

Assessing Chest Injuries for Different Pitch Angles and Drop Heights Rollovers Using Strengthened Roof

Fadi J. Tahan, Kennerly Digges, Cing-Dao (Steve) Kan, Raphael Grzebieta, Mike Bambach

Abstract This research addresses selected rollover initial conditions in order to study one complete (4 quarter-turn) rollover that would lead to chest injuries for belted occupants. Chest injuries correspond to about one third of belted AIS 3+ injuries of rollover crashes.

Two variables, the drop height and pitch angle, were chosen to vary from previous research values while the remaining rollover initial conditions were kept the same. The Ford Explorer and the 50th percentile male Hybrid III FE models were used. The vehicle roof was strengthened to reduce high crush tolerances while supplementary outputs were requested in order to evaluate thoracic injuries from dummy impact with the vehicle interior components during the 3rd and 4th quarter-turn.

Simulation sensitivity study of 9 different vehicle initial conditions show the Hybrid III dummy chest loading at the third quarter-turns does not result in high contact forces as was anticipated. The overall dummy motion is restricted by the (stiff) neck behavior during the contact between the head and roof. Despite these behaviors, the Hybrid III confirms the possible timing and location of injury causes from a typical rollover. In order to evaluate the extent of injuries, a different dummy should be investigated for rollover crash purposes.

Keywords Chest injuries, crashworthiness, finite element, Hybrid III, rollover.

I. INTRODUCTION

The purpose of this study was to better understand the crash factors that are most likely to cause AIS 3+ chest injuries among belt restrained occupants in newer vehicle rollovers. Previous research using the NASS/CDS database, years 1995 to 2005, to examine the percentage of MAIS3+F injured by body region, with severe damage from planar impacts excluded, revealed 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 [1]. This study showed that 36% of severe injuries resulted from contact with the upper vehicle interiors while 44% resulted from contact with the mid vehicle interiors. The upper vehicle includes the roof, headers, windows, frames and pillars. The mid vehicle consists of the side interior, instrument panel and steering wheel.

Bambach et al. investigated the NASS-CDS database from years 2000 to 2009 [2]. The analysis focused on belted occupants in single-vehicle pure rollover crashes with serious injuries. The distribution of serious injuries by AIS body region was 36% to the spine, 23% to the thorax and 20% to the head. Lung and rib injuries dominated the thoracic injury distribution. Unilateral (AIS3) lung contusion (70%) was more common than bilateral (AIS4) lung contusion (30%). Similarly, unilateral (AIS3) rib fracture (83%) was more common than bilateral (AIS4) rib fracture (17%). The distribution of thoracic injury sources was the highest for the interior door panel, while the seatbelt, seat back and the steering wheel/column were the next most frequent sources of thoracic injury. However, most of the cases did not involve intrusion of the door panel. The authors presumed that the contact between the occupant and the door occurred as a result of the occupant moving into the door rather than the door intruding into the occupant in which case the occupant is moving laterally

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into the interior door panel.

The Crash Injury Research and Engineering Network (CIREN) database was examined for over 10 years by Ridella and Eigen [3]. The thorax was the dominant severely injured body region for the multi-event roll group and claimed the second highest percentage of AIS 3+ injuries to the pure roll occupants. Both percentages are just below 30%. 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. The compressive chest injuries in the CIREN database were reported to result from direct thorax interaction with the roof or side interior.

Parent et al. examined the occupant response and injury risk for belted occupants in a parametric study using the MADYMO FE facet model [4]. It was shown that, in general, the far-side occupant showed a greater risk of injury than the near-side occupant. For the far-side occupant, roll angle, pitch angle and roof strength showed a significant influence on head and neck injury risk, while the trip velocity had the most significant influence on chest injury risk due to thorax lateral deflection.

The objective of this current study was to determine the occupant-to-vehicle interactions that are most likely to cause chest injuries. An essential and unique approach to achieve this goal was to simulate occupant kinematics using finite element modeling. Additionally, the goal was to replicate and increase the knowledge gained from the NASS-CDS and CIREN findings.

This study was accomplished by analyzing the influence of changing only two variables, vertical velocity (drop height) and pitch angle, from a list of common rollover initial conditions using a Ford Explorer with strengthened roof and a Hybrid III finite element model. More Hybrid III outputs were requested in order to evaluate thoracic injury from the dummy impact with the vehicle interior components. Each variable had 3 different values. The sensitivity study of 9 different simulations was then evaluated in order to address the potential chest injuries.

