Potential Thoracic Injuries in a Rollover Crash Reproduction

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ABSTRACT - Most rollover studies have been focused on head and spinal injuries, while thoracic injuries, which correspond to one third of belted rollover injuries based on several data sets, have not been fully addressed. The thorax injuries lack the understanding of the injury mechanism in far-side rollover crashes. An accompanying paper focused on reproducing the exterior damage of a vehicle from a real-world crash accident and approximated the initial conditions required to perform this study.
The belted Hybrid III 50th percentile male anthropomorphic test device was used in the simulation. It reveals the potential for chest injuries that can occur during a rollover. In addition, the center console has been added as a supplementary source of chest injury. This injuring contact is caused by a rapid excursion of the upper body across the vehicle that results from an abrupt reduction in the vehicle's angular velocity during wheel contact with the ground. The review of previous full-scale tests reveals that thoracic injury mechanisms are completely reasonable.

Keywords: thorax injury, rollover, finite element simulation, LS-DYNA, vehicle crash safety, crashworthiness.

INTRODUCTION

This study simulates a Hybrid III 50th percentile male anthropomorphic test device (ATD) in a damage reproduction rollover accident using finite element methods. Generally, rollovers are complex crashes since they have several initial conditions that each alone affects the outcome and overall behavior of the crash. These variables include: vehicle position (yaw, pitch, and roll angles); angular velocity and its rotation axis; planar (horizontal) speed and its direction; vertical speed, crash environment, and vehicle roof strength and characteristics. Additionally, the dummy position, restraint system and other factors affect the dummy kinematics, injury measurements and outcome of the rollover. These uncertainties along with their dynamic effects during the rollover are all sources of challenges that the rollover community has been facing for decades.

Researchers have advanced rollover understanding, roof crush and injury mechanisms to the head and spine over the years. Although, thoracic injuries correspond to one third of serious injuries for belted occupants involved in rollovers, there is a lack of research to develop an understanding of chest injury causation in rollovers. This paper addresses only the probable occupant's chest injuries for a damage reproduced real-world case that was addressed in a sister paper.

The research objective was to determine the potential thoracic injuries from a vehicle crash damage reproduction case. The approach is to perform occupant simulation for a complete roll and correlate the thoracic injury to the real-world case that are most likely to produce such an injury.

BACKGROUND

Rollover accidents account for only 2.4% of all vehicle crashes, but account for a disproportionate 33% of passenger vehicle occupant fatalities [1]. The Crashworthiness Data System (CDS), a database of the National Automotive Sampling System (NASS), years 1995 through 2005, shows that for belted front seat occupants, 33% of MAIS3+F injuries occur in single vehicle rollovers without planar impact while the remaining 67% occur in rollovers with minor or moderate planar impact damage [2]. The MAIS3+F population refers to occupants who sustain injuries with classifications of serious (MAIS 3), severe (MAIS 4), critical (MAIS 5), or maximum (MAIS 6) where the fatalities were added to the survivor data at the MAIS 6 level. The percentage of MAIS3+F injured by body region with severe damage from planar impacts excluded, reveals that 33% is attributed to the Head, Face, Neck, and Spine, 37% is attributed to the Chest and Abdomen, and 30% is attributed to the Pelvis, and Upper and Lower Extremities [2]. The percentage of severe injuries by contact region reveals that 36% contact the upper vehicle while 44% contact the mid vehicle [2]. Digges et al., in a previous study of NASS-CDS 1995-2001, show that the percentage of AIS3+HARM for belted and non-ejected occupants by body region is 35% for the head and 30% for the trunk [3].

Additionally, rollover data taken from the Crash Injury Research Engineering Network (CIREN) database over 10 years suggests that rollovers need to be disaggregated based on the number of crash events in order to understand how to describe the scenario that led to the injury [4]. Thoracic injury mechanisms, not just head, neck, and cervical spine injury mechanisms, need to be considered to fully understand the injury causation during multiple event rollover crashes [4]. The compressive chest injuries resulted from direct thorax interaction with the roof or side interior [4]. More recent data from years 2000 to 2009 of the NASS-CDS database for belted occupants in single vehicle pure rollover crashes reveals serious injuries by Abbreviated Injury Scale (AIS) body region as follows: 36% to the spine, 23% to the thorax, 20% to the head, and the remaining percentage to the upper and lower extremities, abdomen, face, and neck [5].

