Vehicle Roof Structure Design Can Significantly Reduce Occupant Injury

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Abstract - Vehicle design has been driven by sales and marketing factors for many years, with a few exceptions like the brutish looking Hummer Sport Utility Vehicle (SUV) which was marketed for its structural safety. While it's partially true for public customers, consumers of work trucks commercial operations like in the oil, gas and mining industry are a large fleet consumer for dual cab transportations and an even larger segment for simple single cab work trucks. These vehicles are designed to meet the minimum specifications for safety equipment and structural tolerances and therefore can be inadequate in various crash modes. Most manufacturers focus on sales in the US where regulations are design determinants, but outside the US, there are some times little or no minimum safety design regulations. The Mitsubishi Triton and the Toyota Hilux 4 and 2 door pickup vehicles, all of which are not sold in the US, require structural reinforcement for safe operation in these non-ordinary environments. This paper focuses on the design and performance of these work trucks and the means by which rollover safety can be measured and significantly improved.

Keywords: FEM testing, roof reinforcement, external rollover occupant protection system, ROPS, load-bearing, single cab

INTRODUCTION

Recently, sales of light trucks have risen to almost 40% of some Original Equipment Manufacturers (OEM's) annual production. While a significant portion of that light truck production is for public consumers a large portion is for work trucks and commercial operations like in the oil, gas and mining industry. There is demand for a large fleet of dual cab transportation and an even larger segment for simple single cab material work trucks.

Since the onset of automotive safety awareness over 60 years ago the only rollover protection solution to be widely acknowledged and used in these non-ordinary environments has been the traditional internal roll cage. These traditional roll cages have been identified as potentially dangerous in other crash modes such as frontal and side impact. Moreover, such roll cages have become out-of-date and in recent testing were shown to be ineffective at the A-Pillar and windshield header, directly over the driver and front seat occupant.

A device developed and patented in 2008, called the HALO™ Rollover Occupant Protection System [1] has been implemented as an aftermarket fitment to a number of manufacturers' models including the Toyota Hilux, the Ford Ranger and the Mitsubishi L200 Triton in their Dual Cab versions. These Dual Cabs seem to serve a good portion of the off road oil, gas and mining industries. The HALO™ patent provides a formula for the shape (the geometry) of the roof and its attachment to the pillars. It covers both OEM and an aftermarket accessory attachment. The device's performance has been validated using the Jordan Rollover System (JRS) rollover crash test rig and dolly rollover tests [2].
Further validation of the aftermarket version HALO™ on the Triton dual cab was demonstrated by a field rollover crash in Mexico.

This paper focuses on the design and performance of these work trucks and the means by which the roof structure capability can be enhanced and rollover safety can be significantly improved.

OBJECTIVE

To sufficiently modify the geometry of the roof profile of a Single Cab work truck, so as to minimize the roof intrusion in the rollover crash mode.

BACKGROUND

Performance Considerations

Static test results

Although the United States (US) has an upgrade coming in 2016, the current performance requirement in the US for roof strength for small pickup trucks is a static measurement of performance where the roof must withstand one and a half times the vehicle weight in five inches of crush. It is likely that the new requirement would only apply to US vehicles, a small portion of the worldwide fleet. An overview of the test procedure and many test results can be found on the Insurance Institute for Highway Safety (IIHS) website. Outside the United States, little or no regulation exists for roof strength requirements. IIHS released the results of the testing of 5 small Dual Cab trucks on February 4, 2010, this is the last time this vehicle type was rated and they have never tested any Single Cab models. Their press release stated the following in Figure 1.

