Chapter 2
Integrity Assessment of Pickup Vehicle Occupants in Rollover Situation Considering Internal ROPS Device: A Numerical Approach

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Abstract The rollover accidents represent a major cause of injuries and death of vehicle occupants and they are also higher among light trucks than passenger cars. The pickup trucks have important applications in mining scenario where protective structures are required to provide safety in case of a rollover during engineering works. The use of safety devices commonly referred to as ROPS-Rollover Protection System in this kind of vehicle has been shown to be an effective manner to mitigate some of the effects caused by this event, ensuring safety and integrity of passengers. Such device can be constructed using steel bars which constitute a framework to be added into the vehicle, like a cage, in order to minimize the structure intrusion in rollover accidents. In this context, this paper makes up the assessing the integrity of pickup truck occupants in rollover events of a priori designed and proposed ROPS. For this a numerical simulation is carried out based on the experimental Roof Crush Test (FMVSS-216 regulation) using the software LS-Dyna® which uses Finite Element Method (FEM). The criteria for neck and head injuries are established in the standard FMVSS-208. The analyses were conducted comparing the vehicle model equipped with and without internal ROPS.

Keywords Rollover • ROPS • Pickup • Integrity • Simulation

2.1 Introduction

According to NHTSA—National Highway Traffic Safety Administration [1], the rollover crashes are responsible for a large number of serious injuries and fatalities compared to other crash modes. Such injuries can cause serious consequences mainly in cervical spine and neck/head [2], thorax and chest [3, 4] and torso region [5]. The risk factors associated to related injuries and to the rollover phenomenon were identified by scientific studies [2, 6] as roof intrusion, the number of quarter turns, far side seating position, vehicle type and occupant physiological characteristics.

Engineering and agricultural machines are vehicles which have large index of rollover accidents, particularly lateral rollover, because of their difficult working conditions, high and unfixed centroid, as well as poor stability [7]. There are international standards [8] which recommends the installation of protective structures, called ROPS, in order to minimize the risk to the driver or operator during a rollover accident.

The Rollover Protective Structures (ROPS) are used in off-highway vehicles to protect operator in case of accidents involving overturning of vehicle. The role of a ROPS is to absorb the energy of Rollover without violating the protected operator zone. The performance of a ROPS is determined by its ability to absorb energy under prescribed loading conditions. The performance depends upon design parameters, such as tube thicknesses, material grades, ROPS tube cross-sections, etc., that define the structure [9].

Special attention must be given to rollover accidents in mining fields. In this environment is usual to have engineering machines, like earth-moving vehicles, and pickup trucks which are used to carry freight and workers through the mine

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operating on sloping and uneven terrain (above ground and underground). Both vehicles have large probability to suffer rollover accidents due to the described operation conditions. The use of the ROPS in these is highly recommended. Although there are not statistics about human injury considering rollover accidents with these kind of vehicles.

The ROPS design involves two main steps: the mechanical study of the ROPS structure and the integrity evaluation of the vehicle occupants due to the safety system performance. The first one needs to guarantee that the ROPS make a big elastic–plastic deformation, thereby absorbing the kinetic energy generated by the rollover motion. The ROPS must be able to absorb the kinetic energy mainly through a plastic hinge (plastic deformation occurs in particular areas creating weaknesses about which the structure bends) formed in the local area [9]. The second step is performed by dynamic tests in which the biomechanical loads measured by anthropomorphic test devices are compared against injury assessment reference values to predict the level of occupant safety and injury. The tests are performance based and codified into vehicle safety standards [10].

Such dynamic tests commonly utilizes real vehicle in rollover tests which is closest to the actual situation in the rollover accident [11]. This is a basic and intuitive method of comprehensively evaluating vehicle safety performance. However, its repeatability is poor and each test needs large amounts of manpower, money, and time. The static loading test method [12] is less demanding than an actual vehicle rollover test, but it is still costly and time-consuming. In order to avoid the listed disadvantages, a good solution is use computer simulation in combination with experimental tests. In this work a numerical approach is shown.

