

Retrofitting For Rollover Crashworthiness Occupant Protection

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Abstract

Mining and petroleum companies are demanding vehicle roof strengthening systems such as internal and external roll cages and roll bars to protect their employees in the event of a rollover crash. A number of internal roll bars and cages in SUV's can be intrusive to the occupants, restricting vision and comfort and preventing firing of internal injury mitigation systems such as air curtains and pretensioners.

The objective of this paper is to demonstrate how roof crush intrusion into the occupant compartment can be prevented using an innovative externally retrofitted HALO™ roof strengthening system that was developed based on an understanding of how vehicles roll and roofs crush during rollover.

Rollover crash test results of a US manufactured production SUV with a seat belted Hybrid III crash test dummy (ATD) subjected to two rollover crashes will be presented. A second strengthened production SUV of the same make and model is then subjected to the same dynamic rollover crash test using the Jordan Rollover System test rig. Injury measures from the ATD, crush and crush velocity from various vehicle locations in the strengthened vehicle during testing were noted and compared to the measurements from the production vehicle and then discussed. Roadway impact loads measured in both vehicles are compared to each other and to the current best performing rollover crashworthy production vehicle.

Results show that when both roof crush and vehicle's centre of gravity fall is prevented using the HALO™, the ATD injury measures and road impact loads are significantly reduced.

Keywords

Rollover, Roof crush, Jordan Rollover System, Roll bars, Roof strengthening

Introduction

Recent investigations by Young [1] of 2004 to 2005 National Coroners Information System data has indicated that rollover related road fatalities constitute around 12% of all road deaths and are now higher than fatalities involving frontal crashes (9%) and side impact crashes (10%). They are at the same level as motorcycle related fatalities (13%), a little over two thirds of pedestrian fatalities (17%), and around half the percentage of fixed object related fatalities (24%). Moreover, in around 29% of all crashes where a vehicle occupant has been killed (excluding motorcyclists, pedestrians, cyclists, etc) the vehicle has rolled over. It is clear that fatalities involving rollover crashes are now significant in Australia and need to be addressed.

The high incidents of rollover crashes have become a concern to mining and petroleum companies because of occupational health and safety requirements. The vehicle is considered a workplace environment and hence, employees travelling in a company vehicle need to be protected in the event of a rollover crash. This is particularly so if the driver was travelling at the posted speed limit, all occupants were seat belted, and the vehicle has crashed through no fault of the driver. However, there are no standards or consumer crashworthiness tests in Australia in regards to passive rollover crashworthiness of small and large vehicles such as passenger cars, four wheel drive (4WD) and sport utility vehicles (SUV) [2]. Moreover, no country or consumer group assesses dynamically the rollover crashworthiness of medium and small size passenger vehicles for the purposes of certification or crashworthiness ratings respectively.

Researchers have also identified a relationship exists between serious/fatal injury and the location where a seat belted occupant sits in the vehicle. The studies of Parenteau et al [3], Digges et al [4], Friedman and Nash [5], and Nash and Paskin [6] all observed that occupants seated on the leading (near) side of roll are less likely to experience serious or fatal injuries than those on the side following (far side).

To mitigate the injuries observed in rollover crashes, a number of mining and petroleum companies have attempted to install rollover protection bars such as the examples shown in Figure 1 and Figure 2. Although such roof strengthening may at first appear to provide a survivable interior space to protect occupants against roof crush, these quick fix methods demonstrate a lack of understanding of how vehicles deform and occupants are injured in rollover crashes.

Firstly, interior roll bars reduce survivability space. They can significantly exacerbate and/or cause other injuries resulting from body strikes to hard surfaces in other crash modes such as side and frontal impact. Secondly, such interior reinforcement may also impede the firing of critical passive devices such as side air curtains and seat belt pretensioners that help reduce occupant impact forces. Thirdly, Figure 2 shows how despite the installation of an internal roll bar the roof has collapsed at the front header rail on the front passenger side of the vehicle. Not only does such deformation reduce the survivability space for the seat belted front passenger, it can substantially increase head roof contact loading and head impact velocity which lead to severe and fatal injuries. Fourthly, Figure 2 and Figure 3 show how when the vehicle pitches forward during the rollover because of the engine mass, the A-pillar deforms approximately to the yellow line. This usually occurs when the A-pillar is weak, and rollover contact support and roof crush resistance is mainly provided by the front fender and the stronger B and C pillars.

In regards to occupant position in the vehicle, Parenteau et al [3], Digges et al [4], Friedman and Nash [5], and Nash and Paskin [6] observed that occupants seated on the far side of the vehicle (side opposite to the leading side of roll) are more likely to sustain serious or fatal injuries than those on the near side (leading side of roll). This is because the roof deforms more readily on the far side as illustrated in Figure 4 and Figure 5. When the roof first contacts the ground on the leading near side (left frame in Figure 4) the reaction load transmitted to the roof is in a direction that compresses the A-pillar. When the vehicle continues to roll it strikes the far side (right frame in Figure 4). The reaction load is in a direction such that the A-pillar is loaded somewhat similar to a cantilever beam. Connectivity between the pillars and the roof are very weak, offering little or no moment transfer [7, 8]. Hence the A-pillar can be treated essentially as a cantilever beam with a weak pinned-end support. It is well known in structural mechanics that columns subjected to an axial load can tolerate much higher loading than the load required to bend the column like a cantilever. This is of course on the condition that the column is stout (not slender) and does not buckle under the applied axial load. Figure 5 shows two vehicles where the occupants injured in the vehicle were on the far side of the roll direction where the roof crushed.