"As a group, small pickups aren't performing as well as small cars or small SUVs in all of the Institute's safety tests. None of the ones we tested is a top-notch performer across the board. In fact, no small pickup earns our Top Safety Pick award," says Institute senior vice president David Zuby. The Frontier came close to winning the 2010 award, but it's rated acceptable instead of good for protection against neck injury in rear crashes. Nearly 10,000 people a year are killed in rollovers. When vehicles roll, their roofs hit the ground, deform, and crush. Stronger roofs crush less, reducing the risk of injury from contact with the roof itself. Stronger roofs also can prevent people, especially those who aren't using safety belts, from being ejected through windows, windshields, or doors that have broken or opened because the roof deformed. Roofs that don't collapse help keep people inside vehicles when they roll. Rollovers are much more common for SUVs and pickup trucks than for cars. In 2008 almost half (47 percent) of all pickup occupants killed in crashes were in trucks that rolled over. This compares with 58 percent of deaths in SUVs and 25 percent in cars."

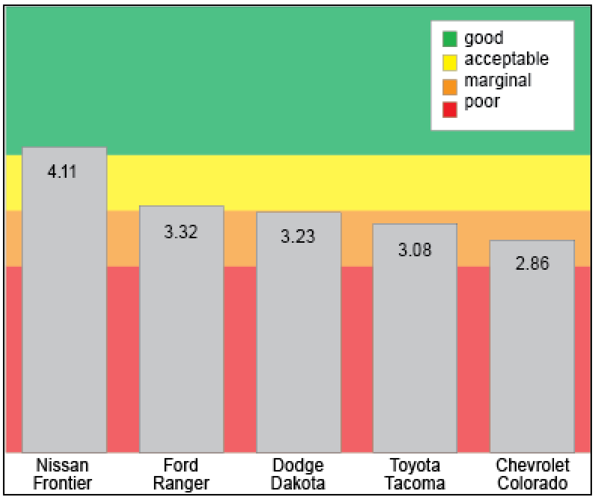

Figure 1. Roof strength-to-weight ratio within 5 inches of crush

It is clear from these numbers that risk of severe injury in pickup trucks is quite high when the crash mode is rollover. Almost half of all the people killed in pickup truck crashes were in rollover events.

Dynamic test results

A dynamic test was performed on an early model extended cab Ford Ranger on the Jordan Rollover System (JRS). The test was performed at specifications that were similar to the JRS testing of SUV's and passenger cars. More details of the test results can be provided upon request to the authors. The Ford Ranger roof structure did not perform well in the test and resulted in 10" of roof crush over the driver's seating position as shown in Figure 2.

Figure 2. Dynamic testing results of an early model Ford Ranger

Design Considerations

The geometry of the roof has a substantial effect on the roof-to-ground loading and therefore roof crush. The test graphs in Figure 3 show the near- and far-side loading of a 1993 Jeep Grand Cherokee in a dynamic rollover test and result in almost 30 cm (12 inches) of deformation at the A-pillar. Figure 4 shows the loading and negligible deformation of 3cm (3/4") of an identical vehicle with a simple modification (i.e., rounding the roof geometry longitudinally and some strengthening of the B-pillar). The vehicle was rolled two more times with no significant additional roof crush. This geometry change was achieved by installing an innovative patented aftermarket device, the HALO™ ROPS, used by the Oil Gas and Mining industry.

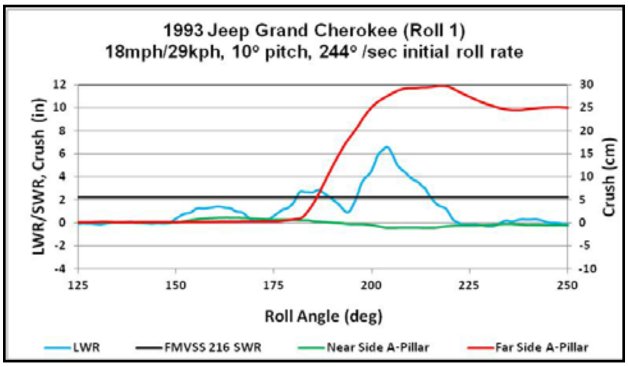

Figure 3. Red Line = Far Side A-Pillar intrusion for Production Jeep in Dynamic Rollover Testing.

