

Flaws in Malibu I and II interpretation of test results that have influenced many poor rollover roof designs

E C Chirwa, M Mao, T Chen, J Latchford

Bolton Automotive & Aerospace Research Group, Department of Engineering & safety, The University of Bolton,
Deane Road, Bolton BL3 5AB, UK

Abstract – The majority of recorded world rollover accidents show the final roof deformation to be characterized by catastrophic intrusion into the safety cell. This roof collapse mechanism is still the subject of intense debate as to whether occupant fatalities, severe injuries such as quadriplegia, paraplegic, and brain injuries observed in some occupants after rollover are the consequence of roof intrusion.

This paper for the first time proves that there is a causal relationship between roof intrusion and Injuries sustained by occupants. To achieve this solution, it was necessary to revisit the Malibu I and II rollover experimental tests carried out by General Motors more than 20 years ago. Using forensic methodologies with simple mathematical operations, it was shown that the original Malibu I and II interpretations of experimental test results were flawed because test engineers misunderstood the results they had obtained from the conducted tests. The Malibu I and II results themselves prove that there is a 100% causal relationship between the high neck loading that was recorded by the dummy's neck and the roof intrusion.

In order to prove that is the case, the famous Figure 13 in SAE paper 902314 [10] that gives roof crush and neck loading with respect to time was digitised for the first time and the roof crush curve differentiated twice to obtain the roof acceleration characteristic. This roof acceleration curve shows to have peaked at precisely the same time as the peak neck loading and at this same time the roof was intruding into the safety cell at a rate of 1.952 mph. Finally the proof has been derived; unfortunately, this has come more than twenty years later after which all cars with poorly designed roofs on the roads today have based their roof design philosophy on the misinterpreted Malibu results and conclusions.

Keywords: Roof crush, rate of intrusion, crashworthiness, Malibu I & II tests, load path, collapse mechanism, head and neck injuries, rollover

INTRODUCTION

Rollover accident scenario continues to be one of the sources of occupant serious injury threat. Statistical analysis shows that all road user casualties in Great Britain during 2000, 12,005 (4%) were injured occupants of cars that had an element of rollover. For killed or seriously injured (KSI) casualties, this figure was 2,320 (6% of all KSI road user casualties). The fatality rate rose from 0.8% for all car casualties to 2.0% for casualties in a car that had an element of rollover, hence accounting for 245 fatalities in year 2000. Of all cars that had fatal occupant or occupants, 15% had an element of rollover. The overall KSI casualty rate for cars in crashes with an element of rollover was much higher at 19% than for non-rollover cars at 9% [1-2].

In the USA, the NASS and FARS 1999 accident data show an exponentially increasing number of fatalities and seriously injured occupants in rollover accidents that has reached 6,934 in 1999 as compared to 1,400 in 1969 [3]. This is a large increase that is causing concern among the US car safety authorities. Indeed, the statistics also illustrate that about 26% of rollover crashes have roof intrusions within the safety cell and that may have potentially contributed to occupant serious or fatal injuries. In addition, the data show the effect of rollovers on injuries to be closely related to higher crash speed. This latter phenomenon was observed earlier by Terhune when the North Carolina Accident Database and National Accident Sampling System (NASS) data were used in determining the relationship between speed and rollover severity [4].

Still the subject of intense debate is the relationship between roof intrusion and occupant injury. No one disputes that rollover crashes are associated with high rates of serious injury and high-up in these data are roof crush and occupant ejection. Garrett in his work of rollovers in rural United States re-emphasized these findings [5].

However, in 1970 Mackay and Tampen [6] disagreed with Garrett findings and said that roof crush and injury level were not necessarily related because both could be consequences of high collision forces. It has now transpired that this conclusion was not correct as Friedman and Nash paper [7] have

shown that this is a myth since many rollovers actually induce low forces. In addition, real world accident data over the last 30 – 37 years show occupants being fatally and seriously injured in rollovers by roof intrusions [7].

The understanding of causal relationship between roof crush and head-neck injury was different in the mid seventies when the diving theory was proposed by General Motors or to be specific by their employee Moffatt [8]. This non-quantified theory that described the way occupants attributed injuries in rollover was flawed from start. To satisfy the management, General Motors test engineers decided to experimentally test Moffatt's theory in 1983 [9] and again in 1987 [10]. These tests became to be known as Malibu I & II and they have ever since influenced roof designs of most cars on the road today based on the following misconstrued specific outcomes from the test results presented in [9] and [10]:

- Roof deformation is not related to injury severity. This is now known to be based on diving theory that is flawed.
- There is no correlation between roof crush and injurious biomechanical loads. This is now known to be based on poor interpretation of results that was misunderstood.
- When the roof contacts the ground, peak neck compression loads occur prior to any substantial roof deformation. This is not correct, because it is now known that roof acceleration peaked precisely at the same time as the neck load and the roof velocity was greater than zero.
- Research to date has found that roof crush is not causally related to injuries in typical rollover crashes. Not correct, because research has found that roof intrusion is causally related to injuries if results are properly interpreted.

In this paper, forensic methodologies are used on Malibu experimental test results together with some mathematical operations to show that there is a causally relationship between roof intrusion and occupant injuries. The paper also illustrates some extremely poor roof designs that continue to claim lives and in some cases result in occupants after rollover to have permanent disability such as quadriplegia, paraplegic, and brain injuries.

THE FUNCTIONS OF ROOF STRUCTURE IN VEHICLES

In general roof structures have two main functions: (i) to protect occupants from the outside environmental conditions and (ii) to protect occupants by performing work in case of an accident scenario that involves the upper vehicle body.

The second function is the debate of this paper as occupant protection within the vicinity of a vehicle confinement is paramount. In rollover accident the roof should be able to protect the occupants by performing the following duties:

- Upon contact with the ground, the roof must maintain its integrity by delaying the entire roof deformation in the first few milliseconds. The reason being this time period experiences peak loads both in roof structure and occupants. The Malibu I & II results show this effect as it will be seen later.
- The roof must be capable of effectively and efficiently transfer impact forces from the point of roof loading to other structural parts of the vehicle that are not loaded. By performing this task adequately, the roof will maintain its safety cell longer and at the same time will be able to control the deformation to offer that optimised collapse mechanism with the highest rate of energy absorption. The roof structure must be strong with adequate stiffness to be able to

carry out the load transfer function at the same time absorb kinetic energy necessary to maintain the safety cell. The main structural components, namely the A-pillar, B-pillar, C-Pillar, D-pillar if it exists and all roof rails must be designed in such a way that they resist the impact forces by collapsing in a mechanism that efficiently absorb the kinetic energy at the same time maintain the safety cell.

- The local Cartesian co-ordinates of the structural members in the roof must be strategically located within the global vehicle geometry to offer optimised safety. The best roof design that maximises occupant protection is the one that has all its pillars local vertical co-ordinates closer to the global Z-axis. What this does is to keep the pillars away from the bending or swing line and hence tremendously reduce the rate of rotation of plastic hinges that absorb most of the energy in rollover. Many modern cars have aerodynamic effects to reduce drag that subsequently reduce fuel consumption. The A-pillars in these streamlined roof structures are at angles less than 45° to the global longitudinal axes. Unfortunately, this search for reduced fuel consumption has resulted in weakening the A-pillars as they are greatly susceptible to bending under small loads.
- The philosophy of reinforcing roof structures must not be taken in isolation when searching for solutions to roof intrusion problems. The design geometry of the load carrying structural members of the roof in conjunction with the whole vehicle must be taken as a system that has constantly open load paths for effective and efficient transfer of loads. The excessive use of cut-outs in load carrying members must at all cost be avoided, because of high stress concentrations developed about them that tremendously reduce the load carrying capability and hence precipitate earlier collapse with very little work done.

Roof design considerations

Before any vehicle structural design can be considered, many factors need to be addressed including the integrity and load carrying capability of the body shell. The vehicle manufacturers at this stage must be able in their roof design philosophy understand that a strong and good load transferring roof is a priority if occupants' protection in rollover is a key goal.

