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Finite Element Investigation of Head and Neck Injury Mechanism during Rollover Crashes

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ABSTRACT

A set of state-of-the-art FE vehicle, restraint system, dummy, and whole body human models was constructed and validated against several sets of quasi-static and dynamic rollover tests. HIII dummy responses during three selected trip-over scenarios were simulated using an FE vehicle model equipped with four different roof stiffness values. It was found that the high dummy head accelerations and neck loads were mainly caused by the inertia of the occupant's torso compressing the head into the roof/ground before any significant roof crush occurred. Therefore, roof crush is not causally related to the head and neck injuries during the simulated rollover scenarios. However, the roof stiffness of the near-side roof did affect the duration of the head-to-roof impact of the far-side occupants, if two consecutive roof-to-ground impacts occurred in a single roll. It was observed that the stiffer the roof, the lower the head and neck injury risks for the far-side dummies in this scenario. However, no trend between roof stiffness and injury risk was observed when the same simulation was run with the THUMS human body model. This difference in response is most likely due to the ability of the compliant human neck to change impact orientations with different vehicle models, significantly changing the head and neck responses. During all the simulated rollover scenarios, the effect of roof stiffness on the injury risks of near-side occupants was not consistent as no clear trend was apparent. More rollover tests using both the dummy and cadaver are needed to further validate the hypothesis proposed in this study.

INTRODUCTION

The finite element (FE) method, the most up-to-date advanced technology available to aid all types of automotive safety research, has been routinely used in frontal, side, and rear impact analyses. However, it was rarely used for rollover simulations due to the relative long simulation time and complicated vehicle-to-ground and occupant-to-vehicle interactions.

As the most complex vehicular crash type, rollover crash has gained much attention over the past three decades. However, there has been much debate over the occupant injury mechanism in rollovers, especially the relationship between roof crush and serious head and neck injuries. Intuitively, some believe that roof crush reduces the survival space of the occupant and, in turn, will increase occupant injury risk. However, Moffatt (1975) hypothesized that there was no causal relationship between roof crush and head or neck injury during rollover crashes. Three series of rollover tests: Malibu I (Orlowski et al., 1985), Malibu II (Bahling et al., 1990), and Crown Victoria tests (Moffatt et al., 2003) were subsequently conducted with results supporting Moffatt's hypothesis. To the best of our knowledge, these data represent the only published full rollover dynamic tests designed to study the influence of roof strength on occupant injuries. Results of these tests basically showed that occupants were injured as they "dived" upside down into the roof before it crushed. Conversely, some researchers maintain that a weak roof can collapse and buckle in a rollover, imposing forces on an occupant's head inducing head and neck injuries (Syson, 1995; Rechnitzer et al., 1998; Friedman and Nash, 2001).

In general there are three different approaches to investigate the injury mechanisms during rollovers: field data analysis, experimental tests, and computer simulations. Because of the complex and random nature of rollover crashes, field data analyses are often affected by data selection and processing techniques, both of which can dramatically influence the overall conclusion (Hu et al., 2007a). Although experimental data can provide some valuable information about vehicle and occupant kinematics during rollover tests, several test modes are needed to replicate different real-world rollover scenarios (Chou et al., 2005), thus making the whole procedure very expensive. More importantly, no procedure exists to obtain accurate roof crush results during rollover tests based on video camera data recorded inside or outside the vehicle, dramatically limiting the understanding of the association between the roof crush in rollover and occupant injury risk. In contrast to experimental tests, computer modeling presents a great potential for studying rollover crashes. However, presently almost all of the simulated rollover analyses are based on rigid-body models (Chou et al., 1998; Henty et al., 2002). The limitation of rigid-body models is self evident. These models cannot simulate component deformations caused by the contacts between the roof and ground, and thus it would not be appropriate to use them for investigating the occupant injury mechanism in rollovers. Even though the finite element (FE) method is suitable for simulating large dynamic roof deformations and complicated interactions during rollovers, publications of FE rollover simulations are scarce.

For the above reasons, the major objective of this study was to investigate the head and neck injury mechanisms during the most commonly occurring rollover crash modes using FE models. FE vehicle, restraint system, crash dummy, and human models were developed and validated for rollover simulations. Injury mechanisms during rollovers were then investigated to identify the association among the roof crush, roof stiffness, and injury risk.

METHODS

Model construction

A set of state-of-the-art FE vehicle, restraint system, dummy, and human models were developed using LS-DYNA 970 (LSTC, Livermore, CA) to simulate rollover crashes (see Figure 1). The vehicle model was an SUV (Ford Explorer) model previously developed by Hu et al. (2007b). In this model, several sub-models, including a vehicle structure sub-model, four tire sub-models, and two suspension sub-models were first developed and then integrated together. The full vehicle model consisted of about 100,000 elements. Piecewise linear plasticity material were used for most structural members. The power-train components were defined as rigid material. Lumped masses were added to the model to account for all non-structural components. A Mooney-Rivlin type rubber material was defined for the tire, and an airbag model was defined to simulate the tire pressure. The 50th percentile HIII dummy and seatbelt models used in this study were generated by eta/VPG (Troy, MI). The seat, roof interior, and dash panel models were developed based on the estimated geometry of a real Ford Explorer vehicle. The Total HUman Model for Safety (THUMS) version 1.52 FE model of a mid-size adult (Figure 1), previously developed by Iwamoto et al. (2002), was used to simulate the whole body human response during rollovers. In THUMS, bones, ligaments, tendons, flesh, and skin were modeled using about 90,000 elements. A more detailed head-neck model was also developed (Hu, 2007) to predict the cervical spine injury risks during different impact conditions to assist the investigation of injury mechanisms in rollovers.

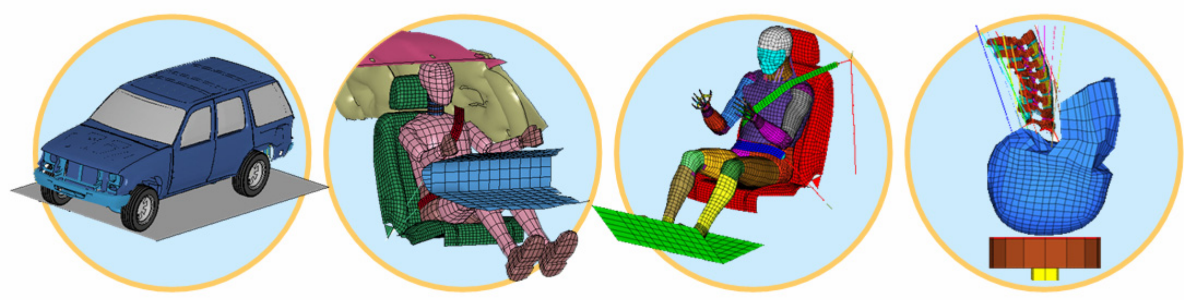
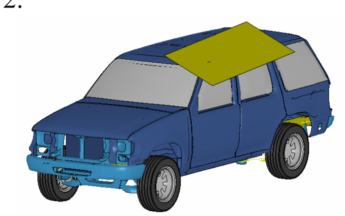


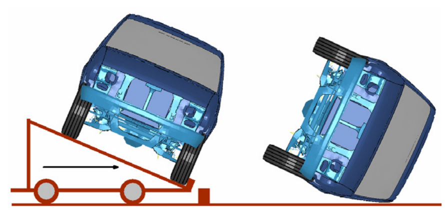
Figure 1: FE vehicle, restraint system with a dummy, whole body human, and head-neck models applied for rollover simulations.

