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AIRCRAFT CRASH SURVIVABILITY FROM VISCOUS INJURY IN VERTICAL IMPACTS

SCHOOL OF APPLIED SCIENCE

PhD THESIS

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ABSTRACT

This research investigated viscous injury from vertical impact loading to determine if it is critical to survivability of aircraft accidents. A unique database was built from autopsy reports and accident investigations combining injury data with the vehicle impact data. Computer models were created and used to assess injury potential. Common design limits and actual crash data from full scale research experiments were used as inputs. The results were analyzed according to published injury thresholds and compared with real accident autopsies to determine the validity of the hypothesis.

Heart and Aortic Injury (HAI) has been considered a critical survivability factor through out the history of mechanized transportation. The mechanisms of HAI in the aircraft environment were never well characterized. Automotive research identified important HAI injury mechanisms related to the forward and lateral impact vectors. This research investigated the vertical impact vector. A model was developed to evaluate the biomechanical response of a simplified visco-elastic system, and incorporated into a system model which included the occupant and aircraft seat. This approach was similar to the development of spine injury criteria and provided the advantage of a macro level evaluation of the injury thresholds and assessment of the criticality in survivable accidents.

Evaluations of real accidents sustaining HAI characterized a range of impact severity and approximate boundaries for survivability with HAI and internal organ injury. Viscous injury potential from vertical impact was found to be less critical than potential spine injury. Detailed analysis of HAI documented in autopsy reports and the corresponding accident investigations found that HAI was associated with cockpit environmental factors rather than inertial displacement mechanisms. Vertical displacement of the heart due to inertial loads is not a critical factor in survivable accidents given current aircraft technology. Inertial loading to the heart and aorta is a contributory factor for viscous injuries in aircraft accidents.

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1. INTRODUCTION

Aircraft design decisions require an assessment of priorities. Seats and restraints are basic safety features functioning in everyday operations, but are also intended to keep the occupants safe during a survivable crash. Different crash conditions and occupant environments produce different types of injury. How sophisticated should crashworthy equipment be to mitigate injury potential? Which types of injury should take precedence? Should the advancements of modern automotive equipment be incorporated into aircraft, or does the cost outweigh the benefit? The answers to these questions are generally driven by aircraft interior design requirements and the impact severity limits they represent. Production equipment rarely exceeds minimum design requirements, which is logical for efficient design. But safety equipment priorities, especially in automotive, are affected by pressure from safety marketing and user demand. The design of crash survival equipment in small aircraft is increasingly affected by similar considerations.

Crash protection versus crash avoidance is relatively balanced in automotive. Both antilock brakes and airbags fit with the "Safety Sells" mantra because accidents are part of everyday life for the general public. Aviation on the other hand has traditionally focused on operational safety and crash avoidance, especially for large aircraft. The small aircraft (General Aviation – GA and Light Sport) community places a higher priority on crash protection. Passenger airbags and the Ballistic Recovery System (BRS) are now commonly marketed directly to the end user, and often installed where the safety regulations were already satisfied. The opportunity to mitigate specific impacts and associated injuries based solely on perceived need places a burden on priorities. The topic of this thesis is urgent because soft tissue and organ injuries are a current automotive priority. Shared objectives and transfer of knowledge between automotive and aviation has the potential to improve the cost to benefit ratio for mitigating Heart and Aortic (HAI) in aircraft accidents, but only makes sense if these injuries are an important factor in surviving aircraft accidents.

Surviving a crash depends on impact energy management, both at the vehicle and occupant levels. Poorly developed vehicles permit injuries at relatively low impact levels. Survivability levels have been improved through Energy Absorbing (EA) systems or by redirecting the impact energy away from the occupant and changing the time basis for loading the body structures. Injuries can be classified as either localized or distributed trauma. Localized trauma is force critical, with a relatively short duration load. Distributed trauma is energy critical, with relatively long load duration. Modern automobiles have mitigated localized trauma to the extent that distributed trauma has become a higher priority (Nielson 1986). Skull fractures, for example, were once the primary concern for injury research. But the introduction of safety equipment including the seat belt, collapsible EA structures, and airbags has since shifted focus onto non-penetrating, distributed injuries such as viscous brain injury and thoracic organ injuries.

The introduction of improved safety equipment is evident in US automotive Statistics. The accident fatality per 100k miles driven decreased by 23% from 1975 to 1992, and an additional drop of 2.4% occurred from 1992 to 2000 (NHTSA 2002). The reduced improvement from 1992 to 2000 reflects the maturity of automotive safety design. The introduction of airbags in the late 1980's helped achieve a decrease of the US automotive injury rate per 100k miles driven of 14% from 1988 to 1992 (NHTSA 2002). A similar cycle is occurring with aircraft, although the trend is at least 10 years behind automobiles. Civil aircraft safety standards were greatly improved in 1988 by adding dynamic load requirements to the existing static load structural requirements for seats. The dynamic loads are applied using a crash test with a seat, restraint and Anthropomorphic Test Dummy (ATD). These requirements (FAR 25.562) made it possible to measure the potential for occupant injury. Now that ATD's and injury measures are commonly used in aviation, prioritizing available safety technology is very important.

Fortunately most of biomechanical safety research is applicable to any vehicle. Forward movement makes them all susceptible to longitudinal and lateral impacts. The aircraft environment, however, has the unique issue of a vertical impact component (both for crash landings and ejection seats). Injuries resulting from vertical loads are of little interest outside aviation and thus suffer from a lower knowledge base. Spinal injury was one area where design limits for vertical loads have been characterized, greatly benefiting aviators. The mechanisms of vertical spine injury involve bone fractures and can be described as localized trauma. Distributed trauma from vertical loads on the other hand, has virtually no basic research from which to draw opinions. The most important and potentially vulnerable soft tissue, the heart and aorta, are assumed to be a key to survivability. Evaluating injury mechanisms such as a fractured rib puncturing the heart or lacerating the aorta are relatively simple. Quantifying the injury mechanism associated with vertical inertial force acting on the organs is much more complicated. Historically vertical impacts were not understood but assumed to be important. Should HAI and other organ injuries be a concern as the seats and restraints designed to dynamic load conditions increase the survivable boundary? If HAI is a concern for automobiles, how does the vertical aspect of the aircraft environment relate? These questions helped form the research hypothesis that heart and aortic injury resulting from vertical impact component of aircraft crashes are a significant causal factor of fatality in survivable aircraft accidents.

1.1 Scope

Small, General Aviation (GA) aircraft were the primary interest of this research. The accident rate and therefore effectiveness of crashworthy technology are disproportionately high for this class of aircraft. Figure 1-1 illustrates the accident rates (grey bars) and fatality rates (black lines) over the period from 1984 to 1996 comparing transport and GA aircraft (Li 1999).

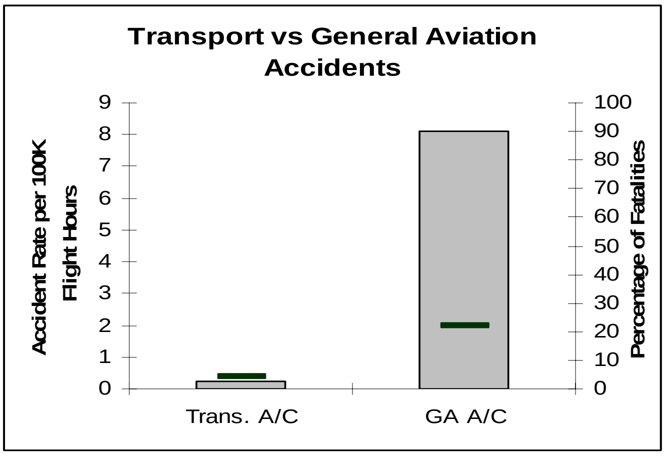


Figure 1-1. Comparison of Transport and GA Accident/Fatality Rates (Li 1999)

The scarcity of survival factors data for GA aircraft necessitated drawing on information from all aircraft types. The predominant source of HAI cases was found in military helicopter accident files.

1.2 Objectives

The primary research objective was:

- To establish if vertical displacement of visco-elastic tissues (heart and aorta) is a critical factor in the survivability of small aircraft accidents.

In order to resolve the primary objective, the secondary objectives were:

- Assess the relationship between the vertical component of aircraft impacts and the motion of the heart and aorta.

Assessing the vertical impact / viscera motion relationship required a means to measure or otherwise quantify the displacement as a function of the impact.

- Develop knowledge of the aircraft environment and impact characteristics and establish accident cases to be evaluated.
- Establish a method to assess the relationship between the vehicle impact severity and potential for viscous organ injury.

This created a means to estimate the survivable boundary for aircraft impacts, and required a historical perspective to understand what would be considered survivable. HAI was selected to be the focus as this trauma is found in injury listings and critical for survival, and was thus a good indicator for critical viscous injury.

- Establish the occurrence of heart and aortic injury in aircraft accidents via real world occurrences of these injuries.
- Establish the severity of crashes when HAI occurs.

1.3 Thesis Structure

The thesis is presented in 10 chapters. Chapter 1 includes the scope, hypothesis and objectives. The remaining chapters and their primary sub-sections are listed here. The thesis has two primary elements: Computer Modelling and Accident Studies. The computer model created a means to assess the potential for HAI, while the Accident studies established the occurrence of HAI in real world events. These were used together to estimate the survival limits of vertical aircraft impact and determine if HAI occurs within this boundary.

Chapter 2: Literature Survey

The literature study is broken down into three sections starting with the aircraft level and working down to the body tissues.

- Crashworthiness and Aircraft Safety Design Requirements
- Injury Measures (Basis for methods to evaluate HAI)
- HAI Survey (History and basis for accident studies)

Chapter 3: Methods for Computer Modelling

- Aircraft / Seat / Occupant System (Means to measure seat/body response)
- Occupant Spine / Aorta / Heart System (Quantifies heart/aorta response)

Chapter 4: Impact Characterizations and Model Calibrations

- Impact Characterizations (GA, Rotorcraft, Transport Aircraft, used for inputs in chapter 6)
- System Model Calibrations
- Heart and Aorta Model Calibrations

Chapter 5: Accident Study Methodology

- Published Accident Studies (Occurrence of HAI and Survivability envelope)
- Database Research Methodology (Occurrence of HAI related to aircraft impact)

Chapter 6: Model Results

- Impact Pulse Evaluations (Results for six impacts selected from Chapter 4)
- Comparative Model Results

Chapter 7: Accident Study Results

- Results from Published Accident Papers and Reports
- Database Research Results (Evaluations of injury listings and autopsy records)

Chapter 8: Analysis and Discussion

- Modelling of Aircraft Crash Impacts
- Accident Research Studies

Chapter 9: Conclusions

Chapter 10: Future Work

1.4 List of Abbreviations

This thesis drew upon an extensive list of sources related to aircraft crashworthiness and survivability. Thus there are many organizations and other abbreviations used. The full name of very common abbreviations such as USA are provided here but are not spelled out in the text. All other abbreviations are spelled out for the first usage in each chapter, with only the abbreviation given in subsequent use.

AAIB	Air Accident Investigation Branch (UK)
AAIR	AmSafe Aviation Inflatable Restraint
AARL	Army Aviation Research Laboratory
ACAP	Advanced Composite Airframe Program
AFRL	Air Force Research Laboratory (USA)
AGATE	Advanced General Aviation Transportation Experiment Program
ATD	Anthropomorphic Test Dummy
APROSYS	Advanced Protection Systems
AS	Aerospace Standard
CAA	Civil Aviation Authority
CABS	Cockpit Airbag System
CAMI	Civil Aero-Medical Laboratory
CAR	Civil Aviation Regulation
CEF	Cockpit Environmental Factors
CFC	Channel Frequency Class
CFR	Code of Federal Regulations
COG	Centre of Gravity
CSDG	Crash Survival Design Guide
CRDA	Co-operative Research and Development Agreement
CREEP	crashworthiness acronym for the following factors: Container, Restraints, Environment, Energy Absorption, Post Crash Factors
DOD	Department of Defence (USA)
DOT	Department of Transportation (USA)
DRI	Dynamic Response Index
EA	Energy Absorber
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration (USA)

FAR	Federal Aviation Regulation
FE	Finite Element
FEA	Finite Element Analysis
FSF	Flight Safety Foundation
GA	General Aviation
HAI	Heart and Aortic Injury
INRETS	Applied Biomechanics Laboratory of the French National Institute for Transport and Safety Research
IRDF	Impact Dynamics Research Facility
JAR	Joint Airworthiness Requirements
JSSG	Joint Service Specification Guide (USA)
NASA	National Aeronautics and Space Administration (USA)
NCAC	National Crash Analysis Center (Ford Motor Company)
NHTSA	National Highway and Traffic Safety Administration (USA)
NTSB	National Transportation Safety Board (USA)
PMHS	Post Mortem Human Subject
SAE	Society of Automotive Engineers
TSO	Technical Standard Order
UK	United Kingdom
US	United States
USA	United States of America
WPAFB	Wright Patterson Air Force Base (USA)

2. LITERATURE SURVEY

The literature survey has three sections:

- Crashworthiness and Aircraft Safety Design Requirements: Survey of crashworthiness history and existing civil and military requirements provided idealized aircraft impact pulses with established injury severity.
- Injury Measures: Survey of basic injury principles and measurement supported the modelling approach and estimation of the onset (or threshold) of viscous injury.
- HAI Survey: Survey of all HAI literature (automotive and aircraft based) supported the rational for the model approach.

The surveys of crashworthiness and injury followed the research objectives which were focused on the unique aspects of the aircraft environment. Automotive or any other applicable literature was included as required.

2.1 Crashworthiness and Aircraft Safety Design Requirements

Transportation in any form has always been known to involve some level of risk, and aviation accidents in particular are considered severely hazardous. Crashworthy designs are defined as features incorporated into the aircraft to provide enhanced protection or mitigate injury during a crash. Seat belt restraints in aircraft date from before World War I, although primary purpose was not for crash protection (Chandler 1994). The first seatbelts were used to help maintain control of the aircraft by restraining the occupant from shifting or flailing in the cockpit during flight. Crash protection combines the structural design limits of the aircraft and the biomechanical limits of the occupants. Biomechanical impact research dates back to the early 1940's by German aircraft manufacturers who needed to reduce the occupant loads from ejection seats (Payne 1963). Ideally crash loads transferred to the occupants are managed within survivable limits up to the point that the primary aircraft structure is compromised.

A founding father of crashworthiness was Hugh DeHaven; an aviator with the Canadian Royal Flying Corps during World War I who began research in the 1920's and continued into the 1950's. His principles of crashworthiness included the concept of maintaining a survivable cabin volume and restraining the occupants by distributing the applied forces below injury thresholds (Hurley 2002). These basic principles, in an expanded form, are often described by the acronym CREEP as described below (Hurley 2002).

C = Container — Maintain appropriate volume of living space.

R = Restraints — Reduce flailing of the occupant, transmit crash loads safely.

E = Environment — Minimize injurious objects, noise, chemicals, etc. in the occupant space and maximize egress.

E = Energy Absorption — Maximize the aircraft and equipment to absorb impact.

P = Post crash Factors — Minimize items that can impede egress such as fire and toxic materials.

CREEP relates to the research objectives as illustrated in Figure 2-1.

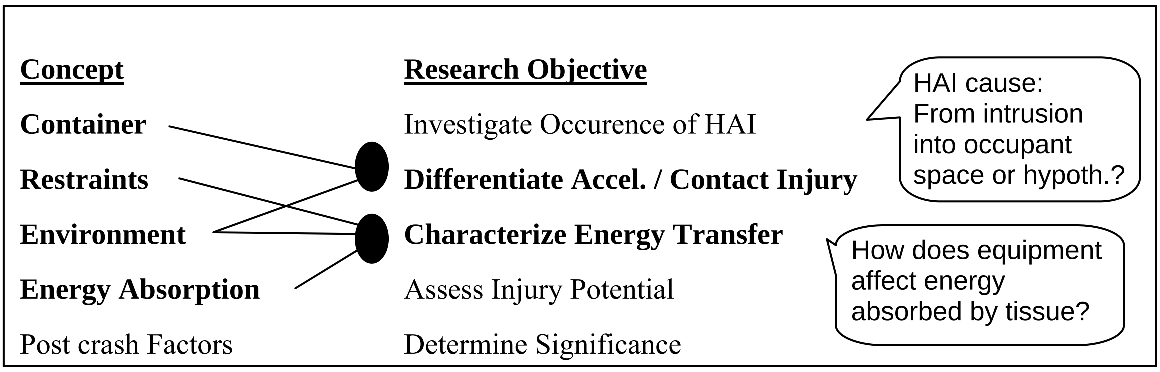


Figure 2-1. CREEP Related to Research Objectives

The Aviation Crash Injury Research Division of the Flight Safety Foundation (FSF) was formed in the late 1950's for the purpose of investigating aircraft accidents and reporting injuries. This was also the timeframe in which the first crash scenarios to define the survivable limits of US Army helicopters were developed (Desjardins 2004). In 1965 the US Army initiated a project to consolidate crashworthy design guidelines for use by aircraft design engineers, which lead to the US Army Crash Survival Design Guide (CSRD). The first publication of this document was in 1967, and was issued as a technical report. It was revised in 1971, which provided the basis for the military standard MIL-STD-1290 (Light Fixed and Rotary Wing Aircraft Crash Resistance), and again in 1980 which expanded it to five volumes. The latest revision was issued in 1989 (Coltman 1989). The five volumes address:

- Volume I: Design Criteria and Checklists
- Volume II: Aircraft Design Impact Conditions and Human Tolerance
- Volume III: Aircraft Structural Crash Resistance
- Volume IV: Aircraft Seats, Restraints, Litters, and Cockpit/Cabin De-lethalization.
- Volume V: Aircraft Post crash Survival.

Volumes II, III and IV were used in this research as described in this and the other sections of the literature survey. Volume I is a listing of the more detailed information provided in the other volumes. Volume V addresses factors after the primary impact, which was beyond the scope of this research.

Two other documents have been created which incorporate much of the same information as the five volume design guide but provide focus for military and small fixed wing aircraft. Both are intended to provide guidance to design engineers for crash protection systems. The military focused document is:

<u>US Department of Defence (DOD) Joint Service Specification Guide (JSSG)</u>
(USDOD 1998)

- Combines material from a wide range of crashworthiness specifications, guidelines, regulations and other publications, both military and civil
- Provides design criteria pulled from the source material, with a discussion of the rational and limitations for each.

The Small Airplane Crashworthiness Design Guide was created by the Advanced General Aviation Transportation Experiment Program (AGATE), and was published in 2002 (Hurley, 2002). AGATE was a government (FAA and NASA) and industry alliance formed to improve the safety of General aviation.

AGATE Small Airplane Crashworthiness Design Guide (AGATE Guide):

- Created based on the US Army Crash Survival Design Guide but with a focus on single engine, two to six passenger GA aircraft
- Includes research conducted by AGATE and information about crashworthiness technologies established after the last issue of the Army Guide in 1989

NASA has been involved with aviation crashworthiness since the 1970's. The former Lunar Landing Research Facility in Hampton Virginia was converted to an aircraft crash test laboratory named the Impact Dynamics Research Facility (IRDF). The facility has a steel A-frame gantry structure which is 73m high, 122m long, and 81m wide (Jackson 2004) as shown in Figure 2-2.

Figure 2-2. NASA Langley Impact Dynamics Research Facility (Jackson 2004)

The large scale facility is capable of conducting full scale aircraft and rotorcraft crash tests with forward velocity capability, unlike a drop tower. Aircraft are suspended by cables in a pendulum configuration. The aircraft swings down to a controlled impact, with the cables pyrotechnically severed just prior to impact. Since the first test in 1974, approximately 50 full scale aircraft and helicopter crash tests have been conducted. The facility was closed in 2003 and plans were made for it to be demolished in 2007, which never materialized. The FAA has indicated that the facility will reopen during government and industry cooperative meetings (Abramovitz 2008), although no official news from NASA was found.

The wide variety of aircraft types tested at the IRDF and the data available from literature of the crash tests provided valuable information for this research. Acceleration time histories at various points on the aircraft, seats, and Anthropomorphic Test Dummy (ATD) were obtained, and provided the means to evaluate impact characteristics. This data facilitated estimations of survivable impact thresholds and also provided calibration data for the computer models. The IRDF tests provided real world examples of aircraft impacts to compare with the design requirements.

2.1.1 Aircraft Static Design Requirements

Commercial aircraft safety regulations and military aircraft specifications establish design standards for the aircraft and minimum performance standards for the equipment. The earliest safety standards date to the late 1920's when US Aeronautics Bulletin 7-A mandated safety belts in aircraft in 1929 (Soltis 2001). Various safety requirements independent of crash loads exist such as Federal Aviation Regulation (FAR) 23.785 which requires shoulder harnesses in General Aviation (GA) aircraft (US CFR 1996 a) and FAR 25.785 which requires seat belts in transport aircraft (US CFR 1996 b). Federal Aviation Administration (FAA) Technical Standard Orders (TSO) C-22g and C-114, establish minimum performance standards for passenger restraints based on static loads, flammability and other tests (US CFR 1993 and US CFR 1987 respectively). Fundamental to this research however, were design requirements for aircraft that are related to dynamic crash impacts. These provided an estimate of the survivability envelope of the aircraft, because they indicate the structural limits that are considered important for designers. The crash load based design requirements can be classified based on the test method for applying the loads, either static or dynamic.

Structural considerations of the seats were introduced by the U.S. Civil Aviation Regulation (CAR) Part 03. This regulation introduced static load factors in 1946 (Lee 2001, US CFR). These basic aircraft cabin seat structure requirements are still in use today. The US and European commercial aircraft regulations (USCFR) are harmonized and specify the seat structure static loads for three aircraft types: GA Aircraft (FAR/JAR Part 23), Transport Aircraft (FAR/JAR Part 25), and Rotorcraft (FAR/JAR

Part 27 and 29). The static requirements apply loads to the seat according to the aircraft axis using a "body block", referring to a wooden form belted into the seat, and acting as the interface between the seat and the applied load. The magnitude of the design loads vary by direction, and are defined in terms of an occupant mass multiplied by the acceleration factor as shown in Table 2-1. Note that GA aircraft have an additional factor which must be applied to the load factor for aircraft with stall speed greater than 61 knots (USCFR FAR 23.562). The Aerospace Standard SAE AS8049 defines the acceptable test methods (SAE 1997). Figure 2-3 illustrates a static load test set up.

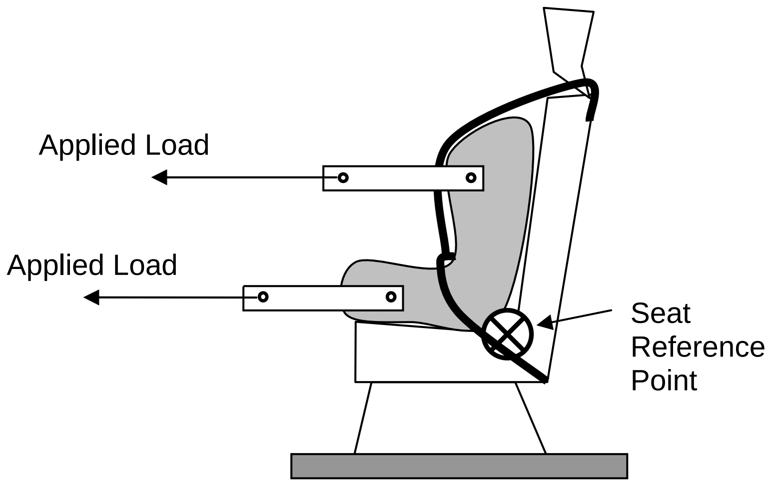


Figure 2-3. SAE 8049 Static Test Set Up

Table 2-1. Static Load Factors – Civil Aircraft (USCFR)

Direction Relative to Aircraft	General Aviation Load Factors (FAR 23.561)	Transport Aircraft Load Factors (FAR 25.561)	Rotorcraft Load Factors (FAR 27/29.561)
Forward	18 g	9 g	16 g
Downward	6 g	6 g	20 g
Upward	3 g	3 g	4 g
Sideward	4 g	1.5 g	8 g
Rearward	na	na	1.5 g

Rotorcraft have additional requirements to retain mass items which could intrude into the occupant space or damage internal fuel tanks (USCFR). High mass items must be designed to withstand load factors of 12g forward and downward, 1.5g upward and rearward, and 6g sideward. The fuselage structure in the area of internal fuel tanks must also be designed to withstand load factors of 4g forward and downward, 1.5g upward, and 2g sideward. Military design requirements are defined by each specific program, but the established guidelines are often adopted. The recommended static load requirements are provided in Table 2-2 (USDOD 1998).

Table 2-2. Static Load Factors – Military Aircraft

Direction Relative to Aircraft	Rotorcraft and Light Fixed Wing Aircraft Load Factors		
		Body Weight	Deflection Limit
Forward	35 g	113.5 kg	5.1 cm
Downward	25 g	90.8 kg (EA Seat)	No req. (EA Seat)
Upward	8 g	113.5 kg	5.1 cm
Sideward	20 g	113.5 kg	10.2 cm
Rearward	12 g	113.5 kg	5.1 cm

2.1.2 Dynamic Design Requirements of Military and Civil Aircraft

The standards evolved as survivability studies indicated the need for improved crash protection. In addition to static load factors, methods for testing and designing according to dynamic loads were developed. The impact parameters are based on military and commercial crashworthiness studies which established target impact velocities relative to the aircraft axis. These target impact velocities are based on providing protection for 95% of the survivable accidents in the study. Survivability studies that began in the early 1960's have been updated periodically as more aircraft accident data was incorporated. The history and results of these survivability studies are documented in the various design guides, including the US Army CSDG (Coltman 1989, Desjardins 1989, Johnson 1989), the JSSG Handbook (USDOD 1998), and the AGATE Guide (Hurley 2002). The types of design criteria contained in the guides and handbooks include survivable impact velocities specific to some aircraft types and impact surfaces (Coltman 1985, Coltman 1989), and dynamic impact conditions as well as performance criteria for the floor attachments, seats, restraints, and the ATD.

<u>Military Aircraft</u>

The requirements for military crew seats are contained in MIL-S-58095(AV) which was first issued in 1971 and then updated in 1986. Military troop seat requirements are contained in MIL-S-85510(AS), issued in 1981. The military rotorcraft and light fixed wing aircraft impact parameters are shown in Figure 2-4 and Table 2-3 (USDOD 1998).

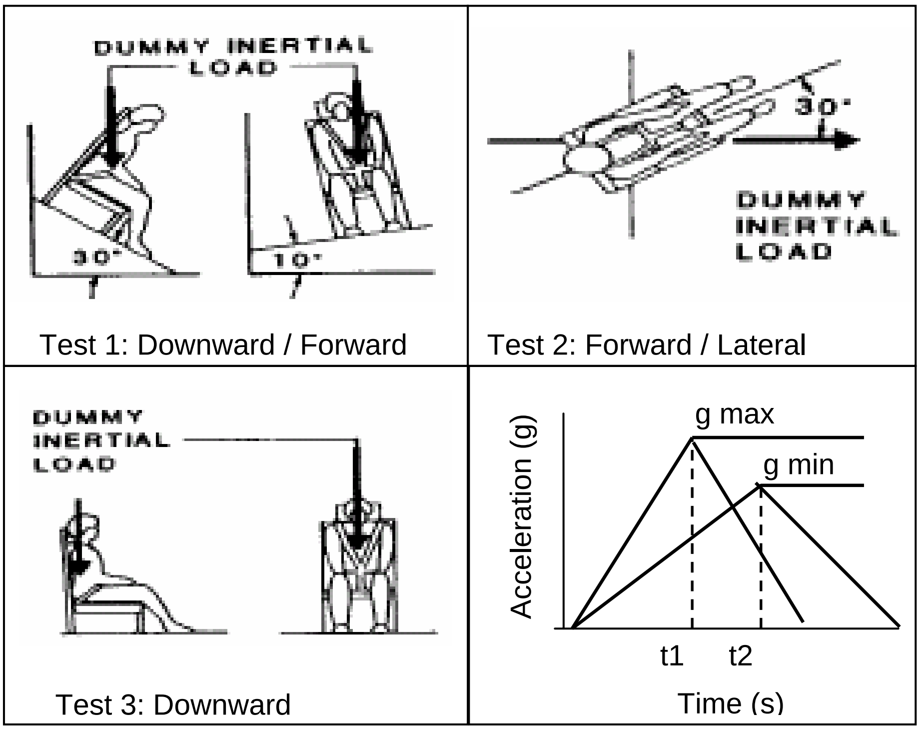


Figure 2-4. Impact Parameters for Military Aircraft Seats (USDOD 1998)

Note: The second half of the impact pulse (from the peak g back to zero) is controlled by specifying a minimum velocity change (ΔV), which is the integral, or area under the acceleration – time curve.

Table 2-3. Impact Values for Military Aircraft Seats

Test	Cockpit Seats	Cabin Seats
1. Downward / Forward / Lateral	t1 = 0.043 s t2 = 0.061 s gmin = 46 g gmax = 51 g ΔV = 15.2 m/s	t1 = 0.059 s t2 = 0.087 s gmin = 32 g gmax = 37 g ΔV = 15.2 m/s
2. Forward / Lateral	t1 = 0.066 s t2 = 0.100 s gmin = 28 g gmax = 33 g ΔV = 15.2 m/s	t1 = 0.081 s t2 = 0.127 s gmin = 22 g gmax = 27 g ΔV = 15.2 m/s
3. Downward	t1 = 0.036 s t2 = 0.051 s gmin = 46 g gmax = 51 g ΔV = 12.8 m/s	Not Applicable

Terms: t is time, actual peak must fall between t1and t2
g is acceleration, actual peak must fall between gmin and gmax
ΔV is the velocity change or total energy of the impact

There are a range of impact pulses defined for military aircraft. The US Army developed the Cockpit Airbag System (CABS) for use in helicopters (Bark 1995). The performance specification for this system includes modified impact pulses similar to those in Figure 2-4 and Table 2-3. Impact pulses are specified for the UH-60 and OH-58 helicopters, and they are described in military specification AVNS-PRF-10085 (US ACIS 2001). The UH-60 impact pulse modifies Test number 1 (Table 2-3) by adding a low severity impact at the beginning, which more accurately represents the landing gear energy attenuation. This could have an important affect on the deployment of the CABS system. The added portion rises to 8g in 0.005 seconds, and then remains at 8 g until at least 0.040 into the impact. The rest of the pulse then follows the same onset rates, duration, and total velocity change as the standard pulse. Other configurations for forward and lateral impacts are also included, but do not contain a vertical impact component. The OH-58 impact pulses contained in the CABS performance specification adds a combined downward / forward test similar to test 1. The pitch angle is 30 degrees and with zero roll or yaw. This impact is a symmetric triangle pulse reaching 30 g in 0.030 seconds and with a velocity change of 9.1 m/s. Forward and lateral impacts are also added, similar to the UH-60, but also do not contain a vertical impact component.

Civil Aircraft

Commercial aircraft regulations added dynamic performance requirements for aircraft seats in 1988 with the following FAR amendments (USCFR):

- Amendment 23-39 to FAR 23.562 (General Aviation), August 1988
- Amendment 25-64 to FAR 25.562 (Transport Aircraft), May 1988
- Amendment 27-29 to FAR 27.562 (Rotorcraft), November 1989
- Amendment 29-29 to FAR 29.562 (Transport Rotorcraft), Nov. 1989

The new rules initially only applied to new aircraft developed with a certification basis dated after these amendments. This left most of the transport aircraft flying in service unaffected. Since 1988 only a small number of aircraft types have been developed under the new rules, including the Airbus A340 and A380, Boeing B777, and commuter transports such as the BAE J-41 and the Bombardier CRJ 700 and 900. The original rule does not apply to the majority of transport aircraft including the Airbus A330, A300, A318/319/320 family and the Boeing B747, B767, B737.

A “retrofit” rule for transport aircraft, requiring replacement of seats for existing aircraft was under consideration between the FAA and Industry. Cost benefit studies concluded that more expensive, heavier seats were justified by the potential lives saved and injuries reduced (Cannon 1985, Coltman 1985, Kirkham 1982). Industry disagreed, and after years of debate, the proposed rule was published in October of 2002 (DOT 2002). This proposed rule was supported by a new cost/benefit analysis prepared by RGW Cherry and Associates for fully compliant (passing both structural and injury requirements) dynamic seats (DOT 2000). However, the proposed rule was cancelled in favour of a rule that imposes the requirements for aircraft delivered after October 2009 (USCFR 2005). This rule was adopted with amendment 121-315 of US CFR Part 121 in September of 2005. A primary argument for eliminating retrofits in favour of a deadline for fully compliant seats was based on regular replacement cycles for transport aircraft interiors. New interiors phase in seats meeting the structural aspects of the rule, providing a significant partial benefit. Compliance with the head strike injury requirement affects seating density and revenue generated from the aircraft (USCFR 2005). The final rule was based on an updated cost benefit study which compared structurally compliant seats with fully compliant seats (USCFR 2005). The history and political manoeuvres of the dynamic seat rules illustrate the difficulty in determining how safety equipment should be incorporated onto aircraft. The importance of good science and appropriate priorities should be emphasized because changes are difficult and decisions last for a long time.

The impact pulses, representing an estimate of the maximum survivable limit, differ between transport and GA. Transport pulses have a smaller impact peak and onset rate than that of GA aircraft. Each type includes two basic impact scenarios, one with a combined forward / downward impact and the other longitudinal / lateral. Figure 2-5 and Table 2-4 provide the civil aircraft test parameters and impact values.

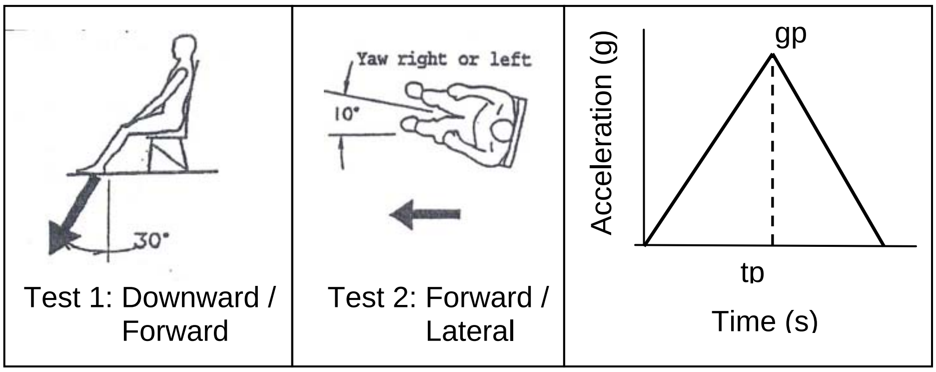


Figure 2-5. Civil Aircraft Impact Parameters (USCFR)

Table 2-4. Impact Values for Civil Aircraft Seats (USCFR)

Test	GA Aircraft	Transport Aircraft	Rotorcraft (all)
1. Downward / Forward	tp = 0.050 s (crew) tp = 0.060 s (pass.) gp = 19 g (crew) gmax = 19 g (pass.) ΔV = 9.5 m/s	tp = 0.080 s gp = 14 g ΔV = 10.7 m/s (passenger)	tp = 0.031 s gp = 30 g ΔV = 9.1 m/s
2. Forward / Lateral	tp = 0.050 s (crew) tp = 0.060 s (pass.) gp = 26 g (crew) gp = 21 g (pass.) ΔV = 12.8 m/s	tp = 0.090 s gp = 16 g ΔV = 13.4 m/s (passenger)	tp = 0.071 s gp = 18.4 g ΔV = 12.8 m/s

Note: Terms are as previously defined.

The dynamic tests use an ATD representing the 50% male as defined by a US CFR Title 49, Part 572, subpart B, weighing 170lb (77.18kg). The ATD made measures of occupant response and evaluation of injury criteria possible. The purpose of this survey was not to address all injury responses. Various measures and limit criteria are applied depending on the seat configuration. The injury limit values are specified in the regulations (USCFR 1996b) with background information available in the advisory circular AC 25.562 1-B, and the performance standards for aircraft seats AS8049 (SAE 1997).

Pulse Character of Military and Civil Design Requirements

The military and civil design limits (dynamic impact pulses for the seat tests) were used as a guide for the boundary of survivability and to represent the typical impact pulse for the aircraft types covered by the regulation. Figure 2-6 graphs the impacts according to peak acceleration magnitude and the time to peak acceleration. These were used as a basis for inputs to the computer models which assess the relationship between the vehicle impact and the body tissue response, and were also used to characterize the limit of survivability for all the aircraft types.

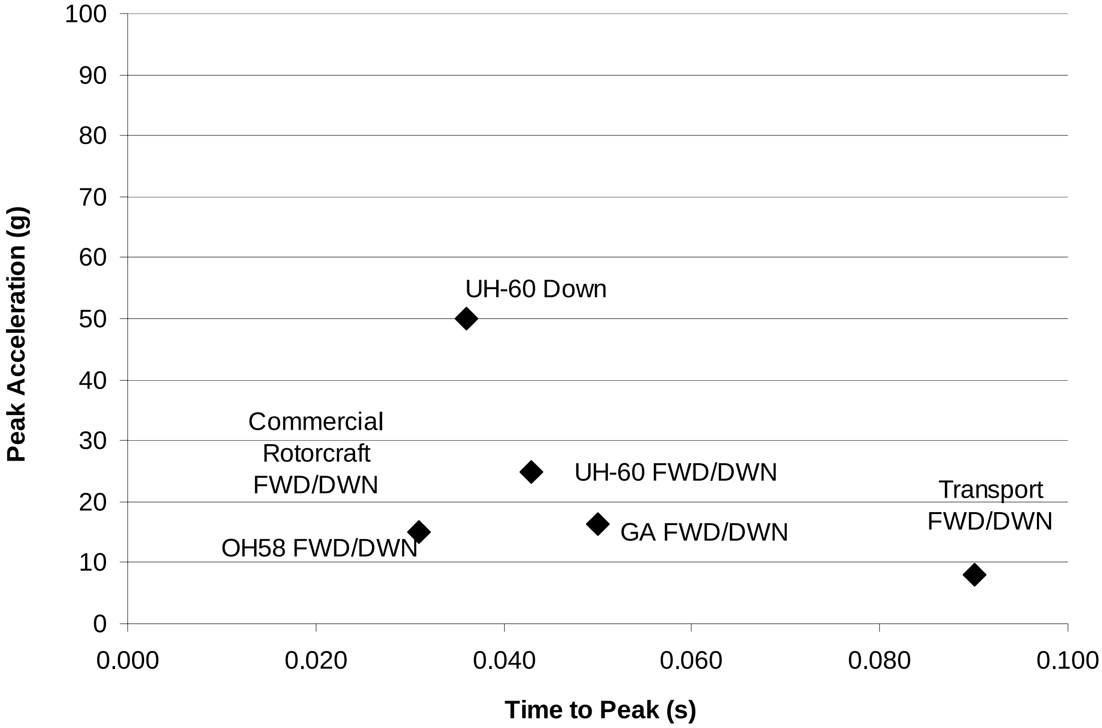


Figure 2-6. Transport Aircraft and Rotorcraft Impact Pulses, Vertical Peak Acceleration vs Time to Peak Acceleration

2.2 Injury Measures

The CREEP acronym was explained at the beginning of this chapter (section 2.1) and illustrated in Figure 2-1. Different types of injury potential are associated with the different principles. The “C” for container represents the need to maintain a survivable occupant container or cabin space. If the cabin space is compromised, the injuries are predominantly localized trauma because intrusion of the structures results in loads applied in a concentrated, localized manner. The first “E” is for Environment and refers to the occupant’s surroundings. Proper padding and placement of objects within the cabin help to avoid injuries from the occupant striking the interior. The types of injury potential associated with the C and first E principles are largely associated with contact injuries and are commonly called Cockpit Environmental Factors (CEF).

The second "E" of the CREEP acronym is for Energy Absorption. It addresses the manner in which either the vehicle structure or the occupant's immediate surroundings affect load transfer during the crash. The goal is to have effective energy absorption characteristics. This will allow the vehicle and ultimately the occupants absorb the energy from more severe impacts and survive. Another classification of injuries can be made, which unlike contact injuries, result indirectly from the forces applied to the body. If the forces are well distributed the affect on the immediate tissue may be minor, but the collective, indirect effects on neighbouring tissue can be severe as the energy is absorbed and transferred. A primary objective of this thesis was to differentiate contact and accelerative based injuries from vertical impact. This was important for establishing the causal factors and threshold for which injury begins to occur.

2.2.1 Overview of Injury Principles

Understanding the basic relationship between impact load and injury tolerance was critical for evaluating survivability. The ATD provides measures of injury potential which are compared to limit values. These limit values are based on an injury tolerance threshold developed through biomechanical study. Experiments are conducted on biological structures and the response must then be correlated to results from tests using a surrogate system to represent the true biological tissue. There are two types of measurements: direct or indirect. Skull fracture from impact onto a hard surface, for example, can be measured directly by the force on skull bone or indirectly by measuring the acceleration and building a relationship to the injury via research. The ATD does not have a load cell in the forehead, but it can measure acceleration at the centre of mass of the head. Accelerations produced from the ATD are compared with limit criteria. The limit criteria were developed from biological experiments that estimate the injury threshold and relate it to the measurable response of the ATD. Tests using the surrogate system can then be used to predict head injury, and to serve as a design guide. The most common injury criterion in aircraft design is the Head Injury Criterion (HIC). It influences virtually all modern seat and interior configurations. This research had the objective to develop a surrogate measure of potential viscous injury.

Injury Tolerance for Vertical Spine Loads, Dynamic Response Index (DRI)

Payne in 1963 and Stech in 1969 made important contributions to the understanding of the mechanical properties of body tissues and how they are affected by factors such as age, mass distribution and health. The biological research basis for the vertical spine injury criterion accounted for the body mass distribution and age of the subjects. The mass supported by each vertebra relates to the critical breaking strength. The lower vertebras are larger, as they must support more mass. Stech (1969) published a range of vertebra breaking strength, stiffness, and damping coefficients as a function of age. The parameters for a single degree of freedom spring-mass-damper model of the spine loaded in compression provide a measure of the forces on the critical vertebra. The critical vertebra was determined to be the L4. The nominal values represent an averaged aged (27.9 years) and weight (177 lb) air force aviator. The system is represented in Figure 2-7. The spring-mass-damper values used are given below.

Dynamic Response Index (DRI) is defined as the peak force measured in the model. DRI is usually expressed in dimensionless G units by dividing the spring force by the weight of the upper body acting on the spring.

- Critical vertebra L4, with breaking strength listed in G units is 21.3g
  (or can be expressed in units of Newton as: 21.3g x 42.06kg x 9.8G = 8789N)
- Stiffness of the spine k = 2057.742 kN/m
- Mass = 42.06 kg
- Damping ratio c = 0.23 (at peak spring force of 15g)
- Natural frequency = 8.45 cycle per second (51 rad/s)

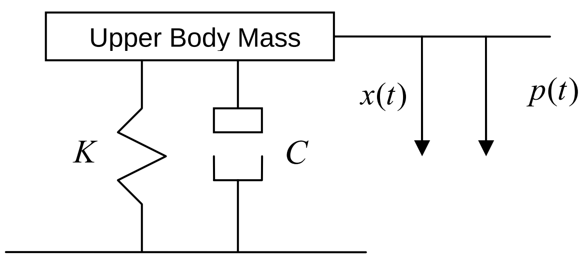


Figure 2-7. Single Degree of Freedom Spine Model

This model was used to develop an injury threshold for spinal compression fractures. The kinetic response of an occupant in an aircraft is compared to the model and the potential for spinal injury is estimated. Stech established a loading threshold approximating a 50% injury frequency. The critical value depends on the loading characteristics. There is a critical value for relatively long duration or steady state loading and another for very short duration (impulse) loading. The values are provided below and then explained in the following paragraphs.

- Critical steady state G value = 21.3g
- Critical Impulse Velocity Δ V = 6 m/s

The steady state load assumes that the applied acceleration does not vary with time, and remains applied for a relatively long time. In other words, the total period of loading (or pulse duration) is long compared to the natural frequency of the system. The breaking point is simply a function of the peak acceleration. The rate at which the load is applied to reach steady state will also have an affect. If it's very fast, it will cause a dynamic overshoot. The maximum overshoot for a step function is 2 times the applied load (Craig 1981). Figure 2-8 illustrates this case by graphically depicting the injury tolerance limit (fracture threshold) of a simple spring on a logarithmic chart of the load.

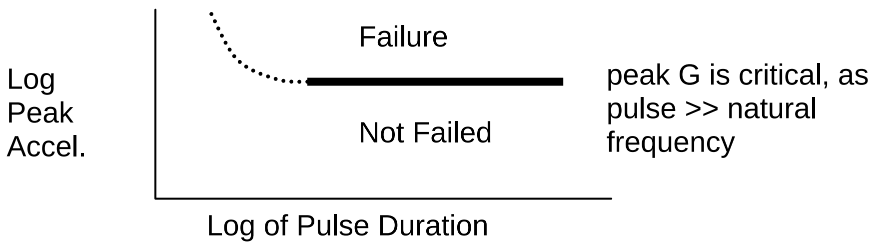


Figure 2-8. Injury Threshold, Very Long Duration Pulse

The fracture threshold (represented by the black line) is flat because the pulse duration is long. The dotted line indicates the onset region of the pulse. If the load is applied very slowly, the system will have no dynamic overshoot. On the other extreme, an instantaneous load (step function) will react as a forced vibration which overshoots to a value twice the static deflection of the spring. The overshoot will then decay to the static deflection at a rate depending on the damping. If the step function returned to zero (square wave), the forced vibration would end and the spring deflection would decay to zero. This case has a very long duration with respect to the natural frequency, and thus the response is a function of the peak load, p. Structures subjected to rapid loads often use a safety factor of 2, corresponding to the max overshoot of an under damped system (Craig 1981 pg 112).

The duration of loading in an aircraft crash is certainly not steady state, and may also not have a long duration compared to the natural frequency of the system. For impulse loading, Stech established the critical impulse velocity change reported as $\Delta V = 6$ m/s. Impulse load durations much shorter than the natural frequency of the system have a fracture threshold which depends on the velocity change (integral) of the acceleration pulse. If the natural frequency and impulse duration are similar, the response is a complex combination of both (Stech 1969). The behaviour of "Short" impact pulses are illustrated in Figure 2-9.

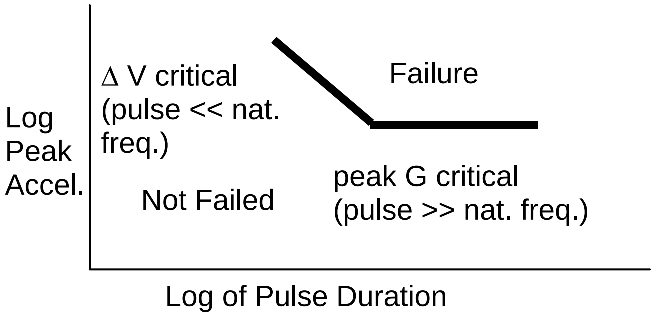


Figure 2-9. Fracture Threshold, Short Duration Pulse

The response for a pulse of very short duration is a function of the velocity change (ΔV) of the input pulse. This is the integral of the load versus time, and related to the total energy absorbed by the mechanical system.

In summary, there are three load cases for injury thresholds:

- Very Short duration impact is completed before the system has time to react, thus the response is dependent on the total energy applied.
- Very Long duration loads act like a static force. The system response depends on the maximum force.
- Middle duration loads (near the natural frequency) cause a combined response.

The research objectives required understanding of how crash loads affect the heart and aorta response. This is analogous to the spinal compression injury criteria first developed for tolerance to ejection seats with rocket catapults (Lobdell 1972). Of the large variety of injury criteria developed, only a few have been applied as design criteria for aircraft. Each body tissue will have a unique tolerance curve. Bones are much stiffer than soft tissue such as ligaments and organs. The lower natural frequency of soft tissue shift their response and critical values to lower frequencies.

2.3 Heart and Aortic Injury

Heart and Aortic Injury (HAI) was assumed to be the most critical viscous injury for vertical impact, and was the focus of this research. A literature survey of HAI was conducted and is presented in three sections: The first addressed HAI injury mechanisms, including automotive, aircraft, or any other sources; the second addressed information about body tissue response to impact loading; the third provided notes from case studies. The first case reports of HAI date from the late 1880's (Gable 1963), and research of HAI is becoming more prevalent as these injuries are increasingly associated with modern crashworthy automobiles (Siegle 2000).

2.3.1 HAI Mechanisms

One may expect all heart and aortic injuries to be non-survivable, but a significant percentage do survive aortic injuries (Creasy 1997). Partial tears to one or more of the three layers comprising the aorta can result in an aneurysm. Surprisingly, timely and accurate diagnosis rather than the extent of damage appeared to be the primary factor affecting survivability. Survival rate at the scene ranged from about 10 percent to 20 percent (Beal 1969). Some studies indicated post event survival rates of up to 30 percent, with 60 to 70 percent of these successfully repaired (Creasy 1997). Case studies with successful repair of complete trans-section were also found, including Parmerly 1958, who noted 9 of 38 survivor cases had complete trans-section, and Beal 1969. Survival rates of heart injury were not found cited in literature.

The theories of HAI mechanisms found in literature were related to one of the following: direct force, pressure effects, relative movement of body tissues, or a combination. Direct force from contact to the heart or aorta seemed to be a relatively simple injury mechanism. Intrusion of cockpit structure or a broken rib lacerating the organs (penetrating injuries) are straightforward causes of injury. However intrusion of the vertebral column from severe chest compression (Creasy 1997) and force applied from other body tissues have no clear cause and effect. These injuries would be the result of crushing, and will affect all of the surrounding tissues. Shatsky (1974) discussed various aetiology of heart injury. Posterior displacement of the heart between the sternum and the spine produced myocardial contusions in blunt impact experiments on anesthetized primates. Although these injuries involved movement of the heart, the movement was initiated by direct compression of the chest and ultimately the heart. Shatsky also theorized that rotational movement of the base of the heart may cause torsion stresses and aortic ruptures. Shatsky's experiments indicated stress to the aortic isthmus due to anterior impacts at the level of the abdomen, even though they did not cause direct compression. The potential for heart rupture was also theorized, but no ruptures were found in the Shatsky experiments.

The HAI mechanism theory of hydrodynamic pressure continues to be investigated. Compression of the chest was found to cause blood pressure spikes with experiments using rabbits (Viano 2004). The pressure spikes were not however found to be a direct cause of heart HAI. Producing traumatic rupture of the heart or aorta has been difficult. Cavanaugh (2005) reviewed several impact studies, some with and some without HAI. He suggested that the methods of pressurizing the cadaver vascular system and age of the subjects affected the occurrence of traumatic rupture. Studies of the heart tissue properties have shown differences in ultimate tensile stress based on direction and affected by hydrodynamic pressure (Mohan 1983), suggesting that a combination of movement and hydrodynamic effects are important.

A predominant mechanism theory of HAI formation has been the relative movement of tissues. Deformation of the chest wall and inertia from impact forces will cause movement of surrounding tissues. Hass in 1944, Stapp in 1957, Viano in 1983 and Hill in 1989, suggested that one part is decelerated at a different rate as another, causing stress at connection points proportional to the differential rates of deceleration. The details of how relative movement induces the stress to cause HAI are not yet understood. All of modern research found regarding HAI (since 1970) focused on automobiles and the longitudinal or lateral impact directions. No single mechanism was apparent and certainly a combination of factors, including direct force, relative displacements and hydrodynamic pressure appeared likely. Creasy (1997) found non-penetrating HAI trauma to be associated with stress induced by displacement of the heart, aortic arch, or abdomen, however the source of the displacement could not be clearly identified.

Aviation has always been concerned with the occurrence of HAI in aircraft accidents, although active research to study the cause of HAI specific to aircraft was not found dating past the 1960's. A review of HAI research applicable to the aviation environment, (either directly related to aviation or focused on inertial or vertical injury mechanisms) was reviewed. The vertical impact vector present in aircraft accidents has been associated with HAI. Parmerly (1953) suggested the relatively moveable heart in contrast to the aorta fixed to the pulmonary wall was a potential cause of HAI found in aircraft crash autopsies. A NASA study in 1963 (Gable) emphasized the accelerative force as a significant factor in the morbidity of aviation accidents. Sevitt suggested vertical displacement of the heart as a mechanism in 1977, as illustrated in Figure 2-10.

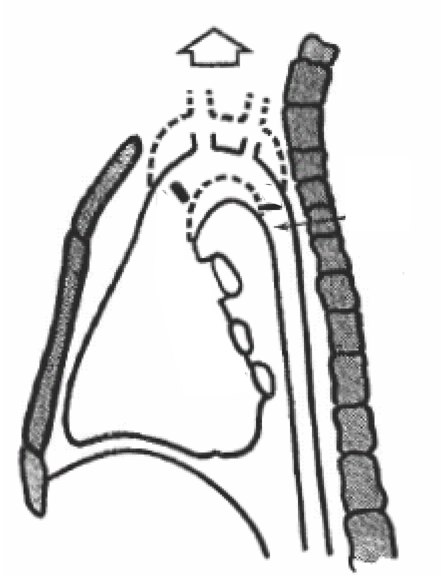


Fig. 2-10. Heart Displacement Injury Mechanisms (Sevitt 1977)

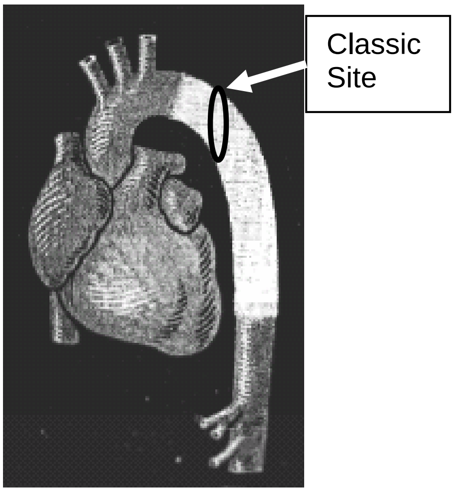
Most modern HAI research focuses on longitudinal and lateral impacts associated with motor vehicle crashes. A recent study correlated HAI to the impact severity (Siegel 2000). Aortic injuries were found most likely to occur in car impacts above 336 Kilojoules and velocities greater than 64 KPH.

Correlating cardiac movement to inertial loading and HAI has proven difficult. The only studies that focused on inertial forces that were found to successfully identify great vessel injury were due to caudal-to-cranial forces (+g_z) in pigs (Aldman 1962) and in dogs (Hanson 1967). Aldman used a rectangular box enclosure and Hanson used a form fitting plastic capsule. The degree of crushing was not quantified. Several studies concluded that movement of the heart was associated with aortic rupture, but only from blunt impact (Roberts 1966, Shatsky 1974, Viano 1983). Nusholtz in 1985 was unable to link cardiac inertia in various directions to aortic injury in a canine study. Recent injury research by Philipenns (2007) investigated injury in the aircraft environment, specifically side facing aircraft seats. The PMHS tests were focused on neck injury, but other thorax injuries including injury to the great vessels were reported. Intimal tearing of the carotid artery was shown to occur in the aircraft environment resulting from lateral deformation of the thorax and flailing of the head/neck.

Attempts to induce aortic aneurisms or trans-section by distributed force in humans have been unsuccessful. Foreman (2005) was not able to find a link between accelerative factors and HAI in longitudinal cadaver impacts. The subject was enclosed in a tank of porous media of plastic balls achieving a very high level of load distribution in the Foreman experiments. Melvin (1998) studied professional race car crashes. Peak vehicle accelerations averaged 51 G for 13 frontal and 53 G for 143 lateral impacts with no significant chest injuries. Seven of the Melvin impact cases exceeded 100 G. The subjects of the both the Foreman and Melvin research were restrained at a much higher level than is common for a car or even an aircraft pilot. The restricted movement of the occupant reduces local deformations by distributing the load and in turn reduces internal movement of the organs.

2.3.2 HAI Frequency and Location

Up to 85 percent of automotive cases are attributed to the “classic site” (Dolney, 1978). This is the descending thoracic aorta isthmus, near the attachment of the ligamentum arteriosum, and just distal to the left subclavian artery. Figure 2-11 illustrates the classic site and aortography repair (Kosak 1971). Figure 2-12 shows an intimal aneurysm in a patient sustained in a car crash (Roughneen 1995).