Many modern car roof structures assessed from numerous real world accident data point to the contrary showing a catalogue of weakness and poor load transfer capability. Catastrophic collapse or excessive early failure mechanisms of many roofs in rollover accidents show that manufacturers have forgotten the most important function of the roof, which is to protect occupants. Many roofs in many vehicles on the road today have been designed not as load bearing but as functional with inability to transfer and let alone carry rollover impact loads. This design philosophy that is attributed from mostly the belief that roof intrusion is not a causal element of occupant injuries has resulted in roofs that are lethal and dangerous to occupants.

For better roofs with a high degree of occupant protection, the roof-system components must be designed to perform maximum work during service mode and during rollover accident mode. All pillars are there to support the roof and hence maintaining the safety cell that has been created by the pre-designed headroom. If the supporting pillars lose their capability to sustain the roof, then intrusion is inevitable. It may also be argued that the roof rails that are poorly designed in almost all the vehicles today must be load bearing and able to transfer enormous load from the left side of the roof to the right side of the roof and vice versa, then followed by sending those loads to the lower parts of the vehicle into the floor. In many of the roof structures this is not happening due to the fact that loads are being built up in numerous and unnecessary stress concentration cut-outs and holes that are causing premature collapse of the roof-system, hence intrusion at very high rates that is catastrophic [2, 11-13].

As a result, the whole roof-system intrusion follows into the occupant safety cell reducing the headroom, which is the distance between the occupant's top of the head and the interior roof height. If the headroom has to be maintained during most of the rollover duration, the structural components that support the roof and prevent excessive intrusion into the safety cell are to be designed so that they keep an optimum headroom h at all time or most of the time. If intrusion has to occur, which is the case when the roof is performing work, the intrusion must be sustained within the headroom band without protruding into the H_V zone, Figure 1.

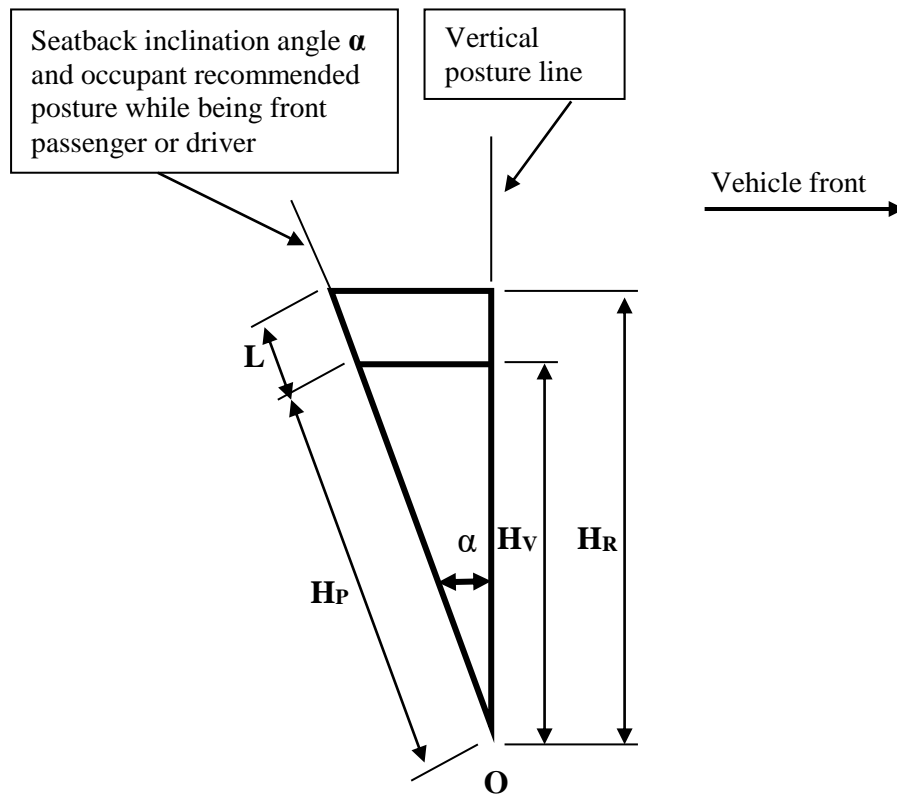


Figure 1. Headroom geometry of occupant seating position based on anthropometric measurements

To calculate the optimum headroom $h = H_R - H_V$, simple trigonometric functions can be deduced from Figure 1 as follows:

- (i) The only known parameters in Figure 1 are the occupant seating height H_P that can be obtained from numerous databases containing anthropometric measurements; the seatback angle α that offers occupant protection to frontal impact airbag deployment and to rear impact protection as the head should be as close as possible to the headrest and the internal roof height H_R measured from H-point O .
- (ii) What parameters are not normally at hand are the relative vertical occupant seating height H_V and the optimum headroom h required for particular occupant physique. These measurements are essential in the design of vehicle roof-systems that accommodate most of the population in the vulnerable band, which is the group with long upper bodies.

Therefore, from Figure 1 based on the properties of similar triangles, the seat back angle is given by

$$\cos\alpha = \frac{H_V}{H_P} \quad \text{and} \quad \cos\alpha = \frac{H_R}{H_P + L} \quad [1]$$

Equating the two equations result in

$$\frac{H_V}{H_P} = \frac{H_R}{H_P + \frac{h}{\cos\alpha}} \quad [2]$$

Where,
$$L = \frac{h}{\cos\alpha} \quad [3]$$

The optimum headroom is therefore

$$h = H_R - H_P \cos\alpha \quad [4]$$

Equation 4 illustrates that when $\alpha \rightarrow 0$ the required headroom diminishes, risking the occupant making contact with the roof quite early in the rollover process despite the effectiveness of the seatbelt pre-tensioner system and when $\alpha \rightarrow 45^\circ$ and beyond the headroom increases and the occupant is offered more protection as the roof requires a longer travel time and distance before contact is made. The latter in most cases result in low loads being experienced by the occupants as the peak roof acceleration would have gone by the time contact is made. These outcomes were also achieved in [14] when calculations were made for the post-crash headroom over the injured occupant. In this same work it was shown that headroom and its clear definition is important and plays a major role in occupants experiencing head injuries. In conclusion it was also noticed that when the headroom was higher, the incidence of head injury was reduced.

Roof load bearing structural components design philosophy

There is no doubt that the collapse mechanisms in many roof systems seen in real world accident collected data could be avoided by employing proper design philosophy based on structural design principles. Many of the existing load-bearing structures in the roof-system are very poor giving an impression that designers have forgotten the fundamentals of structural mechanics. Sometime some of the mistakes being made by manufacturers can only be associated with undergraduates who are for the first time reading applied mechanics.

In order to understand the reasoning behind some of the designs in vehicles on the road today, some examples are given herewith and full assessments of the pros and cons are made. The examples chosen are typical of the hundreds of vehicles of different makes and models driven around the world.

All the roof-systems are composed of poorly designed pillars and roof rails that upon loading in rollover, quickly lose their main load carrying capability and as a result protection to occupants is minimised. So what are the purposes of the roof super structural components? The main functions of the pillars and beams in the roof-system are as follows:

- All the pillars, which are A-pillar, B-pillar, C-pillar and D-pillar in some designs, are there to perform work and transfer load under normal service mode and under crash mode such as rollover. In both these modes the load must be able to be transferred freely and quickly from the point of load application through the pillars on the right side of the vehicle to those on the left side and vice versa.
- The performance mechanism can be described using an example say, if the upper A-pillar is loaded by a rollover load, this force will tend to bend and compress the upper A-pillar. If the A-pillar is well designed, then it will quickly transfer some of the load in stress form along the upper A-pillar's local longitudinal axis into the roof rails that pick up longitudinal forces along their local principal axes. The bulk of the load is pushed to the lower A-pillar and into the floor. The roof and the floor will further transfer these loads to the unloaded parts of the vehicle through defined load paths.
- For the upper A-pillar to perform adequately in rollover crashes, the angle of incidence, that is the angle the upper A-pillar makes with the vehicle global longitudinal axis should be between 90° and 45° as shown in Figure 2. Otherwise if the angle of incidence is too low as seen in many streamlined vehicle body shells that are designed to offer low aerodynamic coefficient, the upper A-pillars become susceptible to early bending with very little energy absorbed. Old vehicles (built between 1930-1960) that had upper A-pillars between 90° and 45° are seen to be stronger than modern aerodynamically shaped vehicles for this simple reason that they resist bending better and delay the rate of rotation of plastic hinge failure. In SUVs, which are still designed within this angle bracket, the pillars are mainly weakened by excessive cut-outs as it will be shown later.

