NUMERICAL SIMULATION OF ROOF CRUSH TEST FOR ASSESSING PASSENGER DAMAGE IN ROLLOVER SITUATION: ROPS DEVICE EVALUATION

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Abstract

Rollover crashes are the most significant vehicle accidents that could severely affect passengers physically. One manner to assess their effects is through virtual models using suitable tools like LS-Dyna®, which is a generalpurpose Finite Element program appropriate for developing non-linear analysis. The protective capability of a safety device called ROPS is evaluated by damage criteria presented in FMVSS 571.208. The vehicle involved in the study is a pickup truck, which can travel inside or outside of mine environments. This is done through simulations of a rollover in the moment of the first impact of the vehicle's roof with the ground. These simulations consider the pickup equipped or not with ROPS device. Four dummies (Hybrid III 50th percentile – adult males) are placed into the vehicle, two in the front and two in the back. The purpose here is to study the kinetic and internal energies involved in the event; roof intrusion and abidance with the limit values of standard requirements for both situations. The simulations reveal that external ROPS perform well in protecting the passenger against dangerous situations related to rollover crashes. According to the standard requirements, all the results are under the limit values. The findings show that installing the proposed ROPS externally to the pickup truck is a reliable way to protect the occupants.

Index Terms: *pickup truck, ROPS, FMVSS 208, roof crush, passenger integrity.*

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1. INTRODUCTION

Rollover crashes are considered to be a long-duration event compared with frontal, rear or side impacts. Consequently, the vehicle occupants are exposed to the dangerous effects of these accidents for a longer period of time. For this reason, the occupant kinematics and injury mechanisms for this rollover scenario have been of great interest to many researchers [1],[2],[3], [4], [5] and [6].

Considering the physical complexity of a rollover, the development of math-based models simulating this event based on rigid body or deformable-body based models have significant importance in understanding this type of crash. Many authors agree that the numerical models are a great tool for the study of crashing as they save time and money [7], [8], [9] and [10].

In general, it is the national or local traffic authorities that specify the standards and guidelines to be applied to traffic and safety regulations. The Federal Motor Vehicle Safety Standards (FMVSS) in the USA are federal regulations established to achieve a minimum level of crashworthiness for motor vehicles protecting vehicle occupants in crash events, an example, is the FMVSS 208 part 571 [11].

The purpose of the standard is to specify performance requirements to protect vehicle passengers, which includes multipurpose passenger vehicles, such as pickup trucks. The injury criteria are determined for a Hybrid III test dummy related to the head, neck and chest.

Furthermore, the FMVSS 571.208 specifies equipment conditions for active and passive restraint systems, like airbags or seat belts. It does not, however, mention the Rollover Protection System (ROPS) device as passive safety equipment for any kind of vehicle (FMVSS 571.208, 2008). ROPS is a structure made of steel tubing that can be installed internally or externally to the passenger compartment.

The real conditions of this study consider that the pickup truck may travel inside and outside of mine environments and in a dangerous scenario, the vehicle is susceptible to rollover. In this context, this paper presents a numerical model developed in LS-Dyna® software, which is composed of a virtual pickup truck with four Hybrid III male test dummies and a test setup, which aims to simulate the pickup roof crush under some geometrical and physical conditions. It is important to highlight that the suggested virtual test simulates a rollover situation representing the moment that the vehicle roof impacts the ground.

The numerical simulations are carried out considering a pickup truck equipped or not with an external ROPS device. This is done in order to check the performance of the ROPS against great intrusion of the roof compartment and whether the head and neck injury criteria are fulfilled according to FMVSS 571.208.The main results show that external ROPS device performs well in terms of protecting vehicle passengers.

2.NUMERICAL MODEL: VEHICLE AND TEST SETUP

The proposed numerical model represents a quasi-static test that can virtually simulate some realistic conditions associated with real rollover accidents. The model consists of a virtual setup that is used to apply a force capable of crushing the left side of a pickup truck.

The model of the pickup truck is available to public access at the website of the National Crash Analysis Center – NCAC [12] (http://www.ncac.gwu.edu/vml/models.html – accessed in January 2014). Some features of the pickup truck are: 2007 model year; 1500 2WD pickup truck; 4 door crew cab short box pickup truck; tires P245/70R17; wheelbase of 3.664 m; CG (rearward of front wheel) is at 1.664 m and it has a weight of 2,617 kg. The NCAC has been developing vehicle finite element models for use with LS-Dyna® software. The model used for the purposes of this research was re-meshed (using ANSA® software and after imported to LS-Dyna®) reducing the number of elements to 153,616 (number of nodes equaling 160,057) by increasing the time step from 1x10-6 s to 2.5 x10-6 s. The elements have an average size of 28x10-3 m.

The virtual test device consists of a rigid plate whose lower surface is a flat rectangle measuring 762 mm by 1,829 mm as shown in Fig. 1. The roof crush test device was modelled by the authors using LS-Dyna®. The impact device (plate) is modelled using solid elements. A rigid horizontal support (Fig. 1) called the supporting structure is modelled imposing no displacement. For the contact modelling between pickup truck and impact device master-slave criteria was used, where the whole pickup was defined as slave and the impact device as master.
To orient the plate in the pickup roof, some geometrical measurements are considered. These include pitch and roll angles of 25º and 5º, respectively, in order to realistically load the roof and supporting structure. The value of 254 mm is measured forward of the forwardmost point on the exterior surface of the roof (Fig. 1). The pickup depicted in Fig. 1 is not yet equipped with de external ROPS device. This will be shown in the section5.

