Evaluations and Survivability of Inflatable Restraint Systems in Small Fixed Wing Aircraft

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ABSTRACT

This paper evaluates aircraft impact survivability based on a literature review and dynamic impact tests. Commercial aircraft are considered, but the focus is small fixed wing and General Aviation (GA) aircraft. Aortic injury is evaluated as it relates to the aircraft impact environment. Dynamic tests using standard and the AmSafe Aviation Inflatable Restraint (AAIR) are evaluated. The results are presented with the objectives of gaining perspective, drawing conclusions, and making recommendations for improved survivability.

INTRODUCTION

Aircraft cabin safety has improved since the introduction of new safety regulations in 1988. New seat structures are certified using dynamic impacts with some basic injury measures included.* The full benefit of these changes have not been fully realized due to issues which have yet to be addressed. These include retrofit of older aircraft and full compliance to injury requirements.**

Improved crashworthiness raises the survivability threshold and ultimately causes accelerative/inertial injuries to play a larger role. These injuries are caused by the inertial movement of body tissues, when the impact force is well distributed to the body. The other type of injury is referred to as "contact" or force based. These occur usually from excessive occupant flailing, and direct forces cause localized trauma. The widespread use of automotive air bags provides a good example of how improved restraint changed survivability environment.

*Federal Aviation Regulation (FAR) 25.562 (Transport Category) and 23.562 (General Aviation) added dynamic performance criteria for aircraft seat systems.
**The "Retrofit Rule" was published in the Federal Register on September 27th, 2005 (Docket No. FAA-2002-13464-2; Amendment No. 121-315).

Air Bags have mitigated blunt trauma to the head and chest making higher energy impacts survivable. Priorities in automotive safety are shifting toward non-penetrating organ injury (accelerative) and lower leg fractures (contact).

Trends in aviation show increasing use of smaller airports and smaller aircraft as well as the introduction of more sophisticated seats and safety technology such as the Ballistic Recovery System and the AmSafe Aviation Inflatable Restraint. All of these factors are affecting the survivability threshold as well as public perception of safety. This is particularly true for small aircraft, which have the highest accident occurrence and fatality rate.

A study of the survivability environment for aircraft is presented with a focus on small fixed wing aircraft. A literature study and an evaluation of dynamic impact tests are included.

AIRCRAFT ACCIDENT STUDIES

Immediately apparent is a disparity between the survivability of commercial (part 121) and GA (Part 91 and 135) accidents. One study based on data from 1984 to 1996 notes the GA accident rate as 32 times that of commercial aircraft, and a fatality rate of 22% compared with 4% for commercial operations. (Li 1999) More recent NTSB statistics indicate a growing disparity due to the drop in commercial accident rate. Major commercial aircraft accidents per million flight hours dropped from 0.40 (average from 1984 to 1996) to 0.12 (average from 1997 to 2004), about 56 times that of GA. The year 2004 had 14 commercial fatalities while there were 556 GA fatalities. (NTSB, 2005)

The distribution of injury in fatal GA accidents indicates the importance of the head and neck, but also of the thoracic region as illustrated in figure 1. (Chalmers 2000, Kirkham 1982, Wiegmann 2003)

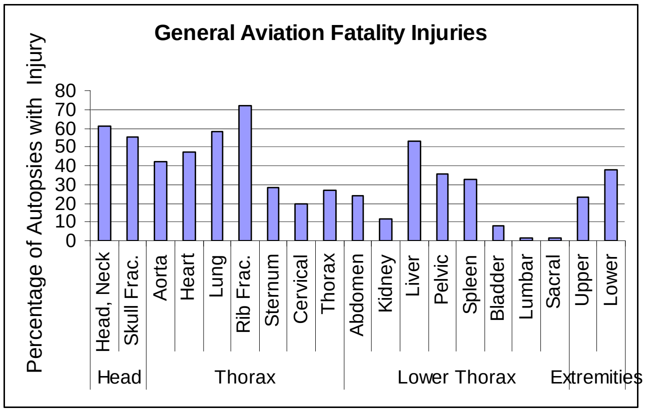

Figure 1. Injury Distribution

Inertial injuries to organs (such as heart/aorta, lungs, liver and spleen), is recognized as a major concern. But the complexity of the injury mechanisms makes them difficult to measure and assess. Another issue is the relatively small amount of GA human factors study. These events are a much lower priority due to public and media focus on larger scale events.