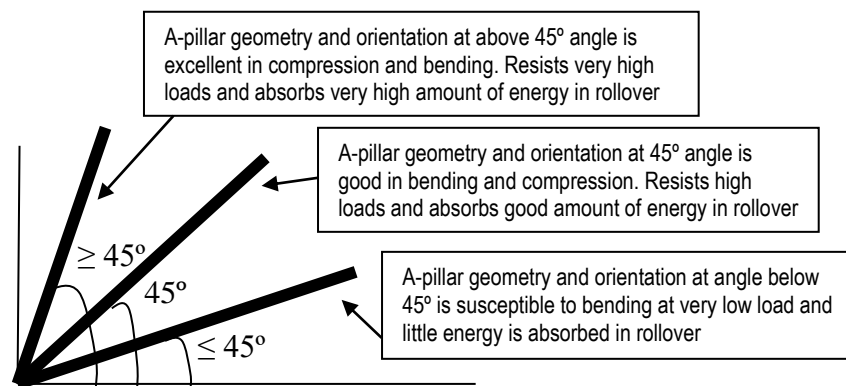


Figure 2. Upper A-pillar design geometry and orientation

- In addition to the design geometry, the section cross-section properties, reinforcement methodology and materials used are also extremely important in producing a perfect upper A-pillar. The same design philosophy applies to all the pillars. In terms of perfect roof rails, their design should not incorporate open sections which are poor structural sections and are susceptible to warping rather than absorbing energy through pure bending. For the roof rails to be perfect they should be of closed sections, Figure 3, and should be resisting the bending moment about the largest or major second moment of area. Most current designs have the bending moment being resisted about the lowest or minor second moment of area.

Analysing Figures 3a, 3b and 3c it can be seen that roof rails are still constructed poorly with no aim of creating efficient load bearing components. It will help a lot if the cross-section in figure 3c could

be used in modern cars as the intrusion of the roof rails could be delayed, minimised and hence the overall roof-system intrusion rate could be smaller.

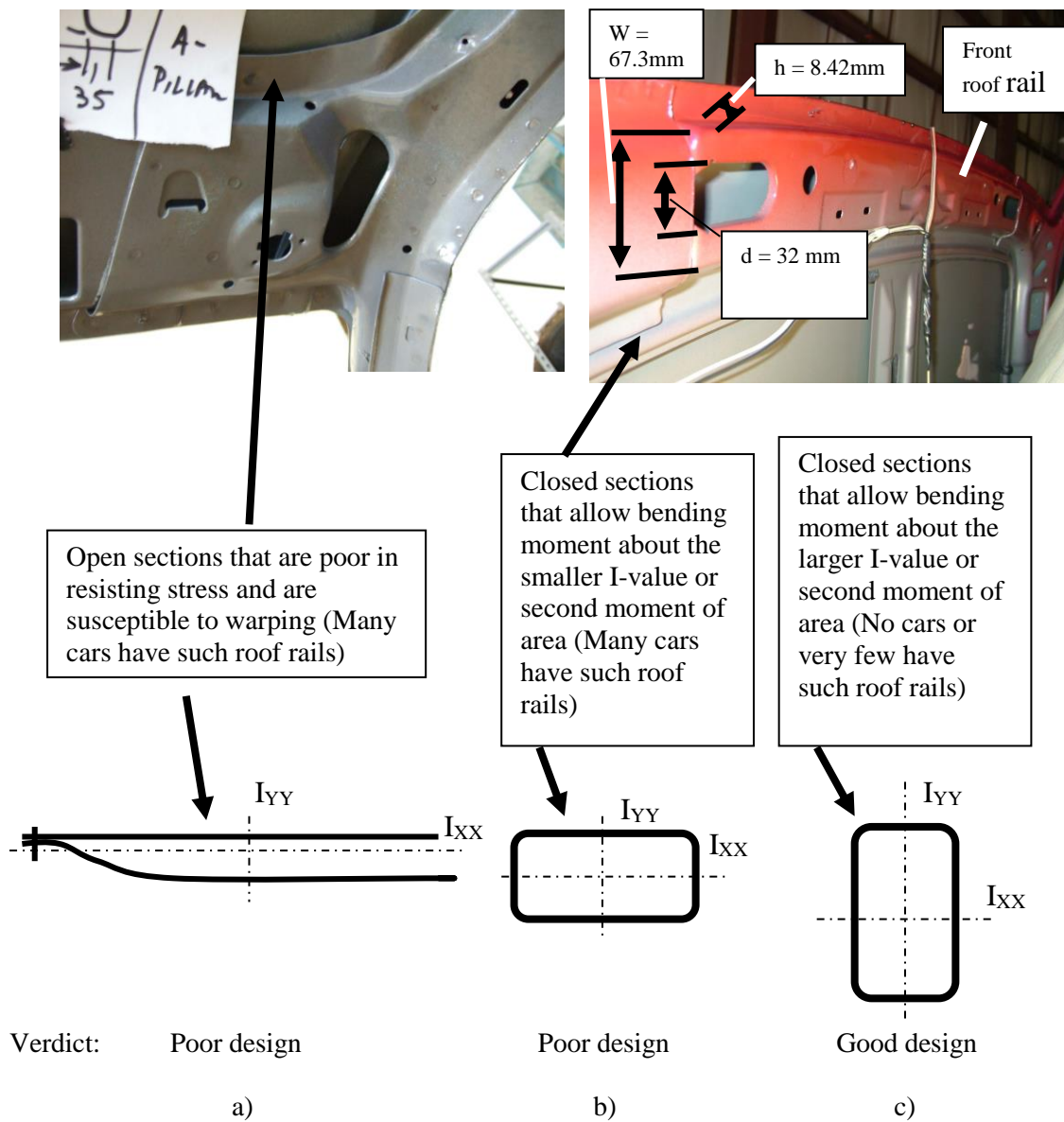


Figure 3. Roof rail design under bending loads

THE ROOF STRUCTURAL COLLAPSE MECHANISM IN MODERN VEHICLES

To develop a picture of how vehicle roofs collapse when subjected to rollover loads, it was necessary to assess a number of real world accident data. Some of that assessment are presented here for clarification and understanding of the mechanics. Figure 4 shows final collapse of some typical passenger cars, while Figure 6 depicts some SUV collapse behaviour under rollover. These failure mechanisms are typical and are observed in many rollover accidents. They are analysed herein because they present the sort of intrusions that have had retrieved occupants with permanent disabilities such as such as quadriplegia, paraplegic, and brain injuries.