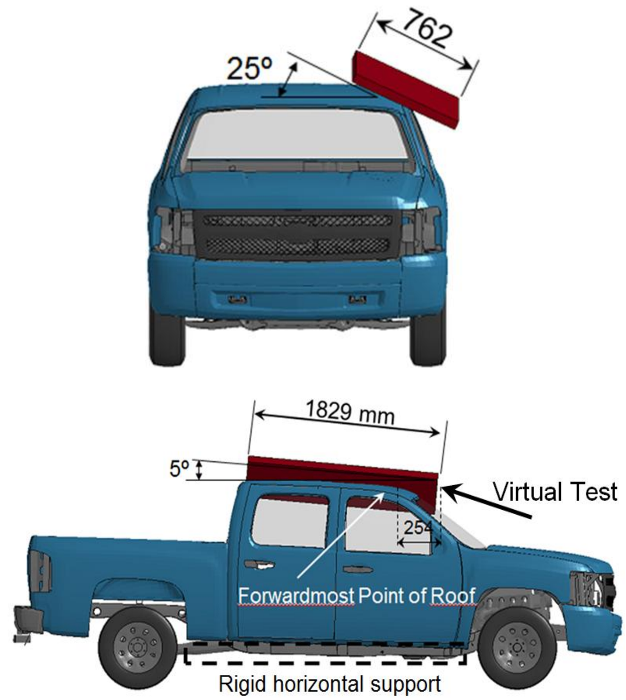


Fig-1: Frontal and lateral view of the pickup truck model placed in the virtual setup

To determine the force to be applied in the CG's plate of the virtual test device (Fig.1), a previous numerical study concerning the dolly rollover test was developed based on the SAE J2114. In this study, the experimental dolly rollover test was virtually modelled, also using the LS-Dyna® software. Notice that Fig. 2(a) depicts five stages of a virtual rollover accident considering 1s of simulation. The goal was to proceed to energy and kinematic analyses concerning rollover events. When performing this virtual test the kinetic and internal energies involved in the first roll of the vehicle followed by the first impact of it against the ground could be determined as illustrated in Fig. 2(b). In this figure, the interval from 0.667 s to 0.778 s corresponds to the impact time window, i.e., the time interval that the pickup impacts the ground. The increment of Internal Energy, ΔEi, stored in the pickup truck during the impact time window corresponds to the difference between the initial internal energy 5 x 103 J (at 0.667 s) and the final internal energy 32 x 103 J (at 0.778 s). It results in ΔEi = 27 x 103 J and this value represents the best estimation of the impact energy.

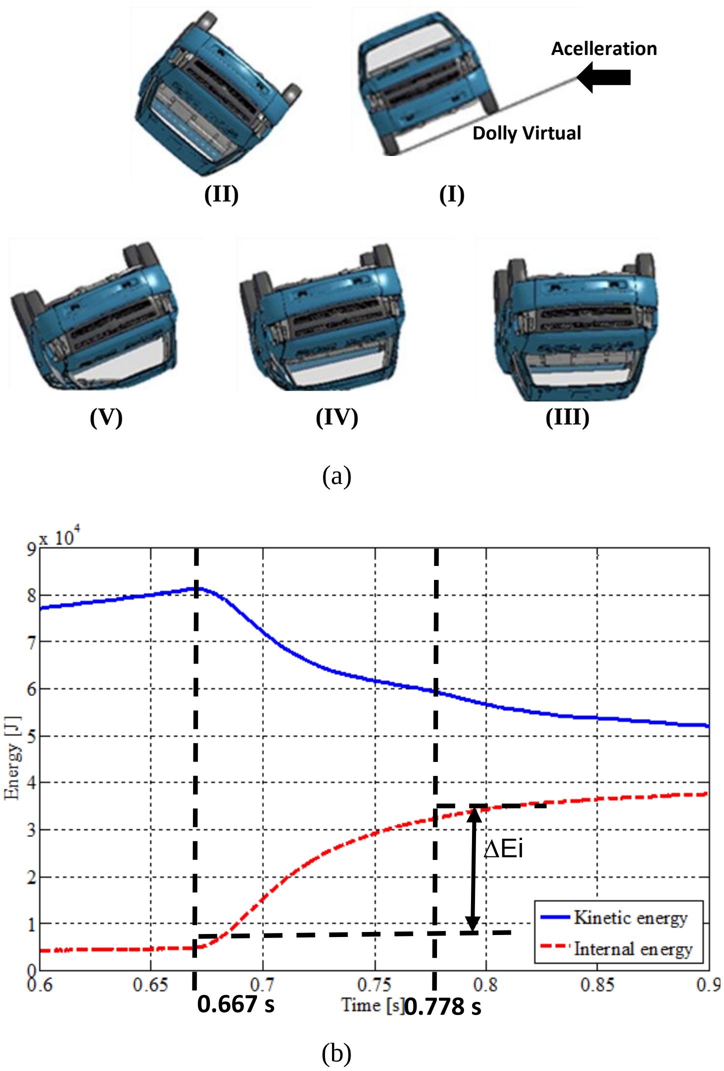


Fig-2:(a) Numerical simulation of the dolly rollover experimental test (b) Estimation of the kinetic and internal energies involved in a dolly rollover test

The translational velocity of the vehicle's CG at the moment of the impact represents an important physical parameter also determined from the virtual simulation of the dolly test. According to the simulation, the resultant of the translational velocity is 6,000 mm/s. In the context of the virtual dolly test simulation, no dummies were considered given that the interest here is not to evaluate occupant injuries. What is under evaluation is the behavior of the pickup truck with respect to a dynamic test concerning mechanical energy transformation.