The literature study highlighted a problem with aviation safety. First, Small aircraft are disproportionately unsafe. Second, the knowledge for improvement is inadequate because the impact environment is not well understood and human factors investigations are seldom done. The technology for a drastic improvement exists, as will be seen later in this paper. Setting future priorities for implementation of new technology will require better understanding of injury thresholds and how they relate to the impact environment.

Aortic injury was selected for study and preliminary findings are presented here. It was chosen to learn about the aviation specific impact environment in general, and because it has good potential for improving survivability.

Aortic Injury – Indicator of Impact
Aviation crash studies have always shown a high incidence of aortic injury, but the threshold and design limits have never been established. The aortic injury mechanism is related to the impact vector, and thus is a key to understanding the event and estimate potential for other organ or visco-elastic injuries.

Aortic injury often results from the combined effects of direct chest compression and acceleration factors. A consensus on the more complicated circumstances has not been established. However, basic trends with respect to acceleration are evident. Non-penetrating trauma is associated with stress induced by inertial displacement of the heart, aortic arch, or abdomen. Aircraft have a significant downward impact vector as compared to longitudinal impacts found in automotive. This can been seen in the distribution of injury location on the aorta. Up to 85% of automotive cases are attributed to the “classic site”. (Dolney, 1978) This is the descending thoracic aorta isthmus (arch), near the attachment of the ligamentum arteriosum. Longitudinal impacts cause the arch to move forward, inducing stress at the ligament, which is fixed to the pulmonary wall. A survey of automotive case studies yields an approximate distribution as shown in figure 2. (Allmendiger 1977, Beall 1969, Degiannis 2003, Dolney 1978, Kosak 1971, Marsh 1957, Mure 1990, Parmerly 1958, Roughneen 1995, Seiling 1975, Sevitt 1977, Warrian 1988)

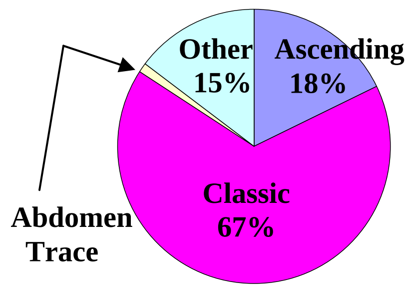

Figure 2. Aortic Injury Distribution, Automotive Autopsy

Aortic Injury - Aircraft Environment
The aircraft environment has a very different distribution as shown in Figure 3. (Gable 1963) The ascending and abdominal aorta locations are most frequent. Injury in these locations is associated with vertical displacement of the heart or abdomen, stressing the interface between the organ and the aorta.

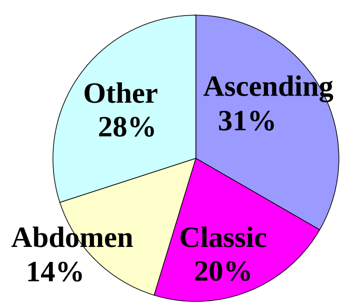

Figure 3. Aortic Injury Distribution, GA Aircraft Autopsy

One may expect all aortic injury to be non-survivable, but a significant minor percentage do survive. Partial tears to one or more of the three layers comprising the aorta will often result in an aneurysm. Surprisingly, timely and accurate diagnosis rather than extent of damage appear to be primary for survivability. Survival rate at the scene ranges from about 10% to 20% percent (Beal 1969), and up to about 30%, with 60 to 70% successfully repaired. (Creasy 1997) Case studies with successful repair of complete trans-section can also be found, including Parmerly, who noted 9 of 38 survivor cases had complete trans-section. (Beal 1969, Parmerly 1958)

Survivability Threshold and Injury Tolerance
Understanding the basic relationship between impact load and injury tolerance is critical for evaluating survivability. A simple spring analogy and the criterion developed for spinal injury provides a good means to illustrate injury tolerance. Aircraft safety regulations include a lumbar spine compressive load limit criterion of 1500 lb (7 KN). Figure 4 illustrates injury tolerance limits by graphically depicting the fracture threshold of a simple spring on a logarithmic chart of the load.

