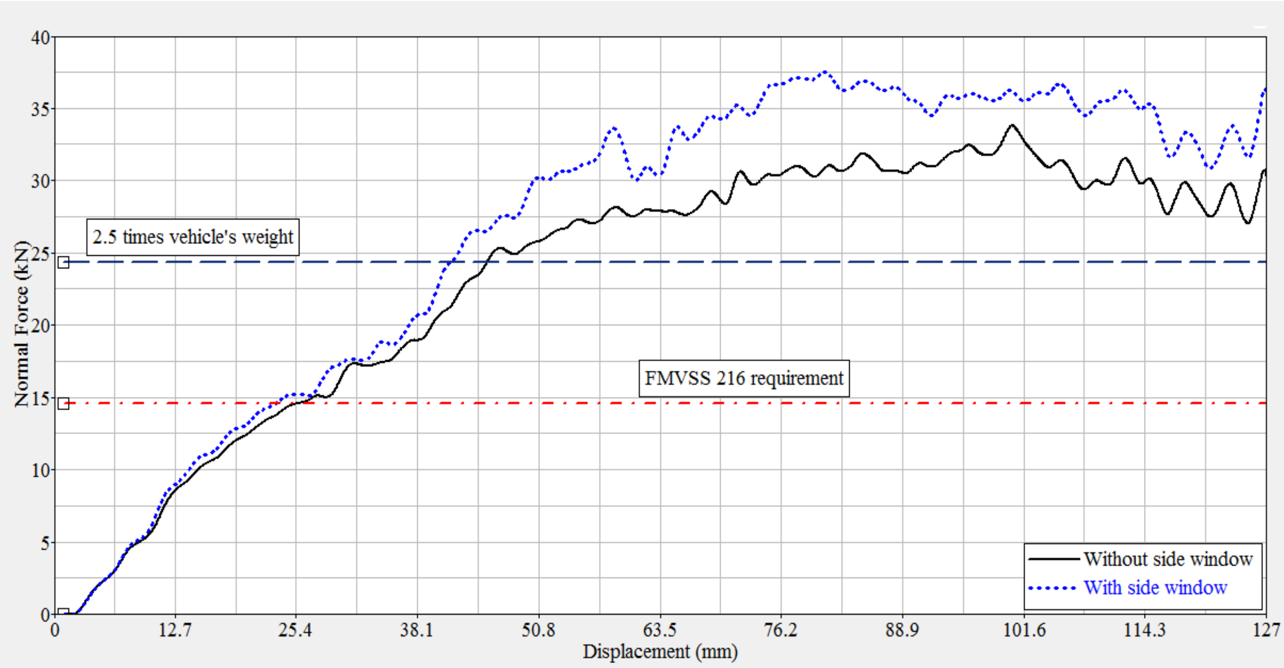

Figure 5. Numerical results of normal force vs. roof displacement for the FMVSS 216 test simulations.

According to the simulation results, the side windows are responsible by an increase of roughly 10% in the resistance of the roof (Lima, 2009), provided the windows do not fail. As it will be shown in section 3.3, the dynamic loads found in the drop test indicate a value of approximately 2,2 times the vehicle's weight, much greater than the value proposed by the FMVSS 216 standard. Therefore, two reference loads are compared in Fig.5: 1.5 and 2.5 times the vehicle's weight. The maximum allowed roof crush is not reached in none of them, though.

3.2. Inverted Drop Test – SAE J996

Numerical results for this test are shown in Figs.6 and 7. Figure 6 presents the force vs. time plots obtained in the simulations for both drop heights. The normal contact force peak between vehicle and the ground during the inverted drop test is 2.0 and 2.9 times the FMVSS 216 requirement, for 304.8 mm and 457.2 mm drop heights, respectively. As one can expect, this test is more severe than the FMVSS 216 test, and obviously take into account the dynamic effects more realistically, since the test vehicle actually falls on the ground.