When considering all of the above and how the roof deforms in lateral trip rollover crashes, any roof strengthening system must be effective in preventing the front A-pillar from crushing. Hence, an external rollover protection system called the HALO™ was developed to overcome the disadvantages of internally fitted rollover protection systems. The system was developed based on an understanding of how vehicles roll and roofs crush during rollover and then tested using the Jordan Rollover System (JRS) shown in Figure 6. However, in order to describe how the HALO™ system works to reduce road impact loads and injury measures, the crash characteristics and how it was tested needs to be described first.

Rollover crash characteristics and the JRS test rig

Rollovers have been classified into several categories in the US [9, 10] based on typical rollover crash initiation scenarios. However, Eigen [11] investigated a large number of these crashes that occurred between 1995 and 2001 using the National Automotive Sampling System Crashworthiness Data System (NASS-CDS). She observed that:

- 81% of all rollover crashes were single vehicle events,
- 71% of these single vehicle rollovers were initiated by the mechanisms known as the trip over

Eigen concluded that the most common form of rollover crash in the US was a single vehicle event initiated by a tripping mechanism, which caused the vehicle to enter a lateral rollover.

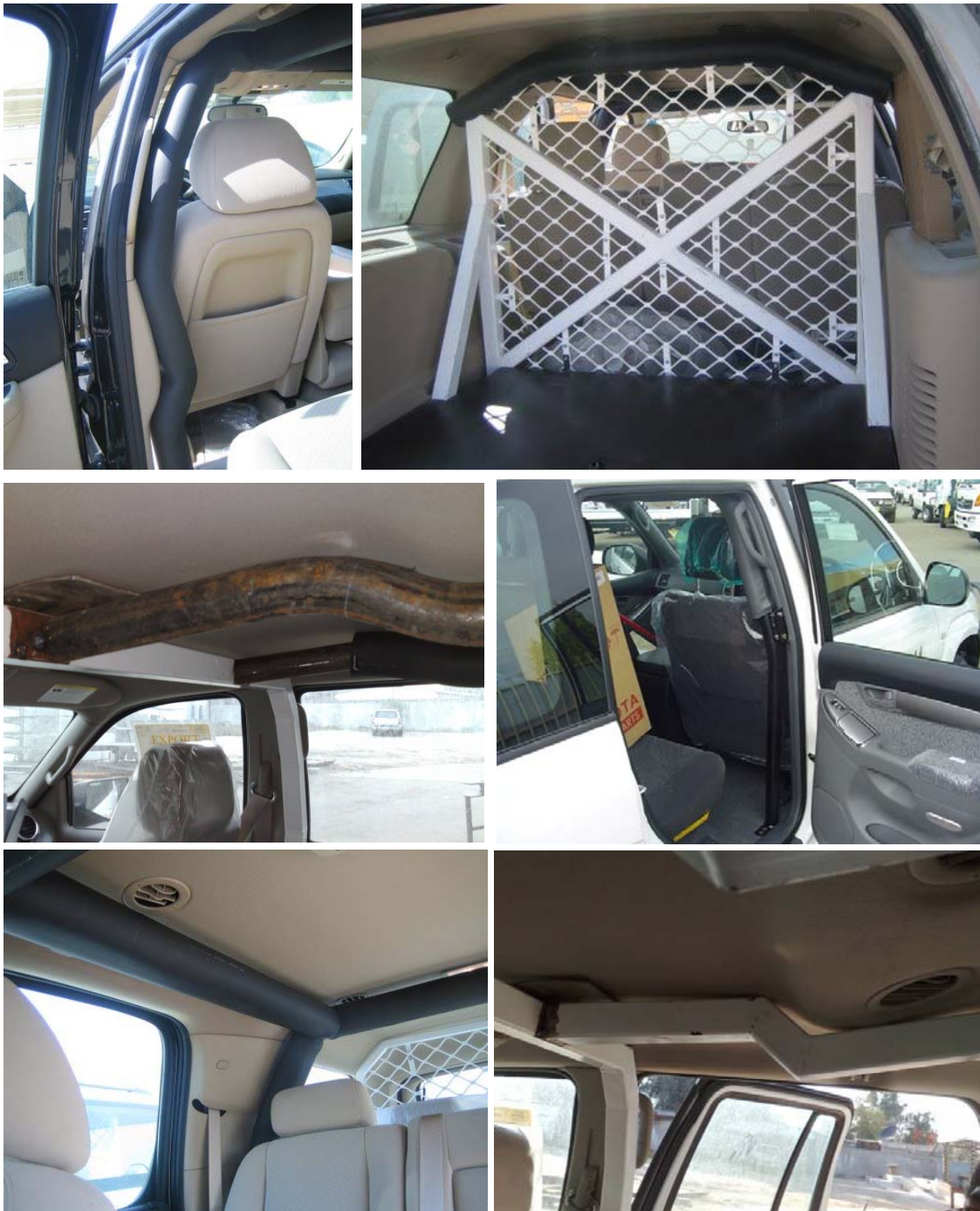


Figure 1: Examples of roof strengthening using internal rollover bars.

Young [1] has also identified, from all Australian rollover crashes in the years 2004 and 2005 where a fatality occurred, the most common mechanisms initiating Australian rollovers where the occupant is contained within the vehicle during a rollover only crash event, are the trip over and turn over.

