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Forensic Engineering Investigation of Roof Failure in Rollovers

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Abstract

During automotive rollover, the preservation of the occupant survival space is a critical aspect of crashworthiness. This paper examines the forensic aspects of roof performance to include forensic indicators, failure mechanisms, occupant injury, and legal aspects. The level of expected impact force and current state of technology are reviewed. The "reasonable alternative design" is discussed along with case studies.

Keywords

Roof strength, rollover, crashworthiness, diving injury

Introduction

Roof crush is recognized as a safety issue in passenger vehicles. Saab, Volvo, Mercedes-Benz, and BMW have all highlighted their roof strength in marketing campaigns at one time or another[1]. In fact, in their exuberance, Volvo's marketing agency created a television advertisement that showed an oversized truck driving over a row of numerous vehicles; only the Volvo sedan withstood the loading. It was later revealed that the particular Volvo "tested" (and the Volvo only) had had its roof strengthened at the direction of the advertising agency[2]. In fact, while Europe has no codified roof crush standards, all of the European manufacturers listed above perform dynamic rollover tests.

Regulatory Aspects

The American regulation governing the laboratory performance of most passenger automobile roofs is found in the Code of Federal Regulation, *49 CFR Ch. V, 571.216 Standard 216; Roof Crush Resistance*[3]. The FMVSS-216 replaced the FMVSS-208 provision for a dolly rollover test, and is generally used instead of the now-rescinded SAE recommended practice J996, *Inverted Drop Test*. The 216 pre-amble states, "The purpose of this amendment…is to add a new Motor Vehicle Safety Standard…that sets minimum strength requirements for a passenger car roof **to reduce the likelihood of roof collapse in a rollover accident**" (emphasis added). Kahane[4] of NHTSA restated this commitment to roof integrity, indicating that, "*The relationship between roof crush and occupant injury is self-evident and supported by statistics*." Baccouche[5] gave a concurring statement, "The crush resistance of roof structures is critical to minimizing injuries and enhancing occupant survival during rollover crashes." Of note, the automotive industry has historically installed roll cages in developmental vehicles to increase the safety of the test drivers, as documented below.

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Heavy commercial vehicles are not regulated for roof strength. This produces predictable results. The roofs of many Class VIII trucks are little more than aluminum and/or fiberglass tents that are designed to keep out the elements, but have no appreciable rollover strength.

Roof Failure in Rollover

Crashworthiness of transports has been a scientific study since at least 1952 when Hugh DeHaven published his treatise on occupant survival during crashes of airplanes and automobiles[9]. Franchini[10] of Fiat was the first to use the term, "occupant survival space," which is a rather straightforward engineering analysis of the amount of volume necessary for occupants to survive collisions without encroachment. This theme was repeated the following year by a representative of Peugeot[11], who gave a bit of historical perspective, "Before the fifties, the goal sought after was an absence of deformation of the whole car. That was a legacy of wood construction…It has been very long and painful to demonstrate to journalists, customers and even technicians that if the lives of cars' occupants were to be preserved two conditions had to be satisfied:

1. Maintain a "survival volume" in the passenger's compartment.
2. But absorb kinematic energy in such a way that the residual energy transmitted to the said passenger compartment be as little as possible."