RESEARCH APPROACH AND METHODS

Digges et al. [6] performed a case review of NASS rollovers to better understand thoracic injuries for belted occupants in pure rollover crashes. The selection criteria for cases of far-side belted occupants with AIS 3+ chest injuries to be examined were filtered by passenger cars, pick-ups or SUVs; single vehicle rollover; driver only or with right front passenger with minor injuries not related to driver injury; and right side leading rollover (driver on the far side of the rollover). Sixteen cases met the initial criteria but only eight cases were analyzed since the eliminated cases had either severe damage, or more severe roof contact head injuries than their thorax injuries, or missing data.

Case 2 from Digges et al. 2012 research was selected from the NASS cases reviewed since the vehicle in the crash is similar to the vehicle available in finite element model [6]. This case corresponds to year 2005, PSU 48, and NASS case number 248, (2005-48-248) [7]. The 1994 Ford Explorer has some roof damage and was subjected to a 4 quarter-turn trip-over, passenger side leading. There was no air bag deployment. The 54 year old male driver, belted, sustained:

- Abbreviated Injury Scale (AIS) 4 bilateral lung contusion attributed to the left interior
- Two AIS 3 left arm fractures and AIS 1 skin abrasion attributed to the roof
- AIS 2 head injury attributed to the roof
- AIS 1 Abdominal contusion attributed to the belt/webbing buckle

This case is ideal for examining any thoracic injury potentials since it has only one complete roll, severe thoracic injury to the driver, and moderate damage to the vehicle. Additionally, the real-world case vehicle is an SUV from the same manufacturer as the available finite element model that was developed at the National Crash Analysis Centre (NCAC) under a co-operative agreement between Federal Highway Administration, National Highway Traffic Safety Administration, and The George Washington University. Finite Element (FE) modeling was used for this work since it has proven to be indispensable in the development of component design, and vehicle crashworthiness evaluations. This study utilized LS-DYNA commercial FE code to simulate the rollover accident [8].

VEHICLE MODEL VALIDATION

The FE model of a 2003 Ford Explorer has been validated to several sub-system tests and to a full frontal rigid barrier test conducted by NHTSA, and many component coupon tests conducted by NCAC [9]. The validation report and the FE model are available from NCAC website [10]. Additional validation work was performed to validate the FE model to the following test: Canada motor vehicle safety standard (CMVSS) 212-301, side new car assessment program (SNCAP) [11], and offset deformable barrier IIHS tests [12]. Additional component FE model validation was carried using 2 FMVSS No. 216 quasi-static tests conducted by NHTSA with different roll and pitch angles [13, 14]. These tests validation were presented in the first paper [7].

FE MODEL SETUP

In order to perform occupant simulation, the FE vehicle model was missing the door trim, restraint system, and other interior components, especially the roof headliner and any subsequent energy absorbing components. A generic replacement had to be borrowed from other validated models in order to carry out the occupant simulations. For this research, the door and the B-pillar trims were scaled from a 2010 Toyota Yaris FE model [15] to fit the Explorer model. The steering wheel of the Yaris was positioned and connected to the Explorer firewall. The steering wheel is considered essential since it constrains excessive vertical dummy leg motion, especially when the vehicle is upside down. The seatbelt was used from a generic restraint system. These components are shown in Figure 1.