Digges and Eigen [12] also identified that 8 quarter turns (i.e. two full rolls) or less accounted for more than 90% of all rollover crashes in Single Vehicle Rollovers for Non-Ejected Front Seat Belted

Occupants Ages 12+ and Non-Ejected Front Seat Belted Occupants Ages 12+ with Maximum Abbreviated Injury Score (MAIS) 3+F Injuries.¹

As a result of these observations and how vehicles deform during real world rollovers as shown in Figure 2, Figure 3 and Figure 5, the JRS rollover crash test rig (Figure 6) was developed together with a rollover crash testing protocol. Detailed descriptions of how the test rig functions are described elsewhere [13], [14], [15].



Figure 2: Vehicle reinforced with internal roll bar at B-pillar and external roll bar behind C-pillar. Note buckle of front windshield header rail intruding into occupant compartment.



Figure 3: Note deformation line of A-pillar approximately matches yellow line shown. The line indicates how the vehicle has pitched forward during rollover as a result of the engine mass.

The ends of the vehicle are mounted on towers on an axis of rotation through its Center-of-Gravity (CG). The vehicle is simultaneously rotated and released as a roadbed moves under it. The test starts from an almost vertical orientation to the road bed position similar to that shown in the first frame in Figure 6. During the simultaneous rotation and fall, the vehicle strikes the moving roadbed below on the leading side of roll (near side – frame 3) at the side roof rail at the prescribed roadbed speed, vehicle angular rate, drop height and impact pitch angle. After striking the near side, the vehicle continues to roll and strikes the side opposite to the leading side (far side – frame 4). The vehicle is then captured. The motions of the vehicle and roadway are coordinated so that the touchdown conditions can be controlled and thus repeated within a narrow range.

A 50th percentile Hybrid III Anthropomorphic Test Dummy (ATD) is used to monitor head and neck loads in the driver seat position. String potentiometers are used to measure roof intrusion and intrusion rates, as well as the ATD's motion. High speed cameras also record vehicle and ATD motions. The ATD is setup according to the FMVSS 208 protocol. In the first roll, the vehicle is set at 5° pitch angle whereas in the second roll the vehicle is set at 10° pitch angle. Roll rate at 190° per second, yaw at 10° and roadway speed at 24 km/h (6.7 m/s) are the same for each of the two rolls.

¹ The AIS is a classification system for assessing the impact injury severity. It was developed and published by the Association for the Advancement of Automotive Medicine (AAAM)

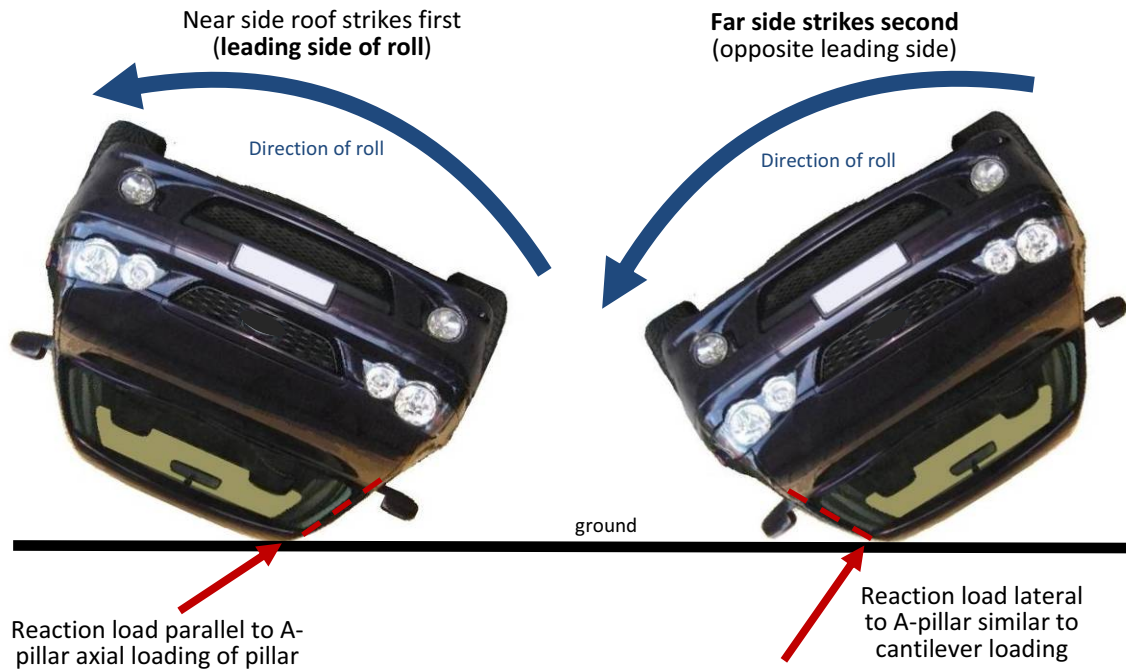


Figure 4: Loads applied to vehicle's roof during rollover.