Thus, taking into account the best estimation of the impact energy (ΔEi = 27 x 103 J) and the resultant of the translational velocity (6,000 mm/s), the plate mass of the virtual test device (Fig. 1) could be estimated at 1.5 tons (by using the kinetic energy equation) moving at 6,000 mm/s for 150ms [13].

According to the authors, the proposed virtual model (Fig. 1) provides a suitable manner to evaluate the efficiency of the external ROPS device against rollover crashes by means of a low cost computational model. Actually, the simulation exclusively considers the moment of the first roof impact on the ground, when it is possible to evaluate the magnitude of the roof structural intrusion and, consequently, to analyze the integrity of the vehicle occupants, according to damage criteria (FMVSS 208 part 571) as will be denoted in section 5.

3.MODELLING INTERIOR COMPONENTS OF THE VEHICLE AND ROPS DEVICE

The interior components such as, the dashboard, the instrument panel (IP), the IP beam, the steering wheel and column, the front and rear seat and the interior trimmings were modelled by FE, because the occupants could collide with the vehicle's interior components during the simulation. The dashboard; IP and centre console; IP beam; steering wheel and column; seat divided in foam, headrest bars, frame and foam fabric cover; seatbelts and interior trimmings components were modelled according to the characteristics shown in Table 1.

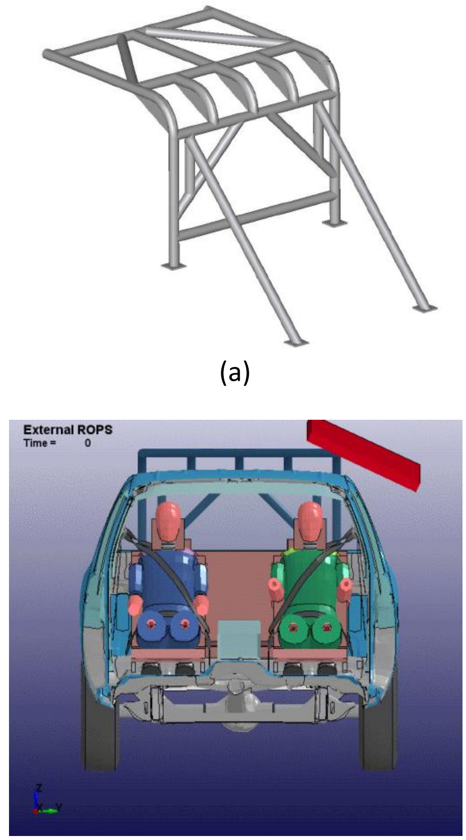
The seats were rather simplified considering that they would not have a great influence on the roof crush impact. The foam cover material was modelled, as shown in Table 1, to simplify the contact with the dummies and get faster runtime simulations. The seatbelts include the buckle and d-ring latch. It can be noticed that the interior trimmings have a direct effect by absorbing part of the energy of impact denoted by roof intrusion into the vehicle compartment.

As said, four dummies were placed into the pickup, two in front and two behind. They are denominated as Hybrid III 50th percentile adult male dummies. The position of the front dummies in the seat is 185.5x10-3 m and 122 x10-3 m (distance to the roof and to the trimming, respectively) and, 187 x10-3 m and 104.5 x10-3 m related to the rear dummies.
The ROPS device was installed external to the cabin of the pickup truck in the numerical simulation. Fig. 3 (a) illustrates a view of the CAD model of the external ROPS made in steel tubes. Fig. 3 (b) depicts the virtual set pickup truck and test setup with the external ROPS safety device.

Table-1: Name of the table

Interior	Type and	Definition in LS-	Properties of

components	size elements	Dyna®	the element
Dashboard, IP and centre console	Shell elements Average size: 60 mm; 3 mm of thickness	Standard plastic with elastic behaviour (*MAT_ELASTIC	Density = 1 kg/m3 Modulus of Young = 10 GPa Poisson's ratio = 0.3
IP beam	Shell elements Average size: 25 mm; 1.8 to 4.2 mm of thickness (depending on the part of the column)	Standard steel with elastic-plastic with strain rate behaviour (*MAT_PIECEWISE_ LINEAR_PLASTICITY - *MAT_024)	Density = 7.89 kg/m3 Modulus of Young = 210 GPa Poisson's ratio = 0.3 Static yield stress = 300 MPa
Steering wheel and column	Shell elements Average size: 14 mm; 1.4 mm and 3 mm of thickness	Standard steel with rigid behaviour (*MAT_RIGID)	Density = 7.89 kg/m3 Modulus of Young = 210 GPa Poisson's ratio = 0.3
Seats	Solid elements for the foam; Beam elements for headrest bars; Shell elements for the frame and foam fabric cover	Seat foam: rigid (*MAT_RIGID with foam properties) Foam cover: standard plastic with only elastic behaviour (*MAT_ELASTIC with plastic properties)	Foam cover: Density = 1 kg/m3 Modulus of Young = 10 GPa Poisson's ratio = 0.3
Seatbelts	Shell elements	Elastic behaviour (*MAT_ELASTIC) Buckle and d-ring latch: Plastic rigid (*MAT_RIGID with plastic properties.	Seatbelt material: Density = 4 kg/m3 Modulus of Young = 50 GPa Poisson's ratio = 0.07
Interior trimmings	Shell elements Average size: 38 mm; 3 mm of thickness	Standard plastic with elastic behaviour (*MAT_ELASTIC	Density = 1 kg/m3 Modulus of Young = 10 GPa Poisson's ratio = 0.3



(a)

(b)

Fig-3:(a) 3D CAD model of the external ROPS (b) front view of the pickup truck with the external ROPS device

The 3D CAD model was analysed using ANSA□ pre-processing software. The modelling method consists of taking the neutral fiber and meshing it using discrete shell elements designated QUAD and TRIAS. The material properties applied to the meshed ROPS have a yield tensile stress of 490 MPa; ultimate tensile stress 590 MPa; modulus of Young 207 GPa and Poisson's ratio 0.3. The ROPS safety device was inserted in the pickup virtual model in LS-Dyna®, the material was considered as elastic-plastic behaviour (*MAT_PIECEWISE_LINEAR_PLASTICITY).