Vehicle model validation

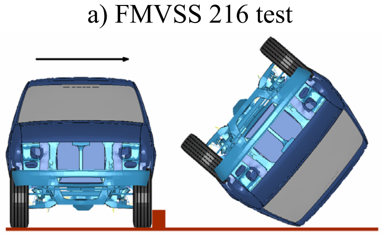
This set of FE models have been validated against several sets of experimental data under rollover scenarios. The validation of the vehicle model was reported by Hu et al. (2007b), in which the model predicted roof deformation-loading curve matched the experimental data favorably well in FMVSS201 quasi-static roof crush test. The calculated vehicle kinematics (i.e. angular velocity, vertical acceleration and lateral acceleration) were also compared well with experimental data during three dynamic rollover tests, including an SAE J2114 dolly test, a curb-trip test, and a corkscrew test. The setups of these tests are shown in Figure 2.



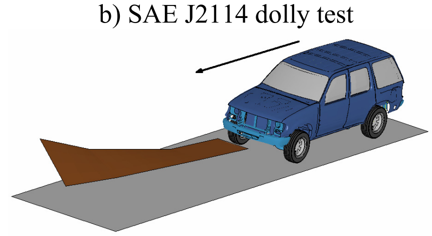
a) FMVSS 216 test



b) SAE J2114 dolly test



c) Curb-trip test



d) Corkscrew test

Figure 2: Setups of rollover-related tests for model validation.

Dummy and human model validation during inversion and rolling tests

The HIII dummy and THUMS models were validated and used extensively in frontal crashes previously (Iwamoto et al., 2002), but they have never been validated under rollover conditions. Therefore, in this study the head excursions of the dummy and THUMS during static inversion and dynamic rolling tests were calculated and compared with the experimental data obtained from dummy, human cadavers and volunteers. During those tests, the dummy or human model was placed in a full vehicle rotated about its center of gravity, which is representative of vehicle rotation during the airborne phase of a rollover. A general three-point seatbelt system with a lap belt oriented at an angle of 60 deg with respect to the horizontal plane restrained the occupant. During the static inversion test, the vehicle was fixed upside down and 1 g acceleration was added to the entire system. During dynamic rolling tests, a stable roll rate about the vehicle's center of gravity was added to the whole system. Two roll rates, 220 deg/s and 360 deg/s, were simulated. The only output monitored during the simulation is the maximum vertical head excursion. As shown in Figure 3, the model predicted head excursions were all within the test corridors developed by Hu (2007).

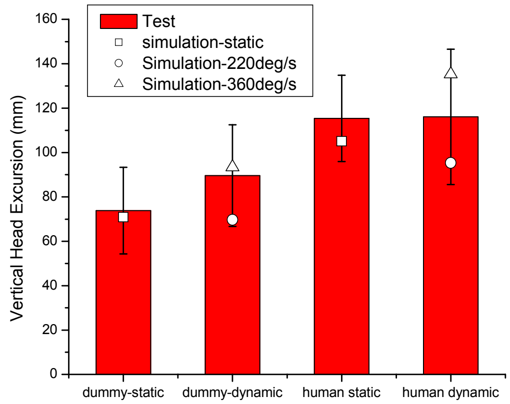
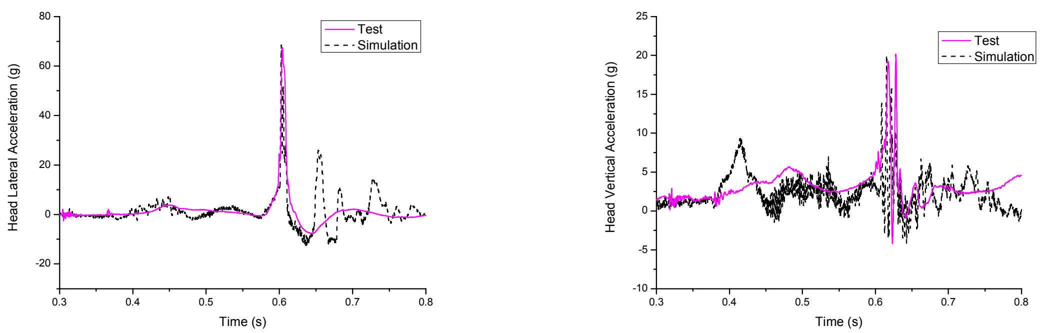


Figure 3: Comparison between test and simulation results in static inversion tests and dynamic rolling tests.

Validation of Dummy Responses in SAE J2114 Dolly Test

Near-side dummy responses

As shown in Figure 4, the model predicted head vertical and lateral accelerations of the near-side dummy correlated reasonably well with the experimental data. The timing and location of the most severe impact of the dummy's head predicted by the model matched the experimental data as well (see Figure 5). The axial neck force was very small in the tests, hence was not compared with simulation result.



a) Dummy head lateral acceleration b) Dummy head vertical acceleration

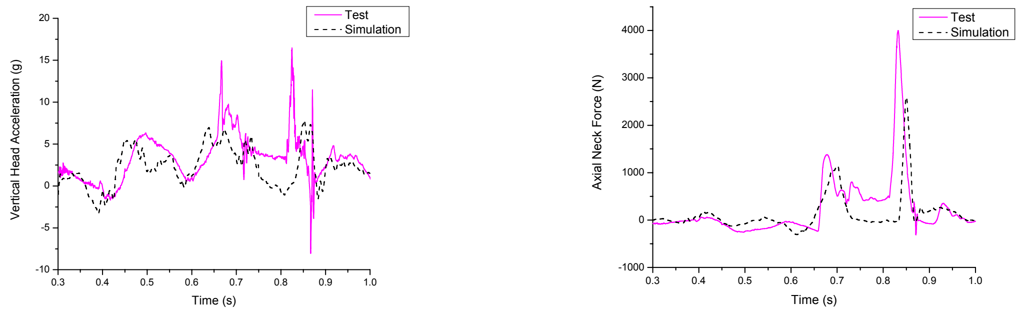
Figure 4: Comparison of the near-side dummy head accelerations between experimental and simulated results of an SAE J2114 dolly test.

a) Experiment (at 0.602s) b) Simulation (at 0.602s)

Figure 5: Experimental and simulated timing and location of the most severe impact to the near-side dummy's head during an SAE J2114 dolly test.