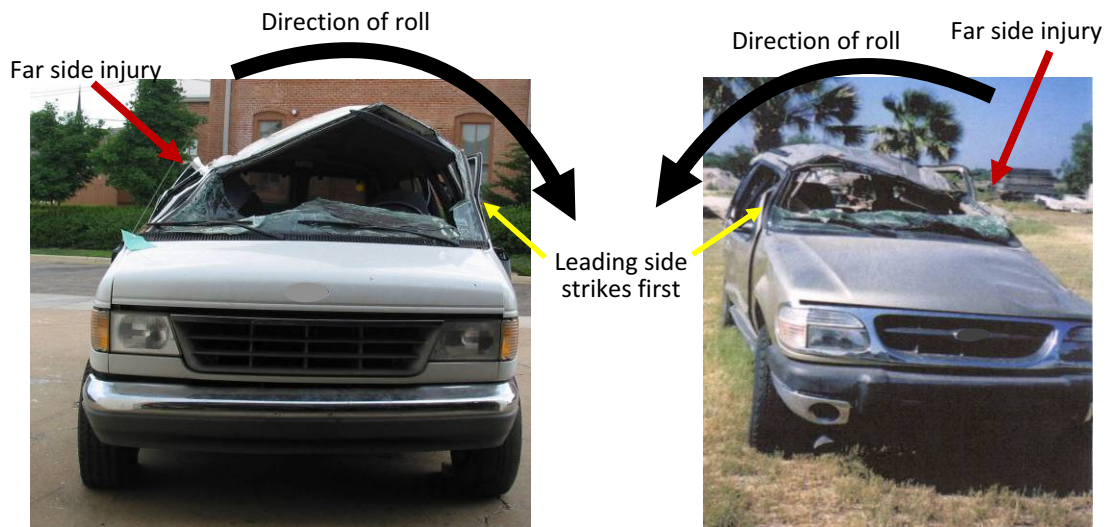


Figure 5: Injuries are usually to occupants seated on far side of rollover where roof crush occurs.

Measured parameters include: motion of the CG; the roll angle and rate; the pitch angle and its variation; the dummy motion relative to the seat through a string pot to the dummy buttocks; the load to the dummy's head and neck; the intrusion of both sides of the roof; and the forces between the vehicle roof, the roadbed and the towers.

Rollover Roof Crush Mechanism

A series of JRS tests were conducted on 5 passenger cars and 5 sports utility vehicles (SUV) by the Center for Injury Research based in Goleta, California. The tests were funded by the Santos Family Foundation through the US Center for Auto Safety. The vehicles were supplied by the US State Farm Insurance Company. Descriptions of the tests and test results are provided elsewhere [16, 17]. The

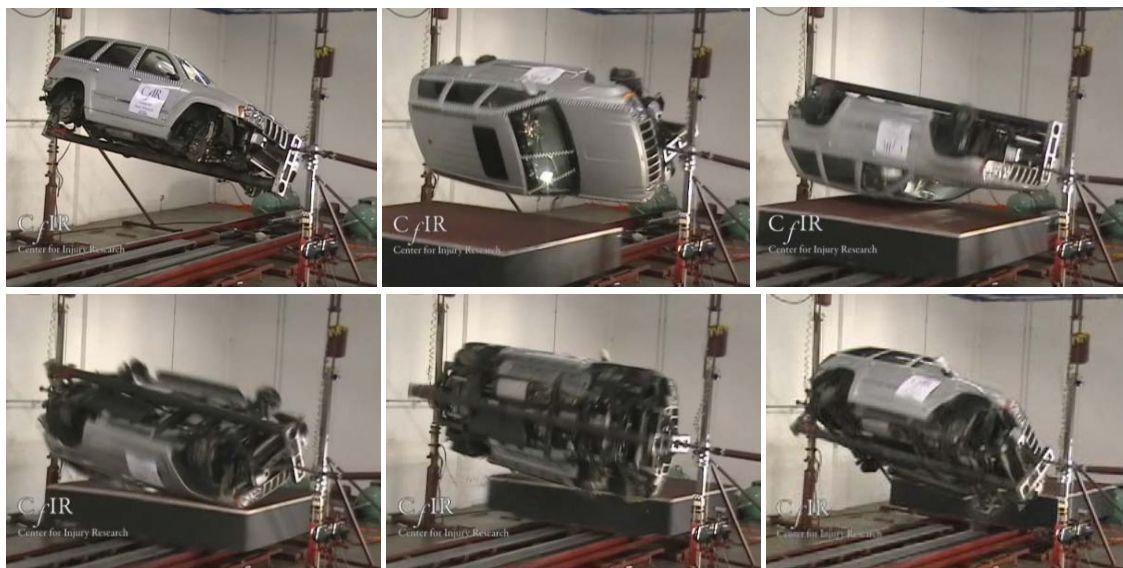


Figure 6: Still frames of a production SUV with SWR of 2.2 subjected to a JRS test (Roll 1). Note: frame 3 near side strikes floor; Frame 4 far side strikes floor.

relationship of the forces between the ground and the roof and the deformation of the roof as a function of roll angle were investigated. High speed films of the tests were also recorded.

This paper focuses on the rollover crash tests carried out on a sample production vehicle with a low roof strength to weight ratio (SWR)² of 2.2, a strong roof vehicle with a SWR of 4.6 and a similar make low roof strength vehicle with a HALO™ prototype attached. Figure 6 shows the low strength vehicle being tested in the JRS. Figure 7 shows exterior and interior views of the roof structure with and without the ATD after two rollover tests. It is clear from Figure 7 there is significant roof crush. The neck loading was significant at around 9.7 kN with a 60% probability of an AIS 3-4 neck injury. ATD neck injury measures are also provided in another paper elsewhere [16].

The test shown in Figure 6 and Figure 7 are of a 2007 production vehicle. To reduce testing costs, an earlier model 1993 vehicle from the same manufacturer was used to fit the HALO™ and compare results to a JRS test of the 1993 production model (Figure 8). Details and discussion concerning this comparison is presented in an earlier paper [17]. The SWR for the 1993 model is 2.3 albeit the roof deformation appeared a little larger than the 2007 model and the neck load was close to 10 kN. This paper focuses on the roof ground contact interaction and how the HALO™ reduces the loads to the roof and the occupant.