Considering that the driver remain in the same relative position to the seat during the inverted drop test, the head would strike the roof 0.045s after the contact between roof and ground, for the 304.8 mm drop height. Figure 7 shows a detail view of the finite element mesh of the driver's head at about the contact instant.

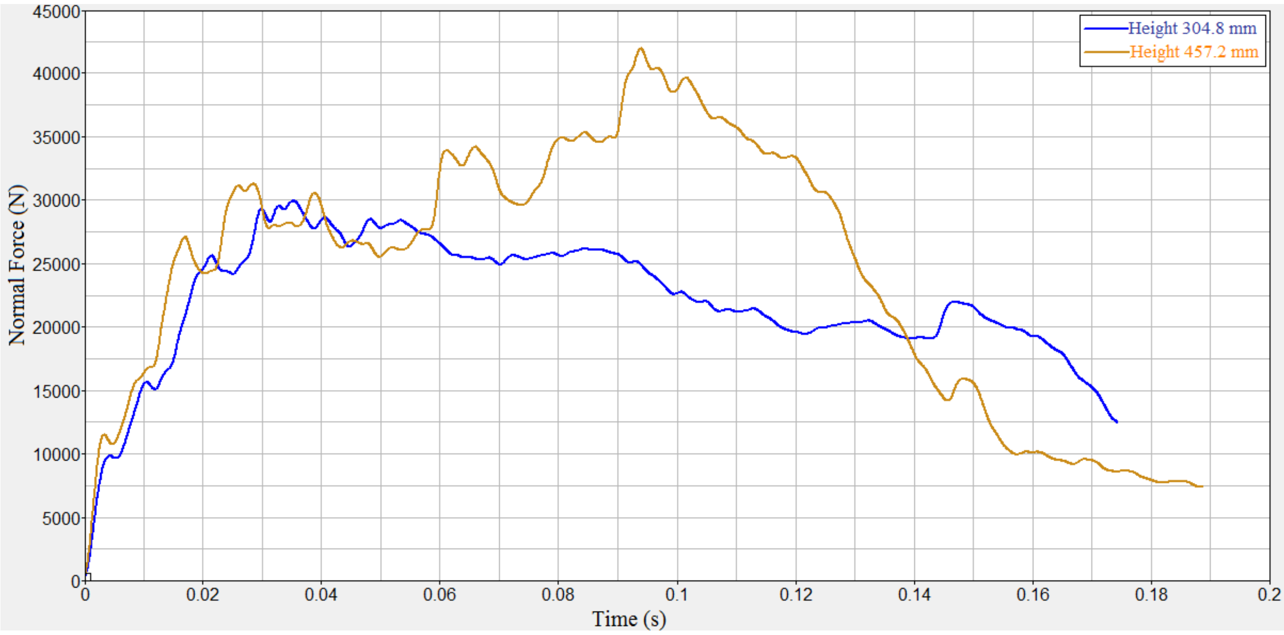

Figure 6. Numerical results of normal force vs. time for the SAE J996 test simulations.