This paper aims to use simulation analysis methods in order to verify the effectiveness of a designed internal ROPS related to the human injury mechanism during a dynamic rollover accident. The considered vehicle is a pickup truck with four dummies inside it. The numerical simulation is carried out based on the experimental Roof Crush Test [12] using the software LS-Dyna®. Prior papers published by the authors [13, 14] describe in detail the finite element (FE) model of the pickup truck and show the numerical validation using impact energy analysis between both rollover models: the dynamic Dolly Rollover test [11] and the quasi-static Roof Crush test [12]. The authors investigated too the rollover accident effect in the dummies when used a external designed ROPS [14]. The roof crush device model is adopted in [14] and in this paper in order to reduce computational time. The criteria for neck and head injuries are established in [10]. The analyses were conducted comparing the vehicle model equipped with and without internal ROPS.

2.2 Roof Crush Numerical Model

The Roof crush test is regulated by the American standard FMVSS-216 [12] which establishes strength requirements for the passenger compartment roof in order to reduce deaths and injuries due to the crushing of the roof into the occupant compartment in rollover crashes. In practice this standard establish a quasi-static test although it simulates experimentally rollover accident. This standard applies to passenger cars, trucks and buses with a gross vehicle weight rating (GVWR) of 2,722 kg or less.

This standard describes the test device like shown in Fig. 2.1. The test device is a rigid unyielding block whose lower surface is a flat rectangle measuring 762 mm × 1,829 mm. It establishes that the lower surface of the test device must not move down more than 127 mm. The applied force in Newton is equal to 1.5 times the unloaded vehicle weight of the vehicle, measured in kilograms and multiplied by 9.8 m/s^2.

The roof crush setup shown in Fig. 2.1a was modeled by FE method as well the pickup truck model [13, 14]. The pickup base model used in this work is available in the website (http://www.ncac.gwu.edu/vml/models.html) of the National Crash Analysis Center (NCAC). The NCAC developed this vehicle finite element model for use with LS-Dyna® software. The pickup has the following characteristics: 2007 model year, 1500 2WD pickup truck, 4 door crew cab short box pickup truck; 4.8L V8 engine; 4-speed automatic transmission, tires P245/70R17, wheelbase of 3.664 m. The CG (rearward of front wheel) is 1.664 m and it has a weight of 2,617 kg.

The roof crush numerical model is shown in Fig. 2.1b (measures in millimeters). The original NCAC pickup truck model was re-meshed reducing the number of elements to 153,616 (number of nodes equal 160,057) by increasing the time step from 1×10^{-6} to 2.5×10^{-6} s. The elements have average size of 28×10^{-3} m. In order to evaluate the occupants integrity only the device test setup was based in the FMVSS-216.

The boundary conditions of the simulations (plate mass, translation velocity of the impact device and stored impact energy) was estimated prior using the dolly rollover simulation and impact energy analysis [13]. It emphasizes the aim of this work which consists in to evaluate occupants integrity resulting from roof impact in the ground, using a low cost computational model (roof crush model instead dolly rollover model and reduced FE model). The inputs to the roof crush simulation is: plate mass of $1{,}500 \times 10^3$ kg, velocity of $6{,}000 \times 10^{-3}$ m/s, 27×10^3 N m.