II. METHODS

Finite Element (FE) analysis was used in this study since it is a proven method that can help vehicle development and design, as well as vehicle crashworthiness evaluation. This work made use of the commercial FE-solver LS-DYNA by the Livermore Software Technology Corporation (LSTC) [5] to evaluate the 2003 Ford Explorer.

This section describes the changes that the vehicle and then the dummy finite element models were exposed to in order to measure the needed and useful information to investigate the thoracic injuries.

2003 Ford Explorer FE-Model Setup

The Finite Element (FE) model was obtained from the National Crash Analysis Center (NCAC) at the George Washington University. The NCAC digitized a 2003 Ford Explorer at its Vehicle Modeling Laboratory (VML) and published the FE model in 2007 on the NCAC website [6]. The model has been validated towards several sub-component tests and a full frontal rigid barrier test known as the New Car Assessment Program (NCAP), which was conducted by NHTSA. The material data for the FE model were derived from coupon tests and are therefore assumed to be realistic. Additional validations were performed for the Canada Motor Vehicle Safety Standard (CMVSS) 212-301, the side New Car Assessment Program (SNCAP) tests and the Insurance Institute for Highway Safety (IIHS) offset deformable barrier (ODB) test [7].

For this particular study, the modeling of the windshield was improved in order to get a more realistic behavior under this specific type of load. It has been suggested that the windshield and its bond to the vehicle frame contribute a significant role to the roof strength, up to 30 percent when measured in the tests [8]. The original vehicle model used a single layer of glass, which was replaced by a polymer layer between two layers of glass in the modified model, simulating a common laminated windshield. Furthermore, the glass modeling was changed from an elastic to a piecewise linear plastic material with a considerably low plastic strain as failure criterion to represent the brittle behavior of glass. The polymer layer was also modeled as a piecewise linear plastic material, with a high Young's Modulus and a high failure criteria. The model was then further validated towards two FMVSS 216 quasi-static roof crush tests performed by NHTSA with the 2003 Ford Explorer. The first test (test C0139 [9]) used the required platen angles of 25° roll and 5° pitch, whereas the second test (test

C0140 [10]) used a roll angle of 45° and a pitch angle of 10° . The simulation results generally show good correlation with the real world tests as shown in previous research [11].

In order to reduce roof deformations, the roof components have to withstand additional forces at the various drop heights. This has been accomplished by strengthening the roof to comply with current roof strength standards (SWR of 3.0) when loading both sides of the roof structure sequentially. The roof strength is considered an independent variable in this study while addressing occupant kinematics. Every component associated with the roof was considered. The A-, B-, C- and D-pillars, all the interior pillar reinforcements and the side panel components were strengthened as shown in Figure 1.

Additionally, several nodes on top of the inside roof structure circumference were tracked in order to primarily output the intrusion characteristics. These nodes, which were on the roof header middle point, the middle position of the roof rail between the A- and the B-pillars, and all the pillars for both sides of the vehicle, were measured in a local coordinate system. This local system corresponds to the Center of Gravity location of the vehicle. Figure 2 shows a top view of the nodes reviewed and their location descriptions [12].

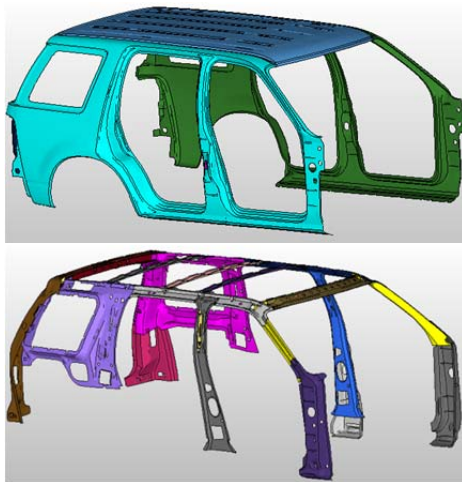


Fig. 1. Strengthened Roof Components of the 2003 Ford Explorer FE Model (outside and inside roof structure)