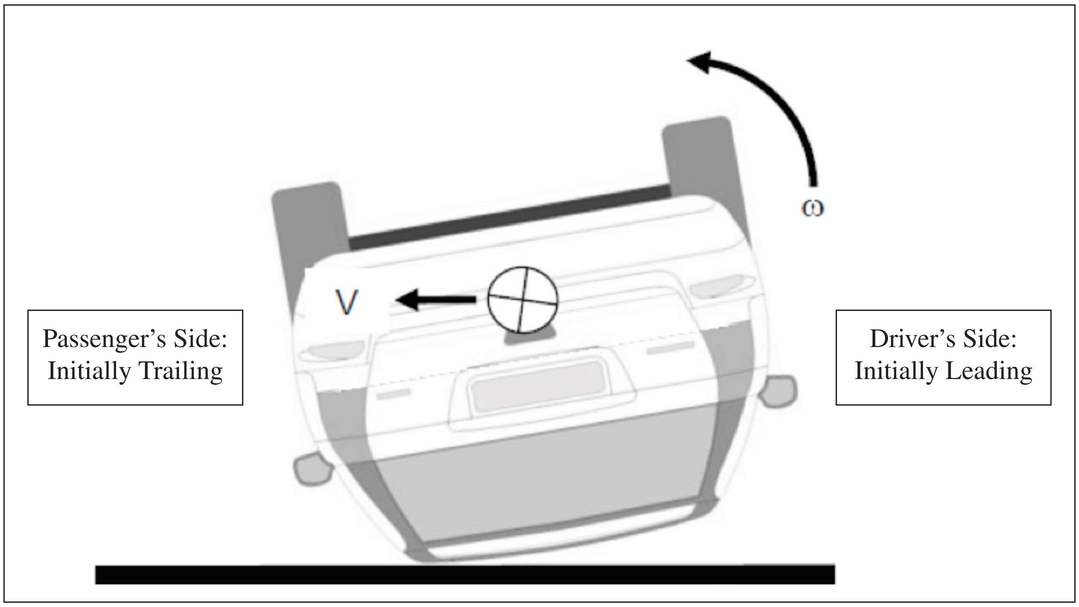
The failure of the roof through deformation both intrudes into the occupant's survival space and breaks windows, facilitating ejection. An analysis of rollover kinematics and accidents shows that there are two disproportionately

Corvette on GM test track with roll cage[6].

First generation production Ford Explorer in stability testing[7].

Fatal rollover of a 2007 Kenworth tractor
showing loss of roof integrity[8].

severe impacts to roofs[12]. The first type is the initial significant roof engagement in friction-tripped barrel rollovers. The unloading of the suspension on the leading side of the vehicle causes the initially leading rail of the roof to typically receive only minor or no contact force. The initially trailing side typically receives a much more forceful initial impact, and frequently "matchboxes" the roof downward and toward the initially leading side. This deformation can usually act as a reliable indicator of the initially leading side. The second significant impact type occurs when the vehicle comes to rest on the roof and the sliding friction that had previously acted now transitions to the more vigorous static friction. The researchers Segal and McGrath[13] wrote that significant roof crush is more closely associated with vehicles landing on the roof than on the number of roll quarters.



Roof contact in barrel rollover showing that the passenger's side of the roof receives the first major impact during this driver's side leading rollover[12].

Requisite Roof Strength

Experience from both on and off road racing shows that the very stiff, strong roofs provide their occupants with a great deal of protection. However, it is reasonable to suppose that these vehicles have roofs designed not only to handle their own weight, but even great forces from impacts due to the other vehicles and some fixed objects like the spectator stands. It is unlikely that production roofs will ever be built that will sustain essentially no deformation in rollover collisions regardless of the number of rolls.