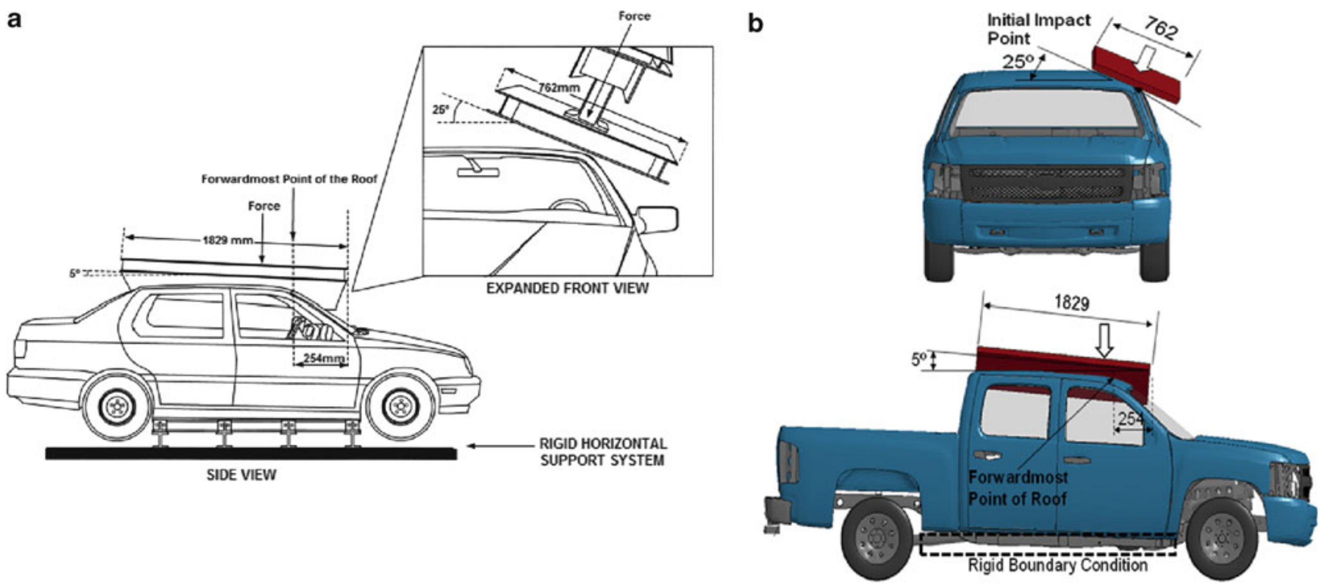

Fig. 2.1 (**a**) Test device orientation for roof crush test [12]. (**b**) Roof crush setup used for numerical simulation

In order to insert the dummies in the interior vehicle, the interior components of the vehicle must be considered in the modeling. The plastic components like Dashboard, IP and centre console, were modeled with shell elements. The seats where modeled with solid elements for the foam, beam elements for the headrest bars and shell elements for the rest (frame and foam fabric cover). The interior trimmings will have a direct effect absorbing part of the impact of the roof intrusion to the dummy heads and they were modeled with shell elements of 3×10^{-3} m thickness.

The considered dummies in this work is male Hybrid III 50 % percentile. The dummies position is highly important in this kind of analysis. For the front dummies the established distances were: distance to roof = 185.5×10^{-3} m and distance to roof trimming = 122×10^{-3} m. For the rear dummies the same distances were: distance to roof = 187×10^{-3} m and distance to roof trimming = 104.5×10^{-3} m.

2.2.1 Numerical Model with Internal ROPS

The internal ROPS considered here were design prior using solid mechanics concepts. So the aim of this work is not to focus in the ROPS design. Here the ROPS have already been designed and it will be analyzed in terms of efficiency for safety purposes and occupants integrity. It was modeled using FEM.

From geometry file of the ROPS, the neutral fiber (surface of the part in the middle of the thickness) was used to mesh it in discrete shell elements. The elements size is 18 mm and it thickness is 9 mm. The shell formulation is the Belytschko-Tsay with five integration points. The main material properties are: Modulus of Elasticity = 207 GPa and Poisson's ratio = 0, 3.

Figure 2.2a shows the FE model of the internal ROPS considered. Figure 2.2b shows the roof crush FE model with dummies (drive and co-drive) and the internal ROPS (grey color tubes inside the pickup). In the numerical simulations were considered the four dummies: drive, co-drive, left and right occupants.

2.3 Integrity of Occupants: Head and Neck Injury Criteria

This topic will discuss the criteria involved in respect to damage and injuries involving occupants of vehicles in case of accidents. In this work two body regions will be considered: head and neck. In order to evaluate head injuries the criteria *HIC15* (Head Injury Criteria) and *A3ms* (Head Peak Acceleration at 3 ms) were used. The parameters: Normalized Neck Injury Criteria (N_{ij}), Peak Moment (M_{max}) and Peak Force (F_{max}) were used to evaluate neck injuries. These are based on standard FMVSS 208 [10] with exception of *A3ms* and M_{max} which were removed from the current FMVSS 208 but classical papers [15, 16] show that these two parameters are important to evaluate head and neck injuries. In the next topics each criteria is defined.