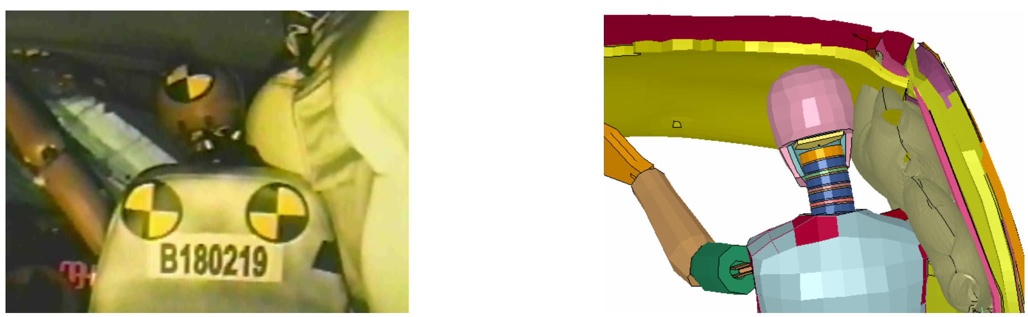
Far-side dummy responses

As shown in Figure 6, the model predicted head vertical acceleration and neck vertical force of the far-side dummy correlated reasonably well with the experimental data. The location of the most severe impact of the dummy's head predicted by the model matched the experimental data as well (see Figure 7). However, the calculated timing of the most severe impact of the dummy's head was slightly delayed.



a) Dummy head vertical acceleration b) Dummy axial neck force

Figure 6: Comparison of the far-side dummy head accelerations and neck force between experimental and simulated results of an SAE J2114 dolly test.



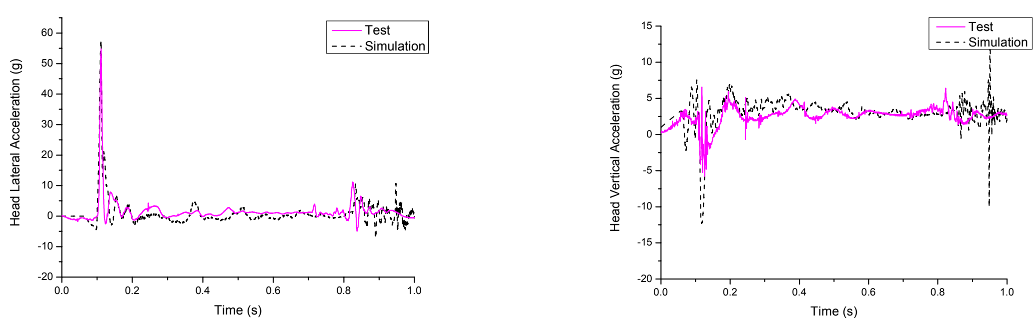
a) Experiment (at 0.824s) b) Simulation (at 0.852s)

Figure 7: Experimental and simulated timing and location of the most severe impact to the far-side dummy's head during an SAE J2114 dolly test.

Validation of Dummy Responses in Curb-trip Test

Near-side dummy responses

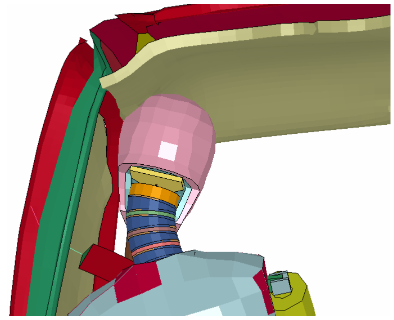
As shown in Figure 8, the model predicted head vertical and lateral accelerations of the near-side dummy correlated reasonably well with the experimental data. The timing and location of the most severe impact of the dummy's head predicted by the model matched the experimental data as well (see Figure 9). The axial neck force was very small in the tests, hence was not compared with simulation result.



a) Dummy head lateral acceleration b) Dummy head vertical acceleration

Figure 8: Comparison of the near-side dummy head accelerations between experimental and simulated results of a curb-trip test.

a) Experiment (at 0.112s)

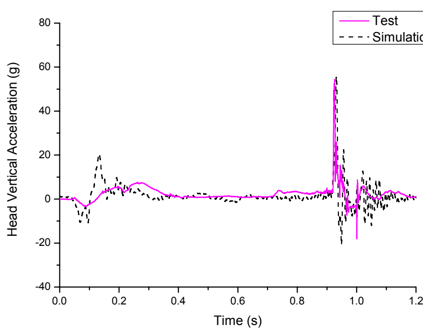


b) Simulation (at 0.112s)

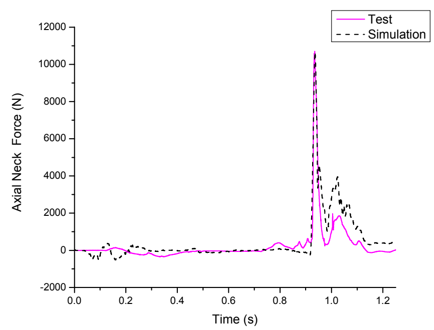
Figure 9: Experimental and simulated timing and location of the most severe impact to the near-side dummy's head during a curb-trip test.

Far-side dummy responses

As shown in Figure 10, the model predicted head vertical acceleration and neck vertical force of the far-side dummy correlated reasonably well with the experimental data. The timing and location of the most severe impact of the dummy's head predicted by the model matched the experimental data as well (see Figure 11).



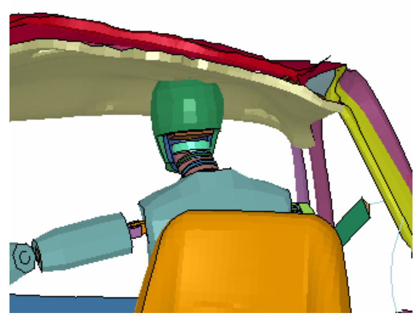
a) Dummy head vertical acceleration



b) Dummy axial neck force

Figure 10: Comparison of the far-side dummy head accelerations and neck force between experimental and simulated results of a curb-trip test.

a) Experiment (at 0.938s)



b) Simulation (at 0.939s)

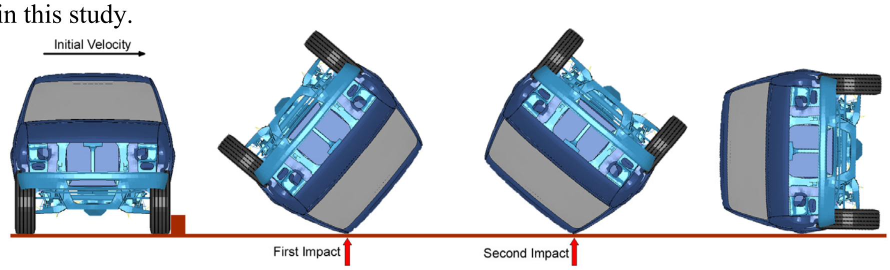
Figure 11: Experimental and simulated timing and location of the most severe impact to the far-side dummy's head during a curb-trip test.