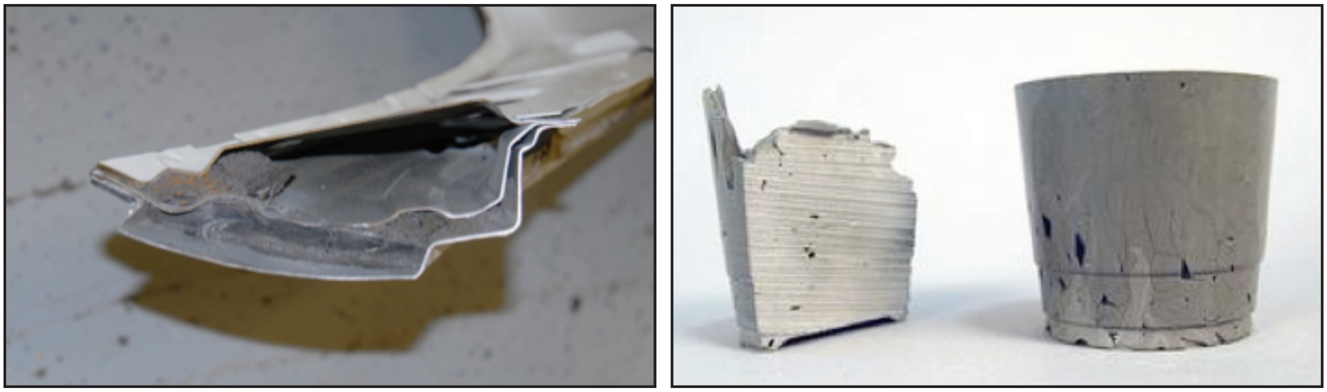
Batzer[14] showed that while the force that the roof applies to the ground is chaotic and somewhat unpredictable, significant impacts range between twice up to three times the vehicle's weight. By designing the roof to meet this three times vehicle weight plus a factor of safety, a robust roof is designed. Of further benefit, when a roof is substantially stronger than the current law requires, the windshield (which provides significant strength) receives less damage and can provide greater reinforcement to the roof by transferring loads from one side of the vehicle to the other, ensuring that both A-pillars are engaged.

Design Elements of Rollover Crashworthy Roofs

Manufacturers have never contended that they cannot make strong roofs, such as roofs strong enough to be used in rally car racing. They merely contend that such an activity would have no statistically significant impact on occupant injuries or deaths; or *worse*, that stronger roofed vehicles would be top-heavier and more rollover prone, increasing the number of rolls, and actually increasing the risk to the occupants. This is a qualitative claim made without quantification. Therefore, production roofs are just as strong as the respective corporate policy dictates.

The structural components of a roof typically weigh on the order of 100 lbs, representing ~ 3% of the mass of the vehicle. This means that only a small fraction of the vehicle's mass is purpose-designed to protect the very essence of its occupants – the cranium, neck and spine – which resides above the windowsill level. A review of available technical fixes was given by Herbst, et al.[15], all low-tech improvements that can be made at reasonable wholesale cost:

1. **Stronger steel** in the form of any number of commercially available high strength low alloy (HSLA) grades, "bake hardenable" formulations, or "boron" steels can be used to replace lower strength plain carbon grades in key stampings in the pillar and rail structures. This does not need to be a large amount of steel for the overall vehicle.
2. **Thicker steel** can be used for individual stampings to attain the same function as stronger steel, substituting mass for tensile strength.
3. **Gussets** at the roof rails and pillar intersections can dramatically increase the cross-sectional moment of inertia and the strength of these key components.
4. **Closed sections** in the header and pillars rather than open sections to improve the strength disproportionately to the increase in mass required.
5. **Fewer cutouts** and holes within structural for secondary functions (e.g., wiring, hardware mounting). Holes placed in tubular sections (present for a variety of design and manufacturing reasons) significantly weaken these tubes in bending.
6. **Rigid foam** can be applied to weak points of linear members to prevent column buckling. Thin-wall segments are inherently susceptible to collapse. Foam can be added during assembly to pillars and side and head rails cost effectively and quickly. This material will add strength, rigidity, and reduce vibration. Foam is currently used for NVH (Noise, Vibration and Harshness) attenuation in many automobiles. Lilley and Mani[16] studied foam additions to hollow structural sections, and confirmed the assertion that filling A and B pillar sections with foam increased their strength. Higher densities of polymer yielded stronger, stiffer structures. For a mass penalty of 1.24 kg per vehicle, foam could be applied to the B-pillars and realize a 14% roof strength increase. As early as 1974, Fiat used structural foam in the A-pillars of their Experimental Safety Vehicle, with good results[17].



(L) Dampening foam (soft and lightweight) to reduce noise, vibration, harshness.
(R) Structural foam (rigid and dense) to support void spaces and increase crashworthiness.