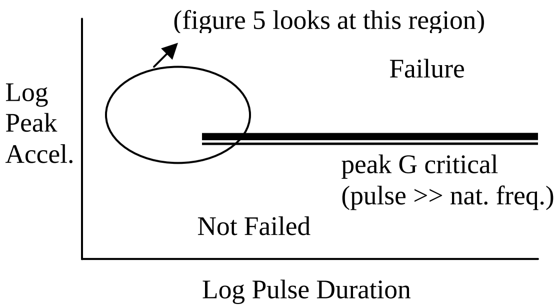

Figure 4. Fracture Threshold, Long Duration Pulse

The threshold above is flat because the onset rate does not affect the response. The load is essentially a step function with infinite energy. Now consider shorter impact pulses, whose duration is similar to the natural period of the spring. The rate of loading and total energy of these pulses will have an affect on the shape of the fracture threshold. Figure 5 shows the velocity change domain.

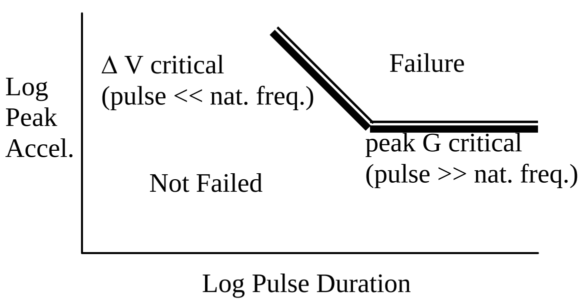

Figure 5. Fracture Threshold, Short Duration Pulse

The slope of the Δ V portion is a function of the onset rate. The max slope will be for a square pulse, which has a dynamic overshoot equal to twice the peak for an un-damped structure. Increased damping will decrease the slope. A critically damped system becomes a flat line with zero overshoot. (Craig 1981)

The spring analogy can be applied to virtually all measures of injury potential. The lumbar criterion is based on the Dynamic Response Index (DRI). DRI is defined as the peak amplitude of the impact pulse divided by the weight of the occupant. (Stech 1969) This peak value is force based, indicating that the spine is stiff and has a short natural frequency relative to the impact pulses considered.

Each body tissue will have a unique tolerance curve. It is unknown the extent that the lumbar design requirement mitigates aortic injury. The aortic injury tolerance curve has yet to be estimated. Differences in seat, restraint and aircraft factors will affect the potential for a clear estimation of this tolerance curve. Although these types of factors were able to be overcome with DRI, which was originally developed for spinal tolerance to ejection seats with rocket catapults. (Lobdell 1972) Improved capability of computers to model visco-elastic materials and work developing detailed finite element models of the aorta provide valuable tools. (Shah 2001)

Evidence exists suggesting that at least a portion of the aorta injury tolerance curve is within the survivable domain. Occupants of small aircraft are more susceptible to acceleration injury than those in large aircraft. Less crushable structure transmits the impact pulse more directly to the occupants. However, aortic injury has been found even in survivable large transport aircraft crashes (Pezzella 1996). It should also be noted that factors such as age and calcification of the arteries negatively affect the injury threshold.

DYNAMIC IMPACT TESTS

The literature and injury study in the previous sections indicate benefits from learning about the downward impact environment associated with aircraft. Until more information is developed, this case is established only for the lumbar spine. In order to evaluate a larger variety of contact and energy based potential injury, impact tests in the longitudinal direction were evaluated.

Several dynamic sled tests were conducted at the AmSafe Aviation Impact Dynamics Laboratory in Phoenix Arizona. Generic rigid seats with either standard or airbag restraint systems were used. Generic configurations provide a means to evaluate energy transfer and injury potential while minimizing the effect from installation specific factors. Complete test reports are filed at the laboratory according to the AmSafe Sequence Numbers: F0115 (Forward); F0252, F0270, F0272 (Side Facing).

The performance measures evaluated do not always match those currently part of the Federal Aviation Regulations (FAR). The tests are development in nature and measures used are selected to best illustrate injury trends rather than show compliance to a requirement.

Results – Forward Facing Seat

Figures 6 and 7 show a forward facing, longitudinal dynamic test with an impact pulse of 21 g over 140ms and a total velocity change of 42 ft/s. The high speed video images are taken at the time of peak web load (85ms) and the maximum flailing (150ms) respectively. The left ATD (when viewed from the top) is fitted with a four point AAIR restraint. The right ATD is fitted with a standard four point restraint.

This test illustrates the energy management of the occupants during an impact. Mitigating contact injury from secondary impacts to interior structure requires less occupant flailing. The AAIR restraint shows this affect, with the occupant more directly coupled to the seat.