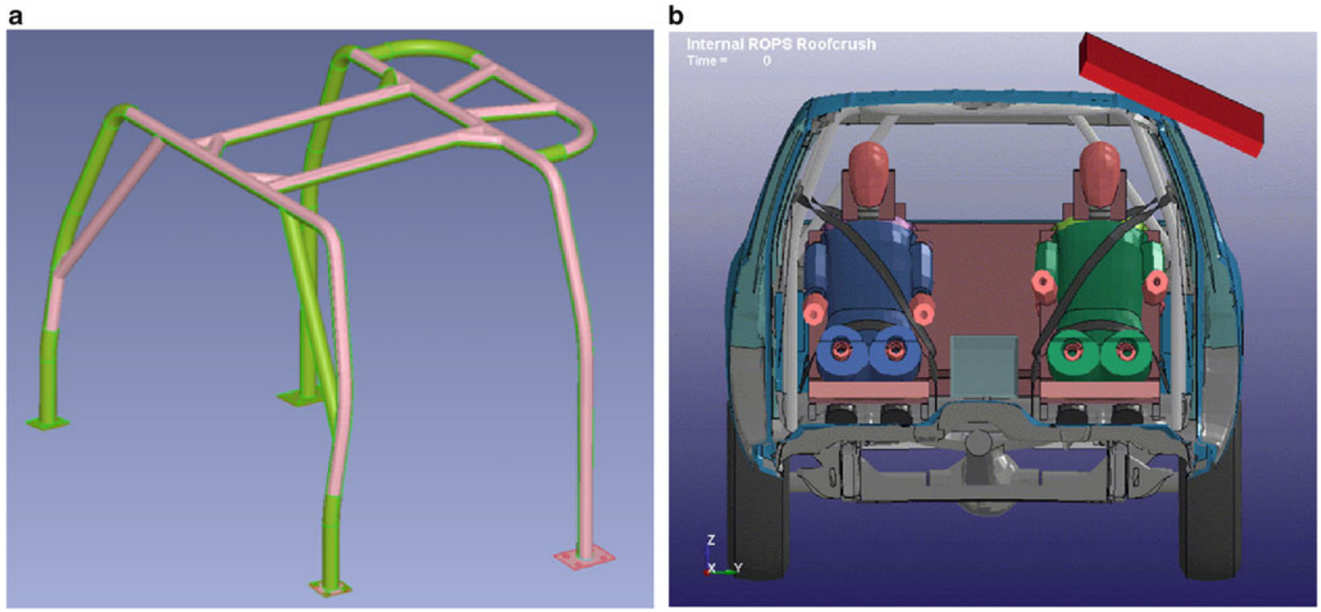

Fig. 2.2 (**a**) FE model of the internal ROPS. (**b**) Roof crush FE model with dummies and the internal ROPS

2.3.1 Head Injury Criteria (HIC15)

For any two points in time, t_1 and t_2, during the accident event, which are separated by not more than a 15 ms time interval and where t_1 is less than t_2, the *HIC15* shall be determined using the resultant head acceleration (a_r) at the center of gravity of the dummy head, and, expressed as a multiple of the acceleration of gravity and shall be calculated using Eq. (2.1). The maximum calculated *HIC15* value shall not exceed 700 for male Hybrid III 50 % percentile.

$$HIC = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a_r(t)dt\right]^{2,5} \tag{2.1}$$

2.3.2 Head Peak Acceleration at 3 ms (A3ms)

According to [15] the resultant head acceleration (a_r) shall not exceed 80 g's (where $g = 9.8$ m/s^2) for more than 3 milliseconds (ms). Peak acceleration values must last 3 ms. This requirement has reasons of measurement technique and is supported by the assumption that decelerations of shorter duration do not have any effect on the brain.

2.3.3 Normalized Neck Injury Criteria (N_{ij})

The estimative of N_{ij} is obtained from Eq. (2.2).

$$N_{ij} = \frac{F_z}{F_{zc}} + \frac{M_{ocy}}{M_{yc}} \tag{2.2}$$

where: F_z is the axial force [it can be either in tension (t) or compression (c), corresponding to index i] and M_{ocy} is the occipital condyle bending moment [it can be either in flexion (f) or extension (e), corresponding to index j] which they shall be measured by the dummy upper neck load cell for the duration of the accident event; F_{zc} and M_{yc} are values defined in the

Table 2.1 Maximum values for the considered injuries criteria

Injury criteria	Maximum value
HIC15	700
A3ms	80 g's
N_{ij} (N_{te}, N_{tf}, N_{ce}, N_{cf})	1
F_{max} *compression/tension*	4,000/4,170
M_{max}	57 N m

standard FMVSS 208 [10]: $F_{zc} = 6{,}806$ N when F_z is in tension; $F_{zc} = 6{,}160$ N when F_z is in compression; $M_{yc} = 310$ N m when a flexion moment exists at the occipital condyle; $M_{yc} = 135$ N m when an extension moment exists at the occipital condyle.