Trip-over scenario selection and FE simulation setup

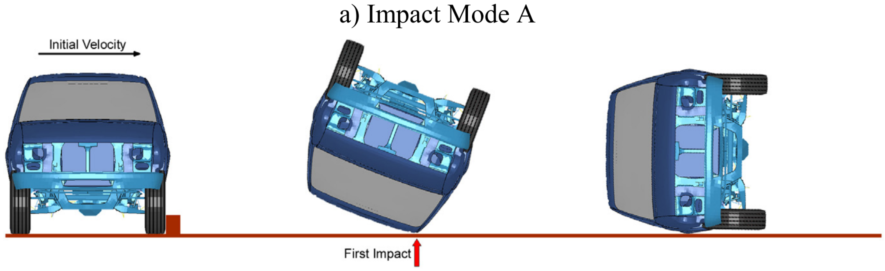
Based on the NASS-CDS database (NASS-CDS, 1997), rollover crashes are divided into 10 different categories: trip-over, flip-over, turn-over, climb-over, fall-over, bounce-over, collision with another vehicle, other rollover type, end-over-end, and unknown. Trip-over accounted for more than 50% of all the rollover crashes (Parenteau et al., 2003) and more than 60% of rollover cases with MAIS 2+ injuries (Hu et al., 2005). Therefore, trip-over is the major rollover type of concern in this study. A trip-over, as defined by the NASS-CDS database, occurs when the vehicle's lateral motion is suddenly slowed or stopped, inducing a rollover. The opposing force may be produced by a curb, pot-holes, or by the wheels of the vehicle digging into the pavement/soil. To improve occupant safety during trip-overs, curb-trip and soil-trip tests are generally used (Parenteau et al., 2003), both of which are considered real-world tripped rollover scenarios (Chou et al., 2005). In a typical curb-trip test, the test vehicle is placed laterally on a sled against a 150 mm curb (see Figure 2c). The sled is then towed to a predetermined velocity and released from the tow device prior to the impact with the curb. In general, the vehicle will experience a rather large lateral deceleration (maximum of 7-12 g's), thus producing a high roll rate. In a typical soil-trip test, the test vehicle is towed to the test speed along its lateral axis and released just prior to entering the soil test section. In comparison with the more aggressive curb-trip test, the lateral acceleration of the vehicle during soil-trip test is relatively low. An average lateral deceleration of less than 1.5 g's of a test vehicle during the tripping phase has been reported previously (Cooperrider et al., 1998). And the lateral acceleration has been reported to be very consistent for soil-trip tests, even though the initial velocity is different from test to test.

In this study, curb-trip and soil-trip crashes were simulated to investigate the injury mechanisms during high and low lateral g-level trip-over crashes, respectively. For curb-trip simulations, the FE model was set up very similar to the curb-trip test configurations. Different FE curb-trip scenarios were simulated by adjusting the curb height and vehicle lateral velocity. However, a simplified model setup similar to the one developed by Ootani and Pal (2007), was used to simulate soil-trip due to the difficulty in simulating the interactions between the soil and tires. For the soil-trip setup, a small moving curb, representing the aggregated soil debris during a soil-trip, was used to induce the vehicle rollover. The initialization of the soil-trip rollover can be adjusted by varying the initial velocity of the vehicle and the height and movement of the curb.

By changing the parameters of the model setups, several different curb-trip and soil-trip scenarios were simulated. It was found that there were basically two types of roof-to-ground impact modes during a single roll of trip-over crashes. In impact mode A as shown in Figure 12a, there were two consecutive roof-to-ground impacts during a single roll, one to the near-side roof and one to the far-side roof. On the other hand, there was only one far-side roof-to-ground impact during a single roll in impact mode B, as shown in Figure 12b. Theoretically, there should be a third impact mode in which only one near-side roof-to-ground impact occurred during a single roll. However, this impact mode could not be reproduced during the simulations in this study.



a) Impact Mode A

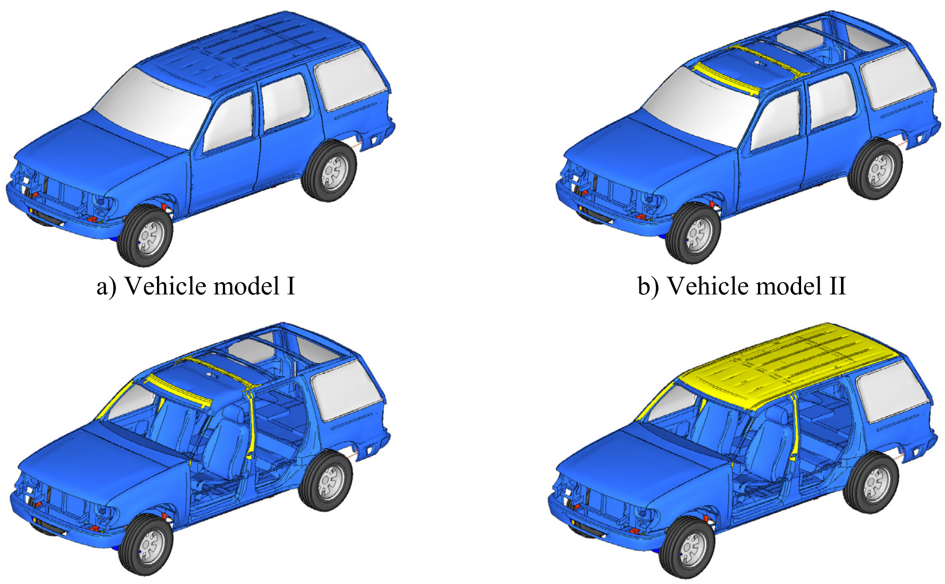


b) Impact Mode B

Figure 12: Roof-to-ground impact modes in tripped rollover simulations.

Impact mode B was typically associated with curb-trip scenarios. The lack of impact to the near-side roof during the first roll was due to the high lateral acceleration of the vehicle which in turn induced a high roll rate. Curb-trip scenarios with impact mode A were relatively limited. On the contrary, for all the soil-trip scenarios, the vehicle experienced two consecutive roof-to-ground impacts in the first roll, one to the near-side and one to the far-side roof, associated with impact mode A.

In this study, two curb-trip rollovers with impact mode A and B, respectively, and one soil-trip with impact mode A were selected to represent the typical trip-over scenarios. Two curb-trip simulations were set up in accordance with the curb-trip laboratory test configurations shown in Figure 2c. The initial velocity was decreased to generate impact mode A and increased to generate impact mode B. The soil-trip simulation setup was similar to the curb-trip test configuration, but the height and the deceleration pulse of the curb were reduced as well as the duration was prolonged. The original vehicle model and three vehicle models with modified roofs (Figure 13) were used in three trip-over scenarios to investigate the injury mechanism and the relationship between roof crush/stiffness and head and neck injury risk. Vehicle model I, the original vehicle model, was considered the baseline model without any modifications to the roof structure. In vehicle models II, III, and IV, the material properties of different parts of the roof structure were varied (Figure 13). Roof stiffness was increased from model I to IV.



a) Vehicle model I b) Vehicle model II

c) Vehicle model III d) Vehicle model IV

Figure 13: Four roof designs with different roof stiffness.
The yellow/light color of the roof structure indicates rigid material.
Vehicle model I: Baseline model with fully deformable roof.
Vehicle model II: Vehicle model I with rigid roof header and rigid first roof rail.
Vehicle model III: Vehicle model II with rigid A- and B-pillars.
Vehicle model IV: Vehicle model III with rigid roof top.