Figure 9 shows a view from the high speed video from the floor inertial reference point. Frame 1 ($t=1.712$ sec) shows the vehicle during vertical release. Frame 2 ($t=1.788$) shows near side touch-down. Frame 3 (1.908 sec) shows that the middle of the roof touches down. This touchdown of the middle of the roof is important. It indicates that the vehicle's centre of gravity (CG) about which it rotates continues to move vertically downwards. The radius of rotation about the CG from the moment shown in frame 2 to the moment shown in frame 3 has now reduced by around 10 cm. In frame 4 ($t=1.920$ sec) the far side of the roof comes into contact. It is at this point in the roll the vehicle must raise the CG (increase its radius of rotation) to continue to rotate. In other words, the roof must be strong enough to lift the vehicle back up. Because the roof is weak, it collapses as shown in frames 5 to 9 ($t=1.944$ sec to 1.992 sec). The ATD's head being adjacent to the ground contact gets caught in the buckling roof and remains momentarily stationary (frames 4 to 7 – $t=1.920$ sec to $t=1.960$ sec). The ATD's torso continues to move forward and thus loads the ATD's neck. In frames 7 to 9 ($t=1.960$ sec to 1.992 sec) the roof buckles so much that the ATD's head is thrust upwards relative to the ground. The peak roof intrusion speed relative to the interior of the vehicle was around 12.6 km/hr (3.5 m/sec) [17].

² The strength to weight ratio (SWR) is the load measured at five inches of roof crush divided by the weight of the vehicle during a one-sided quasi static roof crush test. The crush test is carried out using a small platen applied to the A-pillar at a pitch angle of 5° and roll angle of 25°.

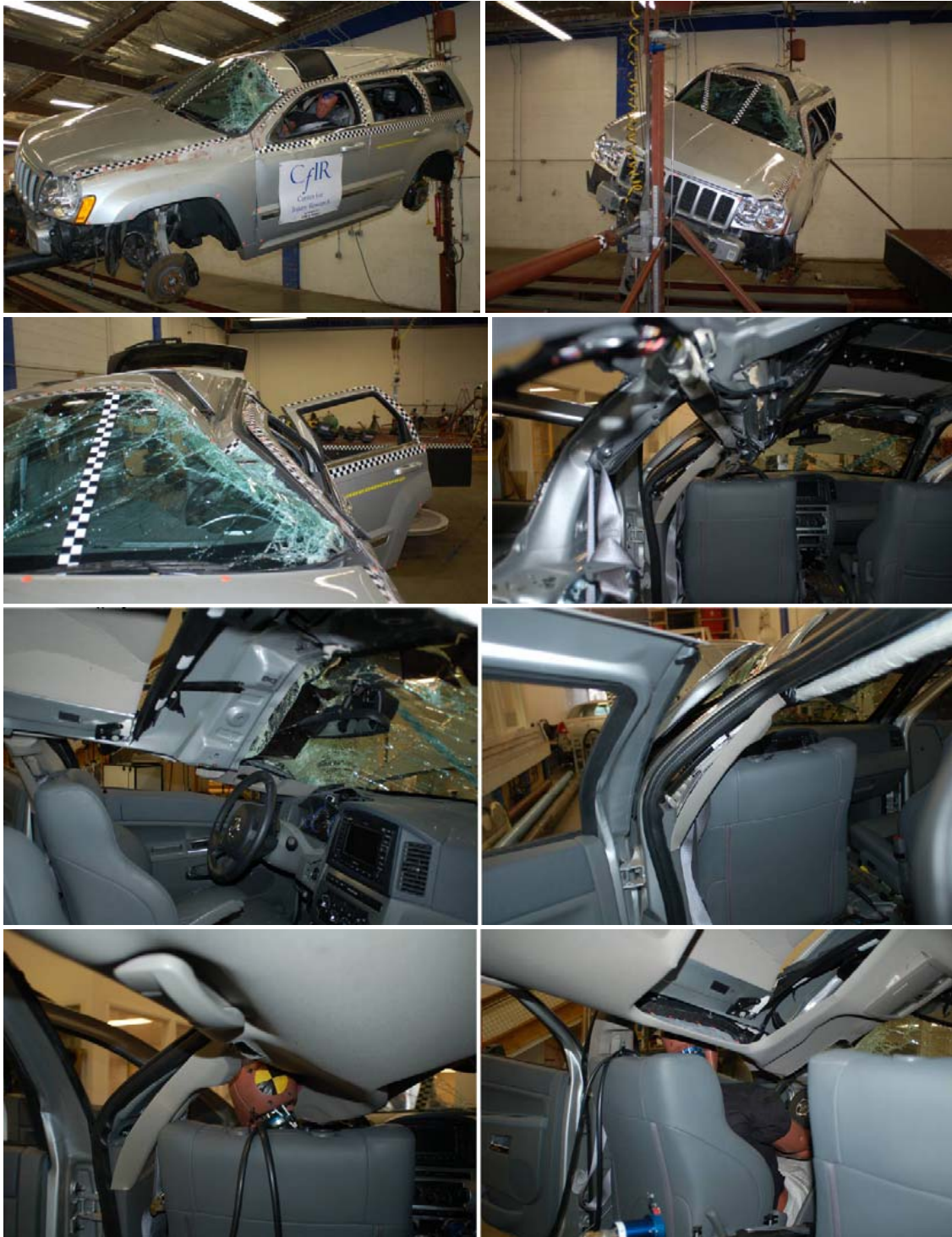


Figure 7: Deformed roof structure of low roof strength (SWR = 2.2) vehicle after roll 2 JRS test.