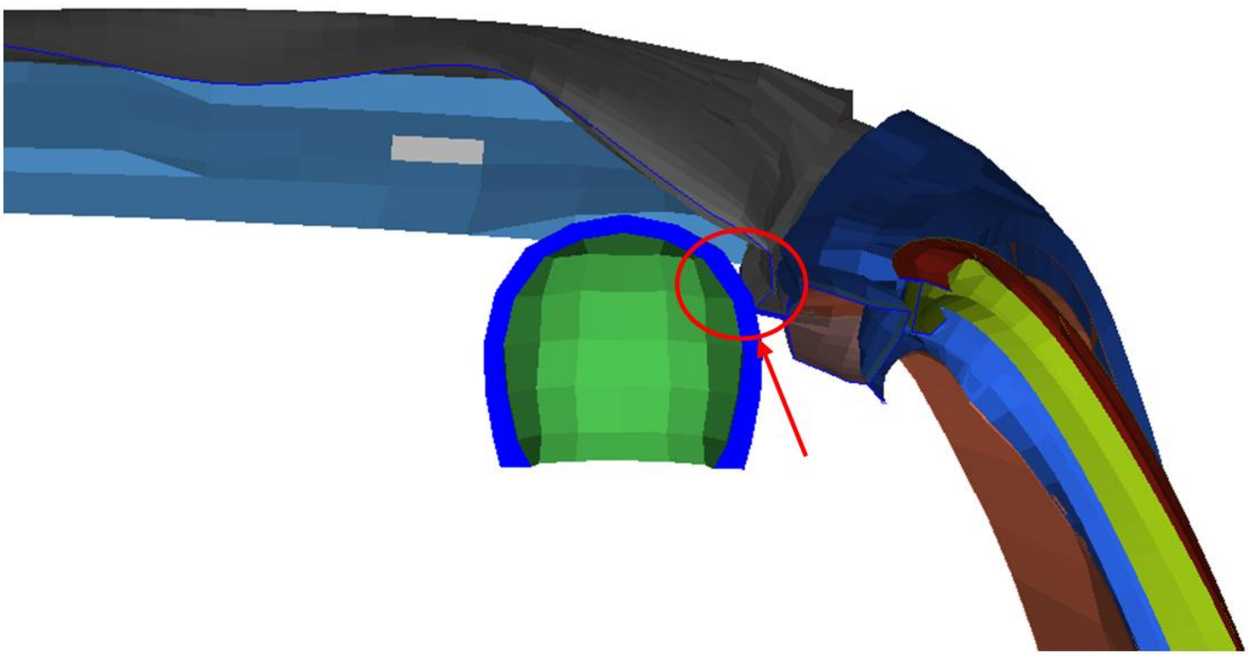

Figure7. Detail view of the roof rail/dummy head contact during the inverted drop test (304.8 mm drop height) finite element simulation.

Because the dynamic effects, the region of the roof just above the driver's head (dummy) shows larger deformation in the inverted drop test (SAE J996) than in the roof crush test (FMVSS 216). This is expected, since besides the inertia effects, the latter does not allow rotation of the vehicle once it comes in contact to the ground, i.e., the orientation of the contact area in the roof crush test remains unchanged during the test.

3.3. Dolly Rollover Test – SAE J2114

The objective of this simulation was to reproduce numerically the rollover test. The finite element model used is shown in the Fig. 8. Obviously, the dolly rollover test simulation demanded much more computational effort and time than the previous ones. Besides the inherent greater complexity of the numerical model, it was found that it is required at least 1500 ms of simulation to capture all relevant events of the test, resulting in a huge computational cost.