RESULTS

Dummy model responses

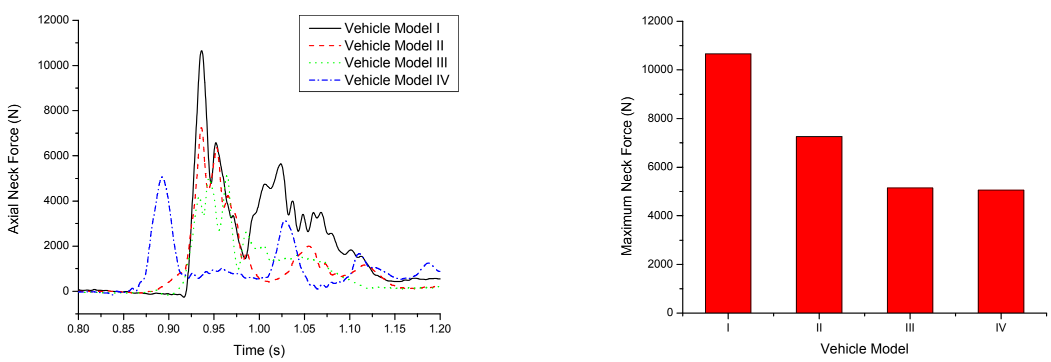
Dummy responses, including the head resultant acceleration and neck axial force, were output for each trip-over scenario experienced by both the near-side (i.e. driver) and far-side (i.e. right front passenger) occupants, since the driver-side is the leading side of rollovers in the tests and simulations. Generally, the near-side dummy sustained two major head-to-roof impacts during the first roll of a rollover. The first major head-to-roof impact was caused by either the initial lateral acceleration of the vehicle in the curb-trip scenario or the first roof-to-ground impact in the soil-trip scenario. The second major impact was caused by the following roof-to-ground impact in both curb-trip and soil-trip simulations. In contrast to the near-side dummy, only one major head-to-roof impact was observed for the far-side dummy in all the simulated scenarios, which occurred during the far-side roof-to-ground impact in all the simulated rollover scenarios. Head acceleration and neck force curves were calculated for each head-to-roof impact as two sets of curves for the near-side dummy and one set of curves for the far-side dummy. Since the roof stiffness increased from vehicle model I to IV, it was hypothesized that a consistent increase of the dummy head and neck responses from vehicle model I to IV subjected to the same crash scenarios might indicate a strong association between the roof stiffness and injury risk. Otherwise, no clear association between the roof stiffness and injury risk would exist.

Near-side occupants

During the first major head-to-roof impact, the maximum head acceleration and axial neck force of the dummy are almost unchanged regardless of the stiffness of the roof. During the second major head-to-roof impact, the maximum head acceleration and axial neck force of the dummy could either increase or decrease with an increase of roof stiffness. Combining the results in the three trip-over simulation scenarios, it is difficult to conclude any clear trend indicating an association between the roof stiffness and occupant injury risk.

Far-side occupants

In curb-trip with impact mode B (Figure 12b), no clear association can be found between roof stiffness and occupant injury risk. However, in two trip-over scenarios with impact mode A (Figure 12a), both resultant head acceleration and axial neck force in dummy responses showed very strong association with the roof stiffness. An example is shown in Figure 14, which demonstrated that increasing the roof stiffness could have the effect of reducing head and neck injury risk.

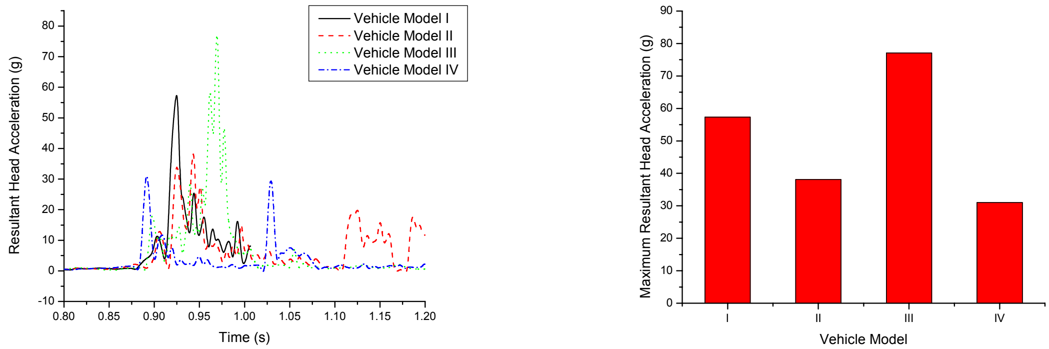


a) Axial neck force b) Peak value of axial neck force

Figure 14: The axial neck forces of far-side dummy with different vehicle models during a curb-trip with impact mode A.

Human model responses

The results of dummy responses showed that the roof stiffness affected the head and neck injury risks only for the far-side occupants during trip-over with impact mode A, i.e. two consecutive roof-to-ground impacts occurring in a single roll. To further confirm this conclusion, the THUMS model was used to predict the head and neck injury risk of a far-side occupant during a curb-trip with impact mode A. An example of resultant head accelerations with different vehicle models is shown in Figure 15. The clear trend of dummy responses could not be duplicated by the human model.



a) Resultant head acceleration b) Peak value of resultant head acceleration

Figure 15: The resultant head accelerations of far-side human model (THUMS) with different vehicle models during a curb-trip with impact mode A.

DISCUSSION

"Diving Induced Injury" or "Roof Crush Induced Injury"?

The major controversy in rollover injury mechanism is whether the inertia of the occupant's torso pushes the head into the roof causing injury (diving induced injury) or the roof collapses in a rollover, imposing forces on the occupant's head causing injury (roof crush induced injury).

Typical curves of roof crush and dummy neck force versus time recorded in the Malibu II study (Bahling et al. 1990) are presented in Figure 16. It is clear that the peak axial neck force occurred approximately 10 ms after the adjacent roof panel struck the ground, before any significant roof crush occurred. The overall roof crush took about 150 ms, thus had no effect on the neck force. It was also mentioned by Bahling et al. (1990) that the dummy buttocks were off the seat during the entire rollover event, proving that the volume reduction of the occupant compartment did not affect the neck force. Although the roof crush reported in this study may not be extremely accurate due to the complex nature of the test and lack of means for measuring the exact crush at the point of head to roof contact, the results shown in Figure 16 demonstrate to some extent that "diving induced injury" is the only possible injury mechanism observed in these rollover tests. A similar sequence of events was observed in the current simulation study as shown in Figure 17. Although the duration of the neck load and the timing of the maximum roof crush are different from case to case, the maximum axial neck force always occurred before any significant roof crush occurred. Therefore, both the previous Malibu II tests and computer simulations conducted here demonstrate that the dummy neck load resulted from "diving" type of impacts where the head was first stopped by the roof, and then the impact momentum of the torso compressed the neck. Although, in theory, roof crush could cause the dummy to be compressed between the roof and seat, this situation did not happen in the Malibu II tests nor did it happen in the three simulated trip-over scenarios in this study.