4.DAMAGE CRITERIA FOR VEHICLE OCCUPANTS: STANDARD FMVSS 571.208

The scope of the FMVSS 571.208 is to establish the performance requirements to protect vehicle passengers from death and serious injury in crash accidents. The standard presents specifications with reference to forces and accelerations registered on anthropomorphic dummies in test crashes.

To define some requirements in [11], vehicle occupants are represented by test dummies, such as the Hybrid III 50th percentile adult male, 5 th percentile female, 6-year-old child, 3 year-old-child and 12-month-old CRABI for crash tests (49CFR, Part 572.208, subpart E, O, N, P and R, respectively). In this paper, head and neck injury criteria will be considered for the Hybrid III 50th percentile adult male, thus the test dummy will meet the injury criteria of item S6 in the [11].

4.1 Head Injury Criteria

For the head injury, two criteria will be considered: Peak Head Acceleration at 3 ms (A3ms) and the Head Injury Criteria at 15 ms time intervals (HIC15). Both refer to the resultant acceleration calculated from the output of the dummy head at the center of gravity and they are expressed as a multiple of "g" (gravity acceleration).

However, A3ms provides a value, which shall not exceed 80 g's for any continuous period of more than 3 ms, except for intervals whose cumulative duration is not more than 3 milliseconds [14], [15]. HIC15 is calculated for any time interval between t1 and t2. In this case, the measured time interval for determining HIC15 cannot be more than 15 ms and t1 should be less than t2 during the crash event. Thus, HIC15 shall be calculated by Eq. (1). Considering the Hybrid III 50th percentile adult male, HIC15 shall not exceed 700.

$$HIC15 = \left[\left(\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a_r dt\right)\right]^{2.5} (t_2 - t_1) \qquad \text{Eq.(1)}$$

where a_r is the resultant head acceleration of the dummy head at the center of gravity, given as a multiple of "g".

4.2Neck Injury Criteria

Neck injuries can occur due to some mechanisms that may provoke such trauma. These mechanisms are considered from the biomechanical concepts with an analysis of the force that can act on the cervical column (bending moment, axial compression, axial tension, torsion moment and shear). According to the neck injury criteria in [11] item S6.6, two of these forces are take into account the bending moment, which can be a flexion or extension moment and also an axial effort that can be in compression or tension.

All of these forces can be measured by the dummy upper neck load cell, which represents the human occipital condyle during the crash event. In this paper, this is done by dummies virtually placed in a pickup truck. Depending on the plane that the analysis is carried out on ('XZ', 'YZ' and 'XY'), Nij can be defined as the force combination between axial force and bending moment. According to the coordinate reference system 'Oxyz" positioned on the cervical spine shown in Fig. 4, where axis "y" is perpendicular to the 'XZ' plane, the neck can move to the right and left in plane 'YZ' and forward and backward in plane 'XZ'. Thus two planes are considered 'XZ' and 'YZ' as will be shown in the section5.

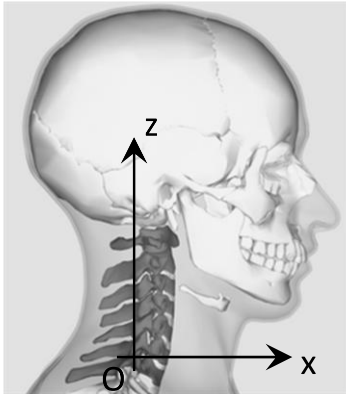


Fig-4:Part of cervical spine with the coordinate system (Adapted from: http://en.wikipedia.org/wiki/Cervical_vertebrae)

The Nij (Eq. 2) represents the neck injury criteria, which is a dimensionless quantity with the maximum value of one. Considering plane 'XZ', the values of 'Fz' (compression and tension) and 'My' measured in the occipital condyle, 'Mocy', that can be in flexion or extension; Nij can have four possible load combinations: tension-extension (Nte), tension-flexion (Ntf), compression-extension (Nce), compression-flexion (Ncf).

$$N_{ij} = \left(\frac{F_z}{F_{zc}}\right) + \left(\frac{M_{ocy}}{M_{yc}}\right) \qquad \text{Eq. (2)}$$

where Mocy is the bending moment measured in the occipital condyle, Fz is the axial force measured in the neck, and Myc and Fzc are the bending moment and axial force critical values established in the standard as shown in Tab. 2.

Table-2: Critical values of bending moment and axial forces usedin the Nij calculation

Critical Values	
Myc (N.m)	**Fzc (N)**
310 (flexion moment)	6806 (tension)

135 (extension moment)	6160 (compression)

Also, the peak values for Fz in tension and compression shall not exceed 4170 N and 4000 N, respectively. The value of the peak or maximum bending moment in extension, 57 N.m, is also considered as a criterion [15].

Table3 presents the maximum values to be adopted in this study/paper according to the FMVSS 571.208 standard and the scientific literature concerning damage criteria for the head and neck.