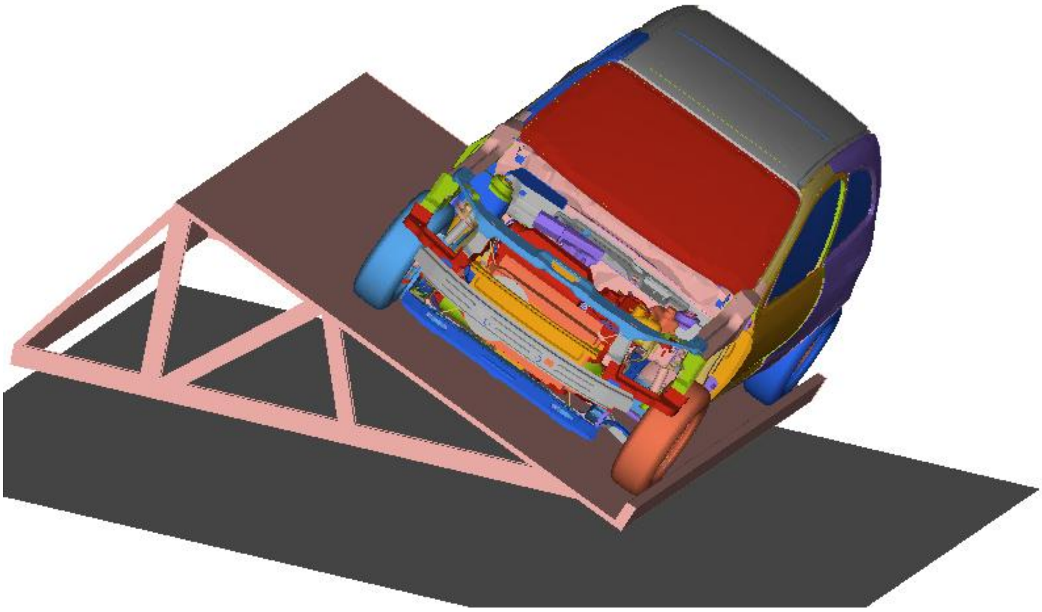

Figure 8. Finite element model of the passenger car used in the dolly rollover test simulation.

The figure 9 shows images of the first contact between the tire and the ground (375 ms) as well as the first contact between the roof and ground (530 ms). Although the number of complete rolls during the rollover event is an important parameter, in ninety percent of the cases the car do not exceed a complete turn (Friedman and Nash, 2001). During the present study it was found that one the tests which better estimate the number of complete turns of the vehicle is actually the J2114, as recommended by the Society of Automotive Engineers (SAE J2114, 1999). Figure 9 also shows the

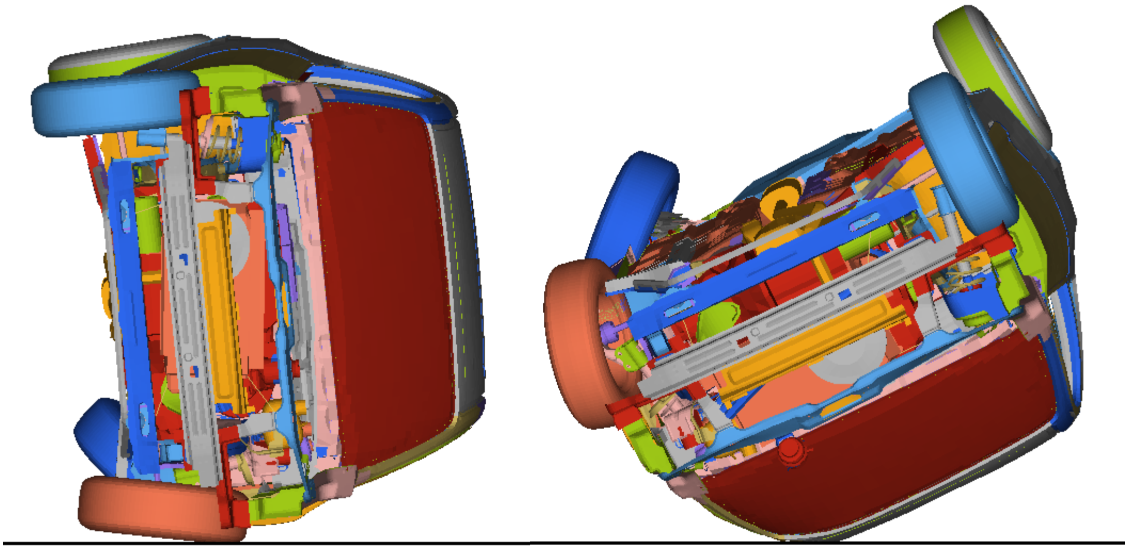

Figure 9. Images of the first contact between the tire and ground (375 ms) and the first contact between the roof and ground (530 ms). SAE J2114 full vehicle simulation.

The graph in Fig.10 shows the contact force history obtained during the simulation. The peak contact force between the roof and the ground obtained is 22,000 N. This value is approximately 2.2 times the weight of the vehicle. This is an important aspect found during this work, since it differs considerably from the 1.5 factor specified by FMVSS 216.