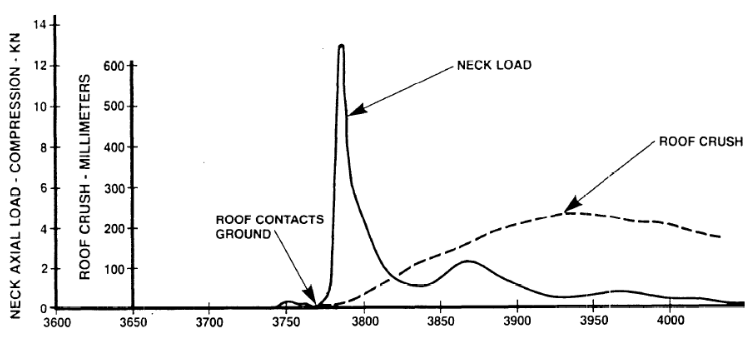
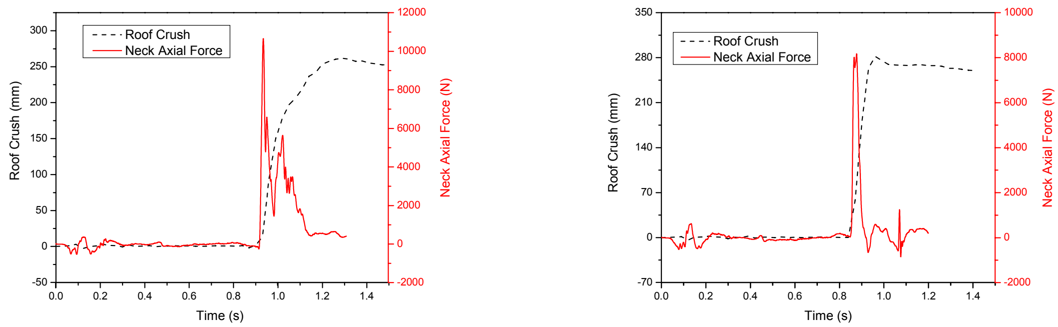


Figure 16: Roof crush and neck load vs. Time in Malibu II (Bahling et al., 1990).



a) Curb-trip with impact mode A b) Curb-trip with impact mode B

Figure 17: Roof crush and neck load vs. Time in two simulated trip-over scenarios.

Protection from Seatbelts

Some researchers who purport “roof crush induced injury” argue that the seatbelt can hold the occupants during rollovers so that the impact between the head and roof could be very minor if the roof was strong enough and did not deform. Though this may seem intuitive, it is not the reality of real-world rollover crashes. Seatbelts were originally designed for occupant protections in frontal impacts. Although they have been proven to be very effective in reducing the injury risk and ejection rate during rollover, seatbelts cannot completely eliminate head excursion. Moffatt and James (2005) conducted an extensive literature review pertaining to seatbelt restraint systems and concluded that typical vertical headroom for an occupant is about 100 mm, and the normal head excursion for belted occupants during a rollover is about 200 mm. In this study, the vertical headroom for an occupant was about 90 mm, but the simulated head excursions of occupants would be more than 150 mm if the head-to-roof impact was not simulated. Thus, regardless of the degree of roof deformation, the head of the occupant will most likely strike the roof. Unless a very effective seatbelt system is designed to reduce the head excursion during rollovers, “diving induced injuries” will still be predominant in rollover crashes.

The Relationship between Roof Stiffness and Occupant Injury Risk

If “diving induced injury” is considered the major neck injury mechanism of rollovers, one can deduce that roof stiffness will not affect occupant injury risk since the head will, in essence, make contact with the ground during the roof-ground-interaction. Therefore, regardless of roof stiffness the injury is actually caused by the impact between head and the ground. However, this conclusion would only apply to near-side occupants or far-side occupants in impact mode B. As stated earlier, the simulated head and neck injury risks of the far-side occupants decreased consistently with increasing roof stiffness in impact mode A simulations.

The reason behind these conflicting views between roof stiffness and injury potential in modes A and B impacts is explained in Figures 18 and 19. In impact mode A, there were two consecutive roof-to-ground impacts during the first roll. As shown in Figure 18, the starting times of head-to-roof impact in vehicle models I and III were approximately the same (T = 0.90 s). At that time, the contact point between the roof and the head was not fully coupled with the ground yet, but was moving toward the ground as evidenced by the negative velocity they sustained at 0.90 s. Note that the positive vertical velocity is defined as pointing to the upward direction. After a certain period of time, the head vertical velocity approached zero, indicating that the contact point between the head and roof contacts the ground, but the duration of this period of time was different between vehicle models I and III . In vehicle model I, it was about 50 ms, but in vehicle model III it was about 80 ms (see Figure 18). It is the longer duration of head-to-roof impact in model III that produced the lower head acceleration and neck force observed by the dummy. Figure 18 also reveals that the duration of head-to-roof impact is dependant on the stiffness of the near-side roof. If the near-side roof is weaker, it will collapse faster during the first roof-to-ground impact, causing the far-side roof to contact ground quickly, thus decreasing the duration of head-to-roof contact and increasing neck force. On the other hand, if the near-side roof is stronger, it will prolong the time interval between the first and second roof-to-ground impact, giving the head more time from the impact to the roof to the impact to the ground, thus decreasing the head acceleration and neck force.

However, in impact mode B, because there was only one roof-to-ground impact, the duration of the head-to-roof impact was approximately the same between vehicle models I and III (Figure 19). Therefore, the head acceleration and neck force were approximately the same for these two vehicle models.

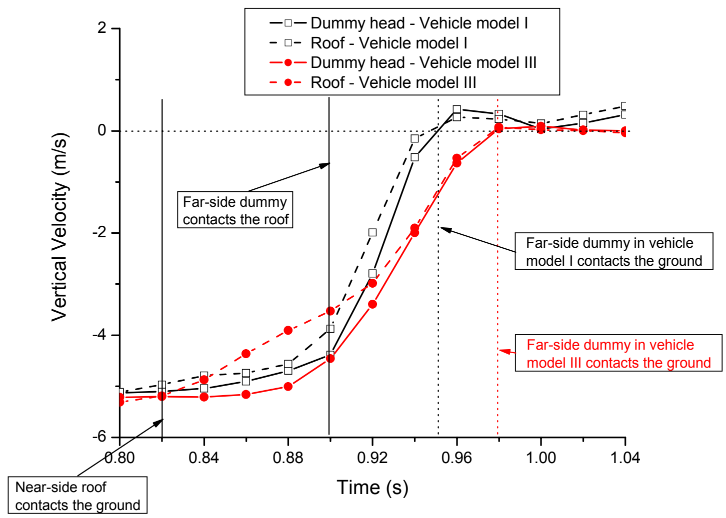


Figure 18: Head-to-roof contact point and head C.G. velocities of far-side dummy during curb-trip with impact mode A using vehicle models I and III.