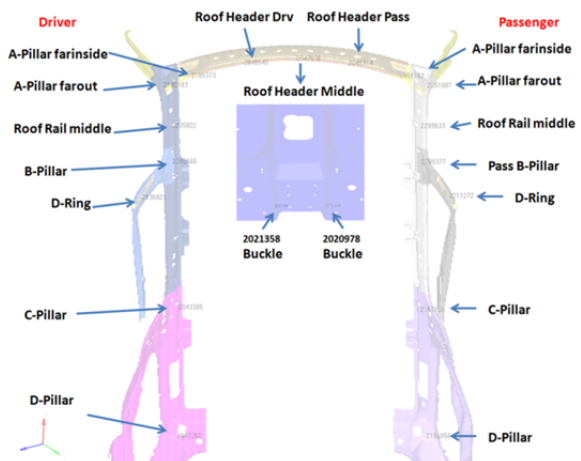


Fig. 2 Local intrusion outputs of key roof components measured from the center of gravity (top view)

In addition to the interior components that were in the model, a generic steering wheel, door trim and restraint system were fitted in the Explorer finite element model in order to perform occupant analysis. The complete interior components were validated in a frontal oblique test and are shown in Figure 3 [13].

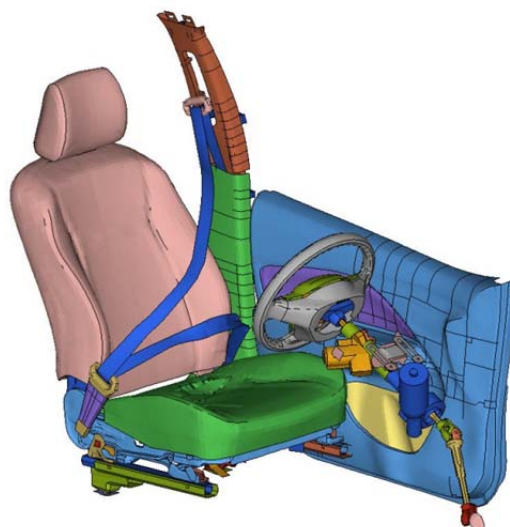


Fig. 3. Generic vehicle interiors, restraint system and steering wheel fitted into the FE Model

For computer running time reduction, the simulation was begun at the time of initial contact between the vehicle roof and the ground. The initial conditions were specified relative to that instant in time. The simulation

was continued until the vehicle came to rest. The sensitivity study matrix has only 3 different positions based on each pitch angle since the angle variation affects the initial point of contact between the vehicle and the ground. Figure 4 shows the three models side by side; starting from left to right are the “-10°, 0°, and +10°” pitch angles, respectively. The three models with different pitch angles clearly show the variances between the center of gravity heights of each model. The negative pitch increases the center of gravity height (1453 mm) by 312 mm (12.28 in.) while the positive pitch slightly increases the center of gravity height (1196 mm) by 55 mm (2.17 in.) from the 0° pitch angle center of gravity height (1141 mm) [12].

