16

SEAT-BACK YIELDING AND COLLAPSE:

A DANGER TO OCCUPANTS DURING REAL-WORLD COLLISIONS

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ABSTRACT

A vehicle occupant is best protected when his restraint ensemble, including the seat, maintains its integrity during crashes up to the level of established human-tolerance limits. Occupant protection is needlessly compromised when a seat yields or collapses at levels below the human-tolerance limit during a rear line-of-force collision. During actual vehicle collisions (real world), excessive seat yielding and/or collapse often result in catastrophic injuries to front-seat occupants as well as to the passengers seated behind them. "G" level exposures during these mishaps are generally only a fraction of demonstrated and accepted human-tolerance limits. Major reduction in "Societal Harm" could be afforded these victims by employing state-of-the-art techniques in designing seat structures and seat cushions. This paper examines human tolerance to rear line-of-force collisions, seat-back performance under dynamic conditions, expected and actual kinematics, and injury patterns. Several real-world case studies and other data are provided to support the findings.

INTRODUCTION

Occupant research has demonstrated that the tolerance of the human body to crash forces is dependent not only on the energy of an acceleration exposure but the direction as well. The common directions are expressed in terms of a standard Cartesian coordinate system with tolerance data gathered along the X (front and back), Y (side to side) and Z (up and down) axes, with minimal research conducted at vector combinations. Having participated in much of this research both individually and collectively, it has become abundantly clear to these authors and others in the industry that whole body acceleration tolerance is the strongest when the accelerations are applied from the rear and the torso and the head are properly supported.

When the acceleration vector is applied from the rear, the occupant reacts to the forces by moving rearward into the seat- back surface. The seat back thus becomes an essential element in restraining occupants in these rear-line-of-force collisions. Designers must consider many variables in designing a seat to ensure that it provides protection to the expected occupant population throughout the range of human tolerance. Characteristics such as human tolerance to acceleration and energy levels of the impact must be considered as primary factors, along with such elements as dynamic overshoot, ergonomics and comfort.

Real-world accidents as well as industry testing have demonstrated that front seats too often fail when a vehicle is impacted from the rear. The acceleration exposures within the occupant compartment experienced during these collisions are well below the tolerance of the human, yet many injuries result. The observed seat failures are thus failures of the seats' restraining capabilities during what can be described as "protectable" exposures.

One of the main objectives of a seat is to guard an occupant in a protectable rear-end collision by retaining the occupant within a survivable envelope and precluding serious injuries due to a lack of retention or change in position. The most effective means to accomplish this is to utilize a "rigid" seat. A "rigid" seat is defined by the authors as a seat which maintains its integrity to a point where the stated objective can be realized. Of course, limited deformation (both plastic and elastic) of this "rigid" seat is tolerable, but only within the framework of achieving the main objective and where further rigidity is impractical.

OVERVIEW OF REAR-FORCE COLLISIONS

An analysis of motion during rear line-of-force collision shows that the upright occupant will compress rearward into the seat. If the occupant compartment accelerations remain below human-tolerance injury levels, and the seat remains intact and anchored in position, the occupant will be restrained and retained in the seat throughout the collision energy transfer. Thus, the occupant is provided maximum protection from rear-end crash injuries. If the angle of the seat back becomes too shallow, the inertial forces acting on the body will cause the occupant to slide up the seat back and lose the restraining effect that the seat can offer. This upward motion is called "ramping." Ramping occurs naturally when a seat back yields excessively or collapses during a rear line-of-force collision.

CRASH-ENERGY MANAGEMENT CONSIDERATIONS

In a seat with a properly maintained back angle, with a truly rigid structure but without cushioning, the occupant would theoretically experience the same exposure as the seat. The same rigid structure, with standard cushioning, would allow elastic compression and thus amplify the acceleration to the occupant by what is known as dynamic overshoot. Further, use of energy-absorbing cushioning as opposed to the standard cushioning provides the opposite effect and thus lowers the accelerations to some degree as seen on the occupant. With either type of cushioning, if the structure is allowed to yield excessively or collapses, the situation becomes more complex.

Theoretically, yielding of the structure lowers the accelerations on the occupant as long as the yielding is continuous throughout the full acceleration profile and if the occupant is maintained relative to all restraining surfaces. Occupant retention, thus, can best be maintained with a nearly upright seat back in the rear-end collision scenario. Excessive yielding that increases the seat-back inclination voids the effect of acceleration reduction by releasing the occupant along the ramp. Since many current harness-restraint configurations are not designed for this acceleration vector, the release can be dramatic. A true acceleration-controlling-structure design would necessitate proper yielding. Proper yielding of the structure requires maintaining the relative angle between the seat back and seat bottom, as well as maintaining upright or near-upright posture of the occupant, relative to the acceleration vector. This would require a considerable expenditure of material deformation and a translation of the seat and occupant into a zone that would present a strike hazard with other occupants or structures within the seating area. This structural yielding is referred to as energy absorption (or more accurately identified as energy management).