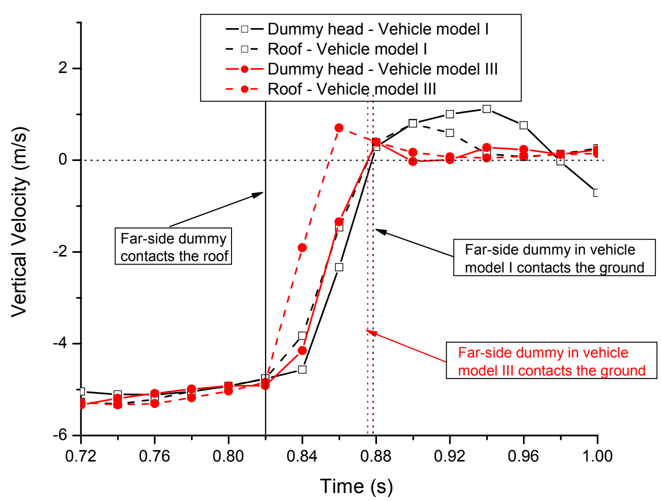


Figure 19: Head-to-roof contact point and head C.G. velocities of far-side dummy during curb-trip with impact mode B using vehicle models I and III.

Difference between human and dummy responses

The dummy responses showed that the roof stiffness affected the head and neck injury risks only for the far-side occupants during trip-over with impact mode A, i.e. two consecutive roof-to-ground impacts occurring in a single roll. However, when the THUMS model was used to represent human in the simulation, a similar trend was not observed. As discussed earlier, "diving" is the major contributing injury mechanism during the simulated rollover scenarios. However, while the occupant torso is diving towards the roof, the orientation of the head and neck plays a very important role on impact severity, which has been proved by previous cadaver experiments (Nightingale et al., 1997) and computer simulations (Hu, 2007). If the impact surface is perpendicular to the longitudinal direction of the neck, all of the impact momentum will be borne by the head and neck. On the other hand, if the impact direction is not in the same direction of the impact momentum of the torso, the head and neck may escape the impact momentum of the torso, resulting in much less injuries. The human model, especially the human neck, is more compliant than that of the dummy model. Changing the vehicle model can change the orientation of the head of THUMS model during head-to-roof impact, thus changing the head and neck responses significantly. Compared to the THUMS model, the impact orientation of dummy model is not very sensitive to the change of vehicle models. Hence the impact orientation between the head and roof is approximately the same for different vehicle models. Since there is no validation of the THUMS model against real-world dynamic rollover tests, no conclusions can be drawn based on the computed differences between the dummy and THUMS model.

Parallel computing

It is generally known that one of the major challenges involved in using an FE model to simulate a rollover event is to reduce the computational time. Chou et al. (1998) estimated that the maximum number of elements should be 15,000 based on the computational technology in 1998. However, with the rapid increase in computational capability, the element limit in this study has far exceeded their recommendation. The current vehicle model (structure-suspension-tire), the dummy model, the restraint-system sub-model, and the curtain airbag sub-model consisted of about 100,000, 10,000, and 25,000 elements, respectively. In order to reduce the computational time, an Opteron Cluster System with 16 nodes+1 master (Sun V20z dual AMD Opterons 250 with 4G RAM) linked by a Myrinet network was used to perform the calculations. Generally, for a 1.5-second rollover simulation, it took approximately 10 hours when four nodes (8 CPUs) were used. The speedup (how much a parallel algorithm is faster than a corresponding sequential algorithm) and efficiency (how well-utilized the processors are in solving the problem, a value typically between zero and one) of the cluster system is shown in Figure 20. Based on the speedup ratio, if 16 nodes were used, a 1.5-second rollover simulation would only take about 3 hours. Further reduction of the computational time can be expected if more CPUs on a larger cluster system are used. It has also been suggested by Chou et al. (1998) that switching between a rigid body mode during the airborne phase of the rollover and an FE deformable mode once the vehicle strikes the ground can greatly decrease the CPU time based on an educated conjecture. However, in the current study, it was found that the kinematics of the vehicle in different laboratory-based rollover tests were very different, thus making this switching method less useful. For example, during the SAE J2114 dolly test, the airborne phase was very short, and the impact timing of different rollover tests also varied. Such variations in timing made it very difficult for users to pre-define a general switching time for all the simulations. Although LS-DYNA3D has a provision that allows automatic switching between the rigid-body and deformable-body modes by monitoring the contact forces, this function currently is rather unstable and yields dramatic differences in results between simulations with and without switching. Therefore, in this study, switching between the rigid-body and deformable-body modes was not used.

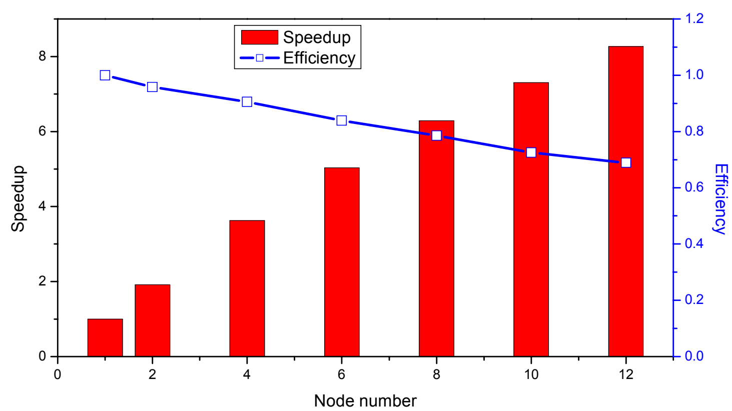


Figure 20: Speedup and efficiency of the cluster system.

Limitations

First, this study only focuses on the effects of roof stiffness on occupant head and neck injury risks, without attempting to find the optimal roof stiffness to prevent injury. Hypothetical roof stiffnesses were assumed for all four vehicle models by assuming that the material properties of certain components are rigid. Therefore, the simulated roof stiffness does not represent any real roof structure modifications. Rather, the intent is to use an idealized concept to demonstrate the effects of increasing roof stiffness.

Second, the three trip-over scenarios used in this study are only simulated situations, thus representing neither real rollover tests nor real accident events. Thus, the results represented here need to be further validated by experimental tests.

Third, the THUMS model was not validated against any rollover test data due to the unavailability of human cadaver/volunteer data for rollover tests. Although the dummy model was validated against responses of HIII dummy used in several dynamic rollover tests, the biofidelity of the HIII dummy during rollover is still being explored by automotive safety researchers. Human responses data for rollover are critically needed to validate the biofidelity of the current dummies and to verify the results reported in this study.