Figure 4. External view of roof deformation and internal view of roof intrusion

Figure 4a and Figure 5 can be used to assess these typical collapse mechanisms. Overall the roof final collapse pattern can be summarised as follows:

- (i) Predominantly the upper A-pillar on the near side (rollover leading side) of the front passenger seat bent inwards towards the occupant safety cell in a form of a cantilever collapse with a plastic hinge forming at about 1/3 of the distance from the upper A-pillar and lower A-pillar joint;

- (ii) The side roof rail on the near side remained almost parallel to its original form with small bending indentations that were localised;
- (iii) The front roof rail collapsed inwards into the occupant safety cell taking with it the roof that is weak to loads applied outside its plane. The maximum roof deformation is 215.9 mm that is a roof intrusion of about 74% above the headrest of the front passenger seat. The roof intrusion diminishes in magnitude along a line following the global longitudinal axis resulting in its minimal collapse near the right upper C-pillar. The residual headroom at the maximum roof intrusion was 76.2 mm.
- (iv) Damage was also noted on the driver side. However, this was extrusion rather than intrusion. The advantage of having an extrusion failure mechanism is that it delays the head roof contact time hence resulting in very small impulsive loads that may or may not impose injuries to the head-neck system.

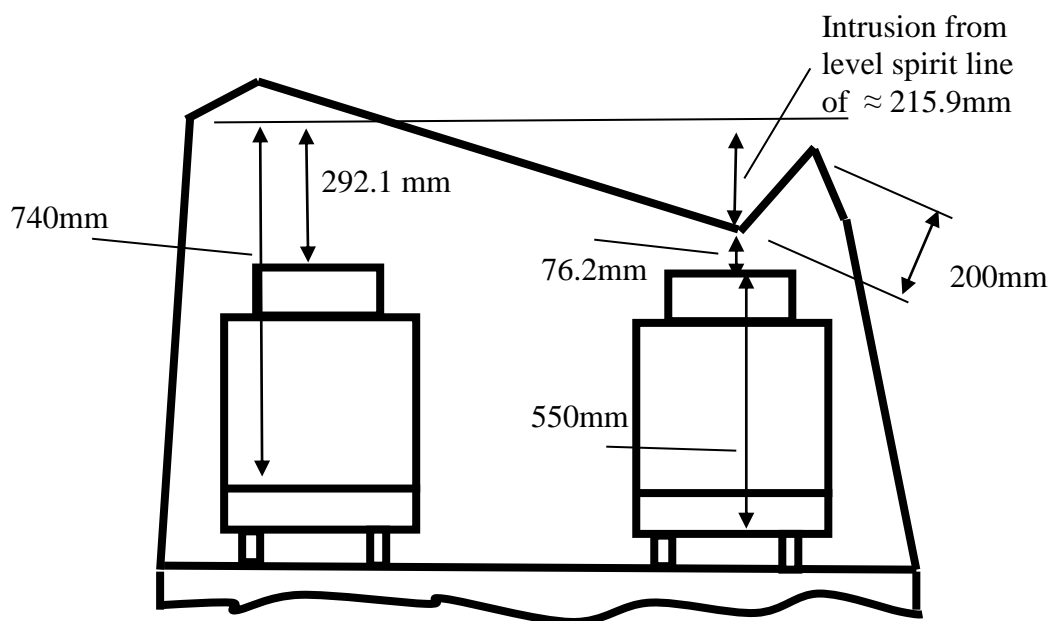


Figure 5. Schematic diagram depicting the roof structural deformation pattern for vehicle (Figure 4a) and seat positions – view from the rear to the front (Not to Scale)

The other physical measurements that aided the construction of the final failure mechanism of the roof collapse in Figures 4a and 5 are the internal intrusion readings. The images clearly show the extent of intrusion with the maximum deformation at the front roof rail directly above the front passenger's head (Figure 4b). The occupant in the passenger seat (right) had permanent disability paralysed from neck down. This assessment deduces that the roof is not strong enough to carry the vehicle load under rollover. Similar failure mechanism can be seen in Figure 4c to Figure 4f, however with greater roof intrusion.

The research herewith also assessed Sports Utility Vehicles (SUVs) and their failure mechanisms in order to understand why their collapse in most rollover cases is catastrophic. Figure 6 shows a typical SUV of the worse case that illustrates poor design philosophy employed in this body shell and in many of those on world's roads.



Figure 6. Collapse mechanisms occurring at cut-outs locations in a typical SUV under rollover

In analysing images in Figure 6, it can be seen that this SUV had a complete collapse of its roof because of poor design principles employed by manufacturers. Similar near identical collapse mechanisms have been observed in vehicles within the NASS cases.

The question is why the above vehicle roof (Figure 6) and those SUVs in the NASS cases had roofs collapse that were catastrophic in real world accidents when they had passed [15] the FMVSS 216 that yielded a complete different collapse mechanism with little intrusion showing only the lozenging effect of the roof-system with some cracking of the windscreen? The answer to the question is that the FMVSS 216 and the updated new FMVSS 216 are not representative test protocols that simulate real world accident scenarios in rollover. The work in [12, 15-17] demonstrate clearly that under the FMVSS 216 test procedures, the vehicles are loaded in such an orientation as to give artificial strength that is not experienced in real world accident cases.

The SUV in Figure 6 has also shown some of the worse pillar design philosophies. All important load bearing pillars including some roof rails are excessively perforated and have cut-outs so large that the whole roof-system is tremendously weakened. No wonder the resultant collapse mechanism seen in Figure 6.

The upper and the lower A-pillars (Figure 7) have large cut-outs and perforations at strategic locations where they are weakening the pillar system. The whole upper A-pillar is strong along its length, but has poor joint design with large holes just in positions of strategic importance in terms of load carrying capability and load transfer.

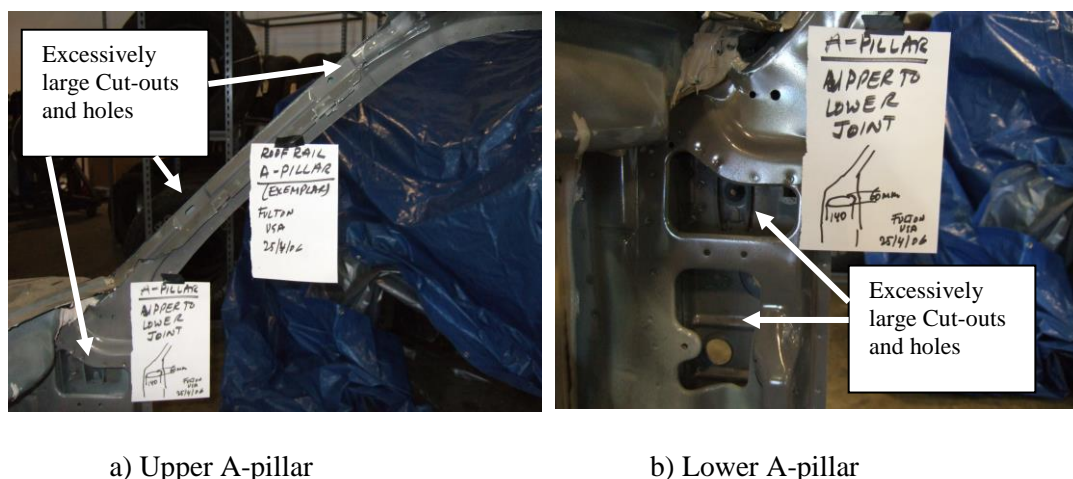


Figure 7. The upper and lower A-pillar showing cut-outs at strategic locations for load bearing capability

The B-pillar too in Figure 8 has not been thoughtfully designed. The principles of design employed in this B-pillar are flawed as excessive large cut-outs are located in areas that require resisting maximum loading. In Figure 6, the B-pillar is shown to collapse at near the waist line where the large cut-outs are as shown in Figure 8. The B-pillar is full of cut-outs and holes that have diminished the capability of not only being good at transferring load, but have also eliminated adequate occupant protection in side impact.

What is not clear is the rationale manufacturers employed in designing such B-pillars when in rollovers the impact is applied at the B-pillar roof joint. In such situations, the B-pillar must be able to perform well in bending (Figure 6) as a cantilever with the maximum bending moment at the waist line. How can a proficient engineer locate a cut-out at that precise location experiencing the maximum bending moment? This reasoning is beyond comprehension and inexcusable. Indeed, the design must

have been signed off by other engineers. Why didn't they foresee the behaviour of this extremely poor location for cut-outs, is not clear.