In the case of a strong roof vehicle, the mechanism loading the ATD's neck is significantly different. Figure 10 shows the individual frames of the roof structure as it contacts the moving floor. What is interesting to note is that the ATD's head does not move relative to the front header rail line during the roll process. Frame 3 ($t=1.900$ sec) also shows the vehicle is airborne at that moment of the roll event. That is, the roof at the midpoint is not in contact with the floor. Hence when the far side of the vehicle comes into contact with the floor in Frames 4 ($t=1.932$ sec) and 5 ($t=1.960$ sec), the amount of lift of the vehicle's CG is not as great as in the case of the weak roof vehicle (Figure 9, Frame 4, $t=1.920$ sec). It



Figure 8: Older 1993 model of vehicle (SWR 2.3) shown in Figure 7.



Figure 9: ATD interaction with low roof strength vehicle's (SWR 2.2) roof and floor during near side and far side touch down.

should be noted that the axial neck load measured by the ATD was 3.6 KN in the second roll and the maximum roof intrusion velocity relative to the vehicle interior was 5.1 km/hr (1.41 m/sec).

It was this observation that led to the concept of fitting a hoop bar (Figure 11) to the outside of the vehicle's roof that helped maintain the vehicle's roll radius. Obviously if the roundness of the roof about the vehicle's CG is maintained, the roll action will be smooth, somewhat similar to that of a round tyre. Figure 12 shows the individual frames of the (1993) low strength roof structure fitted with a HALO™, as it contacts the moving floor. The HALO™ also strengthened the roof. Internal flat plating was attached to the B-pillars to strengthen them as well. The ATD's head is visible in the frames. Note how the vehicle is supported by the round bar when the vehicle is rotated at 180° (T=1.652 sec). The frames show the ATD's head does not move towards the vehicles CG relative to the inside windshield header rail. Transition from the near side to the far side is smooth.

Figure 13 shows the loads measured by the moving floor and roof crush versus roll angle. The dark black line in the plot indicates the vehicle's SWR capacity. The load to weight ratio (LWR – blue line) is a non-dimensional value of the load measured by the floor divided by the vehicle's total weight. The red and green lines indicate roof crush at the far and near side A pillar roof rail connection.

Figure 13 shows that for both (1993 & 2007) low roof strength production vehicles the load demand exceeds the vehicle's A-pillar capacity to sustain the load. The high load peak loads at 205° for the 2007 vehicle and 215° are likely interactions of the vehicle's dash board and side door as a result of complete roof collapse. The load demand for the high roof strength vehicle on the other hand is within the vehicle's pillar load capacity. Moreover, the load peaks for the high roof strength vehicle are uniform, indicating two evenly distributed peaks. On the other hand, the low strength roof vehicle displays uneven



Figure 10: ATD interaction with high roof strength vehicle's (SWR 4.6) roof and floor during near side and far side touch down.



Figure 11: Prototype HALO™ fitted to roof of low strength (1993) vehicle.



Figure 12: ATD interaction with (1993) low roof strength vehicle's (SWR 2.3) roof and floor during near side and far side touch down. ATD's head is circled.

peaks when comparing the near side load interaction with the far side load interaction. The far side load interaction is also very large relative to the vehicles SWR. Of particular note is the plot of the road loads for the (1993) low strength roof vehicle with the HALO™ fitted. It is clear that the roof load is distributed relatively evenly over the whole roll. Moreover, the magnitude of the load has been significantly reduced from a LWR of around 6 to around 2.5.

Figure 13 also shows that for both (1993 & 2007) low roof strength production vehicles, the maximum and residual roof crush is very large in comparison to the high strength vehicle and the vehicle with the HALO™. Indeed the maximum roof crush is an order of magnitude less than the low strength vehicle's maximum roof crush and the residual roof crush for the high strength vehicle is barely discernable.