Table-3: Critical values of bending moment and axial forces usedin the Nij calculation

Damage criteria for head	Maximum value
HIC15	700
A3ms	80g
Damage criteria for neck	**Maximum value**
N_{ij} (N_{te}, N_{tf}, N_{ce}, N_{cf})	1
M_{max}	57 N.m
F_{max}	4000 N (compression) 4170 N (tension)

5.RESULTS AND DISCUSSION

This section aims to present the main results obtained from the safety analysis of the pickup truck occupants using LS-Dyna® software. For this, four virtual instrumented dummies (Hybrid III 50% percentile male) were employed to simulate the four occupants: driver, right front passenger, left rear and rear right, inside the vehicle.

The pickup model was submitted to a roof crush virtual setup as shown in Fig. 1, considering both conditions: with and without an external ROPS device (Fig. 3). The critical values of bending moment and axial forces, and the maximum injury values applied to the head and neck, which were mentioned in previous topic (Tab. 4), will be used to guide the analysis and evaluate the obtained numerical results.

Importantly, chest injury criteria were not verified because during the simulations no contact between the dummies' chest and the instrument panel or frontal seat (for rear occupants) was observed. Considering the symmetry of the pickup and occupants' position, the roof crush simulation was carried out only on the left side.

The first numerical simulation considered the vehicle without ROPS. After, the external ROPS was inserted in the model and the same simulation was performed. Figure 5a and 5b depict the driver and right front passenger dummies inside the vehicle with and without external ROPS, respectively, submitted to the roof crush virtual test. These figures show the maximum intrusion obtained at plane 'YZ' on both configurations, with and without ROPS respectively, during a total time simulation of 0.15 s.

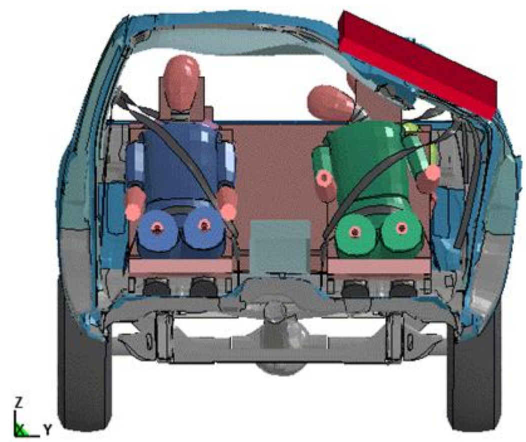
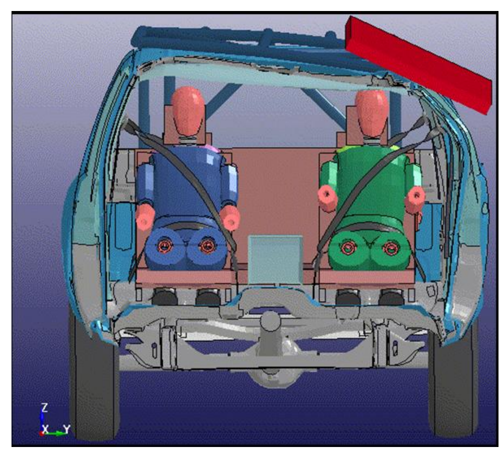


Fig-5a:Maximum intrusion for frontal passengers under roof crush test without ROPS



Fig–5b:Maximum intrusion for frontal passengers under roof crush test with external ROPS

Due to the characteristics of the roof crush test, the right occupants should have low damage criteria values considering that the roof crush impact occurs on the left side. So, it is easy to note that the left occupants (driver and rear left occupant) of Fig. 5b suffer less damage when compared with the same occupants in Fig. 5a. The influence of the ROPS in these results is clearly visible when both figures are analysed together.

Considering the differences of contact between the plate's virtual setup and the vehicle roof's surface during the impact, it is possible to note (comparing Fig. 5a and 5b) that the head of the driver dummy and that of the left rear passenger have different movements in the cabin during the simulation.

Figures 6a to 6c show the intrusion reached in each column (respectively column A, B and C) of the vehicle (considering the driver side or left side) during the entire simulation time.

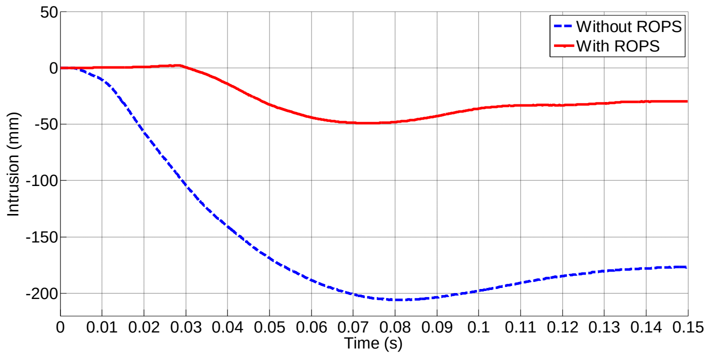


Fig-6a:Intrusion in column A at driver side

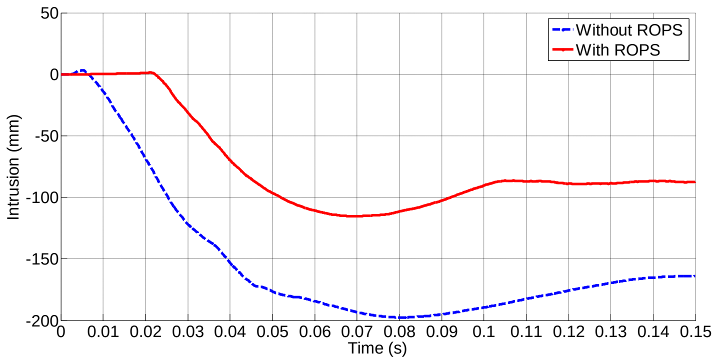


Fig-6b:Intrusion in column B at driver side

The difference between the maximum intrusion in the vehicle in both situations: with and without ROPS which corresponds to 156.97 mm can be seen in Fig. 6a. Fig. 6b reveals that this maximum intrusion difference is 82.1mm. Finally, Fig. 6c shows that the maximum intrusion difference is 126.46 mm. These three illustrations show that the ROPS device absorbs impact energy during the test.