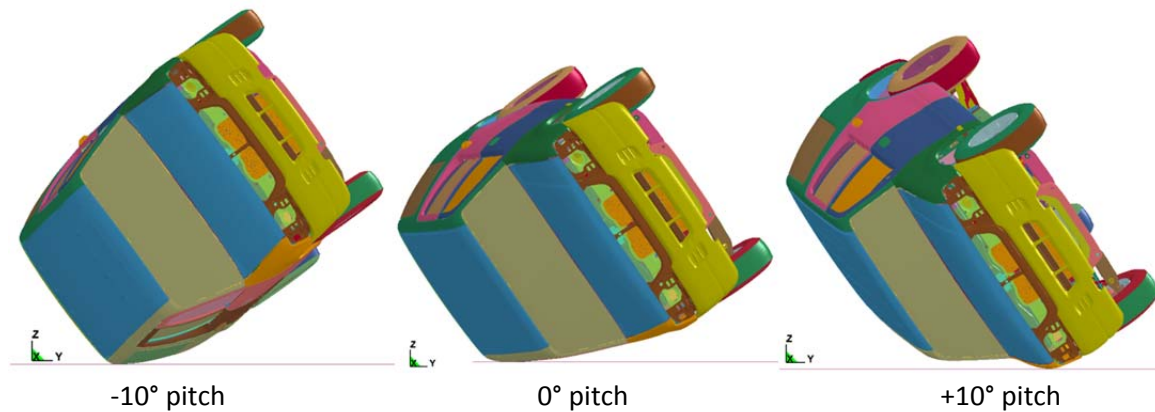


Fig. 4. -10° pitch, 0°, and 10° pitch angles of the 2003 Ford Explorer FE Models

For number of quarter-turns restricted to 6 or less, a standard set of initial conditions was established for the roll rate and horizontal velocity. It was found that a roll rate of $190^{\circ}/\text{sec}$ and a horizontal velocity of 6.71 m/sec produced less than 6 quarter-turns for pitch and yaw angles in the range of -10 to +10 degrees. A vertical velocity of 1.4 m/sec, 1.73 m/sec and 1.99 m/sec was used to represent the 100 mm (0.1 m, 4 in), 150 mm (0.15 m, 6 in) and 200 mm (0.2 m, 8 in) drop heights, respectively [12].

In the FE model, the vehicle's body was free of any restrained from its environment. Several *RIGIDWALL_GEOMETRIC_FLAT planes [5] representing the ground, which is stationary, were generated in order to measure the ground contact force of the following components: vehicle body sheet metals except both fenders and the hood, the vehicle front fenders and hood only, the front left tire and wheel, the front right tire and wheel, the rear left tire and wheel, and the rear right tire and wheel. This representation allowed having a different coefficient of friction between the tires and the ground, which was set to 0.9, and between the sheet metals of the vehicle body and the ground, which was set to 0.45 [12].

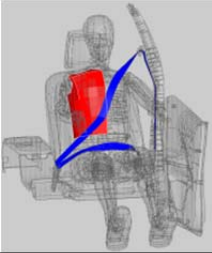
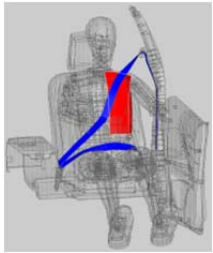
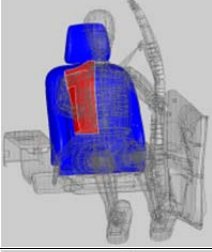
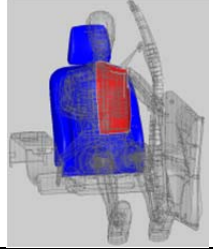
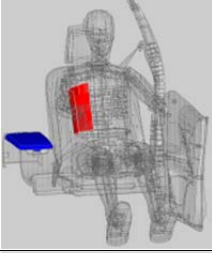
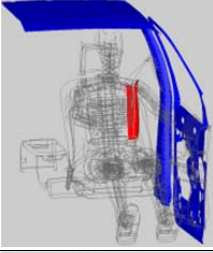
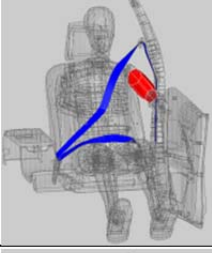
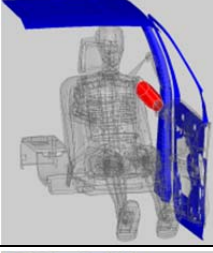
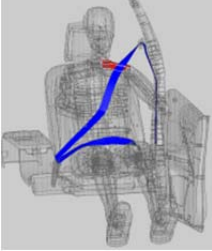
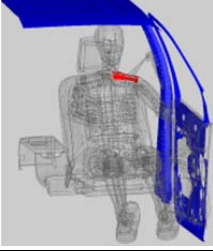
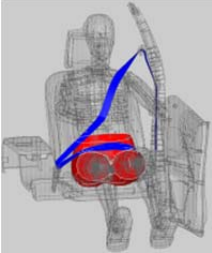
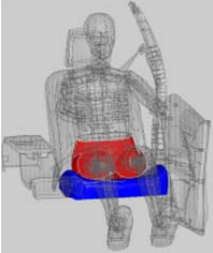
50th percentile Hybrid III dummy Setup

The simplified 50th percentile Hybrid III dummy was used in the analysis since it has a small number of elements for fast turn-around simulations. Additional dummy output was requested in order to provide better insight towards dummy impact velocity and contact forces when interacting with the vehicle interiors. The *CONTACT_FORCE_TRANSDUCER_PENALTY_ID card in LS-DYNA was used. 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 elements are the set of slave elements on the dummy and the blue elements are the set of master elements on the vehicle interior parts. Dummy interaction with the seatbelt, seatback, left B-pillar structure and middle trim (center console) are measured. Additionally, the head contact with the left B-pillar structure is also measured (not shown in Table 1).

