An Overview of Rollover Associated Injuries and Prevention

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Abstract: Rollover crashes have been receiving more attentions in recent years, due to high rates of severe injury and fatality. Comparing with frontal and side impacts, rollover crashes are complex and chaotic by their very nature. Consequently, a systematic approach combining field data analysis, experimental test, and computer simulation is needed to understand such complex events so that methods could be derived to prevent rollover-associated injuries. In this study, we briefly reviewed the recent literature and reported: 1) **what** is the most common injury, 2) **why** the injury occurred, and 3) **how** to prevent them during rollover crashes.
Keywords: Rollover, Injury Prevention, Injury Mechanism, Field Data Analysis, Finite Element Model

1 Introduction

Rollover crashes are the most dangerous vehicular crashes among all crash types. Although there were only 2.6 percent of passenger vehicle crashes resulted in rollovers, they accounted for 5.3 percent of injury crashes and 21.1 percent of fatal crashes in the US [40]. According to the Fatality Analysis Reporting System (FARS), in 2005 alone, 10,816 people died in rollover crashes, which accounted for more than one-third of all deaths from passenger vehicle crashes in the US. Accordingly, the comprehensive cost of injuries and fatalities associated with rollovers is nearly $50 billion per year [5]. It should be noted that the fatal rollover rate for light trucks, especially for SUVs, was considerably higher than that for passenger cars [40]. Therefore, the changing vehicle mix and the rise in the number of rollover crashes of light trucks are an increasing concern in reducing the number of transportation related fatalities.

In comparison with planar crashes, rollover crashes generally involve multi-directional linear and rotational accelerations and result in complex vehicle and occupant kinematics. Rollover associated injuries are very difficult to predict since rollovers can be initiated by various types of mechanisms, induce multiple contacts between the occupants and vehicle interior, and lead to complicated vehicle deformation. Even though much research has been carried out in an effort to mitigate rollover injuries over the past three decades, many questions and problems still exist:

a) Contradictory field data analyses: The most controversial issue in rollover crashes is the causal relationship between roof crush and occupant injuries. Partially due to the chaotic nature of rollover crashes, different data processing and analysis methods have led to totally different conclusions, even within similar datasets. It is obvious that a more rigorous and reliable method for field data analysis of rollover crashes is critically needed.

b) Unknown injury mechanisms and tolerance limits: Many studies have reported on injury mechanisms, mechanical responses, and tolerance values of different body regions [32; 33]. However, injury mechanisms and tolerances for various sizes, ages, and body regions under conditions similar to real world rollover scenarios have never been investigated. Consequently, knowledge needed to design countermeasures for occupant protections in rollovers is largely lacking.

c) Lack of rollover regulation: To date, only one quasi-static roof crush test (FMVSS 216) is included in the federal regulations related to structural requirements pertaining to rollover crashes.

According to this roof test requirement, any vehicle to be sold in America must be able to withstand 1.5 times its own weight when loaded at a rate of 13 mm/s. However, the causal relationship between the injury risk and the magnitude of roof crush is still controversial in the automotive safety research community. Although the FMVSS 208 dolly test is included in the federal regulation, it is not a realistic or repeatable test, and it is not technically required to be conducted by law. Henty et al. [26] concluded that a set of repeatable and realistic dynamic rollover test procedures is critically needed before federal regulations can be established.

d) Lack of physical surrogate: Currently, there is no anthropomorphic test device (ATD) specifically designed for rollover crash testing. As a result, the Hybrid III (HIII) dummy, originally designed in the 1970's as a surrogate for frontal impact tests, has been used in most rollover tests. The biofidelity of HIII dummy in rollovers has never been demonstrated, thus it is unknown if actual occupant responses can be represented by this ATD during rollovers. Before dynamic rollover tests are prescribed to evaluate vehicular crashworthiness during rollovers, a new ATD designed specifically for rollovers or an improved version of the HIII dummy is required.