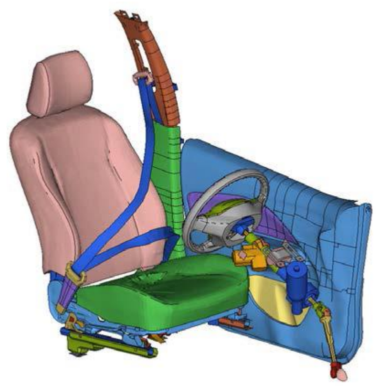
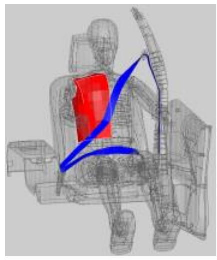
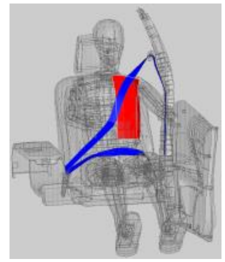
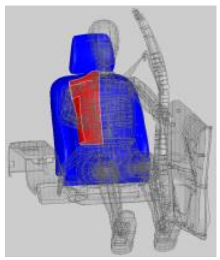
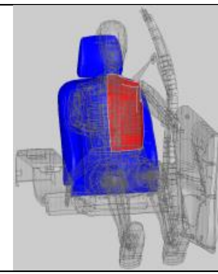
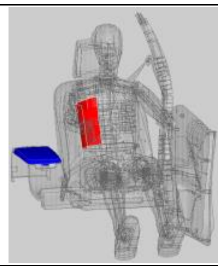
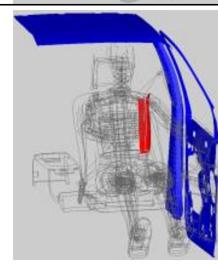
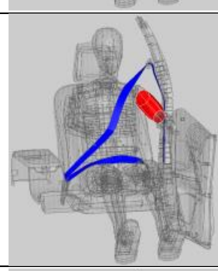
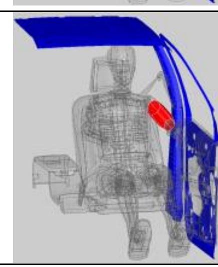
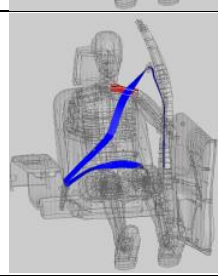
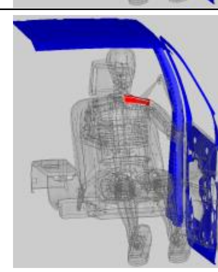
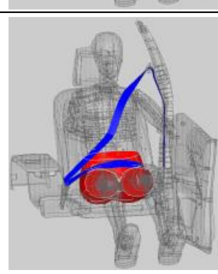
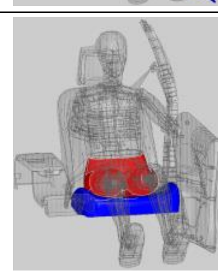


Figure 1. Generic vehicle interiors, restraint system, and steering wheel

Regarding the occupant simulation, the Hybrid III (HIII) dummy has been used in rollover testing due to lack of a rollover dummy. Since the HIII dummy is primarily used for frontal impacts, some modifications were necessary in order to use it in the rollover simulation. The simplified Hybrid III 50th percentile male dummy was used to evaluate occupant kinematics and potential thoracic injury risks in the initial phase. The dummy was modified to measure the contact forces between the dummy exterior surfaces and the surrounding vehicle interior components using the *CONTACT_FORCE_TRANSDUCER_PENALTY_ID card in LS-DYNA [8]. The specified card measures the contact forces between sets of slave and master elements. For visualization, Table 1 shows the different measuring forces. The red surface elements are the set of slave elements and the blue surface elements are the set of master elements. Dummy interaction with the seatbelt, seat back, B-pillar left structure, and middle trim (center console) are measured. Additionally, the head contact with the B-pillar left structure is also measured (not shown in Table 1). Additionally, nodal history outputs of all the dummy ribs on each side and points at the vehicle interiors were measured in order to know dummy impact velocity relative to its surroundings. The *DATABASE_HISTORY_NODE_ID card in LS-DYNA [8] was used.

Table 1. Contact forces between the dummy and the vehicle interiors. (Parts are shown in red and blue)

Contact between (and)		**Visual Representation**	**Contact between (and)**		**Visual Representation**
Dummy Right Front Jacket	Seatbelt		Dummy Left Front Jacket	Seatbelt	
Dummy Right Rear Jacket	Seat Back		Dummy Left Rear Jacket	Seat Back	
Dummy Right Side Jacket	Middle Trim		Dummy Left Side Jacket	B-pillar Left Structure	
Left Arm	Seatbelt		Left Arm	B-pillar Left Structure	
Left Clavicle	Seatbelt		Left Clavicle	B-pillar Left Structure	
Pelvis	Seatbelt		Pelvis	Seat Cushion	