At each point in analysis time, only one of the four loading conditions (tension/extension—N_{te}, tension/flexion—N_{tf}, compression/extension—N_{ce} or compression/flexion—N_{cf}) occurs and the N_{ij} value corresponding to that loading condition is computed and the three remaining loading modes shall be considered a value of zero. None of the four N_{ij} values shall exceed 1.0 at any time during the event.

2.3.4 Neck Peak Force (F_{max})

Two conditions is available for this parameter. For the neck under extension the tension force measured at the upper neck load cell shall not exceed 4,170 N at any time. If the neck is under compression force, the measure made in the same place as cited in the prior sentence shall not exceed 4,000 N at any time.

2.3.5 Neck Peak Moment (M_{max})

The maximum occipital condyle extension bending moment measured at the upper neck load cell shall not exceed 57 N m. Tolerance levels for flexion and extension bending moments were based on sled tests conducted on volunteers and cadaver subjects [16]. Volunteer tests provided data up to the pain threshold, and cadaver tests extended the limits for serious injuries. Ligamentous damage occurred in a small stature cadaver subject at an extension moment of 35 ft-lbs. This value was scaled up to an equivalent 50 % male level of 42 ft-lbs (57 N m).

Table 2.1 summarizes the injuries criteria used in this work and their acceptable limits.

2.4 Simulation Results Considering Dummies and Internal Rops

The methodology adopted was: firstly the roof crush simulation was conducted without the ROPS and all five injury criteria described in item 3 were evaluated for each dummy. After, the internal ROPS which was previously designed were inserted in the same pickup truck FE model and the same numeric evaluation was followed. The initial conditions for the roof crush simulation are described in item 2. It is important to highlight that the mechanical design of the internal ROPS was done using CAD software and the principles of solid mechanics as well as material science theory.

From roof crush simulation the Fig. 2.3a, b show the resultant intrusion in the numerical model in the last impact instant considering absence of ROPS (higher intrusion is reached at t = 100 ms) and the insertion of the ROPS (higher intrusion is reached at t = 45 ms) respectively. 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. So, it is easy to note that the left occupants (driver and rear left occupant) of Fig. 2.3b suffers less damage when compared with the same occupants of Fig. 2.3a. The influence of the ROPS in these results is clearly visible when we analyze both figures.

In order to estimate the injury criteria of item 3 the software Matlab® was used for data pos-processing. The result data were obtained from each virtual sensor settled in the dummies. The estimated results may prove that the left two occupants are the most affected by the impact, which testify this same affirmation based on Fig.2.3 analysis. The results show that the right two occupants have injury criteria values below the limits established by FMVSS 208 considering both situations: without and with ROPS. Due to space constraints in this work will be present the injury criteria values (Table 2.2) for only the two left occupants: driver and rear left occupant. Note that the grey filled cells in Table 2.2 corresponds to parameters that had it value above the limit established in Table 2.1.