e) Lack of numerical simulation models: Previous literature surveys found that only rigid-body dynamic simulation software, such as ATB and MADYMO, have been used for rollover simulations [11; 26]. It is well known that this class of simulation models cannot be used to investigate component deformation and structural crashworthiness of vehicles. As a result, occupant kinematics predicted using rigid-body models may not yield realistic results. Finite element (FE) vehicular models have been widely used to simulate frontal and side crashes, but are rarely used for simulating rollover crashes due mainly to the relatively long duration of a rollover crash. However, with recent advances in computational technology, FE models have proven to be a very powerful and cost-effective tool for designing crashworthy vehicles in the automotive industry. Similarly, FE human models have been developed for injury investigations. Integration of vehicular and human models will aid in the designing of safer vehicles, especially with respect to rollover protection.

To overcome some of the limitations of current rollover studies, the objectives of this study were to briefly review the recent literature and report: 1) **what** is the most common injury, 2) **why** the injury occurred, and 3) **how** to prevent them during rollover crashes.

2 Injury patterns and sources

Rollover crashes are very complex events, because of their various initiation mechanisms. NASS-CDS database [39] coded the rollover initiation type into ten 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. It was found that trip-over crashes accounted for more than 50% of all rollover crashes [47; 50; 62] and more than 60% of rollover cases with MAIS 2 to 6 injuries [29]. Therefore, trip-over tests (curb-trip and soil-trip tests) should be adopted as the most important laboratory-based rollover test mode to evaluate real-world rollover crashes.

Analyses of NASS-CDS database have demonstrated that serious injuries were most frequently seen in the regions of head and thorax [5; 15; 29; 48; 49]. However, inconsistent results were reported for the neck region. For example, Bedewi et al. [5] reported that neck injury only accounted for 5% of AIS 3+ injuries, which was fewer than the lower extremities, upper extremities, and the abdomen. However, Hu et al. [29] found that the neck was the third most commonly injured body region for belted non-ejected occupants with AIS 2+ injuries and AIS 3+ injuries. Neck injury was often a focus in previous rollover testing, not only because it was fairly common during rollovers, but also because the incidence rate of AIS 3+ neck injuries in rollovers was nearly 4 times those in frontal and side crashes

[65], and they often leaded to permanent disabilities.

Atkinson et al. [2] made a very detailed analysis of the NASS-CDS database to determine specific types of injury and noted that subarachnoid hemorrhage (SAH), unilateral lung contusion, clavicle fracture, cervical spine fracture without cord injury, and spleen laceration were the most common injuries to the head, thorax, shoulder, neck, and abdomen, respectively. More recently, Hu et al. [29] conducted a more comprehensive NASS-CDS database analysis and concluded that brain injury occurred much more frequently than skull fracture. The high incidence rate of SAH suggests that future numerical models designed to study rollovers should be capable of simulating this form of cerebral hemorrhage. In thoracic injury, the occurrence of rib cage fracture is higher than internal organ injury. Most neck injuries are cervical spine fractures; therefore, future numerical models developed to study this injury mechanism should have the capability of simulating cervical spine fracture.

Regarding the sources of injuries in rollovers, roof has been reported as the major coded-source of head and neck injuries for non-ejected occupants [5; 29; 47], which demonstrated the importance of avoiding or reducing the impact between head and roof during rollovers. When considering the ejected occupants, ground is the major coded-source of head and neck injuries [5; 29]. It has also been reported that the major coded-source of thoracic injuries is the vehicle interior for belted and steering wheel for unbelted occupants [29; 47].

3 Risk Factors and Injury Causation

There has been much debate over the factors associated with occupant injury causation in rollovers, especially the relationship between roof crush/stiffness and serious head and neck injuries. Intuitively, the increase magnitude of roof crush and associated reduction in the survival space of the occupant will increase occupant injury risk. However, in 1975, Moffatt hypothesized that no causal relationship existed between roof crush and head or neck injury during rollover crashes [36]. This hypothesis was proved subsequently by several field data analyses [1; 46] and experimental tests [3; 37; 44]. However, some researchers maintained that a weak roof structure could collapse and buckle in a rollover, imposing forces on an occupant’s head inducing head and neck injuries [21; 53; 60].