Regarding the Hybrid III dummy position at the initial rollover condition when the roof contact the ground (when the simulation starts), several tests were reviewed. From these tests, the videos of NHTSA Test No. 6960 were of interest to this paper and were examined closely (TRC 2010) [16]. Three videos from the rollover test were superimposed and synchronized in order to examine the driver dummy motion at various times of the rollover. Figure 2 shows the images of different views at the same time. The left image shows the dummy in the vehicle, in the vehicle coordinate system. The upper right image shows the rear view and the lower image shows the oblique view of the vehicle, in the earth-based inertial coordinate system. Figure 2 shows the vehicle when the roof is contacting the ground at an initial roll angle similar to the FE simulation of the reproduction NASS-CDS case (between 125° and 180°). The left image in Figure 3, which is the same as the left image in Figure 2, shows the dummy has moved slightly upward and outboard of the center during the initial 145° of the rollover, since the dummy chest and seat belt marker are less than an inch apart. Therefore, the Hybrid III dummy position in the simulation at the beginning of the roof contact, as shown in Figure 3, is in agreement with the Hybrid III dummy in the test.

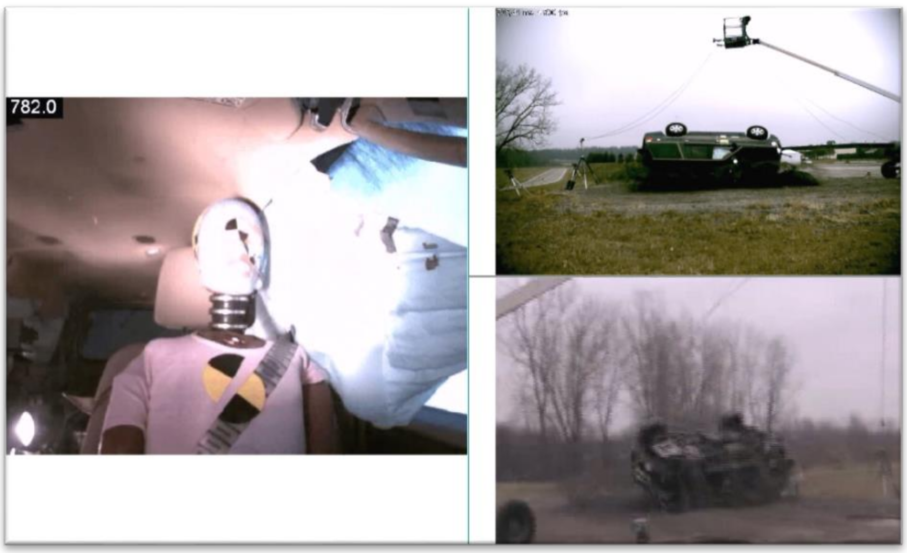


Figure 2. NHTSA Test No. 6960 Vehicle initial conditions contact (superimposed and synchronized video)

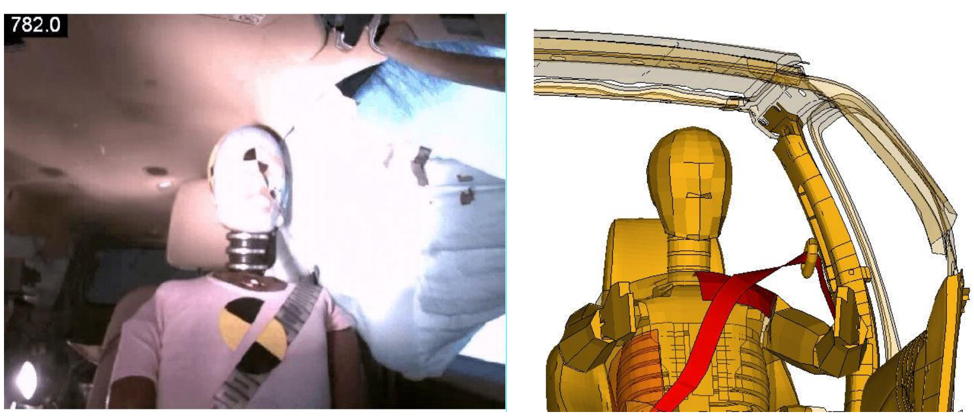


Figure 3. NHTSA Test No. 6960 dummy initial position when the vehicle roof contacts the ground compared to -10Y,-10P, 145R, 190RR, -15mph, 4DH – Hybrid III dummy initial position (0 ms)

The model is set up based on the real-world damage case reproduction finding [7]. The vehicle initial conditions were: -10° yaw, -10° pitch, 145° roll, 190 $^{degree/second}$ roll velocity, 6.7 m/s lateral velocity, and 100 mm vertical drop height.