Incorporating an energy absorption capability into a passenger seat can thus be defined as trading off the peak acceleration loading with the increased probability of an interior strike hazard. Figure 1 graphically illustrates that if the acceleration level is expected to be above the human-tolerance limit, then increasing the time reduces the peak acceleration. Application of this technology has been developed and extensively evaluated by the authors and others to convert nonsurvivable helicopter crashes (where the crash forces were known to exceed human tolerance) to survivable crashes. To increase survivability, seats for these helicopters are designed to maintain a constant seat-bottom to seat-back angle and to stroke through a predetermined distance. The stroking occurs at a controlled force level which is optimized to use all crash energy in most accidents. During this stroking process, occupants can be exposed to a higher probability of interior strikes, but this is balanced against nonsurvivable crash loads if energy absorption is not employed.

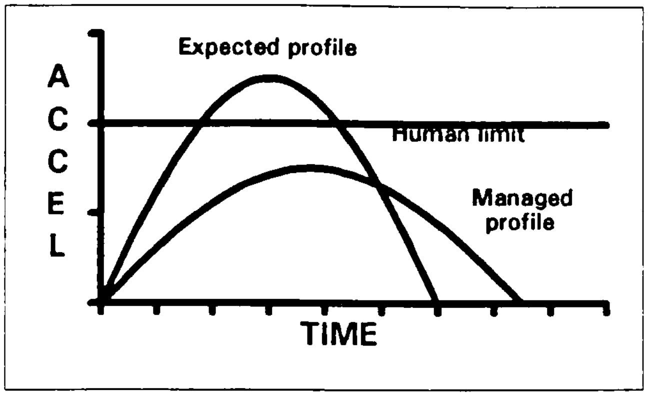

FIGURE 1. ENERGY MANAGEMENT

Yielding and collapse of contemporary automobile seats in rear-end impacts often occur at very low acceleration levels representing only a fraction of known human-tolerance levels. The very low levels of energy managed by the collapse of the automobile seat back and the resulting loss of occupant retention are contrary to the basic principles of energy management for occupant protection. This excessive seat yielding and collapse allow the impact forces to act on the occupant, resulting in the occupant ramping up the seat back. The seat's increased open angle dynamically changes, and the surface providing restraint disappears before dissipating all the crash energy. This occupant motion creates the possibility of serious injury to the motorist. These are not reasonable tradeoffs. As the body slides up the seat back, the head is free to extend over the headrest, causing hyperextension of the neck. Alternately, the occupant could translate rearward and potentially impact against the car's interior or a passenger in the rear seat. The human tolerance to these types of motions and contacts is considerably less than that for the supported human in a noncollapsing seat.

Ejection through the rear window or hatch is also a potential hazard of seat collapse. Since most seat-belt systems are attached to fixed vehicle structure, the motion of the seat back and the subsequent ramping of the occupant allow the occupant to move away from the seat belts. Any protection during a subsequent frontal collision is thereby voided. In addition, the ramping of the occupant along the seat back increases the distance between the occupant and the vehicle's controls. This precludes the possibility of maintaining vehicle control even in low-level collisions. Thus, the yielding and collapse experienced are extremely dangerous and expose the occupants of the vehicle to many avoidable injury mechanisms.

HUMAN-TOLERANCE ISSUE

Tolerance limits have been defined and must be used in order to achieve an effective seat design to increase occupant safety in rear-end collisions. Human tolerance to impact acceleration has been defined in many ways and can be described as a painful reaction or, using the criteria of Dr. Stapp, the subject or experimenter voluntarily fears to go lest there be serious injury. The limits of voluntary tolerance have also been defined as resulting in either debilitation or traumatic injury[1].

[1]. Snyder, Richard G., "Human Impact Tolerance," SAE 700398, 1970 International Automobile Safety Conference Compendium, Society of Automotive Engineers, May 1970.

Tolerance limits have been established through observation, human volunteer experiments and animal experiments. Variability in individuals has been considered when establishing these limits, since it has been observed that not only will limits vary from person to person, but the same volunteer will encounter varying tolerances under identical conditions from time to time.