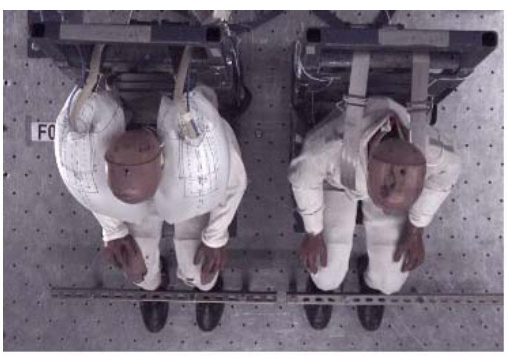

Figure 6. Forward Impact at Time = 85ms

The impact energy is transferred over a larger period of time and at lower peak accelerations. This is evident in the web loads as shown in figure 8. The position of the ATD's look about the same at 85ms, but the energy transfer to the occupant has begun to occur earlier with the AAIR. This is evident in the web loads and ultimately in the view at 150ms. The ATD without the AAIR has significantly more flailing and forward excursion, increasing the potential for secondary impact to the interior.

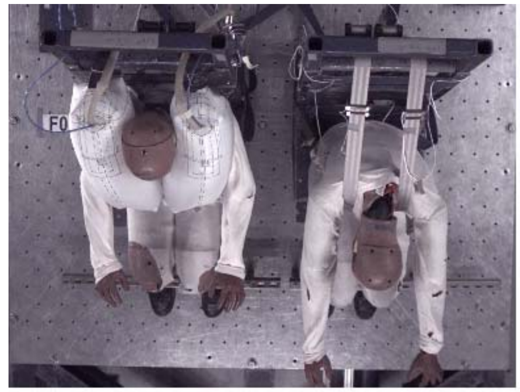

Figure 7. Forward Impact at Time = 150ms

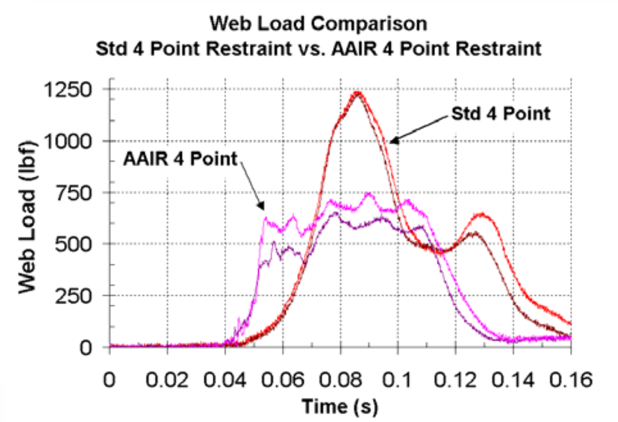

Figure 8. Forward Impact Test Web Loads

Results – Side Facing Seat, Pelvic/Rib Evaluation

Three side facing seat tests are evaluated. The occupants are exposed to the regulatory standard 16g pulse with a duration of 180ms and a total velocity change of 44 ft/s. The tests have the configurations shown in Table 1.

Table 1. Side Facing Test Configurations

Center Position	Armrest Position	Both Occupied
3 Point Std Restraint	3 Point Std Restraint	3 Point AAIR Restraints
Hybrid III ATD	ES1 ATD	Hybrid III (Cntr)
		ES1 (Armrest)

The first evaluation is at the point of peak pelvic acceleration, about 85ms into the event as shown in Figures 9, 10, and 11. The figures are shown at this time to illustrate the potential injury associated with the acceleration based pelvic injury criteria. This criterion has a threshold limit value of 130g.

Figure 9. Center Seat Figure 10. Armrest Seat
(at Time = 100ms, maximum pelvic acceleration)