RESULTS

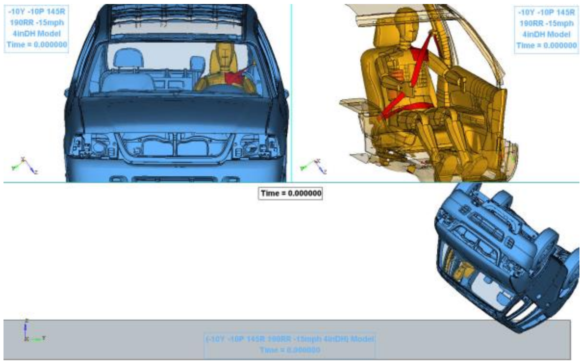
The Hybrid III 50th percentile male finite element dummy model with associated seating and restraint system was incorporated into the interior of a reduced Explorer FE model as was described before. The simulation results are shown in Figure 4. The images, taken from animation outputs, show the progressive motion of the vehicle and dummy at 0.2 second intervals during a four quarter-turn rollover. Three images appear in each time step. The upper left image shows the structural model motion (vehicle) to show the dummy in the vehicle, in the vehicle coordinate system. The upper right image shows the dummy in the reduced model, in the vehicle coordinate system. The lower image overlays the reduced and the vehicle models to show the vehicle and dummy in the earth-based inertial coordinate system.

Figure 4 provides insights into possible injury mechanisms during the simulated rollover. An overall examination of the dummy motion shows an initial motion in the direction of the left side of the vehicle followed by motion toward the center. The flailing of both arms is also evident. The motion of the left arm toward the left window at 0.2 seconds and continuing out the broken window at 0.3 seconds suggests opportunities for serious fractures of the forearm, as observed in the crash. The opportunity for head contact with the left structure beginning at 0.3 seconds is also evident. Another opportunity for arm fracture occurs at 1.1 seconds when the torso comes out of the belt and the belt stops the flailing left arm.

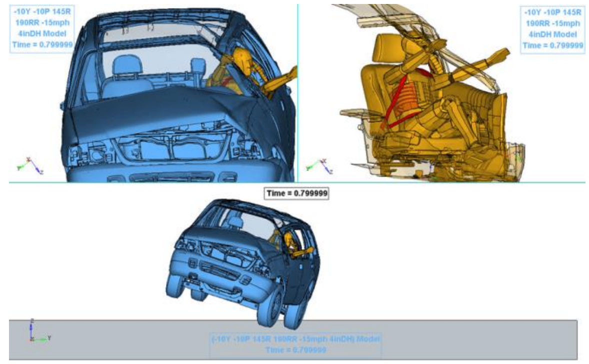
With regard to chest injuries, there are several opportunities for chest contacts. The first occurs during the initial motion of the dummy towards the left structure. At 0.3 seconds the dummy is being restrained by the shoulder belt so that the contact is minimized. However, for a belt with different geometry and slack, a severe contact may occur. It is interesting to note the loading on the dummy during the period from 0.2 seconds through 0.7 seconds. During this period the vehicle is rolling with ground contacts changing from the roof to the left front fender and then to the left front wheel. The motion of the dummy during this period is upward and to the left, loading the shoulder belt. This loading might produce left clavicle fractures or with other belt/occupant configurations may permit an impact with the B-pillar, causing chest and/or clavicle injuries.

The second opportunity for chest injury occurs on the 4th quarter-turn. As the right wheels contact the ground, the dummy begins to move toward the vehicle center. This motion is due to the abrupt reduction in the vehicle rotational speed. At 1.0 seconds the dummy moves downward into the seat and the torso moves toward the center due to the contact of the right wheel. This right wheel contact at 1.1 seconds causes the dummy to slip out of the belt, allowing for a sharp contact with the center console. The center console and arm rest are made of elastic materials, but since it is bounded by both the driver and passenger seats, the center console has less flexibility in lateral motion. Subsequent, less severe impacts between the chest and the center console occur when the vehicle loads both right wheels at 1.5 seconds.