Previous analysis of dummy motion in rollover tests found that the dummy position at the time of the first ground impact was close to its initial position, and this position was used in the simulations.

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

Contact between	Visual Representation	Contact between	Visual Representation
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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	Left B-pillar Structure	
Left Arm	Seatbelt		Left Arm	Left B-pillar Structure	
Left Clavicle	Seatbelt		Left Clavicle	Left B-pillar Structure	
Pelvis	SeatBelt		Pelvis	Seat Cushion	

III. RESULTS

To evaluate the effects of individual initial position, the results for each pitch angle with different drop height are presented separately. Each drop height model, 100, 150 and 200 mm, are represented in green, blue and red colors, respectively. The vehicle structure and dummy output measurements provided overwhelming results; only a few are presented here.

The Hybrid III dummy behavior resulted in an unlikely occupant motion during the roof impact with the dummy head. The head impact transmitted a restraining force to the chest through the stiff neck of the Hybrid III, reducing the severity of chest contacts with the vehicle interior. Since the Hybrid III dummy is calibrated as a frontal crash dummy, the lateral stiffness of its neck and spine have not been certified as being representative

of a human when subjected to lateral acceleration in a rollover. However, the Hybrid III has been used extensively by NHTSA in rollover testing and its response has been used to evaluate safety features in support of Standard FMVSS 226, Ejection Mitigation. Although its response may be imperfect, the Hybrid III model used in this study confirmed the possible timing and location of chest injury causation.

Since the thoracic velocities were affected by Hybrid III neck stiffness in axial loading, only the dummy contact forces for each simulation are compared with each other [12].

-10° Pitch Simulation Results

The contact forces that measure the resultant force between each part of the dummy and its surroundings, as described in Table 1, are shown in Figure 5. The forces are filtered with SAE filter 180. Pictures from Table 1 are embedded in the figure in order to give force measurement clarity. In general, the force tolerance levels have been determined. The force limit when the thorax of a human cadaver is impacted under dynamic loading with a 6-inch diameter pendulum at the center hub is 3.3 kN. When the impactor is distributed with shoulders, the force limit is 8.8 kN [14].

The contact force values for most measurements are below 1 kN. The contact between the dummy left back and the seat back is about 1.6 kN during the roof near-side impact. This contact force is the only high force value to the rear of the left chest side during the roof near-side impact. The force values are similar for all 3 drop heights. On the other hand, the contact force between the dummy right back and the seat back is about 1.2 kN during the roof far-side impact. Additionally, the contact force between the lateral inboard side of the chest and the center console reaches at least 2.5 kN for the 100 mm and 200 mm drop heights, while it reaches 7.5 kN for the 150 mm drop height. In addition to the chest loading, the contact force between the left upper arm and the vehicle structure is about 3 kN for all models and it reaches about 6 kN for the 100 mm drop height.