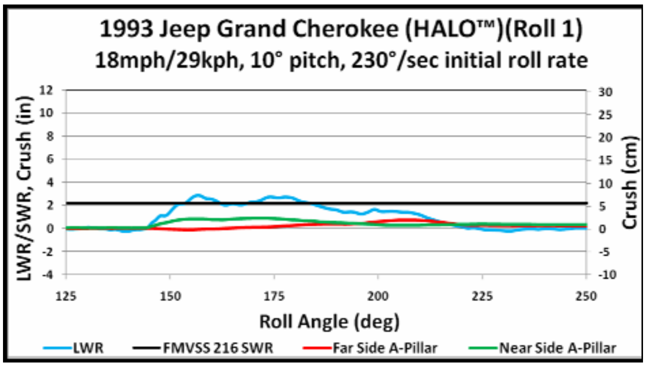

Figure 4. Far Side A-Pillar intrusion for HALO™ equipped Jeep in Dynamic Rollover Testing.

Real World Rollover Crash

Modifying the geometry of the vehicle was further shown to be effective in a real world crash of a 2011 Mitsubishi L200 Triton Dual Cab truck that occurred in Hidalgo, Mexico. Photos of the vehicle at rest and then being pulled from the roadside are shown in Figures 5-8. There was minimal crush to the roof and the windows remain intact. Both the driver and passenger were uninjured.

Except from the incident report:

" …employee reports the following details about vehicle incident: Employee was driving with another passenger on highway about 25 km/h and while negotiating a curve, the employee noticed the truck was losing power and accelerated to avoid it from turning off. Employee accelerated to 35 km/h and just ending the curve, employee noticed there were some diesel tanks located at the side of the road and to avoid collision with these, he swerved to the left losing control of the vehicle, colliding with the mountain causing the vehicle to roll over. The vehicle was severely damaged but no injuries to the driver neither the passenger." ***Resolution Details:*** *The employee was re-evaluated by our traffic specialists and it was determined that the employee is not qualified to drive a company vehicle.* ***Investigation Required:*** *No,* ***Reason Investigation Not Required:*** *No injuries occurred"*

Figure 5. Post Rollover Position

Figure 6. Being dragged from ditch

Figure 7. Vehicle balanced on HALO™ ROPS

Figure 8. Vehicle after being righted

METHOD

A Dual Cab truck with occupants in the rear seats generally results in a neutrally pitched rollover. That's not the case for a Single Cab truck which is generally negatively pitched in a rollover and sometimes by more than 10º. Due to the weakness in the A-Pillar and windshield header, and from our experiences with the Dual Cab trucks, it was concluded that the only effective means of protecting front seat occupants in a Single Cab truck in a rollover is to preclude ground contact with the A-pillar.

Considerations

The main difference between the Dual Cab and the Single Cab versions of vehicles is the loss of the most rearward pillar in a Dual Cab, usually referred to as the C-Pillar. Therefore, the Dual Cab HALO™ design rear feet have no connection point on a Single Cab truck. An initial HALO™ design was attempted with a new C-Pillar built into the bed of the truck. Although this method would work and was an easy way to mount the rear of the HALO™, it was found that significant enough variations in the production vehicles occur and therefore it could not be counted on that the bed and cab would always line up.

Additionally, some testing on the amount of movement between the cab and the bed showed that there could be as much as 15 mm of movement in any direction from regular driving. The forces that would be exerted on the truck sheet metal with the externally mounted structure could potentially result in vehicle body cracking, as we have seen from other "in the bed" mounted ROPS devices. Therefore, placement of the rear supports in the bed of the truck was unacceptable.

RESULTS

The HALO™ for the 2012 Toyota Hilux Single Cab was designed using the same methodology as the Dual Cab and Sport Utility Vehicle to protect front seat occupants. The Single Cab design adds reinforcements to the B-pillars and a rear panel and roll hoop to substitute for the rear compartment structure of the Dual Cab design. The reinforcement to the B pillar is more robust than in the Dual Cab and additional cross member attachments are used to tie the whole unit together. As in the Dual Cab, substantial forward pitched roll forces are taken up by the HALO™/B-Pillar and the top of the front fender and hood, protecting the weak A-pillar from collapsing. The B-Pillar is first "re-skinned" with a 3mm thick plate which is riveted to the inside B-Pillar skin shown in Figure 9. This reinforces the interior skin of the B-Pillar and increases the local section modulus. The B-Pillar "skin" utilizes a 10mm tall weld boss which is welded to the 3mm plate to space out a second 5mm thick plate for providing additional column strength to the pillar. This essentially provides what is equivalent to adding a second "thin walled" tube to the pillar for reinforcement.