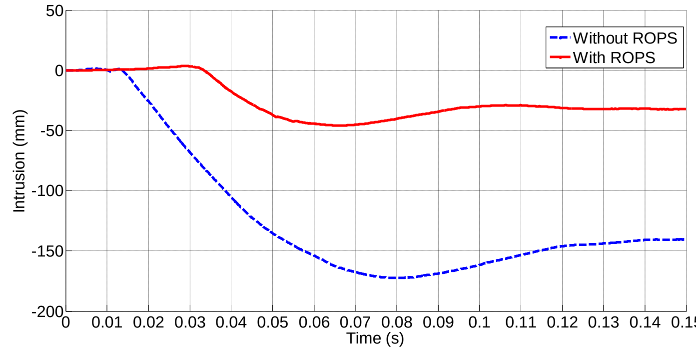


Fig-6c:Intrusion in column C at driver side

In addition to the results presented previously, Fig. 7 shows the energy involved in the rollover event, considering the ROPS device installed externally and not on the pickup truck. The curves related to kinetic and internal energy are shown in the illustration.

The curves of Fig. 7 provide a correct balance of energy, where the kinetic energy of the impact device/roof is transformed into internal energy due to the deformation of the bodywork (considering absence of the ROPS). Considering the ROPS installed in the pickup, the kinetic energy is transformed into internal energy from the bodywork and external ROPS. This explains the higher values of this late curve when compared with the first one. In other words it computes the deformation of the safety device.

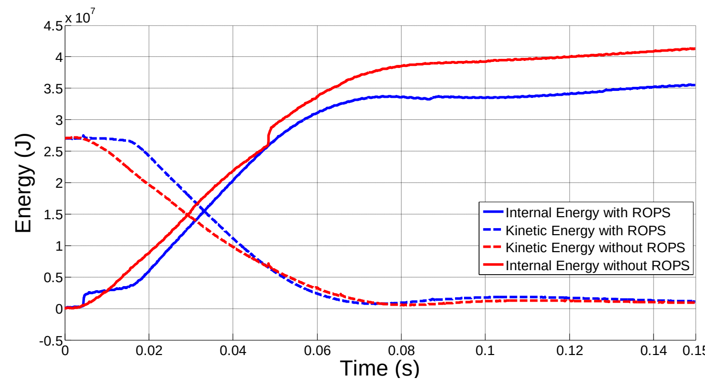


Fig-7:Energy analysis with and without ROPS

The damage criteria evaluations will be conducted for the occupants of the vehicle for both simulations: with and without ROPS. Figure 8a shows the driver head resultant acceleration (where g is the acceleration of gravity) throughout the total time simulation.

Figure 8b shows the same result for the left rear passenger. The damage criteria results for the four occupants was estimated and analysed. So, in this work only the graphic results for the driver and rear left passenger will be shown given that these occupants presented the higher levels of damage in the head and neck. For the other occupants the damage results will be shown in table form.

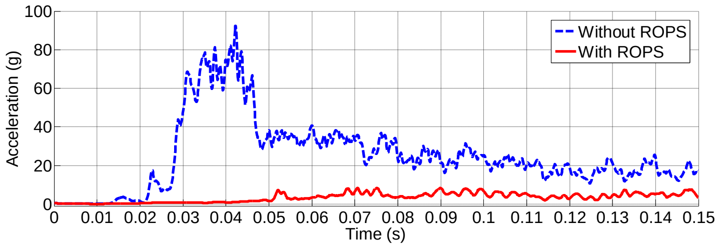


Fig-8a:Driver head resultant acceleration

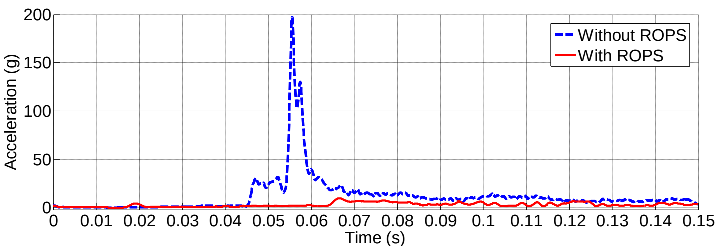


Fig-8b:Rear-left occupant head resultant acceleration

Tables. 4 and 5 show the head injury values estimated for the right and left side occupants, respectively, using the equations presented above and the simulation data. The second column of each table presents the maximum values permitted for each criteria according to theFMVSS 571.208 standard (2008).

Table-4: Head damage criteria estimated of the left side occupants

Head Damage Criteria	Maximum value	Driver		Left rear passenger	
		Without ROPS	With ROPS	Without ROPS	With ROPS
HIC15	700	590.90	1.35	664.70	0.55
A3ms [g]	80	69.86	5.35	102.60	4.80

Table-5: Head damage criteria estimated to the right side occupants

Head Damage Criteria	Maximum value	Right front passenger		Right rear passenger	
		Without ROPS	With ROPS	Without ROPS	With ROPS
HIC15	700	0.29	0.55	0.24	3.80
A3ms [g]	80	3.50	4.80	4.18	12.00

From Fig. 8a, notice that the driver suffers a higher impact (92.34 g) at 0.042 s in the absence of the ROPS. Analyzing Tab. 4, it can be seen that in this configuration (driver without ROPS), the damage criteria for the head is not over the legal limits established by the standard, although the simulated values are very high.