3.1 Field data analysis

Over the past decade, many field data analyses have been conducted to investigate the injury mechanisms and the main factors affecting injury risks during rollovers. Factors such as rollover leading side [15; 47; 49], number of quarter-turns [45; 49], number of potential roof impacts [17], rollover initiation type [50], occupant headroom reduction [52], average roof deformation [20], seatbelt usage [17; 45; 49], occupant ejection status [17; 49], occupant age and gender [12; 46] have all been reported to be associated with occupant injury risks. Unfortunately, many research results were contradictory. For example, Rains et al. [52] reported that pre-crash headroom is an important indicator of the risk to head injuries. However, Padmanaban et al. [46] found that the relationship between the pre-crash headroom and occupant injury risk was not statistically significant. Due to chaotic nature of rollover crashes, a more advanced set of procedures to select, process, and analyze the field data are necessary.

Hu et al. [28] conducted a comprehensive field data analysis on factors affecting the odds of head, face, and neck (HFN) injuries during rollover crashes using a weighted logistic regression method. It was found that, in non-ejected occupants, unbelted occupants have statistically significant higher HFN injury risks than belted occupants. Age, the number of quarter-turns, rollover initiation type, maximum lateral deformation adjacent to the occupant, A-pillar and B-pillar deformation are significant predictors of HFN injury odds for belted occupants. Age, rollover leading side, and windshield header deformation are significant predictors of HFN injury odds for unbelted occupants. This analysis also reported that, for head and face injury odds, the significant predictors are rollover initiation type and lateral roof deformation. On the other hand, the significant preditors of neck injury odds are the occupant age, weight, number of quarter-turns, and vertical roof deformation.

3.2 Experimental study

There were three series of rollover experiments, Malibu I [44], Malibu II [3], and Crown Victoria tests [37], conducted with results supporting Moffatt's hypothesis that roof deformation did not increase the risk of neck injury. To the best of our knowledge, these data represented the only published full rollover dynamic tests designed to study the influence of roof strength on occupant injuries. In these tests, the number and magnitude of axial neck loads were not significantly different between roll-caged and production vehicles. Typical roof crush and neck force time histories in the Malibu II study [3] are presented in Figure 1. It is clear that the peak axial force of the neck 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 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 these studies may not be extremely accurate due to the complex nature of the tests and inability to calculate the exact crush at the point of head to roof contact, the results shown in Figure 1, demonstrated, to some extent, that "diving induced injury" is the only possible injury mechanism observed in these experimental rollover tests.

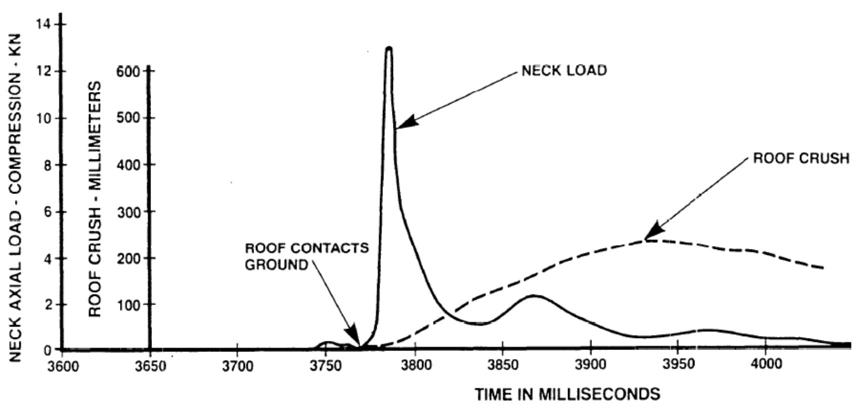

Figure 1 Roof crush and neck load time histories in Malibu II test series [3]