Figure 9. Single Cab HALO™ B-Pillar Reinforcement

As a result of the complexity of the B-Pillar and cross-member system and the potential variations in the production vehicles, the attachments had to have some level of adjustment. The cross-member to B-Pillar attachment bracket has some sliding adjustments built in for ease of fitment as shown in Figure 10.

Figure 10. Built in adjustment for variations in OEM products

Both B-Pillars are tied together through a cross-member which spans horizontally behind the driver and passenger seats as shown in Figure 11. This section is also tied in to the new rear mounted roll hoop via an "L" type brackets on the interior of the vehicle. This was designed so as to allow full seat adjustment as per the production vehicle specifications. This cross-member is riveted to the rear panel of the cab and tied to the B-Pillar reinforcements, to minimize cab distortion, prevent B-Pillar buckling, and limit match-boxing.

Figure 11. Single-Cab HALO™ B-Pillar Cross-member

A new rear mounted roll hoop was designed and placed above the truck bed and around the rear window. This new roll hoop functions as the "C-Pillar" of the vehicle and is supported by robust base plates attached to a cross plate that spans the rear of the cab. The rear feet of the HALO™ roof top component is mounted to this rear roll hoop as shown in Figure 12.

Figure 12. HALO™ roof top mounts to rear roll hoop

PERFORMANCE

The performance of the Single Cab in a rollover was evaluated by using the Solidworks Finite Element Model in a variety of lateral impact modes much in the same way as the Jeep Grand Cherokee was tested. Figure 13 is the resulting model after the simulation, showing that the Single Cab had only a few inches of deformation at the A- and B-Pillars and in fact reduced the crush versus the production vehicle by approximately 83% at the A-pillar and 92% at the B-Pillar and 90% at the head location.

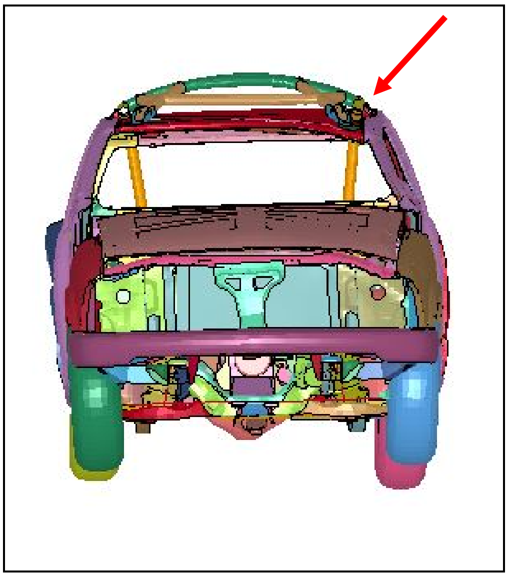

Figure 13. Finite element analysis model test run results of Single Cab with HALO™

CONCLUSION

The conclusion that can be drawn from the FEM analysis and the crash investigation presented is that the HALO™ system is effective in reducing roof crush over the front seat occupants, particularly at the A-pillar location. In effect the HALO™ system changes the roof geometry such that the amount of load the roof is subjected to during a rollover crash is reduced substantially when compared to a an equivalent vehicle albeit with square shape roof structure. Rounded roof shapes, where the vehicle rolls about the major radius, allow the vehicle to roll like a cylinder and will have the least point loading on the roof structure, preventing a single pillar or header from taking the majority of the load. This distribution of the loads across the entire vehicle significantly reduces roof collapse, preventing occupant injury.

ACKNOWLEDGEMENTS

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REFERENCES

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