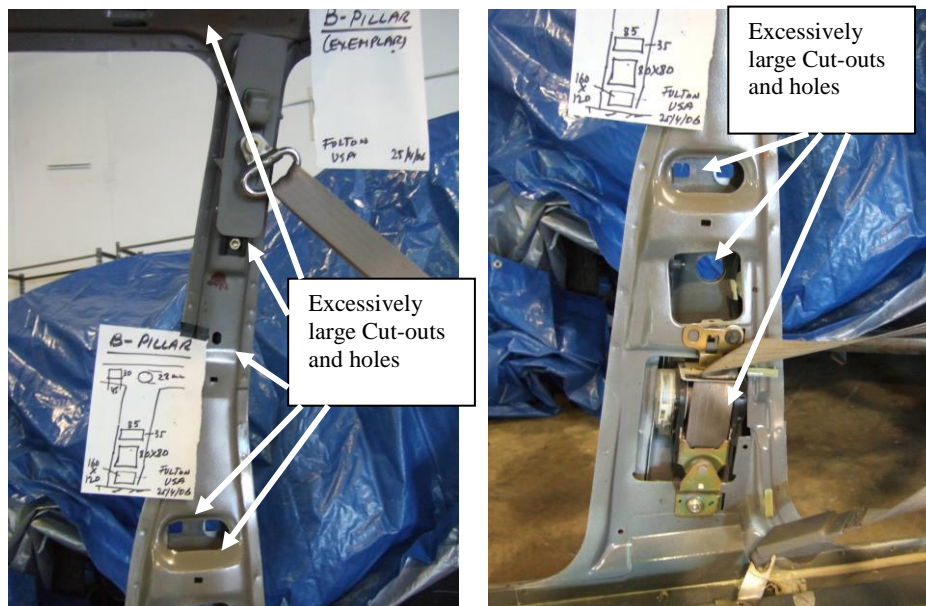


Figure 8. The B-pillar showing cut-outs that diminish the capability of the pillar

The C-pillar and the D-pillar are also poorly designed in the same manner. The C-pillar has also a hole at the point of maximum bending moment and the D-pillar has no hole but has a cross section profile discontinuity that changes drastically and hence the location of that change becomes a stress concentration point that experiences accumulated stresses that rise beyond the section allowable maximum stress and thus collapse catastrophically similar to those pillars with cut-outs.

Many SUVs have similar designs. However, this rationale in the design of excessive cut-outs is not only seen in SUVs. Many passenger vehicles also have similar problems that need rectifying. For instance, the vehicle in Figure 9 shows a typical family saloon or sedan car that is poorly designed.

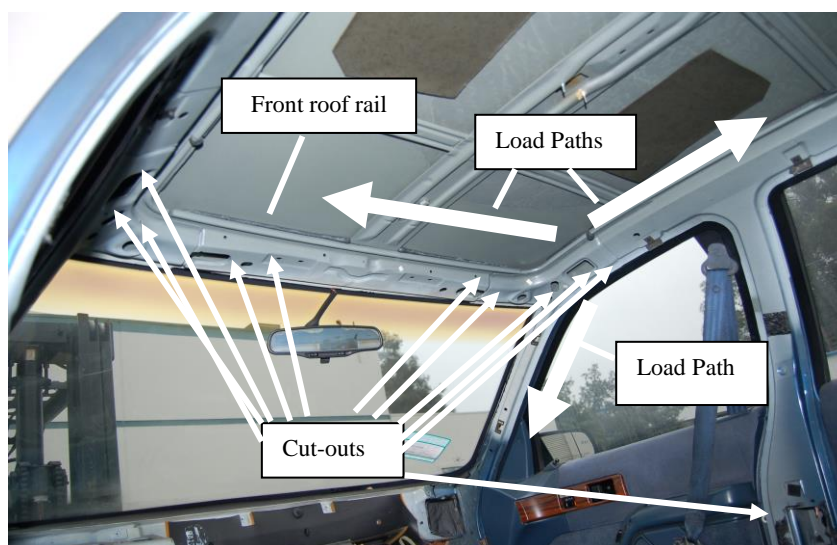


Figure 9. The roof-system of a passenger car showing cut-outs and intended load paths

Effects of cut-outs and perforations in load bearing structural components

Images in Figure 3 to Figure 9 show that engineers have not utilised the basic fundamental principles of mechanics when designing load bearing structures with holes and cut-outs. Therefore, assessing Figure 9 for instance, it can be said that the front roof rail in a car is a load carrying member that should transfer load from the point of application on the right side of the vehicle structure to the left side and vice versa. The roof itself as mentioned earlier carries very little directional load, but plays a part in transferring shear loads in its own plane. Therefore, in this case roof rails (front, side and rear) require to be properly designed (Figure 3) so that under rollover the load from say the joint at the top of A-pillar front roof rail and side roof rail could be able to be transferred quickly from that joint to the rest of the structure through defined load paths (Figure 9).

If the rails have cut-outs, then their ability to transfer that load quickly and effectively is compromised and as a result inevitably weakened. Figure 9 shows the number of cut-outs in the front roof rail to be unacceptably high and hence the front roof rail remains highly impact sensitive. Figure 9 also shows the sudden changes in stiffness and strength caused by these cut-outs often give rise to undesirable stress concentrations.

A number of stress-strain teaching materials show the consequences of not designing cut-outs properly. These materials illustrate the limit in the cut-out design as well as detailing the compromise that needs to be taken into account when designing high strength structural components while introducing cut-outs for lightness. If this compromise is not thoroughly assessed and rules not obeyed, the outcome is always a premature failure [18].

It is now acceptable that the angles of roll and pitch dictate the direction of the applied impact load under rollover [2, 12, 16, 17]. Once that load has been induced into the roof structure it will become stress that will travel following the load paths given in Figure 9. The value of the stress concentration factor, which is assumed to be a ratio of the applied load and some material physical and geometrical phenomena dictate the speed at which the load can be transferred from the point of application to other parts of the structure.

This in general depends on the design philosophy employed as stress concentrations in all the vehicle pillars and roof rails assessed herein are high because of large cut-outs that create structural discontinuities resulting in rapid loss of potential transfer of load through the roof rail from the passenger front side to the driver side and vice versa. As a consequence, stress concentration values are beyond the maximum allowable stresses and hence failure follows.

To illustrate this phenomenon, a finite element model of the front roof rail in Figure 3 and Figure 9 was built and it is shown here in Figure 10. The boundary conditions were identical to those used in the real structure. Therefore, the load was applied in compression through the longitudinal axis of the roof rail and the constraints were fixed translationally but free to rotate about the global longitudinal axis at the support.

The finite element results (Figure 10a) show clearly the stress concentration build up in the roof rail about the largest cut-out to be extremely high precipitating a plastic failure in the same region of maximum stress. Once the plastic hinge has formed (Figure 10b) due to allowable stresses being exceeded, the roof collapse begins as the hinge rotates about the axis with the least second moment of area. The rate of intrusion thereafter is high almost catastrophic.

In such situations where catastrophic roof intrusion is experienced, the roof begins to collapse quite early in the loading cycle as the structure quickly becomes a mechanism with little resistance, hence allowing much of the roof penetrating into the safety cell with ever increasing intensity.