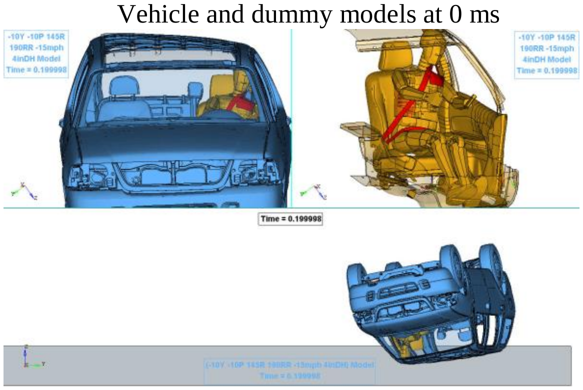
Regarding the thoracic force tolerance, the force levels have been determined but do not correlate over the full range with AIS. The force limit when measured at the center of a narrow object is 3.3 kN while the force limit when distributed with shoulders is 8.8 kN [17]. Figure 5 and Figure 6 show close-up views of the dummy contact with the center console, the vehicle orientation at the time of contact, and plots of the magnitude of the contact force vs. time at two different times. The contact at 1.15 seconds shows a peak of 5.5 kN between the dummy side and the center console, as in Figure 5. The contact after 1.5 seconds involved two force spikes caused by contacts with two different dummy ribs, as shown in Figure 6. These forces are above the recommended 3.3 kN localized chest force limit.