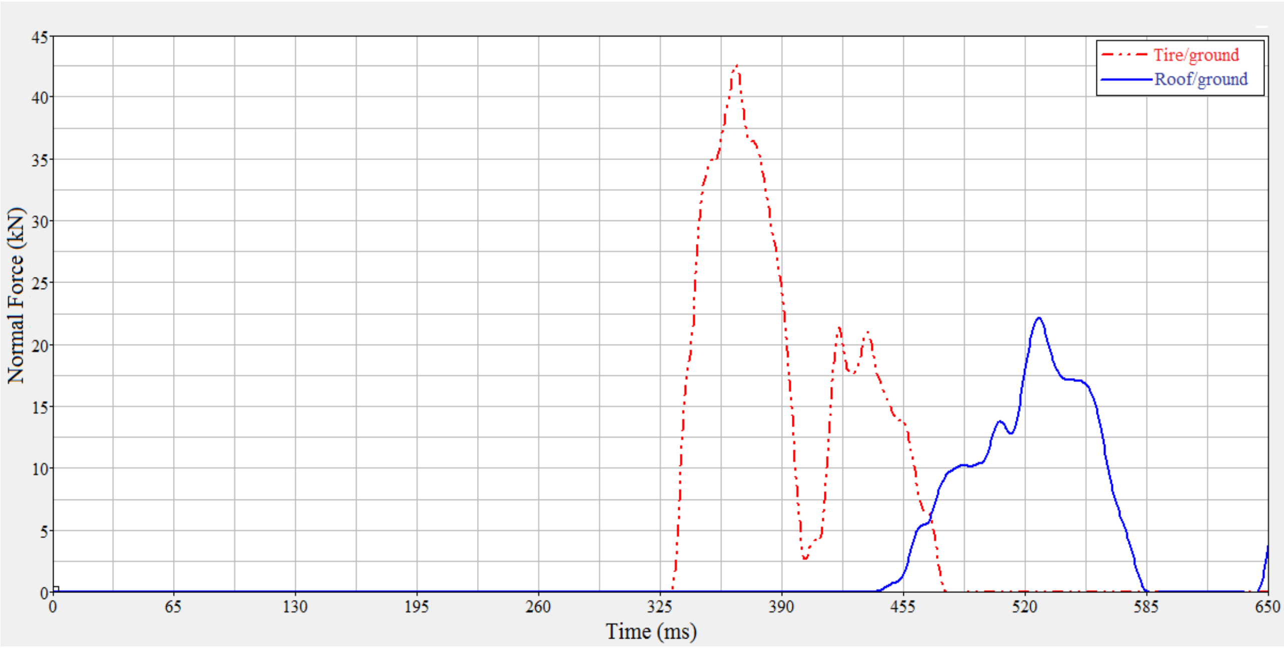

Figure 10. Normal contact force for tire/ground and roof/ground. SAE J2114 full vehicle simulation.

Although highly expensive, the simulation of SAE J2114 procedure represents more faithfully the full size phenomenon, and incorporates more accurately the dynamic effects that occur during a rollover accident. Therefore, as the main conclusion of the present study, it is suggested that the FMVSS 216 standard cannot prevent or minimize the trauma and injuries in the vehicle occupants. Evidently conclusive claims will depend on of the actual conditions of the rollover, but the significant discrepancy found between the load factors of both methodologies, and the more faithful simulation of the SAE J2114 point out in favor of the SAE standard.

Even though the SAE J2114 procedure also does not require the use of dummies, the present study advises to do so, at least in numerical simulations, since it provides an interesting way to verify directly integrity of the vehicle occupants. Furthermore, numerical models for dummies are available, and they can be used to estimate the loads applied on occupants during the crash, helping to approve design changes.