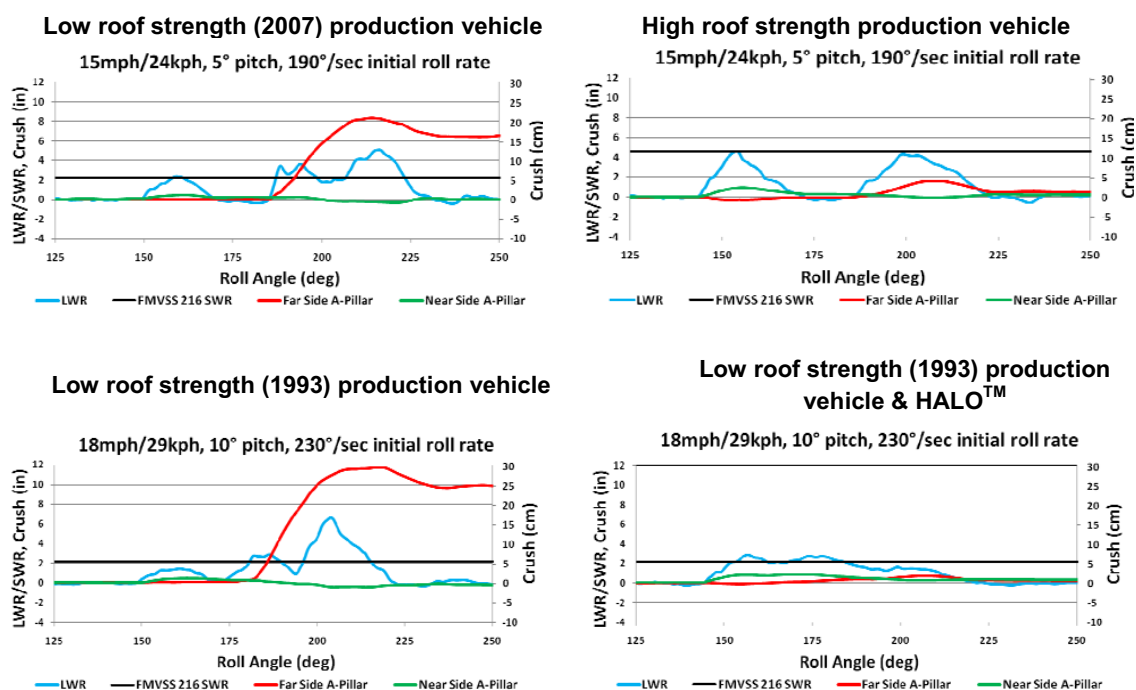


Figure 13: Loads measured in moving floor for: low roof strength (1993 & 2007) production vehicles; high roof strength vehicle; and low roof strength (1993) vehicle with HALO™.

Figure 14 shows three frames in each row from the high speed video taken respectively for the high strength roof vehicle, the low strength (2007) roof vehicle, and the (1993) low strength roof vehicle with the HALO™. The rotation angles were matched (vertically) in the Figure. The yellow line is a reference line drawn relative to the vehicle's rear view mirror. The red circle shows the location of the ATD's head in each frame. The yellow line shows how the vehicle rotates about its CG and how the ATD's head moves relative to the line as well as relative to the moving floor. Figure 14 clearly shows that for the low strength roof vehicle (middle three frames) that the ATD's head moves towards the vehicle's seat base despite the rotation of the vehicle. This is the result of the vehicle's roof buckling and forcing the head inward towards the vehicle's seat base. Figure 14 also shows that the ATD's head is moving away from the floor for the low strength roof whereas in the case of the high strength roof, as well as for the HALO™ reinforced roof vehicle, the ATD's head moves closer to the floor and continues in a circular motion without any violent reverse direction motion.

In the case of the (1993) low strength roof vehicle fitted with the HALO™, the ATD's axial neck load was 1 kN and the peak intrusion velocity was 1.6 km/hr (0.44 m/sec). Clearly when the roof of a vehicle is strengthened, the load imparted onto the occupant as a result of roof crush is significantly reduced. Moreover, the results presented in this paper also demonstrate that loads imparted to an occupant's head and neck when they are seated in the vicinity of where the roof crushes, is causally linked to roof crush.

Conclusions

The results presented show that when both roof crush and a vehicle's centre of gravity fall is prevented, ATD injury measures and road impact loads are significantly reduced. This was demonstrated experimentally using the JRS test rig and a low strength roof vehicle fitted with an external (HALO™) device that provided constant radial support about the vehicle's CG during the rollover event.

The results from the JRS test series also show that occupants seated in a vehicle where the roof crushes above their heads, suffer significantly higher loads to the head and neck than if they were seated in a vehicle with a strong roof. This also clearly indicates that the loads imparted to the head and neck of a seat belted occupant located under a crushing roof, is causally linked to the roof's crush.