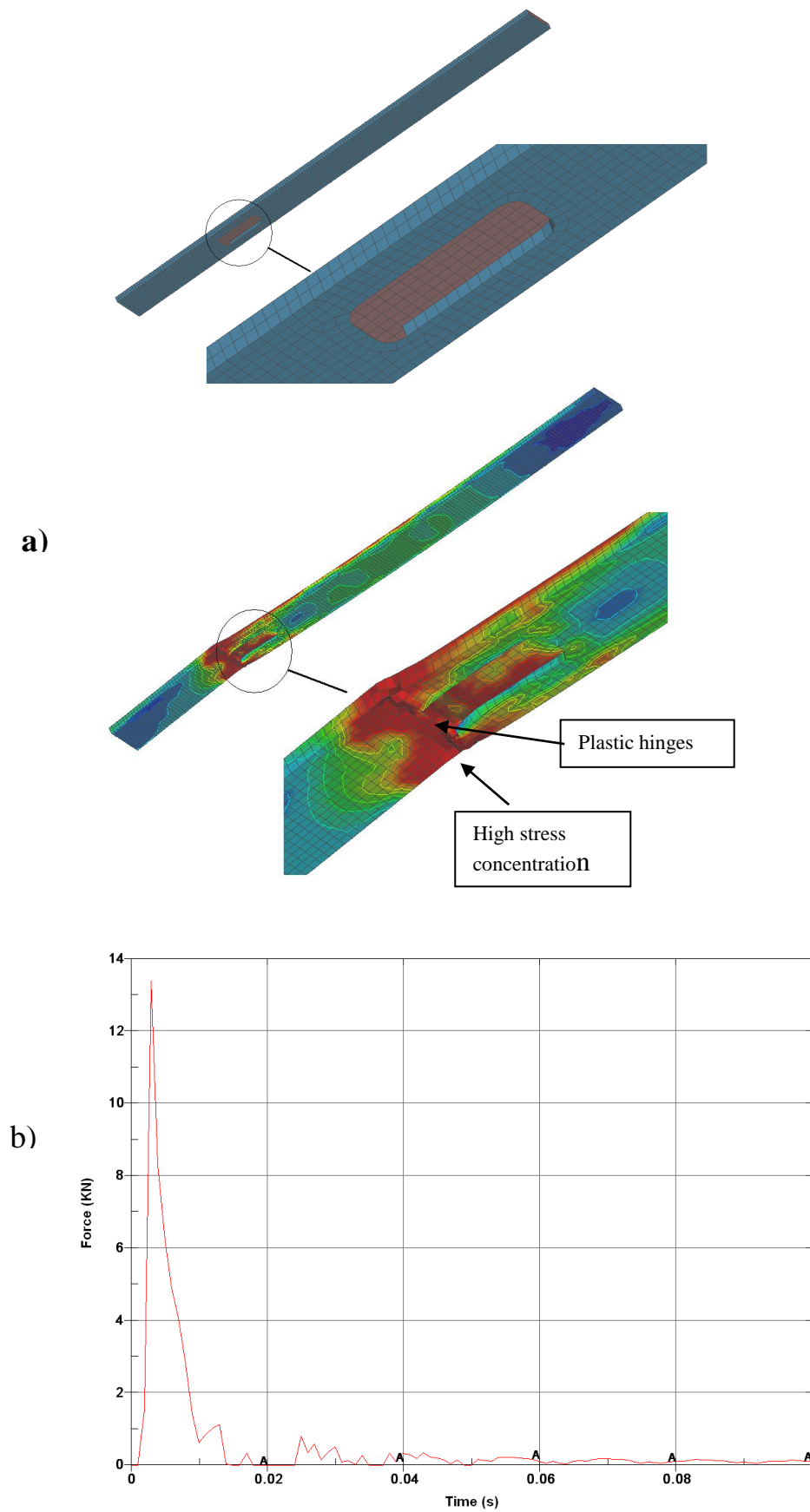


Figure 10. Finite element analysis results for the front roof rail model

It was also necessary to quantify the amount of loss in strength when a cut-out has been introduced in a pillar design. Figure 11a shows a typical C-pillar of a passenger car that was tested experimentally, and then modelled without and with a cut-out (Figures 11b and 12a). The results are given in Figure 12d.

The C-pillar (Figure 11a) was mounted in a concrete block that was fixed in all degrees of freedom employing a specially designed jig. The load was then applied through a bar that had a built-in load cell to record the load resistance. The experimental tests were followed by the finite element modelling of the C-pillar as shown in Figure 11b.

After the simulation of the C-pillar without a cut-out was successful depicting good agreement with the experimental results, it was necessary to model the same C-pillar but this time with a cut-out (Figure 12a) in the same location as in some of the vehicles with side airbags. The cut-outs in the C-pillars of these vehicles act as access for pipes leading to the energising chamber stored in the boot regions.

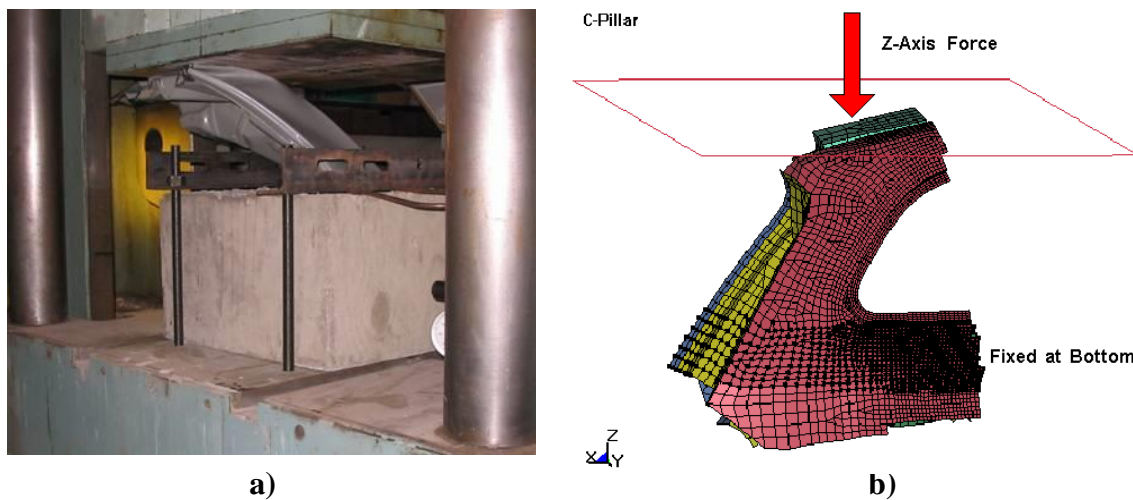


Figure 11. C-pillar under combine bending and compression experimental test and FE model

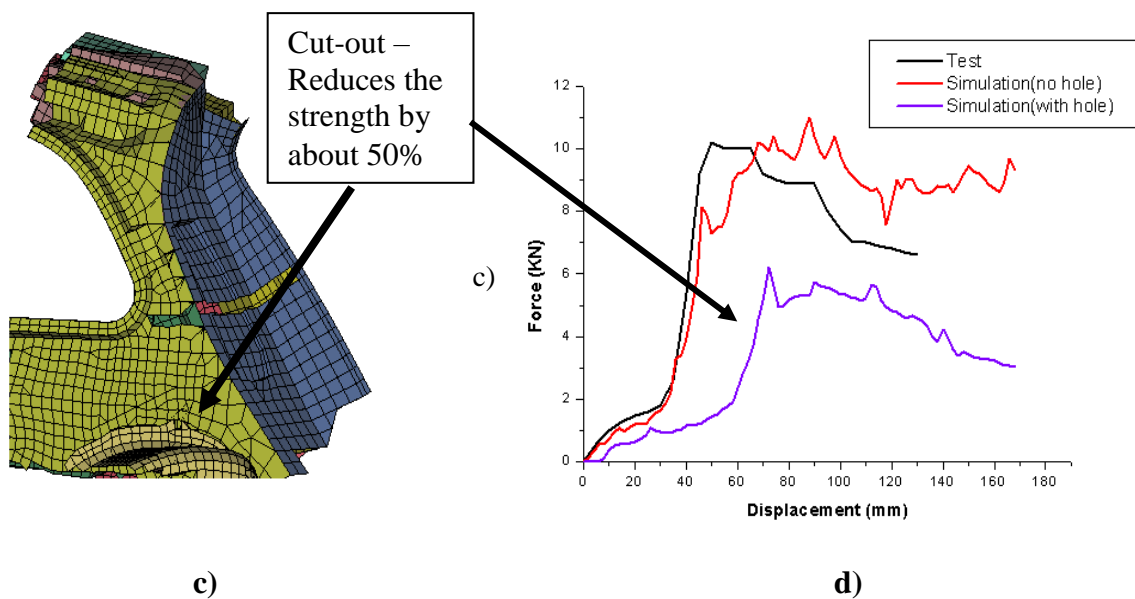


Figure 12. C-pillar FE analysis with a cut-out and the results for comparison

It is clear that the hole or the cut-out introduced in the C-pillar is causing a lot of concern. The maximum C-pillar strength in this case is reduced by 50% when the cut out is introduced. This finding is important to designers who excessively introduce cut-outs in their designs for whatever purpose. The 50% reduction is shown when one cut-out is introduced. When many cut-outs are designed-in, the strength reduction can go all the way to 80%. This is the phenomenon observed in the SUV presented in Figure 6.