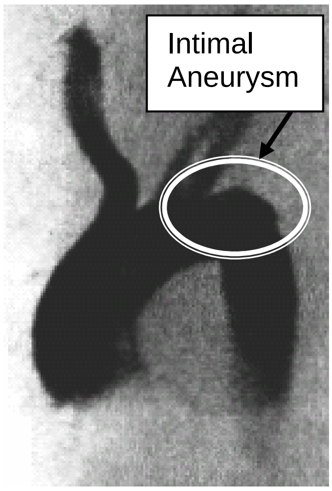


Fig. 2-11. Classic Site of Aortic Injury   Fig. 2-12. Aortagram of Intimal Aneurysm

The classic site is associated with longitudinal and lateral impacts. The injury mechanism theories discussed in section 2.3.1 suggest that the aortic arch, relatively large and filled with blood, is itself displacing forward or laterally, causing stress on the ligament which connects the aortic arch to the pulmonary wall of the chest. Longitudinal and lateral impacts to the torso occurring in automobiles were caused by the occupant striking the interior or steering wheel. Cavanaugh (2005) studied seventeen Post Mortem Human Subject (PMHS) lateral impact experiments. Five of the seventeen cadavers sustained aortic tears, all at the classic site. The aortic tears were associated with the less padded impact surface.

A study by Gable (1963) provided the frequency of heart, aortic, and other vessel injury for aircraft accidents. The study listed 504 cases with cardiac, aortic and great vessels injury from a population of 3400 accidents. Aortic injury was the most common injury with 51.4% (259), followed by heart injury at 35.1 % (177), and then by major vessel injury at 13.5% (68). This distribution is shown graphically in Figure 2-13. This distribution showed that aortic trauma is more common than heart trauma. Although a similar distribution for great vessel and heart injury in automobiles was not found in my review of the literature, a qualitative assessment of all the literature reviewed for this thesis suggested aortic injury was the primary concern for automobiles. Automotive studies referred to heart injury much less frequently than aviation studies.

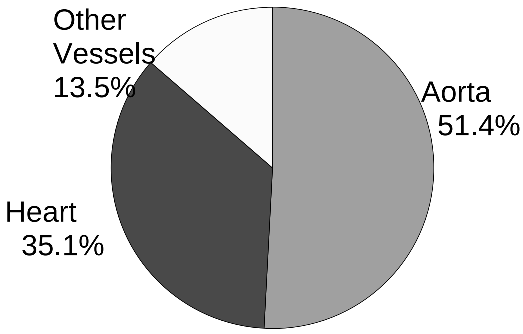


Figure 2-13. Distribution of Heart, Aorta and Other Vessel Injury in Aviation Accidents (Gable 1963)

Evaluating the frequency of aortic injury only (not considering heart injuries) revealed an interesting difference between automotive and aircraft based aortic injury. The frequency distribution for aortic injury location appeared quite different for the cases reviewed. The results are shown in Figures 2-14 and 2-15. Figure 2-14 is based on automotive literature which did not provide one source with the relative frequency for all the typical locations. A survey of several sources indicated that when a frequency was noted, the frequencies were comparable, usually within a few percentage points. The automotive values shown in Figure 2-14 were estimated from a survey of the following automotive literature: Allmendiger 1977, Beall 1969, Degiannis 2003, Dolney 1978, Kosak 1971, Mure 1990, Parmerly 1958, Roughneen 1995, Seiling 1975, Sevitt 1977, Warrian 1988. The frequency of injury at all of the common locations for aviation was cited in one large study by Gable in 1963, and is shown in Figure 2-15. Note that the Gable study included a small number of ejection seat and parachute cases, and that the aortic injury cases without a defined location were removed.

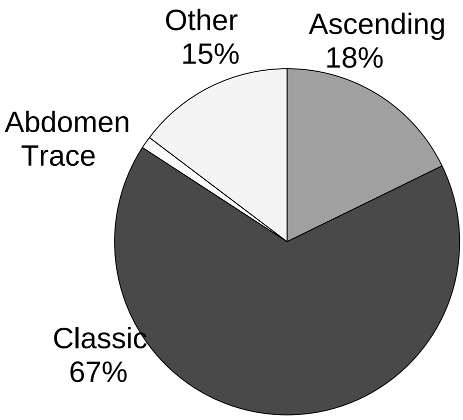


Figure 2-14. Aortic Injury, Automotive
(Various references, see above)

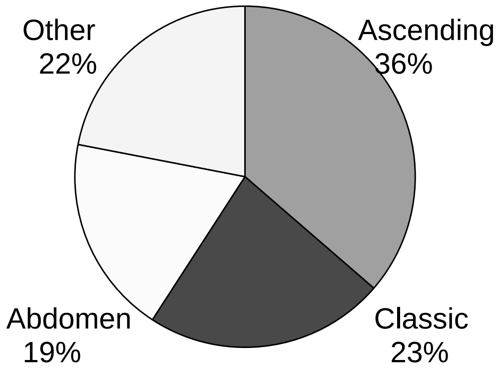


Figure 2-15. Aortic Injury, Aviation
(Gable 1963)

The majority of aortic injury in automotive crashes occurred at the “classic” site. In contrast, the aircraft accidents appeared to have a much higher percentage of aortic injury at other locations. A notable predominance appeared at the ascending and abdominal aorta. The apparent shift in injury frequency from the classic site common in automotive accidents to other locations such as the abdominal and ascending aorta may be due to vertical component found in the aircraft impact environment. A study of individual HAI cases was conducted to identify sources of HAI injury locations. Automotive and aircraft environments may have different causal factors.

2.3.3 HAI Case Studies

A large number of publications were found on the topic of heart or aortic injury, but few addressed inertial movement of the tissues or accelerative force specifically in the mechanisms. Notes taken from these publications are provided below.

- A study of injury to the aorta by Creasy 1997 noted that injury to the ascending aorta was found in 20-25% of autopsy cases, but only 5% clinically. This is related to the finding that 80% of injuries to the ascending aorta have grave complications such as valve rupture. These finding supported his conclusion that the critical injury mechanism for longitudinal impacts is acceleration of the arch rather than the heart.
- Significant numbers of aortic trauma were found even with normal mediastinum, supporting acceleration as a primary factor (Degiannis 2003).

- Non-penetrating deceleration injury of the chest indicated aortic injury occurrence 80-85% with other major vessels also significant at 25%. Hyperextension of spine noted as mechanism for disruption of major vessels. Cases presented at classic location and at the proximal subclavian (Dolney 1978).
- A Case with primarily longitudinal deceleration with flexion of the vertebral column was noted as a contributing mechanism (Kosak 1971).
- Specific reference to longitudinal acceleration associated with injury at classic site and vertical acceleration at ascending aorta were provided. Also noted was the relative elasticity of young patients, often with no visible chest trauma (Mure 1990).
- A large study was conducted in 1953 with 296 cases of non-penetrating aortic trauma, including 275 aortic ruptures and 21 lacerations. It was noted that half would have died of other injuries. Location of rupture at isthmus supported idea that relatively fixed isthmus and moveable heart and thoracic aorta was a primary mechanism. This study postulated that acceleration alone is not enough to cause rupture. It was theorized that a combination of increased pressure effect is needed. Survival was noted as 13.8 % and that extent of rupture not important to survival. Nine of thirty-eight who survived had complete trans-section, most survived long enough for possible surgical help (Parmerly 1958).
- Study specific to commercial airline crashes conducted in 1996, 3 crashes studied, all large transport category aircraft. Higher than expected occurrence with 25 of 535 victims having aortic injury. The 212 Fatalities included 24 of those with aortic tears, and 1 of those with aortic tears survived. Nine (9) of 24 died primarily of the aortic injury. Accidents studied were Continental at Stapleton November 1987; United at Sioux City July 1989; Avianca at Cove Neck January 1990. Location of transport aircraft specific aortic injuries were Isthmus 14, ascending 2, aortic arch 3, descending 1, innominate artery 1, left subclavian 1, multiple laceration 3. Important note for FE models of pressure factors is that they do not account for the combined tissue movement affects (Pezzella 1996).

- Roughneen (1995) noted that some cases can be treated without surgery.
- Sevitt conducted a study of 37 autopsies in 1977. It stresses importance of accelerative factors because typical sites indicate that fixation points are relevant. The location noted 25 of 37 cases were at classical site, with 7 of 37 at ascending aorta. Injuries were primarily to intima and media (internal tearing), nearly all transverse. Some tears directly opposite dislocations of the spine.

The case studies with reference to accelerative factors revealed that a person sustaining HAI will usually die, either from HAI or often from other life threatening injuries (Parmerly 1953). However it was clear that survival is possible. More modern case studies support the idea of acceleration as a contributing factor (Degiannis 2003), but also raised the point that HAI may not occur by acceleration alone (Pezzella 1996). The case studies supported the injury mechanism theories discussed in section 2.3.1 and 2.3.2. This survey of HAI indicated the need to establish a basis for HAI in the aircraft environment related specifically to the hypothesized factor of inertia rather than direct force. Aircraft accident injury research was incorporated to the thesis.

2.4 Modelling Techniques

2.4.1 Simulating Injuries

Computers have become essential for evaluating injuries. A variety of tools and techniques were considered for accomplishing the goals of this research. Physical ATD's have been continuously refined throughout the history of biomechanical research, however they are poorly suited for evaluation of visco-elastic tissues. The issue of creating a tool which is intended to measure failures but must remain intact and consistent over repeated impacts is difficult. Deformable materials that are susceptible to not only the force magnitude but rate of loading is significantly more complex. Efforts have been made, such as the improved thorax for the Hybrid III ATD (Schnieder et all 1992), which included a biofidelic frangible abdomen via fluid filled bladders. However computer models offer the capability to load virtual bodies in a realistic manner. Early computer models of the human body were often very simple linear spring models. These types of lumped mass models remain useful when gross body motions and their relationships need to be evaluated. Figure 2-16 represents a model used by Ksiazek (2005) to study vibrations in the human body.

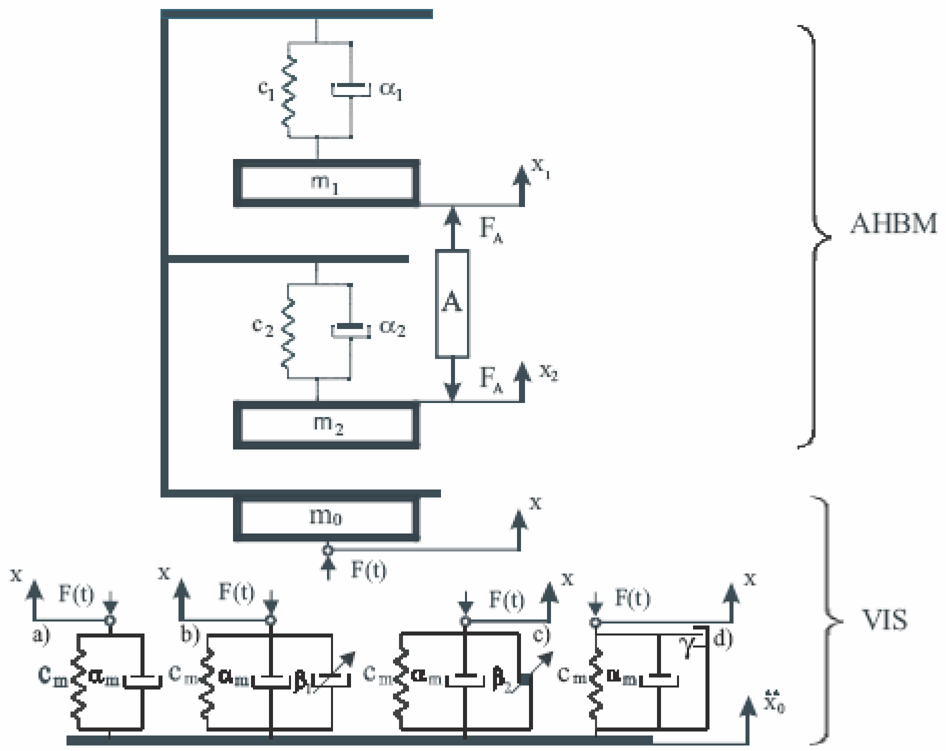


Fig. 1. Active Human Body Model (AHBM) and sequence of linear and non-linear Vibration Isolation System (VIS)

Figure 2-16. Lumped Mass Biomechanical Model by Ksiazek 2005

Finite element models of the human body became more common as computer technology and the FEA tools advanced. King (1991) developed a rigid body model of the thorax using MADYMO software. This model was later refined by Huang et al (1994 a) and was validated against lateral impact post mortem human subject (PMHS) experiments. Plank and Eppinger (1989) developed a simple FE model of the thorax which they used to predict force-deflection characteristics. Huang (1994 b) also developed a simple FE model of the torso based on the same PMHS tests of the King (1991) and Huang (1994 a) models. This model had the capability to measure the four basic chest injury criteria; Compression (C), viscous (V*C), Thoracic Trauma Index (TTI), and Average Spine Acceleration (ASA). C and V*C are deflection based criteria developed by Viano1985 and Lau 1986. TTI and ASA are acceleration based criteria. TTI was developed by Eppinger (1984) and Morgan (1986). ASA was developed by

Cavanaugh (1993) from combining PMHS lateral impact data from NHTSA and Wayne State University (WSU). The existing chest injury criteria have been used to relate longitudinal and lateral blunt trauma to aortic ruptures in automotive studies. However these injury criteria are not useful or establishing the relationship between HAI and vertical aircraft impacts. This thesis established a simple model to begin understanding this relationship.

The Huang (1994 b) model was of interest for evaluating the approach to the modelling of this thesis because:

- It was used to understand the basic parameters affecting thoracic injuries rather than making an attempt at modelling specific injury mechanisms. The model lumped all of the viscera together as one elastic solid, while the ribs were modelled as shell elements.
- It included the whole torso in order to evaluate the shared load path affects of the shoulder and pelvis.

Figure 2-17 illustrates the simple FE model of the torso by Huang (1994 b).

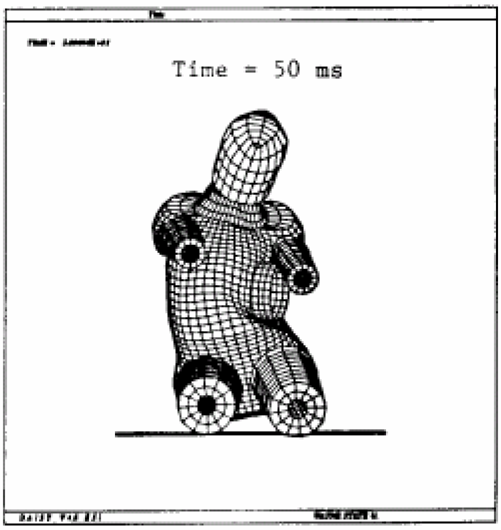


Figure 2-17. FE Torso Model by Huang 1994b, Kinematics of a Pendulum Impact of 6.5 m/s.

As computers evolved, more detailed models were developed such as the FE human thorax model by Deng (1999). The model included individual organs such as the heart and lungs, but was validated to gross motion force-time histories or deflection-time histories from PMHS impacts. The local motion of the organs was not possible to evaluate.

Component level modelling is the logical method to focus on specific body regions. Going beyond skull fractures for head injuries requires a means to account for the brain. The example in Figure 2-18 (Bandak 1994) used a Kelvin model to achieve visco-elastic properties of the brain tissues.

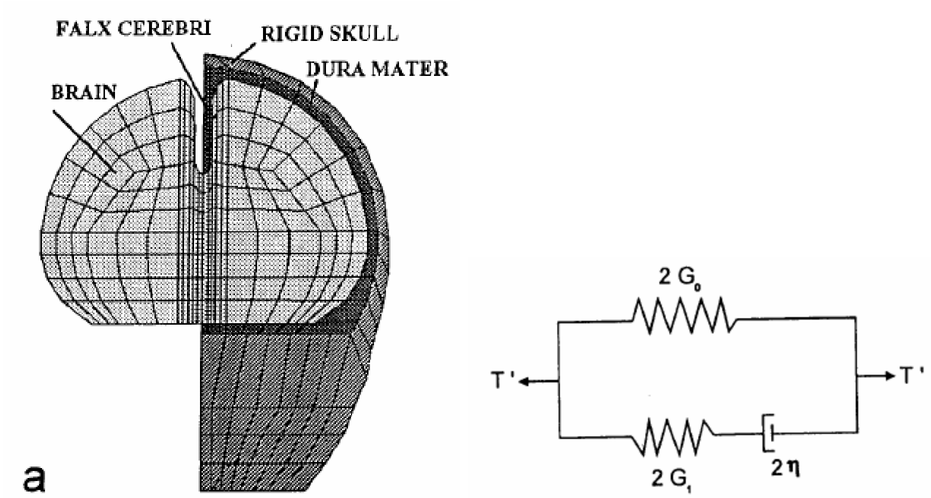


Figure 2-18. FE Head and Brain Model by Bandak 1994 with the 3 Parameter Visco-elastic Kelvin Model of the Brain Material

The material properties are based on tissue sample tests and refined within the model depending on the validation method. Examples of material property studies include McCulloch (1991) and Guiccione (1991) for the heart muscle, Bass (2001), Carson (1990) and Mohan (1983) for the aorta. Myers (1995) describes the challenges and limitations of developing soft tissue properties for finite element models. Other examples of soft tissue studies include Viano 1986, Fung 1993 and Woo 1994 (various soft tissues), Fung 1978 and Vawter 1980 (lung), Prange 2000 (brain).

Detailed finite element models of the thorax and internal organs exist. Shah (2001) included a detailed model of the aorta within the thorax and surrounded by the other organs and bones as shown in Figure 2-19. The intent of the aorta model was to evaluate the potential for ruptures resulting from lateral impacts. Shah notes that neither animal or cadaveric studies have been able to provide internal thoracic kinetics or kinematics. The model was validated against global chest force-time and deflection-time histories and was thus unable to evaluate local affects of the aorta.

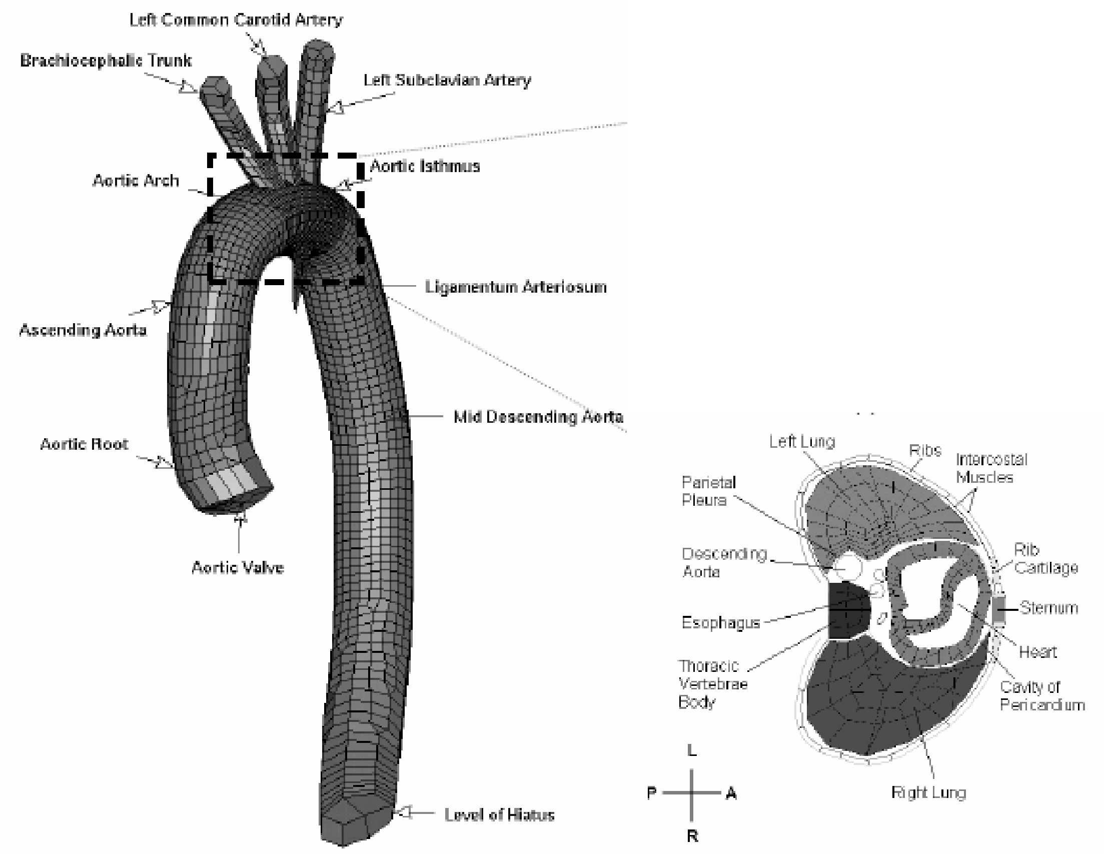


Figure 2-19. FE Model to Predict Aortic Rupture by Shah 2001

Lee (2001) created an FE model related to the Shah model described above. The model included detailed representations of the liver, spleen, kidneys, spine, skin and major blood vessels, while hollow organs such as the stomach and intestines were grouped into bags to maintain inertial properties and relative position among the other organs. Again the model was validated according to cadaveric impact tests in the lateral direction. The lack of experimental data for internal organ kinetics is noted as the issue blocking full validation of the model and limiting it's use in evaluating vehicle crash impacts.

An updated version of the whole body model developed at Wayne Statue University (Shah 2004) has been used to study aortic injuries in automobile crashes (Shah 2005). The study was part of joint project at George Washington University and Wayne State University to investigate aortic injuries. The project is funded by the Ford National

Crash Analysis Center (NCAC) (Ford 2008). The Shah 2005 study created a virtual simulation of an automobile crash which resulted in aortic injury. The human body model was used to visualize the motion of internal organs and subjectively asses stress points on the aorta, which were compared to autopsy findings from the real world crash. The limitations of the virtual crash are carefully noted. No quantification or direct conclusions could be made of the virtual model due to lack of biomechanical data to validate the models.

Another portion this same Ford NCAC project has developed a biaxial testing machine for the purpose of characterizing aortic tissue material properties for the rates and conditions that will be useful for automotive impacts (Mason 2005). Improved material properties will help refine the models, but further knowledge of the internal local movement of the tissues due to impact force and/or inertia is needed. Pressure mechanisms appear to be a bit easier to investigate. Wang 2002 conducted two types of tests to characterize aortic rupture for his FEA model. Some tests were done by pressurizing an excised aorta while others tests pressurized an aorta while it remained in the body of a cadaver. Conducting pressure tests on a stationary aorta is of course much more simple than trying to characterize inertial movement from impact.

Recent human body models have achieved exceptional levels of detail through the use of modern CT-scanning technology for accurate tissue geometry. One example is the HUMOS project, which began in 1997 with the objective to develop a refined biofidelic human numerical model for use in crashworthiness. Fourteen partners including car manufacturers, suppliers, software companies, and research institutions were involved. Robin (2001) describes the initial validations of the model, which is shown in Figure 2-20.

Figure 2-20. Detailed FE Human Model HUMOS (Robin 2001)

Further developments were conducted in the HUMOS2 project, which has been described by Vezin 2005. Modifications of the HUMOS models have also been conducted through the European Integrated Project on Advanced Protection Systems (APROSYS), which has participation from various companies. The Applied Biomechanics Laboratory of the French National Institute for Transport and Safety Research (INRETS) is focused on biomechanics while the software company Altair Hyperworks have provided tools to generate the FE mesh and run the models using the RADIOSS finite element solver. The solid organs are modelled as incompressible solids with visco-elastic behaviour, while the hollow organs are non-constant volumes with internal pressure.

Validations of the HUMOS lower thorax model shown above were based on cadaveric impacts included multiple directions. Lateral impacts produced pubic bone fractures and joint fractures; anterior/posterior compressions produced symphysis fractures (midline cartilaginous joint connecting the left and right pubic bones) and sacroiliac dislocations (joint between the sacrum at the base of the spine and the illium of the pelvis); vertical shear produced sacroiliac and symphysis dislocations. Literature found on the subject of the HUMOS models focused on forward longitudinal and lateral impact injuries that are of interest in automotive crashes. Examples include simulations of lateral impacts to the human thorax and pelvis Compigne (2004), simulations of lateral impacts to the shoulder complex (Duprey 2005), and simulations of brain response to frontal impacts (Vezin 2004).

2.4.2 Simulation of Aircraft Crash Tests

Computer modelling techniques have not been applied to aviation crash safety as extensively as automotive. Most have evaluated the aircraft structure rather than occupant response and many were done in conjunction with crash tests conducted by NASA. The computer simulations were done with various levels of sophistication, as noted in a history of NASA aircraft crash tests by Jackson (2007). Older simulations of a B720 (Fasanella 1987) and a Boeing B707 (Fasanella 1990) used an early Finite Element Analysis (FEA) computer code developed by Grumman Aerospace Corporation. The code was called the Dynamic Crash Analysis of Structures (DYCAST) computer program (Pifko 1987), and had very limited capability by modern standards. The models did not exceed a few hundred elements, as shown in the DYCAST model in Figure 2-21 reproduced from Jackson 2007.

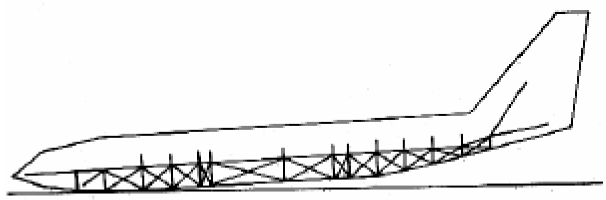


Figure 2-21. DYCAST Model of B720 (Jackson 2007)

Another early crash code called KRASH was developed originally by Lockheed for the USArmy in the 1970's (Jackson 2006). This program has been updated and managed by the company Dynamic Response Inc. and is now known as DRI/KRASH and is still in use with added features such as water impact and landing gear modules as well as simple occupant models (DRI 2008). Tests conducted in the 1980's or later began using modern FEA programs such as MSC Dytran (Lahey 1994), as shown in the example of a Sikorsky aircraft in Figure 2-22.

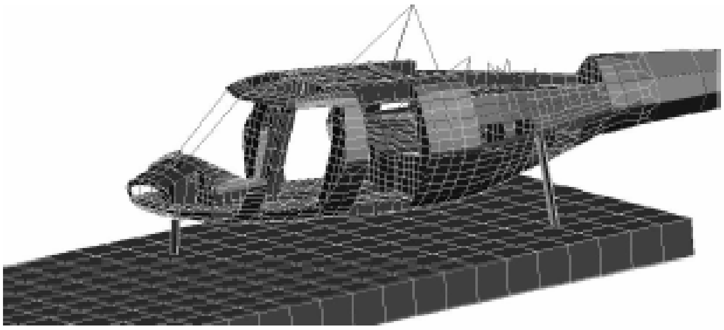


Figure 2-22. MSC Dytran Model of Sikorsky Aircraft (Lahey 1994)

Crash tests evaluated during this research were accompanied by computer simulations, including the Cirrus SR-20 (Terry 2000), B737 (Fasanella 2004), ATR-42 (Jackson 2004b), and Sikorsky (Fasanella 2001). Most of the examples focus on the structure of the aircraft and either did not simulate the occupant response or included only simple Occupant models. The simple ATD model called the Articulated Total Body (ATB) model (Cheng 1998) is often used when only the occupant kinematics are required. A cross section of a composite aircraft modelled in MSC Dytran with the occupants modelled in ATB correlated the simulated occupant response with the actual ATD's (Jackson 2003a).

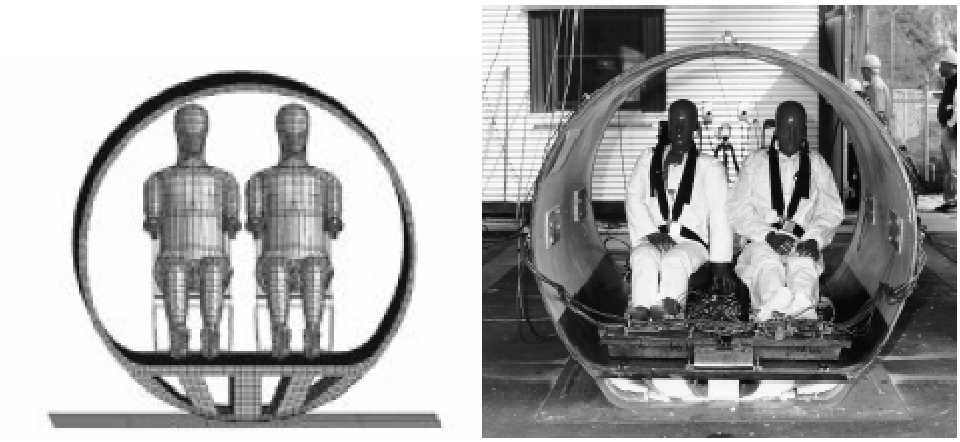


Figure 2-23. Simulation and Test of Composite Aircraft Section (Jackson 2003a)

More recently, computer simulation techniques are being applied to a wider variety of aviation crash injuries. DeWeese (2007b) used computer algorithms to augment analysis of potential brain injury. Soltis (2007b) provided an overview of various areas computer simulations have been used to study specific aircraft injuries, such as lateral neck loads, and are being developed for use as a certification tool.

3. MODEL METHODOLOGY

A computer model was developed that evaluated the relationship between the vehicle impact vector, it's transmission through the seat and into the occupant, and ultimately the potential effect on the movement of the occupant's organs. A complete finite element model of the aircraft and occupant system (for a single occupant) was created. The modelling approach was developed after considering various techniques and the current understanding of HAI associated with the vertical impact direction. Section 3.1 provides further explanation of the modelling approach. The rest of the chapter was organized as follows.

- Injury Model Theory (Section 3.2)
- Aircraft and Seat Sub-System (Section 3.3)
- Occupant and Spine Sub-System (Section 3.4)
- Heart and Aorta Sub-System (Section 3.5)
- Method for Conducting a Simulation (Section 3.6)

Note that the model descriptions provided in this chapter list identification numbers next to the elements. These numbers provide a reference to the detailed list of the model provided in Appendix A.

3.1 Modelling Approach

The heart and aorta model approach was fundamental to the research and affected the development of the entire system model. Several points pertinent to this approach are explained here. The detailed model description follows in the subsequent sections, progressing from the aircraft level to the seat, then occupant, and finally the heart and aorta.

A very simple model of the heart and aorta system was established. An existing ATD model was modified to incorporate the heart/aorta model and then placed into a model of a seat and aircraft system which was created to represent a typical small aircraft. The literature survey review of modelling techniques (Section 2.4) illustrates that complex human body models exist. Several past and current research projects developed detailed FEA constructions of the heart, aorta, surrounding organs and other body parts. The option to develop a human body model with similar representations of the organs that could affect the motion of the heart from vertical impact was investigated. Figure 3-1 shows the heart and aorta in the ESI Group Inc. Human Articulated Rigid Body (HARB) 50th percentile male (ROBBY 2) model (ESI 2005), with arrows and lines representing the connections which would have been starting points for the pertinent connections.

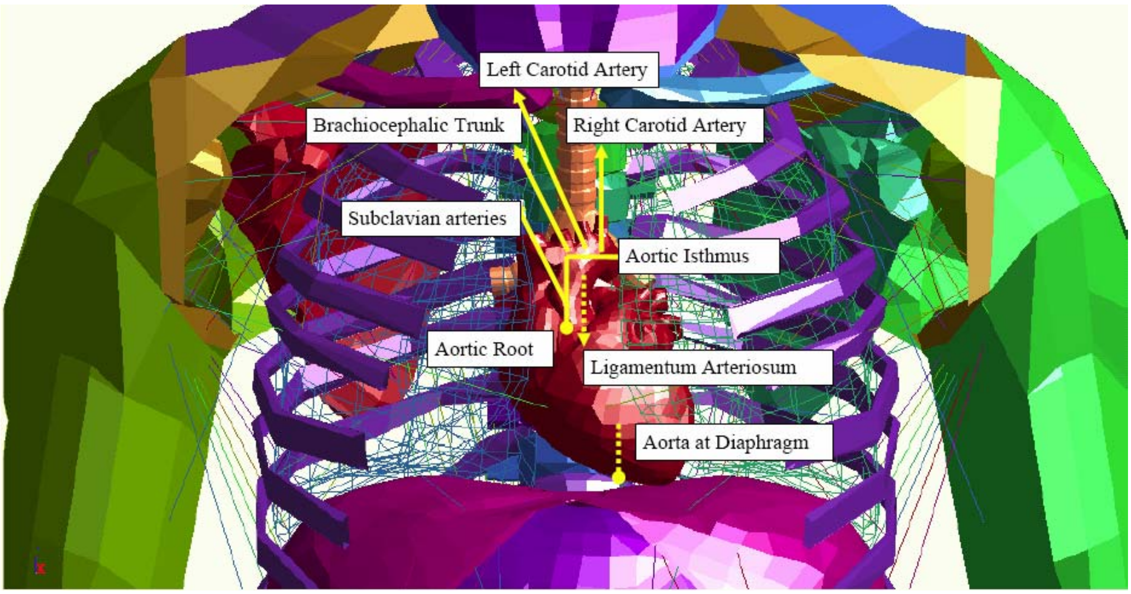


Figure 3-1. Human Body Model Considered for Developing the Heart and Aortic Motion Due to Vertical Impacts

The approach to develop a human model and represent local motion of the heart and aorta for this application was not feasible. The objective of this model was very different from the existing human FEA models, most of which simulate hydrodynamic loads. Insufficient biomechanical data exists to validate simulations of tissue interaction from blunt impacts, as indicated in section 2.4. Additionally, all existing simulations found were concerned with longitudinal forward or lateral impacts (Bass 2001, Cavanaugh 2005, Deng 1999, Huang 1994, Lee 2001, Richens 2004, Shah 2001, Wang 2002). The interest of this research was the forces acting on the internal visco-elastic organs from vertical impact. The forces acting on the heart and aorta may be directly applied by other internal organs or indirectly by inertia. Studies of longitudinal loading do not often focus on inertial loads because in automobile accidents the longitudinal loads are not well distributed as compared to vertical loads. The seated occupant pressed vertically downwards into the seat benefits from broad load distribution through the seat pan. Current biomechanical data is insufficient to support validation of local tissue response for the forward longitudinal and lateral directions, and it is essentially non-existent for the vertical load direction. Validation of a detailed model would not have been possible.

The thesis hypothesis asked if vertical displacement from inertial loads was a legitimate injury mechanism, and if it occurs in survivable crashes. Thus a simple model capable of relating visco-elastic organ response to the vehicle impact for a determination of survivability was appropriate. Two changes were made to the originally envisioned modelling approach. First, the heart/aorta model was created as a simple single degree of freedom Kelvin model, representing the entire thorax viscera, which was consistent with the available validation data. Second, ATD numerical models rather than a human body model were developed for the system evaluations. ATD models instead of a human model were used because the global energy transfer from the seat into the occupant had to be taken into account. Crash tests and design validation tests existed with response data that was used to check the system model. Although some data was found for human response in vertical impacts (WPAFB 2005-2007), an adequate range of severity was not available. Note that the term "heart and aorta model" and the outward appearance of the model remained the same, although the model more accurately represented the total visceral mass. Figure 3-2 illustrates the simple heart and aortic model incorporated into the Hybrid II ATD model.

Figure 3-2. Simple Heart and Aortic Model in the Hybrid II ATD

A simple heart and aorta model representing only a global viscera response for vertical inertia had limitations. The simplified model did not represent actual tissue displacements, and thus did not help in identifying the actual injury mechanisms causing injuries to the heart or aorta. Instead it was only capable of identifying boundaries for viscous injuries in general. The primary response data of the heart model was displacement and velocity of the mass (heart) attached to the visco-elastic tissue (aorta). The displacement response was useful for comparative analysis between simulations and did not provide quantifiable data for use outside of the research. The velocity response was comparable to general visco-elastic injury limits. These limitations were similar to the limitation of other human body models which are validated to global deformations of the chest. While the external deformation was accurate, the internal movements of the organs can not be verified, and were thus limited to comparative evaluation rather than quantification of true organ response. These limitations were found to be acceptable given the lack of knowledge surrounding the vertical load case. The heart and aorta model satisfied the research objectives.

The full system model consists of the following sub-systems. Three sets of spring / mass / damper models control the local behaviour of the seat, spine, and heart/aorta, as described below and illustrated in Figure 3-3.

- Seat Sub-system: The properties are tuned to represent vertical energy absorbing characteristic of the seat. A typical GA seat has about 4 inches of EA stroke (Hurley 2002), while some military helicopter seats have up to 11 inches of EA stroking capability (Desjardins 2004).

- Occupant Sub-system: The simulated occupants include a spine injury criteria developed by NASA (Stech 1969). The upper torso and lower body are lumped masses, connected by a spring at the L4 vertebra.

- Heart and Aorta Sub-System: This sub-system is a simple approach consisting of a rigid heart "hanging" on a viscoelastic aorta. The model measures global response of the viscera in the vertical direction.

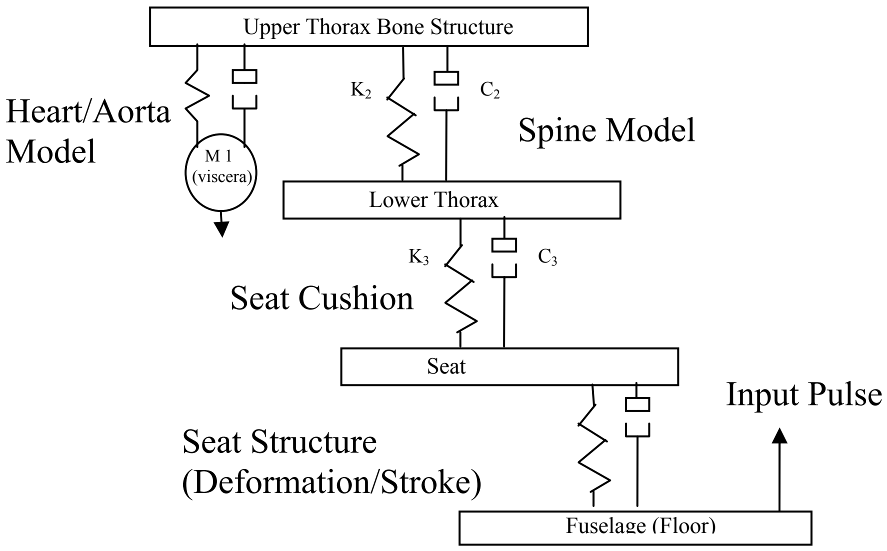


Figure 3-3. System Model with Spring-Mass-Damper Systems

3.2 Model Theory

The model used for this research was a series of rigid bodies connected by spring mass damper elements. The mass distribution and inertial properties of each rigid body were held constant. A deformable mesh was not used as the research hypothesis required evaluation of global forces and accelerations absorbed by the bodies rather than the local forces causing deformations of these bodies. The chosen mass and inertial properties and the spring-mass-damper properties governed the responses. The connections between the bodies were linear or visco-elastic spring/dampers depending on the simulated material. A Kelvin-voigt model was used (Craig 1981) as shown in Figure 3-4. This was the same type of model used for the spine injury criteria discussed in section 2.2.1.

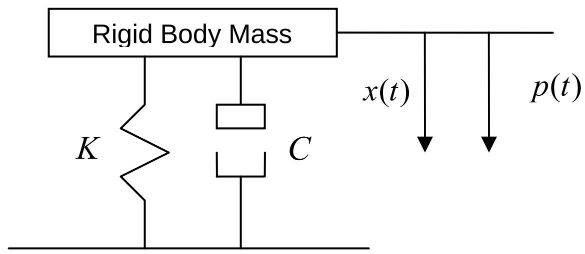


Figure 3-4 Kelvin-Voigt Model

The equation of motion for a linear, single degree of motion spring mass damper system (starting at equilibrium) is: $p(t) - f_s - f_D = mx$.

Where: $p(t)$ = load as function of time (N) x = spring displacement (m)

f_s = spring force = kx (N) $\dot{x}$ = velocity of x (m/s)

f_D = damping force = $c[\Delta x]$ $\ddot{x}$ = acceleration of x (m/s^2)

m = mass (kg) c = viscous damping coefficient

k = spring stiffness (N/m) f_n = natural frequency (cycles/s)

w_n = natural frequency (rad/s)

The equation can be written as: $\ddot{x} + 2\zeta w_n x + w_n^2 \dot{x} = \left(\frac{w_n^2}{k}\right) p(t)$

Where: $w_n = \sqrt{\left(k/m\right)}$ and $\zeta = c/c_{cr}$ and $c_{cr} = 2mw_n$ (critical damping coefficient)

Long Pulse Duration (Pulse >> Natural Frequency)

Considering a step function with the load (p) applied with infinite slope and for infinite duration, for a viscous, under damped system which starts at rest, the solution is:

$$x = \frac{p}{k} + 1 - e^{\zeta w_n t}\left[\cos w_d t + \left(\frac{\zeta w_n}{w_d}\right)\sin w_d t\right]$$

where: w_d = damped circular frequency for under damped systems $w_d = w_n\sqrt{1-\zeta^2}$

This response is a forced vibration which overshoots to a value twice the static deflection of the spring, and decays to the static deflection at a rate depending on the damping. If the step function returned to zero (square wave), the forced vibration would end and the spring deflection would decay to zero. This case has a very long duration with respect to the natural frequency, and thus the response is a function of the peak load, p.

The Dynamic Load Factor is defined as: $R(t) = kx / p_{max}$, where $R_{max} = 2$.

Structures subjected to rapid loads often use a safety factor of 2, corresponding to the max overshoot of an under damped system (Craig 1981 pg 112). Using the spine model example of section 2.3.1, the maximum deflection of the spine spring before fracture was calculated using Stech's model parameters. The critical, steady state load value for acceleration was 21.3g. The breaking force was the mass (42kg). The static deflection of the spine spring for this condition was:

x = (*21.3*g)(42kg)(*9.81*m/s^2) / *2,057,742* N/m = *4.3* mm.

The maximum overshoot was about 2 times this value ≈ 8.6mm. The actual overshoot was something between 4.3 and 8.6 mm depending on the pulse duration and the damping. This deflection represents the lowest possible injury threshold with respect to force, as the system was absorbing essentially infinite energy. The next case, short duration loads, look at the opposite case in which the system was able to sustain high forces, but only for short durations and little energy.

Short Pulse Duration (Pulse << Natural Frequency)

The equation of motion and variables are the same:

$p(t) - f_S - f_D = mx$ can be written as: $m\ddot{x} + kx = p(t)$ For this case $t_d << T_n$

where T_n = natural period and $T_n = 1/f_n = 2\pi / w_n$

T_d = damped natural period

$T_d = 2\pi / w_d$

The general solution is: $m\dot{x}(t) + kx_{avg}t_d = \int p(t)d(t)$

The solution in terms of x(t) for an un-damped system is the Impulse Response. The impulse is defined a constant force (p_o) acting on the system for a period of time (t_d) whose duration is much less than the natural period, or can also be expressed as:

$$I = \int p(t)d(t) = p_o t_d = m\Delta V$$

The solutions for un-damped and viscous damped systems are shown below.

The $kx_{avg}t_d$ term from the general solution is zero because the short duration of the load relative to the natural period.

Impulse Response

$$x(t) = \frac{\int p(t)d(t)}{mw_d} \sin w_n t$$

Impulse Response Function for $\zeta < 1$

$$x(t) = \frac{\int p(t)d(t)}{mw_d} e^{-\zeta w_n t} \sin w_n t$$

It can be seen from the above equations that the maximum spring deflection occurs when the oscillation was equal to 1. Again using the spine model example of section 2.2.1, the spring deflection representing the injury threshold was calculated for this ideal case. Using the critical parameter by Stech of $\Delta V = 6$ m/s, the max deflection occurred at ($\sin \omega_n t = 1$), and was: x = (42.06 kg)(6 m/s) / (895.9 kg) (51 rad/s) = 5.5 mm. The value of 895.9 kg was used for the mass in the denominator as this was the breaking strength mass (42.06 kg) (21.3 g/G) = 895.9 kg. Multiplying the breaking strength mass by gravity provided the breaking force of 8792N, as given in Section 2.2.1.

Half-Sinusoidal Loading with Relative Motion and Pre-load

The loads applied to the model systems can be approximated by half-sine functions. The primary point of interest is often the relative motion between the chest and the heart and aorta system, as illustrated in Figure 3-3.

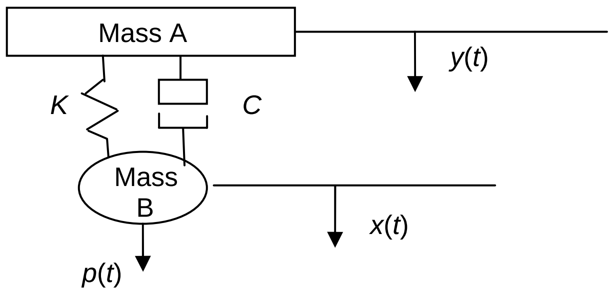


Figure 3-5 Relative Motion Spring-Mass-Damper System

The previously defined variables are the same. The difference of the absolute displacements of the two masses is defined as: $z(t) = x(t) - y(t)$.
The mass will move as defined by the ordinary differential equation:

$$\ddot{z}(t) + 2\zeta\omega\dot{z}(t) + \omega^2 z(t) = \frac{p(t)}{m}$$

$p(t)$ is the time history of external force applied to the element.

The models have the force of gravity acting on the masses when evaluated for the vertical impact case. For the case where a constant pre-load $p = \frac{F_p}{m}$ is applied, Mass B and the acceleration of Mass A is: $\ddot{y} = G \sin w_b t$, for $0 \le t \le t_1$
where G is the gravitational constant, w_A is the natural frequency of the Mass A system, u(t) is the impulse response and $t_1 = \frac{T_A}{2} = \frac{\pi}{w_A}$. When $\ddot{y} = 0$ for all other t, the equation of motion is: $\ddot{z} + 2\zeta\omega\dot{z} + \omega^2 z = -G \sin \omega_A t + p - G \sin \omega_A(t - t_1) \cdot u(t - t_1)$.
The above equation was solved by the computer model based on the how the motions of the other connected masses were affecting the system.

3.3 Aircraft and Seat Sub-System

A Finite Element model of the aircraft environment (floor, steering yoke/dashboard), seat, and occupant system was created. The aircraft environment was created to represent a typical single engine GA aircraft. Dimensions for the placement of the seat within the interior relative to the belt anchors, foot-well, dashboard and steering yoke were based on measurements of a Mooney M20 aircraft interior. A fuselage and interior of a Mooney M20 were made available at AmSafe Aviation in Phoenix AZ as shown in Figure 3-6.

Figure 3-6 Mooney M20 Aircraft Fuselage Used for Interior Dimensions and an Image of a Complete Mooney M20 Aircraft

Representations and a simple mesh of the pertinent contact surfaces and objects were created directly into a PAM-CRASH/SAFE computer model using SAFE-Editor 2002 (ESI 2002). The Finite Element model was compiled with PAMCRASH SOLVER (ESI 2004), and run in the PAM-CRASH/SAFE (ESI 2004) environment. Iterations to material properties, loads, constraints and interfaces were also made directly in the PAM-CRASH/SAFE environment. The results were visualized and data files as well as video files were generated using PAM-VIEW 2004 (ESI 2004). The resulting data files were also imported to Microsoft Excel 2003 for graphical representation.

The aircraft and seat subsystem was based on a rigid floor with foot platform and an instrument panel with steering yoke constructed with shell elements. These components served as the reaction surface for the seat, restraint, and occupant. The floor also provided the body through which crash impact inputs were applied. The aircraft and seat sub-system was made of rigid bodies of material type 100, which have no time step calculation (material and part specifications from ESI 2003, Solver Notes). The following rigid bodies are shown in Figure 3-7.

- Floor (Material / Part 9900),
- Seat Cushion (Material / Part 9901) and Back seats (Material / Part 9902)
- Instrumental Panel (Material / Part 9903)
- Belt attachments (Material / Part 9904)
- Steering yolk (Material / Part 9905)

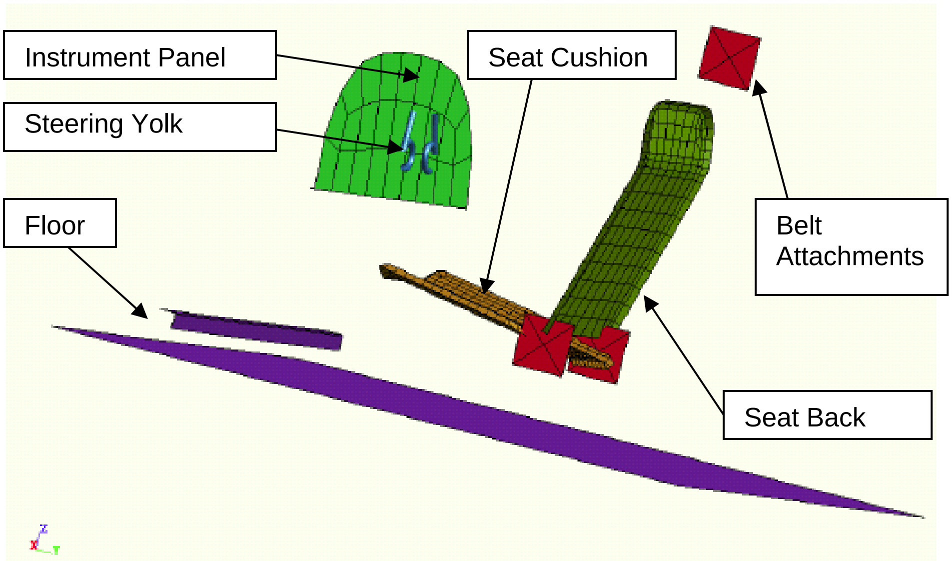


Figure 3-7 Aircraft and Seat Sub-System

The steering yoke was mobile fore and aft for a short distance (160 mm forward and 60mm aft of nominal) without friction. The mobility of the steering yoke was defined via Translational kinematics joint 99110020. The whole model was exposed to the gravity field (Function 99003) and initial velocity defined according to the impact pulse. The impact deceleration pulses were applied by defining the acceleration time history and applying it to the aircraft and seat sub-system Centre of Gravity (COG).

The intent of the model was to provide a generic system representing a typical response possible from a range of aircraft, and thus generic values were used for the cushion compression. The force required to compress the seat cushions had a linear increase from 0 to 1 KN in the first 45mm of compression, then steepened to 2.5 KN from 45 to 50 mm.

The seat pan also incorporated vertical Energy Absorbing (EA) translation or “stroke”. This simulated stroking mechanism was activated by a defined force – distance relationship achieved with a Beam/Bar type 230 Kinematic Joint. When the vertical downward force threshold was reached, the seat translated downward up to a maximum specified distance, corresponding to the desired total EA capability of the seat. Different EA characteristics were used to represent a range of civil and military aircraft seats.

3.3.1 Seat Stroke Characteristics

Commercial GA Seat Characteristics

This section addressed the commercial GA seat design adopted for the model. Actual GA seats found in service can be old designs with no-crashworthy features, but this is not state of the art. Modern seats conforming to the USCFR FAR 25.562 typically have a limited vertical EA stroke (often from crushable honeycomb or deformable structure) and special cushions. A generic/ideal version of a commercial GA seat was incorporated into the model by providing a rigid seat pan with a force limited vertical stroke. The parameters for the commercial GA (referred to as “GA Seat”) were:

- Vertical stoke distance = 100 mm
- Stroke activation force (load limit) = 17 kN

The response of the seat during an impact was a function of the mass acting on the seat driven by the impact pulse. The masses for the seat and ATD are given in Table 3-1.

Table 3-1. Seat and ATD Mass

Model Components	**Mass (kg)**
Seat	48.40
ATD Head/Neck	5.72
ATD Upper Torso(without Viscera)	13.30
ATD Viscera (HAI model)	2.60
ATD Shoulder/Arms/Hands	12.80
ATD Lower Torso	17.74
ATD Legs/Feet	24.52
Total	**125.08**

The g force required to begin stroking the seat can were calculated as:

Activation Threshold = 17 kN / (9.81 m/s^2) (125.08 kg) = 13.8 g

The total energy absorbing capability of the seat were calculated as:

EA Limit = ½ kx^2 = (0.5)(17 kN / 0.1 m)$(0.1\ m)^2$ = 0.85 kJ

<u>Military Long Stroke Seat Characteristics</u>

The military long stroke seat (referred to as "military EA seat") had the same mass (48.40 kg) and was based on military specifications. The military seat parameters were:

- Vertical stoke distance = 368 mm
- Stroke activation force (load limit) = 23 kN

The g force required to begin stroking the seat were calculated as:

Activation Threshold = 23 kN / (9.81 m/s^2) (125.08 kg) = 18.74 g

The total energy absorbing capability of the seat were calculated as:

EA Limit = ½ kx^2 = (0.5)(23 kN / 0.368 m)$(0.368\ m)^2$ = 4.23 kJ

3.4 Occupant and Spine Sub-System

The occupant interfaced with the rest of the model through defined contacts. The contact between body parts and hard surfaces used a symmetric node to segment, type 33 (ESI 2003, Solver Notes). This contact type had a master and a slave. The nodes of the slave part were checked against the segments/edges of the master. The slave was allowed to penetrate into the master a specified distance and resisted by a specified force. The feet to the floor and hands to dashboard used this type of contact. The contact values were:

- Feet to Floor: Contact thickness 5mm, Constant Friction Coeff. 0.1, Factor for non-linear penalty stiffness 3.
- Hands to Dashboard: Contact thickness -1 mm, Constant Friction Coeff. 0.1, Factor for non-linear penalty stiffness (inactive).

The hands to the steering yolk used a similar contact which adds a feature to tie them together, contact type 32. The pelvis and upper legs used contact type 21 to the seat cushion (9901), which is a body to multi-plane contact and incorporates defined force deflection or stress-strain relationships. This same type of contact was used for the thorax to seat back (9902). The force penetration curve was as noted in section 3.3 for the cushions, there was zero damping, quadratic unloading, and the first ramp velocity factor for friction was 0.01, the second ramp velocity factor for friction was 0.1.

Occupant Model

The models were created with three occupant types, based on existing models from ESI Group (ESI 2000). The 50th percentile male Hybrid II ATD, the 50th percentile male Hybrid III ATD, and the 50th percentile male HARB ROBBY2 were all modified to include the heart and aortic model. The two Anthropomophic Test Dummy (ATD) models were modified by altering the spine to incorporate a compressible spine model based on the Dynamic Response Index (DRI). The ROBBY2 model was not modified with the spine model as the spine was already deformable. The two ATD occupant models are shown in Figure 3-8 and the HARB ROBBY2 occupant model is shown in Figure 3-9.