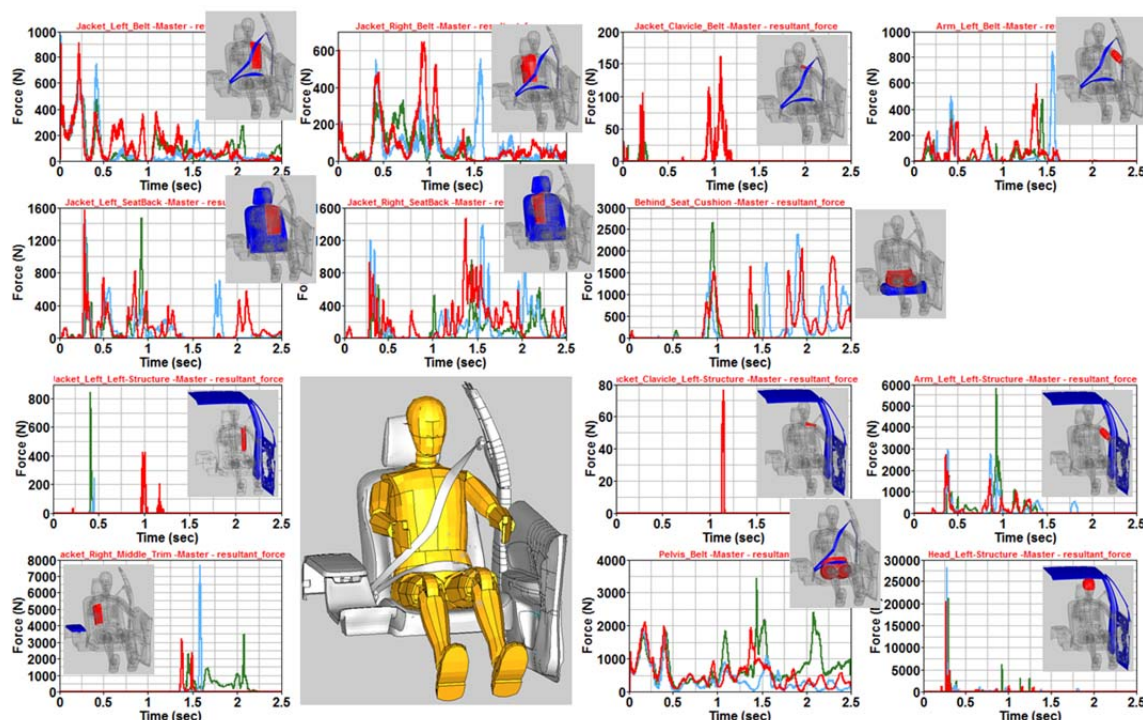


Fig. 5. +10°Y, -10°P, 125°R, 15mph, 190RR, 4, 6, & 8 in. DH – Hybrid III Resultant Contact Forces – SAE-180

+10° Yaw, 0° Pitch; 125° Roll; 15 mph Horizontal Velocity; 190^{deg/sec} Roll Rate; 4, 6, & 8 in. Drop Height Simulation Results

The contact forces that measure the resultant force between each part of the dummy and its surroundings are shown in Figure 6. The contact forces values for most measurements are below 1 kN. The contact between the dummy left back and the seat back is about 0.9 kN during the roof near-side impact. The contact force

between the dummy right back and the seat back is about 1.5 kN during the roof far-side impact. The contact force between the lateral inboard side of the chest and the center console is less than 0.5 kN for the 100 mm and 200 mm drop heights, while it reaches 1.7 kN for the 150 mm drop height. The contact force between the left upper arm and the vehicle structure is less than 0.8 kN, except for the 200 mm drop height when it reaches 1.2 kN.

+10° Yaw, +10° Pitch; 125° Roll; 15 mph Horizontal Velocity; 190 ^{deg/sec} Roll Rate; 4, 6, & 8 in. Drop Height
Simulation Results

The contact forces that measure the resultant force between each part of the dummy and its surroundings are shown in Figure 7. The contact forces values for most measurements are below 1 kN. The contact between the dummy left back and the seat back is about 2 kN during the roof near-side impact. The contact force between the dummy right back and the seat back is about 1.4 kN during the roof far-side impact. The contact force between the lateral inboard side of the chest and the center console is less than 1 kN. The contact force between the left upper arm and the vehicle structure is less than 1 kN except for the 150 mm drop height when it reaches 2.4 kN.