The other point that requires addressing is the rate of intrusion as a function of sudden change in stiffness. This occurs at locations of drastic change in the second moment of area. To alleviate this problem designers are advised to gradually change the cross-section properties in steps so that a smooth transition is achieved and hence no stress concentration can be built up in the regions of change.

RE-ANALYSIS OF MALIBU I & II TEST RESULTS

As a step towards determining the causal relationship between roof crush and head or neck injury potential, a catalogue of rollover experimental tests were carried out by General Motors in the nineteen eighties in order to validate the diving theory proposed by their employee Moffatt [8]. The whole programme comprised of 16 rollover experimental tests that were conducted on 1983 Chevrolet Malibu sedans in two series of eight tests in 1983 [9] and the other eight tests in 1987 [10]. These tests became to be known as Malibu I & II, and they have ever since influenced roof designs of most vehicles on the road today.

In Malibu I series of eight tests, four vehicles were production models, while the other four had reinforced strong roll cages installed in them to represent a strong roof. In addition, these tests had two unbelted Hybrid III dummies in the driver and the right passenger positions. In Malibu II the tests conditions were similar to those in Malibu I, except that they were conducted with dummies using three-point seat belts with cinching latch plates. The dummies were instrumented with triaxial head accelerometers and neck transducers. This measured axial compression and tension, anterior/posterior shear and bending moment, including lateral shear and bending moment.

For just over two decades since Malibu I series of tests were conducted, the only results General Motors made available to the public were the two papers [9 and 10]. Since then, there has been an on going debate between safety experts over whether there is a causal relationship between roof crush and head or neck injuries.

It was not until 2004 when General Motors finally realised the full data of the Malibu tests in public domain. Soon after, many researchers including Friedman and Nash [11] made a complete analysis of the available high-speed film together with the histograms from which a couple of main definitive understanding were made as follows:

- (i) The most severe neck injuries occurred to dummies seated on the farside in tests vehicles without roll cages;
- (ii) The vertical velocity at the centre of gravity is small and survivable; and
- (iii) The cause of injury cannot be due to diving into the roof.

Despite all this evidence the industry position is still that roof crush does not cause injuries.

What this paper has done is to carry out some forensic studies and using simple mathematical principles has led to prove that surely there is a 100% causal relationship between roof crush and head-neck system injuries.

Proof of causal relationship between roof crush and head and neck injuries

To enable the proof be derived, it was necessary to use Figure 13 on page 108 of the original test 7L4 conducted on a 1983 Chevrolet Malibu vehicle with production roof [10]. This particular test was chosen because it produced the highest neck load 13.2 kN according to reference [10]. This graph attributed from the results is reproduced herein as Figure 13.

Before the re-analysis of the Figure 13 could be made, it is necessary to mention that the authors have had no access to the video material released into the public domain by General Motors. The only exposure to the video material is the analysis made from the results presented in [11]. Therefore, re-analysis being carried out here for the proof purposes is solely based on the test result characteristics published in Figure 13 of reference [10].

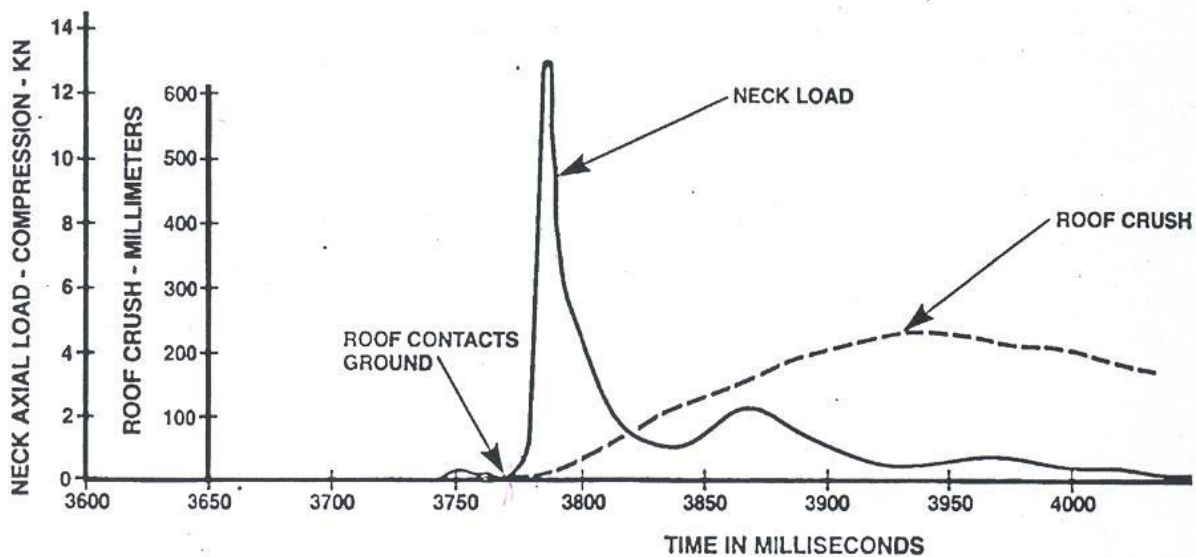


Figure 13. Roof crush and neck load vs time driver impact 7L4 [10]

The re-analysis process was as follows:

- (i) First Figure 13 [10] was digitised using a digitising software at very small intervals in order to increase the accuracy of the translation from analogue to digital;
- (ii) Both neck loads and roof crush data were saved in ASCII format and imported into Matlab suite;
- (iii) The crush data and the neck load characteristics were plotted;
- (iv) The crush characteristic was then differentiated once to get the velocity;
- (v) Then the velocity curve was differentiated once more to get the roof acceleration characteristic;
- (vi) After plotting all the curves, neck load, roof crush, roof velocity and roof acceleration to the same time scale (Figure 14), a picture began to emerge showing what we always suspected.