Considering the driver in the absence of ROPS in Tab. 4, the HIC15 values equal to 590.9 was measured in the time interval of t1 = 0.0305 s and t2 = 0.0456 s and A3ms equal to 69.86 g in the time interval of t1 = 0.0397 s and t2 = 0.0427 s. The HIC15 for driver simulation with ROPS was determined in the time interval of t1 = 0.0887 s and t2 = 0.103 s and, the A3ms head acceleration between t1 = 0.146 s and t2 = 0.149 s. The values highlighted in gray in the tables are over the limits established in FVMSS 571.208.

Fig. 8b illustrates the behavior of the left rear passenger in relation to the damage criteria. The left rear passenger is on the impact side, thus he suffers some damage as well as the driver. For Fig. 8b, considering the absence of ROPS, the parameter HIC15 is obtained from the time interval t1 = 0.0547 s and t2 = 0.0582 s and A3ms from t1 = 0.0549 s and t2 = 0.0579 s. In the same figure, considering the ROPS curve, the HIC15 is obtained in the time interval t1 = 0.065 s to t2 = 0.080 s and, the A3ms between t1 = 0.0653 s to t2 = 0.0683 s. Results of the integration for the curve of the head resultant relative to both time intervals is shown in Tab. 4.

It can be noticed in Tab. 4 and 5 that all of the results with ROPS are lower than the damage criteria limits established in the FMVSS 571.208. The results indicate the positive influence of the ROPS device, and it can be seen that the ROPS device is suitable in protecting vehicle occupants during rollover events. This device causes an important reduction in head acceleration. The acceleration A3ms, for example, is 7.7% of the A3ms value without ROPS (69.86 g), considering the driver occupant.

From the analysis of Tab. 5, it is possible to note that the values for the head damage criteria applied to the right front and rear right occupant are not exceeded, thus they do not suffer any damage. Notice the accelerations are not zero, because the bodywork displacement of the seats is felt.

The neck damage will be analyzed for the four occupants. Figure 9a shows the driver neck resultant force during the entire simulation time considering both configurations: with and without ROPS. Figure 9b shows the same result to rear-left occupant. The neck resultant moment is shown in Fig. 10a and 10b to driver and rear-left occupant, respectively.

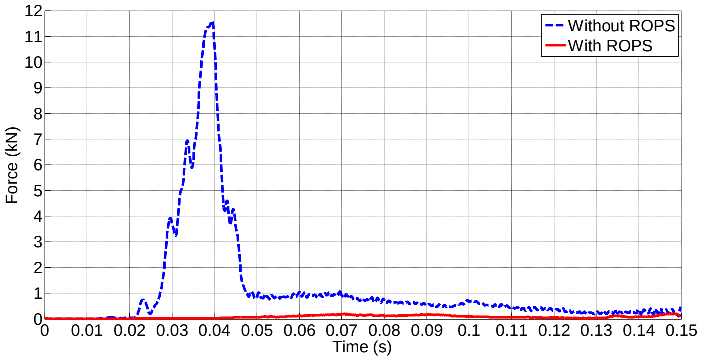


Fig-9a:Driver neck resultant force

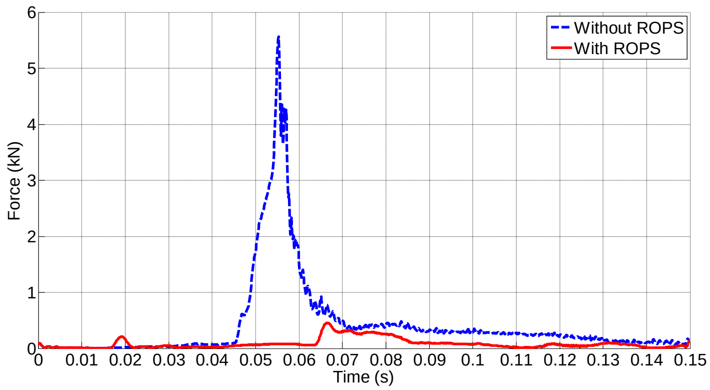


Fig-9b:Rear-left occupant neck resultant force

The Figures 9a to 10b are used to estimate the parameters of Tab. 6, in addition to the equations presented in the previous topic. Thus, the maximum values of Nij in these planes, considering combinations of axial force and bending moment are shown.

The graph results used to estimate these parameters for the right side occupants are not shown, because the values are so low when compared to the left side occupants. Listed in Tab. 7 is the estimated neck damage parameters for the rightt side occupants. The maximum force in Tab. 6 and 7 is relative to compression.