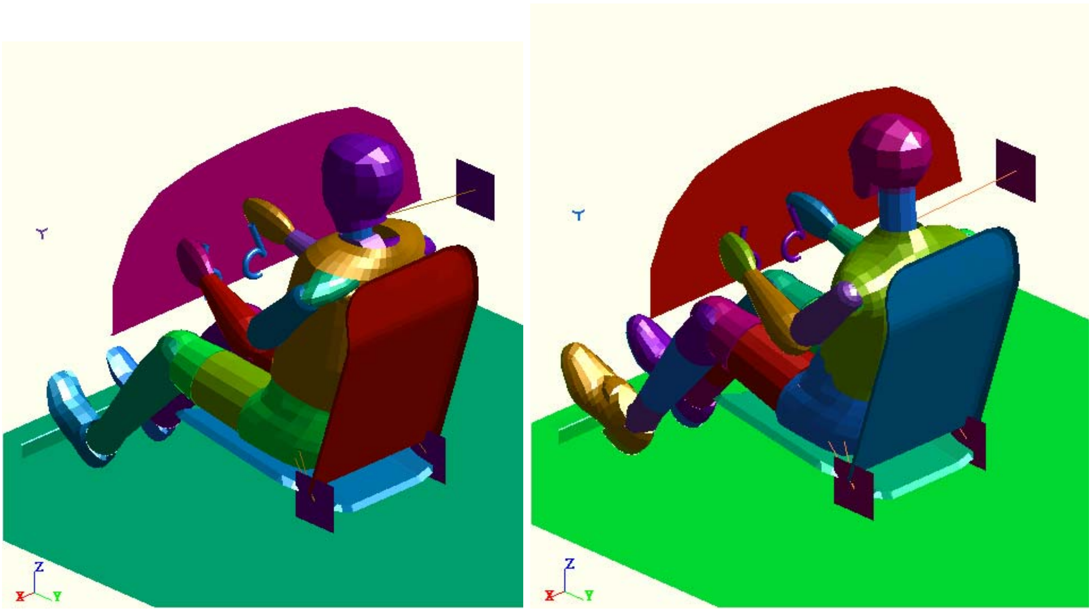


Figure 3-8 Hybrid II and Hybrid III Occupant Models

Figure 3-9. ROBBY2 Occupant Model

The structure of the simulation files was same for all cases, only the numbering of parts in entities (contacts for example) changed according to the particular model numbering. The spine models for the ATDs were created by dividing the original lumbar spine into 2 parts at the level of vertebra L4. This corresponds to the same used for the DRI model as discussed in Section 2.3.1. Since the geometry was divided in a ratio of 1:2, the original lumbar spine mass was also divided in according to this ratio. The new inertia was computed based on the new mass and cylindrical shape (exact shape for Hybrid II 50%, and an estimated shape for the Hybrid III 50%).

For a cylinder $I_x = \frac{1}{2}mr^2, \quad I_y = I_z = \frac{1}{12}mh^2 + \frac{1}{4}mr^2.$

New COG's were created at the geometrical mid point of each new part. In the mid point of the dividing circle, a translational kinematics joint defining the force transmission was introduced. The Hybrid II and Hybrid III compressible spine models are shown in Figure 3-10.

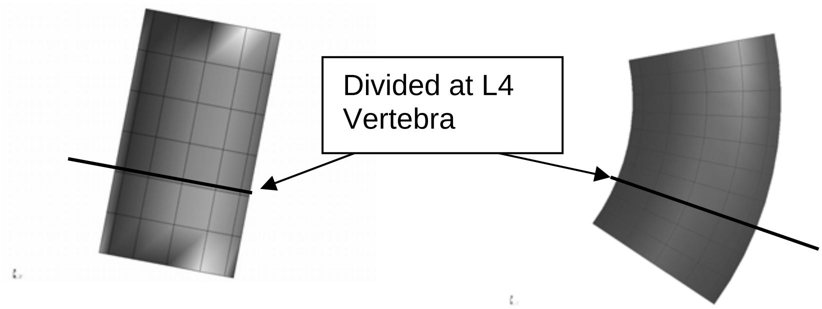


Figure 3-10 Hybrid II 50% (left) and Hybrid III 50% (right) Divided Spine

The model evaluation for the thesis used the Hybrid III occupant model because this was the most biofidelic model and was used in the most comparison experiments. The ROBBY2 model was not used in the thesis evaluations because it did not compare to the ATD's used in the full scale aircraft crash tests or the design requirements. Additionally, Spine compression force measurements were feasible with the ROBBY2, but not comparable to the DRI injury criteria. The simplification of the spine into a region above and below the L4 vertebra was not compatible with the Robby model.

The DRI model and the common limit of 21.3g (as discussed in section 2.2.1) was chosen to evaluate the potential for spine injury. The civil aircraft regulations (Section 2.1.1) use a simple load limit criteria of 6720 N (1500 lbf) when measured by the ATD during a dynamic test. The advantage of using DRI was that it is independent of the occupant size (21.3g translates to a 8789 N limit load for an averaged sized air force aviator as given in Section 2.2.1). Another advantage was that many of the full scale aircraft crash tests conducted at the NASA Impact Dynamics Research Laboratory (IRDF) reported DRI, and DRI is a standard evaluation parameter for vertical Energy Absorbing (EA) rotorcraft seats. These types of seats were very important to this research because most available information about the vertical aircraft impact environment is associated with these systems. A limitation of using DRI as an evaluation parameter was that physical ATD's can not measure it as originally developed. The physical ATD does not have the spine partitioned as described above. Thus surrogate accelerations (often at the pelvis or seat pan) were used to derive a DRI value. The purpose of this research required only a general evaluation of DRI, and the potential for error produced in the various measures were deemed inconsequential.

Restraint System Model

The restraint model was incorporated onto the occupant using slip rigs. The end elements of the belt were then tied to hard points in the seat model. The restraint was a bar belt system (Material / Part 9905) with a locking inertia reel. The inertia reel was specified to lock at 4ms after 1.5g load. The restraint properties were based on typical polyester restraints which were applicable for GA aircraft and automobiles (using Function 9905). The restraint properties did not have a large affect on the results because the vertical load case used in this research produces relatively low forces on the restraint webbing as compared to a forward longitudinal impact case. The longitudinal failing envelope of the occupant was not critical. Figure 3-11 provides a graph of the restraint force/elongation properties used in the model.

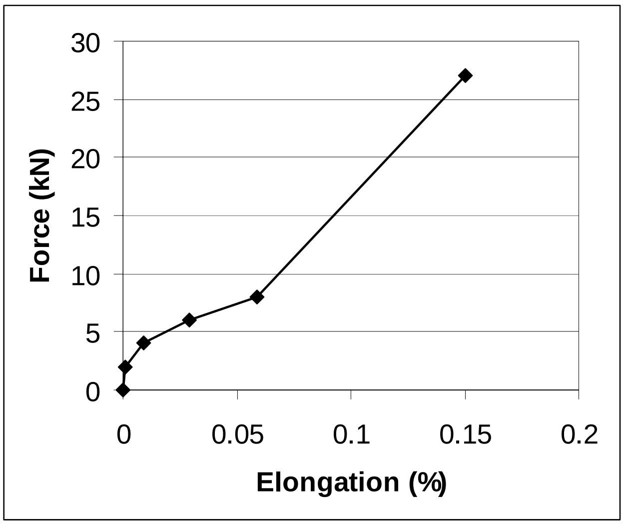


Figure 3-11 Restraint Belt Properties used in the model

Three slip-rings were used on the thorax, 1 slip-ring in lower belt attachment and 2 slip-rings on pelvis. The slip rings allowed the belt elements to slide though, but were attached to the occupant and transmit the reaction forces. Figure 3-12 provides a view of the Hybrid III ATD with clear view of the 3-point restraint.

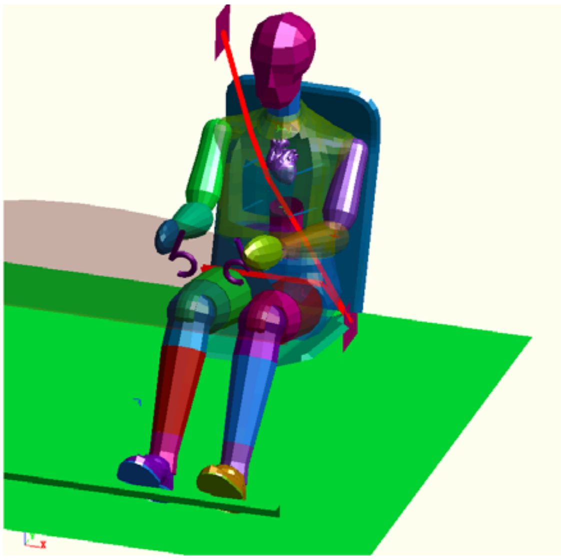


Figure 3-12 Hybrid III Model with 3-Point Restraint

3.5 Heart and Aorta Sub-System

The heart and aorta model was developed and calibrated by itself, and then incorporated into the ATD model. A simple model consisting of a heart mass "hanging" in a visco-elastic element representing the aorta was developed. Figure 3-13 shows the heart and aorta model inside the ATD.

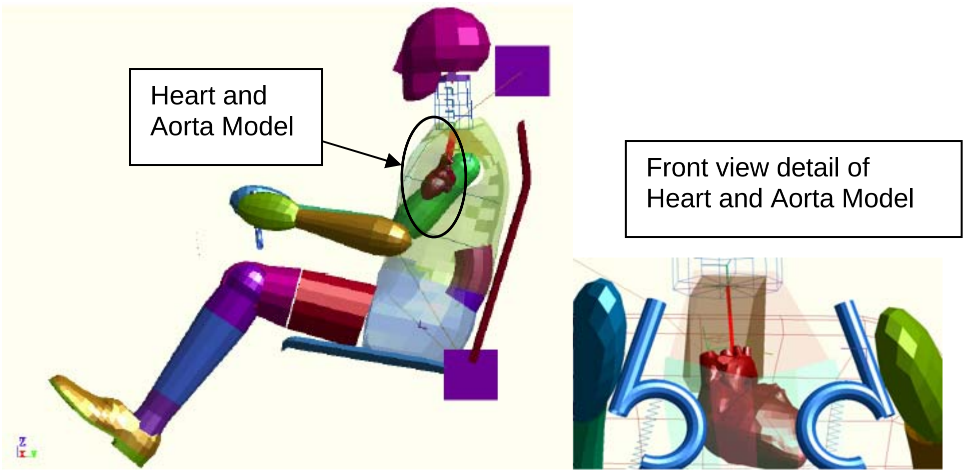


Figure 3-13. Heart and Aorta Model in the Hybrid III Occupant

The objective of this model was to evaluate the basic relationship of the vehicle impact to the inertial energy absorbed by the heart and aorta as transmitted through the seat and body. This provided the means to evaluate and determine critical characteristics of the impact vector. The approach did not provide information about local deformations or detailed injury mechanisms (such as where an aneurism is likely to initiate). These details were not of interest in developing the research conclusions and would be premature for the study of vertical impacts.

The heart/aorta model used a rigid body of shell elements for the heart and a bar element with visco-elastic material properties to represent the aorta. The heart shells were based on the geometry, mass, and moments of inertia of the ROBBY human body model (ESI 2005). The mass was applied through the centre of gravity. The aorta bar element deforms as governed by nonlinear functions in the vertical axis. The affect of other organs resisting the heart displacement downward were accounted for by the selection of the aorta bar element. The top of the bar was connected to the upper thorax of the ATD and the bottom of the bar was connected to the heart. Initially the heart was free to move in all directions, and the affect of other organs causing resistance for the heart to move in directions other than vertical were not included, as the impacts applied at the seat were vertical. The occupant motion will cause some bending and rotation of the upper torso even in vertical aircraft impacts, and the effects were deemed sufficiently small and neglected. It was hoped that allowing movement in other directions would provide another parameter for assessment of potential injury mechanisms. However, allowing lateral movements had the effect of confounding the energy being transferred into the system. Since the primary objective was to assess survivable boundaries as a function of this energy transfer, the heart model was then fixed to translate only in the vertical direction. Figure 3-14 shows the heart and aorta model. The node numbers reference model details which can be found in Appendix A. The top node on the aorta (30300013) was fixed in x,y,z to the ATD thorax. The bottom node was shared with the heart node (30301266) at x,y,z = (0.02,0.00,0.42). The COG node 30300001 was located at x,y,z = (0.03, 0.009, 0.364). Translation of the COG was fixed in x,y, and free in z. Rotation is fixed in x,y,z. An acceleration field was applied for gravity.

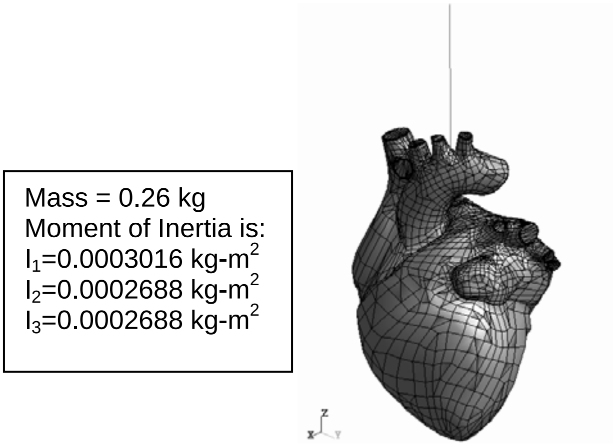


Figure 3-14. Heart and Aorta Model

The material properties of human soft tissues are viscoelastic, meaning that the properties vary as a function of load rate and geometry. A time dependent function is commonly described for viscoelastic soft tissue consisting of an initial region of exponential increase followed by a linear region, and finally with a nonlinear region at material failure. FEA aorta models have used various methods for defining the stress strain relationship. Sevitt (1977) developed elastic properties of the aorta in his model to resist deformation by tension. He assigned an elastic modulus (young's modulus) as the ratio of the stretching force (stress) to the amount of stretch (strain) per unit cross-sectional area. This method made the assumption that the arterial wall was incompressible, and he used an elastic modulus per cross-sectional area for the aorta of 3.5E6 dyn/cm^2. Deng (1999) separated the elasticity of the aorta into circumferential and longitudinal directions, indicating the aorta to have a Young's modulus of 0.36 to 0.4 Mpa in the circumferential direction, and 0.22 to 0.3 in the longitudinal direction. Shah (2001) provided the average stress at failure from uniaxial loading as 3.53 Mpa longitudinally, and 5.07 Mpa transversely. Biaxial loading produced the average stress at failure of 1.97 Mpa. Wang (2002) reviewed a range of material properties and methods for aortic properties. The Wang model was non-isotropic, with different stress / strain relationships for the longitudinal and transverse directions, and also included a failure feature based on an extension strain limit of a 1.6 stretch ratio.

The simplified heart and aorta model approach of this research used a rigid body for the heart and a visco-elastic bar element for the aorta. Thus the material properties were defined not in terms of stress strain, but in terms of force / elongation. Because the model was not attempting to deform as a real aorta, the properties were not matched to the tissue properties of a human aortic properties. Instead, the properties needed to represent the motion of the viscera due to vertical impacts. Thus the aorta bar spring and damping properties were developed from calibrating the response to vertical displacements of the viscera found in literature (Weiss 1967).

Experimental data for heart displacement from acceleration was very limited, and only a few examples from human and animal tests were found in literature (Hansen 1967, Weiss 1967, Kroell 1986). Although these sources were attempting to measure heart displacement, limitations of the measuring technique resulted in measuring the general displacement of the viscera. For example, rapid x-ray machines were used, but the lack of image resolution made it impossible to differentiate the heart from other organs. The spring and damping properties used in the heart and aorta model were derived by running simulations of the model organ response and iteratively changing the properties to achieve representative motion to the results of the Weiss (1967) experiments. The element type used was PAMCRASH type 204. The force elongation properties for the final spring and damper are represented graphically in Figures 3-15 and 3-16.

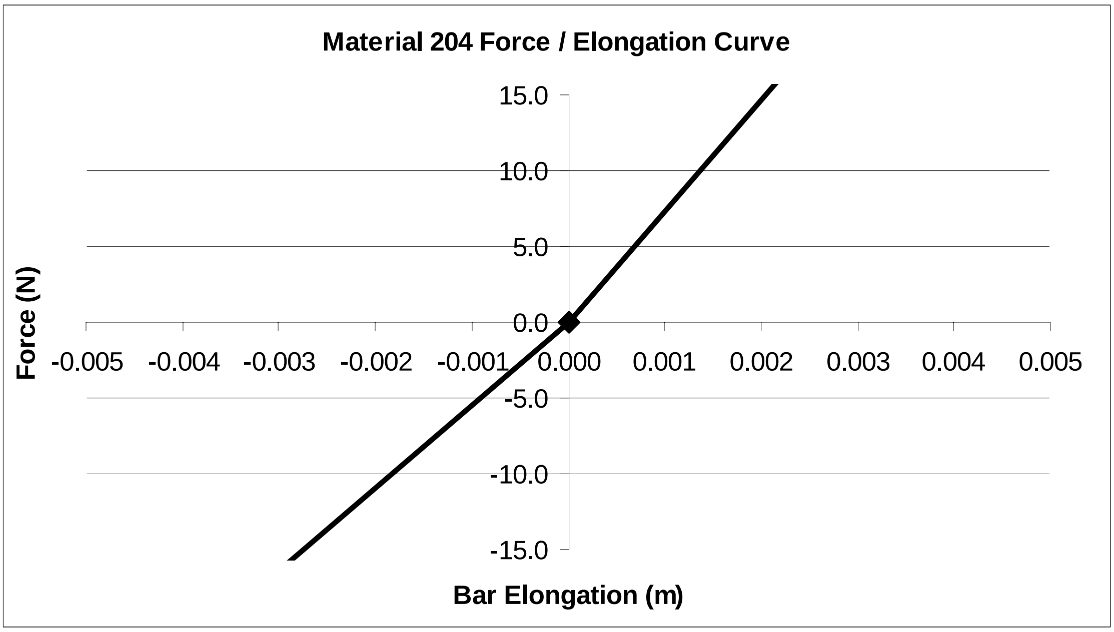


Figure 3-15. Aorta Spring Force

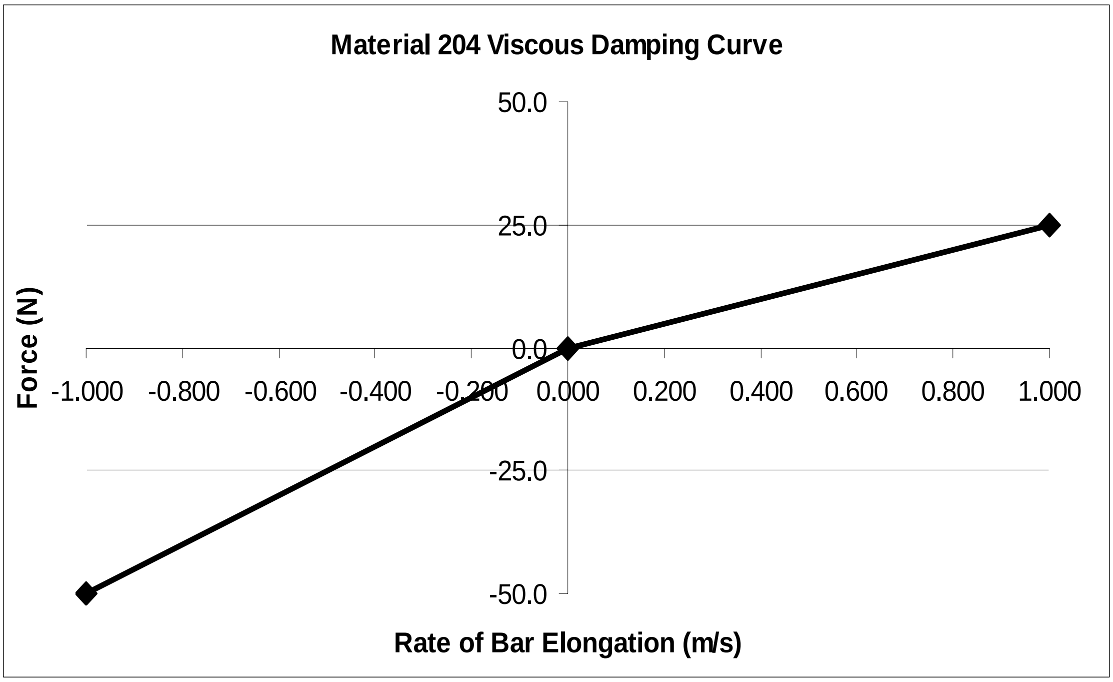


Figure 3-16. Aorta Damper

3.6 Method for Conducting a Simulation

There were three types of models for each simulation: the system model, sub-system models, and a test conditions model. The functions of these three models are described in Table 3-2. Figure 3-17 provides a hierarchy of the full system model printed directly from the CRASHSAFE Editor (ESI 2004). The model parameters and functions can be changed using this graphical interface or directly by changing the text files using a text editor such as Microsoft Notepad. The models have standard names with the root "H350v2004" which referred to the 2004 version of the hybrid III ATD.

Table 3-2. Description of Simulation Model Types

Function	Items Affected / Description
System Model	
Specifies PAMCRASH software parameters	Input version 2004, CRASH Solver, Explicit Analysis
Specifies other parameters	units, files and data check options
Specifies the model and time base for the simulation	total time base (200ms) data interval (0.1ms) image interval (5ms)
Specifies the data plots to be generated	Various (for example accel. vs time or force vs displacement)
Incorporates sub-system models	ATD, Seat, Heart, Restraint
Incorporates Test Condition model	(see model description below)
Sub-System Models (these include: ATD, Seat, Heart, Restraint)	
Specifies materials	type, density, strain rate, modulus, poison's ratio
Specifies the parts of this model and their parameters	time-step, contact thickness, cross section area, shear effective area
Specifies nodal points and definitions for the rigid bodies	(list of coordinates)
Specifies elements and definitions	(shell, bar/beam etc.)
Defines functions	(forces, damping, hysteresis, friction)
Defines loads	(initial velocity, boundary conditions, contacts, acceleration fields – gravity, constraints)
Defines Auxiliaries	(coordinate frames, sensors, curves)
Test Conditions Model	
Defines boundary condition	(parts list)
Defines loads	Gravity
Specifies the Initial Velocity function	This is the aircraft crash pulse input. A curve is specified.
Defines the Curve specified by the Initial Velocity	Coordinates for time / accleration

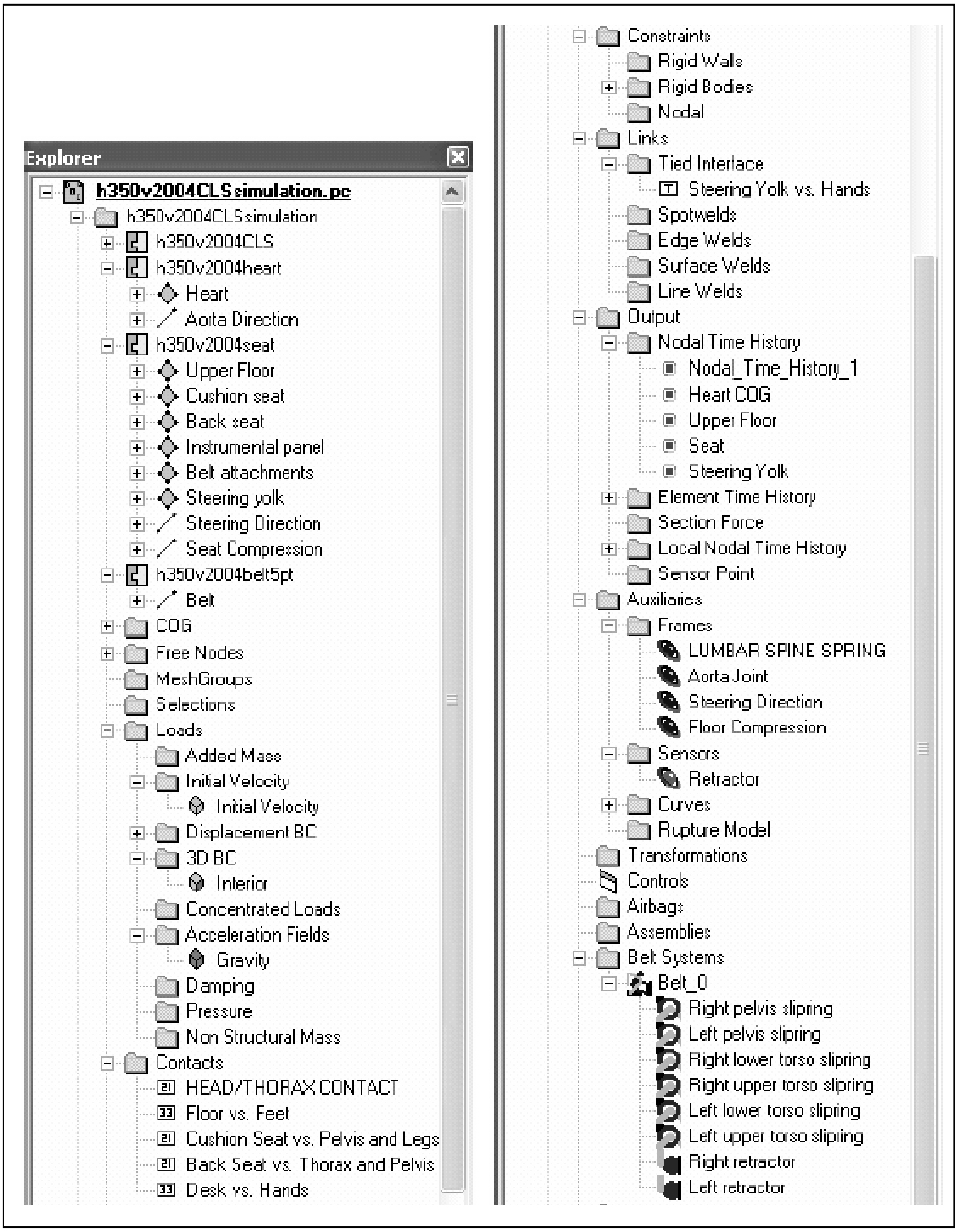


Figure 3-17 Hybrid III Model with 3-Point Restraint

The explorer view shown in Figure 3-17 illustrates the relationship of the models which appears at the top left column followed by loads and contacts. The top level System Model was named h350v2004CLSsimulation.pc. This model icon shown in Figure 3-17 was not expanded to show every part of the ATD. The subsystem models are shown below the ATD name in Figure 3-17, and were expanded to show all the components.

The left column of Figure 3-17 shows folders for the centre of gravity (COG) and Free Nodes followed by the loads. The COG and Free Node folders were also not expanded because the lists were extensive. The right column continues with the constraints, links, outputs, auxiliaries and the belt system. Note again that the folders marked with a + sign were not expanded due to the length of the list that was contained within.

Each group of models as described above were created for each aircraft crash simulation. These executable files were then compiled using the PAMCRASH SOLVER (ESI 2004). The solver performed the calculations as specified in the models. Each simulation followed these basic steps:

1. Select the Initial Velocity Curve which defines the impact pulse. This was done by editing the curve specified in the Test Conditions Model.
2. Select the Seat Vertical Force/Deflection Curve which defines the EA Characteristics of the seat. This was done by editing the curve specified in the Seat Model.
3. Select the time base and other parameters in the System model which define the outputs.
4. Compile / Run the models.
5. Debug the model if the solver crashed. The primary debugging involved adjusting time-steps and contact parameters during initial runs. Errors such as incorrectly placed card items or incorrectly specified elements had to be resolved.
6. Adjust parameters to give the desired output data.
7. View the results in PAMVIEW (ESI 2002) to determine data desired for further review or presentation.
8. Generate output data files and manipulate. Microsoft Excel (Microsoft 2003) was used for data files and Motion Analysis Video Viewer (Concurrent Processing, 1999) was used for video files.

4. IMPACT CHARACTERIZATIONS AND MODEL CALIBRATIONS

The system level computer model described in chapter 3 required input accelerations from a variety of aircraft and impact severities. This research was focused on small GA aircraft, but data all types of aircraft helped to characterize impact environments and how the impact loads are absorbed by the airframe and transferred to the seats and occupants. Aircraft size and construction, impact surface and orientation, and impact velocity and flight path all affect the loads transferred through the floor and into the seat.

The crash tests evaluated were conduced from late 1970's through the 1990's at the NASA Langley Impact Dynamics Research Facility (IDRF) as described in section 2.1. Crash tests from the following aircraft types included:

- Smaller GA Aircraft, approximately 1,000 kg nominal weight (Section 4.1.1)
- Larger GA Aircraft, approximately 3,000 kg to 6,000 kg nominal weight (Section 4.1.2)
- Transport Aircraft, approximately 15,000 kg or larger (Section 4.2.1)
- Rotorcraft, approximately 5,000kg to 20,000 kg (Section 4.2.2)

The computer models of chapter 3 were calibrated as described in the second half of this chapter. Calibration simulations were done separately for the aircraft system model and the heart/aorta model. The calibrations were based on the following:

- Aircraft System Model calibration based on the YAH-63 helicopter crash test (Section 4.3)
- Aircraft System Model calibration based on Sikorsky ACAP crash test (Section 4.4)
- Heart and Aorta Model calibration based on Human Experiments (Section 4.5)

4.1 Impact Characterization – GA Aircraft

The coordinate system used for velocity, accelerations, force components, and for pitch, roll, and yaw were used according to a typical standard format as given in Figure 4-1.

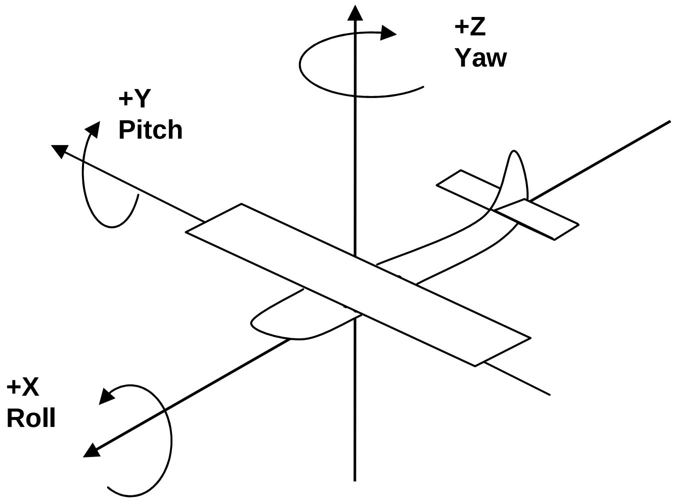


Figure 4-1. Aircraft Coordinates and Attitude Directions

The full scale aircraft crash tests were conducted at the NASA Langley IDRF (Jackson, 2004). The tests included high speed video data and measured responses including acceleration time histories from various points on the aircraft, seat, and Anthropomorphic Test Dummy's (ATD's). Figure 4-2, reproduced from Vaughan 1979 is a diagram of the facility.

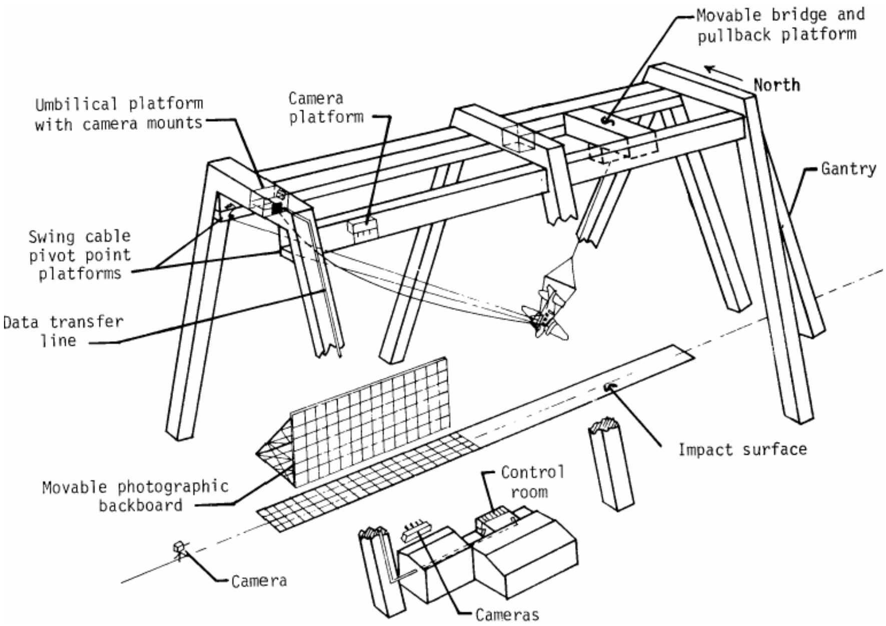


Figure 4-2. NASA Langley Impact Dynamics Research Facility (Vaughan 1979)

An example of a crash test is shown in Figure 4-3. The Cirrus SR-20 was crash tested with a flight path and pitch angle of -30 degrees (0 degree angle of attack), 0 degree roll, and an impact velocity of 25 m/s (Terry 2000). There were four crash tests of the Cirrus SR-20 in the 1990's as part of a government and industry cooperative effort for improving crash safety named the Advanced General Aviation Transportation Experiment (AGATE) program.

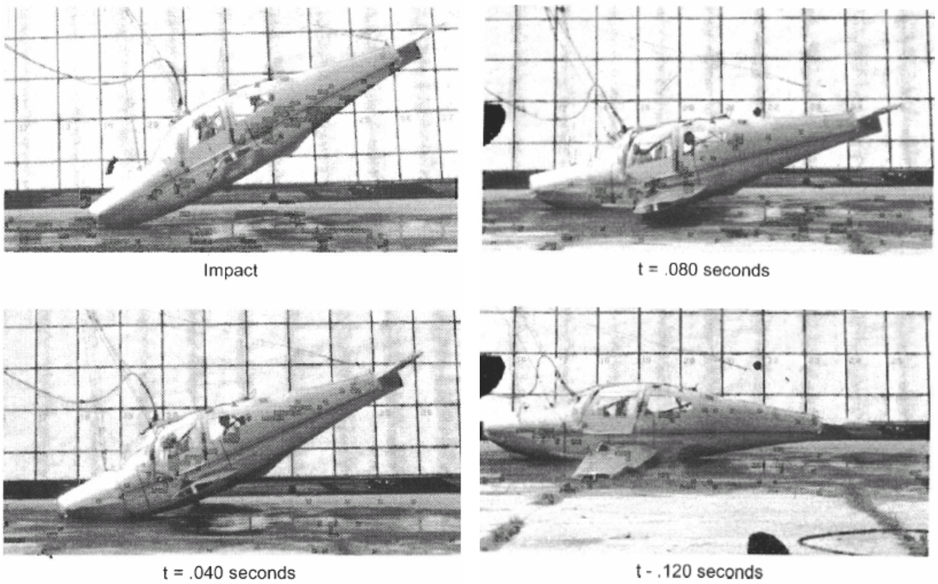


Figure 4-3. AGATE Crash Test of Cirrus SR-20 (Terry 2000)

The following sections summarize the crash tests conducted at the IDRF. A group of impact pulses (acceleration versus time profile of the aircraft floor) and the corresponding occupant responses were established. The evaluations also identified important survival factors. Further detail is provided in Appendix B as noted.

4.1.1 Crash Tests of Smaller GA Aircraft (Approximately 1000 kg)

High Wing GA Aircraft (Vaughan 1980)

Four identical high wing, single engine, aluminium GA aircraft (Cessna 172) were crash tested with a variety of pitch angles and impact surfaces. Appendix B1.1 provides details of the test conditions. The least severe test was a hard landing with a pitch angle of 13.5 degrees and produced essentially a flat impact onto concrete. The aircraft vertical accelerations were under 10 g and vertical pelvic accelerations peaked between 10 to 15 g. No injuries would have been likely. The other three impacts with nose-down pitch angles, were severe. Two were non-survivable due to the loss of survivable cabin volume. One of these was an impact onto soil, causing the aircraft to invert during the crash sequence. The pelvic accelerations produced for all three of the nose-down high wing GA aircraft crash tests were significantly above the 20 g limit discussed in section 2.2.1, and would likely have been non-survivable.

The increase in aircraft and occupant accelerations from concrete to soil for the nose down experiments indicated that the soil "catches" the aircraft, concentrating the impact into a shorter pulse and resulting in more severe and less survivable conditions. The concrete nose down and roll impacts resulted in vertical accelerations proportional to the pitch angle of the aircraft. A flat pitch angle resulted in higher vertical accelerations as the aircraft "slapped" the ground. The roll impact may have demonstrated lower vertical accelerations either by crushing at the wing prior to the fuselage contact, or by crushing the side of the fuselage. Lower vertical accelerations can result from increased lateral impact, and would reduce the potential for vertical spine impact injury, but would also increase the potential for damage to the cabin and possible collapse of the structure. Appendix B1.1 contains further detail and simplified aircraft impact pulses and pelvic responses for the high wing GA aircraft crash tests (Vaughan 1980).

Light Low Wing GA Aircraft (Castle 1983)

Three identical low wing, single engine, GA aircraft were crash tested with a variety of pitch angles and impact surfaces with the details provided in Appendix B1.1. Acceleration versus time data for the pelvis acceleration was available only for the +10 degree concrete impact, and Figure 4-4 compares the vertical seat pan acceleration to the pelvic acceleration for this test (Castle 1983). The results were similar to the high wing pitch up test. This pelvic acceleration was only slightly above 20 g, suggesting the potential for spinal injury did exist, but it would not have been life threatening.

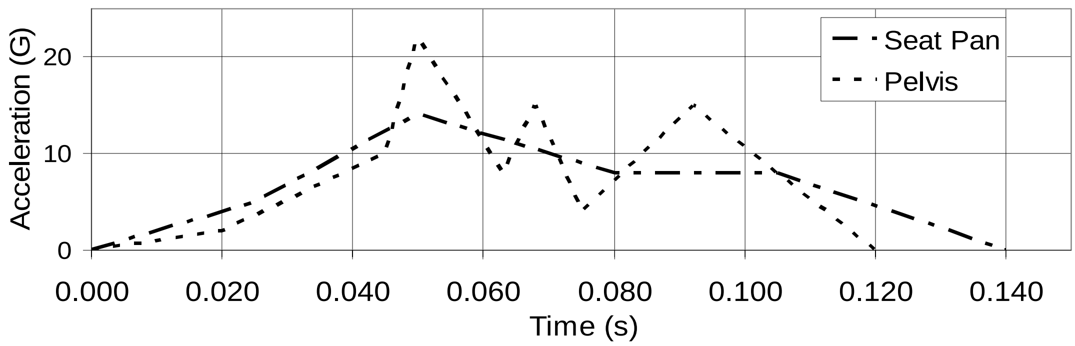


Figure 4-4.Comparison of Seat and Pelvic Accelerations Resulting from the +10 degree impact on concrete shown in(Castle 1983)

A description and graphical representation of the floor accelerations for these crash tests published by Castle (1983) is provided in Appendix B1.1.

Modified Cirrus SR-20

Four crash tests of a light composite, single engine, low wing aircraft (Cirrus SR-20) were performed by AGATE, which was a government and industry cooperative group that worked to advance crash safety. The tests consisted of two onto concrete and two onto soil, all with similar impact parameters, which are provided in Appendix B1.1. Although the NASA reports from this contract are unpublished, limited information about the series was contained in the Small Aircraft Design Guide (Hurley 2002) and an SAE technical paper by Terry (2000).

The two impact tests onto concrete had high vertical accelerations, approaching 100g at the aircraft floor. Pelvis load rather than acceleration was recorded. One of the tests onto concrete had rigid pilot and co-pilot seats with Energy Absorbing (EA) foam. The vertical spine loads for these seats were far above the commonly accepted injury criteria (680 kg limit load, chapter 2), with values ranging from 1,090 kg to 1,725 kg. Replacing these seats in the other concrete test with prototype EA seats reduced the spine loads to survivable levels, ranging from 500 kg to 770 kg.

The two soil impacts transferred much of the acceleration from vertical to longitudinal direction. As a result the vertical accelerations in the soil impacts were under 20 g. Accurate pelvis or lumbar measurements were not possible for the soil impacts due to errors with installation of the restraint. However the low vertical loads would have produced very low, non-injurious spine loads. Flailing injuries in the longitudinal direction were the primary survivability concern for the soil impacts.

Summary of the Crash Tests of Smaller (Approximately 1000 kg) GA Aircraft

The light GA impacts illustrated the large influence of pitch angle, impact surface, and the interior design on the duration and peak accelerations of the impact. Strong interactions between the factors affect the ultimate survivability for the occupant. As noted above, a steep nose down pitch can concentrate the impact, causing shorter duration high acceleration spikes in the longitudinal direction. Even though the vertical accelerations may be fairly low for this case (below spine injury levels), the high longitudinal impact loads risk cabin collapse or flailing injuries. A soft soil impact surface will amplify this response by “catching” the aircraft.

The vertical loads can be very high with a flat or positive pitch angle due to the aircraft rotating and "slapping" the ground. Alternatively, impacts with a roll component or a nose up pitch that allow the wings or tail of the aircraft to strike first can have the affect of mitigating the vertical loads. For example the +10 degree pitch test onto concrete (Castle 1983) hit the tail on the ground first, followed by impacts points progressively forward on the aircraft. Impact energy was absorbed by each progressive ground strike. The composite aircraft crash tests exhibited the longest impact durations due to "springy" characteristics of the composite fuselage, which will bounce and slide more than aluminium.

4.1.2 Crash Tests of Larger GA Aircraft (Approximately 3,000 to 6,000 kg)

AGATE conducted several crash tests of larger GA aircraft in the late 1970's, all using the same aircraft type and test configuration. The aircraft type was a twin engine, six passenger Piper Navajo with a nominal weight of 2,700 kg. Several crash test series were run, evaluating a different variable for each series:

- Impact Velocity (NASA Technical Paper 1042, Alfaro-Bou 1977)
- Flight Path Angle (NASA Technical Paper 1210, Castle 1978)
- Roll Angle, (NASA Technical Paper 1477, Castle 1979)
- Pitch Angle, (NASA Technical Paper 1481, Vaughan 1979)

A brief description of each is provided with further information contained in Appendix B1.2.

<u>Piper Navajo - Impact Velocity (Alfaro-Bou 1977)</u>

Two tests were conducted at different impact velocities with a pitch angle of -15 degrees (0 degree angle of attack). The initial impact was absorbed by the nose of the aircraft and the highest cabin accelerations occurred after the initial impact. One objective was to evaluate survivable cabin volume, which was maintained through both tests. The seats remained attached to the floor in both tests. The peak to peak vertical accelerations at the floor were about 85 g for the 13 m/s test and 150 g for the 27 m/s test, and the average accelerations were 63 g and 112 g respectively. The vertical ATD pelvis peak to peak acceleration was not measured in the 13 m/s test and was 76 g for the 27 m/s test. Although the cabin space was maintained, the vertical loads at the occupant of the 13 m/s test would have been very severe based on the floor accelerations, and the 27 m/s test would have been non-survivable.

Piper Navajo - Flight Path Angle (Castle 1978)

Three tests were conducted with different flight path angles and a velocity of 27 m/s (along the flight path). The test at -15 degrees maintained a survivable cabin space during the impact sequence. The -30 degree test experience significant destruction of the region forward of the firewall and damage surrounding the cabin, but the survivable volume was concluded to have been maintained. The cabin of the -45 degree test collapsed and was not survivable. The vertical floor accelerations of the -15 degree test were nearly double that of either the -30 degree and -45 degree tests. The acceleration was transferred to the longitudinal direction for the steeper angle tests, registering values three to four times the -15 degree test. The vertical accelerations measured at the floor near the seats were highest for the -15 degree test at 130 g, and lower for the -30 and -45 degree tests at about 70 g and 80 g respectively. The pelvic accelerations followed a trend with smaller flight path angles producing the higher vertical accelerations. The -15 degree, -30 degree, and -45 degree tests produced 76 g, 40 g, 30 g respectively. The collapse of the cabin structure in the -45 degree tests was attributed to limiting the accelerations as the cabin broke apart. A photo sequence of the -30 degree test is provided in appendix B1.2.

Piper Navajo - Roll Angle (Castle 1979)

The impact sequence for all of the tests was first onto the nose, followed by the cabin. The roll angle factor did not have a significant affect on the accelerations at the nose, but did at the cabin. The vertical accelerations at the floor, seat, and ATD pelvis were reduced as a result of the roll angle. The roll angle caused impacts at the wings which altered the direction of the acceleration forces, reducing vertical loads at the seats. The 0 degree roll test resulted in floor accelerations ranging from 106 g and pelvis accelerations of 76 g. The roll angle tests at -15 degrees and -30 degrees had peak vertical floor accelerations of 80 g and 91 g respectively. The pelvis accelerations for these two tests did not exceed 20g at the seat pan or at the pelvis of the ATD’s because the roll caused the ATD’s to move in the cabin during the impact. A survivable cabin volume was maintained in all three tests. Further detail is provided in Appendix B1.2.

Piper Navajo - Pitch Angle (Vaughan 1979)

Three tests were conducted at pitch angles of -15, 0, and +15 degrees and an impact velocity 27 m/s (along flight path), roll angle 0 degrees. Although the impact accelerations were very severe, it was noted that a survivable cabin volume was maintained in all three tests. The accelerations transferred to the seats were well beyond current regulations and beyond the structural capabilities of the seats. Table 4-1 provides peak acceleration values for the fuselage, front seat location and occupant (measured at the pelvis of the ATD). The +15 degree pitch aircraft hit tail first, then mid section and then nose. The accelerations increased as they moved forward through the impact. The pitch down test had the opposite affect. The flat pitch test acceleration was highest in the centre. The flat pitch test had the shortest initial impact duration, as the aircraft rotated very little.

Table 4-1. Peak Vertical Accel. of 3 GA Crash Tests, Front Seat (Vaughan 1979)

Test (Pitch Angle)	Fuselage Structure	Floor at First Seat Legs	ATD Pelvis
-15 degrees	80g	80g	55g
0 degrees	150g	80g	40g
+15 degrees	200g	50g	30g (submarined)

The loads measured at the occupant locations would likely be fatal for all three tests.

Beech Starship

AGATE performed a full scale impact test of a Beech Starship aircraft at the NASA Langley Drop Test Facility in Hampton Virginia (AGATE C-GEN-3451-1). This is an all-composite, nine passenger GA aircraft. The aircraft was filled with seat and occupant experiments from various companies and researchers. Accelerometers were mounted on the floor at 3 of the seat passenger seat locations. The composite fuselage was very stiff and crushed little, and thus the accelerations varied significantly between seat stations, depending on where they were relative to the impact. The aircraft impacted flat, with a -18 degree flight path and a +18 degree pitch. The initial impact was 8.84 m/s vertical and 27.13 horizontal. Most of the horizontal velocity was retained through the first impact and dissipated in a second horizontal impact after slide out. The left and right seat track acceleration time histories are shown in Appendix B1.3. One seat in particular was mounted on a beam which deflected 3.6 inches downward during the primary vertical impact. This deformation attenuated the peak acceleration, measuring 32 g at this beam while a location nearby measured 124 g. The simplified aircraft floor impact pulse for 3 locations on the fuselage is shown in appendix B1.3.

4.1.3 Observation of General Aviation Impact Characterization

The GA impact pulse characterizations supported the objectives given in section 1.2. A range of impact pulses was generated that were used as a basis for inputs to the computer models which assess the relationship between the vehicle impact and the body tissue response. The range of pelvic accelerations found for the fixed wing aircraft provided data to compare with the seat/occupant model results, helping to understand the severity of the impact. The GA impacts from section 4.1 are shown together in Figure 4-5 by graphing peak acceleration versus the time to peak acceleration.

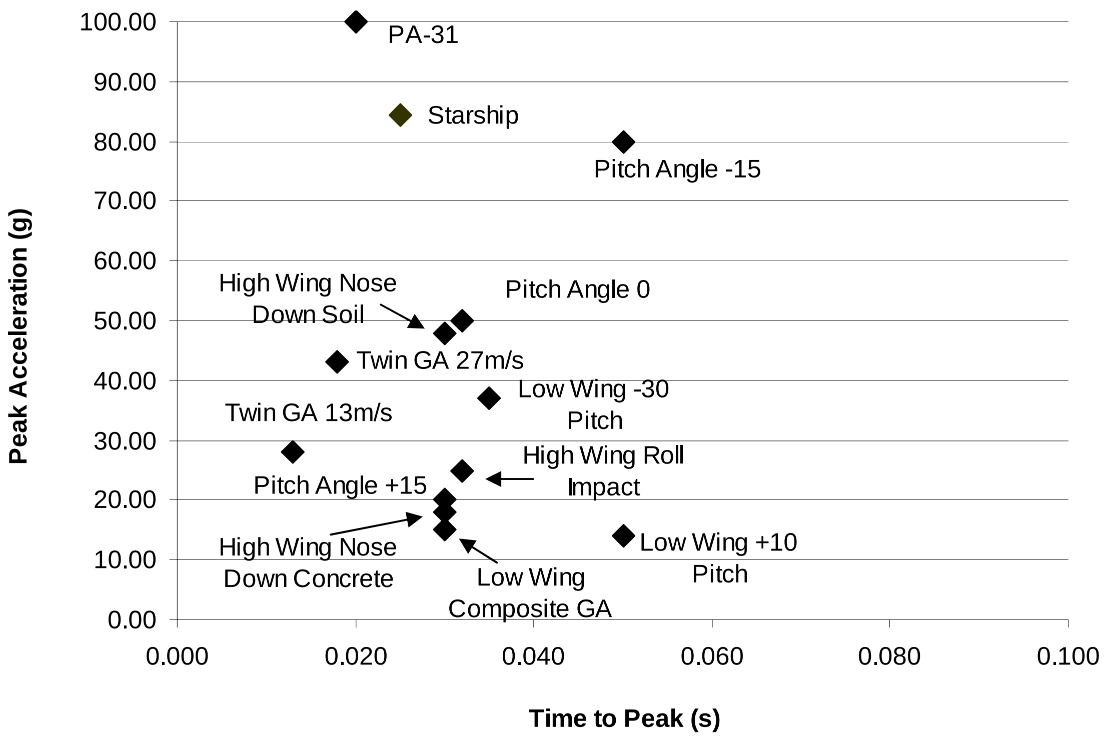


Figure 4-5. GA Impact Pulses, Vertical Peak Acceleration vs Time to Peak

Peak floor accelerations provided a means of evaluating the severity of the pulse for injury mechanisms that are susceptible to localized trauma. High peak accelerations are a dominant factor in forced based injury. The evaluations also included the time to peak acceleration as a means to compare pulse duration. The peak and the time to peak together gave an indication of the total pulse energy (area under the curve), and is a dominant factor for distributed trauma injuries. The impact characterizations of the smaller and larger GA aircraft provided a full range of minor injury to non-survivable impacts.

4.2 Pulse Characterization – Transport Aircraft and Rotorcraft

4.2.1 Transport Aircraft

ATR 42 (Jackson 2004)

Available crash test data for transport category aircraft was small. Transport aircraft are too big and expensive for the pendulum configuration at NASA IDRL. Instead, vertical drop tests of transport category aircraft and fuselage sections were found. In July of 2003 an ATR42-300 aircraft was dropped from a height of 4.27 meters, as shown in Figure 4-6, reproduced from Jackson 2004. The ATR42 is a commuter class aircraft with a seating capacity of 42 to 50 passengers and a gross take-off weight of about 16,700kg. The impact severity was considered survivable and had a nominal velocity change of 9.14 m/s. The structures of the occupied passenger seats failed, as shown in Figure 4-7, reproduced from Jackson, 2004. The impact accelerations for the left and right outboard seats are provided in Appendix B2.

Figure 4-6. ATR42 Drop Test

Figure 4-7. Interior View of ATR42

Boeing 737 (Jackson 2004)

A ten foot long passenger section of a Boeing 737 fuselage section was drop tested in November of 2000 (Jackson 2004). The purpose of the test was to evaluate the response of the overhead storage bins during a severe but survivable impact. The impact velocity was 9.12 m/s. The onset rate if the acceleration was shown to be lower as the fuselage size increases due to a relatively large crush zone. The ATR demonstrated similar accelerations for the left and right side, and the crush of the fuselage floor was symmetric. The asymmetric response of the B737 was attributed to the presence of a cargo door on the lower right side of the fuselage section. There were only two transport impacts evaluated and thus the graph of peak acceleration vs time at impact and the observations are combined with the rotorcraft.

Fansanella (2002) describes a vertical drop test of a conceptual composite fuselage section also with conceptual energy absorbing floors and seats. The accelerations for various structures and occupants were reported, but they did not represent actual aircraft or seating systems in service, and thus were not included in the impact characterizations.

4.2.2 Rotorcraft

YAH-63 (Smith 1986)

A US Army YAH-63 attack helicopter was crash tested at the NASA IRDF in 1981, (Smith 1986). The purpose of the test was to evaluate the crashworthy features that had been incorporated into the helicopter for a severe but survivable crash. The helicopter was equipped with energy absorbing struts which were standard for this aircraft. The crew stations both had Energy Absorbing (EA) seats, but of two design standards. The forward (pilot) seat was representative of those in modern AH-64-Apache Helicopter while the rear seat (co-pilot) was of an older design. The accelerations of the aircraft, seat and ATD for the forward seats were designed for about 0.31 m of vertical stroke at a constant load of 14.5 g for a 50^{th} percentile ATD. The measured accelerations of the aircraft floor, the seat, and ATD pelvis for the pilot seat position are summarized in Figure 4-8. The aircraft weighed 6,245 kilograms and had a vertical impact velocity of 14.6 m/s.

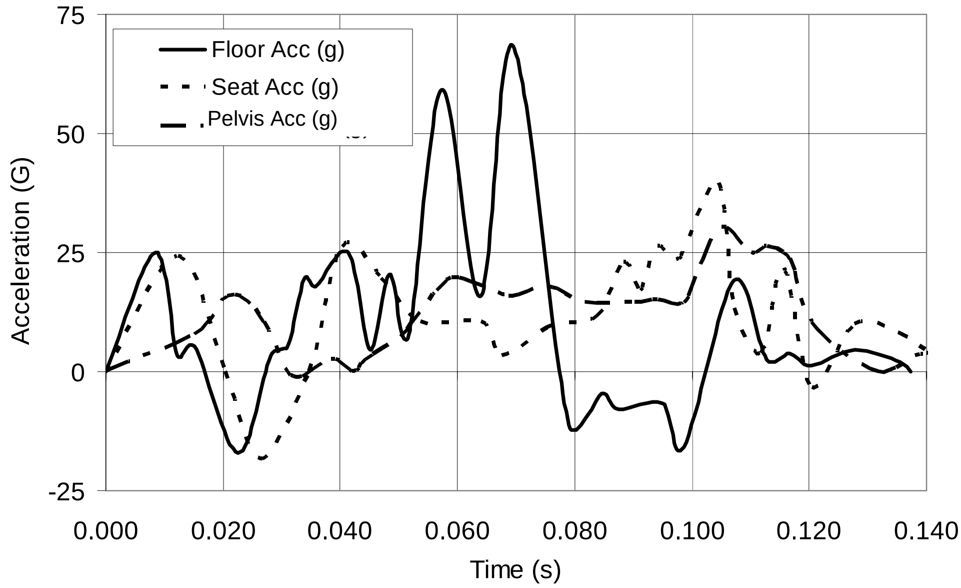


Figure 4-8. YAH-63 Fuselage and Pilot Accelerations (Smith 1986)

The landing gear absorbed the impact until about 45 milliseconds into the crash, when the nose of the aircraft impact occurred. The co-pilot seat position experienced seat failures and the fuselage accelerations at this location were also difficult to measure, and thus the co-pilot position was not evaluated. The crash severity and vertical loads transmitted to the pilot through the seat were concluded to be of moderate injury potential for spinal fractures. The seat bottomed out, using its entire stroke, resulting in an acceleration spike of 31 g. The high mass items remained attached to their mounting locations, with peak accelerations measured as follows: Engines 38.3 g, Main Transmission 30 g, Tail Rotor Gearbox 64 g.

SH-60/UH-60 and UH-1H

The US Navy investigated ground and water impacts using computer simulations of the SH-60 helicopter and a full scale crash test of a UH-1H Helicopter (Schultz 2000). All of the impacts were flat, except the UH-1H ground impact. The impact velocities and acceleration rise rates are given in Table 4-2. The results showed how water impacts exhibited much steeper acceleration rise rates. The basic vertical impact pulse shapes are shown in Appendix B3.

Table 4-2. Ground and Water Impacts of UH-60 and UH-1H (Schultz 2000)

Aircraft	Impact Velocity (m/s)	Vertical Accel. Rise Rate (g/s)	Rise Time (s)
UH-60 Ground	9.14 (vertical)	580	0.052
UH-60 Water	9.14 (vertical)	8,800	0.005
UH-1H Ground	12.19 (vert.) / 9.75 (horz.)	420	0.090
UH-1H Water	7.93 (vertical)	5,400	0.010

Sikorsky Advanced Composite Airframe (Jackson 2002 and 2003)

A full scale crash test of a prototype composite helicopter was conducted at the NASA IDRF in 1999 (Jackson 2002). The aircraft was built by the Sikorsky Advanced Composite Airframe Program (ACAP) and was based on the S-76 commercial helicopter. The aircraft had EA landing gear struts, EA floor construction, and was fitted with EA crew seats and ceiling mounted EA troop seats. The vertical impact velocity was 12.5 m/s in a 5 degree pitch angle (nose-up) and 3.5 degree roll angle (left-down). Figure 4-9 shows the aircraft post test, as reproduced from Jackson 2003. The high mass items remained attached to their mounting locations with the exception of the tail rotor. The following peak accelerations measured: Tail Rotor 19 g, Main Rotor 28 g, Right Engine 43 g, Left Engine 41 g.