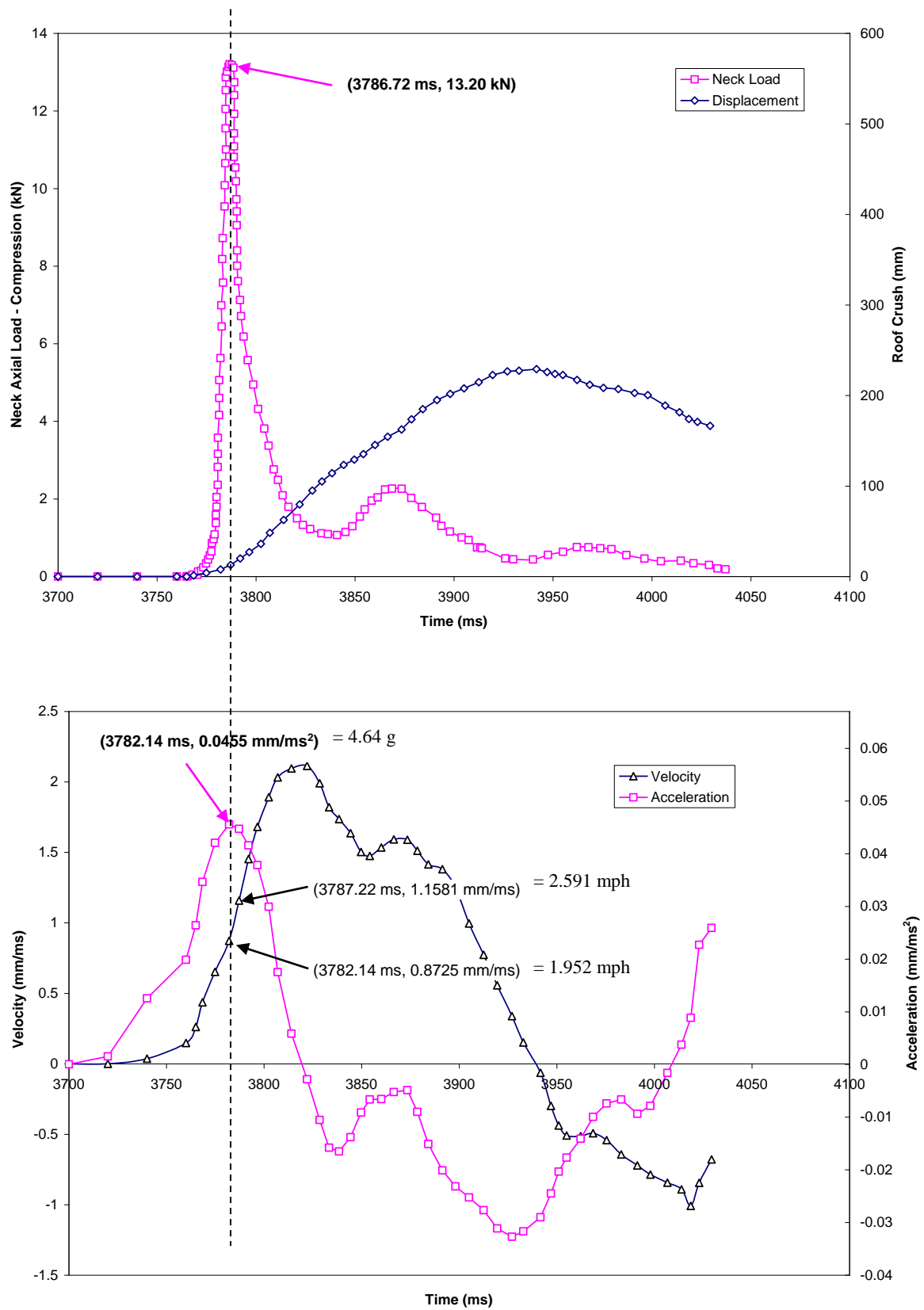


Figure 14. The digitized test 7L4 (Figure 13 [10]) results depicting acceleration and velocity derived from the differentiation of the roof crush curve

Analysis of the curves plotted to the same time interval (Figure 14):

- (vii) The most important finding of them all is the roof acceleration peaking at precisely the same time as the maximum neck load. This means that the roof was accelerating at the time it made contact with the dummy's head. The acceleration value can be derived from the acceleration characteristic that has been drawn from the twice differentiated roof crush curve. The results show that the head contact occurred when the roof was accelerating into the safety cell at maximum value of $0.455 \text{ mm/ms}^2 = 45.5 \text{ m/s}^2 = 4.64 \text{ g}$.
- (viii) At that same time when the roof was accelerating at 4.64 g, the rate of roof intrusion was $0.8725 \text{ mm/ms} = 0.8725 \text{ m/s} = 1.952 \text{ mph}$. This shows that the roof was intruding, separated from the ground when the maximum force of 13.2 kN was imposed in the dummy's neck.

The proof of roof crushes causing neck injuries:

- (ix) According to the analysis made in [10] they concluded that the load on the dummy neck was as a result of the dummy head stopping against the roof when the roof was against the ground.

The re-analysis carried out here on the test 7L4 results shown in Figure 14 depicts a complete different scenario and series of events. According to the roof acceleration, roof velocity and roof crush characteristics in Figure 14 it can be clearly seen that the peak roof acceleration and the peak neck load occur at precisely the same time. At this same time the roof rate of intrusion is not equal zero as the case may be when the roof is against the ground, but equal to 1.952 mph. The roof at this moment in time has therefore practically separated from the ground and every contact made between it and the dummy's head is entirely with the inward accelerating roof.

The analysis in [10] also claimed that when the dummy head stopped, the dummy torso continued to move toward the head, causing high axial force in the neck. The mechanics of what happened is the reverse of what was reported. The re-analysis of results shows that when the roof was intruding at that ever increasing velocity, the dummy was also moving in the opposite direction but at a smaller velocity than the roof intrusion. The roof acceleration at the time of contact with the head was maximum hence the roof imposed a high load on the dummy's head resulting in a momentarily head stop while the torso still had momentum to move forward. In order for the roof-head-neck system loading to be in equilibrium, the softer and weaker occupant body absorbed the high load so that the sum of forces were equal to zero when a balance was struck. This contact sequence is common in rollovers and the mechanics obey Newton's Third Law.

The re-analysis also shows that the roof was increasing in speed as it intruded and rate of increase was high. The finding can be better shown by taking two points on the velocity curve. One point is taken at precisely 3782.14 ms when the acceleration is maximum and the velocity reading is 0.8725 m/s or 1.952 mph. The other point is taken at a time 5.08 ms after and the velocity reading is 1.158 m/s or 2.59 mph. The change in velocity during this extremely small change in time is 0.64 mph. That is termed as high for the duration that is very small duration.

The findings herein throw out the "diving theory" that has dominated the philosophy of roof design under rollover. The roof acceleration and roof velocity curves in Figure 14 prove that the dummy received serious head-neck injuries only after the roof had contacted the ground and the roof was crushing at an intrusion rate of 1.952 mph. It is not correct to suggest otherwise, even to say that the neck load occurred prior to roof crush.

- (x) General Motors engineers misunderstood their results and did not appreciate the severity of rollover despite that it occurs at low speeds. Most of the severe injuries occur when the occupant's head make contact with the rapidly intruding roof. By the time when the roof had reached its maximum deformation, the rate of roof intrusion at precisely that time is zero. The Malibu test 7L4 results also show this and thereby tell us that when the roof intrusion rate is zero, the neck load is very small and the roof is at its highest or near its highest deceleration point.

In short, head-neck load that causes injuries occur quite early in the rollover accident scenario when the roof is accelerating and when the roof rate of intrusion is increasing.

CONCLUSIONS

This paper for the first time proves that there is a causal relationship between roof intrusion and Injuries sustained by occupants. To achieve this solution, it was necessary to revisit the Malibu I and II rollover experimental tests carried out by General Motors more than 20 years ago. Using forensic methodologies with simple mathematical operations, it was shown that the original Malibu I and II interpretations of test results were flawed because the test engineers misunderstood the results they had obtained from the conducted tests. The Malibu I and II results themselves prove that there is a 100% causal relationship between the high neck loading that was recorded by the dummy's neck and the roof crush.

The re-analysis carried out here on the test 7L4 results shown in Figure 14 depicts a complete different scenario and series of events. According to the roof acceleration, roof velocity and roof crush characteristics in Figure 14 it can be clearly seen that the peak roof acceleration and the peak neck load occur at precisely the same time. At this same time the roof rate of intrusion is not equal to zero as the case may be when the roof is against the ground, but equal to 1.952 mph. The roof at this moment in time has therefore practically separated from the ground and every contact made between it and the dummy's head is entirely with the inward accelerating roof.

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In short, head-neck load that causes injuries occur quite early in the rollover accident scenario when the roof is accelerating and when the roof rate of intrusion is increasing.

Finally, the proof has been derived; unfortunately, this has come more than twenty years later after which all cars with poorly designed roofs on the roads today have based their roof design philosophy on the misinterpreted Malibu results and conclusions.

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