Technical literature dating back to 1942 reveals documentation of +Gx human-tolerance limits.[2] In 1959, Martin Eiband, in his classic memorandum stated: "The results also indicate that adequately stressed aft-facing seats offer maximum complete body support with minimum objectionable harnessing."[3]

In 1968, one of the authors participated in an experiment where human volunteers at the Daisy Track were subject to acceleration exposures to assess the effects of sudden shock to the changes in blood chemistry. To ensure subject safety, the +Gx rear-end collision direction was chosen with volunteers seated, fully supported, in a rigid seat and a full headrest. Exposures were conducted at levels up to 30G without injury and considered to be well below human-tolerance levels.

Human tolerance to rear-end collisions has been set at approximately 40+ G. A classic example of this is the 1963 Daisy Track test. A human volunteer, Captain Eli Beeding, was decelerated at a velocity change of 14.6 meters/second (48 feet/second). The sled reached a peak level of 42G and 83G on the accelerometer package attached to Captain Beeding's chest. Since some minor injury occurred, further testing was stopped. This test was noted to confirm the limit of human tolerance in the rear-end direction.

The Daisy Track test and other observations over the past 50 years demonstrate that +Gx is the most tolerant direction of the human body if the head and body are fully supported.

Because of these findings, military transport aircraft have been equipped with seats that face aft. In addition, the *Apollo* couch was developed so that the astronauts would receive their most severe loads from the back.

Human-tolerance-impact data forms the foundation for the design of all occupant-protection systems. Classically, seating and restraint designers have started with the human-tolerance values and then worked to apply the accelerations in the most favorable manner.

As an example of how human-tolerance data is applied, consider a specific phase of aircraft seat ejection. The ejection seat protects an occupant from a stricken aircraft by "crashing" the occupant out of the plane. Applying the "crash" to the occupant as rapidly as possible provides the largest envelope of safe ejection. Typically, the first event in an ejection sequence is to accelerate the flyer upward (+Gz vertical acceleration) until the pilot clears the aircraft structure. For many years it has been known that the human tolerance to +Gz is nominally 25G when the midaxillary line of the spine is parallel to the acceleration vector. Either forward or aft displacement of the midaxillary line rapidly decreases this value. Using this information, ejection-seat designers chose an input acceleration level of approximately 18G and later dropped it to 15G. The difference between this exposure and human tolerance accounts for dynamic overshoot and midaxillary positioning as well as a comfortable safety margin. To optimize the spinal positioning and minimize dynamic overshoot, the designers used a contoured seat bottom with a thin foam layer and a powered retractable seat belt. Merely by understanding the tolerance of the human body and applying it to seat design, this approach has provided a reasonably effective design to minimize ejection hazards.

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2. DeHaven, H., "Mechanical Analysis of Survival in Falls from Fifty to One Hundred and Fifty Feet," War Medicine 2:586, 1942.

3. Eiband, A. Martin, "Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature," NASA Memorandum MEMO 5-19-59E, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, June, 1959.

HUMAN TOLERANCE AND REAR-END COLLISIONS

Figure 2 illustrates the comparison of human volunteer experiments to the rear-end collision tests to the test conditions in which most automobile seats have collapsed (FMVSS 301). This comparison clearly indicates that these automobiles experience nothing close to 40G acceleration levels or the safe test exposures of the Daisy Track, yet excessive yield and collapse occur. For example, a typical FMVSS 301 test, which constitutes a 48 kph (30 MPH) moving barrier, induces acceleration levels to the occupant compartment at approximately 12G. Based on these results and the authors' many observations, it is difficult to project that an occupant compartment could see even a 30G collision and still maintain a survivable volume with most automobiles.

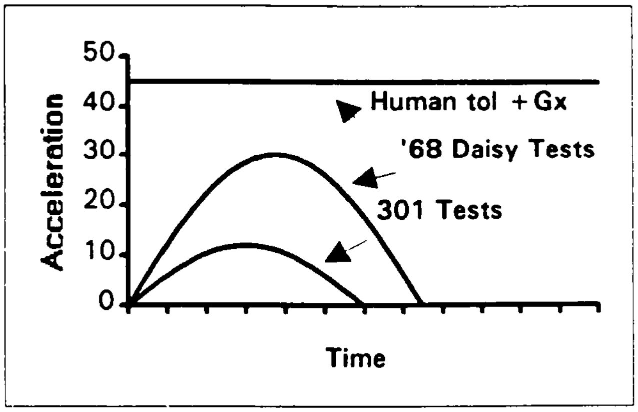

FIGURE2. HUMAN TOLERANCE TO $+G_X$ ACCELERATION

It is reasoned that to protect an occupant in a rear-force collision, one must consider energy management ("absorption") only if the crash presents a 40G acceleration level to the vehicle interior, adjusting, of course, for a small but reasonable safety factor. Therefore, no attenuation is needed below that level. Based on the proper use of human-tolerance data, one can rationally conclude that seats should remain rigid during most rear-end exposures seen in automobile collisions, since the acceleration level of the human tolerance is rarely seen. Hazards resulting from yield and collapse of the front seat back are devastating. There is obviously no engineering or human-tolerance basis for such inadequate designs.