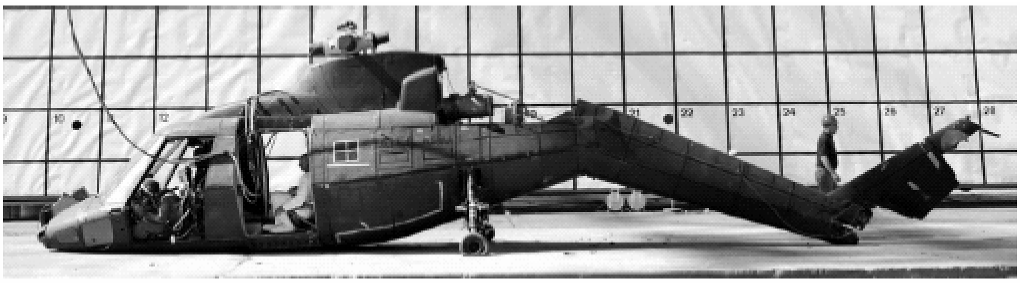


Figure 4-9. Sikorsky ACAP Crash Test (Jackson 2002)

The test was conducted along with computer model simulations, and thus extensive data was collected and reported. This data was used in the research to calibrate the computer models as described in Chapter 5. Figure 4-10 provides representative accelerations for the floor, seat, and occupant for the pilot crew station (Jackson 2002).

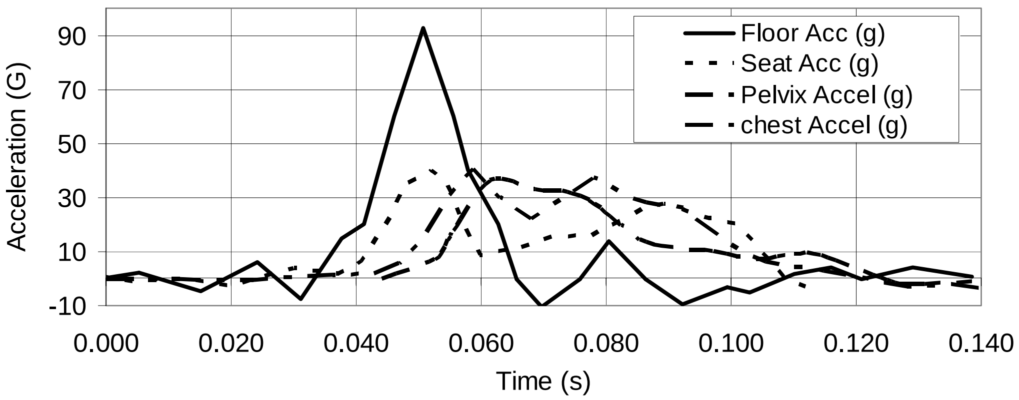


Figure 4-10. Sikorsky ACAP Fuselage and Pilot Accelerations (Jackson 2003)

CH-47 (Castle 1976)

A US Army CH-47C helicopter was crash tested at the NASA IDRF in 1975 with a vertical impact velocity of 12.0 m/s (Castle 1976). The rear of the aircraft hit the ground first, resulting in the highest accelerations measured directly above the impact point of 180 g. The aircraft rocked forward and the cockpit hit the ground in a secondary impact about 0.20 seconds later. The measured peak vertical accelerations varied from about 60 g along the fuselage to 110 g at the cockpit. The energy absorbing crew seats (cockpit) had two separate peak accelerations of about 50 g during the primary impact and -40 g during the secondary, about 0.160 s apart. ATD data for the crew seats was not reported. The energy absorbing troop seats (cabin) experienced significant acceleration only during the primary impact. The peak floor accelerations at the troop seat were about 70 g to 80 g. Accelerations on the troop seats were not reported. The EA troop seat reduced the floor loads about 60%, resulting in peak ATD pelvic acceleration of about 28 g, occurring at a time about midway between the primary and secondary impact.

4.2.3 Observations from Transport and Rotorcraft Pulse Characterization

The transport aircraft and rotorcraft impact pulse characterizations supported the research objectives. Just as the GA impact pulse characterizations (section 2.1.2) were used as a basis for inputs to the computer models which assess the relationship between the vehicle impact and the body tissue response, these were used to characterize the pulses for transport aircraft and rotorcraft. The range of pelvic accelerations found for the transport aircraft and rotorcraft provided data to compare with the seat/occupant model results, helping to understand the severity of the impact. Figure 4-11 graphs the peak acceleration versus the time to peak for the transport aircraft and rotorcraft impacts.

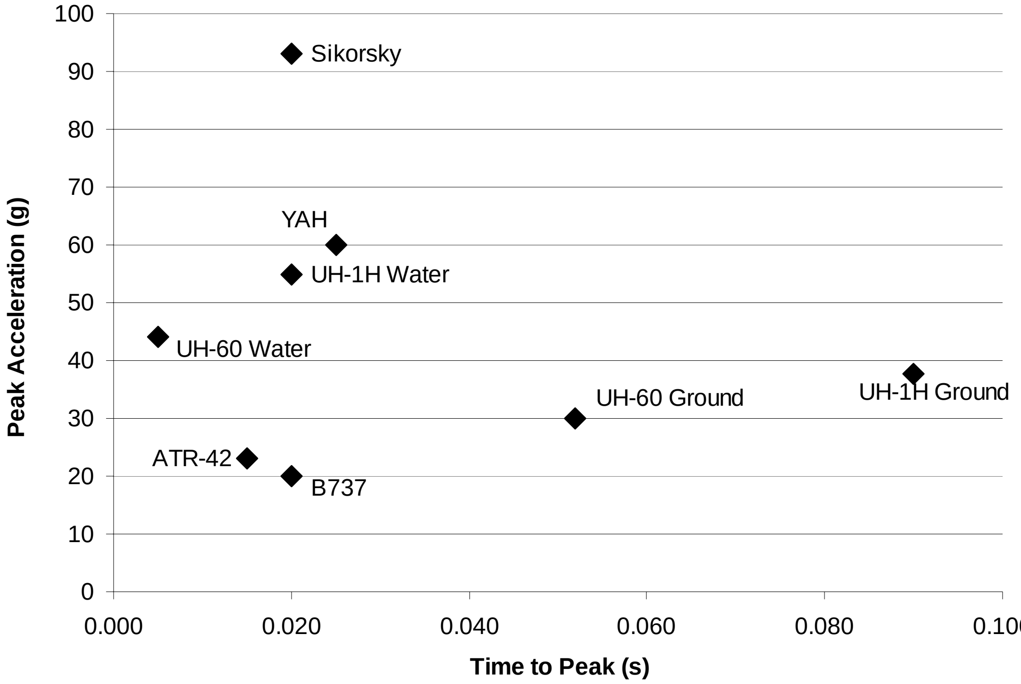


Figure 4-11. Transport Aircraft and Rotorcraft Impact Pulses, Vertical Peak Acceleration vs Time to Peak

Observations:

- Larger aircraft absorb and attenuate vertical acceleration due to crushing of the fuselage structure. The impact pulsed transferred to the seat have slower onset, lower peak accelerations, and longer total durations.
- Water impacts create extremely high acceleration onset rates.
- Landing gear and fuselage sections absorb and attenuate significant energy.
- High items of mass are important for rotorcraft, and can support accelerations on the order of 50 g peak for well designed rotorcraft.
- Rotorcraft provide more complete estimation of vertical survivability thresholds due to well developed vertical energy absorbing seats and associated research.
- Vertical EA seats in rotorcraft provide a basis for the maximum energy absorbed by the occupant at the design limits.
- Rotorcraft vertical design limits (for modern crashworthy rotorcraft) represent the state of the art in vertical impact survivability.

4.3 Aircraft System Model Calibration Based on YAH-63 Crash Test

The system model was constructed to take vertical aircraft input accelerations and absorb / transfer them into the seat model. The resulting loads were in turn absorbed or transferred through the occupant, spine and heart/aorta models. The option of including a crushable floor structure into the model was investigated. This option was abandoned in favour of applying the loads at the floor directly into the seat structure. Modelling the floor crush characteristics would have been unnecessarily complex. It was not needed because both the design requirements (Section 2.2.2) and the full scale crash tests (section 4.1, 4.2) provided floor acceleration versus time profiles at the seat track. The basic seat design was taken into account by creating appropriate seat energy absorber properties.

In order to determine if the complete system model was yielding reasonable estimation of the aircraft/seat load transfer, an evaluation was conducted by comparing the results with two full scale helicopter crash tests done at NASA Langley Impact Dynamics Research Laboratory. The objective of the evaluation was to confirm that the model was capable of providing characteristic results for the seat systems of interest. The response measures included acceleration versus time for the seat, pelvis and chest.

The first crash tests selected was the YAH-63 (Smith 1986). This crash tests was selected for to calibrate the system model because:

- The published data includes clear response data for the floor, seat, pelvis, and chest.
- The aircraft and seat are appropriate for comparison to the autopsy data obtained from the US Army.
- The seat deformation conforms to a known load/deflection specification (The seats have a large energy absorbing system which has been incorporated into the model).
- The impact was of the target severity and duration. The YAH-63 impact had a relatively long impact duration with significant floor accelerations at the floor near the seat spanning more than 100ms.

The published test data separated the longitudinal from the vertical components for the impact and responses. Only the vertical components were considered in this evaluation. The impact severities for both tests were severe enough to exceed the design criteria for modern military aircraft. They were near the limit, but within the survivable range for an energy absorbing pilot or co-pilot seat. These impacts would not have been survivable for an occupant seated in either a non-EA military seat or a typical civil aircraft seat. Both of the real-world crash tests used modern military EA seats (Desjardins 2004). The YAH-63 crash test used a modern AH-64 co-pilot seat with 0.312 m stroke and an activation threshold of 14.5 g for a 50% male aviator (Smith 1986). The Sikorsky pilot and co-pilot test seats had 0.368 m of stroke and a threshold of about 20 g for a 50 percentile male occupant (Jackson 2002). A basic EA stroking mechanism was created in the seats as described in section 3.3. The simulation stroking distances were set to correspond to the actual seat capability. Although this feature was set to represent the actual seat, note that seat model was not intended to represent a particular seat structure. Individual and local behaviour of the seat structures and cushions were not developed in the model. The simulations were filtered according to SAE CFC class 60 filter, which was similar to the filtering used in crash test data.

<u>YAH-63 Simulation Inputs</u>

The vertical impact component of the YAH-63 crash test (Smith 1986) had a peak of 68 g at 70 ms and a velocity change is 12.2 m/s. Figure 4-12 provides an image during the impact.

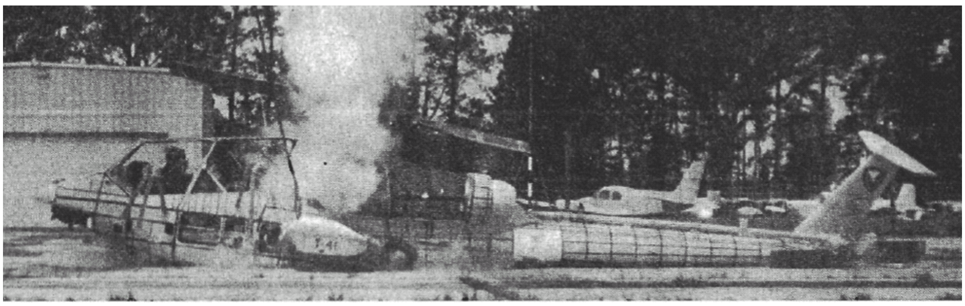


Figure 4-12. YAH-63 Crash Test (Smith 1986)

The vertical impact acceleration versus time data at the location of the cockpit seats was approximated to generate the input acceleration curve used for the simulation. The cockpit seat EA characteristics were also taken from Smith 1986 and the input parameters for the seat simulation were set accordingly. The co-pilot seat and ATD response from the crash test were selected for comparison, as the report contained the most clear data for this seat position. During the crash test the co-pilot seat “bottomed out”, using the entire available stroke and causing an acceleration spike in the seat and pelvis. The simulation inputs for the floor acceleration and seat vertical EA parameters are shown in Figure 4-13.

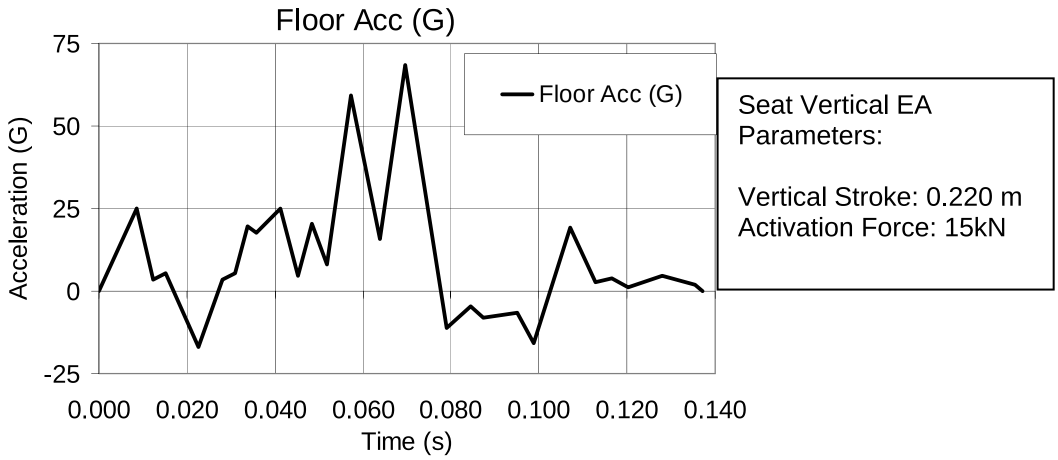


Figure 4-13. YAH-63 Simulation Floor Acceleration Input Curve and Seat Vertical EA Parameters

YAH-63 Simulation Response

The simulation produced a reasonable ATD response when compared to the measured seat acceleration and ATD pelvis acceleration reported for the YAH-63 crash test (Smith 1986). The Figure 4-14 compares the simulated co-pilot seat acceleration with that measured during the test. Figure 4-15 compares the simulated and measured co-pilot pelvis acceleration.

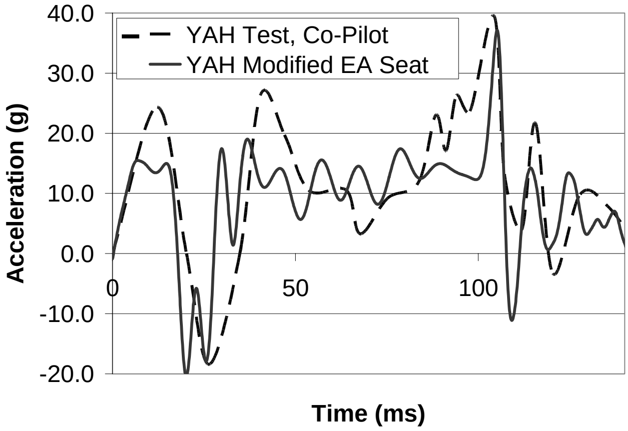


Figure 4-14. YAH-63 Experimental (Smith 1986) and Simulated Seat Response

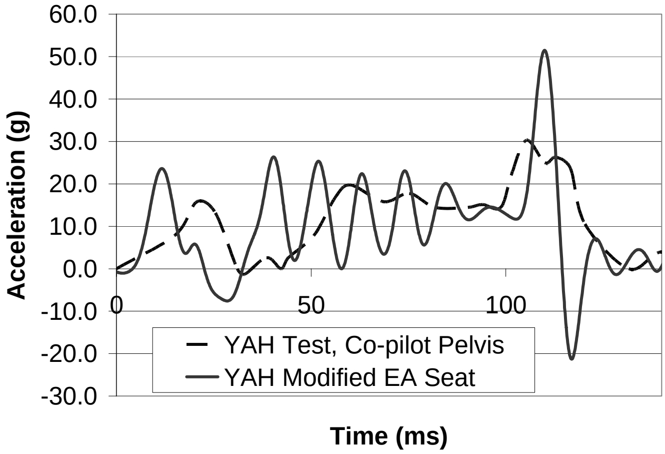


Figure 4-15. YAH-63 Experimental (Smith 1986) and Simulated Pelvis Response

The seat and pelvis curves generated by the simulation were determined to be reasonable for time base and magnitude, however the curves demonstrate variations in the curve shape. Higher frequency oscillations and overshoots occurred. These were attributed to the rigid body model's lack of local deformations, which is a typical artefact of this model type. The simulations were determined acceptable as they met the modelling objectives described in the modelling approach (section 3.1). Independent examples of this behaviour are provided in Figures 4-16 and 4-17. Measured and simulated response for thorax vertical accelerations were found exhibit similar curve fit.

First Technology LS-DYNA Model simulation and test of a Combined Downward/Forward Impact (test 1) as described in Fig. 2-21and Table 2-6

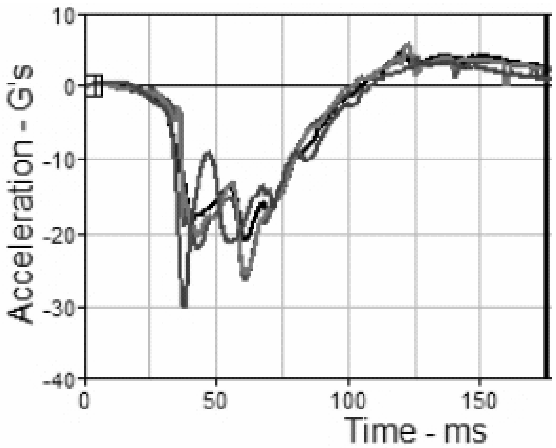


Figure 4-16. Independent Example of Rigid Body Model Response Compared to Measured ATD Response in Dynamic Impacts (Van De Velde 2008)

Altair Enginnering RADIOSS Model of a Forward Impact (test 2) as described in Fig. 2-21 and Table 2-6

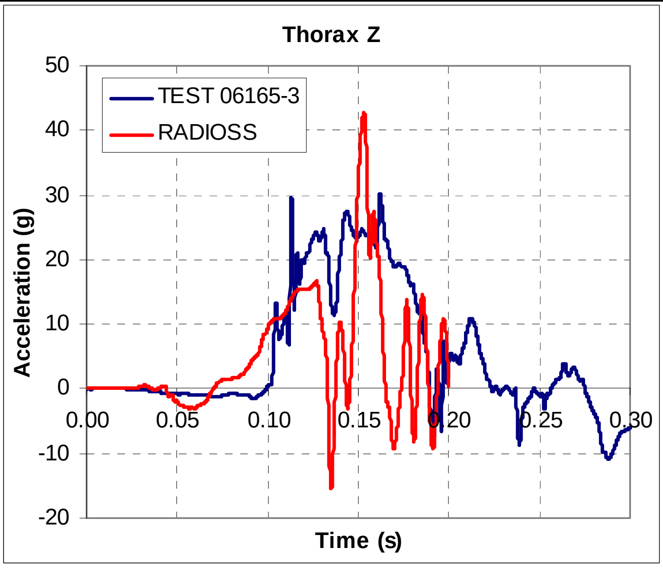


Figure 4-17. Independent Example of Rigid Body Model Response Compared to Measured ATD Response in Dynamic Impacts (Terrier 2008)

The examples shown in Figure 4-16 and 4-17 were taken from validation tests comparing numerical ATD response to physical ATD response using civil aircraft impact requirements. The numerical ATD validation effort is part of the SAE SEAT Committee, Analytical Working Group for Certification by Analysis.

Smith 1986 also reported a measured value for the Dynamic Response Index based on the seat pan acceleration. The peak magnitudes were compared as given in Table 4-3.

Table 4-3. YAH-63 DRI Comparison, Crash Test (Smith 1986) and Simulation

	DRI Test	DRI Simulated
YAH-63 Co-Pilot	26.9 g at 130 ms	30.3 g at 117 ms

The physical ATD did not contain a spine element corresponding to the Kelvin model specified for DRI as defined by Stech (1969). It therefore was unable to give a measure of DRI that is directly representative of DRI as measured by the simulated ATD. The crash test analysis estimated the DRI response based on the seat acceleration. Seat accelerations are commonly used due to the inability to measure the appropriate accelerations using the physical ATD. The values are similar as long as the appropriate model parameters are used. The simulation provided a reasonably accurate measure of DRI, and the simulation results correlated reasonably well with the crash test.

4.4 Aircraft System Model Calibration Based on Sikorsky ACAP Crash Test

Sikorsky ACAP Simulation Inputs

The Sikorsky ACAP crash test impact pulse was roughly triangular in shape with a peak of 93 g at 17 ms and a velocity change of 11.6 m/s (Jackson 2002). The input acceleration pulse and seat vertical EA parameters are provided in Figure 4-18.

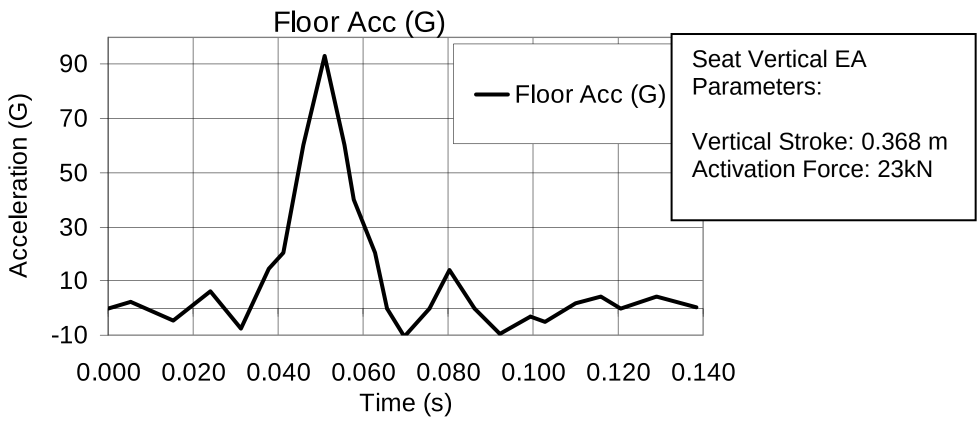


Figure 4-18. YAH-63 Simulation Floor Acceleration Input Curve and Seat Vertical EA Parameters

Sikorsky ACAP Simulation Response

Again the simulation produced reasonable response when compared to the measured seat accelerations and ATD pelvis and chest accelerations. This test report had clear measured values for the both the pilot and co-pilot seats, and thus both measured responses are given. The pilot and co-pilot seat configurations were equivalent. The same curve shape issue addressed in section 4.4.2 occurred. Figure 4-19 provides a comparison of the measured crash test and simulated seat response.

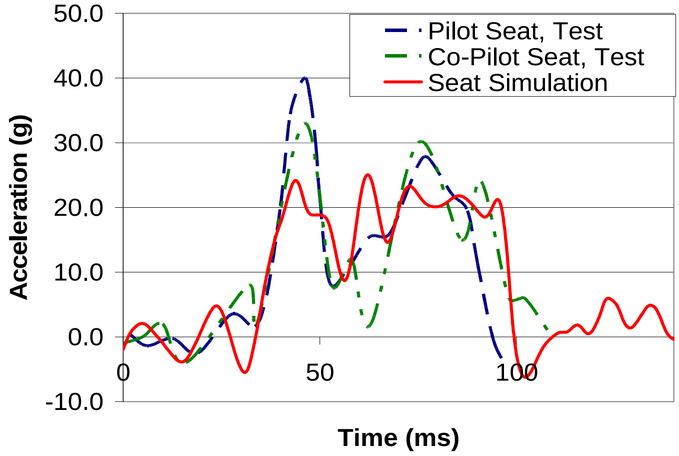


Figure 4-19. Sikorsky Experimental (Jackson 2002) and Simulated Seat Response

The aircraft seat energy absorber activates at forces which will maintain a load of about 20 g per military seat specifications (given a 50 percentile male occupant size). The real pilot and co-pilot test seats exhibited variation between each other and significantly overshot the target specification (20 g load limit). Some issues with binding of the seat mechanism were noted in the literature (Jackson 2002). The model seat responded much closer to the 20 g design point, as was to be expected with simulated (and therefore ideal) EA characteristics and load conditions. The pelvic response comparison for acceleration versus time is shown in Figure 4-20.

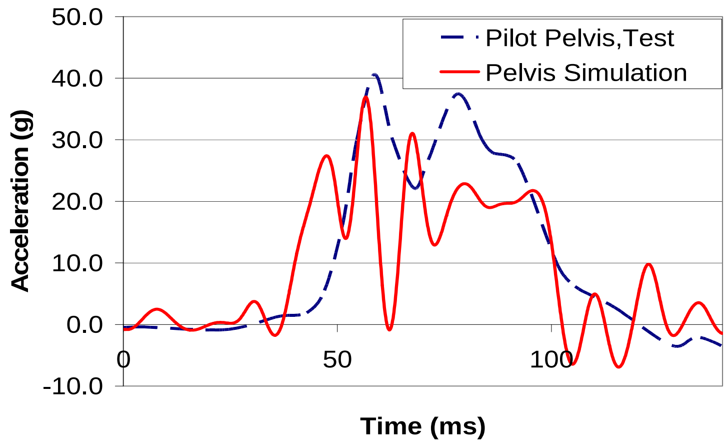


Figure 4-20. Sikorsky ACAP Experimental (Jackson 2002) and Simulated Pelvic Response

The thoracic acceleration versus time comparison is shown in Figure 4-21. Significant variation was evident between the pilot and co-pilot thorax acceleration responses. This was considered normal as the pilot and co-pilot seat positions were exposed to similar acceleration magnitudes, but with the normal variation occurring at different locations in the aircraft. Note that there was a difference in how the test measured thorax acceleration and how the simulation generated thorax acceleration. The test had accelerometers mounted to the sternum of both the pilot and co-pilot Hybrid II 50% male ATDs, and the thorax acceleration was measured at this point. Alternatively, the simulation generated the thorax acceleration via a selected a node on the rigid upper torso of the simulated Hybrid II 50% male ATD.

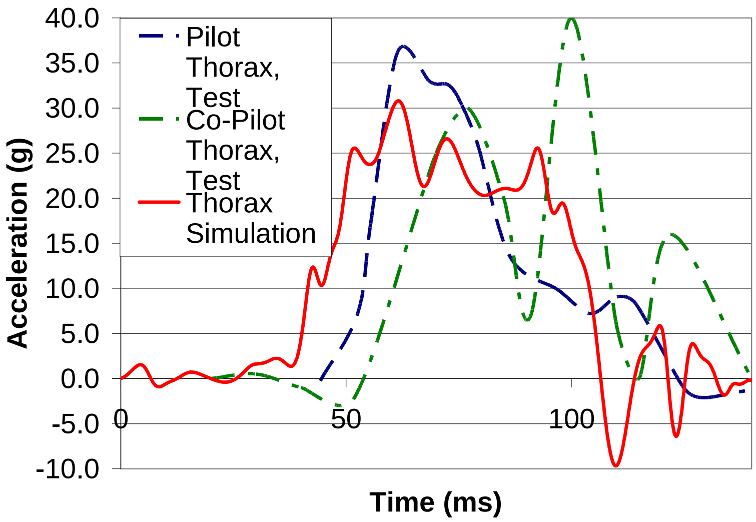


Figure 4-21. Experimental (Jackson 2002) and Simulated Thoracic Response

Table 4-4 provides a comparison of the measured and simulated DRI response for the Sikorsky ACAP crash test.

Table 4-4. Sikorsky ACAP DRI Comparison,
Crash Test (Jackson 2002) and Simulation

	DRI Test	DRI Simulated
Sikorsky Pilot	22.3 g at 69 ms	27.2 g at 62 ms
Sikorsky Co-Pilot	28.6 g at 72 ms	

The crash test DRI response was measured in a similar manner to that noted in the YAH-63 test, and used seat acceleration rather than the spine model defined by Stech (1969). The simulation provided a reasonably accurate measure of DRI.

4.5 Heart and Aorta Model Calibration to Human Experiments

The best validation case found for establishing displacement of the heart was a series of low severity human impact tests performed in the 1960's at the U.S. Air Force Research Laboratory (AFRL). (Weiss 1967) The input pulse of the experiment is shown in Figure 4-22. The impulse was a non-injurious impact applied to seat of human volunteer. The Impulse duration was shorter than natural frequency of organ system, therefore the system was not driven by the impulse, and low severity impulse was used to establish system response for extrapolation to injurious pulses of short duration.

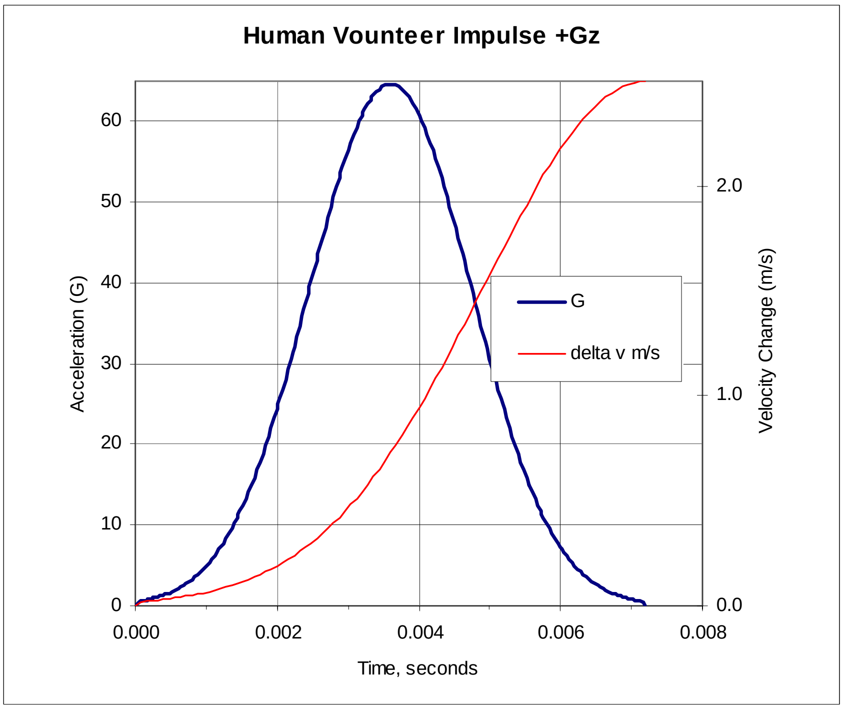


Figure 4-22. Input Pulse for Heart Displacement Human Experiment (Weiss 1967)

The human response was measured using radiographs taken at 17 ms intervals, (60 Hz). The experiment included the subjects with tensed and relaxed muscles, producing two response curves. The heart and aorta model was calibrated with the objective to fall in the middle of these two responses.

A significant limitation of the experiment was the high speed resolution of the x-ray imaging machine. It was insufficient to discern individual organs, and thus the response curves provided in the literature were confounded with other organs. The model is thus unable to accurately represent the heart alone. The literature study was unable to identify sources for the motion of the heart alone. The heart mass was thus assigned the value of 2.6 kg, based on published upper torso muscle/organ data with moments of inertia adjusted accordingly. This value for the “heart” mass was able to achieve the initial displacement reported in the experiment. It was recognized that the model in this form does not represent an accurate measure of the heart alone, and the results were generalizations of the viscoelastic organ response. Figure 4-23 illustrates the experimental response published in literature (Weiss 1967) compared to the simulated response of the heart and aorta model. The peak values and oscillation frequency for the Weiss experimental values are noted in Table 4-5.

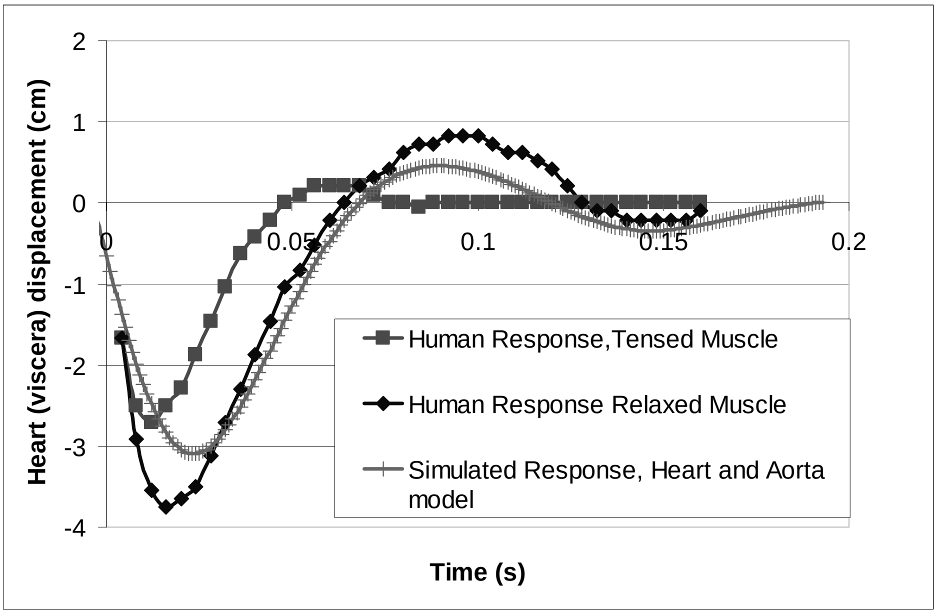


Figure 4-23. Heart Displacement Response, Experimental (Weiss 1967) and Simulated

Table 4-5. Critical Values from Experimental Heart Response (Weiss 1967)

Response	Frequency	First Peak	Second Peak
Human, Tensed	19.6 Hz	-2.7 cm at 27 ms*	0.2 cm at 78 ms
Human, Relaxed	13.5 Hz	-3.7 cm at 31 ms*	0.8 cm at 110 ms

The system model calibrations resulted in reasonable estimation of the impact loads as they transfer from the floor through the seat, then through the body and spine, and ultimately in to the heart and aorta system model. Completion of the system model as a whole created a tool capable of evaluating various aircraft impacts and measuring the dynamic response.

5. ACCIDENT STUDY METHODOLOGY

Research of available aircraft accident data provided critical information to the thesis. This chapter explains the methodology used to generate the information that was needed to understand the model simulations and put them in context of survivability limits.

Sufficient information regarding HAI in the aircraft crash environment was not found during the literature survey. The relationship between the vehicle impact vector and injury patterns was poorly represented. Specific information about HAI injury as a function of the impact vector was non-existent. The accident study was created to meet the following objectives:

a) Collect and evaluate citations of injury related to the vehicle impact vector in published aircraft accident studies.

b) Collect and evaluate injury statistics from small aircraft to develop a general understanding this aircraft environment.

c) Conduct original research of available aircraft accident databases containing both injury and vehicle impact data. Then narrow down this information to resolve questions specific to HAI injury from accelerative factors.

The work to complete the above objectives came from two sources. The methods for achieving these objectives are presented in Section 5.1: Published Accident Studies, and Section 5.2: Database Research.

5.1 Published Accident Studies

The method for evaluating published accident studies consisted of extracting and evaluating all information about injuries related to the vehicle impact accelerations found in the sources identified during the Literature Survey.

<u>GA Aircraft</u>

Small aircraft accident investigation reports did not have good survival factors information available because the accidents and the investigations were small scale events. The investigations were focused on causal factors and rarely go to the detail required for the purposes of this research. Autopsy surveys and other published literature addressing the survivability of GA accidents provided injury distributions and limited data regarding the impact severity. A four part NTSB study that was focused on GA survivability (NTSB1980b, NTSB 1983, NTSB 1985a, NTSB 1985b) also provided data on a case by case basis. This study was done to support regulatory changes for aircraft interiors and includes some limited discussion of HAI.

Transport, Rotorcraft and Military Aircraft

Large transport aircraft accident reports and studies were included in this research because the large scale of these events allows for more detailed survival factors investigations. NTSB survival factors reports for severe but survivable accident were obtained by making a request to the NTSB. The reports were reviewed to identify citations relevant to HAI injury. Other published studies of transport aircraft survivability were reviewed for relevant information. Survivability studies published for military aircraft were reviewed for citations of HAI. The US Army was found to conduct the majority of research on vertical aircraft impacts. The US Army also maintains the only database found to have a significant quantity of accident fatality and survivor injury listings that are also related to aircraft impact data. This prompted the database research at the US Army.

5.2 Database Research Methodology

Inquiries to obtain data from GA accidents were presented to Air Accidents Investigation Branch (AAIB) of the United Kingdom, the US NTSB, and the US FAA. Information was not available from the AAIB or NTSB (other than that published in reports), and very limited information was available from the FAA. The FAA information was provided by the FAA Civil Aeromedical Institute (CAMI). Insufficient civil aircraft accident data was available to meet the research objectives. A military source was found with the unique combination of a large population of accidents documented with both vehicle impact information and injury and autopsy records. The source was the United States Army Aviation Research Laboratory (USAARL) at Fort Rucker Alabama. A Cooperative Research and Development Agreement (CRDA) was established with the US Army to gain access to this database.

Method for Evaluating the FAA CAMI Database

The FAA Communication Center in Washington DC maintains records containing a variety of information of all GA incidents and accidents. Very basic data is published each weekday on the FAA website at: http://www.faa.gov/data_statistics/accident_incident/preliminary_data/. This is the primary source for tracking events as they occur, although the data is very limited. An example of a typical accident listing is provided in Figure 5-1. Europe did not have a source for tracking GA accidents that was available outside of government accident investigation agencies. Soon after the FAA data is published to the website, it is classified as either an incident (minor aircraft damage and no injury), or an accident (substantial aircraft damage or injury/fatality). Accident reports are published by the NTSB. Appendix D contains accident reports for those used in the research.

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**********************************************************************
**   Report created 12/29/2006   Record 1
**********************************************************************
IDENTIFICATION
  Regis#: 457S       Make/Model: SR22      Description: SR-22
  Date: 12/18/2006     Time: 0000
  Event Type: Accident   Highest Injury: Fatal     Mid Air: N    Missing: N
  Damage: Destroyed
LOCATION
  City: PAYSON   State: AZ   Country: US
DESCRIPTION  ACFT CRASHED UNDER UNKNOWN CIRCUMSTANCES,
SUBJECT OF AN ALERT NOTICE, THE ONE PERSON ON BOARD WAS
FATALLY INJURED, WRECKAGE LOCATED AT A REMOTE AREA 4500 FT
ON THE FORT APACHE INDIAN RESERVATION EAST OF PAYSON, AZ