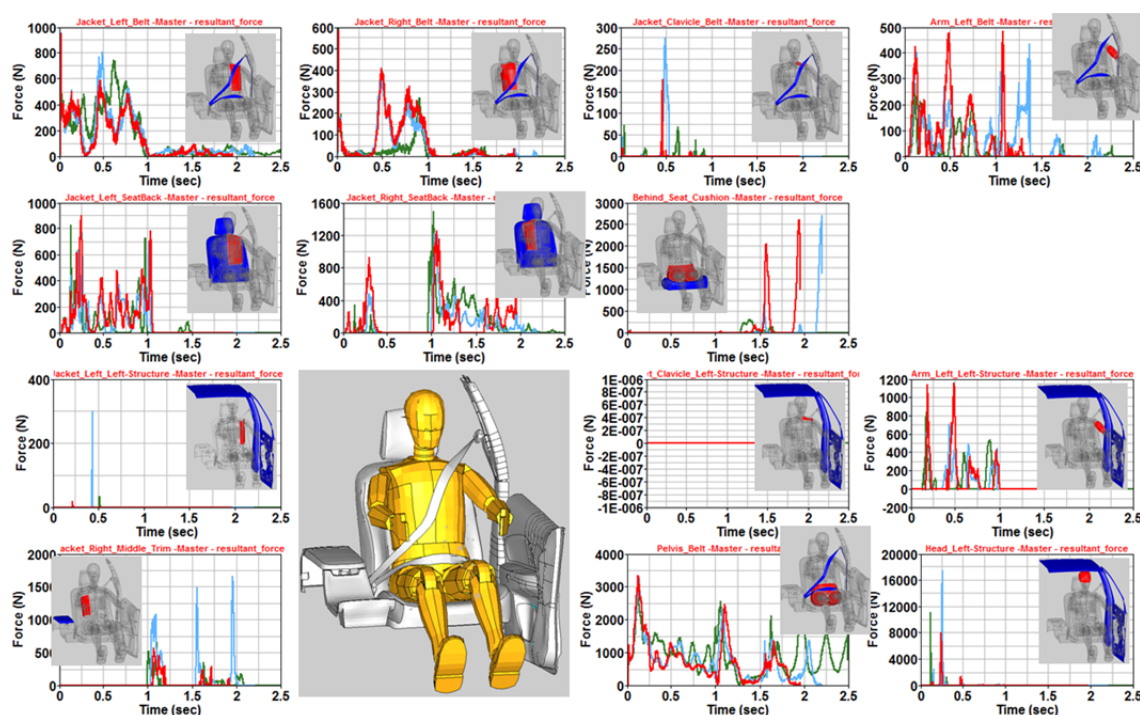


Fig. 6. +10°Y, 0°P, 125°R, 15mph, 190RR, 4, 6, & 8 in. DH – Hybrid III Resultant Contact Forces – SAE-180

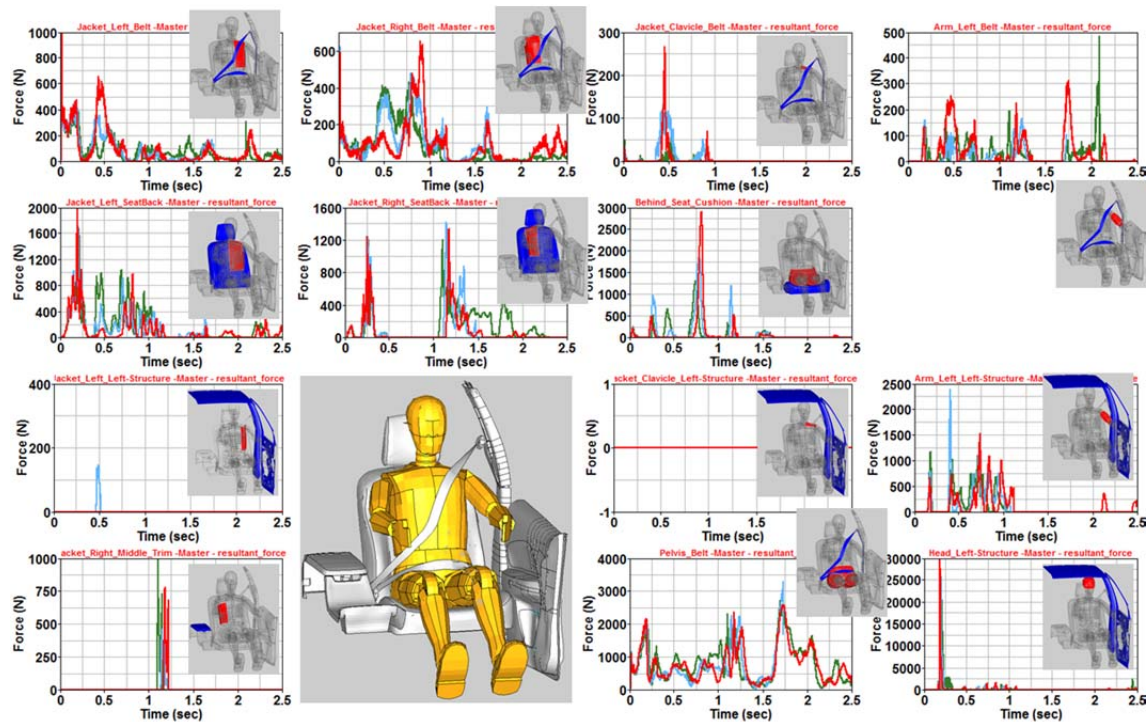


Fig. 7. +10°Y, +10°P, 125°R, 15mph, 190RR, 4, 6, & 8 in. DH– Hybrid III Resultant Contact Forces – SAE-180