7. **Stiffening ribs** inside of pillars can do the same thing as does rigid foam. This increases the sectional density of the column without affecting the existing parts.
8. **Triangulation of the A-pillar** as per older vehicles. Late model Aerostar vans featured these "quarter lites" (AKA "whale eye" windows), which would (or could) significantly strengthen the A-pillar.
9. **Seam welding** of intersecting stampings in which the entire intersecting lap is fused. This would replace the small resistance spot welded "buttons."
10. **Reinforced doors.** Window frames provide significant strength to the roof. Doorframe locks at the top of the can be made to lock to the roof rails. This is done on the "half" doors present on several extended cab pickup trucks. This would link the door to the roof, allowing the doorframe to absorb loading, and also to prevent the door from peeling away from the roof during rollover.

Case Study 1 – Catastrophic Roof Loss

This was a single vehicle accident that occurred in the eastbound lanes and south roadside of Interstate 84 in Utah on September 26, 2005. The van had just completed passing another vehicle. At a point after the passing maneuver, when the van driver was reentering the right (outside) travel lane; the left rear tire began to experience a tread separation. Following the tread separation, the van exited the right (south) side of the road, as it was experiencing a clockwise yaw. After leaving the pavement, the van rolled over

1994 Dodge Ram Van, 3 rolls, driver's side leading, roof avulsiongrity[18].

in a driver's side leading roll. The van rolled down a hillside and came to rest on a small outcrop above a ravine. During the rollover event all eleven of the van occupants were ejected, resulting in nine of them dying. The vehicle's roof had 80+% spot weld failure at the drip line.

Case Study 2 – Crush due to Insufficient Strength

On July 30, 2006, two young men were in a 1995 BMW 325is on Blue Star Memorial Highway in Maryland. The vehicle traveling to their front made an erratic lane change which caused the BMW driver to conduct an accident avoidance maneuver. His vehicle exited the roadway to the right side of the road and rolled over. The front right passenger, though belted and retained in the vehicle, received a spinal injury due to roof crush during the single contact of the roof above his head.

1995 BMW 325is. The roof has been cut off by first responders and placed back into position for this photograph[19].

Case Study 3 –Matched Pair Occupant Comparison

It has been claimed that automotive roof crush is irrelevant as an injury mechanism in rollover, as the injuries that are sustained are "diving" injuries in which torso augmentation compresses and injures the neck[20]. This narrative is without field confirmation[21]. Further, this counter-intuitive theory is not supported by matched pair comparisons such as the following.

On October 10, 2006, the driver of a group of car poolers was driving a 2003 Ford Taurus northbound on the Dallas North Tollway. In the vehicle with him were three passengers. The driver encountered standing water on the roadway and lost directional control of the vehicle. The vehicle yawed clockwise and traveled to the right at which time it struck and climbed a concrete bridge barrier. The Taurus traveled along the barrier until the right rear corner struck a utility pole, and it rolled passenger's side

2003 Ford Taurus, ½ roll[22].

leading. The Taurus rolled onto its roof and slid to its final point of rest. The driver was fatally injured due to roof crush as his head was forced down, resulting in multi-level skeletal/ligamentous injuries to his cervical and thoracic spine. The deformation was so great that his chin fractured his sternum. The occupant seated behind him underwent the same "diving" kinematics **without** consequential roof crush, and he walked away uninjured.

Case Study 4 – Rollover Crashworthy Roof

According to Perrone[23], "The efficacy of strong roofs is perhaps best demonstrated by a 2001 Subaru accident which underwent a rollover at approximately 55 mph and rolled laterally almost the distance of a football field. The 70- year-old 5'6" female driver and 69-year-old 6' male passenger both exited the vehicle under their own power after the vehicle came to rest in an upright mode [NASS case number 2002-078-044]."

Left and right oblique views of 2001 Subaru Forester.

Conclusions

The need for roofs that better resist intrusion in rollovers is now recognized by the U.S. Federal government. The newest Federal Motor Vehicle Safety Standard (FMVSS) 216 "Roof Crush Resistance" requires that passenger roofs will resist intrusion with at least twice as much strength as those produced under the previous standard[24]. The first three case studies shown above represent automobile accidents in which inadequate roof strength led to preventable life-altering injury and death.

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