INJURY DATA      Total Fatal:   1
             # Crew:   1     Fat:   1     Ser:   0     Min:   0     Unk:
             # Pass:   0     Fat:   0     Ser:   0     Min:   0     Unk:
             # Grnd:         Fat:   0     Ser:   0     Min:   0     Unk:
WEATHER: NOT REPORTED
OTHER DATA
  Activity: Pleasure      Phase: Unknown      Operation: OTHER
  Departed: WINSLOW, AZ               Dep Date:    Dep. Time:
  Destination: HENDERSON, NV          Flt Plan:           Wx Briefing:
  Last Radio Cont:
  Last Clearance:
  FAA FSDO: SCOTTSDALE, AZ  (WP07)             Entry date: 12/26/2006
```

Figure 5-1. Example Preliminary FAA Incident Report published on http://www.faa.gov/data_statistics/accident_incident/preliminary_data/

The website accessible NTSB data did not include detailed GA accident records. The detailed records, such as autopsy reports, were not found in a searchable database for extracting specific information such as injury listings. Records are managed by the FAA Civil Aeromedical Institute (CAMI) in Oklahoma City OK. Requests of FAA

CAMI were able to produce a small number of accident records with HAI. These records were located manually and do not represent a comprehensive or formally organized search. No information about the number of records held or related data was made available. A control group of accident without HAI was also not available. The records were reviewed and compared with the GA studies published by the NTSB.

5.2.1 Methodology for Evaluating All Injury Types from the USAARL Database

A total of seven formal inquiries were made of the US Army Combat Readiness Center database at Ft. Rucker Alabama spanning a timeframe November 2005 to March 2007. The complete accident files were also reviewed in person on three separate visits to Fort Rucker Alabama USA. Security measures required viewing the files in the presence of a US Army representative, and only hand notes with no photocopies were allowed. The USAARL provided Dr. Parrish Balcena to assist in evaluating the accident files. An example of the key information contained in a requested is:

- All accidents are requested for calendar years 1983 to 2005 that have at least one impact vector with a recorded value above 20 g. (Specifying the minimum acceleration screens out minor accidents.)
- All data fields are requested that relate to the accident description, occupant duty, occupant injuries, aircraft flight, aircraft impact.

The inquiries produce a Microsoft Excel workbook containing data fields that corresponded to various aspects of the accident and occupants as shown in Tables 5-1 through 5-4.

Table 5-1. Data Fields Generated for Accident and Occupant Duty

CASE_ NUMBER	ACCIDENT_ DESCRIPTION	ARMY_ CLASS	AGE	GENDER	DUTY	AT_ CONTROLS	PERSONNEL _CLASS

All occupant identification information such as names or social security numbers was removed prior to release.

Table 5-2. Data Fields Generated for Occupant Injuries

SEVERITY _OF_ INJURY	CAUSE_ OF_DEATH	BODY _PART	BODY_ ASPECT _PRI	BODY_ ASPECT _SEC	INJURY _TYPE	MECH_ ACTION	MECH_ QUAL

CAUSE_ SUBJECT	CAUSE_ ACTION	CAUSE _QUAL	SURVIVABLILTY _DESC

Table 5-3. Data Fields Generated for Aircraft Flight (Pre-Impact)

AIRCRAFT _NUMBER	AIRSPEED	VERTICAL _SPEED	VERTICAL _SPEED_ DIRECTION	FLIGHT _PATH_ DEGREE	FLIGHT _PATH_ DIRECTION	PITCH_ ANGLE

PITCH_ DIRECTION	ROLL_ ANGLE	ROLL_ DIRECTION	ROLL_ DEGREE	ROLL_ DIRECTION	YAW_ DEGREE	LATERAL_ DIRECTION

Table 5-4. Data Fields Generated for Aircraft Impact

LATERAL _G	LONGITUDINAL _AREA	LONGITUDINAL _G	VERTICAL_ DIRECTION	VERTICAL _G	PITCH_ DIRECTION	PITCH_ DEGREE	YAW_ DIRECTION

Impact forces were recorded as estimated by the accident investigator and were in units of the gravitational constant, G. The forces were recorded as they act on the aircraft, which was opposite of how they act on the occupant. For example, a large $+g_z$ (floor to ceiling) force on the aircraft will displace internal organs downward in the occupant. Figure 5-2 provides the coordinate axes for the force directions on the occupant and are consistent with most crashworthy literature (Hurley 2002, Colman 1989).

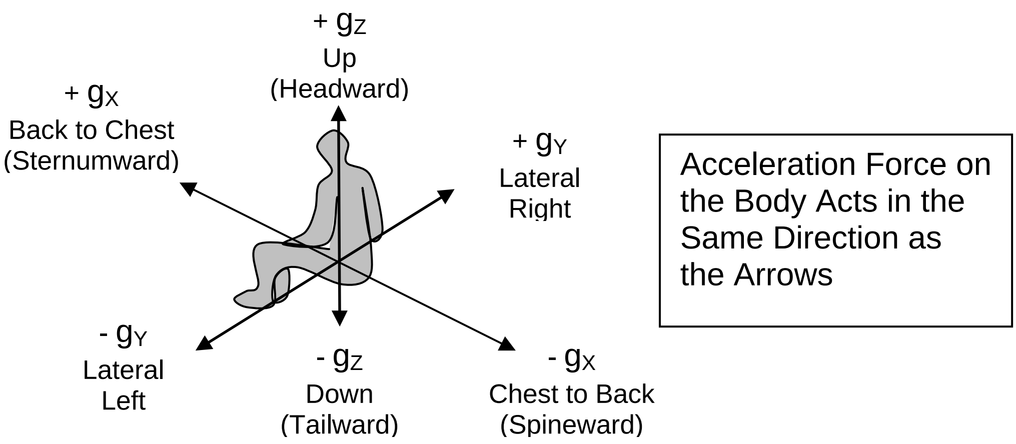

Figure 5-2. Occupant Force Directions

Figure 5-3 provides a representation of the crash force vectors. These are consistent with most crashworthy literature (Hurley 2002, Coltman 1989).

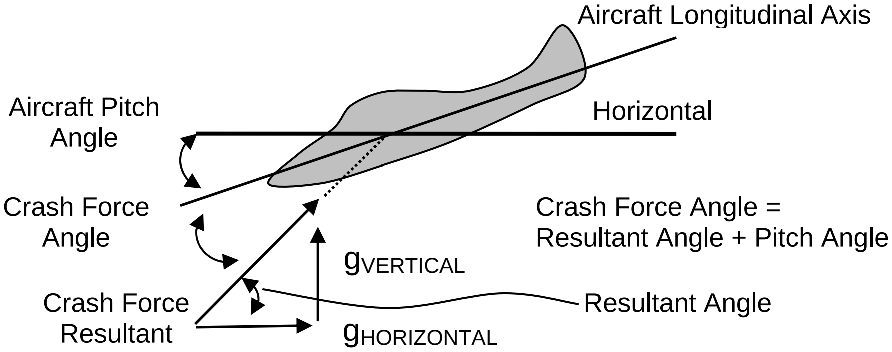

Figure 5-3. Aircraft Crash Vectors

The study was reviewed by the Human Use Committee at the US Army Aeromedical Research Laboratory, and was deemed exempt, as it was a database review with all personal identifying information removed.

The study of all injury types provided a general context in which to evaluate the HAI injuries. This study first evaluated the aircraft impacts, then evaluated the injury distributions, and last compared the impact and injury results. The inclusion criterion was all non-combat US Army aviation accidents from the US Army database. The exclusion criteria were accidents outside the date range 1983-2006; cases with no injury data reported; accidents with acceleration components (longitudinal and vertical and lateral) 20 g and lower.

Methods for Aircraft Impact Evaluation

The impact assessment evaluated the primary crash impact according to the six component directions to determine if any appeared prominent. The impact vectors consisted of peak acceleration estimates, reported by the accident investigator in units of g, for each of the six directions: Left / Right; Fore / Aft; Up / Down. The evaluation attempted to characterize the impact vectors in three ways.

- *Frequency of Occurrence* (number of times an impact value was recorded)
- *Portion of Total Impact* (ratio of the component to resultant)
- *Impact Severity* (frequency of impacts occurring in various severity ranges)

Frequency of Occurrence

The impact acceleration field contained a value and direction, a zero, or was empty. The blank or zero fields were assumed to be a neutral orientation for that axis pair. In order to evaluate the frequency of the various impacts occurring, the number of citations were counted and expressed as a percentage for that axis pair. For example, the Forward / Aft impact direction contained impact values other than 0 for 140 of the 156 accidents. The 140 citations consisted of 86 in the Forward direction and 52 Aft. Thus the forward direction occurred in 51%, the Aft in 33%, and neutral 16%.

Portion of Total Impact

Breaking the impact down into components simplified the evaluations, but the interaction as a portion of the total was taken into account. The ratio of each component to the resultant impact value was observed. The impact resultant and component ratios were calculated as shown below.

- Resultant Impact for each Accident = $(\text{g Long.}^2 + \text{g Lateral}^2 + \text{g Vertical}^2)^{0.5}$
- Impact Ratio for each Direction of Each Accident = Component Value / Resultant

This generated a ratio value for each of the 156 accidents distributed among the 6 possible directions. In order to compare the impact directions, a summation of each was created according to the bottom, middle, or top third percentiles. For example, the Downward Impact direction was cited in 54 of the 156 accidents. Of these, 16 had a ratio in the bottom percentile, 4 in the middle, and 33 in the top. Because the top percentile had the most citations (61%), this suggested that most downward impacts were a large portion of the total.

Impact Severity

The frequency of impacts for a particular direction in a range of acceleration values was assessed. Four acceleration ranges have been used: 0 to 25 g; 26 to 50 g; 51 to 75 g; and Above 75 g. These ranges were selected to provide detail in the survivable range. An impact component above 75 g can generally be assumed non-survivable. The number of impact citations in each range for each impact direction were counted and then expressed as a percentage of the total non-zero values for that direction. The evaluation was conducted with a population of 156 total aircraft accidents.

Method for Injury Distribution Evaluation

A case was defined as an occupant with injuries listed for each of the 156 accidents with 606 occupant cases. Each occupant case consisted of a list describing the injured body part(s). The evaluation placed the listings in groups according to body region and body part. The limitations of the occupant injury evaluation were:

- Not all occupants were accounted for in each accident.
- No consistent protocol was used for the injury listings in the database, thus some cases only severe injuries may have been listed while others may have had a more compete listing.
- Some injury listings were specific (T1 vertebra), others were general (thoracic vertebra). Indeterminate listings such as "general body", or "vertebra" (unknown if cervical, thoracic, or lumbar) were eliminated.
- Occupant location in the aircraft, seating configuration, or restraint type were not taken into account.

5.2.2 Methodology for the Study of HAI

This study examined aircraft impact characteristics and the incidence of cardiac/aortic injury in US Army aircraft accidents. It was also a start in addressing the importance of aortic injury within survivable aircraft mishaps and to differentiate cockpit/environmental versus inertial aetiologies. The process of data collection, format of data received, and occupant and aircraft sign conventions all remained the same as described for the Evaluation of All Injury Types in Section 5.2.1.

Database inquiries first identified all HAI accidents from 1975 through 2005. However the individual files from 1977 to 1982 (n=10) were unavailable, and subsequently the evaluation period was abbreviated to the calendar years 1983 to 2005. Critical data included pre-impact flight conditions, estimated impact forces and occupant injury data. The reported values were based on data from various sources including: mission data, accident investigator estimates, scene photos, aircraft and equipment descriptions, and survival factors analysis. The crash force (impact g) values were reported for each coordinate axis, but calculations and rationale for the values were not available. Pre-impact flight data was reported less frequently than the crash force data and occupant data was reported sporadically.

The study objective was to determine if inertial factors were a predominant injury mechanism using impact severity as a surrogate for the force required to produce a HAI. Two separate issues were addressed: 1) accident severity, comparing measures of impact severity for those accidents with and without HAI injuries; and 2) cardiac/aortic injury, evaluating occupants with and without HAI injuries. The first issue defined HAI relative to the survivability envelope and the second determined if inertial injury mechanisms were significant within this envelope.

Method for Accident Severity Evaluation

The accident severity evaluation defined a case as a single aircraft accident. Incidents with multiple aircraft were treated individually. Inclusion for this evaluation was all aircraft accidents in the database for the years 1983 to 2005. The exclusion criteria were accidents having all impact axes (g_x, g_y and g_z) reported less than 20 g. A 20 g impact was hypothesized to be the lower limit of HAI injury occurrence; this impact level was the approximate activation threshold for an energy-absorbing seat and aircraft sustaining less than a 20 g impact was unlikely to have occupants with severe injury. A single HAI case of less than 20 g (occupant thrown from cockpit and into a tree prior to impact) provided face validity among this population. Note that the exclusion criteria changed slightly from the study of all injuries described in section 5.2.1. The previously described study excluded impacts of 20 g and below for all directions, while this study excluded impacts 19 g and below for all directions. This change was made because several accidents sustaining HAI occurred at this impact level. Including them increased the study population and the control group.

The crash force and pre-impact vertical velocity were compared between HAI cases and controls. The control group was defined as all aviation accidents with an impact greater than 20 g in any axis without an occupant who sustained HAI. The study included calculation of the net crash force resultant as previously described. The pre-impact vertical velocity was calculated by adding the vertical speed (sink rate) to the vertical component of the airspeed, based on the flight path angle.

Frequency and the probability distributions were generated for the impact force and pre-impact vertical velocity. The frequency distributions and population curves were used to visualize characteristic HAI cases versus the control. Statistical analysis for significance used a two-tailed t-test with an alpha value of 0.05.

Method for Heart and Aortic Injury Evaluation

The second evaluation identified and included all occupants involved in HAI accidents from 1983 to 2005, derived from cases included in the Accident Severity study. Exclusion criteria: those occupants for which data was insufficient or not reported; occupants in accidents with a predominant upside-down ($+g_z$ on occupant) impact vector (potential confounder), and those with exclusive cockpit / environmental aetiology. For example, if the occupant space had been intruded by a rotor blade penetration causing aortic injury, it was determined that cockpit / environmental factors were the likely causative agents. This evaluation defined cases as occupants with HAI and controls as occupants without HAI.

6. MODEL RESULTS

This chapter provides the results of evaluations conducted using the complete system model, which combined the heart and aorta model described in section 3.5 and the ATD and aircraft system models (section 3.3 and 3.4 respectively). The complete model provided the means to evaluate the transfer of aircraft impact force and energy through the seat, occupant, and into the heart and aorta model. The response, although not an accurate simulation of the actual organ motion, was used to gauge comparative levels of stress on the viscoelastic soft tissue. These results were compared to limits of survivability and soft tissue injury potential, which supported the research conclusions. This chapter was organized by first describing the selection of the inputs for the system model evaluation (Section 6.1). Section 6.2 through 6.7 provided the results for each of 6 impact evaluations. The last section (6.8) compared the results for the 6 impact cases.

6.1 Impact Pulse and Seat Selection for Model Evaluations

Aircraft crash tests and design specifications for all types of aircraft including GA, large transports, and various helicopters were identified in chapter 4. These created a population of 28 crash impacts as shown in Table 6-1. The table also included critical parameters useful for comparing relative impact severity, listed in order from lowest to highest onset of acceleration (slope of the impact pulse defined as the ratio of the peak acceleration to the time at the peak). Figure 6-1 graphically depicts the 28 impacts by plotting the peak acceleration versus the time to peak. Six impact pulses were selected to represent the range of impacts. The six are highlighted/bold in the table and are shown as large squares on the plot. Also included on the plot are regions of injury potential according to the Eiband injury tolerance curve (USDOD 1998 pg 30) for vertical vehicle acceleration. These regions were general approximations based on uniform accelerations given a square impact pulse. Actual injury potential is dependent on many factors related to the vehicle design.

Table 6-1. Aircraft Impacts Identified in Chapter 4.

	Impact	Slope* (g/s)	time to Peak (s)	Peak (g)	Delta V (m/s)
1	Transport FWD/DWN	88	0.090	8.0	5.4
2	Low Wing +10 Pitch	280	0.050	14.0	12.2
3	**GA FWD/DWN**	**329**	**0.050**	**16.4**	**8.2**
4	PA-31	329	0.050	16.5	8.2
5	UH-1H Ground	420	0.090	37.8	12.2
6	OH58 FWD/DWN	483	0.031	15.0	4.6
7	Commercial Rotorcraft FWD/DWN	483	0.031	15.0	4.5
8	Low Wing Composite GA	500	0.030	15.0	10.0
9	UH-60 Ground	580	0.052	30.0	9.1
10	**UH-60 FWD/DWN**	**581**	**0.043**	**25.0**	**7.6**
11	High Wing Nose Down Concrete	600	0.030	18.0	10.5
12	Pitch Angle +15	667	0.030	20.0	7.5
13	High Wing Roll Impact	781	0.032	25.0	9.7
14	**Military Airbag Threshold**	**1,000**	**0.012**	**12.0**	**3.5**
15	B737	1,000	0.020	20.0	9.1
16	Low Wing -30 Pitch	1,057	0.035	37.0	12.7
17	**UH-60 Down**	**1,388**	**0.036**	**50.0**	**12.8**
18	ATR-42	1,533	0.015	23.0	9.1
19	Pitch Angle 0	1,563	0.032	50.0	7.5
20	High Wing Nose Down Soil	1,600	0.030	48.00	29.4
21	Pitch Angle -15	1,600	0.050	80.0	7.5
22	Twin GA 13m/s	2,154	0.013	28.0	3.8
23	Twin GA 27m/s	2,388	0.018	43.0	7.4
24	**YAH**	**2,400**	**0.025**	**60.0**	**12.2**
25	UH-1H Water	2,750	0.020	55.0	7.9
26	Starship	3,360	0.025	84.5	8.8
27	**Sikorsky**	**4,650**	**0.020**	**93.0**	**11.6**
28	UH-60 Water	8,800	0.005	44.0	9.1

* Slope is defined as the ratio of peak acceleration to the time at peak acceleration.

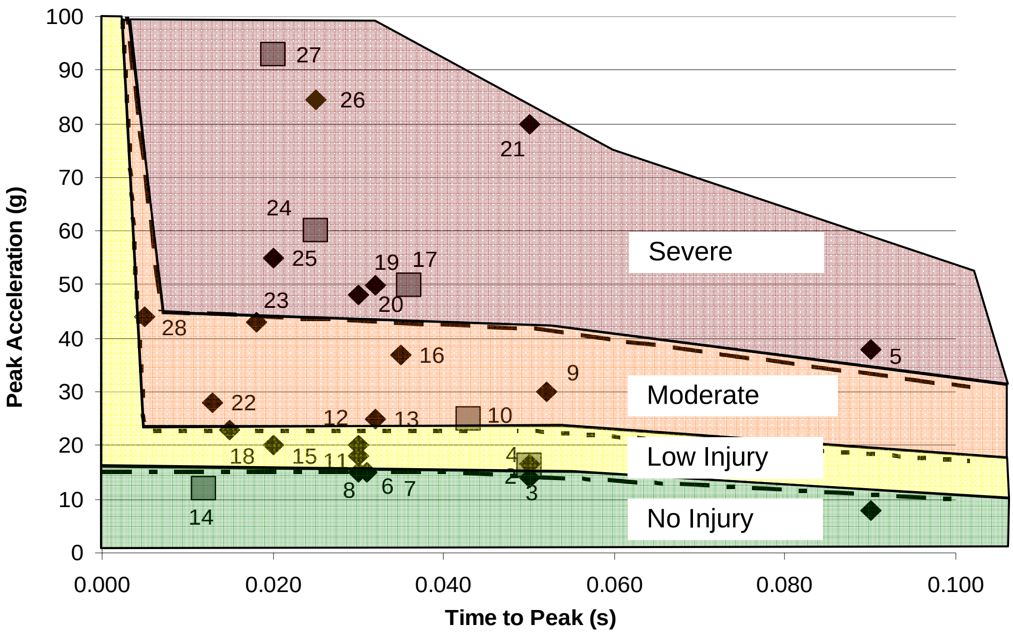

Figure 6-1. Impacts from Table 6-1
with Eiband Regions of Injury Potential (USDOD 1998)

The six impacts for the model evaluation were selected to represent each region of impact severity shown in Figure 6-1. The crash pulses (impact acceleration time histories from the aircraft design requirements (Literature Survey Chapter 2) and the impact characterizations of chapter 4 were evaluated to create groupings according to design standards and common measures of impact severity. No standard exists for impact severity as different factors are critical for different situations. The acceleration slope, peak acceleration, and velocity change were considered. Two impacts were selected for the moderate and severe injury regions in order to account for peak acceleration and velocity change as potential significant factors. The selected impacts fell into the following regions.

No Injury Potential

Mil. Airbag Threshold (USDOD 1998):

The airbag pulse was clearly not an injury threat, but has a fairly high acceleration slope. Viscoelastic tissue is rate sensitive. This impact provided an opportunity to evaluate the significance of onset rate independent of other potentially serious impact factors.

Low Injury Potential

GA Fwd/Dwn (USCFR):

The GA pulse was the design standard for commercial aircraft, and has been widely evaluated, providing a valuable baseline for comparisons. This standard represented the upper design limit for GA seats. The design limits for crash worthy military seats were much higher.

Moderate Injury Potential

UH-60 Fwd/Dwn and UH-60 Down (USDOD 1998):

These impacts were design standards for military seats, and are near the limit of survivability for a commercial GA seat design. Similar to the GA standard, these pulses have been widely evaluated, providing a good indication of the survivability for comparison to the HAI response.

Severe Injury Potential

UH-60 Down (USDOD 1998), YAH-63 (Smith 1986) and Sikorsky (Jackson 2002):

The UH-60 Down impact had the most severe velocity change, but significantly lower peak acceleration and slope than the others. As the most severe military design standard, it was a good comparison point for survivability. The YAH-63 and Sikorsky tests had good response data for the aircraft, seat, and ATD and used well characterized military stroking EA seats. These impacts had much higher peak acceleration but lower velocity change than the UH-60 Down impact. The YAH-63 impact was survivable but very severe, while the Sikorsky impact was at the top limit of survivability, even for state of the art crashworthy equipment.

6.2 Military Airbag Threshold Impact Evaluation Results

The military airbag threshold crash impact (USACIS 2001) was the lowest severity pulse selected and represented the lower boundary for minor injury potential.

Model Input:

The Military Airbag Threshold impact pulse had a peak acceleration of only 12 g with a velocity change of 3.5 m/s, but a moderate acceleration slope (1000 g/s). The peak acceleration was insufficient to activate the EA stroking mechanism for either the GA or military seat.

Model Response – Seat and Spine:

Because the seat stroking mechanisms were not activated, the responses were essentially identical for the GA or military seat types. Figure 6-2 provides the seat acceleration and the Dynamic Response Index (DRI) for the military airbag threshold impact evaluation.

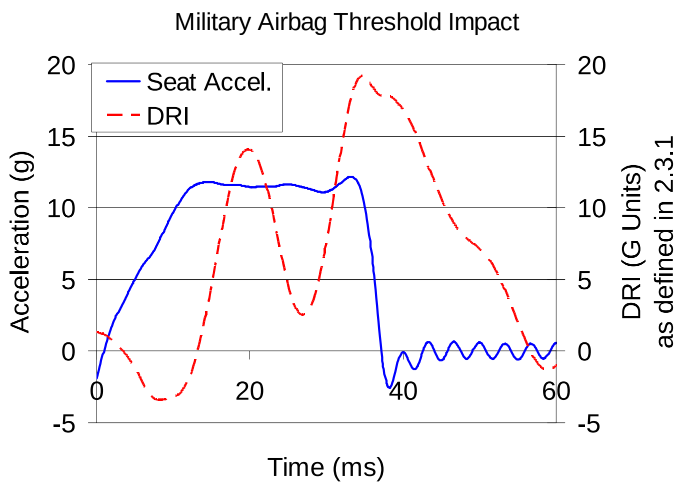

Figure 6-2 Acceleration and DRI for Military Airbag Threshold Impact

The pelvic acceleration is not shown, as it is very similar to the DRI curve. DRI measured the potential for spine injury, with a design limit of 20 G units, which the calculated response approached.

Model Response – Heart and Aorta:

Figure 6-3 provides the calculated HAI model response. The downward displacement of the heart of 39 mm established a point known to be well below the potential for injury. This impact level was not injurious.

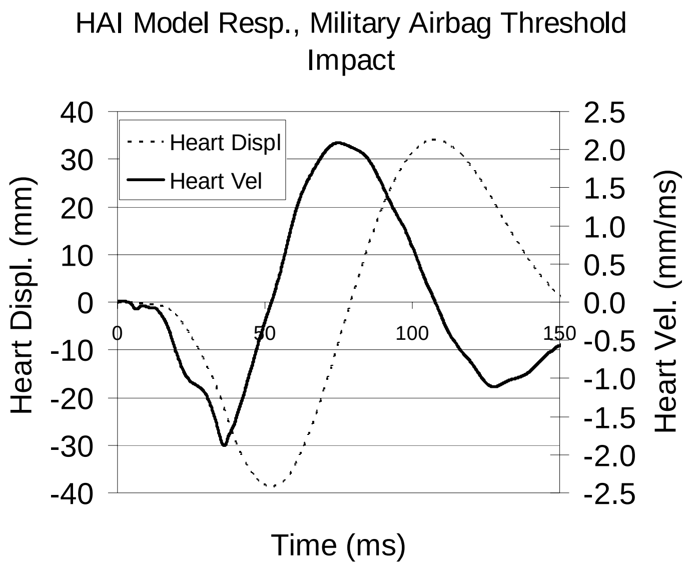

Figure 6-3 HAI Model Response for Military Airbag Threshold Impact

The velocity of 1.9 m/s was also below the range indicated for viscous injury (Coltman 1989, page 52). The HAI model represented the general response of the thoracic viscera and was based on experiments measuring the downward displacement (Section 4.6). Rebound of the heart was not characterized in the calibrations and thus the rebound response of the simulations was not considered. Only the downward displacement and velocity during the first downward cycle were used in the evaluations.

6.3 GA Forward/Down Impact Evaluation Results

The GA Forward/Down impact is the seat design limit for commercial GA aircraft.

Model Input:

The impact reached a peak acceleration of 16.4 g. This was just above the stroking threshold of the GA seat, but below the stroking threshold of the military seat. The velocity change was 8.2 m/s. This impact has a low potential for injury.

Model Response – Seat and Spine:

The GA seat stroking mechanism was activated, and thus the calculated response indicated a small degree of load mitigation. The impact was insufficient to stroke the military seat, and thus the response nearly replicated the input acceleration. The calculated DRI value for the GA seat was 15 G units, while the military seat was 16 G units. Figure 6-4 illustrates the seat accelerations and DRI curves for the GA Forward/Down impact case.

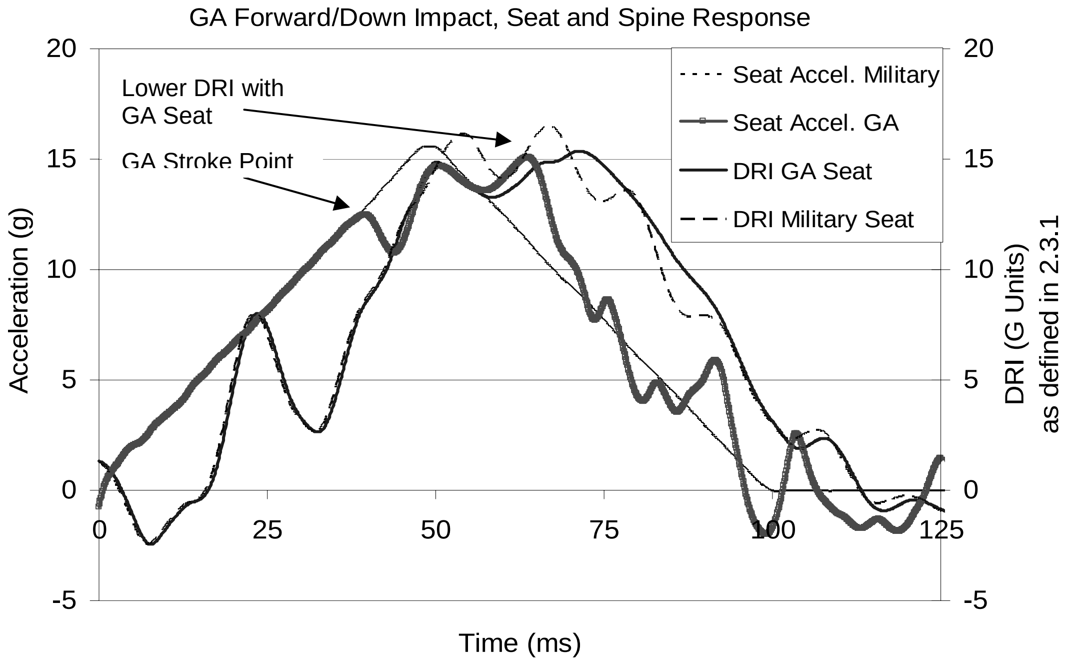

Figure 6-4. Seat Accelerations and DRI GA Fwd/Dwn Impact

Model Response – Heart and Aorta:

The minor force mitigation with the GA seat did not result in a significant reduction in the calculated heart displacement or velocity. The GA and military displacements were 55 and 56 mm, velocities were both 1.6 m/s. The heart displacement and velocity response were similar between the GA and military seat types, and the curves are contained in Appendix C.

6.4 UH-60 Forward/Down Impact

The UH-60 Forward/Down impact was severe enough to see a significant difference between the GA and military seats because the stroking mechanism activated for both types.

Model Input:

Impact pulse had a peak acceleration of 25 g and a velocity change of 7.6 m/s. Although the impact energy was less than the GA Forward/Down case, the higher peak acceleration (25 vs 16.4 g) and the higher slope (581 vs. 329 g/s) were responsible for the increased severity and activation of the stroking mechanisms.

<u>Model Response – Seat and Spine:</u>

The calculated seat accelerations ramped up to their respective limit values and remained at roughly those values throughout the impact (GA~15 g and military ~20 g). The lack of a seat acceleration spike at the end of the stroke indicated that the Energy Absorbing (EA) capability of the seat was sufficient to mitigate the impact loads. The calculated DRI response corroborated this, with values remaining near the design limits. The DRI for the GA seat reached 18 G units and the military 23 G units. Figures 6-5 and 6-6 provide the seat acceleration and DRI responses for each seat type.

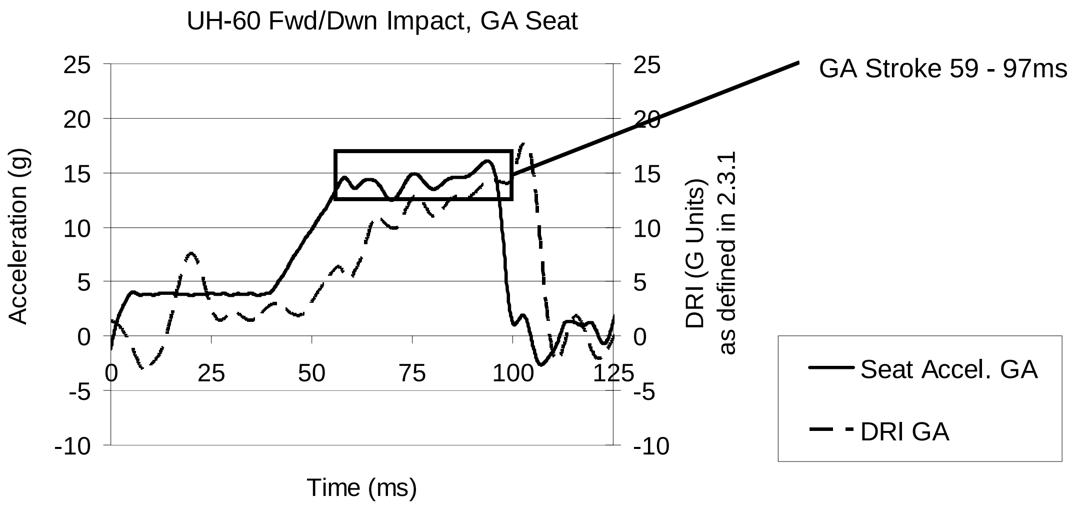

Figure 6-5. GA Seat Accelerations and DRI for UH-60 Fwd/Dwn Impact

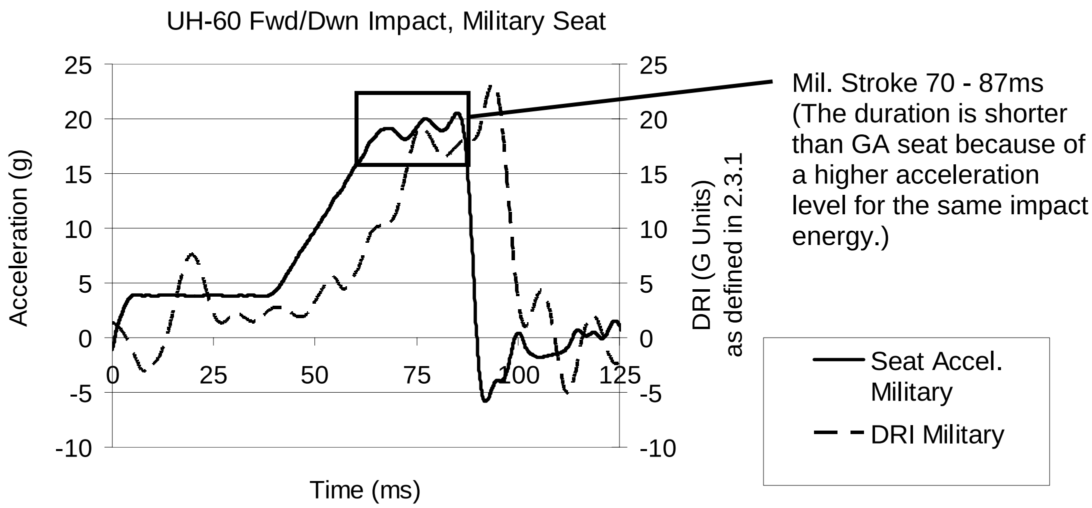

Figure 6-6. Military Seat Accelerations and DRI for UH-60 Fwd/Dwn Impact

Model Response – Heart and Aorta:

The HAI model response for the GA seat is shown in Figure 6-7. The military seat had a higher acceleration threshold for the seat stroking mechanism, which resulted in an increased displacement and velocity for the HAI response. The heart displacement magnitudes increased from 54 to 64 mm and the velocity from 0.9 to 1.3 m/s.

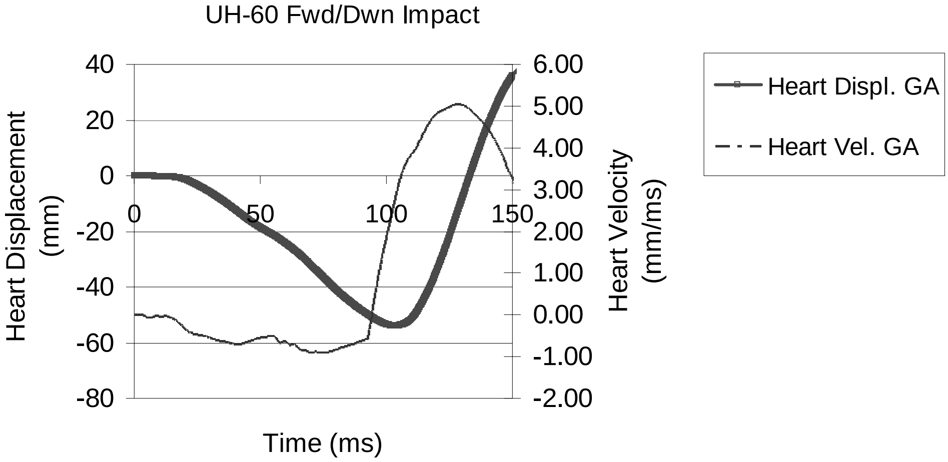

Figure 6-7. HAI Model Response for UH-60 Fwd/Dwn Impact

The HAI model response for the military seat is provided in appendix C. The shape of the displacement and velocity versus time curves for the military seat are very similar to those shown in Figure 6-7 for the GA seat.

6.5 UH-60 Down Impact

The UH-60 Down impact was much more severe than the UH-60 Fwd/Dwn impact, and had a moderately severe injury potential. The impact energy exceeded the EA capability of the GA seat, making it particularly susceptible to injury.

Model Input:

The vertical component of the UH-60 Down impact had twice the acceleration (50 g) and 40 percent higher velocity change (12.8 m/s) than the UH-60 Fwd/Dwn impact.

Model Response – Seat and Spine:

This increase in severity was apparent in the different calculated responses of the GA and military seats as shown in Figure 6-8 and Figure 6-9 respectively. The GA seat bottomed out, with a high seat acceleration spike of 219 g and DRI of 94 G units. These values were well beyond survivable limits.

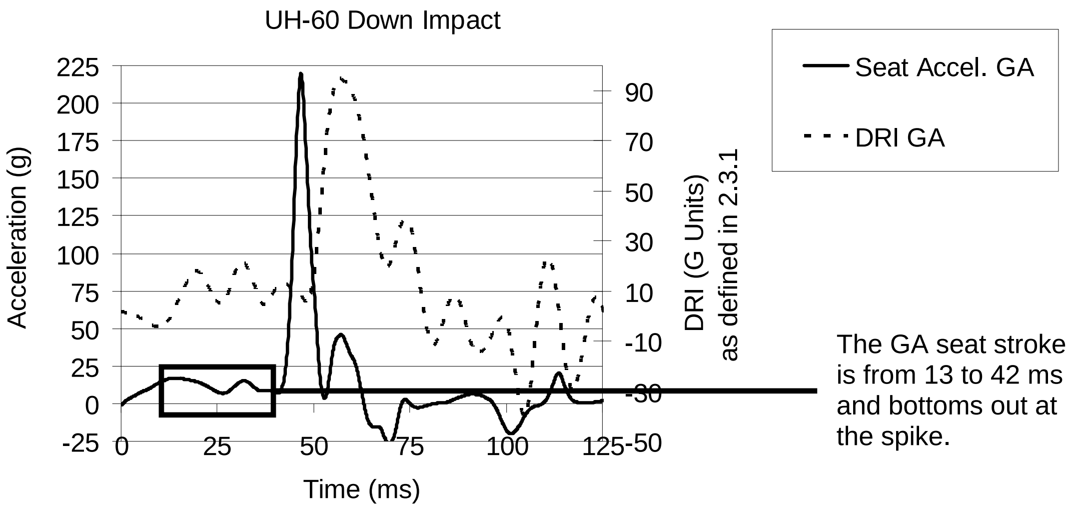

Figure 6-8. Seat Acceleration and DRI for UH-60 Down Impact

The military seat did not bottom out, and mitigated the seat acceleration to a maximum of 24 g and DRI of 31 G units. A DRI value of 31 was potentially injurious, but survivable.

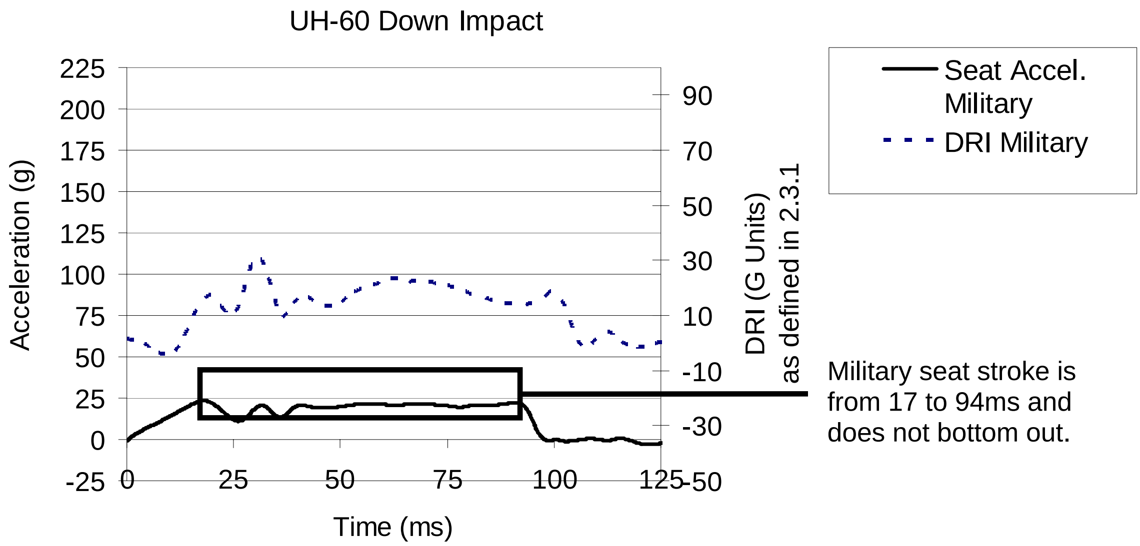

Figure 6-9. Seat Acceleration and DRI for UH-60 Down Impact

<u>Model Response – Heart and Aorta:</u>

The force from the GA seat hitting bottom had drastic effects on the HAI response as shown in Figure 6-10. Comparison to the Military seat (Figure 6-11) indicated the greater heart displacement of the GA seat due to the bottom-out effect. The calculated heart displacements were 155 mm (GA seat) and 83 mm (military seat). The heart velocity exhibited a similar effect, with 8.6 m/s (GA seat) and 2.6 m/s (military seat).

The EA stroke of the military seat caused the heart to remain near its maximum displacement for a relatively long duration.

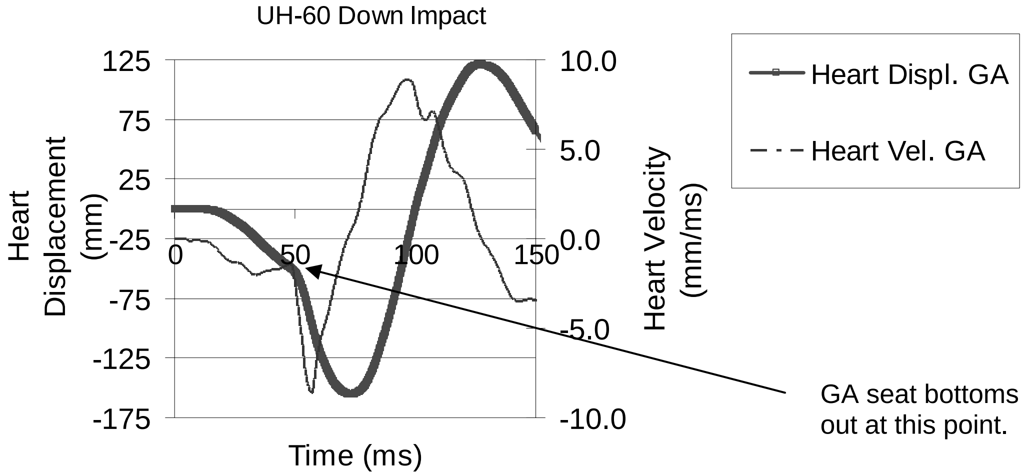

Figure 6-10. HAI Model Response for UH-60 Down Impact, GA Seat

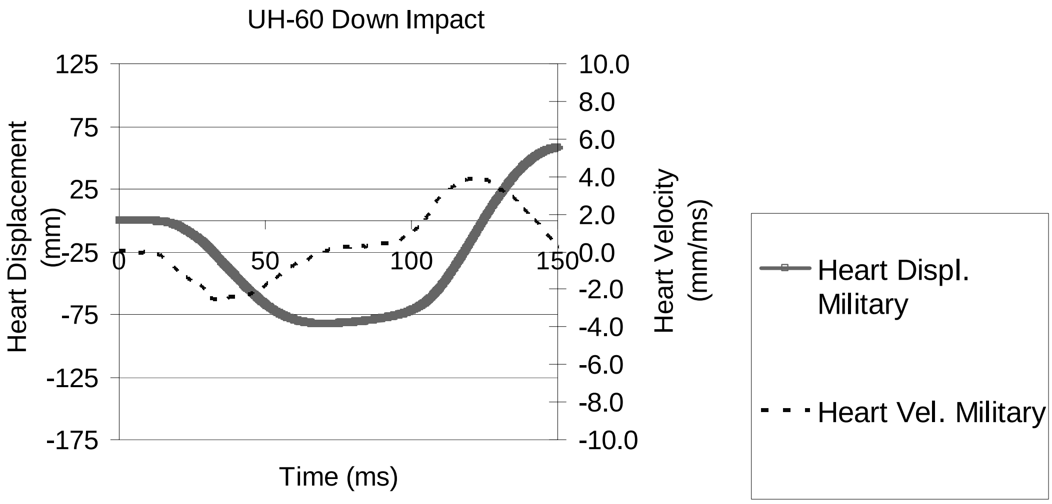

Figure 6-11. HAI Model Response for UH-60 Down Impact, Military Seat

6.6 YAH-63 Crash Test Impact

The YAH-63 crash test resulted in failures of the seats, causing them not to perform as designed. The EA characteristics of the real seats in the test were between the GA and military seats developed for the seat model. Thus for this crash test, a third seat type was developed to provide representative results. The characteristics of the YAH modified EA seat were given in Section 4.3. The GA seat performed the worst, bottoming out with a significant amount of impact energy remaining. The YAH seat also hit bottom, but near the end of it's stroke and with only a small acceleration spike. The military seat performed the best, mitigating the impact loads without bottoming.

Model Input:

They YAH-63 impact had a very high peak acceleration of 60 g and the second highest acceleration slope of 2,400 g/s. The impact velocity was just within the design limits of the Military seat at 12.2 m/s.

Model Responses:

The peak magnitudes of the seat acceleration, DRI, and HAI model results are presented in Table 6-2. Although the YAH-Mod EA seat bottomed out and produced an acceleration spike of 36 g, the DRI was about the same as the military seat, indicating that the impact energy was nearly completely absorbed by the stoke. The heart velocities followed this trend with the YAH Mod EA and Military seats performing significantly better than the GA seat. The Heart Displacement appeared to be more sensitive to the small acceleration spike of the YAH-63 Mod EA seat, as the values was midway between the GA and Military seats.

Table 6-2. Seat Acceleration and DRI Peak Values for YAH-63 Impact

Seat Type	Seat Peak Accel.(g)	DRI (G Units)	Heart Displ. (mm)	Heart Vel. (m/s)
GA	139	69	89	3.8
YAH Mod. EA	36	30	59	1.1
Military	23	34	75	1.6

The calculated seat accelerations for the three seat types are shown in Figure 6-12.

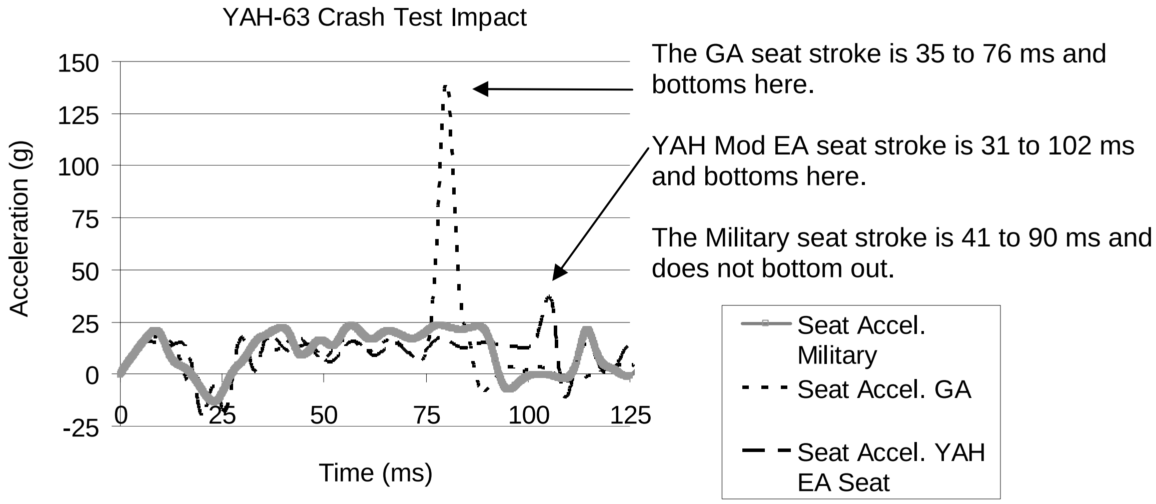

Figure 6-12. Seat Acceleration for YAH-63 Crash Test Impact

The DRI response curves are similar in shape to the seat acceleration curves shown in Figure 6-12. The DRI versus time curves for the three seat types are in appendix C.

<u>Model Response – Heart and Aorta:</u>

The heart displacement was greatest for the GA seat, which was short on EA stroking capability for this impact. The YAH Mod Seat had the smallest heart displacement and velocity, as well as a slightly lower DRI, even though it bottomed out near the end of the impact which resulted in a higher acceleration spike than the military seat (36 g vs 23 g). This suggested that the velocity or stored energy, as apposed to force, was a more important factor for viscous tissue. Figure 6-13 provides the heart displacement for the three seat types and 6-14 provides the heart velocities.

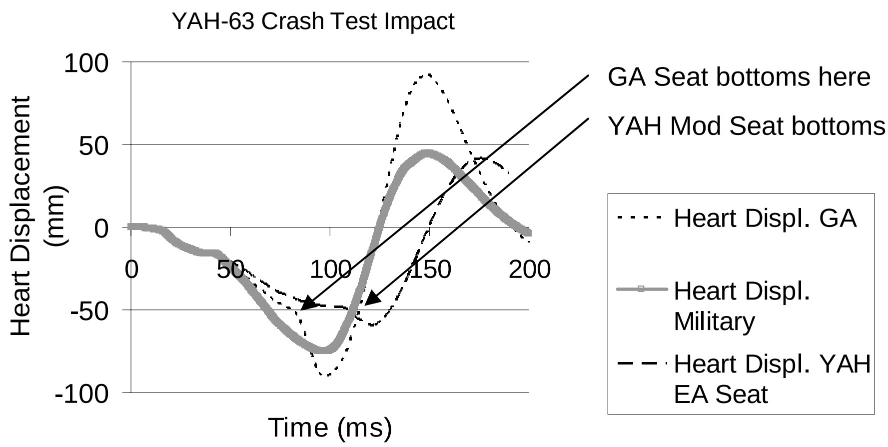

Figure 6-13. Heart Displacement for YAH-63 Crash Test Impact

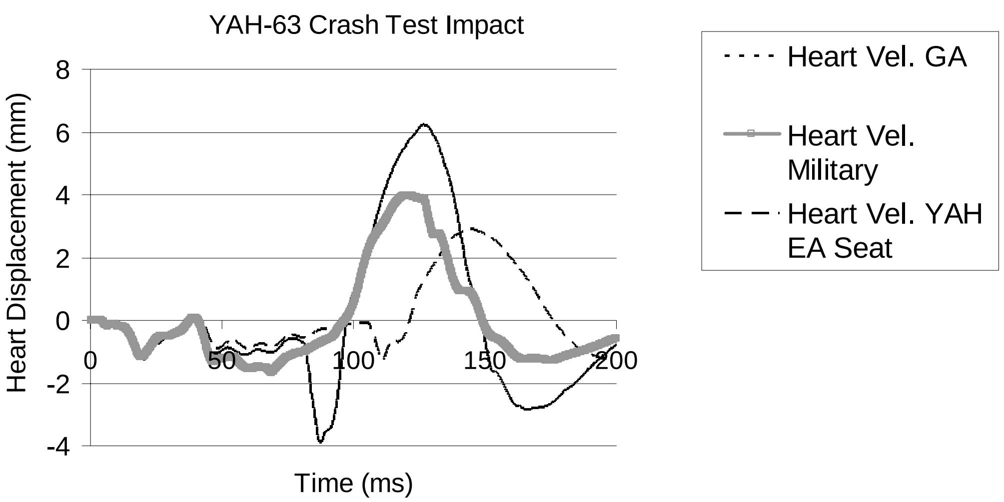

Figure 6-14. Heart Velocity for YAH-63 Crash Test Impact

6.7 Sikorsky ACAP Crash Test Impact

The Sikorsky impact was similar to the UH-60 Down and YAH-63 impacts in terms of velocity change (approximately 12 m/s), but has a much higher acceleration slope and peak. This impact far exceeded the stroking capability of the GA seat and was near the limit of the Military seat.

Model Input:

The Sikorsky impact had an acceleration peak of 93 g at 20 ms, giving it the highest slope of the group at 4,650 g/s. The velocity change was slightly less than the UH-60 Down and the YAH-63 impacts at 11.6 m/s.

Model Response – Seat and Spine:

The GA seat bottomed out relatively quickly while the military seat was able to mitigate the impact acceleration. The peak seat accelerations were 225 g (GA seat) vs. 25 g (Military seat) with corresponding DRI values of 109 vs. 27 G units respectively. The GA seat tested with the Sikorsky ACAP impact performed in a similar manner to the GA seat with the YAH-63 impact. The seat registered accelerations below 20 g until the EA capability of the seat was exhausted. The acceleration then spiked to the 225 g value noted above. The DRI response was also similar to that of the GA seat with the YAH-63 seat. Both the acceleration spike and the DRI spike were much bigger for the Sikorsky impact as compared to the YAH-63. The reason was that the peak acceleration of the Sikorsky impact was 93 g as opposed to 60 g. The total impact energy was roughly the same, and in fact the Sikorsky impact energy was slightly lower than the YAH-63 (11.6 m/s as opposed to 12.2 m/s). The lower energy had no affect on the response for the GA seat because both impact energies far exceeded the EA capability of the GA seat. The calculated seat acceleration and DRI responses for the military seat are shown in Figure 6-15. The GA seat acceleration and DRI response for the Sikorsky impact are provided in appendix C.

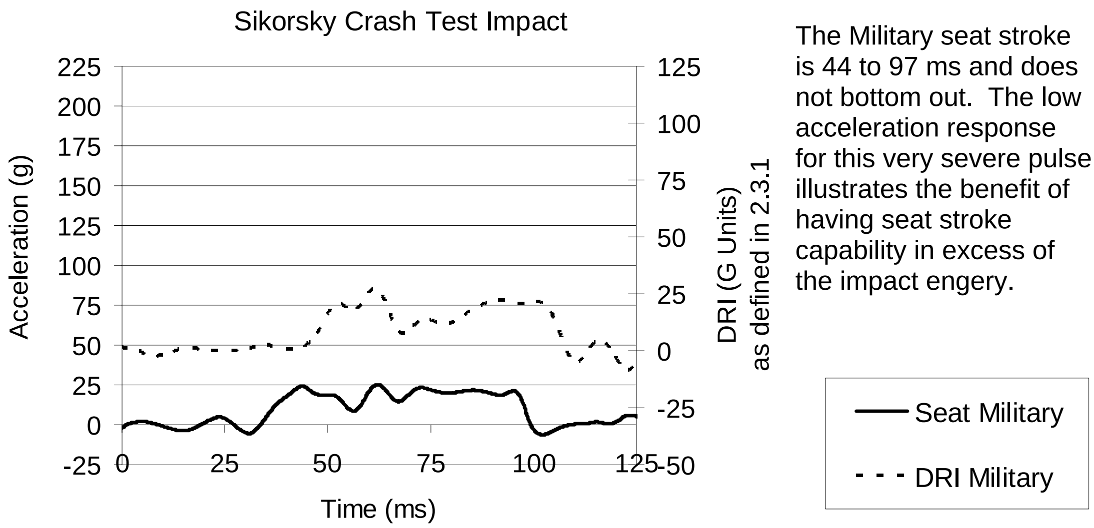

Figure 6-15. Seat Acceleration and DRI for Sikorsky Crash Test Impact

<u>Model Response – Heart and Aorta:</u>

The heart displacement of the military seat was similar to the GA seat (83 vs. 89 mm), even though the GA seat bottomed out with a much higher acceleration. The heart velocity however, indicated the sensitivity of the response to high onset acceleration spikes. The heart velocity of the GA seat was very large at 8.7 m/s while the military seat produced a heart velocity of 2.6 m/s. This illustrated the benefit of the military seat load mitigation. The heart displacement and velocity for the GA seat is shown in Figure 6-16.

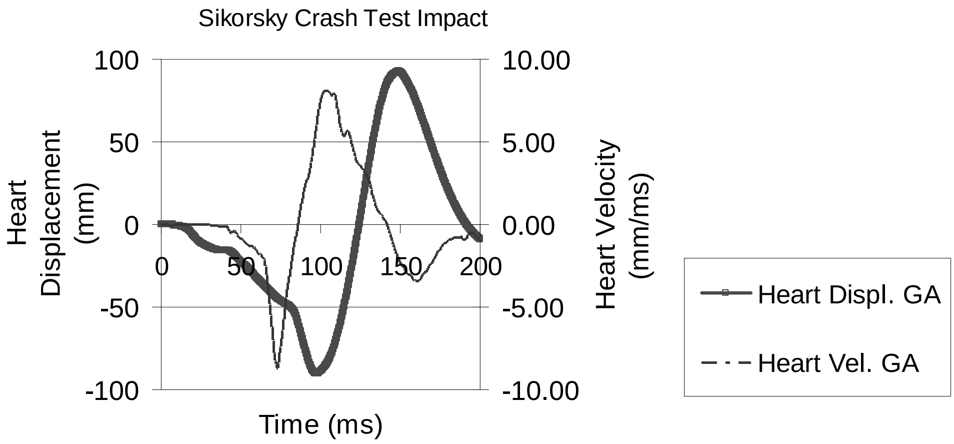

Figure 6-16. HAI Model Response for Sikorsky Crash Test Impact

The heart model displacement and velocity response for the military seat with the Sikorsky impact were similar in shape to the GA seat shown above in Figure 6-16. The heart displacements were similar, but the velocity of the military seat was much lower in magnitude (only 2.6 m/s) as noted above. These curves are given in appendix C.

6.8 Comparative Model Results

The six impact cases were selected to represent a range of impact severities and results for the six individual impact simulations were given in Sections 6.2 through 6.7. This section groups the responses together according to seat type. Section 6.8.1 contains the DRI response and Section 6.8.2 contains the HAI model responses (heart displacement and heart velocity).

<u>DRI Response According to Seat Type for 6 Impacts</u>

The DRI values for the three least severe impacts using the GA seat (Military Airbag Threshold, GA Fwd/Dwn, UH-60 Fwd/Dwn) all remained below 30 G units. These values suggested a low to moderate potential for injury. The three most severe impacts (UH-60 Down, YAH-63, Sikorsky) had DRI values ranging from 70 to 110 G units. They had extremely high potential for injury and likely were non-survivable due to the seat bottoming out (insufficient EA capability). The graph of the GA seat DRI response for the 6 cases is contained in appendix C.

The DRI values when using the military seat remained below 35 G units for all of the impacts (Military Airbag Threshold, GA Fwd/Dwn, UH-60 Fwd/Dwn, UH-60 Down, YAH-63, Sikorsky). The EA stroking mechanism did not bottom out for any seat, and the DRI values suggested a low to moderate potential for injury. The graph is provided in appendix C.

<u>Heart Displacement and Velocity Response According to Seat Type for 6 Impacts</u>

The calculated GA seat heart displacements were less than 60 mm, except the three where the seat bottomed out (UH-60 Down, YAH-63 impacts and Sikorsky). The heart displacement response followed a similar trend as the DRI response. The difference between the three least severe and three most severe impacts was not as pronounced. The Military Airbag Threshold and UH-60 Fwd/Down responses were just short of the mid point of the displacement range at about 60 mm. The YAH-63 response was just over the mid point at about 90 mm. Appendix C provides the graph of the heart displacement response for the six impacts using the GA seat.

Figure 6-17 compares the calculated Military seat heart displacement for the six impacts cases. Because none of the Military seats bottomed out, the heart displacements were grouped together and had similar maximum displacements as compared to the GA seats. The Military Airbag Threshold impact had by far the smallest displacement at around 40 mm. The GA Fwd/Dwn and UH-60 Fwd/Dwn impacts were roughly mid-range, and the UH-60 Down, YAH-63, and Sikorsky impacts were near the high end, approaching 90 mm.

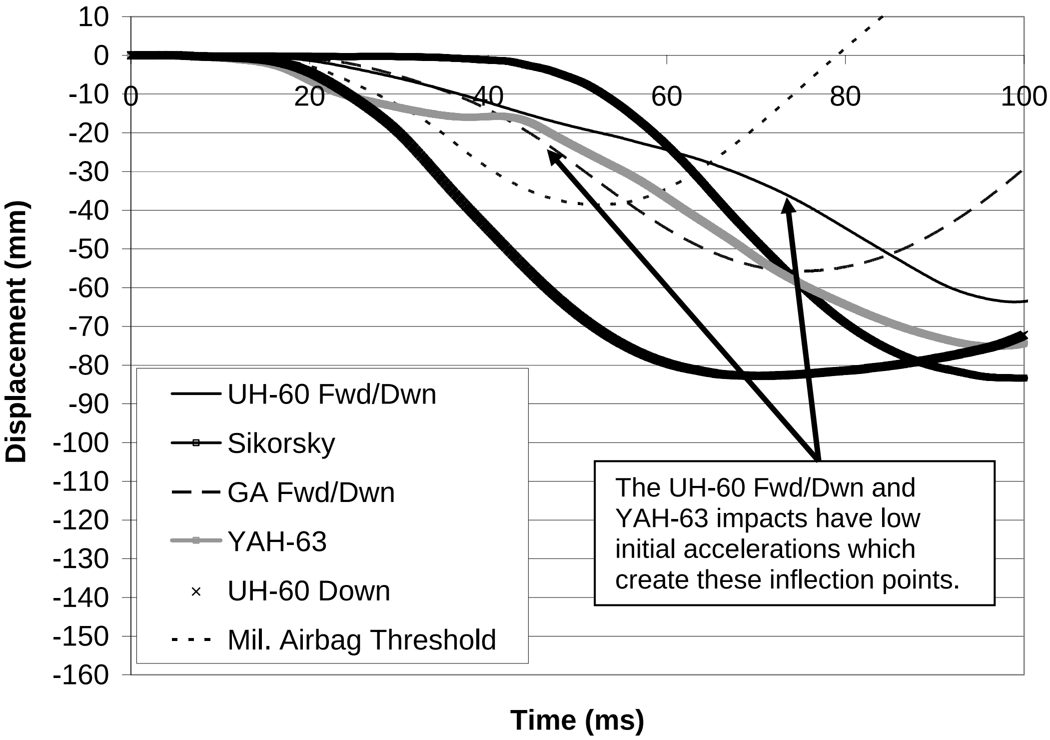

Figure 6-17. Heart Model Displacement for 6 Impact Conditions and Two Seat Types

The GA seat heart velocity responses for the 6 impact cases is shown in Figure 6-18. The heart velocity responses correlated well with the heart displacement results. Seats that bottomed out during the impact had much higher velocities than those which did not. Seats which did not bottom out had velocities below 3 m/s. The YAH-63 GA seat impact response was in the middle at about 4 m/s. The Sikorsky and UH-60 GA seat responses were clearly separate from the rest and were significantly higher with velocities over 8 m/s.

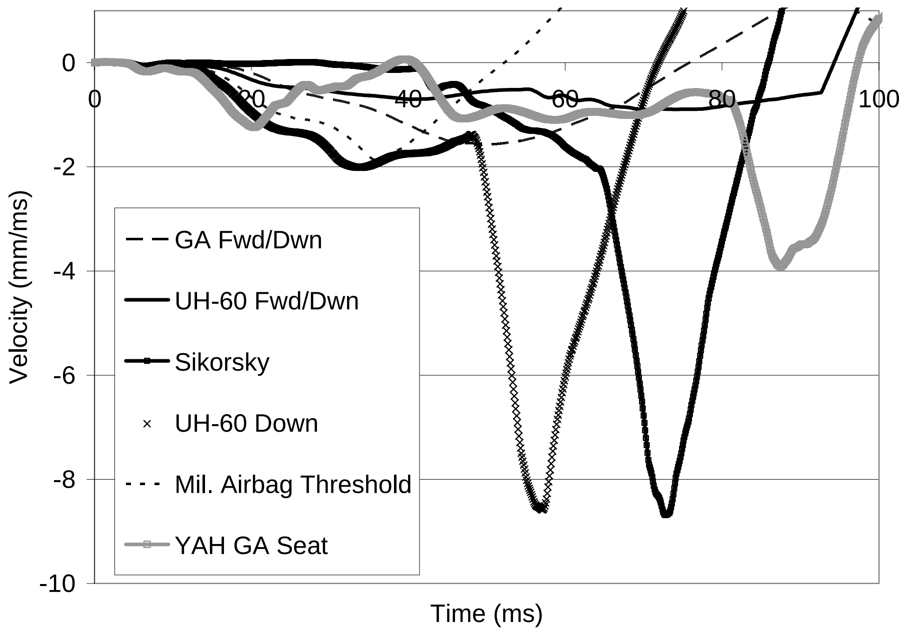

Figure 6-18. Heart Model Velocity for 6 Impact Conditions and Two Seat Types

The military seat heart model velocity response for the six impacts is identical to the GA velocity response (Figure 6-19) up to the point where the large spikes occur. After that point, instead of a spike, a small, rounded peak occurred. The military seat heart model responses for the six impacts are given in appendix C.

7. ACCIDENT STUDY RESULTS

The chapter contains the results of the unique database study and virtually all available data regarding Heart and Aortic Injury (HAI). The database study is unique because it was from the only source found with both injury listing and vehicle impact data for aircraft crashes, and no other studies were found to combine complete injury listings with the aircraft crash parameters. Section 7.1 evaluates the data from published accident papers or reports. Section 7.2 provides the study results from the FAA CAMI and USAARL databases. The USAARL database was the most extensive, contained the vehicle impact data, and was developed with complete injury listings to form a control group with the non-HAI cases.

7.1 Results from Published Accident Papers or Reports

Most of the aviation safety literature was focused on accident causal factors. Survival factors data, especially on the topic of HAI is very uncommon. The basic information is rarely collected for GA aircraft because investigations with details of injury causative factors are not common, as discussed in the methods Section 5.2.1. Transport aircraft accident investigations and rotorcraft survivability studies had more survival factors information, but detail of HAI was not present. Limited survival factors data was available through NTSB reports. Requests were made to the NTSB and several survival factors reports were obtained and included. Results based on sources which were not publicly available were noted in the results and in the references.

The results are presented in two sections, the first for GA aircraft and the second for the all other aircraft types. The results were derived from evaluating the papers or reports as follows;

- Literature study identified sources with content specific to aircraft accident survivability/injury. Each was evaluated and observations were reported.

- Any information specific to deceleration, inertia, or HAI was extracted and evaluated.

- If sufficient detail existed regarding injury listings (any type), an analysis was conducted and the data was summarized here.

Inertial or accelerative injuries to organs (such as heart/aorta, lungs, liver and spleen), were recognized as worthy of concern, but the literature does not reveal studies with clear evaluations and conclusions regarding inertial movement as a causative factor. Sources containing minimal survival factors information included only simple observations. Often the source material had a different focus and thus information on other topics. Information not related to the research was not considered or reported.

7.1.1 GA Aircraft Results

Ast 2000 Results and Observations:

Ast published a study of aviation accidents from the Lower Saxony region of Germany over the period of 1979 to 1996. Most of the ninety-six accidents were in GA aircraft (45). Other types included gliders (18), parachutes (10), helicopters (7), ultalights (5) and others. Of the one-hundred-fifty-four victims, autopsies were performed on 68 (44%). Of these polytrauma was the most common cause of death, cited in 38 cases (56%). Head trauma was the second most common with 18 (27%).
Burning/Drowning deaths were cited with a frequency of 7 (4.5%), Bleeding 3 (2%) and other 2 (1.3%). The observations from this study were:

- Although some the injuries and causes were discussed, inertial factors were not included, and insufficient detail was provided to assess specific body regions.

- The high frequency of polytrauma and he paper discussion suggested that many of the accidents were non survivable.

Baker 1989 Results and Observations:

Baker published a study of mostly GA (90%) accidents in the Colorado Rocky Mountains over the period from 1964 to 1987. The use of shoulder restraints was the topic of the paper, which noted that the fatality rate for front seat occupants not wearing shoulder restraints was 50 percent while those who wore the shoulder restraint were at 13 percent. The observations from this study were:

- Insufficient detail was provided regarding the types of injury to assess body regions. Inertial factors were not discussed.

- The higher fatality rate without shoulder harnesses would likely involve secondary impacts to the aircraft interior and thus would not likely exhibit vertical deceleration of the heart as a primary factor.

<u>Li 1999 Results and Observations:</u>

Li published correlates for pilot fatalities in GA accidents for the region of North Carolina and Maryland from 1985 to 1994. Although this study did not contain injury details, it noted the importance of shoulder harness and the potential of deceleration injuries restricting the occupant's opportunity to evacuate. Only 48 percent of the pilots were noted as wearing shoulder harnesses and 37 percent were unknown. Of the pilots who wore a shoulder restraint, 15 percent were fatally injured as compared to 19 percent who did not wear a shoulder restraint. The importance of adopting crashworthy design features and the problem of the lack of impact level recording for GA aircraft accidents was noted. The observations from this study were:

- Although deceleration injury was mentioned, insufficient detail was provided to conduct an evaluation or make any conclusions.

- The fatality rate with and without shoulder harnesses were nearly the same, which did not correlate with Baker 1989. Combing the non-shoulder restraint cases with the unknown cases put the values very close to those cited by Baker 1989.

<u>Weigmann 2002 Data:</u>

One of the most detailed studies of injury listings was published by Weigmann in 2002. The study includes 559 autopsies from 498 accidents. Figure 7-1 illustrates the frequency of GA pilot autopsy injury listings as organized according to body region. The percentages total more than 100% due to multiple injuries listed for each autopsy. For example, if all of the victims had both brain and pelvic injuries, both of these categories would register 100 percent. Table 7-1 gives the values and number of listings used in Figure 7-1.

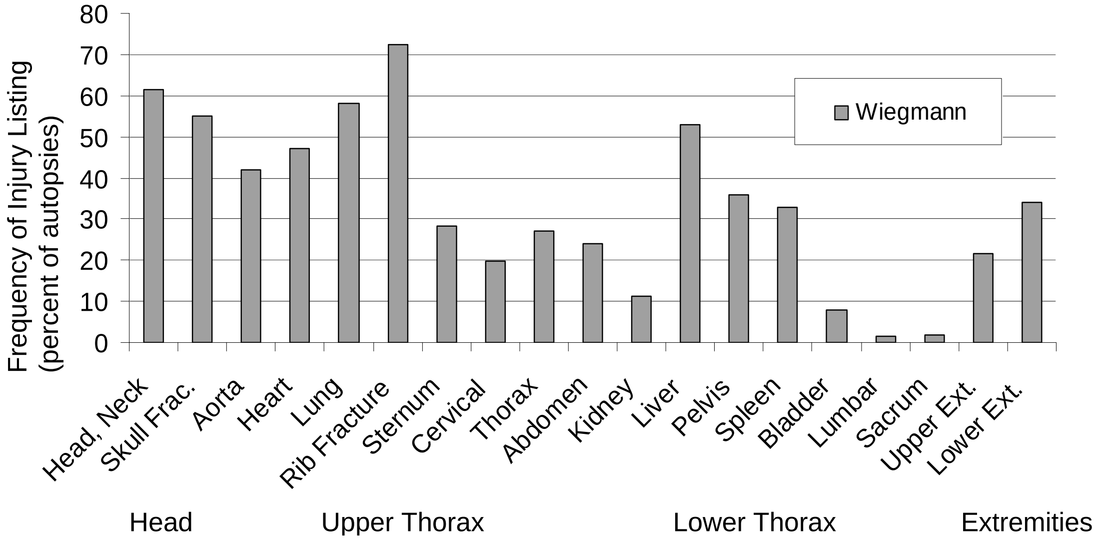

Figure 7-1. Distribution of Injuries from n=559 Autopsies of Fatal GA Accidents (Wiegmann 2002)

Table 7-1. Distribution of Injuries from n=559 Autopsies of Fatal GA Accidents, Frequency of Injury Listings as a Percentage (Wiegmann 2002)

	Head, Neck	Skull Frac.	Aorta	Heart	Lung	Rib Fracture	Sternum	Cervical	Thorax	Abdomen	Kidney	Liver	Pelvis	Spleen	Bladder	Lumbar	Sacral	Upper Ext.	Lower Ext.
%	61.4	55.1	41.9	47.2	58.0	72.3	28.4	19.9	27.2	24.0	11.3	52.9	36.0	32.8	7.8	1.6	1.8	21.6[1]	34.2[2]

Notes: 1. Upper Ext. is average of humerus (23.6%), radius (20.0%), ulna (21.3%).
2. Lower Ext. is average of tibia (31.7%), femur (33.1%), fibula 31.7%).

All of the autopsies were from pilots and most were male (~95 percent) in the Weigmann study. The age distribution indicated that more than 50 percent of the pilots were over 45 years old. About one quarter were over the age of 60 and only 6.6 percent were 25 years of age or younger.

Wiegmann 2002 Observations:

The study indicated that the age distribution was not found to have a relationship to the injuries. Indicators of age factors were expected given the significant portion of victims over the age of 60 years. The study focused on detailed injury listings according to the frequency of the body part, with less emphasis on analysis of injury mechanisms or causal factors. The discussion of injury mechanisms was superficial, although Wiegmann theorized deceleration upon impact may be contributing to internal injuries, especially the lungs and heart. Analysis to support this was not included. This may be the case because Wiegmann did not consider deceleration to be a primary cause, which he attributed to compression of the chest and penetration of the viscera by broken ribs/sternum. The following observations were made from the Wiegmann study:

- The listings suggested that HAI is very frequent, occurring in over 40% of the autopsies for both aorta and heart.
- Inertial factors did not appear to be a primary cause of HAI, but may be a contributing factor.
- Insufficient detail was provided to conduct an analysis of HAI from the published study.

<u>Wiegmann 2002 Data Normalized for Comparison to Other studies:</u>

The injury listings presented in Figure 7-1 were specific to the body part categories and other specific methods chosen by Wiegmann. Comparison of this data to other studies required a means to normalize the data. Thus a ranking system was employed. Figure 7-2 shows the Weigmann (2002) injury listings in descending order of frequency. The Injury Rank was calculated by taking the ratio of the injury listing frequency to the most frequent injury listing. For example, the most frequent injury listing was rib fracture at 72.3 percent, having an injury ranking of 1. The Pelvis was listed half as often, having a ranking of 0.5.

$$\text{Injury Ranking} = \frac{frequency}{most\_frequent}$$

$$\text{Injury Ranking for Rib Fracture} = \frac{72.3}{72.3} = 1.0$$

$$\text{Injury Ranking for Pelvis} = \frac{36.0}{72.3} = 0.5$$

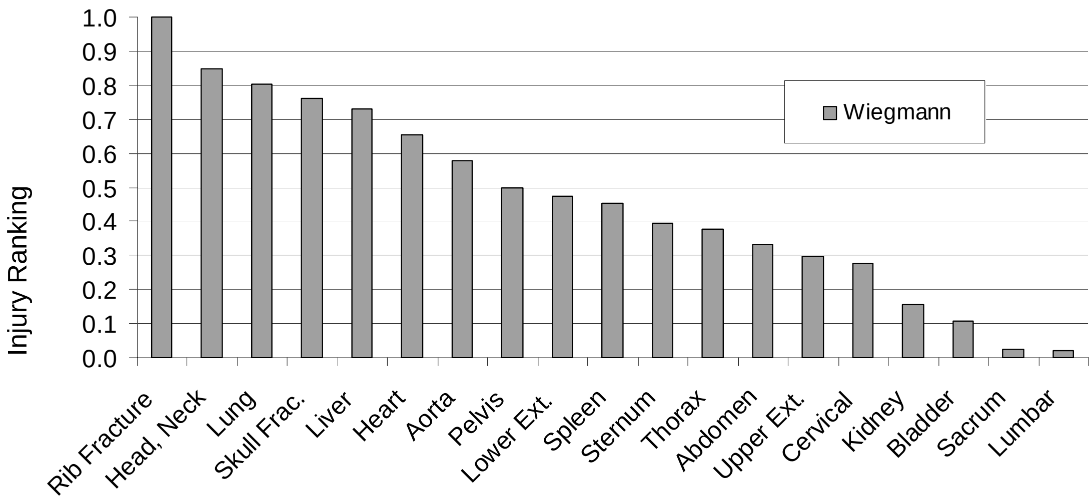

Figure 7-2. Injury Ranking for n=559 Autopsies of Fatal GA Accidents (Wiegmann 2002)

Kirkham 1982 Results:

The FAA published a large study of GA accident survivability that drew the conclusion that injuries can be generally classified as 1/3 to the head, 1/3 to the chest, and 1/3 to the spine (Kirkham 1982). It consisted of 47 survivable or partially survivable accidents investigated by the FAA during the period of 1973 to 1982. The study codified the injuries and included three classifications of HAI (traumatic rupture of heart, tearing or rupture of aorta, and non-lethal contusion of the heart), but a legible copy of the detailed listings could not be obtained. The FAA report made available to the public had a stamp stating “Copy available to DTIC does not permit fully legible reproduction”. Requests for the full DATA were unsuccessful. Thus the proportion of HAI within the roughly 30 percent chest injuries could not be discerned. Evaluating the injury frequency according to body regions that could be extracted from the report are provided in the first half of Table 7-2. The second half of the table provides an assessment of the survivable cabin space. This data has been extracted from the study and reorganized to compare the injuries (top half) to the cabin damage (bottom half).

Table 7-2. Injury and Cabin Survivability,
Evaluation of GA Study by Kirkham 1982

		Pilot	Co-Pilot	Passenger
Injuries	Head / Face	30% (n=11)	30% (n=11)	23% (n=6)
	Chest	32% (n=12)	27% (n=10)	23% (n=6)
	Abdomen	- (n=1)	8% (n=3)	- (n=1)
	Spine	35% (n=13)	42% (n=13)	46% (n=13)
	(total listed)	37	37	26
Cabin Space Survivability Assessment (min=highly survivable, ext.=poor survivability)	Min / Moderate (total n=43)	47% (n=20)	44% (n=16)	57% (n=24)
	Moderately Severe / Severe (total n=36)	42% (n=18)	44% (n=16)	31% (n=13)
	Ext. Severe / Extreme (total n=42)	12% (n=5)	11% (n=4)	12% (n=5)

The injury listings in the top half of Table 7-2 indicated that the Pilot/Co-Pilot (Front seat passengers) were more likely to sustain head and chest injuries while the passengers (rear seats) were more likely to sustain spinal injuries. The cabin assessment shown in the bottom half indicated that the front seat passengers had a higher chance of severe damage to the occupant space rather than a minor/moderately damaged occupant space. (Extreme damage was essentially the same for all positions). The study attributed this to the forward stations of the aircraft being crushed during the accident. Comparison of the injuries to cabin space indicated that head and chest injuries were more common for occupant stations that have more severe damage, while spine injuries were more common in areas with less damage.

Kirkham 1982 Observations:

- Cockpit environmental factors (structural intrusion or secondary impact) appear more critical for the Pilot/Co-Pilot, while distributed loading and acceleration based injury (absorbed through the seat) appear more critical or rear seat occupants.

- The higher incidence of spine injury for passengers can not be attributed to the lower dynamic impact criteria for the passenger seats (Section 2.2.2) because this study was done prior to designs satisfying these criteria.

- Autopsies are less common for passengers, thus autopsy surveys may emphasise injuries associated with the front seat passengers.

Chalmers 2000 Results:

A study of civil aviation in New Zealand was published by Chalmers 2000. The study was based on national injury databases and drew data from the period of 1988 to 1992. It included results for 104 fatalities and 120 hospitalizations. Chalmers provided an injury listing for the common injuries, as represented in Table 7-3. Injuries to the head/neck and chest were the two most common groups. The chest injury group included laceration of the heart and were most frequent, followed by laceration of the lungs, and finally by crush of the chest including internal organs.

Table 7-3. Listing of Common Injuries for
New Zealand Civil Aviation Fatalities, (Chalmers 2000)

Region	Total	Injury	Frequency	% of autopsies
Head / Neck	71	Destruction of cranium and brain	32	45%
		Skull Fracture	16	22%
Chest	72	Heart Laceration	23	32%
		Lung Laceration	17	24%
		Chest Crush / crush internal organs	10	14%
Abdomen	47	Liver Laceration	23	49%
Extremities	66	Femur Fracture	30	45%

An injury ranking using the same method as that shown in Figure 7-2 gave the following ranking from most common to least common. Injury groups were selected to be similar to the Wiegman study where possible, however very different levels of detail do not allow for direct comparison:

Head/Neck 0.67, Liver 0.49, Extremities 0.45, Heart 0.32, Lung 0.24, Chest 0.14

The Chalmers study also included injury information from hospitalizations for 120 non-lethal cases. These listings did not contain any HAI listings, but it was informative to note that internal injuries to the chest, abdomen, and pelvis were a small percentage when compared to other injuries. These injuries together account for only 6.7 percent (n=8) as compared to Fracture of the neck and trunk: 29.2 percent (n=35); lower limb fracture: 18.3 percent (n=22), and intracranial injury (excluding skull fracture): 13.3 percent (n=16). Skull fracture was 5 percent (n=6) and extremities were each < 5 percent. Chalmers also looked at the non-lethal injuries grouped by body region, as summarized in Table 7-4.

Table 7-4. Injuries by Body Region for
New Zealand Civil Aviation Non-Fatalities, (Chalmers 2000)

Injury	Frequency	%
Head / Neck / Face	22	18%
Chest (excluding thoracic spine)	14	12%
Abdomen (excluding lumbar spine)	3	3%
Spine	24	20%
Upper Extremities	6	5%
Lower Extremities or Bony Pelvis	28	23%
Unspecified	8	7%
External ((including burns)	15	13%
Total	120	100%

Chalmers 2000 Observations:

- Table 6-4 indicated that heart lacerations were very common.
- Contact based injury mechanisms appeared predominant because the heart injury listing specifically states laceration and because other potentially accelerative injuries (such as aortic aneurysm) had no listing.
- The non-fatal listing suggested that HAI almost never occurs in survivable accidents because the entire chest region only accounts for 12 percent of all non-fatal listings.

National Transportation Safety Board Reports

The NTSB is a source of significant GA survivability data. Several GA studies were reviewed, but do not contain injury details. These were:

- Single Engine, Fixed Wing General Aviation Accidents 1972-1979, NTSB AAS-79-01, (NTSB 1979a).
- Light Twin Engine Aircraft Accidents 1972-1976, NTSB AAS-79-02, (NTSB 1979b).
- General Aviation Accidents Involving Aerobatics, 1972-1974, NTSB AAS-79-04, (NTSB 1979c).
- U. S. General Aviation Accidents Involving Fuel Starvation 1970-1972, NTSB AAS-74-1, (NTSB 1974a).
- Special Study of Fatal, Weather-Involved, General Aviation Accidents, NTSB AAS-74-2, (NTSB 1974b).
- Review of Corporate / Executive Aircraft Accidents, A Statistical Summary of a Special / Segment of US General Aviation 1964-1968, NTSB AAS-70-AA, (NTSB 1970).

- General Aviation Accidents Involving Visual Flight Rules into Instrument Meteorological Conditions, NTSB-SR-8901, (NTSB 1989a).

The NTSB conducted a major study of General Aviation Crashworthiness, reported in an initial study in 1980, then a three part series in 1983 to 1985 which were:

- The Status of General Aviation Aircraft Crashworthiness, NTSB-SR-80-02, 1980, (NTSB 1980b).
- General Aviation Crashworthiness Project, Phase One, SR--83-01, 6/27/1983, (NTSB 1983).
- General Aviation Crashworthiness Project Phase Two -- Impact Severity and Potential Injury Prevention in G.A. Accidents, SR--85-01, 3/15/1985, (NTSB 1985a).
- General Aviation Crashworthiness Project, Phase Three – Acceleration Loads and Velocity Changes of Survivable General Aviation Accidents, SR-85-02, 9/4/1985, (NTSB 1985b).

The group of studies evaluated 31 full crashworthiness (survival factors) investigations of GA aircraft, from 1980 through December 1982. The airplanes involved were primarily Piper and Cessna (74 percent) and Beech (16 percent). Most of the aircraft were also Single engine (87 percent). These studies helped push for the dynamic seat rules and make great progress in the seats and restraints in GA aircraft. Two of them also provided the most complete information regarding general aviation crash impacts and the injuries sustained, as summarized below.

<u>NTSB-SR-80-02 (NTSB 1980b) Results:</u>

This report provided 14 GA crash evaluation summaries. Accident case No. 11 was of particular interest:

"The pilot survived and extracted himself and the emergency locator transmitter from the aircraft. However, he died shortly afterward from a ruptured thoracic aorta."

This occupant did not have a shoulder harness and suffered a collapsed lung and fractured left rib likely from Impact to the instrument panel and possibly control column. Some of the case studies, such as No. 12, noted injuries such as a crushed chest without specifying the body parts involved. Accident case 13 attributed the cause of aortic injury to accelerative factors, but did not provide evidence of this assertion. The description of accident case 13 noted:

"There was considerable vertical deceleration forces involved since the pilot died of a laceration of the thoracic aorta."

The suggested cause was further brought into question as the occupant was not wearing a shoulder harness and was noted to impact the yoke and have a skull fracture. The occupant did also sustain a fracture of the L1 vertebra, indicative of the vertical deceleration force. Accident case No. 14 noted an occupant who suffered a laceration of the left upper pulmonary lobe and fractured T8. This occupant also impacted the yoke. Another occupant in this same evaluation suffered a laceration of the thoracic aorta and left pulmonary lobe, rib fracture, and impacted the yoke. Other accident evaluations in this series noted occupants with fractured spines but with no indication of HAI.

Observations from NTSB-SR-80-02 (NTSB 1980b):

- The aortic injuries in cases 11 and 13 can not be attributed to the downward impact vector alone due to the other cockpit based injuries due to the occupants not wearing should harnesses.

- The quote provided from accident case No. 13 illustrated the misconception that if aortic injury exists, deceleration must be the primary factor.

- The heart injuries described in case 14 appeared not to have acceleration as a factor because the other injuries were indicative of crushing forces on the chest.

- The existence of spine injuries without HAI indicated that for the aircraft designs in these cases, compression injuries to the spine had a lower injury threshold than the hypothesis.

NTSB SR-85-02 (NTSB 1985b) Results:

The third GA crashworthiness study also included specific injury and impact information. Thirty five accident evaluations were presented. Evaluation No. 28 noted that an occupant suffered a heart laceration due to penetration of the control column. This case was clearly not related to the downward inertial loading. Evaluation No. 29 was a partially survivable accident with one survivor and two killed. The pilot suffered a crushed chest and complete transaction of the thoracic aorta and a heart laceration. Many of the other evaluations noted compressive spinal fractures, and very few occupants had or used shoulder restraints. Organ injuries were prevalent due to lap belt intrusion into soft tissue and the impact severity.

Observations from NTSB SR-85-02 (NTSB 1985b):

- The HAI injuries noted in this study indicated that cockpit environmental factors can cause HAI, as the instances were attributed to penetration and crushing injury to the chest.

General Observations from the Four Part GA Study:

- HAI appeared common, with 44 individual cases of aortic injury described (14 from NSTSB 1980b and 35 from NTSB 1985b). However no control group could be established, as the injuries were disparate sources and the population who did not suffer HAI was not given. The sources of detailed data concerning injures were autopsy records, hospital records, and interviews with victims and medical or rescue personnel.

- The hypothesis of thesis (that the downward impact vector causes HAI through inertial displacement of the heart) was a stated concern, however, no evidence to support this hypothesis was available.

Page 4 of NTSB 1983 states:

"The occupant injuries of concern in the crashworthiness study are those resulting from either accelerative or mechanical sources. Abrupt acceleration (+ or -) of the body or parts of the body may result in injuries, such as hyper extension of the cervical spine (whiplash) from longitudinal acceleration, or ***transection of the aorta from acceleration in vertical direction.****"*

- The description of the accident environment and other injuries suggested that the cases of HAI may also have been caused by factors other than the hypothesis. Evidence of this was found in the injury descriptions summarized for each phase of the study. For example, the description of the pilot who survived with HAI for a short time (NTSB-SR-80-02 Results) indicated that he was not wearing a shoulder harness and sustained other injuries from striking the control column.

7.1.2 Transport Aircraft, Rotorcraft and Military Aircraft

Transport Aircraft

The United States National Transportation Safety Board (NTSB) was the primary source for information on aircraft accident survival factors. Information from other organizations such as the UK Air Accident Investigation Board (AAIB) and journal publications were also found. The following major reports for large passenger aircraft were reviewed, but do not contain the detailed injury information needed:

- Survivability of Accidents Involving Part 121 US Air Carrier Operations 1983 Through 2000, NTSB SR-01/01 (NTSB 2001).
- Commuter Airline Safety, 1970-1979, 1981, NTSB-AAS-80-1 (NTSB 1980a).

Some small publications discuss HAI specifically in aircraft accidents, but did not provide injury rates relative to other injuries and were not complete studies regarding the cause. These included Hass 1944 and McMeekin 1999. Several smaller publications also did not provide individual injury distributions, but were useful in understanding the aircraft crash environment, including Ast 2001, Baker 1989, Hill 1989.

The following major reports did provide information about injuries, including HAI. A summary of the pertinent content for this research is provided.

- Cabin Safety in Large Transport Aircraft, 1981, NTSB AAS-81-02 (NTSB 1981b)
- United Kingdom Air Accident Investigation Branch Report on the Accident to Boeing 737-400 G-OBME near Kegworth, Leicestershire on 8 January 1989, (UKCAA 1989).

NTSB AAS-81-02 (NTSB1981b):

Case No. 1 described a large transport aircraft accident in which there were no fatalities among the 107 occupants, but the majority of the 36 persons seriously injured suffered spinal injury. The downward impact vector was estimated to be at least 10g (impact forces in other directions were not cited).

Case No. 5 lists aortic rupture as one of the common injuries sustained by the fatalities of an accident having 48 persons on board, 16 fatal, and 32 seriously injured. The impact accelerations were estimated at 15g to 25g forward, 5g to 15g downward, and 5g to 10g sideward.

Observations from NTSB 1981b)

- This accident study was a rare example stating estimated impact forces. They suggested that spinal injuries can occur for this aircraft/seat design as low at 10 g, but aortic injury did not occur (Case No. 1).

- Case No. 5 did have HAI and stated vertical accelerations of 15 g, but this force did not appear to be a threshold of HAI according to the thesis hypothesis, due to the much higher acceleration force estimated in the longitudinal direction.

The NTSB conducts extensive investigations on large commercial aircraft accidents. These accidents often have survival factors investigations. Although these reports are not published, they were obtained by direct request to the NTSB. The NTSB was consulted first to help select accidents that may contain pertinent survival factors data. Four accidents of large transport aircraft were identified and the appropriate material was requested. The accidents were selected because the accidents were survivable and impact tolerance and the design of the seats and restraints were a factor. The survival factors group chairman's factual reports and injury distributions for the following accidents were obtained and evaluated:

- DCA89063, Sioux City IA, DC-10, July 19th, 1989 (NTSB 1989b).
- DCA90MA019, Cove Neck NY, B707, January 25th, 1990 (NTSB 1990).
- DCA94MA065, Charlotte NC, DC9-30, July 2nd, 1994 (NTSB 1994).
- DCA99MA060, Little Rock AK, MD-82, June 1st, 1999 (NTSB 1999).

Sioux City (NTSB 1989b) Results:

The McDonnell Douglas DC-10 contained 296 occupants including 285 passengers and 11 crew. There were 111 fatalities (1 crew), 47 serious (6 crew), 138 minor or none (4 crew). The report indicated that 76 passengers died of blunt force impact injuries and 35 passengers died of smoke inhalation without blunt force trauma. Descriptions of seat damage for different regions in the aircraft were provided. The injury listing indicate 2 aorta lacerations with multiple severe injuries and 5 heart injuries (contusions, hemorhage, laceration) also with multiple severe injuries.

Observations from Sioux City (NTSB 1989b):

- Several instances of HAI were found, however none could be attributed to inertial factors due to multiple other injuries indicating cockpit environmental factors (secondary impact to interior components).

Cove Neck (NTSB 1990) Results:

The Boeing 707 had 149 passengers and 9 crew. There were 73 fatalities (8 crew), 82 serious (1 crew), 3 minor. The passengers included 7 infants, 1 fatal and 6 seriously injured. The injury listings indicated 9 occupants with aortic injuries, one case which also included the abdominal aorta, 9 occupants with heart injuries, and 3 occupants with both aorta and heart injuries. All were fatal and all but 2 of the cases were included multiple severe other injuries including rib fractures. Two cases did not include rib fracture or other injuries which may lacerate the heart of aorta.

Observations from Cove Neck (NTSB 1990):

- 21 total cases of HAI were found, none of which can be attributed to inertial factors as the primary cause.
- 2 cases suggest that inertial factors could have been significant because other injuries which could have caused laceration of the heart or aorta were not included. The primary cause could not be attributed to inertial factors due to insufficient information.

Charlotte (NTSB 1994) Results:

There were 57 occupants on the McDonnell Douglas DC-9. There were 37 fatalities (0 crew), 18 serious (1 crew), and 2 minor (1 crew). Descriptions of the interior and seat damage were provided, but no injury descriptions were obtained.

- No observations are made due to the lack of detailed injury information.

Little Rock (NTSB 1999) Results:

The information provided by the NTSB included an injury chart for 100 passengers and 6 crew. There were 10 fatalities (1 crew), 38 serious (4 crew), 58 minor or none (1 crew). The injury descriptions included 1 passenger with a torn aorta and well as several rib fractures. The passenger survived. The captain suffered multiple fatal injuries which included a torn pericardial sac.

Observations from Little Rock (NTSB 1999):

- A torn aorta occurred and occupant survived, but the injury was likely cased by a fractured rib and thus the primary cause can not be attributed to inertial factors, although may have been a contributing factor.

- Two cases of heart injury occurred but both were combined with massive trauma and thus can not be attributed to inertial factors.

Transport Crashworthy Benefit Studies (Cherry 1996, Cherry 2000, Cherry 2006)

The Civil Aviation Authority of the United Kingdom in cooperation with the FAA commissioned three studies of crashworthy transport aircraft passenger seats (Report CAA 96011, Report CAA99003, Report CAA2005/03). These reports evaluated various transport category accidents and conducted benefit analysis for the design standard of the seats. The first study, CAA 96011 found no relationship between the injuries and the impact severity. The second study (CAA9903) provided the most detail of injuries and impact forces. However it did not provide listings of specific injuries. Some of the accidents were also the same as those previously reviewed in NTSB Survival Factors Reports. The third study was a revised analysis of the previous studies and provided no further information about the impacts or injuries. Due to the extensive analysis of the crash impact and seats, if the autopsy information could be obtained, this would have provided scope for further analysis.

Rotorcraft and Military Aircraft

A few studies were found which focused on rotorcraft, including Shanahan 1993, Hicks 1982, and the NTSB Special Study of Rotorcraft Accidents 1977-1979, NTSB-AAS-81-1, (NTSB 1981a). The Shanahan paper used inertial aortic injuries in an explanation of typical acceleration versus contact based injuries: “an example of acceleration injury is rupture of the aorta in a high sink rate crash”. All of these studies, however, did not provide detailed analysis of injury patterns.

Summary Observations from the Transport, Rotorcraft, and Military Evaluations:

- The transport accident data suggested that HAI could be a factor in survivability as cases were identified with survivors sustaining HAI.

- A question regarding the vehicle design was raised regarding how the crush zone of aircraft affects HAI due to differences in the absorption of the impact energy.
- None of the HAI cases found in the evaluations could be attributed to the thesis hypothesis because only detailed injury information was available. Information regarding the crash impact and forces transferred to the occupant would be required to support the hypothesis.
- Although lack of information relating the injury to the impact limits the observations, comparing the HAI with the other injuries suggests the extent to which penetrating trauma versus accelerative trauma was a factor. Two of the Thirty identified cases of HAI were not accompanied by obvious other penetrative injuries. This suggests that cockpit environmental factors were the predominant cause of HAI.

7.2 Database Research Results

The FAA maintains GA aircraft accident records, but not in a searchable database, as noted in the database research methodology, Section 5.2. The only data the FAA was able to provide the files related to 3 accidents with autopsy results that included HAI. All three cases of aortic injury were attributed to non-survivable events. Additionally, the aortic injury was not the primary cause of death. The primary cause of death was predominantly impact trauma to the head or the entire body as a result of the impact and loss of a survivable cabin volume. The notes from the three case files are provided. The files are labelled according to the NTSB records.

<u>NTSB Accident SEA86FA033 (NTSB 1986) Results:</u>

This accident involved a Mooney M20K aircraft which struck a power line and then impacted the ground. The crash was non-survivable, killing all 4 occupants. One of the 4 occupants suffered a tran-sected abdominal aorta, but the primary cause of death was multiple blunt force trauma to the head and massive injuries over the whole body. The aortic injury could not be attributed to inertial factors due to the extent of injuries and the loss of survivable occupant space. Mechanical factors were likely a primary contribution to the aortic injury. The Probable Cause Report is included in Appendix D.

Observations from NTSB Accident SEA86FA033 (NTSB 1986):

- The injuries in this accident were acceleration based, but were the result of the body compressing downward and crushing the tissues rather than inertial displacement of the tissue. The pathological diagnosis found on page 1 of the medical examiner's report states *"This woman's death is attributed to deceleration blunt impact injuries to the…"*.

NTSB Accident ATL89FA035 (NTSB 1989c) Results:

This accident involved a Hughes 269C helicopter which lost power and impacted the ground. The crash was non-survivable, killing both occupants. One of the 2 occupants suffered a rupture of the myocardial attachment at the aorta, but also massive blunt force injuries over the entire body. A basic evaluation of the vehicle impact parameters was conducted. The aircraft impact was primarily vertical, with no yaw or roll, and very little pitch (15 deg nose down) noted. Although the accident notes indicated that high g forces caused severe injuries and that the seats were not energy absorbing, the aortic injury could not be attributed to inertial factors. The extent of injuries and the loss of survivable occupant space created mechanical factors which could have contributed or been the primary cause of the aortic injury. This civil helicopter accident was similar to the results found in studying the US Army helicopter crashes. The Probable Cause Report is included in Appendix D.

Observations From NTSB Accident ATL89FA035 (NTSB 1989c):

- This case was typical of the few HAI cases which appeared to be good candidates for the hypothesis, as it is clearly non-survivable. This impact had the appropriate downward impact vector, as indicated by the diagram on page 2 of the FAA form 8025-3 "Seat and Restraint Crashworthiness Data", found in the docket.
- The accident also had injuries which appeared to be caused by accelerative factors (ruptured organs). For example, the autopsy describes *"The lungs are hemorrhagic, but do not appear to have any major tears."* But the accident was clearly non-survivable.

NTSB Accident ANC95FA073 (NTSB 1995) Results:

This accident involved a Piper PA-18 aircraft which collided with mountainous terrain with a slight nose down attitude (propeller received minor damage). The crash was non-survivable, killing both occupants. One of the 2 occupants suffered a large laceration of the descending aorta 5 cm below the takeoff of the left subclavian artery. The primary cause of death was multiple blunt force trauma to the head. There was extensive fire damage but no sign of smoke inhalation and little blood flow into the region around the aorta laceration. This indicated that the aortic laceration was not the cause of death. This aortic injury may have been caused by inertial factors or by a fractured rib (extensive bilateral). If the injury was caused by inertial factors, it was well beyond the survivable envelope. The Probable Cause Report is included in Appendix D.

Observations from NTSB Accident ANC95FA073 (NTSB 1995):

- This accident supported the observation above that HAI cases are predominantly non-survivable and that deceleration injuries are often caused by crushing of the body on itself rather than inertial displacement with in the chest cavity (as opposed to the inertial movement of the upper thorax onto the lower). Page 1 of the medical examiner's notes *"Autopsy reveals that the probable cause of death ... is multiple blunt impact deceleration injuries…".*

7.2.1 Evaluation Results for the USAARL Database, All Injury Types

The study of all injuries considered the complete distribution of injuries listed in the USAARL database for 156 US Army aircraft accidents from 1983 to 2005. The methodology for this study is described in Chapter 5, Section 5.2.1. The results first evaluate the aircraft impact and then the injuries. Comparisons of the two are then presented.

The inquiry resulted in a population of 156 accidents and 606 occupants. The six most common aircraft types were: OH58, 21 percent (n=32); UH60, 20 percent (31); UH1, 16 percent (n=25); AH64, 15 percent (n=23); CH47/MH47, 6 percent (9); AH1, 4 (n=6) as shown in Figure 7-3. The remaining 19 percent were a variety of other aircraft including fixed wing aircraft. Appendix D includes a description of all the aircraft types involved. A list of all the accident cases with the aircraft, flight and impact conditions is given in Appendix D, Table D1. Each accident was classified according the severity determined by the investigator. The 156 aircraft accidents were listed as: Non-survivable (65.6 percent); Partially survivable (19.8 percent); Survivable (12.7 percent); and 1.9 percent were Not-specified.

Figure 7-3. Most Common Aircraft Types in Accident Database