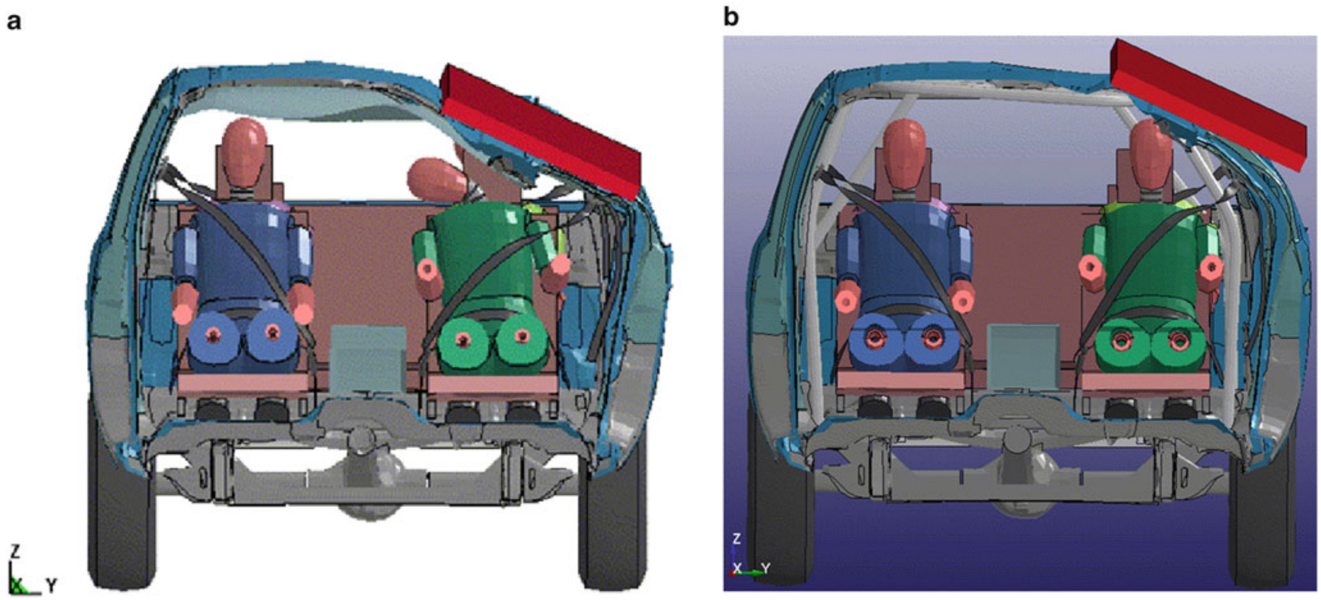

Fig. 2.3 (**a**) Impact intrusion without ROPS. (**b**) Impact intrusion considering internal ROPS

Table 2.2 Injury criteria values for driver and rear left occupant

	Driver		Rear Left Occupant	
Injury Criteria	Without ROPS	With ROPS	Without ROPS	With ROPS
HIC15	591	3	664.7	1.6
A3ms	70 g's	9.4 g's	102.6 g's	8.1 g's
N_{te} (plane XZ)	0.3	0.06	0.25	0.04
N_{tf} (plane XZ)	0.3	0.03	0.01	0.02
N_{ce} (plane XZ)	0.2	0.06	0.25	0.07
N_{cf} (plane XZ)	2.8	0.12	1.4	0.11
N_{te} (plane YZ)	0.4	0.03	0.25	0.03
N_{tf} (plane YZ)	0.1	0.02	0.01	0.02
N_{ce} (plane YZ)	0.3	0.14	0.2	0.11
N_{cf} (plane YZ)	3.2	0.10	1.5	0.08
F_{max} Compression	11600 N	457 N	5560 N	411 N
M_{max}	171.7 Nm	12 Nm	81 Nm	11 Nm

From analysis of Fig. 2.3a and Table 2.2 (second column) it is possible to note that the driver suffers an intense impact when the vehicle is not equipped with the ROPS, although the head acceleration (*HIC15* and *A3ms*) is not over the legal limits, but it is not so far to them. Besides, the neck force (F_{max}) and moment maximum peak limits (M_{max}) exceeded by almost three times the maximum values of Table 2.1. The compression-flexion normalized neck injury criterion (N_{cf} in the plane XZ and YZ) is also almost three times the allowable limit. Due to the rear left passenger is in the impact side so he suffers high damage too when compared with the other occupants. The forces considered in his head and neck (column 4 in Table 2.2 are lower than the suffered by the driver but still quite high, around twice the limits established in Table 2.1. When the results obtained with the inserted ROPS are analyzed (columns 3 and 5 in Table 2.2) we can note that all criteria are below the maximum values of Table 2.1.

In order to analyze the obtained results in time domain the Figs. 2.4 and 2.5, from *a* to *c*, show the three damage parameters: head resultant, neck force resultant and neck moment resultant to the driver and rear left passenger respectively. Note in these figures that the impact time is from 0.022 to 0.048 s. The last figure (Figs. 2.4d and 2.5d) is the intrusion occasioned by the impact device in millimeters. It is the down displacement of the vehicle roof from its application. While the maximum front intrusion is about 200 mm, the maximum rear intrusion is about 175 mm considering the vehicle without ROPS, so it is expectable to obtain more damage in the driver than in the left-rear passenger as the damage criteria showed.

Still analyzing Figs. 2.4d and 2.5d, when the internal ROPS is inserted in the vehicle the maximum front intrusion is reduced to 80 mm and the maximum rear intrusion to 50 mm. It concludes that the design internal ROPS may reduce the intrusion in the driver position about 40 % and in the rear-left about 29 %. The most important aspect is that the internal ROPS keep all injuries criteria below the limits.