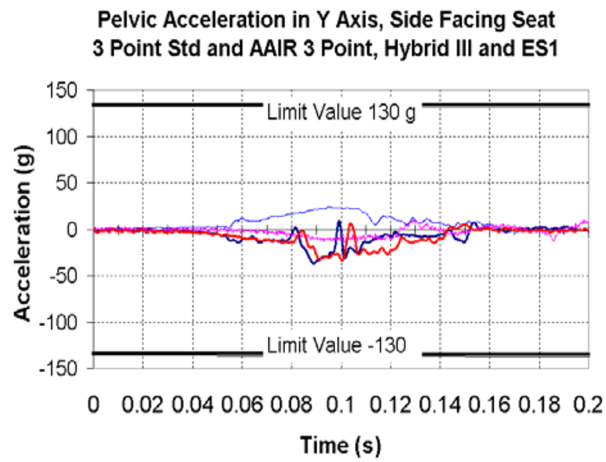

Figure 12. Side Impact Pelvic Acceleration versus Time

Figure 11. Both Seats Occupied, AAIR Restraint, Time = 100ms

Figure 12 provides the Pelvic acceleration versus time for all the ATD's in these three tests. The scale extends to the limit value of + or – 130g. The response is well below the limit criterion, indicating that either the event is not injurious, or that the response measured is not appropriate for the injury mechanism. Aviation regulations have not defined the injury requirements for side facing aircraft seats. The compliance criteria are established through the FAA Issue Paper process. Pelvic acceleration, Head Injury Criteria (HIC), and the Thoracic Trauma Index (TTI) are the common compliance measures used. HIC and TTI are evaluated in subsequent sections.

The side impact tests show significant intrusion of the armrest for the adjacent seat position. This is a classic contact type injury. Side impact ATD's have the capability to measure rib deflection. The generally accepted threshold for injury is 1.6 in (42mm). (Lankarani 1999) Another potential measure for this injury is the pubic symphysis force, with a limit criteria of 2,250 lb (10 KN). Both rib deflection and pubic force are under consideration by the FAA as appropriate injury criteria for side facing aircraft seats. Development work is in progress to refine these measurements, and findings will be published in future publications.

Results – Side Facing Seat, Thoracic Trauma Index

Another acceleration based response is the Thoracic Trauma Index (TTI) with a limit value of 85g. This response is an acceleration based index using the average of the peak acceleration of the lower spine (measured at T12) and the peak rib acceleration. The AAIR restraint produced a large reduction in TTI as shown in Table 2, although both were below the limit of 85g.

Table 2. TTI and Related Responses
Side Facing Impact Tests, ES1 ATD's

Response	Armrest Std 3 Point	Armrest AAIR
	ES1	ES1
TTI	**52g**	**29g**
Peak Acceleration Rib	63g	30g
Peak Acceleration T12	42g	27g

The T12 acceleration versus time provides a useful indication of the torso acceleration comparing the standard and AAIR restraints. Figure 13 provides the T12 acceleration versus time for the ES1 ATDs.

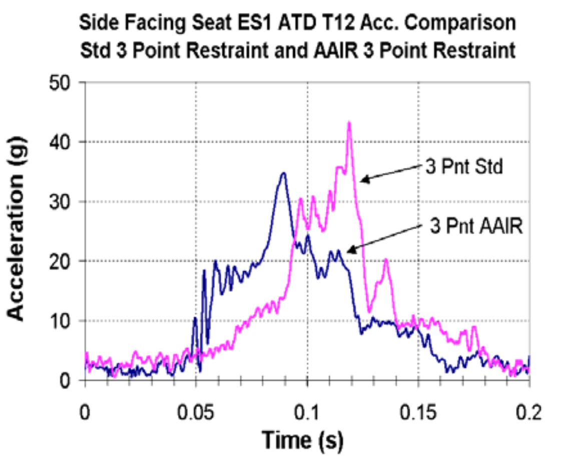

Figure 13. T12 Acceleration vs Time, with and without AAIR Restraint.

The thoracic region is difficult to assess directly from the high speed video. Similar to the web loads seen in the forward test, earlier interaction of the AAIR and more distributed loading to the occupant are evident.

Results – Side Facing Seat, Head and Neck

The Pelvic/Rib/Thorax evaluations are critical mid-event. The other critical point is late in the event, during maximum flailing. This occurs at about 150 ms with the standard restraint and about 140ms for the airbag restraint. Figures 14, 15 and 16 show the three tests at 150ms.

Figure 14. Center Seat, Std Restraint at 150ms

Figure 15. Armrest Seat, Std Restraint at 150ms

Figure 16. Both Seats, AAIR Restraint, at 150ms

The images at 150ms of the tests using standard restraints clearly show severe injury potential to the head and neck. The flailing of the head is extreme. Visual evaluation of the AAIR restrained occupants show drastic improvement.

HIC exhibited a massive difference between the standard and AAIR restraint as shown in Table 3. HIC is based on a calculation of the head resultant acceleration. A formula is used which establishes an average acceleration over a critical time interval (Delta T). Thus both acceleration and the energy associated with the impact of the head affect the final result. In this way, HIC addresses both contact and inertial injury. Short duration, high g impacts are associated with skull fracture, while longer duration, lower g impacts are associated with brain injury. Note that the applicable impact durations are debated, with a maximum of 36ms at 1000 or 15ms at 700 commonly accepted.