CASE STUDIES

Case No. 1.

In the early evening, a male driver, with his female companion in the right-front seat, was driving a 1984 subcompact automobile on a divided expressway. Having passed the exit, the driver pulled off onto the right shoulder and backed up to the exit. As he started up the exit ramp, he was hit in the left rear by a 1987 compact car. The driver's seat back was supported by the intruding structure, and he walked away from the accident uninjured. The belted passenger's seat failed, she then ramped rearward out of the collapsing seat back. She struck her head in the rear and sustained a neck fracture resulting in quadriplegia.

Case No. 2.

A seat-belted female driving her 1990 compact car was traveling in the left lane of a divided highway. She was followed by a tractor-trailer. They approached a highway construction/maintenance zone with a stationary construction vehicle in the right lane. The driver of the compact slowed her vehicle and was struck in the left rear by the tractor-trailer. The tractor-trailer pushed her car to the right. As the tractor-trailer veered to the left into the median, her car was again impacted by the right rear-tandem-trailer tires and spun into the left rear of the parked construction truck. She was ejected through the rear hatch and sustained fatal injuries from a broken neck. Structural failure of the driver's seat consisted of a separation of the seat C-channel from the corresponding floor track; the seat back was reclined to a permanently deformed position equivalent to half the normal recline adjustment range. The occupant compartment remained intact, and the G-level exposure was well within the range of human tolerance.

Case No. 3

A male driver, his female companion in the right front and another couple in the rear (center and right rear respectively), were in a 1978 intermediate car when the car spun out on a wet road and hit a tree, resulting in damage to the rear of the vehicle. The right-front seat remained fairly rigid and, of course, the rear seat remained rigid but the driver's seat collapsed. The driver struck his head in the left-rear occupant compartment and was rendered quadriplegic. The other three occupants in the unfailed seats sustained only minor injuries.

CONCLUSIONS

Research dating back fifty years documents human tolerance to +Gx and yet many occupants in contemporary automobiles are unnecessarily injured because of weak and ineffective seats at exposures of only a fraction of this human-tolerance level.

There is no survival benefit to yielding and collapse of an automobile seat during "protectable exposures."

A minimal amount of strategically applied metal, along with proper seat padding and contour, would eliminate the unnecessary hazards that often result in fatalities or serious injuries.

DISCUSSION

PAPER: **Seat-Back Yielding and Collapse: A Danger to Occupants during Real-World Collisions**

PRESENTER: William H. Muzzy III

FELLOW AUTHORS: Allan Cantor, Donald Eisentraut, Louis D'Aulerio

QUESTION: John States, University of Rochester

A couple of comments, cautions. I think your tolerance level for rebound should be based on a completely different group of subjects, not young, muscular men who are the least likely to sustain whiplash and other lesser neck injuries, but instead the older drivers and motorists on the road who have arthritis in their necks and lost range and motion. They're the people at risk in rear-end impacts and we have no idea what their tolerance is at this point and I'm not sure we are ever going to find out, but it's certainly not that of the subjects you cited. The second caution is that I am concerned that rebound is going to create whiplash and whiplash is something that is totally missed by our current surveillance systems. It doesn't appear in mass and the police don't even like to report, to bother with rear-end impacts and yet for patients that come into an orthopaedic office, 45% have permanent impairment from whiplash or rear end impact. That number is based on separate studies conducted in Los Angeles and the United Kingdom. I think we probably can make seats stronger, but you've got to manage the rebound of the subject very carefully through a combination of restraint system and an air bag. I think it is possible, but it needs to be added into the development as part of the effort.

ANSWER: Excellent point and I'm becoming more aware of the older person, you know, as I start to approach middle age.

Q: Me too.

Q: Guy Nusholtz, Chrysler Corporation

It appears that your 40 G's is based on the fact that you've got the head fully supported and there is something actually putting the force on the head before the acceleration. How do you take care of what happens if the head is forward on the headrest?

A: In all cases, the test that we did, the head was fully supported and it was a rigid seatback. We had one of our subjects, one time, on a 30-G test that was not concentrating, this was out at the Daisy Track in New Mexico, and had his head away from the headrest and he received a headache and that, of course, is a problem that there are fully supported seatbacks out there today and that is what I said, that we have to look at this with a reasonable safety factor, but we are nowhere near that right now.