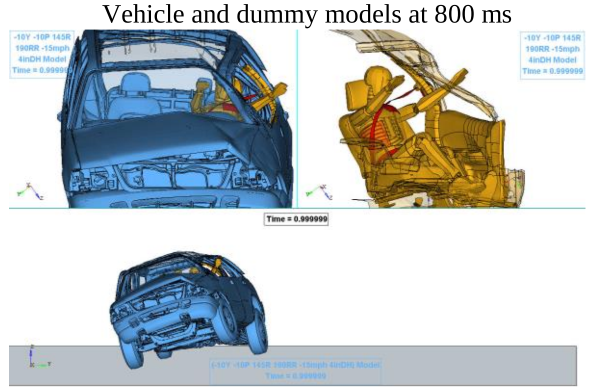
Vehicle and dummy models at 0 ms



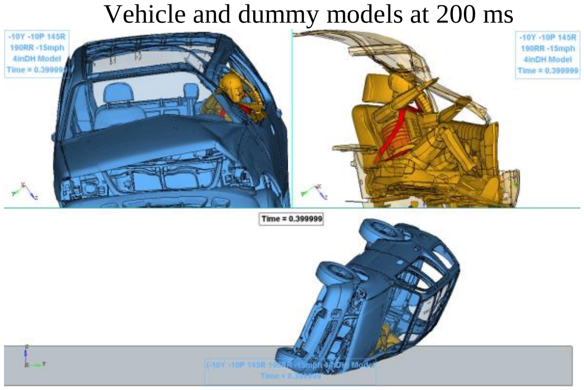
Vehicle and dummy models at 800 ms



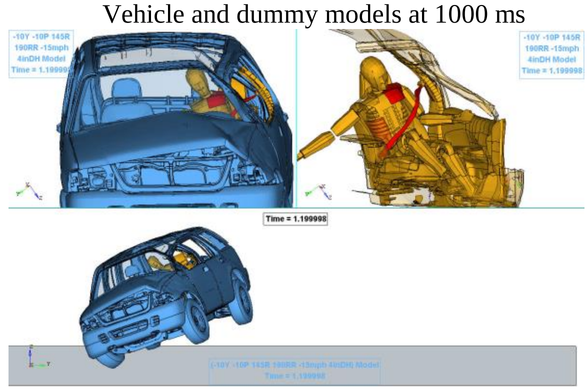
Vehicle and dummy models at 200 ms



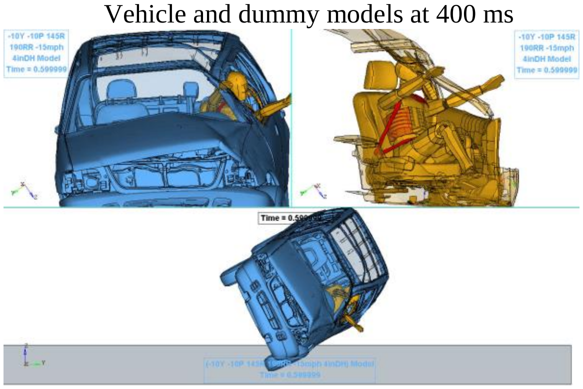
Vehicle and dummy models at 1000 ms



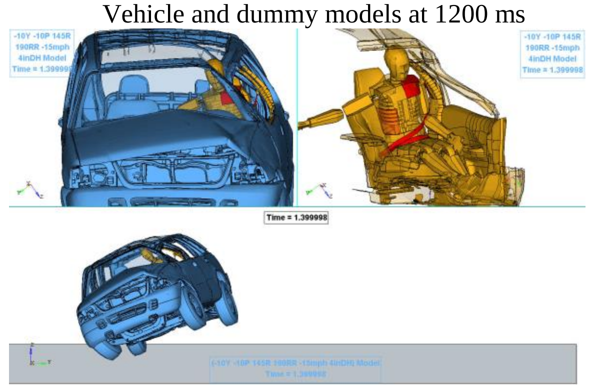
Vehicle and dummy models at 400 ms



Vehicle and dummy models at 1200 ms



Vehicle and dummy models at 600 ms



Vehicle and dummy models at 1400 ms

Figure 4. Case 2005-48-248 FE vehicle and Hybrid III dummy simulation with -10Y,-10P, 145R, 190RR, -15mph, 4DH initial position

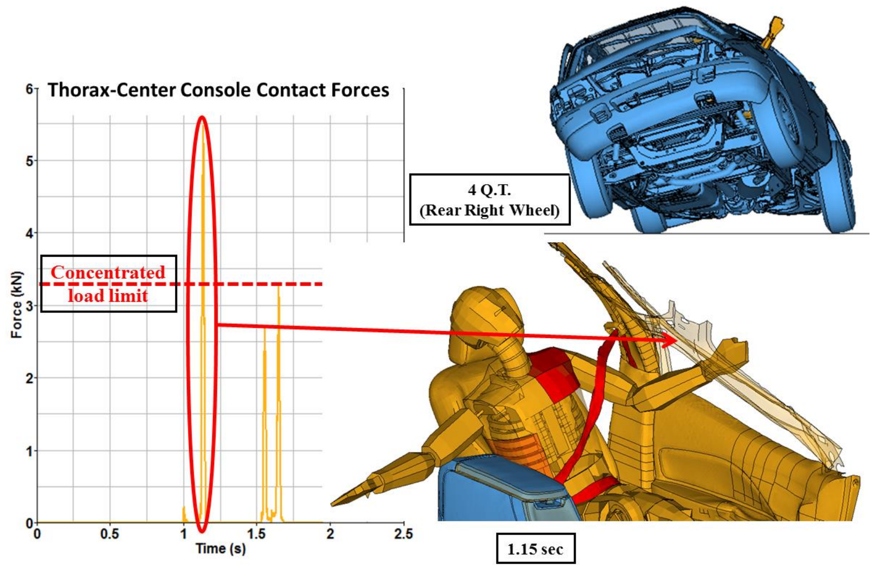


Figure 5. Case 2005-48-248 FE simulation of the right dummy side interaction with the interior and injury opportunity at 1.15 sec