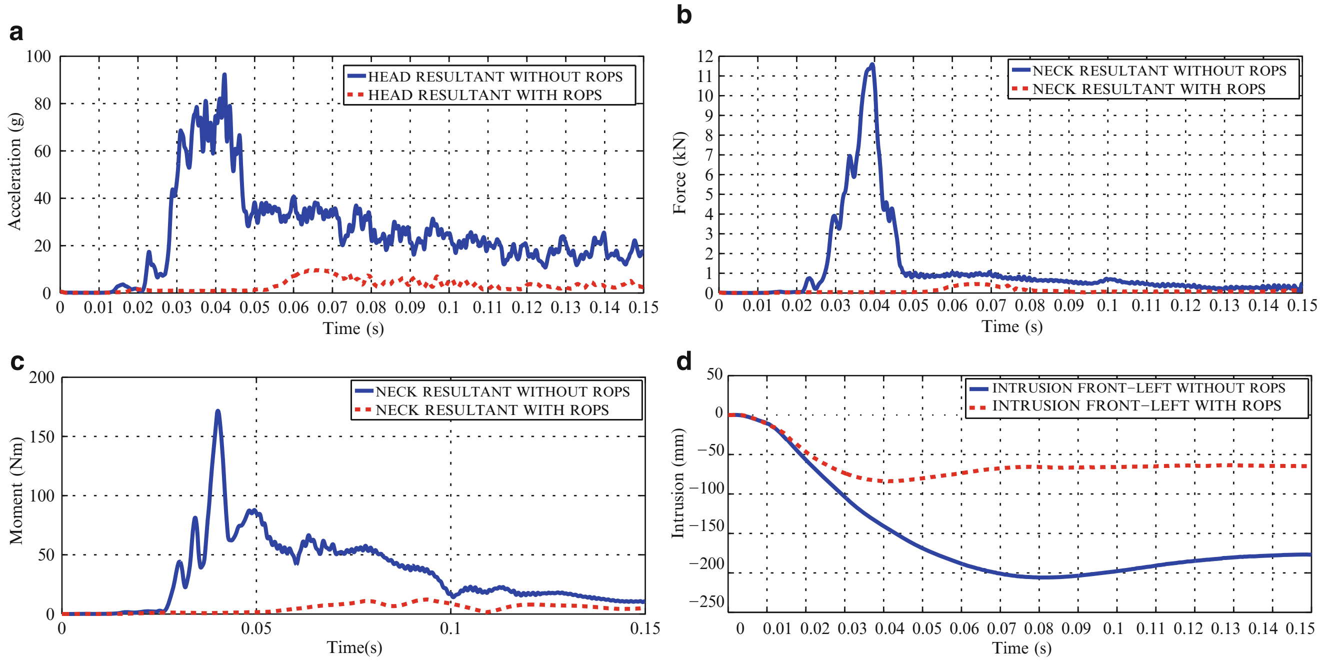

Fig. 2.4 Time evaluation of damage criteria in the driver dummy with and without internal ROPS