3.3 Computer simulations

Computer modeling is a cost-effective way to study rollover crashes. Recently, many researchers have been using computer models to investigate the kinematics of vehicles and occupants, as well as factors influencing the injury risks during rollover crashes. A review of mathematical models for rollover simulation was conducted by Chou et al. [11], in which existing rollover computer models were classified into four different levels of complexity: simple two-dimensional (2D) rigid-body models, rigid-body based vehicle models, rigid-body based vehicle-dummy-restraint models, and finite element (FE) models. Two-dimensional rigid-body models are basically differential equations derived for simplified vehicle system consisting of one rigid body [10; 19] or two/three rigid bodies connected by a suspension system represented by joints, springs, and dampers [18; 24; 25; 57]. Rigid-body based vehicle models are generally constructed by either three-dimensional (3D) accident reconstruction software or gross motion simulators. Models that can be mentioned using 3D accident construction software include HVE (Applied Technical Services, Inc., Marietta, GA) [13; 14] and PC-Crash (DSD, Linz, Austria) [23; 58; 59]. Gross motion simulators, such as ATB (Wright Patterson Air Force Base, Dayton, OH) [8] and MADYMO (TNO, Delft, the Netherlands) [9; 54; 55; 64], were widely used to develop vehicle rollover models. As for rigid-body based vehicle-dummy-restraint models, there are several ATB models [7; 42; 56] reported in the literature. In recent years, MADYMO became the most popular software to simulate the kinematics of vehicle and occupants during rollovers. Many rollovers with different initiation types were previously simulated, such as curb-trip-over [4; 51; 61], fall-over [4], turn-over [16; 61], and flip-over [22]. More recently, a new development of suspension modeling was added to MADYMO for enhancement of its simulation capability [34].

However, limitations of the current rollover models are obvious. As one of the most severe crash types, rollover crashes often involved large vehicle crushes and component collapses. These deformations/collapses can significantly influence the vehicle kinematics and occupant injury risks during rollovers. Because rigid-body based models cannot simulate component deformations, they cannot be used to investigate a rollover event with complex component deformations. To overcome this shortcoming, Burel et al. [6] used priori hypothetical and simple roof deformations added as input to their MADYMO model. However, actual roof deformations during the rollover scenarios cannot be predicted by this model. To date, the FE method, the most up-to-date advanced technology available to aid all types of automotive safety research, has been widely used and validated in frontal and side impact analyses, but was rarely used for rollover simulations due to the long simulation time requirements. Niii et al. [41] developed an FE model of a large-sized bus to simulate rollover. Their study treated the bus model as a rigid-body during the airborne phase, and then changed it into a deformable-body when the model hit the ground. Recently, Ootani et al. [43] developed a methodology by combining PC-Crash software and FEA approach for simulating curb-trip tests with extension to soil-trip. Their model was primarily for reconstruction of rollover accident scenarios selected from the real-world database in NASS-CDS. No validation of their FE model was mentioned.

Recently, a set of state-of-the-art FE vehicle, restraint system, dummy, and human models has been developed by Hu et al. [30] to simulate rollover crashes and investigate rollover injury causations (Figure 2). The vehicle model (Ford Explorer) was used to simulate three laboratory-based rollover test modes, namely the SAE J2114 dolly test, curb-trip test, and corkscrew test. The simulated vehicle kinematics and the dummy head and neck responses were compared favorably with experimental data. Additionally, the THUMS whole body FE model [31] was further validated against the head excursion data obtained from volunteers in dynamic inversion tests [35]. Using this set of FE models of the vehicle and occupant, several trip-over scenarios were simulated with four different roof stiffness levels. Results indicated that the high 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 should not be causally related to the head and neck injuries during the simulated rollover scenarios. However, simulations also showed that 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. The stiffer the roof, the lower the head and neck injury risks for the far-side occupants in this scenario. If there was only one far-side roof-to-ground impact in a single roll, roof stiffness did not affect the head and neck injury risks. However, simulations with the whole body human model did not provide evidence for the previous trend that increasing the roof stiffness would decrease the injury risk of far-side occupants, as seen with the dummy model. The difference was attributed to the more compliant human neck which can change the impact orientations in different vehicle models, significantly changing the head and neck responses [27]. Note that this finding was only based on the simulation results, thus needs to be further validated against experimental results.