The gender distribution for the 606 occupants was 98 percent male, 1.6 percent female, and 0.4 percent unknown. The age range was 19 to 61 for the 379 of 606 reported. The average age was 32, and the most frequent age was 26. Each case was classified according to the severity of injuries. Fatalities were 67.2 percent (407) and non-fatal were 32.8 percent (199). The non-fatal were further listed from minor to severe as: First Aid 8 percent (16); Lost Work 70.9 percent (141); Permanent Partial Disability 19.1 percent (38); Permanent Total Disability 3.5 percent (7); and 1 not reported. There were 2,533 listings for the 606 occupants. Of these, a total of 297 injury listings were eliminated because they did not contain sufficient detail to be useful, 254 fatal and 43 non-fatal. For example, a listing of *"chest injury"* did not indicate which body part was injured. The 2,533 injury listings used in the study were classified as 1,635 fatal and 601 non-fatal. A table of the all the injury listings is given in Appendix D.

The aircraft impacts were evaluated from 3 perspectives, first according to impact direction, second according to the combination of direction and normalized magnitude, and last by relating actual magnitude to survivability.

Aircraft Impact Evaluations Results

Impact Direction

The results of the impact direction evaluated the frequency that each impact direction was cited, based on the methods described in section 5.2.1. The frequency of reported values indicated that no particular orientation was clearly prominent. The frequency of citations according to each axis pair is provided in Figure 7-4. The values added up to more than 100 percent because up to 3 axes could have been recorded for each accident. The total values did not add up to 300 percent because the neutral percentages were not listed in the Figure. The neutral percentages for each axis pair were: For/Aft 16 percent, Up/Down 10 percent, Left/Right 34 percent.

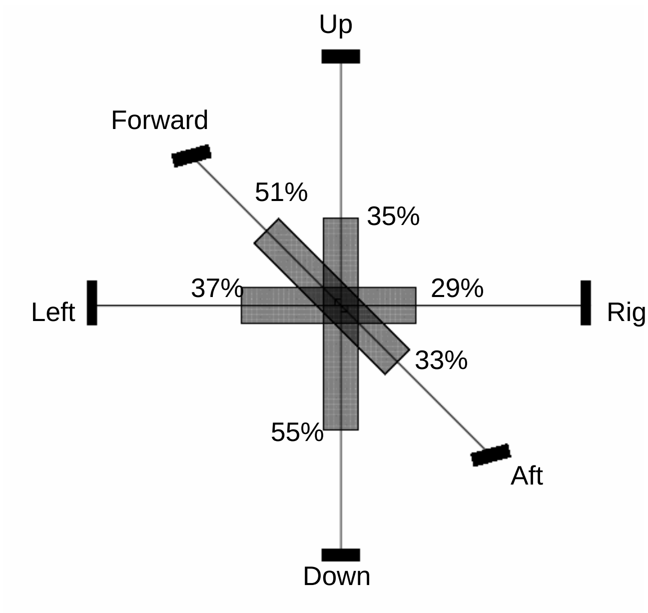

Figure 7-4. Frequency Impact Vector Listings for Each Primary Axis

Rotorcraft accidents were the vast majority (98 percent) of data available. This study had a reasonable sample size of about 150 helicopter accidents as compared to the other studies evaluated which ranged from the NTSB GA study with 31 accidents to Wiegmann 2002 which was by far the largest with 498 accidents (Section 6.1.1). The frequency of occurrence evaluation indicated that all impact directions were significant from a frequency perspective. In general, forward and downward impacts appeared to be somewhat more common than the others, but not to the extent that the others should be discounted. The frequency of forward and downward citations may have been due in part to investigator bias towards these impact vectors. There were many design criteria for aircraft focused on the forward and vertical impact component of the crash (USDOD 1998, Hurley 2002). The wide distribution of impact orientations, without clearly favouring one axis suggested that a bias regarding crashworthy design for any one orientation may not have be the best approach.

Impact Direction and Magnitude

A specific impact direction can be of more concern depending on how large it is relative to the total. This was evaluated by creating the ratio of each impact direction to the total and grouping them according to their relative size as described in the methods (Section 5.2.1). A small ratio of the component to the total was < 0.33, middle 0.34 to 0.68, and high > 0.69. For example, an aircraft impacting the side of a mountain would have had a forward longitudinal impact vector that accounted for most of the total impact. An aircraft impacting the ground with a perfect 45 deg flight path and pitch would have had a forward ration of 0.45 and a downward of 0.45.

This method of looking at the impact direction ratio was expanded to consider the entire population of accidents by calculating the frequency of each ratio for each direction. These were expressed in terms of a percentage. For example if all the aircraft in the study crashed with a downward vector (never upside down), then the frequency of a ratio in the upward direction would be 0 percent. But in fact, many helicopters do crash upside down. Further, when they do, the impact tends to be a large ratio. This could have been that when an investigator sees the aircraft upside down, they tended to attribute most of the impact severity to the upward direction. The data indicated that this may be the case, as the frequency of upside down impacts was most often in the largest ratio group. Table 7-5 and Figure 7-5 provide the impact ratios and frequencies as described above. Looking at the upside down direction revealed that when a vertical up impact direction was cited by the investigator, it was a large ratio of the total 69 percent of the time.

Table 7-5. Ratio of Impact Component / Total Impact

Percentile	Left	Right	Fore	Aft	Up	Down
Bottom Third (Ratio = 0 to 0.33)	56%	71%	40%	33%	23%	30%
Middle Third (Ratio = 0.34 to 0.67)	23%	16%	26%	25%	8%	9%
Top Third (Ratio = 0.68 to 100)	21%	14%	34%	42%	69%	61%

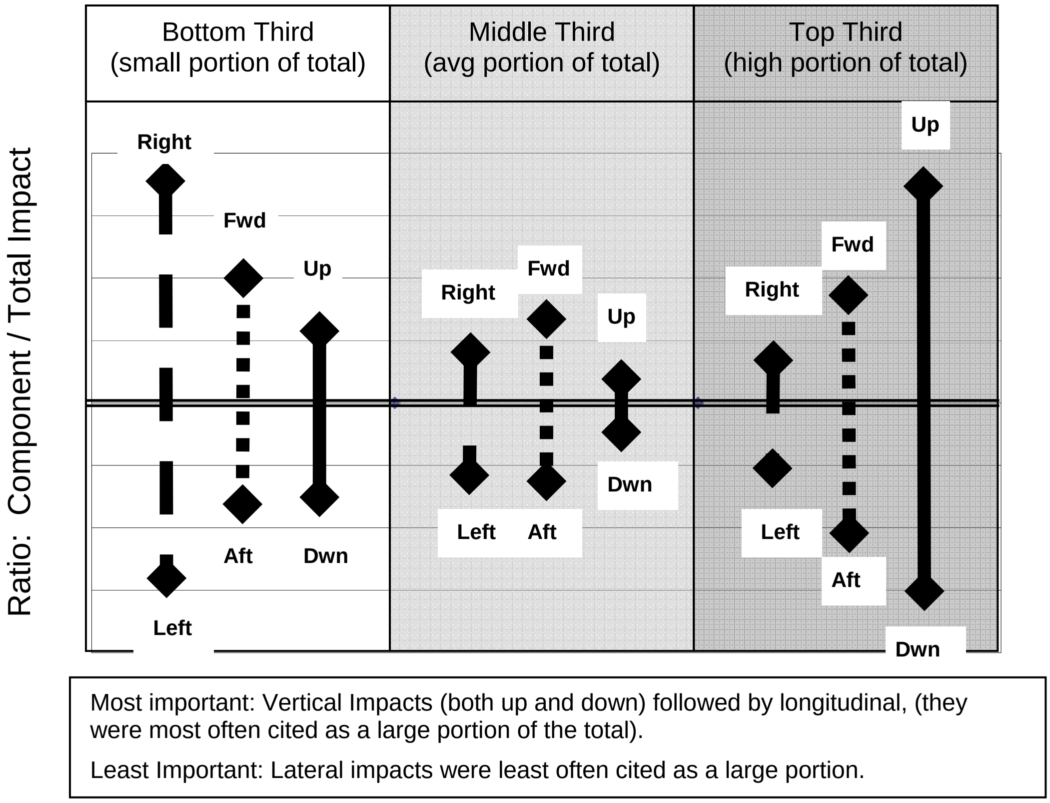

Figure 7-5. Ratio of Impact Component / Total Impact

The impact ratio assessment suggested that lateral impacts were generally a small portion of the total, that vertical impacts tended to be the predominant portion of the total, and that longitudinal were roughly evenly split across the ratio tiers. This ratio provided a perspective for understanding the component's relationship to the whole event. Interestingly, each of the 3 axis were balanced. This was expected for left and right, but is the same for the others as well. This further supported the observation that all impact orientations are important for crash survivability in helicopters. Fixed wing aircraft would likely have had nearly zero impacts in the aft and upward directions.

The limitations of this analysis were considered. The recorded impact acceleration magnitudes may have been confounded with predispositions of the investigator. For example, lateral impacts appeared to constitute a minor portion of the total, but this could have been caused by a focus on the vertical and longitudinal axes by the investigators. Also, the lack of middle values in the vertical axis may have suggested a predisposition to classify an impact as either very minor or very severe.

Impact Magnitude

The impact magnitude indicated the relative severity and was presented by the giving the frequency distribution for a range of impacts as described in the methods (Section 5.2.1). The magnitudes of each impact direction or each accident were placed in to categories depending on their severity. Table 7-6 represents how often a particular direction had an impact occur within each acceleration range. Specifically, the values were the percentage of the impacts cited for that range and direction.

Table 7-6. Impact Magnitude Distribution

Impact Severity Acceleration (g)	Left	Right	Fore	Aft	Up	Down
0 to 25	63%	64%	50%	35%	28%	37%
26 to 50	13%	22%	18%	21%	30%	30%
51 to 75	0%	4%	3%	4%	12%	7%
76 and Above	25%	9%	30%	40%	30%	26%

The impact magnitude for each direction made up a portion of the total. The categories in Table 7-6 represented the actual impact component. The category of 76 g and above was considered non-survivable. This assumption was made because if one component was above 75 g, then the total impact was even larger. The resultant impacts have been related to the survivability of the accidents by calculating the resultant impact acceleration and then separating the fatal and non-fatal. This provided a means to estimate the survivability envelope from the accident data. Figure 7-6 plots the percentage of accidents reported as a function of the resultant impact acceleration. Fatal, Non-Fatal, and all of the accidents together are represented. The fatal curve increased even while the total for all accidents decreases. Fatal case listings are most frequent at about 100 g. The non-fatal and fatal curves cross at about 60 or 70 g. About 95 percent of the non-fatal accidents occured below 125 g.

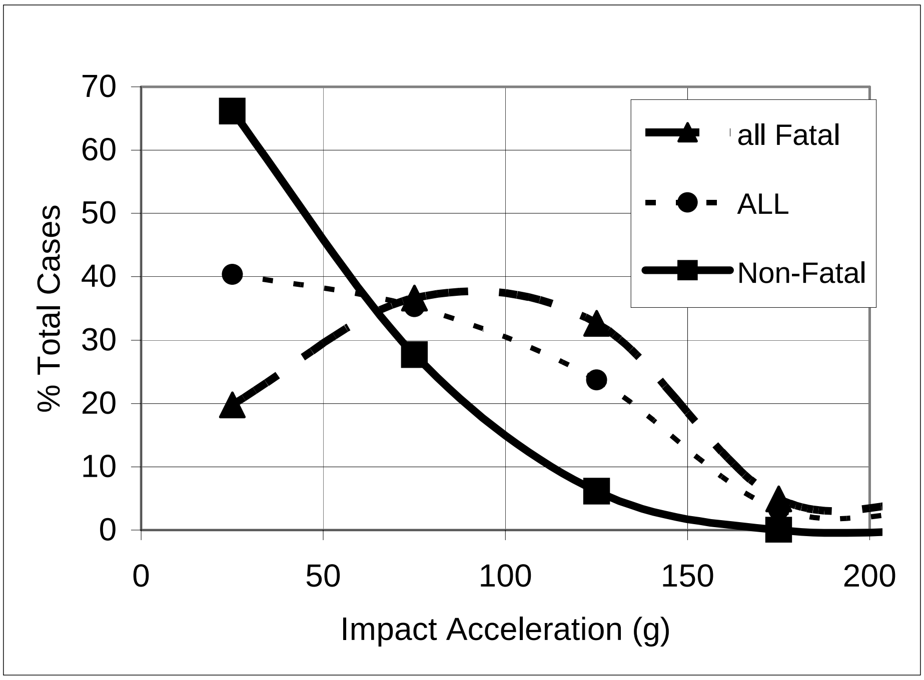

Figure 7-6. Accident Frequency vs. Impact Resultant, Calculated from Data from the USAARL Accident Database

Observations from the Aircraft Impact Evaluations

- The data was predominantly helicopters, which affected the results. All impact directions were indicated as roughly equally important, while this was known not to be the case for small fixed wing aircraft. Data for fixed wing aircraft was not available, but this provided scope for further work.

- The evaluations provided an understanding the impact characteristics of the USAARL accidents to support the discussion and conclusions.

- The impact evaluations also provided a basis to understand the results of the modelling analysis (Chapter 6).

- The survivability envelope (illustrated in Figure 7-6) was used as a basis of survivability of accident analysis for the modelling (Chapter 6), and supported the conclusions.

Injury Distribution Evaluation Results

The injury listings were first presented by region in Table 7-7 and Figure 7-7. These were consistent with the data format used in the evaluation of the published studies (Section 7.1.1), where the body region data represented a percent of the total. The body regions added up to a total of 100 percent. Evaluation of body part injury listings were then provided, which also remained consistent to the data format used in Section 7.1.1. Body part listing value is the frequency of that listing in the cases represented. Thus the totals added up to more than 100 percent, as many body parts were sometimes listed for each case.

Table 7-7. Injuries by Body Region

Region	Total	Fatal	Non-fatal	%Fatal	%Non-Fatal
Above Shoulder	805	606	199	37%	33%
Uppr Torso	628	551	77	34%	13%
Lower Torso	379	272	107	17%	18%
Upper Extremities	171	87	84	5%	14%
Lower Extremities	253	119	134	7%	22%
Total	2236	1635	601	100%	100%

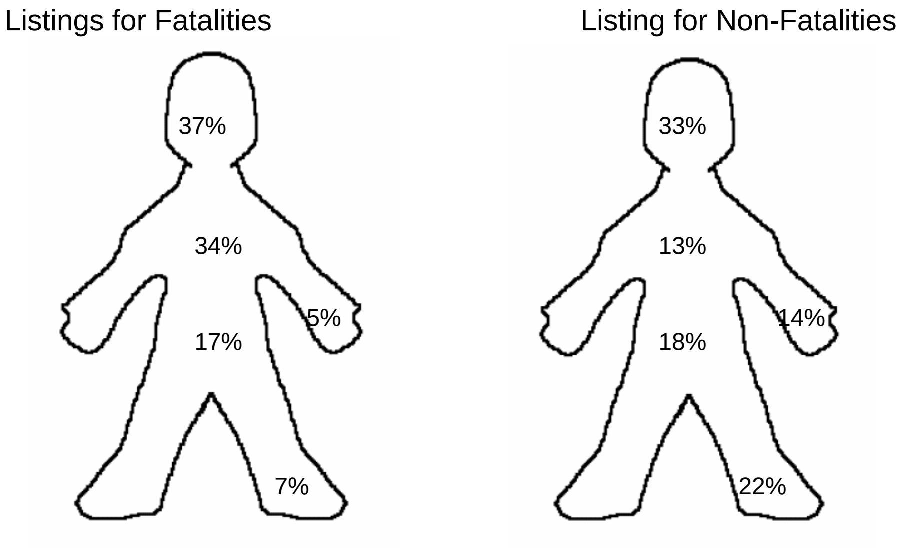

Figure 7-7. Injuries According to Body Region

Table 7-8 provides the injury listings according to body part. The injury listings were also categorized as fatal or non-fatal, indicating if the person suffering that injury died. (It does not indicate that the person died of the specific injury listed.)

Table 7-8. Injuries by Body Part

Part	Total	Fatal	Non-fatal	% Fatal	% Non-Fatal
Head/Skull/Brain	551	462	89	28%	15%
Face/Jaw	132	45	87	3%	14%
Neck, C1-C7	122	99	23	6%	4%
Upper Organs (Heart, Aorta, Lungs)	372	355	17	22%	3%
Upper Torso (chest, ribs, Thoracic Vert)	256	196	60	12%	10%
Lower Organs (abdo, bladder, diaph, kidney, liver, pancreas, spleen, stomach, intestines)	202	172	30	11%	5%
Lower Torso (Hip, Pelvis, L1-L4)	177	100	77	6%	13%
Upper Extremities	171	87	84	5%	14%
Lower Extremities	253	119	134	7%	22%
Total	2236	1635	601	100%	100%

The body part listings were also evaluated using the same categories as the Weigmann data in Section 6.1.1. The US Army data was predominantly helicopters while the Weigmann data was GA aircraft. Various Factors such as the typical flight missions, and aircraft design affect the distributions, thus they were not expected to correlate in some areas. Differences in the study parameters also had an affect. Designations were not identical, which explained why some categories, such as the sacrum, were very different from the Weigmann data. Figure 7-8 and Table 7-9 provide the body part injury listings organized by body region, while Figure 7-9 provides the same data according to Injury Ranking, as defined in Section 7.1.1.

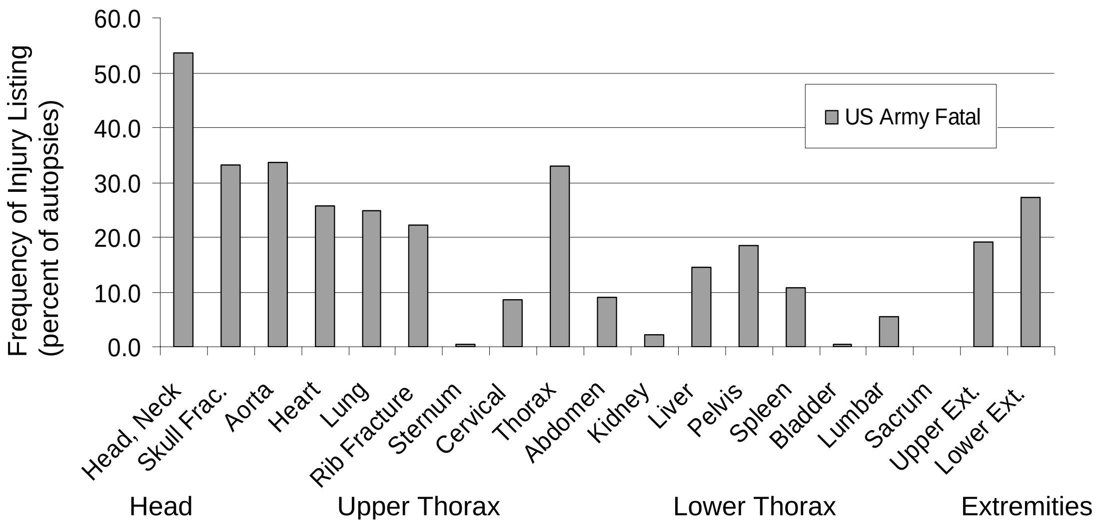

Figure 7-8. Distribution of Injuries from n=407 Autopsies of Fatal US Army Accidents

Table 7-9. Distribution of Injuries from n=407 Autopsies of Fatal US Army Accidents, Frequency of Injury Listings as a Percentage

	Head, Neck	Skull Frac.	Aorta	Heart	Lung	Rib Fracture	Sternum	Cervical	Thorax	Abdomen	Kidney	Liver	Pelvis	Spleen	Bladder	Lumbar	Sacral	Upper Ext.	Lower Ext.
%	53.6	33.2	33.7	25.8	24.8	22.1	0.5	8.6	32.9	9.1	2.2	14.5	18.4	10.8	0.5	5.4	0	19.2	27.3

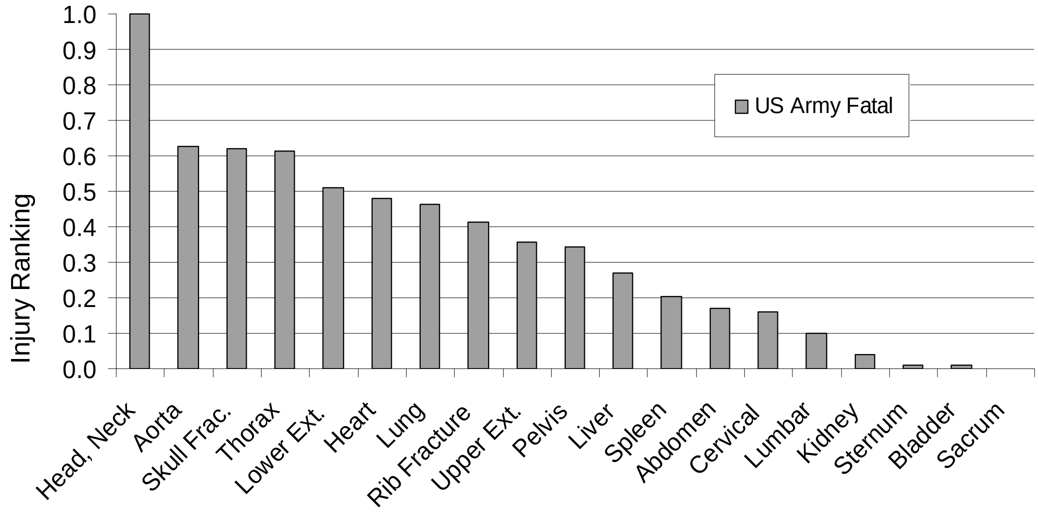

Figure 7-9. Injury Ranking for n=407 Autopsies of Fatal US Army Accidents

The US Army injury listing per body type also included 199 non-fatal occupant cases. The Injury Ranking for these body part injury listings is provided in Figure 7-10.

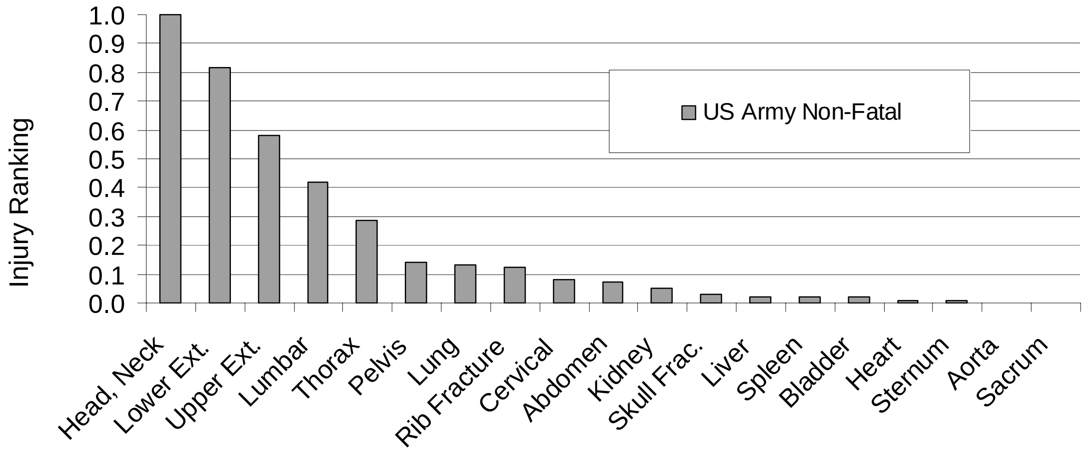

Figure 7-10. Injury Ranking for n=199 Non-Fatal Occupant Cases of US Army Accidents

Observations from the Injury Distribution Evaluation

- The high frequency of HAI as found in published studies was confirmed in the US Army data. The US Army data provided the complete data to establish a control group for a detailed evaluation as presented in Section 6.2.2.
- The lack of HAI in the non-fatal listing suggested that it does not occur in survivable accidents.
- The evaluation provided data for comparison to other research.

7.2.2 Study of HAI, USAARL Database

The study of HAI focused on the injuries listed with respect to the heart and aorta. A control group was also established consisting of the cases without HAI listed. The study was based on the same data from the USAARL database, but due to the slightly expanded inclusion criteria (19 g vs. 20 g as explained in the methodology, section 5.2.2); there were 187 accident cases for the years 1983 to 2005. The methodology for this study was contained in Chapter 5, Section 5.2.1. The results first evaluate the aircraft impact and then the injuries. Comparisons of the two are then presented.

Accident Severity Evaluation

Most of the aircraft in the study were helicopters, as this was the majority of the U.S. Army aviation fleet. The frequency of aircraft types involved in the HAI accidents was similar to those of the control group. HAI was not shown to be airframe-specific. The types of aircraft evaluated were shown in Table 7-10.

Table 7-10. Aircraft Types with HAI

Aircraft Type	No. of Cases (%)	
	All Accid. > 20g (Control Group)	HAI Accid.*
OH-58	42 (23%)	9 (25%)
MH- /UH-60	42 (23%)	5 (14%)
AH-64	28 (15%)	4 (11%)
UH-1	24 (13%)	5 (14%)
AH-1	10 (5%)	3 (8%)
MH- /CH-47	8 (4%)	2 (6%)
Other	33 (18%)	8 (22%)
Total	187 (100%)	36 (100%)

One HAI accident was removed from the evaluations because the injury did not occur while in the aircraft. The occupant in this case was ejected from the aircraft into a tree. This was also the only HAI accident with a resultant impact below 20 g (the impact was reported at 12 g).

The impact force correlates with the frequency of HAI cases as shown in Figure 7-11. HAI occurred less frequently at low severity impacts, occurring in 22 percent (n=36) of impacts between 20 and 60 g, while 59 percent of the control group accidents occurred at low impact levels. The frequency of HAI for severe impacts (180-200 g) was approximately three times that of the control (0.314 and 0.112, respectively). The frequency of HAI cases exceeded the control frequency at 80 g.

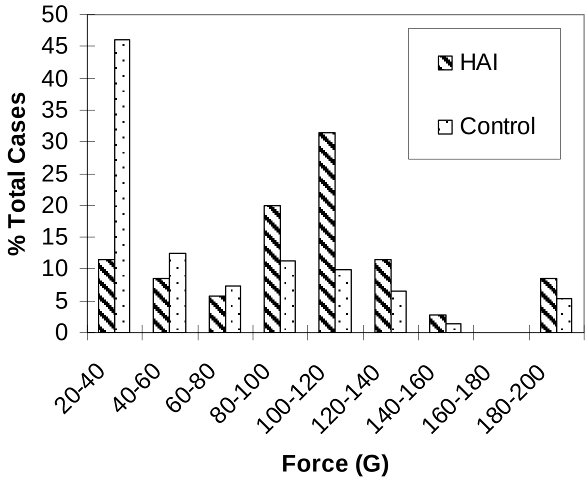

Figure 7-11. Histogram of HAI and Control for Impact Force

The pre-impact vertical velocity did not show as strong of a correlation to HAI frequency as impact force, although the trend was the same as shown in Figure 7-12. The frequency of HAI accidents was 26 percent (n=31) of accidents below 60 Knots, while the control was 39 percent.

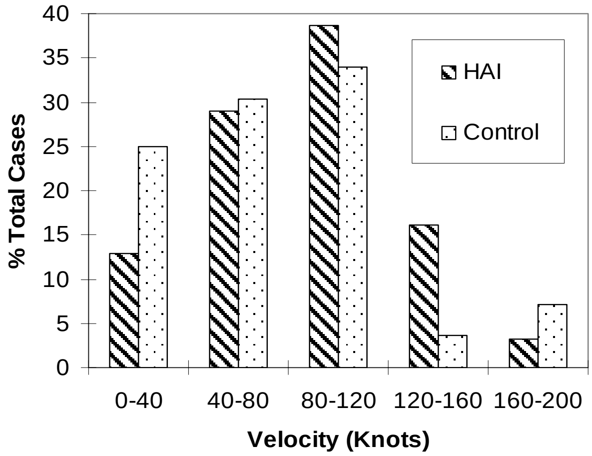

Figure 7-12. Histogram of HAI and Control for Pre-Impact Vertical Velocity

Figures 7-13 and 7-14 illustrate the standard normal distributions based on the means, standard deviations, and number of cases shown in Table 7-11. The HAI cases demonstrated a significant difference in means for impact force but not for flight velocity (p=0.010 and 0.225, respectively). The impact force curve was skewed right, suggesting that HAI occurred at more severe impacts.

Table 7-11. Pre-Impact Flight Velocity and Impact Force

Accident Type (number of accidents)	Measure	Mean (Std Dev)
HAI (n=31)	Velocity (knots)	82 (38)
Control (n=60)	Velocity (knots)	72 (45)
HAI (n=36)	Impact (G)	96 (48)
Control (n=151)	Impact (G)	71 (58)

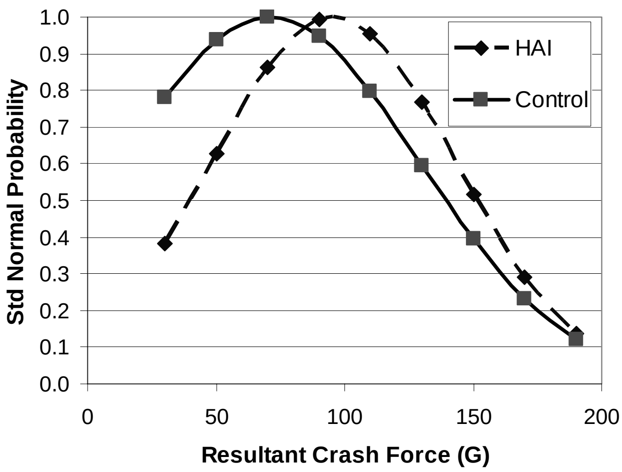

Figure 7-13. Standard Normal Probabilities of HAI and Control for Impact Force

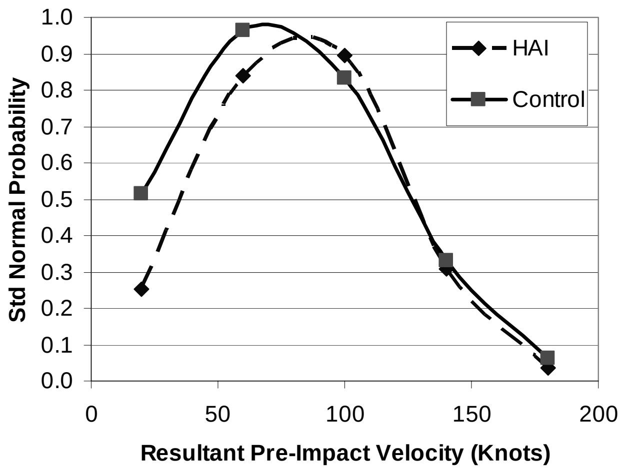

Figure 7-14. Standard Normal Probabilities of HAI and Control for Pre-Impact Vertical Velocity

HAI Injury Evaluation

The study identified 77 occupants suffering HAI in the 36 cases. The pilot or co-pilot positions were the most common with HAI, which was expected as these are the most commonly occupied seats. Seven (7) of the 36 aircraft had only these two occupants on board. The occupants with HAI were distributed as shown in Table 7-12. The occurrence of HAI was not associated to any particular duty position. Thus Table 7-12 also reflected the distribution of duty positions occupied in the aircraft of the control group.

Table 7-12. Occupant Duty

Occupant	No.	% of total
pilot or co-pilot	48	62.3
flight engineer	14	18.2
passenger	12	15.6
gunner	2	2.6
unidentified	1	1.3
Total	77	100

A UH60 case was worthy of note as the only case without either the pilot or the co-pilot suffering aortic injury. The Flight Engineer and four passengers suffered HAI. This case also had a very low resultant impact severity of only 25 g, one of only four cases below 40 g. It is possible that the EA seats used by the pilot and co-pilot mitigated potential HAI.

The total number of occupants in 4 aircraft could not be confirmed, and thus the injury evaluation was conducted with the remaining 32 accidents. The 32 accidents resulted in a total of 172 occupants and 588 injury listings. The ratio of those with HAI versus those without is 41.8 percent (n=72). The average age of the occupants was 31 years, with a range of 19 to 45 years. The frequency of multiple occupants in the same aircraft suffering from HAI was 67 percent (24 of the 36 total aircraft).

To clarify the aetiology of HAI, a qualitative assessment of HAI occupants with a predominant inertial movement of the heart/aorta as the aortic injury mechanism was conducted. This assessment was based on autopsy data compared to the accident scene terrain and post-crash vehicle description/photographs. Two cases showed accelerative force as a clear contributing factor; however, based on scene photos and crash data, neither (0/2) inertial case demonstrated a predominant downward displacement of the heart/aorta from inertial force as the mechanism of injury. This suggested that the impact force and associated accelerations in isolation did not significantly affect the occurrence of aortic injury. Thus the qualitative assessment of the selected full accident files did not support the hypothesis.

The US Army HAI study addressed the hypothesis that displacement of the heart is a significant source of aortic stress and injury during impact; however evidence of this could not be confirmed in these evaluations. Cockpit/environmental factors were the primary cause of HAI for the aircraft designs evaluated. Structural intrusion resulting in blunt trauma (specifically, crushing trauma) appeared to be the prominent source of injury for those without obvious penetrating trauma. Isolated inertial displacement was a questionable mechanism. The results of the pre-impact velocity and impact forces reviews indicate that HAI occurs more frequently in severe crashes, impacts above 80 g and 100 knots, which are well beyond the survivable envelope. The increased frequency of HAI at these impact levels was associated with destruction of the cockpit/cabin rather than inertial loading to the body.

8. ANALYSIS AND DISCUSSION

A combination of computer simulations and accident studies were used to determine if vertical aircraft impacts are a critical factor in crash survivability. The computer model simulations are analyzed and discussed in section 8.1 and the accident studies in section 8.2. Section 8.3 considered the model simulations and accident studies together.

8.1 Modelling of Aircraft Crash Impacts

Modelling programs other than PAM-CRASH could have been used for this research. Modern explicit Finite Element Analysis (FEA) computer codes such as LS-Dyna or MSC Dytran would have been roughly equivalent to PAM-CRASH. All the FEA codes have the ability to distribute element masses at the points on the grid and allow the objects to be deformable at the grid points. This research used a more simple approach with rigid bodies having a lumped mass at the Centre of Gravity (COG). A code based on lumped masses could have been done more quickly in programs such as DRI/KRASH, MADYMO or ATB (Section 2.4). There were advantages to using a full FEA code for this research. The PAM-CRASH code included a Hybrid II and Hybrid III ATD models which were directly comparable to the physical ATD's used in the NASA Langley IDRF crash tests. Another reason was the capability for future model development using more sophisticated models. Every level of the model allows for substitution of refined parts. For example, a deformable seat structure validated to a real seat could replace the rigid seat; an updated ATD model or human body model could be substituted, or a more detailed and refined visco-elastic organ system could be incorporated. The simple heart and aorta model (representing the viscera as a whole) was used because the kinematics of the organs relative to the body was needed to satisfy the research objectives.

The simulation results from chapter 6 were analyzed according to the research objectives as follows: First, the computer model simulations were evaluated for survivability based on the spine model response of Dynamic Response Index (DRI). Second, the simulation responses for the heart and aorta model were evaluated to assess the potential for visco-elastic injuries. Table 8.1 provides a summary of the simulation results from chapter 6.

Table 8-1. Impact Simulation Model Response and Impact Parameter Summary

Model Response					Impact Parameters		
	Peak DRI (G units)	Peak Seat Accel. (g)	Peak Heart Displ. (mm)	Peak Heart Vel. (m/s)	Impact Peak Accel. (g)	Impact Slope (g/s)	Impact Delta V (m/s)
Mil. Airbag Thr.	19.1	12.1	39	1.88	12	1000	3.5
GA Fwd/Dwn	15.4	15.0	55	1.57	16	190	8.2
UH60 Fwd/Dwn	17.8	15.9	54	0.90	25	581	7.6
UH-60 Down	94.9	219.1	155	8.55	50	1388	12.8
YAH-63	69.8	139.6	90	3.92	60	2400	12.2
Sikorsky	109.4	224.7	129	8.68	93	2400	12.2
Model Response					Impact Parameters		
	Peak DRI (G units)	Peak Seat Accel. (g)	Peak Heart Displ. (mm)	Peak Heart Vel. (m/s)	Impact Peak Accel. (g)	Impact Slope (g/s)	Impact Delta V (m/s)
Mil. Airbag Thr.	19.1	12.3	39	1.88	12	1000	3.5
GA Fwd/Dwn	16.5	15.6	56	1.63	16	190	8.2
UH-60 Fwd/Dwn	23.2	20.1	64	1.30	25	581	7.6
UH-60 Down	31.2	23.5	83	2.60	50	1388	12.8
YAH-63	34.2	23.1	75	1.64	60	2400	12.2
Sikorsky	27.3	24.8	83	2.60	93	6200	11.6

Correlations were derived between the aircraft impact input parameters and selected responses shown in Table 8.1. The correlations helped indicate the important factors associated with the impact parameters. The correlation table is provided in Appendix E. Cavanaugh (2005) compared aortic injuries to rib acceleration in lateral impacts (plots are provided in appendix E). A similar approach was considered using DRI, but was not found to be useful. The peak force of the aircraft impact was strongly correlated to Dynamic Response Index (DRI) for the GA seat, but not for the military EA seat. Instead, the greater stroke and Energy Absorbing (EA) capability of the military seat caused impact velocity to be the dominant impact parameter affecting DRI for the military EA seats. For this reason, survivability limits were established according to both peak acceleration and velocity change impact parameters. Impact slope was suspected to be an excellent predictor of visco-elastic response because it incorporates both force (peak acceleration) and energy (velocity change). However it was poorly correlated to the occupant responses. The peak impact acceleration and velocity change provided a better measure of impact severity than impact slope. The visco-elastic response of the heart model, as measured by heart displacement and heart velocity, were best correlated by a combination of the peak acceleration and velocity change depending on the type of seat evaluated.

8.1.1 Survivability Envelope Based on DRI Response

Chapter 6 collected a range of aircraft crash impacts and selected six for computer simulations (Table 6.1 and Figure 6.1). The selections were made to span a range of impact severity and survivability. The DRI responses from the computer simulations were compared to published design criteria. The computer model and crash simulation approach had the advantage of generating responses for specific seat types and impact conditions, allowing the design to be evaluated for survivability with respect to spine injury. The survivability regions in Figure 8.1 correspond to the DRI design limit of 20 g units for the onset of spine injury (Section 2.3.1). Chandler (1983) also presented a guideline of 15 g to 18 g as a threshold of injury for the +gz impact direction. A limit of survivability (as opposed to injury) for DRI was not found in literature, thus an acceleration force applied vertically through the seat exceeding 50 g was deemed an approximate limit of survivability. This value was based in part on the Eiband whole body tolerance curve (US DOD 1998) as well as qualitative assessment from this body of research.

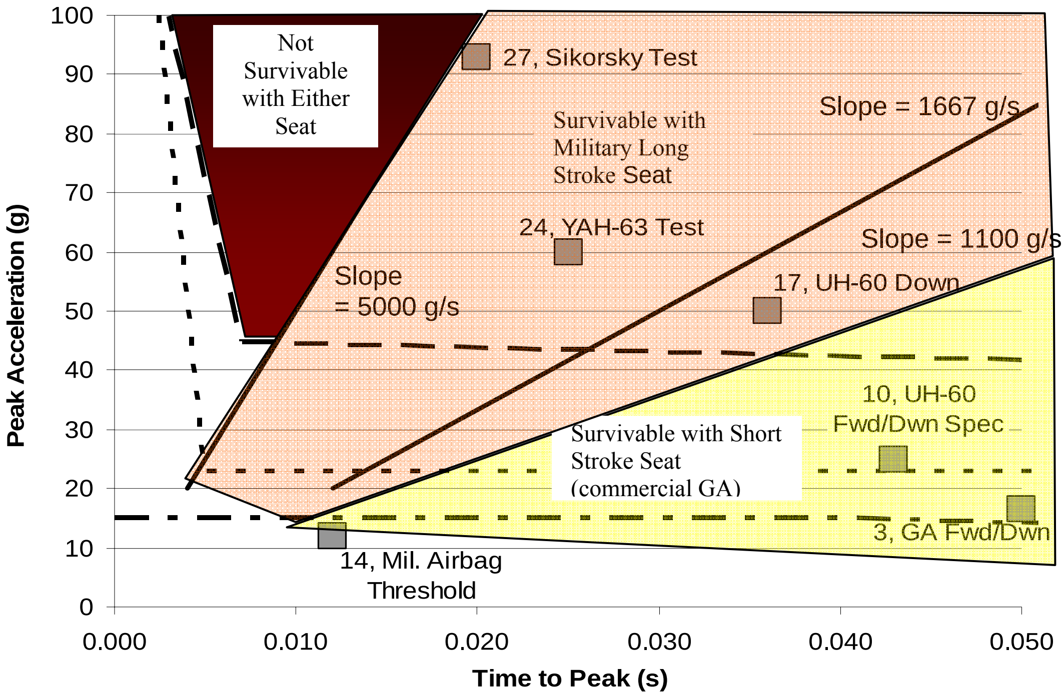

Figure 8-1. Crash Test Simulations with Estimated Survivability Limits

The risk of spine injury as measured by DRI was also related to impact velocity. Estimates of spine injury potential were determined as shown in Table 8-2.

Table 8-2. Impact Severity and Risk of Spine Injury Based on Model Results

Risk of Spine Injury	Impact Velocity	Impact	Seat Used	DRI
Low to Moderate	3.5 m/s to 8.2 m/s	Airbag Threshold	GA or Military EA	19.1 (GA) 19.1 (Mil. EA)
		GA Dwn/Fwd	GA or Military EA	15.4 (GA) 16.5 (Mil. EA)
		UH-60 Fwd/Dwn	GA	17.8 (GA)
High	7.6 m/s to 12.8 m/s	UH-60 Fwd/Dwn	Military EA	23.2[1]
		YAH-63	Military EA	34.2
		UH-60 Dwn	Military EA	31.2
		Sikorsky	Military EA	27.3
Non-Survivable	Above ~ 13 m/s	YAH-63	GA	70
		UH-60 Dwn	GA	95
		Sikorsky	GA	109

Note 1: The DRI value is higher than the same impact with the GA seat, which appeared to be counter-intuitive, as the military seat has better EA capabilities. However, the EA mechanism activation threshold for the military seat is set higher than the GA seat (see Section 6.4). The military seat was designed for more severe pulses, resulting in a trade-off for moderate pulses.

Published accident studies were evaluated for vertical spine injury and the results correlated well to the injury risk shown in Table 8-2. Alfaro-Bou (1981) studied general aviation impact pulses and the corresponding seat and occupant response. He proposed that the maximum space for vertical EA features in a GA aircraft was about 0.25 m, with the potential to mitigate a maximum vertical velocity change of 12 m/s (Alfaro-Bou 1981). The results shown in Table 8-2 indicated a lower threshold of moderate injury (GA seat 3.5 m/s to 8.2 m/s) than Alfaro-Bou, which was attributed to the differences in the seat stroke distances. The simulations defined a typical GA seat with 0.1 m of stroke (section 3.3.1), while Alfaro-Bou (1981) used a theoretical maximum stroke of 0.25 m. The two-and-half times better capability was closer to the military EA seat simulation (stroke distance of 0.37 m). Considering this, the Alfaro-Bou conclusion of 12 m/s mitigated velocity change was in the range of the simulations. The Alfaro-Bou 0.25 m stroking seat was noted as able to mitigate 12 m/s, which was somewhat surprising, as 12 m/s is near the limit of survivability for any seat. The results of this research suggested that a GA seat with 0.25 m of stroke would only be able to effectively mitigate an impact of about 10 m/s, especially considering that the GA seats tend to have a lower stroking activation threshold than military seats. Alfaro-Bou (1981) also noted that 20 g's for durations up to 0.1 second can be sustained without serious injury, but at 40 g, serious injury occurs with durations exceeding only 0.01 seconds. This correlated well with the research results for seat and pelvic accelerations. Section 4.3 and 4.4 reported pelvic and seat accelerations from 40 g to 50 g for the severe injury potential in the impacts of the YAH-63 and Sikorsky crash test simulations.

Helicopter survivability studies also correlated well with the modelling results. Shanahan (1985) noted a strong relationship between vertical velocity change and spine injury. Figure 8-2 compared the three spine injury levels noted above in Table 8-3 with the spine injury distribution curve given in Shanahan 1985.

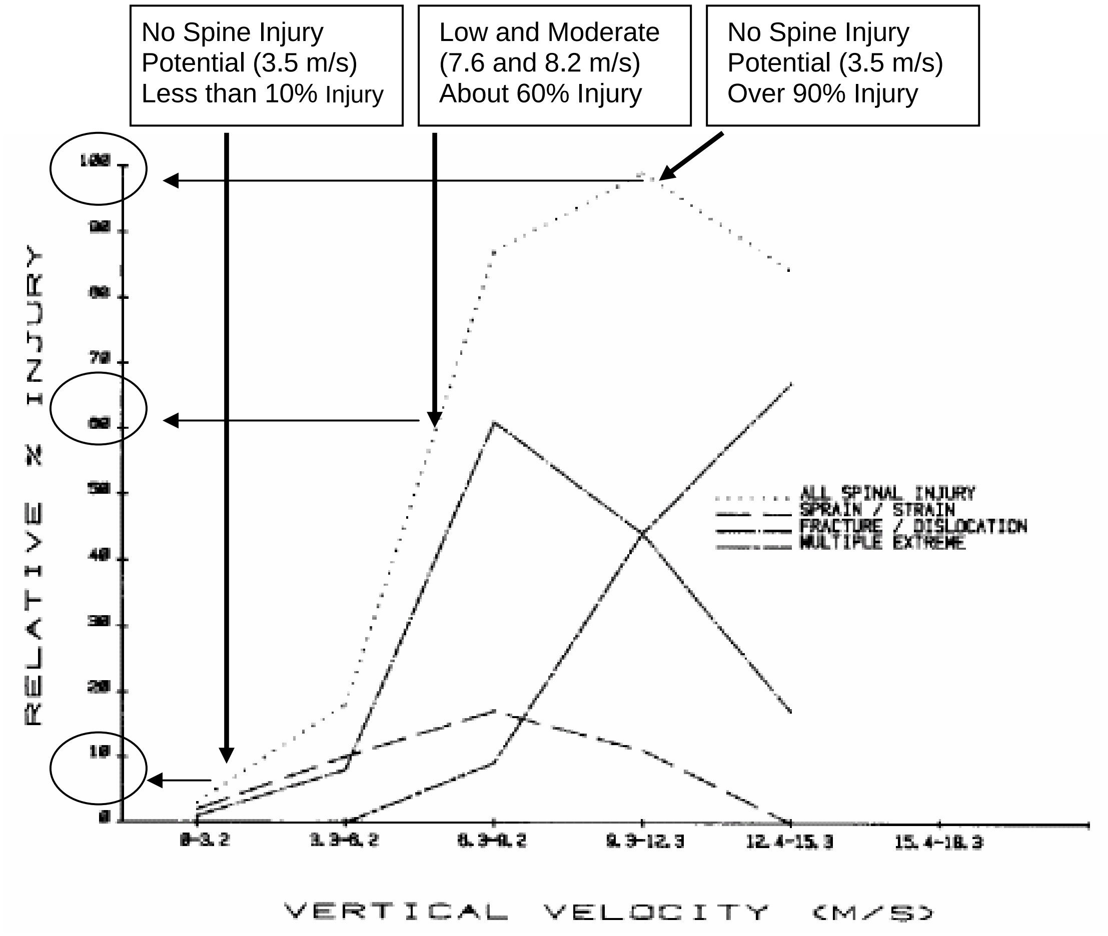

Figure 8-2.Relative % Spine Injury versus Vertical Impact Velocity from Shanahan 1985 and with Thesis Spine Injury Potential from Chapter 6

The comparison in Figure 8-2 suggested that the survivability ranges determined from the research were appropriate. Thus the impacts conditions and seat type corresponding to the survivability envelope given in Table 8-2 were also deemed appropriate.

8.1.2 Heart Model (Visco-Elastic Tissue) Response Analysis

The occupant model together with the rest of the aircraft system was created as a means to evaluate potential injury. The potential for heart and aortic injuries were the specific goal, however the research modelling was not able to achieve the level of detail required to study HAI injury thresholds. Although referred to as the "heart and aorta" model, it did not simulate specific HAI mechanisms, and instead simulated macro movements of the organs and viscera. The decision was made to abandon an approach that would attempt to develop a model of specific heart and aortic response to vertical impacts for the following reasons. It became apparent during the research that insufficient information was available to pursue such a model. The detailed model approach was not selected because it would not have been possible to resolve injury thresholds. As stated in the literature review (chapter 2) and the model methodology (chapter 5), visco-elastic tissue response for the vertical impact direction remains un-quantified. Further, if a threshold was established, the broader understanding of how often and under what conditions HAI occurs would not have been sufficient to solve the hypothesis (HAI due to inertial movement from vertical impact as a significant factor for survivability). Thus the model was made to represent the visco-elastic tissue response of the organs, based on the limited vertical response data found in literature. Although the HAI model did not provide a true measure of heart displacement, the response was useable to approximate the potential of visco-elastic tissue injury for one impact relative to another. The model has the advantage of providing information about potential injury for organ injuries beyond only the heart and aorta. This model approach had the disadvantage of not providing specific information about actual heart and aorta injury mechanisms, limiting the conclusions to general organ response.

<u>Estimating Visco-Elastic Injury</u>

The spine injury evaluation (section 8.1.1) classified the six simulated impacts into three severity ranges: low to moderate, high, or non-survivable. Each simulation compared two seat types, either GA or Military EA. This provides 12 impact/design combinations ranging from no injury to non-survivable with respect to spine injury, as given in Table 8.2. The corresponding heart model responses (displacement and velocity) for the twelve impact/design cases were evaluated according to visco-elastic injury potential, referred to here simply as organ injury. General visco-elastic injury has been associated with tissue deformation rates as follows (Coltman 1989):

- Below 3 m/s were associated with crushing injury and are below the threshold of viscous injury.
- Viscous injury occurs at deformations beginning at rate of about 3 to 20 m/s.
- Values above 20 m/s are associated with shock injury and do not apply.

The assumption was made that the HAI model was a reasonable measure of the viscera deformation rate due to vertical impact loads. Although the model response was calibrated to available literature (chapter 4), the deformation rates were developed for the anterior / posterior direction. These thresholds were used to approximate relative injury between the simulations for general organ injury, and were considered applicable for the purposes of this research.

Low to Moderate Severity Impacts

The Airbag Threshold, GA Dwn/Fwd, and UH-60 Fwd/Dwn impacts were of low risk for spine injury using both seat designs because they are well within the design limit of most aircraft interiors (chapter 2). The corresponding heart displacement responses were all less than 60mm. Because impacts of this severity are associated with only minor injuries, essentially zero risk of organ injury was established for heart displacements less than 60 mm (relative to this model). The tissue deformation rate (peak heart velocity) was well below 3 m/s for all three impacts using both the GA and military seats. The Airbag Threshold pulse produced the highest heart velocity for this group (2 m/s), and higher than impacts with about 4 times the acceleration and velocity change. It appeared that this was due to the relatively high onset rate of the airbag threshold pulse. The heart velocity response was very rate sensitive even at low impact severities. The aircraft impact rate did not have an affect heart displacement.

High Severity Impacts

The YAH-63, UH-60 Dwn, and Sikorsky impact simulations were at a high risk of spine injury (Figure 8-1), but were survivable if the occupant was seated in a highly capable EA seat. The corresponding heart displacement responses were between 60mm and below 90 mm. Heart displacements for these impacts with the military GA seat ranged from 75 to 83 mm. The entire group remained within the 3 m/s tissue deformation guideline, below the risk of viscous injury. The relatively low heart velocity response for these severe impacts suggested that spine injuries will occur prior to organ injury, even for a variety of impact onset rates and seat designs.

Non-Survivable Impacts

The YAH-63, UH-60 Dwn, and Sikorsky impacts were determined to be non-survivable for a GA seat (Figure 8-1). The heart displacements were 90, 155 and 129 mm respectively. The heart velocity response for this group exhibits a greater distinction between the YAH-63 (the least injurious impact of the group), and the UH-60 Down and Sikorsky. The two most severe impacts have nearly the same velocity at over 8 m/s and far in excess of all the others.

A graphical representation of the heart model displacement and velocity responses are given in Figures 8-3 and 8-4. The heart displacement response had the strongest correlation to peak seat acceleration for both the GA Seats (0.97) and EA seats (0.92). The heart displacement versus peak seat acceleration for the twelve cases (six aircraft impact simulations with two seat types each) is shown in Figure 8-3.

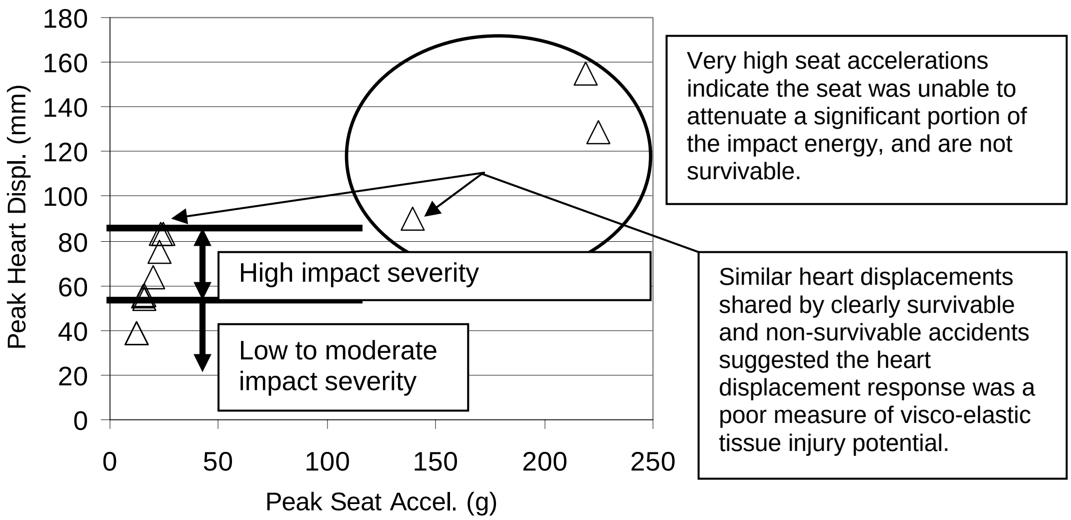

Figure 8-3. Heart Displacement Model Results vs. Peak Seat Acceleration

The three points shown in the circle represent non-survivable events because the seats bottomed out and were unable to mitigate the impact. The two points above 200 g were the Sikorsky and UH60 Down impact simulations using the GA seat. The point at about 150 g was the YAH impact with the GA seat. The YAH impact was the least severe of the impacts which exceeded the stroke capabilities of the GA seats, but the GA seat bottomed out, causing a non-survivable spike in seat acceleration and DRI (140 seat g and 70 DRI G units). However the heart displacement response demonstrated an overlap between some of the survivable and non-survivable events at around 90 mm. This non-progressive response suggested that the heart displacement did not account for an important factor. A progressive, linear response would show a measurable change given changes in the impact severity.

For example, the DRI response demonstrated a very good linear progression for the entire group, independent if the seat bottomed out or not, as shown in Figure 8-4. The equation for the linear fit of the data was calculated along with the correlation coefficient (R^2 value), which represents the proportion of the variance in the ordinate attributable to the variance in the abscissa (Pearson coefficient Devore 1982). While peak seat acceleration was a good indicator of spine injury, the visco-elastic response and presumably potential for organ injury was shown to be more complex. Bottoming out the seat stroke resulted in a DRI spike but not necessarily significant response in the heart displacement.

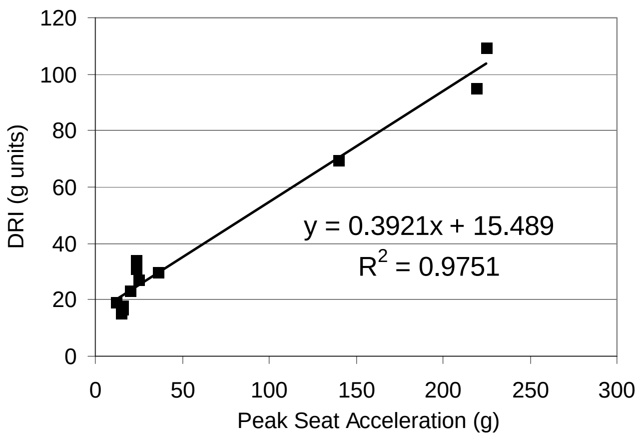

Figure 8-4. DRI vs Peak Seat Acceleration

The heart velocity response demonstrated a similar non-progressive response as heart displacement, although not as severe. Figure 8-5 depicts the peak heart velocity versus peak seat acceleration for the twelve cases.

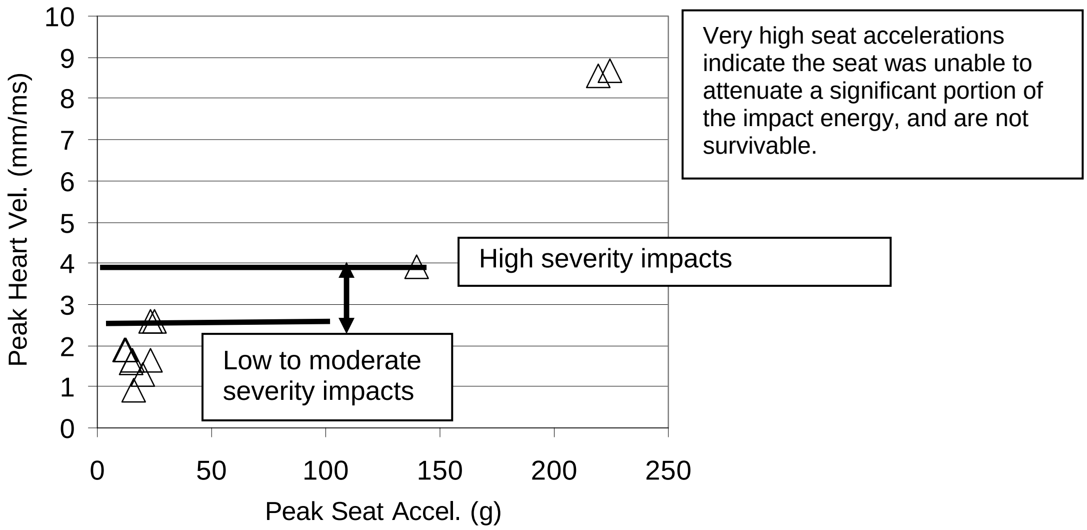

Figure 8-5. Heart Velocity Model Results vs. Peak Seat Acceleration

The research objectives required an assessment of the potential for viscous tissue injury to be compared with the survivability of the impact. The HAI model responses did not provide a measure that was directly useable, and thus the results were evaluated further to identify the appropriate relationship.

8.1.3 Survivability Assessment with Viscous Injury

The heart displacement and peak seat acceleration demonstrated a bimodal relationship. The seat stroke hitting bottom appeared to be the important differentiator. Separating the events that did or did not bottom out the seat stroke mechanism exhibited separate linear relationships to seat peak acceleration, as shown in Figure 8-6.

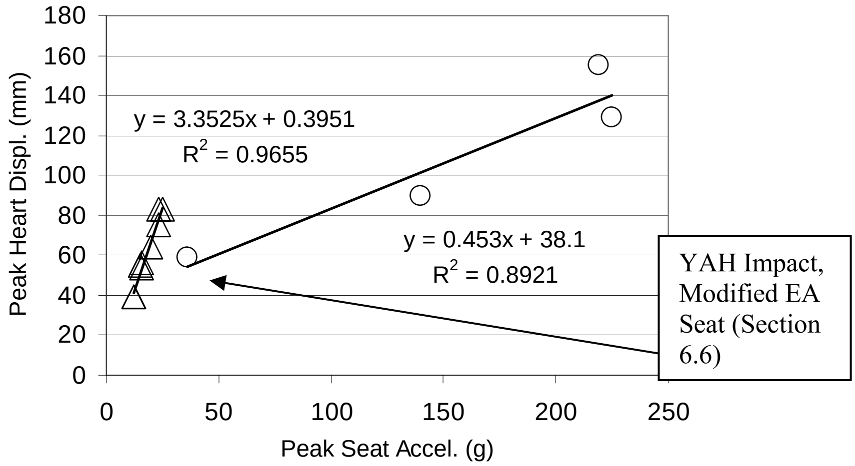

Figure 8-6. Peak Heart Displacement vs Peak Seat Acceleration, Results from Simulations, Chapter 6

The 3 points on the right hand side of Figure 8-6 were the clearly non-survivable impacts using the GA seat (UH-60 Down, Sikorsky, YAH-63). Most of the simulations from chapter 6 compared the GA seat design to the military EA seat design. But a third type of seat was evaluated for the YAH-63 impact, called the YAH modified seat (section 6.6), and had EA characteristics between the GA and military seats. This seat provided an interim point between clearly survivable and non-survivable events. The seat did bottom out, but with little remaining impact energy, and generated a DRI of 30 G units and peak seat acceleration of 36 g.

It was clear that in order to use the model to measure the potential for visco-elastic injury, the impact needed to be characterized not only by the force transferred to the body (seat acceleration). Various relationships between the heart displacement response and potential factors (impact pulse, seat response, or a combination) were explored. A factor was created and labelled "E*Seatg" which was found to have the best linear correlation to the heart displacement across all the simulations. Other factors were evaluated but were not found to reasonably correlate to the heart displacement response, and are given in Appendix E. Bottoming out the seat stroke was important only when accompanied by excessive unmitigated impact energy, giving the heart mass the momentum it needed to have a larger response. E*Seatg was developed to combine energy and force effects.

E*Seatg was defined as the product of the energy that each seat was unable to attenuate and the peak seat acceleration. The energy term was calculated as follows:

> The YAH-63 impact had a velocity change of 12.2 m/s for a 125 kg mass (seat and occupant as given in chapter 3) for an impact pulse energy of 9.3 KJ. The GA seat had an EA activation threshold force of 17 KN for a total energy attenuation capability of 0.85 KJ (with mass = 125 kg). Subtracting the total EA capability of the seat from the impact pulse energy provided the "left over" energy that the seat was unable to attenuate of 9.31 KJ – 0.85 KJ = 8.5 KJ. E*Seatg for the YAH-63 impact with the GA seat was 8.5KJ * 60 g = 305 KJ-g.

The heart displacement response vs E*Seatg for the model simulations is shown in Figure 8-7.

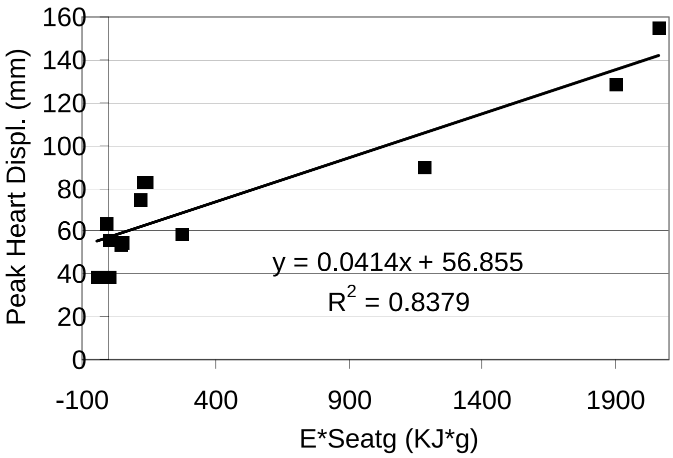

Figure 8-7. Heart Displacement Response vs E*Seatg Factor

The R^2 value of 0.83 was judged as fair, and while not as accurate as the DRI correlation to seat g, indicated that a combined force and energy factor was the appropriate method to characterize the relationship between the impact and the visco-elastic response. Comparing the heart velocity response to E*Seatg provided an even better correlation, as shown in Figure 8-8.

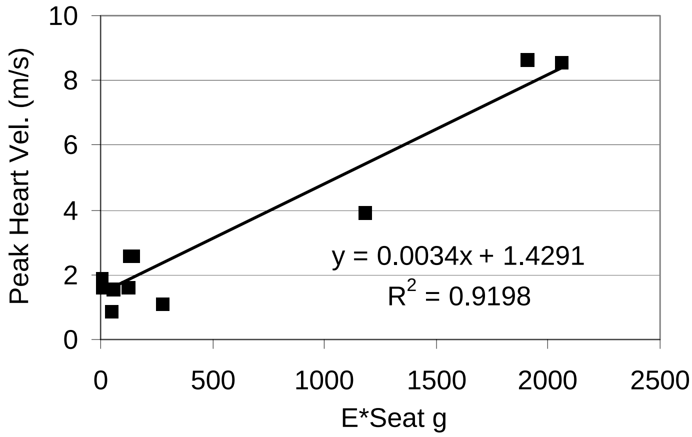

Figure 8-8. Heart Displacement Response vs E*Seatg Factor

The E*Seatg factor provided a scale of the impact severity that allowed a comparison across the measures of potential injury. The injury threshold using DRI was established as 20 g units with a non-survivable threshold of about 40 g units. These data points correspond to E*Seatg values of -14.0 and 471.5 respectively. This range of the E*Seatg factor was used as a representation of the injurious to non-survivable envelope based on spine injury. Calculating the heart displacement and heart velocity at the E*Seatg values of -14.0 and 471.5 gave the values in Table 8-3.

Table 8-3. E*Seatg at Spine Thresholds with Corresponding Heart Model Response

E*Seatg (KJ-g)	DRI (G units)	Heart Displacement (mm)	Heart Velocity (m/s)
-14.0	20 (Injury Threshold)	48.5	1.4
471.5	40 (Survivability Threshold)	96.5	3.0

Evaluating the values in Table 8-3 suggested that the onset of spine injury occurs prior to the onset of organ injury. The heart displacement measure had no reference point, but the heart velocity measure was referenced to the limits described earlier in this section. The spine injury threshold (DRI of 20 G units) corresponds to a heart velocity of only 1.4 m/s, well below the threshold of viscous injury of 3 m/s. The threshold of viscous injury corresponded directly with the estimated spine injury survivability limit (DRI of 40 G units). This indicated that spine injury would be expected to occur prior to organ injury as measured by the heart model (inertial loading as a result of vertical impact).

Further, as the heart model reached a threshold of injury while the spine injury would be expected non-survivable. This suggested that vertical, inertial displacement of the viscera is not a critical factor for survivability.

8.2 Accident Research Studies

The study of published data on accident survivability presented in Section 6.1 had the objective to review survival factors information and identify information relative to HAI. Limited survival factors information was found, and no conclusive information regarding the injury mechanisms of HAI were found. The only information specific to HAI amounted to injury citations and occasional anecdotal comments suggesting causative factors. The study of published accident reports and investigations clearly identified a lack of survival factors information, especially for the small aircraft which crash most often. The study of aircraft accident databases which contain searchable injury listings provided occurrence data for HAI as well as other injuries, but not related information about the crash conditions. The study did indicate significant progress regarding crash worthy design guidelines for aircraft interiors, such as shoulder belt requirements introduced for small aircraft during the 1980's (Section 2.2) and the introduction of the dynamic seat requirements and injury criteria for all commercial aircraft designed after 1988 (Section 2.2.2). The advancements in crashworthy design requirements for commercial aircraft are very important, but unfortunately the results of this progress and the ability to make future recommendations will be difficult, as methods to assess the changes (such as standardized survival factors data collection system) have not been put in place.

8.2.1 Study of All Injuries in USAARL Database

The first study of the USAARL Database looked at all injuries in section 7.2.1. The results of these studies were compared with similar published work.

Comparison to Aircraft Crash Survival Design Guide

The most recognized study of aircraft injury distribution was published in Volume II of the Aircraft Crash Survival Design Guide (ACSDG), page 24-27 (Coltman 1989). It is based on the same database as the USAARL study done for this thesis, but for an earlier time period (1980 to 1985 as opposed to 1983 to 2005). The focus of the ACSDG study was the type of aircraft and the terrain at impact, while the USAARL study was focused on the relationship between injuries and the severity / direction of impact. A comparison of injury by body region indicates very similar results, and is shown in Table 8-4. Note that the selection criteria are somewhat different between the two studies. The thorax abdomen and vertebra are combined because the thoracic bones and organs were not separately defined in the ACSDG study.

Table 8-4. Injury by Body Region Results, Barth Study and ACSDG Vol. II

Barth Thesis Study (Chapter 6, Section 6.2.1)			ACSDG Vol. II (All Mishaps 1980 to 1985)		
Part	Fatal	Non-Fatal	Part	Major / Fatal	Fatal
Head/Skull Brain/Face/Jaw	31%	29%	Head (general)	27%	41%
Neck (C1 – C7)	6%	4%	Neck and Cervical Spine	4%	4%
Upper Torso/Lower Organs/Vertebrae	51%	31%	Thorax/Abdomen/Vertebrae	44%	49%
Upper Extremities	5%	14%	Upper Extremities	7%	0%
Lower Extremities	7%	22%	Lower Extremities	14%	0%
General	(not counted)		General	4%	6%

The results of the two studies were comparable. The time difference did not appear to present any shift in the data.

<u>Comparison to Wiegmann Study</u>

A system was developed in section 7.1.1 to rank injury citations relative to the most frequent injury found. Each injury frequency was divided by the most common injury frequency. The most frequent had a ranking of 1, while an injury with half as many citations had a ranking of 0.5. This system allowed comparison of different, unrelated studies as long as the injury listings were similar. Results were given for the Wiegmann (2002) study in section 7.1.1. This study was based on autopsy records from GA aircraft accidents. The USAARL database study (created as part of this research) results were given in section 7.2.1. The USAARL data had results for both fatal and non-fatal accidents and is based on US Army accident involving mostly helicopters.

The USAARL fatality data was compared to the Wiegmann (fatal) data by creating a stacked bar chart as shown in Figure 8-9. Head and Neck injury was the most frequent in the US Army data, while rib fracture was the most frequent in the Wiegmann study. Although head and neck injury was frequent in the Wiegmann study as well. A high bar with a balanced proportion indicated that the injury is frequent in both studies.

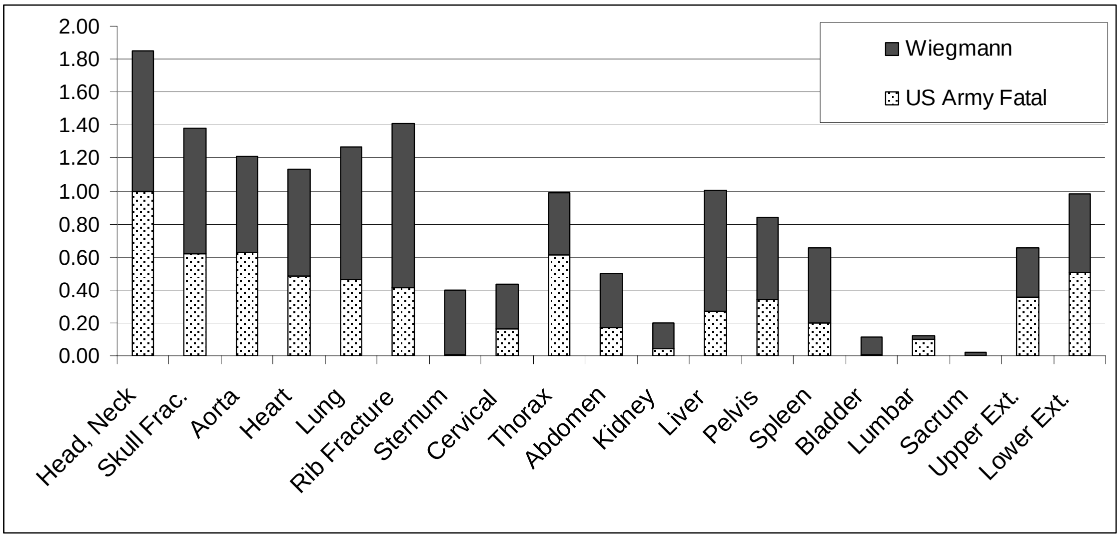

Figure 8-9. Injury Ranking, USAARL Fatal and Wiegmann (2002) Fatal

The injury frequency between the GA aircraft (Wiegmann) and predominantly helicopter (USArmy) were very similar. Head, neck, and chest injuries were most frequent, with heart and aortic injuries quite common in the fatal accidents. Organ injuries appeared more common in GA aircraft. The similar comparison suggested that the predominantly helicopter data from the USAARL database was reasonable for making conclusions about aircraft in general. Although the lower thoracic organs (abdomen, kidney, liver, spleen) were more commonly cited in the Wiegmann study, the heart and aorta listing frequency was very similar.

A comparison was also made using the US Army non-fatal injuries. The Wiegmann study did not include non-fatal injuries, and thus the results were not expected to be similar. Figure 8-10 shows the stacked bar chart injury rankings comparing the Wiegmann (2002) fatal injury listings with the USAARL database study non-fatal listings.

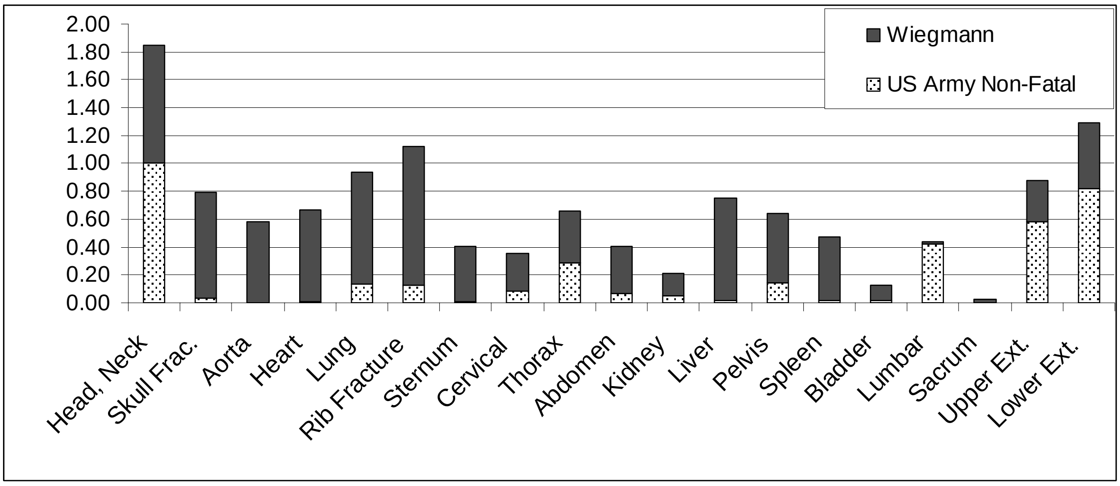

Figure 8-10. Injury Ranking, USAARL Non-Fatal and Wiegmann (2002) Fatal

Important body parts that are frequently listed in the non-fatal accidents are likely to be critical for survival. The comparison of the non-fatal to fatal injury listings suggested that head, neck and chest (thorax, lung, rib) remain important in non-fatal accidents. Heart and aorta injuries were not found in non-fatal accidents. HAI can not be common in non-fatal accidents as they are usually fatal. This particular research comparison suggested that either HAI can save lives if mitigated, or is not very important because it may only occur in otherwise non-survivable accidents. Evaluating the injury frequency as a function of the impact severity indicated relative importance to the injury regions. Figure 8-5 plots injury listings for various body parts relative to the resultant impact.

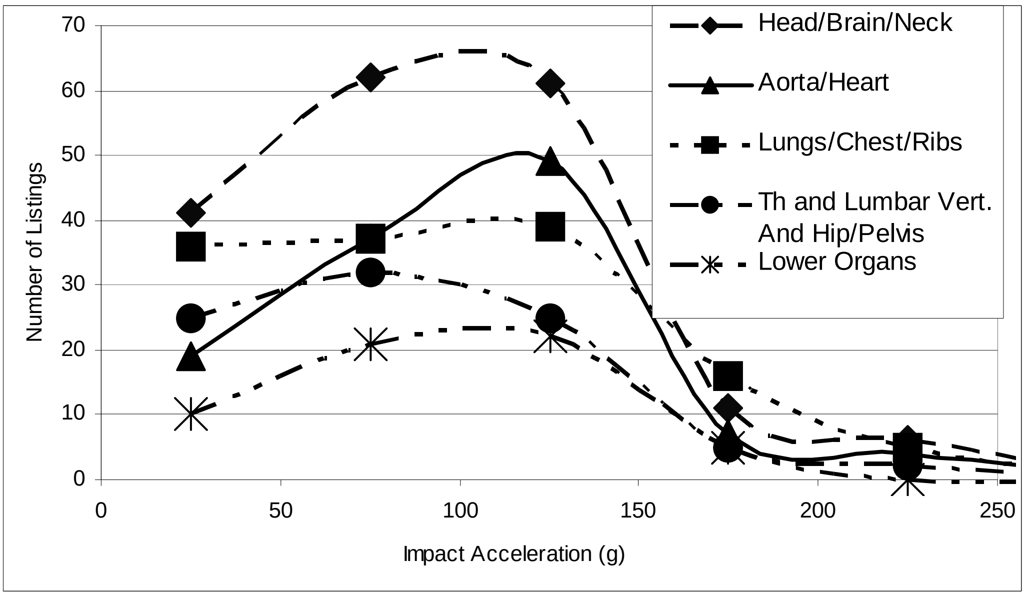

Figure 8-11. Frequency of Injury Listing vs Impact Resultant from USAARL Database Study (Section 6.2.1)

Upper torso injuries appeared nearly as common as head injuries for low severity crashes. This emphasized the importance of mitigating upper torso injuries in lower severity accidents. Heart and aortic injury were relatively uncommon in low to moderate severity crashes. Evaluations of this type can be refined to measure the crashworthy benefits for specific aircraft, equipment, and occupant factors.

8.2.2 Study of HAI in USAARL Database

The accident study results (chapter 7) identified HAI as frequent and likely important. But the hypothesized injury mechanism of heart displacement was rejected, because no clear instance of accelerative based HAI was found in otherwise survivable accidents. It was important to determine the degree to which HAI was associated with the downward impact. If strongly associated, then HAI is not a priority because the hypothesized mechanism addressed the dominant factor. But if HAI was not strongly associated with the downward impact, then the other factors causing HAI may be occur in otherwise survivable accidents. In this case HAI may be an important factor for survivability for other impact directions and conditions. An analysis of the injury data was conducted with the objective to identify if HAI injury listing associated with the vertically downward impact vector were significantly different than the rest of the population.

Twenty-four (24) accidents were determined to be survivable and with a large downward impact based on review of the accident files. This HAI group contained 9 HAI accidents with a total of 56 occupants. The non-HAI group contained 15 non-HAI accidents with 34 occupants. The total evaluation contained 588 Injury listings which were classified according to body regions, resulting in 214 citations. The HAI group contained 136 citations while the non-HAI group contained 78. The lower number of the non-HAI group was due to the lower occupant count. The control group consisted of the HAI and the non-HAI citations combined. The injury distribution comparing the HAI to the control group is shown in Figure 8-12.

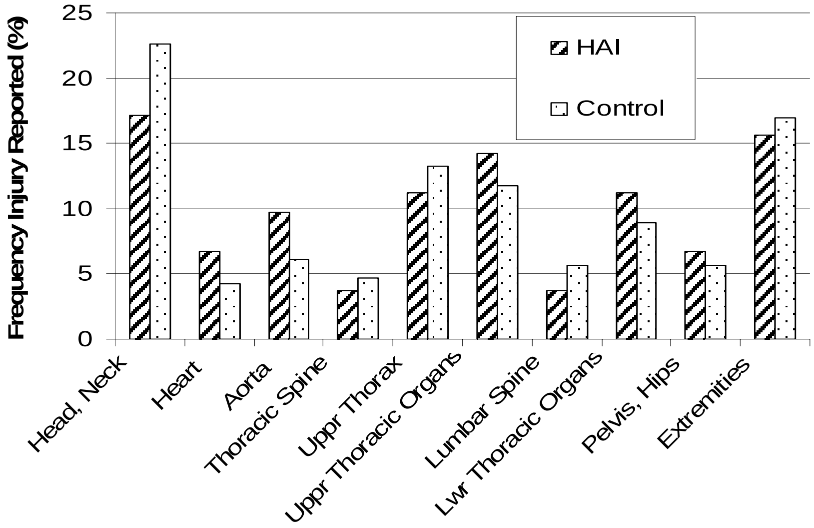

Figure 8-12. Injury Distribution for Survivable, Downward Impacts

Table 8-5 provides the quantity of injury citations broken down into body region. Table 8-6 provides the quantity of fatal and non-fatal occupant cases for the injury listings used for Figure 8-12 and Table 8-5.

Table 8-5. Injury Citations for Survivable, Downward Impacts

	HAI Injury Listings		Non-HAI Injury Listings	Control Injury Listings (HAI + Non-HAI)		Difference of percentages
Head	23	17%	25	48	23%	5.5
Thoracic Spine	5	4%	5	10	5%	2.5
Lumbar	5	4%	7	13	6%	3.6
Upper Thoracic Bones	15	11%	13	28	13%	1
Upper Thoracic Organs	19	14%	6	25	12%	2
Lower Thoracic Organs	15	11%	4	19	9%	2.4
Pelvis	9	7%	3	12	6%	1.9
Extremities	21	16%	15	36	17%	2.2
Heart	9	7%	0	9	4%	1.1
Aorta	15	11%	0	15	7%	1.3
Total	56	100%	78	214	100%	Avg = 2.35 St. Dev. = 1.35

The difference between the both heart and aortic and the control frequency percentage was about one standard deviation from the average difference for all of the injury listings, giving a p value of > 0.13 for both. There was no significant difference between the group with all HAI listings and the group with a large downward impact vector. Cases with a strong downward inertial load did not exhibit increased HAI.

Table 8-6. Occupant Cases for Survivable, Downward Impacts

	HAI Cases		Non-HAI Cases	Control (HAI + Non-HAI)	
Fatalities	22	39%	10	32	
Non-Fatalities	34	61%	28	62	
Total	56	100%	38	94	100%

The results of this analysis again supported the results that the hypothesis was incorrect. But it also suggested that HAI may be important for survivability for other conditions.

Considering this with other published work suggested this may be the case, but the mechanisms are still not understood. Relative movement of the body tissues as a predominant theory of aortic rupture was noted by Viano (1983). Research surrounding the mechanisms of aortic rupture has dramatically increased in the last 10 years, likely due the importance of aortic rupture in modern automobiles. The Wang dissertation on aortic rupture in 2002 called the exact rupture mechanism a mystery. Cavanaugh (2005) noted that several resent advancements in FE modelling will help understand the injury mechanisms, but pointed out that confusion and controversy reigns surrounding the injury mechanisms. A state of confusion was easy to develop, as some research supports the fixed aorta/relative motion of the body tissues theory (Cavanaugh 1993, Viano 1983), while other literature suggests that indirect loading can not cause HAI (Foreman 2005, Melvin 1998). The controversy appeared to be an issue of perspective and the murky boundary between contact and inertial injury. HAI caused by "Non-Penetrating" trauma suggested that inertial mechanisms play a role, as no specific item was responsible, a broken rib or an intruding rotor-blade for example. The injury must have been caused by a movement of organs or other blunt tissue interacting with the either the heart or aorta.

The body of research reported in this thesis points to many examples of non-penetrating HAI caused by movement of the internal tissues during longitudinal and lateral impacts. Inertia is always present during the impact, and thus would be expected to have some effect. However for longitudinal and lateral impacts, the inertial component appeared to be small. Of the many non-penetrating aortic injuries sustained through experiments, all were associated with significant compression of the chest wall (Roberts 1966, Shatsky 1974, Viano 1983, Nusholtz 1985, Cavanaugh 1993, Cavanaugh 2005). Cavanaugh in 2005 conducted 17 lateral dynamic sled tests with cadavers. Aortic injury occurred in 5 of 12 unpadded or stiffly padded impacts. However the few studies that had very well distributed forces (no significant deformation), were unable to find HAI (Melvin 1998, Foreman 2005). The Cavanaugh cadaver sled tests described above also included 5 padded impacts, of which none exhibited aortic injuries. It appeared therefore, that inertia had a minor role in HAI from longitudinal and lateral impacts.

8.3 Discussion of Modelling and Accident Studies

The computer modelling (setion 8.1) analyzed measures of injury potential to evaluate the survivability of individual crash situations. The analysis suggested that the threshold of visco-elastic injury is above the threshold of spine injury in the vertical loading direction. The accident studies analysis (section 8.2) suggested that aortic injuries occur predominantly in very severe accidents, and did not find evidence of inertial injury mechanisms. These results were considered together and compared with published studies and guidelines for aircraft survivability.

Aircraft Impact Velocity

Impact velocity is a key parameter used to define accident severity and injury thresholds. Figure 8-13 illustrates the survivability threshold for vertical and longitudinal impact directions based on military and civil sources. The shaded blocks represented vertical / longitudinal boundaries given for specific aircraft types. These were based on inclusion of 95% of survivable accidents from US Army helicopter crashes from 1979 to 1985 (Shanahan 1989). They were cumulative values from all the accidents recorded in the study. The horizontal lines represented generic vertical boundaries for military and civil aircraft (USDOD 1998, pg 18-19).

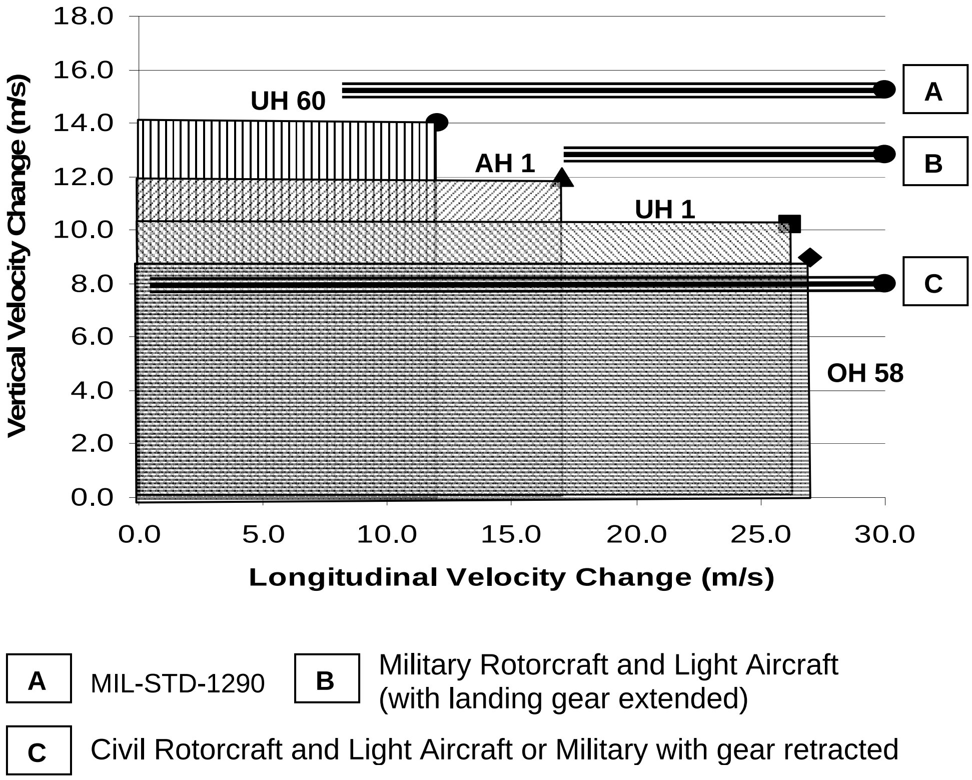

Figure 8-13. Survivable Limits Based on 95% Survivable Accidents (Shanahan 1989)

Note that generalizations of survivability limits based only on impact velocity make many assumptions. The vertical impacts were assumed to be onto a rigid surface, with the fuselage crush characteristics as the primary factor. Longitudinal impacts are even more difficult to generalize due to the wide variety of factors which will affect the survivability. Interactions between the fuselage crush and terrain factors were more significant. For example, the specific design of the fuselage to resist shoveling of the terrain (scooping up earth) during longitudinal impacts has a large affect on the survivability (USDOD 1998, pg 58). Note that landing gear can increase the velocity change limit. The collapsing landing gear absorbs energy, reducing the total transmitted to the interior floor, allowing a higher total limit. Design guidelines transform the velocity change limits into impact pulses by making assumptions about the shape and duration of the primary impact. Dynamic test requirements use idealized impact pulse shapes corresponding to crashworthy research. The computer model simulations of this research accounted for landing gear and fuselage crush factors by applying the impact forces measured at the floor and seat interface.

The three impacts determined to have potential for viscous injury (UH-60, YAH-63 and Sikorsky) are near the survivable limit when using a military EA seat and are not survivable with a GA seat. These impacts using the Military seat transferred loads into the body which resulted in heart velocities below the general viscous injury threshold, while the GA seat heart velocities were above the injury threshold of 3 m/s. The modelling and accident studies analyses, as compared to general aircraft guidelines of Figure 8-10, suggested that viscous injury potential was low for all but the most severe impacts with the GA seat.

<u>Aircraft Operation Kinetic Energy</u>

The JSSG Handbook has a method for calculating a maximum envelope for crashworthy design based on guidance in MIL-STD-1807 (USDOD 1998, pg 21-22). MIL-STD-1807 is the USAF document for military transport aircraft. If the aircraft type and basic flight parameters are known, survivable velocity change limits can be based on the total vehicle kinetic energy. The guidance indicates that the velocity need not exceed that which would result in a kinetic energy two times the maximum take-off or landing. Further guidance is based on sink rate velocities. A crash impact can be considered survivable up to a factor of three times the normal landing sink velocity. These are general limits and are independent of factors such as fuselage crush characteristics and variations of the impact surface. The interior equipment is also important. The aircraft models evaluated in the three impacts found with potential for injury as estimated by the heart model (YAH-63, UH-60 Down, Sikorsky) were survivable when compared to the kinetic injury criteria if using the military EA seats and were severe to non-survivable if using the GA seats. Comparison to the analysis thus supported the observations made in section 8.1.

<u>Retention of Items of Mass</u>

The survivable cabin volume is dependant on the structural attachments of the large mass items, especially those mounted high on the structure. The rotor hub and engines of helicopters are an obvious concern. Fixed wing aircraft also need to have the mounting structure of engines and fuel cells retain their load until the surrounding structure has reached it’s limits, to avoid breaking off into the occupant space. The Crash Systems Protection Handbook (USDOD 1998, pg 58-50) summarized the guidance for retention of high mass items. Ultimate load factors for high mass items are given in Table 8-7.

Table 8-7. Retention of High Mass Items

Impact Orientation	Ultimate Load Factor (Applied Separately)	Ultimate Load Factor (Applied Simultaneously under the conditions A, B, and C)		
		A	B	C
Longitudinal	+/- 20g	+/- 20g	+/- 10g	+/- 10g
Vertical	+20/-10g	+10/-5g	+20/-10g	+10/-5g
Lateral	+/- 18g	+/- 9g	+/- 9g	+/- 18g

The guidance also provides for a roll over requirement, taken from the Crash Survival Design Guide (Desjardins 1989, pg 17-18). The mass items should remain attached when the aircraft is inverted and local loads are applied as follows:

- load factor of 4 times the design gross weight, perpendicular to ground and the longitudinal axis
- load factor of 2 times the design gross weight for the lateral axis.

These survivability parameters provided limits for maintaining a survivable cabin volume (the “C” in the CREEP acronym). Both crushing of the fuselage and mass retention are critical for reducing the potential for intrusion of the occupant space. The impact levels for the YAH-63, UH-60 Down, and Sikorsky were all significantly above the limits shown in Table 8-5 and were at risk for structural intrusion of the cockpit. Comparison of the accident studies analysis of section 8.2 to these guidelines agreed with the observations that cockpit intrusion was a prominent factor causing HAI.

Land Vehicle Considerations

Automotive literature establishes general thresholds for longitudinal vehicle impacts at velocity changes ranging from 6.6 m/s (low) 8.9 m/s (moderate) 11.1 m/s (severe) according to Segui-Gomez 2002. Although the impact direction and structures are not directly comparable, the general magnitudes supported the analysis and observations.

Aircraft Airbag Accident Investigations

During the research a series of survivable factors investigations were conducted by the NTSB as part of a special study regarding aircraft fitted with restraint mounted airbag systems (Barth 2007). The NTSB study is not complete and thus was not able to be included in the accident studies portion of the research. However, some information from selected accidents was able to be used because the factual reports had been issued. That information provided some insight to the research.

A non survivable accident (NTSB 2006c) occurred on September 15, 2006. The Cirrus SR20 was on route from Tooele Utah to Lincoln Nebraska when it impacted terrain near the border of Colorado and Wyoming. The cause of the accident was icing. Both occupants sustained heart and aortic injuries according to the autopsy reports (Galloway 2006). The cause of death for the pilot was “head and internal injuries secondary to blunt force trauma”, and co-pilot “exsanguinations secondary to lacerations involving the heart and aorta”. The aluminium EA blocks under the seats were crushed and indicated a vertically downward and forward motion of the occupant, as shown in Figure 8-14.

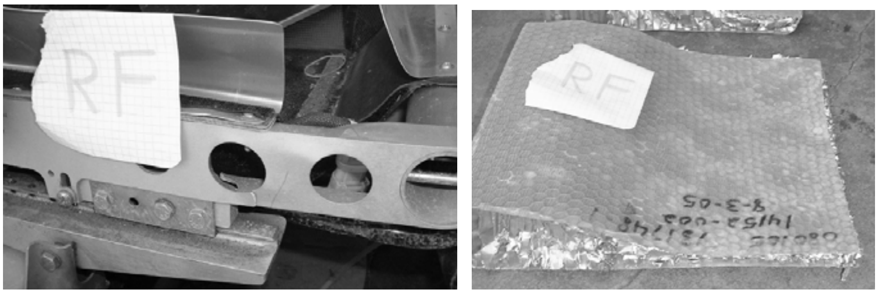

Figure 8-14. Seat Structure Failure and Seat Pan EA Block Crushed, NTSB 2006c

The HAI occurring in a non-survivable accident with a compromised cabin space was consistent with the observations of the accident studies.

An accident occurred on August 28, 2006 which destroyed the Cirrus SR22 aircraft after it impacted a water retention pond shortly after take-off from Eagle Creek Airpark in Indianapolis Indiana (NTSB 2006a). Three passengers sustained serious injuries and the pilot sustained fatal injuries. The survival factors investigation noted “Indications of severe vertical loading indicated a primary impact vector in the vertically downward direction, with significant but minor components in the forward longitudinal and left direction” (NTSB 2006b). The pilot’s cause of death was “multiple blunt force injuries”, and the survival factors notes indicated that all occupants sustained spinal injuries but no heart or aortic injuries (NTSB 2006b).

Figure 8-15. Cirrus SR-22 Crash (NTSB 2006a)

The aircraft had the same seat designs as the Cirrus SR-20 crash described above (NTSB 2006c), and the aluminium EA blocks were crushed from the vertical loads as shown in Figure 8-15.

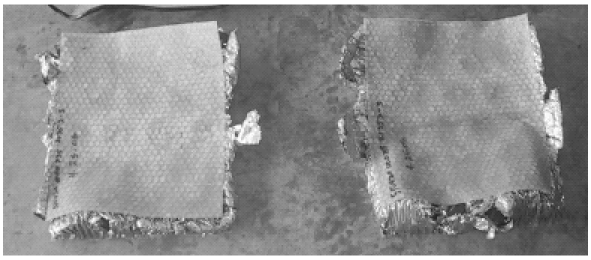

Figure 8-16. Seat Pan EA Blocks from NTSB 2006a

Both the accidents (NTSB 2006c and NTSB 2006a) were of the same design with respect to the vertical energy absorbing characteristics, and both had a severe vertical impact. The water impact was survivable but severe, as one occupant was fatally injured and the other three sustained spinal injuries. This would have been a good candidate for HAI due to vertical impact loads. The fact that none of the occupants sustained HAI suggested that he hypothesis may be false.

9. CONCLUSIONS

The hypothesis was that inertial loads from vertical aircraft impacts are a critical factor in crash survivability. The research revealed that viscous organ injury is common in fatal aircraft accidents. The accident studies created a database capable of studying injury potential as a function of impact severity. The computer model created a tool to apply selected impact conditions and evaluate the combined affects of the impact as the forces are absorbed and transferred though a selected seat configuration and occupant. The research successfully evaluated heart and aortic injury as a surrogate for general viscous organ injury and estimated its criticality in survivable accidents.

The following conclusions resulted from the accident studies:

Injury frequency distributions (for all regions of the body) were found to agree with historical studies based on autopsy records.

Head and Neck followed by upper thorax (aorta, heart, lung, and rib) injuries were found to be the most frequent injury locations in fatal accidents.

The research created a unique database which included non-fatal accident injury distributions.

Head, Neck and upper thorax (lung and rib) injuries were found to be most frequent injury locations in non-fatal accidents. Heart and aorta injuries were very uncommon in non-fatal accidents.

The accident studies identified that organ injuries (lung, liver, spleen and bladder) and rib fractures appear more frequent in fatal General Aviation than fatal helicopter accidents. This was based on comparison between the US Army database research (predominantly helicopters) versus the Wiegmann (2002) GA autopsy study.

The accident studies conducted a comprehensive review of heart and aortic injury cited in literature.

The US Army database study created a unique assessment of heart and aortic injury as a function of impact severity and cockpit environmental factors.

Vertical inertial loading of the heart and aorta in isolation of body deformation was not found to be a cause of heart and aortic injury, rather combined effects of accelerative force and cockpit environmental factors were causative agents. Non-penetrating heart and aortic injuries appear to be caused predominantly by crushing of the body and the resulting stress from relative motion of body tissues.

The database study established a means to evaluate injury potential as a function of the aircraft impact parameters. The analysis of this data determined that all impact orientations are important for helicopter crash survivability, rather than predominantly the downward and forward vectors which traditionally receive the focus.

Evaluations of survivability limits were developed based on frequency of non-fatal versus fatal injury rather than the traditional method of simply accounting for 95% of the survivable accidents. The injury distributions and approximate accident severity thresholds (severe accident at a resultant impact vector of about 60 g and non-survivable of about 125 g) correlated well with published survivability studies. The database is thus a useful tool for evaluating injury priorities.

Heart and aortic injuries occurred predominantly in very severe accidents, suggesting that mitigating these injuries alone would not greatly affect survivability, although various forms of viscous injury occur under the same circumstance. Mitigating viscous injury in general would improve survivability.

The modelling work resulted in the following conclusions:

A general model of viscous injury potential was created and used to evaluate injury potential as a function of impact severity and seat type.

The vehicle impact energy as absorbed and transferred through the seat and occupant affects the potential for viscous injury.

Viscous injury appeared less critical than spine injury in purely vertical impacts given the current range of seat design capability.

Impact force had a larger effect on viscous response as the energy absorbing capability of the seat was reduced.

The impact force and non-attenuated impact energy together provided the most clear indication of viscous response.

Estimates of viscous injury potential were only possible as a function of the seat design.

As the viscous response approached the level of estimated injury, the spine response was approaching the non-survivable level. This supported the conclusion from the accident study that spine injury is more critical than heart and aortic injury in vertical impacts.

The research concluded that inertial displacement of organs in the vertical direction can not be separated from the forces acting on the body and resulting deformation. Viscous injury is a function of combined accelerative and contact mechanisms.

10. FUTURE WORK

The hypothesis of this thesis challenged an injury mechanism historically suspected to be critical for survivability, but never resolved. Solving this hypothesis created the necessary information to help designers prioritize crashworthy equipment for these injuries, provided insight to a wider scope of soft tissue and organ injuries, and identified needed areas of cooperation with related automotive research. HAI in general has been considered a critical survivability factor through out the history of mechanized transportation. Viano (1978) attributed understanding the mechanisms of aortic trauma as fundamental to improving occupant protection, and attributed 20 to 40 percent of automobile accident fatalities to injury of the major thoracic vessels.

The HAI model was able to characterize general potential for viscous injury when compared with the appropriate impact and design parameters. Refining the model would improve its representation of vertical impact injury mechanisms. This would first require improved knowledge of the tissue response in the vertical impact direction. Foreman (2006) conducted cadaver experiments in the lateral and longitudinal directions. These experiments apply well distributed impact loads to identify inertial effects of internal organs. Extending these experiments to the vertical direction would provide the third axis. The vertical representation of viscous response could then be improved, and would be a step to better understand combined impact directions. Inertial displacement of organs do not appear to occur in isolation of body deformations, thus the motion of how the upper thorax collapses onto the lower thorax and pelvis from vertical accelerative loads needs to be better understood.

Although significant progress has been made studying the mechanisms associated with automotive impacts, nearly nothing was known about mechanisms specific to the vertical impact direction. The vertical impact direction is not of interest only for the aircraft environment. As the body articulates, combined load directions introduce complex injury mechanisms in which all axes can be important. Impact loads transferred from one tissue to another, the attachment points and loading geometry can cause the load vector to adopt any direction. Detailed computer models of the human body are limited by the lack of knowledge regarding tissue response. Tissue component tests provide local responses and global body deformations are at least partially known in the longitudinal and lateral directions, but the middle point of organ to organ response is not characterized. This is needed for further development of biomechanical models.

The model of viscous injury potential needs to be refined with respect to the full motion of the viscera, including rebound. This requires dynamic impact experiments using modern tools for measuring viscous response. The E*Seatg factor can be developed into a basic parameter to evaluate seat systems. The factor can be modified to be non-dimensional and applicable across any seat system.

The accident injury database developed with this research is a valuable tool for assessment of injuries with respect the vehicle impact. Evaluations investigating a variety of factors associated with the aircraft, flight parameters, impact parameters and occupants can be used to identify sources of injury and improve crashworthiness.

A limiting factor in improving the survivability of airplane accidents is the lack of survival factors investigations. The data currently collected in accident investigations is poorly retained for use by researchers, and very difficult to access. One of the primary benefits of conducting accident investigations is lost because there is no system set up to catalogue civil aircraft accident data. Small GA aircraft accidents are common enough to support the development of a database for survival factors evaluations. Although detailed survival factors investigations are not practical on a large scale, most small aircraft investigations already include scene photos and autopsy of the pilot. If accessible, this data alone would be extremely useful for researchers to analyze trends in crashworthy design.

What progress was made from the 20 years of dynamic seat rules? What priorities should be placed on future designs? Improved collection, access, and use of investigation data must be done. Otherwise it will be impossible to address these questions for the benefit of future aircraft design and the safety of those who fly.

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Appendix A: Computer Models

Appendix A, Model 1 System Model

The system level model specifies the models and time base for the simulation. It specified the data plots and incorporates the sub-system models. An example is provided below.