Table 3. HIC and Related Responses
Side Facing Impact Tests

Response	Center Std 3 Pnt	Armrest Std 3 Pnt	Center AAIR	Armrest AAIR
	Hybrid III	ES1	Hyb. III	ES1
HIC	**1260**	**736**	**194**	**206**
Peak Acc.	93g	64g	29g	32g
Time Pk	141	138ms	104ms	92ms
Delta T	40ms	53ms	113ms	119ms

Comparing the head resultant acceleration also dramatically illustrates the effect of the AAIR restraint as shown in figure 17. The AAIR restrained occupants show significant deceleration of the head around 50ms as opposed to the standard restraint, at about 80ms. This creates a broad, flat acceleration profile with peak values a fraction of the spike seen with the standard restraint.

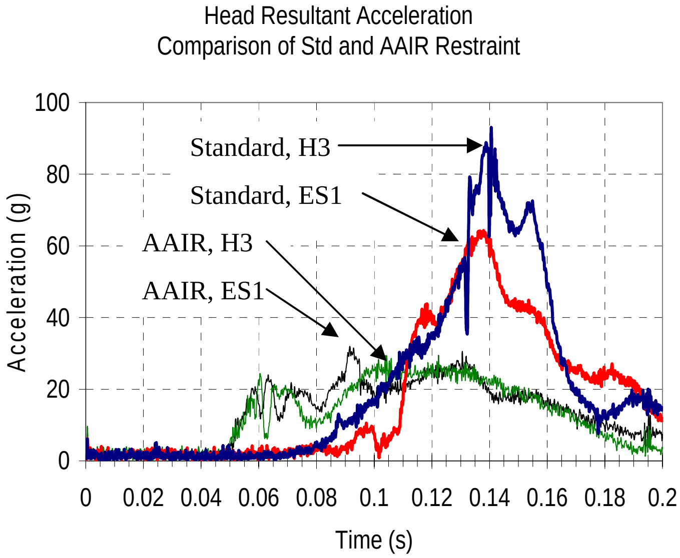

Figure 17. Head Resultant Accel., Side Facing Seats

The high acceleration peaks occurring at about 150ms for the standard restraints also indicate a critical problem with the neck. The peak head acceleration is very different from the torso, whose peak occurred at about 120ms (see figure 13). This difference in relative motion is reacted through loading of the neck. The neck loads for the AAIR restraint are a fraction of that for the standard restraint. The Neck loads for these tests are not presented due to bio-fidelity issues between the ATD types. An accurate assessment of the neck loads to evolving limit criteria is being developed, and will be presented in future publications.

CONCLUSIONS and RECOMMENDATIONS

Published accident analysis and other literature related to the survivability of transport and General Aviation aircraft indicate the problems and opportunities for improved survivability in small aircraft. The technology exits to achieve drastic improvements. Resource priorities should focus on making these aircraft more survivable. This will address the disparity between the small and large aircraft and benefit aviation safety in general.

Study of the distribution of injuries in GA aircraft and the impact environment indicate the importance of aircraft specific research. The study also shows that acceleration/energy based injury in aircraft are relatively poorly understood as compared to the current state of technology and design. The frequency of human factors investigation of small aircraft accidents is inadequate.
A better understanding of the aircraft specific environment should be developed. This knowledge will be needed to support the trend towards smaller aircraft operations.

The aortic injury study and the dynamic test evaluations expose specific concerns and potential benefits for injury mitigation. In the case of aortic injury, which is representative of energy based injury to the body, injury thresholds and potential benefits need to be further developed before conclusive recommendations can be drawn. But in the case of many force based injury, such as neck, ribs, and lower thorax, sufficient understanding exists to standardize performance measures and develop a plan for implementation. The tests also showed that impact survivability can greatly benefit from inflatable restraint technology.

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BIOGRAPHIE

T. H. Barth graduated from Colorado State University in 1989 with a Bachelors in Mechanical Engineering, and is currently two years into a PhD by Research at Cranfield University with the topic of aircraft impact survivability. He has 15 years experience in automotive and aircraft restraint system development and vehicle crash dynamics. Past experience includes positions at TRW Vehicle Safety Systems in Arizona and Munich Germany; Simula Inc in Arizona, and AmSafe Aviation in Arizona and Toulouse France. He is currently the Director of Research and Development for Amsafe Aviation Inflatable Restraints Division.