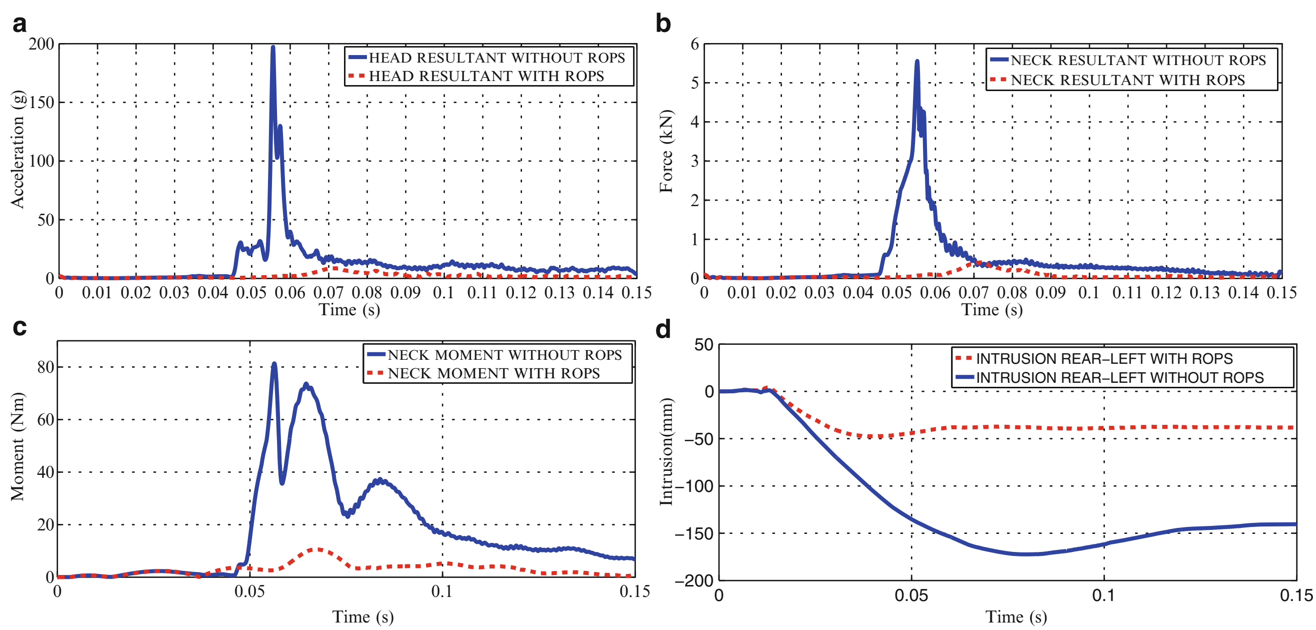

Fig. 2.5 Time evaluation of damage criteria in the rear-left dummy with and without internal ROPS

Figure 2.6 shows the energy behavior during the roof crush simulation in time domain considering the vehicle with the ROPS. There are two curves in this figure: the internal energy and the kinetic energy due to the impact device. The internal energy is caused by the deformation of the ROPS when occurs the impact, it is the absorbed energy. Analyzing Fig. 2.6 we can note that the ROPS internal energy maximum value is 0.82×10^7 mJ at 0.04 s (dashed black curve). It represents the 30 % of the total impacting energy (2.7×10^7 mJ) represented by the blue curve. The remaining impacting energy is absorbed by the vehicle bodywork. There is also some kinetic energy returned to the impact device due to the elastic deformation of the bodywork, justifying why the kinetic energy increases a bit from 0.045 s.

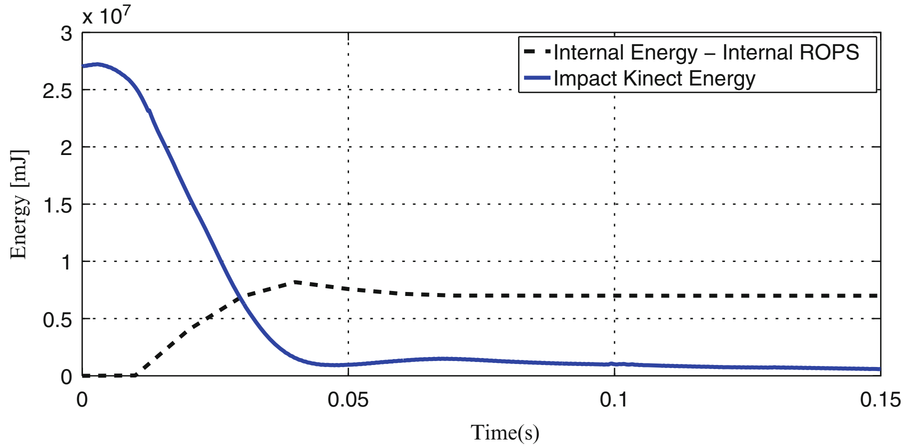

Fig. 2.6 Energy analysis of the internal ROPS

2.5 Conclusions

Comparing the injuries criteria maximum values and these values estimated from numeric roof crush simulation is clear that the proposed internal ROPS has a good performance protecting the vehicle occupants meanly 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: F_{max}, M_{max}, N_{cf} exceeded by almost three times the legal limits. The parameters *HIC15* and *A3ms* not exceed the maximum values but they is not so far to them. The rear left passenger suffers high damages too due to he is in the same side of the impact in which the head and neck forces are around twice 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 values.

Analyzing the intrusion occasioned by the impact device, the vehicle without the ROPS has the maximum front intrusion about 200 mm and the maximum rear intrusion is about 175 mm. When the internal ROPS is inserted the maximum front intrusion is reduced to 80 mm and the maximum rear intrusion to 50 mm. A intrusion reducing of 40 % is obtained in the driver position and about 29 % in the rear-left occupant. The most important aspect is that the internal ROPS keep all injuries criteria below the limits.

The energy analysis showed that the maximum value of the ROPS internal energy represents the 30 % of the total impacting energy. The remaining impacting energy is absorbed by the vehicle bodywork.

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