```
INPUTVERSION 2004
SOLVER CRASH
ANALYSIS EXPLICIT
UNIT MM KG MS KELVIN
SIGNAL YES
FILE 1-Sikorsky-h350v2004CLS
$SHELLCHECK YES      10      4      40      140      30      100
SHELLCHECK NO
SOLIDCHECK YES      4      40      140      30      100
DATACHECK YES
DCOMP LCB
$
TITLE /  50% Hybrid III Male Dummy
RUNEND/
 TIME       200
END_RUNEND
$
OCTRL /
 THPOUTPUT INTERVAL       0.1
 DSYOUTPUT INTERVAL         5
 PRINT NO
$ PREFILTER YES AXYZ CNTF
$included all user selected global time history plots (options page 38 ref man)
 GLBTHP ALL
 SHLTHP DFLT
 NODPLOT DFLT
 SOLPLOT DFLT
 SHLPLOT DFLT
 MPPOUTPUT WRITE REMOVE
END_OCTRL
TCTRL /
 INITIAL                0
END_TCTRL
ECTRL /
 STRAINRATE YES
END_ECTRL
$ Simulation with airbag
$INCLU / h350v2004CLSairbag.pc
$INCLU / h350v2004airbag.pc
$ Simulation without airbag
INCLU / h350v2004CLS.pc
INCLU / h350v2004heart.pc
INCLU / h350v2004seat.pc
INCLU / h350v2004belt5pt.pc
INCLU / h350v2004test.pc
ENDDATA
```

Sub-Systems Models

Sub-systems models exist for each of the following sub-systems: ATD, Seat, Heart, and Restraint. The sub-systems model specifies the materials, parts and parameters. It also specifies elements, definitions, functions, loads, and auxiliary functions. There is a subsystem model for each of the sub-systems listed above, and for each seat type. An example of each of the sub-system models (Seat, Heart, and Restraint) are given below. The examples have deleted repetitive lines and lists of nodes, shells, and other information to conserve space. The purpose of providing the example was to show the structure of the model and some of the critical control parameters, not to provide a functional model. The ATD model was not included as the dataset is marked proprietary and reproduction is restricted. The example is for the Airbag Threshold Impact and the GA Seat.

Appendix A, Model 2 Sub-System Model – Seat