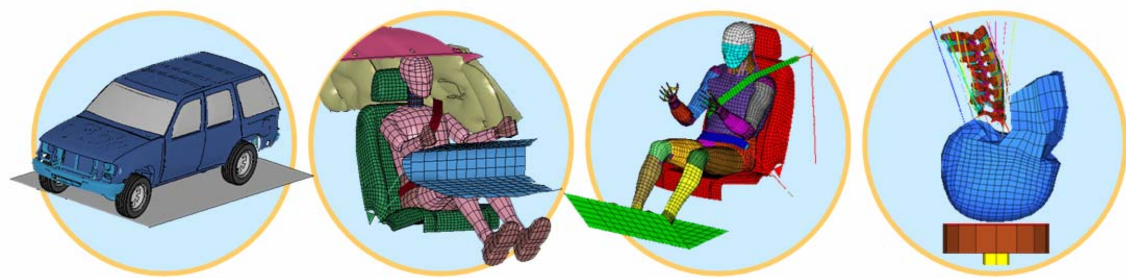

Figure 2 FE vehicle, restraint system with a dummy, whole body human model, and head-neck models applied for rollover simulations at WSU

4 Injury Prevention

Occupant protection devices specifically designed for rollover crashes are not as common as those for frontal and side crashes. To date, the most popular designs for rollover protection are inflatable device (e.g. curtain airbag, roof airbag, etc.) and the related sensing systems, as reported by Viano [63]. Although curtain airbags have been shown to be very effective in reducing occupant ejections during rollovers, the capability of inflatable devices for protecting non-ejected occupants is not clear. Furthermore, the seatbelt system was originally designed for frontal crashes and is inadequate for preventing head-to-roof contact during rollovers. Moffatt and James [38] conducted an extensive literature review pertaining to seatbelt restraint systems, and concluded that typical vertical headroom for an occupant is about 10cm, and the normal head excursion for belted occupants during a rollover is about 20cm. Therefore, an optimized 3-point seatbelt system or a new seatbelt system designed to dramatically reduce the head-to-roof impact velocity is crucial in the neck protection during rollovers. Other than the seatbelt design, our FE simulations using the detailed head-neck model showed that decreasing the coefficient of friction (COF) between the head and impact surface can effectively reduce the risk of neck injury. As long as the COF is in a low level, padding can decrease the risk of neck injury, which is not consistent with the findings reported by many experimental studies in which padding materials were always associated with high COF. Therefore, a new roof interior design following the above criteria might also help reducing the neck injury risks in rollovers.

5 Summary

Field data analyses showed that head, thorax, and neck are the most commonly injured body regions during rollovers. Roof is the major coded-source of head and neck injuries, thus avoiding the head-to-roof contact is crucial for occupant protection in rollovers. Although there are controversies about the causal relationship between roof crush and occupant injury risk, our FE simulations show that roof crush is not the major reason which causes the injuries during simulated rollover scenarios. However, simulations show that the roof stiffness of the near-side roof does affect the injury risks for far-side occupants in some particular scenarios, which needs to be proved by experimental tests. At present, a more effective seatbelt to reduce or avoid the head-to-roof contact should be the major injury prevention device during rollovers. Reducing the COF between the roof and occupant is also needed to reduce the risk of rollover associated neck injuries.

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