On the other hand, the SAE J2114 procedure proved to be extremely complex and demanding huge computational efforts. One should realize that the high costs are not only associated to the complexity of the vehicle structure, but mostly to the solution of nonlinear equations of the problem, which requires extremely high computational resources.

4. CONCLUSIONS

The main conclusions of the present study can be summarized as follows:

- Regarding the FMVSS 216: This standard is not representative of the actual phenomenon. Besides the application of a quasi-static loading, it does not reproduce the real conditions of rollover. More importantly, the 1.5 load factor was found to be much lower than the necessary for an accurate verification. In addition, the relative movement of the occupant is not taken into account.
- Regarding the SAE J996: The inverted drop can be used to provide a better evaluation the roof strength. The computational simulations showed that the load factor in may vary between 2.0 or 2.9 times the vehicle's weight in order to preserve the survival space of the occupant. Although the dynamic effects of this test are present, it does not consider the lateral movement of a rollover. If used with the 457.2 mm drop height, it may be regarded as a conservative design procedure.

- Regarding the SAE J2114: Among the three standards studied in this work, this is the one which more faithfully reproduces the actual conditions of a rollover. If dummies are included in the test, the SAE J2114 procedure allows the reproduction of secondary impacts (dummy movement) and therefore provides an attractive methodology determine the probability of occupant's injuries. According to the results of numerical simulations, the roof must withstand a minimum load of 2.2 times the vehicle's weight. Given the level of detail considered in these simulations, such load factor has the highest level of confidence among the standards tested here.

Therefore, neither the roof crush resistance test nor the inverted drop test accurately reproduces the real dynamics of occupant and vehicle during rollover crashes. Although all the three standards studied can find use to estimate the roof strength, only the SAE J996 and the SAE J2114 should be used to estimate the probability and severity of occupant's injuries. Finally, it is suggested that the load factor used in quasi-static tests such as FMVSS 216 should be 2.5 times the weight of the vehicle.

5. REFERENCES

Friedman, D. and Nash, C. E., 2001, "Advanced Roof Design for Rollover Protection. 17th International Technical Conference on the Enhance Safety of Vehicles", Amsterdam, The Netherlands.

Gillespie, T. D., 1992, "Fundamentals of Vehicle Dynamics", SAE, Warrendale.

Grzebieta, R.H., Young, D., Bambach, M. and McIntosh, A., 2007a, "Rollover Crashes: Diving Versus Roof Crush", 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France.

Grzebieta, R.H., Young, D., McIntosh, A., Bambach, M., Fréchède, B., Tan, G. and Achilles, T., 2007b, "Rollover Crashworthiness: the final frontier for vehicle passive safety", Proc. Australasian Road Safety Research Policing and Education Conference, Melbourne, Australia.

Lima, A., 2009, ", Numerical Simulation of Vehicular Rollover – Comparison Among Standards and Evaluation of Driver's Injury Risk", M.Sc. thesis (in Portuguese), Mechanical Engeneering Dept., Federal University of Rio Grande do Sul.

Moffatt, E. A., 1975, "Occupant motion in rollover collisions", Proceedings of the 19th Conference of American Association for Automotive Medicine.

National Center for Health Statistics – Centers for Disease Control and Prevention, 2007, "Deaths: Preliminary Data for 2005", National Center for Health Statistics.

NHTSA, 2006, National Highway Traffic Safety Administration. Traffic safety facts, 2005. Report no. DOT HS-810-631. Washington, DC: US Department of Transportation.

NHTSA, 2005, National Highway Traffic Safety Administration, "Federal Motor Vehicle Safety Standards: Roof Crush Resistance", FMVSS 571.216. Standard No. 216.

SAE J2114, 1999, "Dolly Rollover Recommended Test Procedure", Surface Vehicle Recommended Practice J2114, Society of Automotive Engineers.

SAE J996, 1967, "Inverted Vehicle Drop Test Procedure", Society of Automotive Engineers.

6. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.