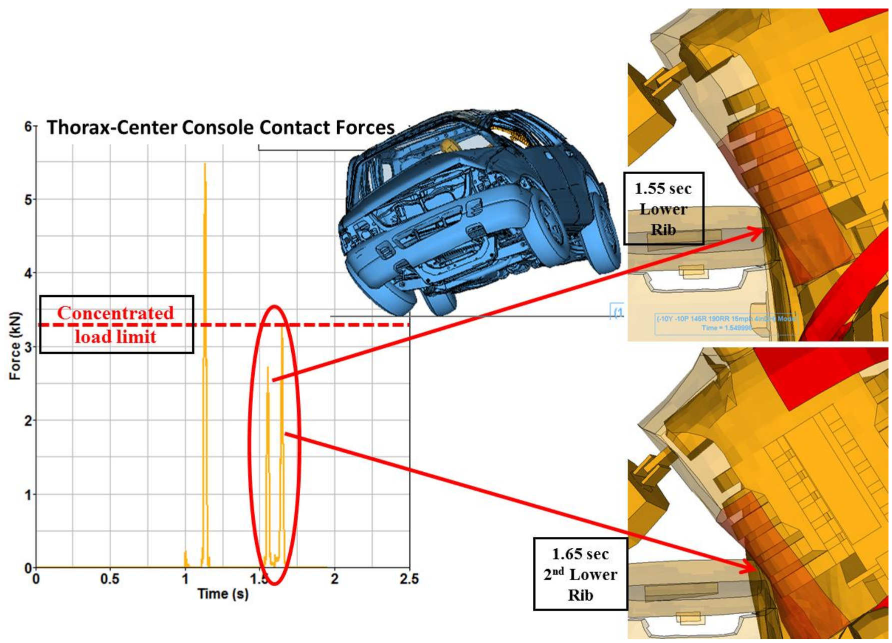


Figure 6. Case 2005-48-248 FE simulation of the right dummy side interaction with the interior and injury opportunity after 1.55 sec

DISCUSSION

For NASS case 2005-48-248, the chest injuries could have been caused by the side contact (after roof contact) and/or console contact (after wheel contacts on 4th quarter-turn). The results indicate that the center console is the most likely cause of the injury. However, additional variation of occupant position, occupant sizes, and belt properties may suggest other opportunities.

Several interesting insights into occupant motion emerged from this study. The analyzed case had pitch and yaw angles sufficient to produce a roll that is not aligned with the vehicle roll axis. This roll motion exacerbated the severity of loading by the left front fender during the 3rd quarter-turn and by the suspension system during the 4th quarter-turn. The 3rd quarter-turn loading drove the dummy upward and toward the vehicle side. Chest and clavicle injuries appear possible under these conditions. The 4th quarter-turn loading initially drove the dummy down into the seat while inducing upper torso motion toward the vehicle center. Possible consequences of this initial dummy motion would be spinal loading and loss of restraint by the shoulder belt. The loss of shoulder belt restraint permitted chest loading of the center console during the initial impact of the right rear wheel and subsequent rebound on the right front wheel. Another potential source of chest injury may be due to the relative internal organs movement during the long loading period and changing kinematics directions.

A review of the NHTSA Test No. 6960 videos shows additional interesting findings. Figure 7 shows three superimposed and synchronized videos from the rollover test at 2 different times. When the vehicle in the test is in its final (8th) quarter-turn, the left tires contact the ground first as shown in Figure 7 at 3924 milliseconds. The Hybrid III dummy in the test as shown in Figure 7 is initially to the left, contacting the outboard side of the vehicle at the curtain airbag. Figure 7 shows the same sequence of the test at 4318 milliseconds when right tires contact the ground to complete the final (8th) quarter-turn. Figure 7 shows the Hybrid III dummy position to the right, as the torso extends past the center of the vehicle. This motion, as previously explained, is due to the abrupt reduction in the vehicle rotational speed as shown in the FE simulation during the final (4th) quarter-turn in Figure 5. The dummy is thrown from the extreme left to the extreme right (Figure 7) in less than 200 milliseconds. Since the center console was removed from the vehicle in NHTSA Test No. 6960, the Hybrid III dummy does not stop by contact, but rather by the seatbelt, which constrains the right side of the dummy. NHTSA Test No. 6960 demonstrates the validity of the rollover FE simulations that were able to identify the inboard chest injury, its timing during the rollover, and a previously undocumented contact source.

Figure 7. NHTSA Test No. 6960 8th quarter-turn left wheel contact the ground at 3924 and 4318 ms

CONCLUSIONS

This research utilizes Finite Element Methods (FEM) in order to identify the causes of real-world chest injury. For a rollover with final rest position wheels down, the highest chest loadings occurred during the final quarter-turn. Rapid excursion of the upper body across the vehicle from the door to the center console was observed in both test and FEM modeling. The results provided insights into how chest injuries and their timing can occur during a rollover crash. This research should improve the ability to develop countermeasures and test procedures.

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