CONCLUSIONS

A set of state-of-the-art FE vehicle, restraint system, dummy, and whole body human models was constructed and validated against several sets of quasi-static and dynamic rollover tests. HIII dummy responses during three selected trip-over scenarios were simulated using an FE vehicle model equipped with four different roof stiffness values. It was found that the high dummy head accelerations and neck loads were mainly caused by the inertia of the occupant's torso compressing the head into the roof/ground before any significant roof crush occurred. Therefore, roof crush is not causally related to the head and neck injuries during the simulated rollover scenarios. However, the roof stiffness of the near-side roof did affect the duration of the head-to-roof impact of the far-side occupants, if two consecutive roof-to-ground impacts occurred in a single roll. It was observed that the stiffer the roof, the lower the head and neck injury risks for the far-side dummy occupants in this scenario. However, no trend between roof stiffness and neck injury risk was observed when the same simulation was run with the THUMS human body model. This difference in response is most likely due to the ability of the compliant human neck to change impact orientations with different vehicle models, significantly changing the head and neck responses. During all the simulated rollover scenarios, the effect of roof stiffness on the injury risks of near-side occupants was not consistent as no clear trend was apparent. More rollover tests using both the dummy and cadaver are needed to further validate the hypothesis proposed in this study.

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DISCUSSION

PAPER: **Finite Element Investigation of Head and Neck Injury Mechanism During Rollover Crashes**

PRESENTER: ***Jingwen Hu, Bioengineering Center, Wayne State University***

QUESTION: *Guy Nusholtz, DaimlerChrysler*
How much mass did you put in the roof to stiffen it?

ANSWER: Well, the mass is basically based on the geometry. It's a finite element. We just compute exactly the same component part and the mass can pretty much match the real vehicle.

Q: Yeah. But when you stiffened it, how much mass did you add to the vehicle?

A: What?

Q: How much mass did you add, or did you just raise the modulus?

A: No, I change it. I changed the radius so that density will be the same, and the modulus—I changed the total radius. So the radial part did not deform at all.

Q: Yes, but how did you do that? Did you add structure to the--?

A: Yes. Yes. I select some of the elements, for example, the roof bar.

Q: Yes.

A: It should be deformable, but I picked part of the elements to read so the roof stiffness will be much stronger.

Q: Okay. So you didn't add any structure to it. You just—

A: No.

Q: You just changed the parameters' modulus or whatever.

A: Yes. Yes.

Q: Or yield or whatever you had.

A: Yes. This is kind of a concept study. I didn't want to jump into the hot water to design a new roof structure. I just make it as a concept. Well, you can make it stronger, but it's not a realistic design.

Q: The reason for it is when you start talking about injury risk— As you add mass to make the roof stiffer as you did, you can't physically do that in any actual vehicle. But as you add mass, you increase the propensity for the vehicle to roll over and you therefore increase the number of rollovers. So you've now got a greater exposure. So when you talk about injury risk, you're talking about given that a collision occurs. But the issue there is overall injury risk, even if you see the results that you saw, for the dummy it still may go up.

A: Yes. Yes.

Q: Because you've increased the number of rollovers. I mean, sometimes to get that level of stiffness that you have, you're ending up adding 30-60 pounds.

A: Well—

Q: Or 10-20 kg.

A: In the real case, maybe yes, but this is just a concept study and not into that area yet.

Q: Okay. But even then with the human, you've still got—you didn't even see the same effect you saw with the dummy. And, you didn't see, really, an effect.

A: No.

Q: So the implication is: Stiffening roof may be negative. It may not even be neutral because you're going to add all that mass and you're not going to see any benefit.

A: Maybe. Well, the current study shows that the impact direction is very, very important. Well, for the dummy for every time even you make the roof stiffer, the impact direction is pretty much the same. However, the human model, the neck is more flexible so the impact direction—If you change the structure, the impact direction might change a little bit. That will affect the injury risk. So right now, this is the current result.

Q: Okay. Thank you.

A: Thank you.

Q: *Erik Takhounts, NHTSA*
I have a question for you. I have, actually, a lot of questions, but I will ask most of them later.

A: Okay.

Q: Since this is just a workshop. It's not actually Peer Review. One of the questions I have: You mentioned yourself that there seems to be a very large sensitivity with regard to the direction of the impact and that means that whatever dummy or human head contacts on the roof, if it's just a little bit off, then you have totally different injury values. Right?

A: Not totally different, but a change. The inner risks change a lot.

Q: Yeah, changing a lot. So I was wondering: That means your neck model, the way you model the neck of humans—I'm not talking about the dummies.

A: Okay.

Q: Human—is very important in how it delivers the head to where it's supposed impact.

A: Yes.

Q: And I was wondering: First of all, how you validated your neck model and secondly, if you tried to change parameters of the neck to see how it changes that impact direction.

A: Yes. Actually, we did a parametric study using the detailed head-neck model and we changed all kinds of impact directions, and we actually changed a lot of other parameters, like the impact velocity, the friction, everything and we find impact, actually, is very crucial. And then, the friction is also very crucial and impact direction is also important. So, we evaluated injury risk by the detailed head-neck model. We actually output the maximum friction draft for each case and compare the results, and that's what we did, so far, for the detailed head-neck model to find some parameters affecting the injury risk of the human neck.

Q: Have you modeled muscles as well in your neck model?

A: We have muscular, but it's very difficult to validate it. However, if we have some active muscle on the human neck—Well during an impact, the injury risk will be increased pretty large. Well that means if you tax your muscle during the impact, you got larger neck injury. That's currently what we have.

Q: Do you think that there's something wrong with the model?

A: I think that makes perfect sense because some previous tasks show that you add more constraint on the neck, you have larger injury risk. And, adding muscle is kind of adding more constraints and you add muscle—active muscle actually is a contrast to the neck and the older strap actually adding the guar so that will increase neck injury. I think it makes sense.

Q: I think it was quite on the contrary from studies from the Duke University where adding musculature actually helped, especially--

A: Well, that's a very difficult thing because the muscle we cannot actually 100% validate those models. We need more studies for sure. So, that's still the first draft. I don't want to talk about muscle too much because I really didn't do a lot of validation for muscle. So, that's a chance.

Q: *Jerry Wang, FTSS*
I saw in your simulation, your arm is penetrating through the roof on all the models across the board. And do you know how much, if you know, if apply the contact information between your arm and the roof and how much it will affect your simulation result?

A: Yes.

Q: Because we're talking about stiffness of the roof and you don't have any constraint between the arm interacting or hand interacting with the roof and whether it will create difference in your results. That's kind of a question for you.

A: Right. Right. You caught me and for some cases, we didn't differentiate contact between the hand and the roof because we thought it's not very important. But after that, we also define the contact. But, we find that the impact is not important at all. So I think it's okay to present the trend here. Thank you.

Q: Yeah, I agree with that if it were for a comparison, yes. But for reality--

A: Yes.

Q: Your arm is going to interact with the roof.

A: You are right.

Q: Okay. Thank you.

A: Thank you.