A summary of all the simulation models' final quarter-turn numbers is given in Table 2.

TABLE II

+10°Yaw, -10°, 0°, & +10° Pitch, 125° Roll, 15mph, 190 Roll Rate, 4, 6, & 8 in. Drop Height – Number of Quarter-Turn Rollover

	100 mm (0.1 m, 4 in) Drop Height	150 mm (0.15 m, 6 in) Drop Height	200 mm (0.2 m, 8 in) Drop Height
+10Y; -10P; 125R; 15mph; +190RR	5 Q.T.	4 Q.T.	4 Q.T.
+10Y; 0P; 125R; 15mph; +190RR	5 Q.T.	4 Q.T.	4 Q.T.
+10Y; +10P; 125R; -15mph; +190RR	6 Q.T.	6 Q.T.	6 Q.T.

IV. DISCUSSION

The Hybrid III driver dummy instrumented to measure contact forces was subjected to rollover conditions described above. The maximum forces on the left side of the dummy occurred during the third quarter-turn at a time period between 350 and 450 milliseconds from the initial ground contact. For the -10 Pitch condition the total force exerted on the arm and chest by the vehicle side and seatback was above 5000 N. For the +10 Pitch conditions the total force was about 3000 N. The HIII dummy in the zero Pitch case sustained at least 1600 N.

Usually the upper arm loading pushes against the thorax as well. In general, the thoracic loading is a summation of the contacts with the belt, vehicle interiors and seat structure, in addition to the internal loading from other parts of the body, such as the shoulders, upper arms, head and neck. Such complex dynamic chest loading has yet to be explored in terms of injury measurements, especially for lung injuries in rollovers.

A second time of high loading occurred to the right side of the dummy during the fourth quarter-turn. As a consequence of the vehicle rebound during the fourth quarter-turn, the right-side dummy loading from the seatback and center console exceeded 2000 N for all three cases of pitch.

The simulation results regarding the Hybrid III dummy are summarized in two main findings:

- Additional drop height did not result in higher forces to the dummy chest loading at the third quarter-turns. However, changes in the roof deformation and dummy motion restrictions exposing the head to roof contact may have moderated the effect of higher drop height.
- The overall dummy motion was restricted by the head and neck behavior during the third quarter-turn

contact between the head and roof. At that time, the dummy chest velocity was in the direction of the vehicle door but the head contact prevented or mitigated the chest contact. The stiffness of the Hybrid III neck affects the dummy chest velocity at the time of the third quarter-turn contact.

V. CONCLUSIONS

The simulations indicated that the most likely opportunities for chest injury occurrence for a belted driver in the 4 to 6 quarter-turn far-side rollovers were: (1) driver left side contacts with the belt and vehicle interior during the third quarter-turn and (2) driver right side contacts with the belt and vehicle interior during the fourth quarter-turn. The forces of these contacts increase with plus or minus 10 degrees of pitch compared to zero pitch.

The chest impact forces during the third quarter-turn were generally below the threshold for serious chest injury. The lack of lung injury criteria for complex loading and the inadequate biofidelity of the dummy in rollovers contributed to the difficulties in predicting chest injury occurrence.

The Hybrid III dummy behavior resulted in an unlikely occupant motion during the roof impact with the dummy head. The head impact transmitted a restraining force to the chest through the stiff neck of the Hybrid III, reducing the severity of chest contacts with the vehicle interior. Despite this deficiency, the Hybrid III confirmed the possible timing and location of chest injury causation.

In order to evaluate the extent of chest injuries, the Hybrid III model needs to be replaced with a dummy that can better correlate to occupant motion in rollovers or with a human finite element model.

VI. ACKNOWLEDGEMENT

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