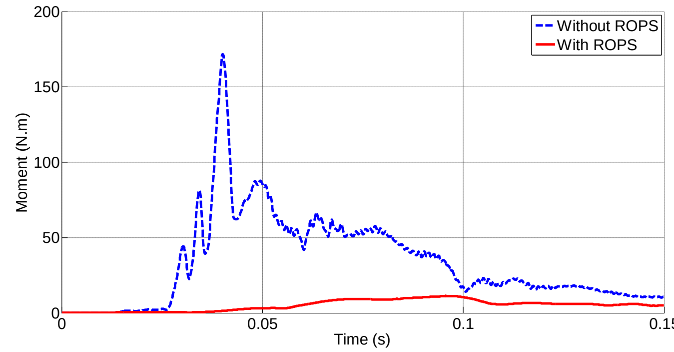


Fig-10a:Driver neck resultant moment

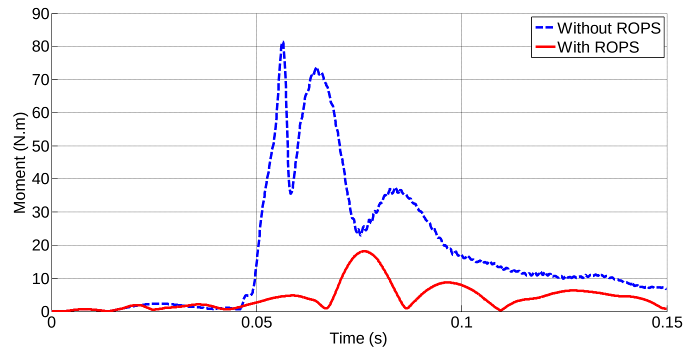


Fig-10b:Rear-left occupant neck resultant moment

From Tab. 6, for the driver, without ROPS, the maximum neck force and moment are 11,600 N and 171.7 nm, respectively. Both are over the values established in FMVSS 571.208. In fact, the maximum force is almost three times the maximum force in compression. Damage criteria regarding head acceleration (HIC15 and A3ms) have a minor influence on the driver. On the other hand Nij, Fmax and Mmax are more relevant for this occupant.

Table-6: Head damage criteria estimated of the left side occupants

Neck Damage Criteria	Maximum value	Driver		Left rear passenger	
		Without ROPS	With ROPS	Without ROPS	With ROPS
F_{max} [N]	4000	11600	210	5560	242
M_{max}[N.m]	57	171.7	11	81	7
N_{te_XZ}	1	0.3	0.05	0.25	0.05
N_{tf_XZ}	1	0.3	0.01	0.01	0.03
N_{ce_XZ}	1	0.2	0.05	0.25	0.12
N_{cf_XZ}	1	2.8	0.06	1.4	0.11
N_{te_YZ}	1	0.4	0.03	0.25	0.02
N_{tf_YZ}	1	0.1	0.02	0.01	0.03
N_{ce_YZ}	1	0.3	0.07	0.20	0.12
N_{cf_YZ}	1	3.2	0.05	1.5	0.10

Considering the same configuration (without ROPS) for the rear-left passenger, the maximum force and moment are lower than those suffered by the driver, but they are still over the limits established by the standard. However, the left rear occupant suffers a force of compression, Fmax, 15% greater than that suffered by the driver.

In Tab. 7 for the right front passenger, notice that although the neck does not suffer any damage, the force and moments are different from zero because it feels the bodywork displacement of the seats, similar to head damage behaviour.

Table-7: Neck damage criteria estimated for right side occupants

Neck Damage Criteria	Maximum value	Right front passenger		Right rear passenger	
		Without ROPS	With ROPS	Without ROPS	With ROPS
F_{max} [N]	4000	158	242	250	500
M_{max}[N.m]	57	6	7	10.4	20
N_{te_XZ}	1	0.01	0.005	0.01	0.04
N_{tf_XZ}	1	0.01	0.01	0.01	0.04
N_{ce_XZ}	1	0.01	0.03	0.01	0.10
N_{cf_XZ}	1	0.01	0.07	0.01	0.13
N_{te_YZ}	1	0.01	0.01	0.01	0.03
N_{tf_YZ}	1	0.01	0.01	0.01	0.02
N_{ce_YZ}	1	0.01	0.09	0.01	0.11
N_{cf_YZ}	1	0.01	0.03	0.01	0.12

From Tab. 6, it can be seen that the value of Ntf in planes 'XZ' and 'YZ' with ROPS device are greater than those without the protection. When the plate of the virtual setup touches the ROPS device it seems that it provokes a greater tension-flexion in the "y" (plane 'XZ') and "x" (plane 'YZ') directions. In addition, this contact causes a small displacement of the seats after the plate's impact as can be seen in the simulation. However, the simulation carried out with the ROPS device leads to very small values of Nij.

Table 7 shows that the right side occupants do not suffer any neck damage and the estimated values are lower than the values established in the standard.

6. CONCLUSION

It seems that the use of the LS-Dyna® software to carry out this study is suitable, because it allows considering non-linear behaviour compatible with the roof crushing and damage criteria evaluation involving the dummies.

The intrusions in column "A" (front), "B" (middle) and "C" (rear) are greatly reduced with the external ROPS device installed on the pickup truck. Although there is some intrusion on the left side, it is not enough to cause any damage to the left occupants according to the standard requirements (FMVSS 571.208).

The internal energy absorbed by the external ROPS is about 13. x 106 J, which means that it is absorbing almost 50% of the impact device total energy 27.0 x 106 J. As for the results concerning the intrusion, it seems sufficient to protect the occupants.

Comparing the damage criteria maximum values, it is clear that the proposed external ROPS shows good performance protecting the vehicle occupants, mainly the right side one.

The numeric simulation showed that the driver suffers an intense impact when the vehicle is not equipped with the ROPS. The parameters: Fmax, Mmax, Ncf exceeded by almost three times the legal limits. The parameters HIC15 and A3ms do not exceed the maximum values but they are not so far from them. The rear left passenger suffers elevated damages too due the fact that he is on the same side of the impact in which the head and neck forces are over the permitted maximum values. When the ROPS is considered in the numeric simulation the results obtained show that all injury criteria are below the maximum acceptable values.

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