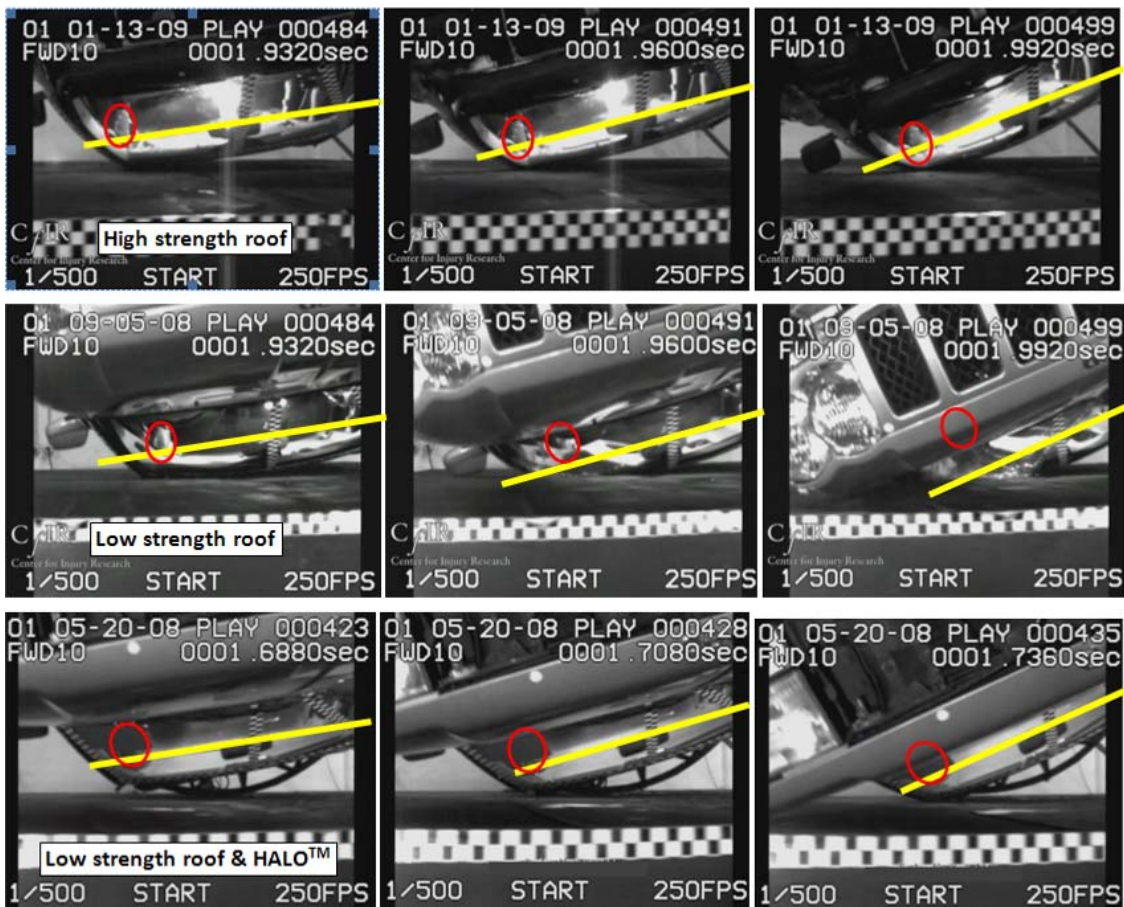


Figure 14: Top row - high strength roof; Middle row: low strength roof;
Bottom row – low strength roof with HALO™

Competing Interests

Raphael Grzebieta is listed on Safety Engineering International's (SEI) website as the General Manager of the Australian Office and has an interest in SEI.

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References

- 1 Young, D., Protecting Occupants In Passenger Vehicle Rollover Crashes, PhD Thesis, Department of Civil engineering, Monash University, 2009.
- 2 Young D., Grzebieta R.H., Rechnitzer G., Bambach M. & Richardson S., Rollover Crash safety: Characteristics and issues, Proceedings 5th Int. Crashworthiness Conf. ICRASH2006, Bolton Institute U.K., Athens, Greece, July 2006.
- 3 Parenteau, C. S., Gopal, M. & Viano, D. C. (2001) Near and Far-Side Adult Front Passenger Kinematics in a Vehicle Rollover. SAE Technical Paper Series. Detroit, Michigan, USA, SAE International.
- 4 Digges, K. H., Eigen, A. M. & Dahdah, S. I. (2005) Injury Patterns In Rollover by Crash Severity. 19th International Conference on the Enhanced Safety of Vehicles. Washington DC, USA.
- 5 Friedman, D. & Nash, C. E. (2005) Reducing Rollover Occupant Injuries: How and How Soon. 19th International Conference on the Enhanced Safety of Vehicles. Washington DC, USA.
- 6 Nash, C. E. & Paskin, A. (2005) A Study of NASS Rollover Cases and the Implication for Federal Regulation. 18th International Conference on the Enhanced Safety of Vehicles. Washington DC, USA.
- 7 Bambach M.R., Tan G. and Grzebieta R.H., Steel spot-welded hat sections with perforations subjected to large deformation pure bending, Thin-Walled Structures, Article in Press, Accepted April 2009.
- 8 Chirwa E. C., Mao M, Chen T, Latchford J, "Flaws in Malibu 1 & 2 Interpretation of test Results That have Influenced Many Poor Rollover Roof Designs", Proc. of The International Crashworthiness Conference ICRASH2006, July 2006, Athens, Greece.
- 9 Gugler J., Steffan H., Lutter G. & Fleischer S. Rollover Scenarios in Europe, Improvement of Rollover Safety for Passenger Vehicles, European Community - R&TD-Project – 5, Framework-Programme "Growth", Results of Work Package 2 "In Depth Accident Analysis".
- 10 Viano, D.C. and C.S. Parenteau, Rollover Crash Sensing and Safety Overview, in SAE World Congress, SAE International, Detroit Michigan, 2004.
- 11 Eigen A.M., Examination of Rollover Crash Mechanisms and Occupant Outcomes, Traffic Safety Facts, Research Note, National Center for Statistics and Analysis, DOT HS 809 692, December 2003, <http://www-nrd.nhtsa.dot.gov/Pubs/809-692.PDF>.
- 12 Digges K.H. and Eigen A.M., Crash Attributes That Influence The Severity Of Rollover Crashes, Proc. 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Nagoya, Japan, May, 2003.
- 13 Jordan A. and Bish J. 2005. "Repeatability Testing of a Dynamic Rollover Test Fixture." 19th International Conference on the Enhanced Safety of Vehicles, Paper Number 05-0362, Washington, DC.
- 14 Friedman, D., C.E. Nash, and J. Bish. 2007. "Observations from Repeatable Dynamic Rollover Tests." International Journal of Crashworthiness 2007, Vol. 12, No. 1, pp. 67-76.
- 15 Friedman, D., C.E. Nash, and J. Caplinger. 2007. "Results from Two Sided Quasi-Static (M216) and Repeatable Dynamic Rollover Tests (JRS) Relative to FMVSS 216 Tests." 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number 07-0361, Lyon, France.
- 16 Friedman, D., and R.H. Grzebieta, A Proposed Rollover and Comprehensive Rating System, 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number 09-0515, Stuttgart, Germany, 2009.
- 17 Friedman, D., and R.H. Grzebieta, Vehicle Roof Geometry and its Effect on Rollover Roof Performance, 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number 07-0361, Stuttgart, Germany, 2009.