```
#INPUTVERSION 2004
$  MATERIAL
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /    9900    100        2.4e-5     0     0     1     0
           0     0     0     0     0     0     1     0
NAME Upper Floor
     10            0.3
(lines deleted)
PART  /    9900SHELL      9900
NAME Upper Floor
(lines deleted)
END_PART
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /    9901    100         2e-6     0     0     1     0
           0     0     0     0     0     0     1     0
NAME Cushion seat
     10            0.3
(lines deleted)
PART  /    9901SHELL      9901
NAME Cushion seat
(lines deleted)
END_PART
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /    9902    100         2e-6     0     0     1     0
           0     0     0     0     0     0     1     0
NAME Back seat
     10            0.3
(lines deleted)
PART  /    9902SHELL      9902
NAME Back seat
(lines deleted)
END_PART
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /    9903    100         2e-6     0     0     0     0
           0     0     0     0     0     0     0     0
NAME Instrumental panel
      1            0.3
```

```
(lines deleted)
PART  /     9903SHELL       9903
NAME Instrumental panel
(lines deleted)
END_PART
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /     9904     100           2e-6       0       0       1       0
             0       0       0       0       0       0       1       0
NAME Belt attachments
      0.1                0.3
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
PART  /     9904SHELL       9904
NAME Belt attachments
(lines deleted)
END_PART
MATER /     9906     100       3.814e-5       0       0       1       0
             0       0       0       0       0       0       1       0
NAME Lower Floor
       10                0.3
(lines deleted)
PART  /     9906SHELL       9906
NAME Lower Floor
(lines deleted)
END_PART
MATER /     9907     100           1e-9       0       0       1       0
             0       0       0       0       0       0       1       0
NAME Compressible Floor
       10                0.3
(lines deleted)
PART  /     9907SHELL       9900
NAME Compressible Floor
(lines deleted)
END_PART
MATER /     9910     100      8.0371e-5       0       0       1       0
             0       0       0       0       0       0       1       0
NAME Steering yolk
        1               0.3
(lines deleted)
PART  /     9910SHELL       9910
NAME Steering yolk
(lines deleted)
END_PART
$  NODAL POINT CARDS
(nodes and shells deleted)

$  RIGID BODY CARDS
NODE  / 99060001       1065.116       -1035.692       -1012.247
THNOD /        0
NAME Lower Floor
       NOD 99060001
       END
RBODY / 99060001              099060001                          0
NAME Lower Floor
       PART>NOD     9906
       NOD      99210020
       END
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
NODE  / 99000001        1065.116       -1035.692        -12.247
THNOD /        0
NAME Upper Floor
       NOD 99000001
       END
RBODY / 99000001              099000001                          0
NAME Upper Floor
```

```
      PART>NOD     9900     9903
(lines deleted)
      END
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
NODE  / 98000001       1065.116      -1035.692       -12.247
THNOD /       0
NAME Seat
      NOD 98000001
      END
RBODY / 98000001             098000001                         0
NAME Seat
      PART>NOD     9901     9902     9904
      NOD 98210021
      END
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
$ STEERING YOLK
NODE  / 99100001     1282.721924     1312.815918      521.596863
THNOD /       0
NAME Steering Yolk
      NOD 99100001
      END
RBODY /     9910             099100001                         0
NAME Steering Yolk
      PART>NOD     9910
      NOD 99110021
      END
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
PART  /     9911KJOIN         0
NAME Steering Direction
(lines deleted)
END_PART
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
(lines deleted)
FRAME / 99110001       0       0
NAME Steering Direction
                   0        -0.994        -0.107
                  -1             0            099100001
KJOIN / 99110020    9911TRANSLAT991100209911002199110001       0       0
        011111
THELE /       0
NAME Steering Yolk
      ELE 99110020
      END
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
FUNCT /    98211       7       1       1       0       0
NAME Seat Compression Z
                     -1368        -50023
                      -100           -17
                      -0.1           -17
                         0             0
                       0.1            17
                       100            17
                      1368         50023
FUNCT /    98212       2       1       1       0       0
NAME Seat Damping Z
                         0             0
                         1             0
FUNCT /    98213       3       1       1       0       0
NAME Seat Compression X
                        -1             0
                         0             0
                         1             0
FUNCT /    98214       3       1       1       0       0
NAME Seat Damping X
```

```
                         -1              0
                          0              0
                          1              0
FUNCT /    98215       3      1      1      0      0
NAME Seat Compression Y
                         -1              0
                          0              0
                          1              0
FUNCT /    98216       3      1      1      0      0
NAME Seat Damping Y
                         -1              0
                          0              0
                          1              0
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /     9821     230          1e-15       0      0      1      0
             0      0      0      0      0      0      1      0
NAME Seat Compression
(lines deleted)
PART  /     9821KJOIN       9821
NAME Seat Compression
(lines deleted)
FRAME / 98210001       0      0
NAME Floor Compression
                   0              0             -1
                  -1              0              099000001
KJOIN / 98210020    9821GENERAL 982100209821002198210001       0      0
$ degrees of freedom
        011111
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
THELE /       0
NAME Seat Compression
       ELE 98210020
       END
$ CONTACTS
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
CNTAC /     9900      33
NAME Floor vs. Feet
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
$ LOCKED!!!!!!!
FUNCT /    99013       3      1     100      0      0
NAME Cushion seat force [Length / Force]
                          0              0
                         45              1
                         50            2.5
FUNCT /    99014       2      1      1      0      0
NAME Seat hysteresis [Length / None]
                          0            0.5
                       1000            0.5
FUNCT /    99015       2      1      1      0      0
NAME Seat damping [Force / Velocity / Length]
                          0              0
                       1000              0
FUNCT /    99016       2      1      1      0      0
NAME Seat friction [None / Length]
                          0           0.62
                       1000           0.62
CNTAC /     9901      21
NAME Cushion Seat vs. Pelvis and Legs
         0        0          FORCE         2    1    0
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
FUNCT /    99018       3      1      1      0      0
NAME Back seat force [Length / Force]
```

```
                        0               0
                       45              10
                       50              25
CNTAC /     9902      21
NAME Back Seat vs. Thorax and Pelvis
       0         0          FORCE         2    1    0
(lines deleted)
CNTAC /     9903      33
NAME Desk vs. Hands
(lines deleted)
$  TIED
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /     9912     301
NAME Steering Yolk vs. Hands
(lines deleted)
PART  /     9912TIED        9912
NAME Steering Yolk vs. Hands
(lines deleted)
END_PART
TIED  /     9912    9912
NAME Steering Yolk vs. Hands
      PART     1901     2301
      END
      PART     9910
      END
```

Appendix A, Model 3 Sub-System Model – Heart

```
#INPUTVERSION 2004
$  MATERIAL
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /     3030     100          1.1e-6       0       0       1       0
           0       0       0       0       0       0       1       0
NAME Heart
     4e-4              0.3
PART  /     3030SHELL       3030
NAME Heart
(lines deleted)
$  NODAL POINT CARDS
(nodes and shells deleted)
$  RIGID BODY
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
(nodes deleted)
RBODY /     3030               330300001303000023030000З              0
NAME Heart
        2.6005   301.6   268.8   268.8
      PART>NOD     3030
      END
FUNCT /     30321       3       1       1       0       0
NAME Vertical Stiffness [Length / Force]
                     -1000             -8
                        0               0
                      1000              8
FUNCT /     30322       3       1       1       0       0
NAME Vertical Damping [Velocity / Force]
                        -1           -0.15
                        0               0
                        1           0.025
FUNCT /     30323       3       1       1       0       0
NAME Horizontal Stiffness [Length / Force]
                     -1000            -16
```

```
                    0             0
                 1000            16
FUNCT /    30324      3      1      1      0      0
NAME Horizontal Damping [Velocity / Force]
                   -1           -0.3
                    0             0
                    1           0.05
FUNCT /    30325      3      1      1      0      0
NAME Lateral Stiffness [Length / Force]
                -1000           -16
                    0             0
                 1000            16
FUNCT /    30326      3      1      1      0      0
NAME Lateral Damping [Velocity / Force]
                   -1           -0.3
                    0             0
                    1           0.05
MATER /     3032     230          1e-15      0      0      1      0
        0      0      0      0      0      0      1      0
NAME Aorta Joint
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
PART  /     3032KJOIN       3032
NAME Aorta Direction
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
CNODE / 30300012     1366.543457     -822.516602      748.321899
NODE  / 30300013     1366.060059     -806.697815      828.120789
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
FRAME / 30320001       0       0
NAME Aorta Joint
             0.48         -15.819         -79.799
               1              0              030300013
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
KJOIN / 30320020    3032GENERAL 303000123030001330320001       0       0
      000111
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
THNOD / 30300001
NAME Heart COG
THELE /       0
NAME Aorta Joint
    ELE 30320020
    END
```

Appendix A, Model 4 Sub-System Model – Restraint

```
#INPUTVERSION 2004
$  MATERIAL
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
FUNCT /    99050      6      1      1      0      0
NAME Belt [None / Force]
                    0             0
          9.999990e-4             2
                0.009             4
                0.029             6
                0.059             8
                 0.15      27.000002
FUNCT /    99051      7      1      1      0      0
NAME Spool Effect [Length / Force]
                    0             0
                   35             2
                   72           3.5
```

```
                       86            4.9
                      386            6.7
                      422       11.400001
                      427       15.000001
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
MATER /     9905     205           1e-6       0       0       0       0
            0       0       0       0       0       0       1       0
NAME Belt
    99050    0
     0.34      0.57
       0         0         0
     1.2-4        0
       0.1        0

$  PART
PART  /     9905BAR         9905
NAME Belt
(lines deleted)
$  BELT SYSTEMS
(nodes deleted)
(bar elements deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
SENSOR/    99050       1
NAME Retractor
            4
RETRA / 9904002099040020   0.001       2     0.1              1
NAME Right retractor
(lines deleted)
RETRA / 9904004099040040   0.001       2     0.1              1
NAME Left retractor
(lines deleted)
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
SLIPR /   550090  550090      0    0.01     0.1
NAME Right pelvis slipring
(lines deleted)
SLIPR /   550287  550287      0    0.01     0.1
NAME Left pelvis slipring
(lines deleted)
SLIPR /   530552  530552      0    0.01     0.1
NAME Right lower torso slipring
(lines deleted)
SLIPR /   530483  530483      0    0.01     0.1
NAME Right upper torso slipring
(lines deleted)
SLIPR /   530266  530266      0    0.01     0.1
NAME Left lower torso slipring
(lines deleted)
SLIPR /   530186  530186      0    0.01     0.1
NAME Left upper torso slipring
(lines deleted)
```

Appendix A, Model 5 Test Conditions Model

The test conditions model sets the boundary conditions, defines loads (such as gravity), and specifies the initial velocity function (which serves as the impact pulse). A test conditions model exists for each of the six aircraft impact simulation cases run. An example of the Airbag Threshold Impact simulation is provided below.

H350v2004test (Airbag Threshold Pulse)

```
$ units: mm, ms, kN, GPa
$$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
$TRSFM /
$NAME Rotation
$       NOD 1:99999999
$       END
$$           angle   center      vx      vy      vz
$       ROTA      10 99060001      0      1      0      0      0
$       END
BOUNC / 99060001  110111
NAME Lower Floor
BOUNC / 99000001  110111
NAME Upper Floor
FUNCT /    99003      2      1      1     0.0     0.0
NAME Gravity [Time / Acceleration]
                        0       -0.00981
                      200       -0.00981
ACFLD /       1      0      1      0      1   99003      1
NAME Gravity
       NOD 1:99999999
       DELNOD 99000001 99060001 99100001
       END
INVEL /       0      0      0  -3.473      0      0      0            0
NAME Initial Velocity
       NOD 1:99999999
       END
ACC3D /       0      0      0    9909      1      1      1      0
NAME Interior
$ lower floor
$       NOD     99060001
$ upper floor
       NOD     99000001
       END
FUNCT /     9909      4    1000 0.00981      0      0
NAME Deceleration-z [Time / Acceleration]
                        0             0
                   0.0120            12
                   0.0350            12

                   0.0360
```

Appendix B: Impact Characterizations

Chapter 4 noted that a large variety of aircraft crash tests were evaluated in order to characterize the range of acceleration magnitudes and durations that occur in survivable accidents. The evaluations of the floor acceleration time histories are provided here. This appendix is organized according to the section of chapter 4 which addresses each aircraft type.

High Wing GA Aircraft (Section B1.1)
Low Wing GA Aircraft (Section B1.2)
AGATE 9 Passenger Aircraft (Section B1.3)
ATR and a Boeing B737 Transport Aircraft (Section B2)
UH-1H and UH-60 Rotorcraft (Section B3)

B1.1 Crash Tests of Smaller GA Aircraft (Approximately 1000 kg)

High Wing GA Aircraft (Vaughan 1980)

A group of four identical high wing, single engine GA aircraft were crashed under varying conditions (Vaughan 1980). All the aircraft had a nominal mass of 1043kg and a nominal impact velocity of 25m/s along the direction of the flight path.. The impacts were onto either concrete or soil surfaces and were conducted with various flight paths and aircraft orientations at impact. The important parameters and results for these tests are summarized below.

High Wing Aircraft No. 1:
Hard landing test was onto a concrete surface producing a flat impact.
Flight path was -17.5 degrees and the pitch angle was 13.5 degrees.
Aircraft vertical accelerations were under 10g and less than 0.100 seconds.

High Wing Aircraft No. 2:
Impact was on concrete with flight path angle of -34.5 degrees, pitch angle of -39 degrees, and roll angle of 18.6 degrees
High Wing Aircraft No. 3 and 4:
Both Nose-down impacts had a flight path angle of -32 degrees, pitch angle of -30 degree (No. 3) and -34.5 degrees (No. 4).

Figure B1 provides simplified interpretations of the vertical floor accelerations based on the data curves provided in Vaughan 1980.

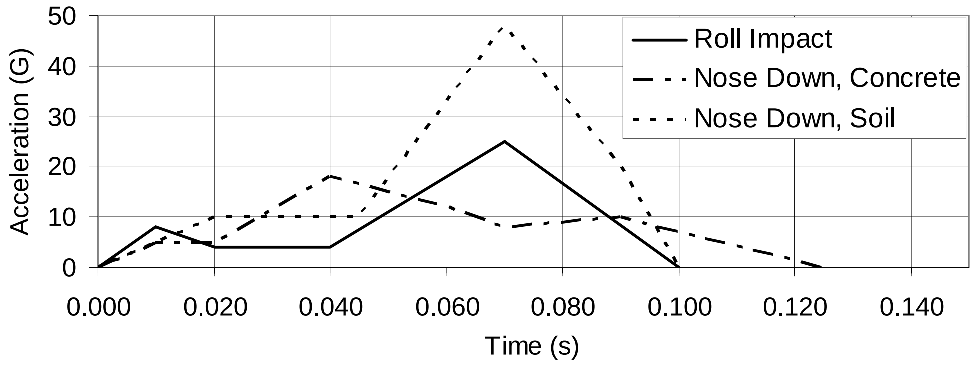


Figure B 1.High Wing GA Aircraft Impacts, Vertical Floor Accel. (Vaughan 1980)

The first of the four impacts would best be described as a hard landing rather than a crash. The positive pitch angle of 13.5 degrees produced essentially a flat impact and was onto concrete. The results were not severe, with aircraft vertical accelerations under 10 g. Vertical pelvic accelerations peaked between 10 to 15 g and would not have been likely to produce injuries. The other three impacts however, had significant nose-down pitch angles, and were much more severe. Two of the three nose-down, severe high wing crash tests were deemed non-survivable due to the loss of survivable cabin volume. These included the crash with a roll component onto concrete and another without roll, but onto soil, causing the aircraft to invert during the crash sequence. The other nose-down, severe high wing crash (without roll) was onto concrete and maintained a survivable cabin volume. Figure B2 provides simplified interpretations of the pelvic accelerations based on the response data provided in Vaughan 1980.

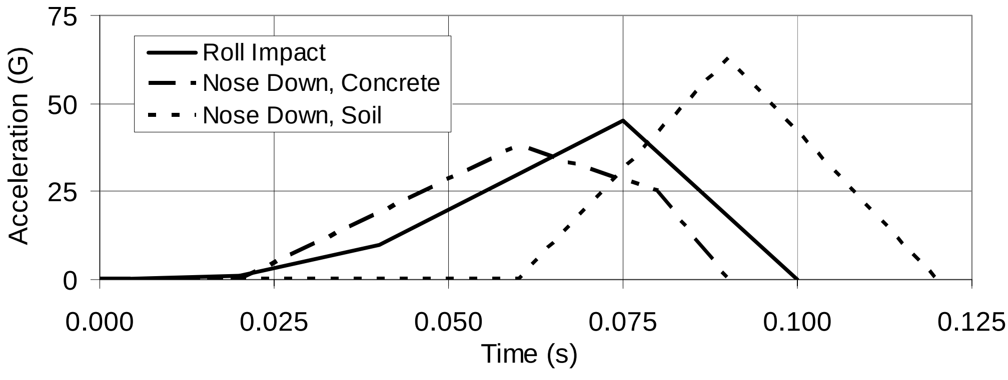


Figure B2.

Figure B 2 Simplified Vertical Pelvic Accelerations from the High Wing Crash Tests (Vaughan 1980)

The pelvic accelerations for all three of the nose-down high wing GA aircraft crash tests shown in figure B2 are associated with non-survivable impact levels because they are significantly above the approximately 20 g limit discussed in section 2.2.1. The increase in aircraft and occupant accelerations from concrete to soil for the nose down experiments indicated that the soil "catches" the aircraft, concentrating the impact into a shorter pulse and resulting in more severe and less survivable conditions. The concrete nose down and roll impacts resulted in vertical accelerations proportional to the pitch angle of the aircraft. A flat pitch angle resulted in higher vertical accelerations as the aircraft "slapped" the ground. The roll impact may have demonstrated lower vertical accelerations either by crushing at the wing prior to the fuselage contact, or by crushing the side of the fuselage. Lower vertical accelerations can result from increased lateral impact, and would reduce the potential for vertical spine impact injury, but would also increase the potential for damage to the cabin and possible collapse of the structure.

<u>Light Low Wing GA Aircraft (Castle 1983)</u>

A series of 3 identical crash tests of low wing, single engine GA aircraft with a nominal mass of 1043kg were conducted at NASA Langley IDRF in the early 1980's (Castle 1983). These aircraft had the same nominal mass and impact velocity (25m/s) as the high wing aircraft tests.

Low Wing No. 1, 2, and 3:

Aircraft 1 and 2 had a concrete impact surface with pitch angles of +10 degrees and -30 deg. Aircraft No. 3 had a soil impact surface with a pitch angle of -30 degrees. The modified Cirrus SR-20 (Hurley 2002and Terry 2000) had vertical acceleration pulse impacts onto concrete and soil at -30 degree pitch and an impact velocity of about 25 m/s. Figure B2 provides simplified vertical accelerations for the +10 deg and -30 deg pitch aircraft on concrete (Castle 1983).

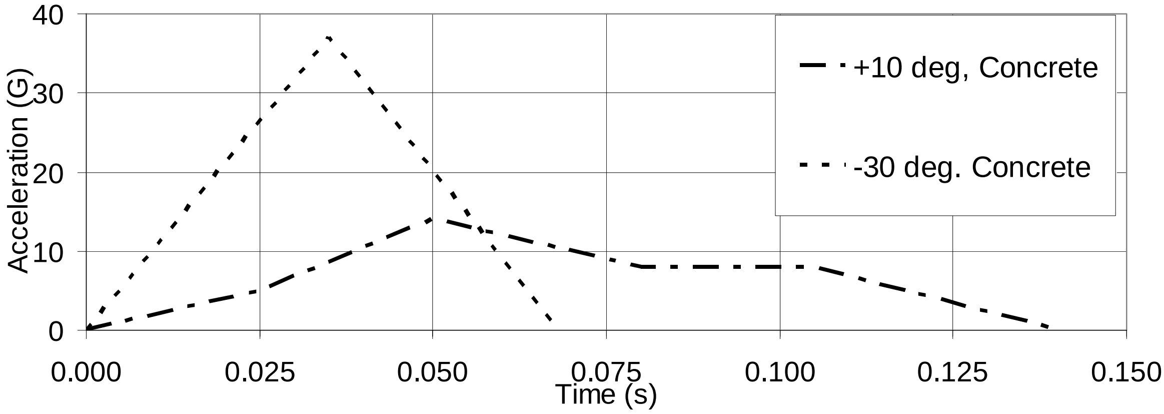


Figure B 3.Vertical Impact of Low Wing Aircraft (Castle 1983)

The acceleration plot for the Castle impact on soil was not graphed because the impact was primarily longitudinal, and the vertical accelerations peaked at about 8g.

Modified Cirrus SR-20

The simplified vertical acceleration for the low wing composite Cirrus aircraft (Hurley 2002) is provided in figure B3.

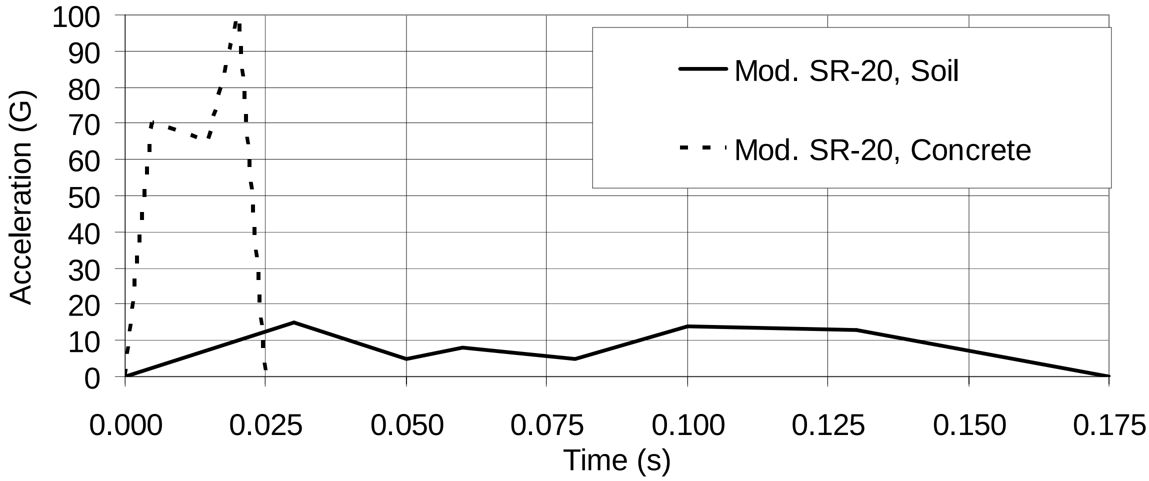


Figure B 4.Vertical Impact of Low Wing Composite Aircraft (Hurley 2002)

The acceleration plot for the low wing composite aircraft impact onto concrete is represented by the accelerations at the firewall because literature did not provide the accelerations for the passenger compartment. The literature noted that the peak accelerations were lower further back on the aircraft (Terry 2000).

B1.2 Crash Tests of Larger GA Aircraft (Approximately 3,000 to 6,000 kg)

Piper Navajo - Impact Velocity (Alfaro-Bou 1977)

Two tests, one at an impact velocity of 13 m/s, the other at 27 m/s

Flight path and pitch angle of -15 degrees (0 degree angle of attack)

Piper Navajo - Flight Path Angle (Castle 1978)

Three tests at flight path angles -15 degrees, -30 degrees, and -45 degrees

Impact velocity of 27 m/s (along flight path) and roll angle 0 degrees

The -30 degree test was also reviewed in a publication by Hayduk (1980) which compared the crash test to a real accident of a Piper PA-31 in similar conditions. The label "PA-31" is used to refer to this impact test in the thesis.

A typical impact sequence of photo's taken from a crash test of a Piper Navajo aircraft is shown in Figure B4 (Castle 1978). The resulting accelerations measured at the passenger seats were approximately 100 g, and produced ATD pelvis acceleration that exceeded 60g in the vertical direction. The primary vertical impact in the region of the cabin lasted a duration of about 0.040 s, shown roughly from the frames (d) to (e) in figure B4. The firewall was heavily damaged an the survivable space of the front seats was questionable. This crash test was conducted to compare with a real crash which was not survivable.

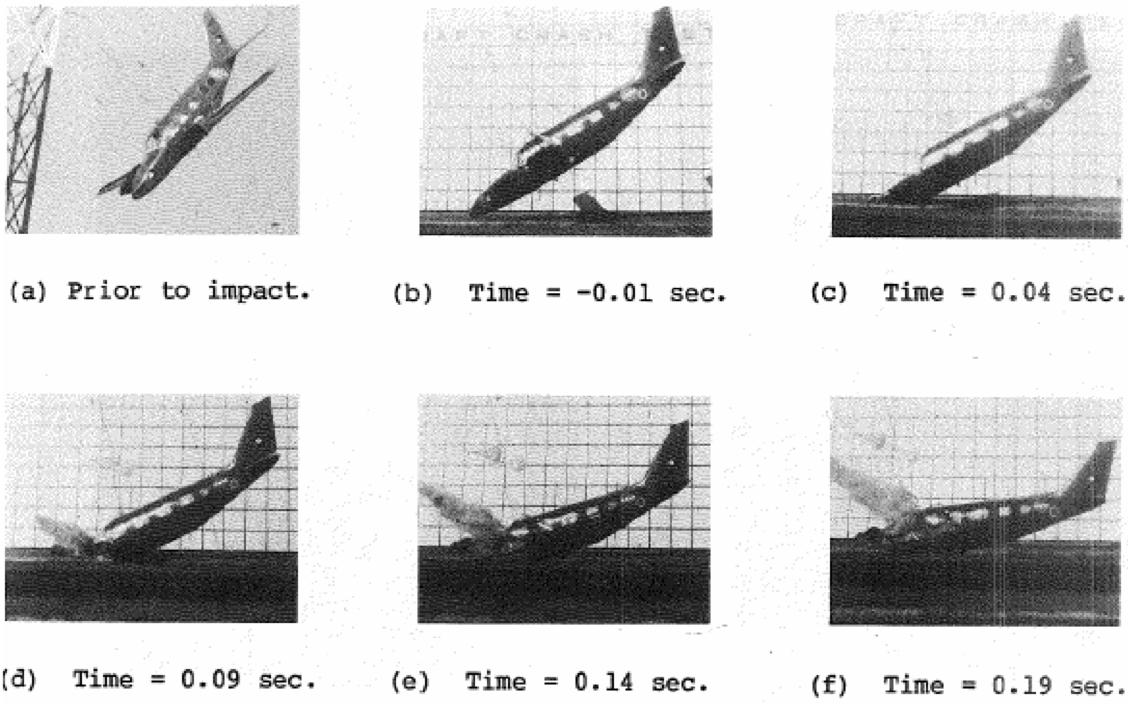


Figure B4
Figure B 5. Piper Navajo Crash Test from Castle 1978

<u>Roll Angle</u>

Three identical 2700 kg low wing GA aircraft were crash tested at roll angles of 0 degrees, -15 degrees (left roll), and -30 degrees (left roll) (Castle 1979). The impact velocity was 27 m/s and the flight path angle was -15 degrees. The impact sequence for all of the tests was first onto the nose, followed by the cabin.

The survivable cabin volume was maintained during the roll test at 0 degrees. The nose crush occurred at 0.070 s, followed by the main cabin section at 0.120 s, and then a split occurring in the fuselage at 0.170 s. The aircraft continued to slide out through 0.220 seconds. Peak vertical accelerations at the floor near the fist passenger seats reached about 130 g. Pelvis accelerations of up to 76 g were recorded.

The nose of the -15 degree test occurred at 0.030 s, followed by firewall at 0.080 s, and then the fuselage at 0.130 s. The right wing slap-down occurred by 0.180 s and fuselage separation also by 0.180 s. The tail slap-down occurred at 0.230 s. Vertical floor accelerations did not exceed 20 g. The ATD moved toward the left window following the wing impact and then back into an upright position, which generated a 10 g spike at the pelvis and seat pan.

The -30 roll test hit the left with early in the event and then the aircraft pivots on the left wing for about 0.300 s before impact with the right wing occurs. Floor accelerations at the seats were recorded in the 40 to 50 g range, and 20 g at the seat pan and pelvis.

B1.3 AGATE Nine passenger Beech Starship Crash Test

The AGATE Alliance performed a full scale impact test of a Beech Starship aircraft at the NASA Langley Drop Test Facility in Hampton Virginia (AGATE C-GEN-3451-1). This is an all-composite, nine passenger GA aircraft that weighed 6,441 kg. The crash test was done at a flat aircraft (0-degree) pitch angle. The range of acceleration pulses measured is given in Figure B5. The aircraft impacted flat, with a -18 degree flight path and a +18 degree pitch. The initial impact was 8.84 m/s vertical and 27.13 horizontal.

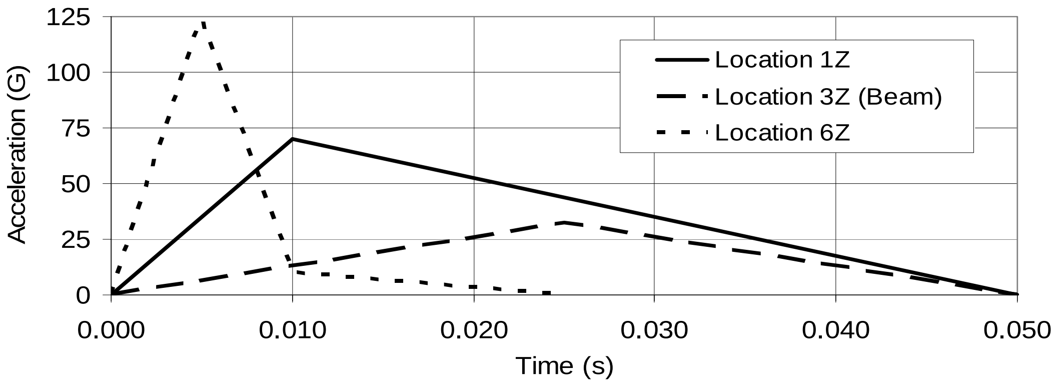


Figure B 6. Vertical Interior Impact Pulses of Beech Starship Crash Test

The locations in figure B5 correspond to accelerometer locations on the aircraft floor. Location 1Z is the vertical acceleration at the firewall, 3 Z is the floor beam just forward of mid cabin, and the 6Z location is the floor acceleration just aft of mid cabin.

B2 Pulse Characterization – Transport Aircraft

In July of 2003 an ATR42-300 aircraft was dropped from a height of 4.27 meters. The impact severity had a nominal velocity change of 9.14 m/s. The test aircraft weighed 15,060 kg including about 4,000 kg of water which represented fuel. The impact accelerations for the left and right outboard seats are provided in Figure B4. A ten foot long passenger section of a Boeing 737 fuselage section was drop tested in November of 2000 (Jackson 2004). The impact velocity was 9.12 m/s, and the left and right seat track accelerations are shown in figure B5.

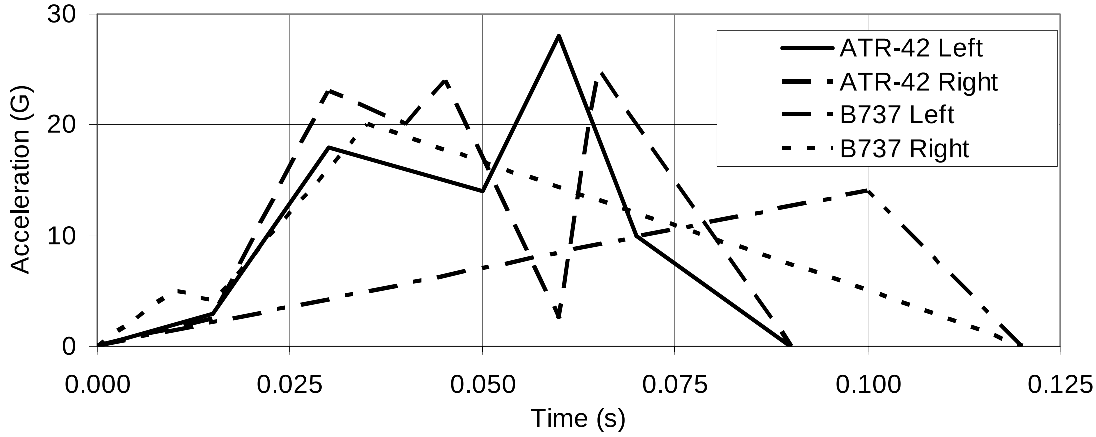


Figure B6
Figure B 7. Outboard Seat Track Acceleration,
ATR42 and B737 Drop Tests (Jackson 2004)

B3 UH-1H and SH-60 Rotorcraft

The US Navy investigated ground and water impacts using computer simulations of the SH-60 helicopter and a full scale crash test of a UH-1H Helicopter (Schultz 2000). The UH-1A has a nominal weight less than 4,300 kg and UH-60 less than 22,000 kg. All of the impacts were flat, except the UH-1H ground impact

Figure B6 provides the basic vertical impact pulse shapes. The SH-60 curves were simulations using the KRASH software computer program and the UH-1H curves were from full scale crash tests.

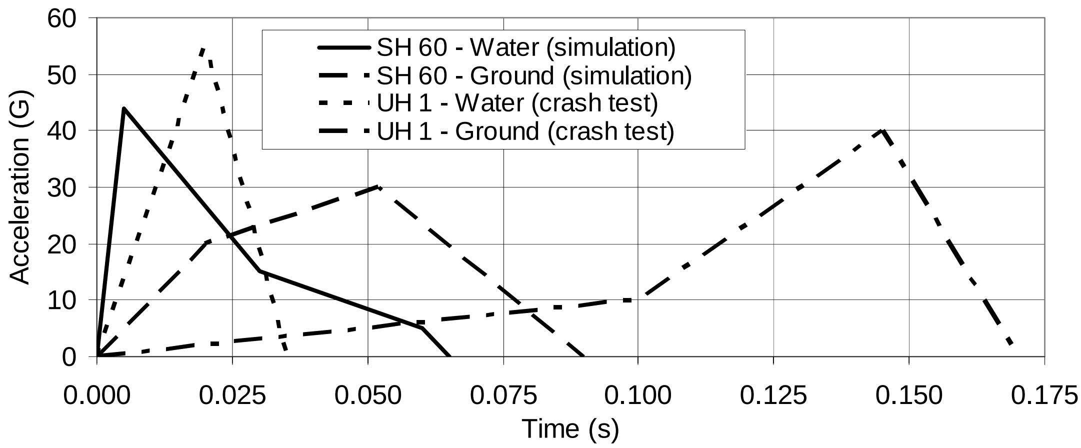


Figure B 8. Acceleration vs Time, SH 60 Simulations and UH-1 Crash Tests

Appendix C: Model results

GA Forward/Down Impact Evaluation Results

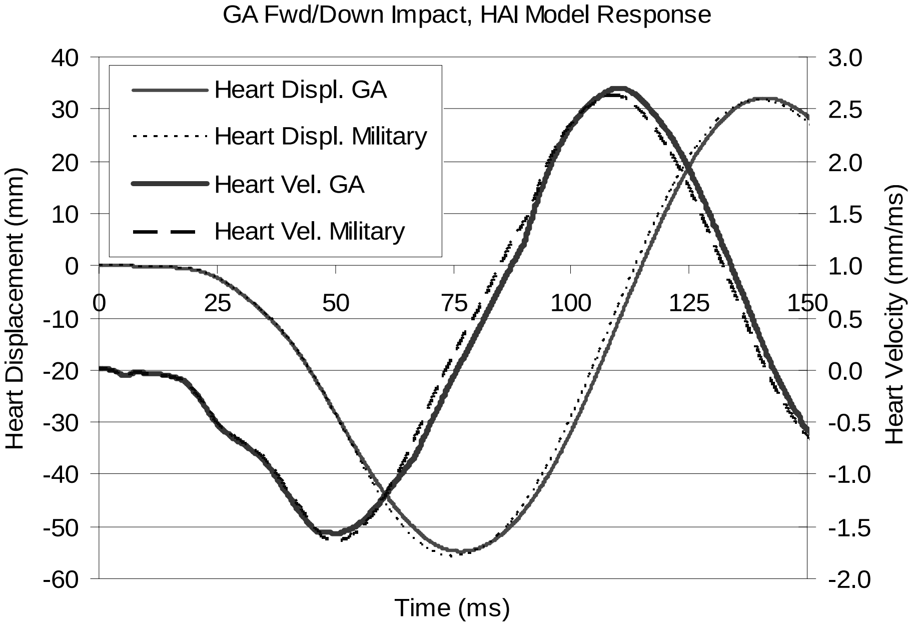


Figure C 1. HAI Model Response for GA Fwd/Dwn Impact

UH-60 Forward/Down Impact

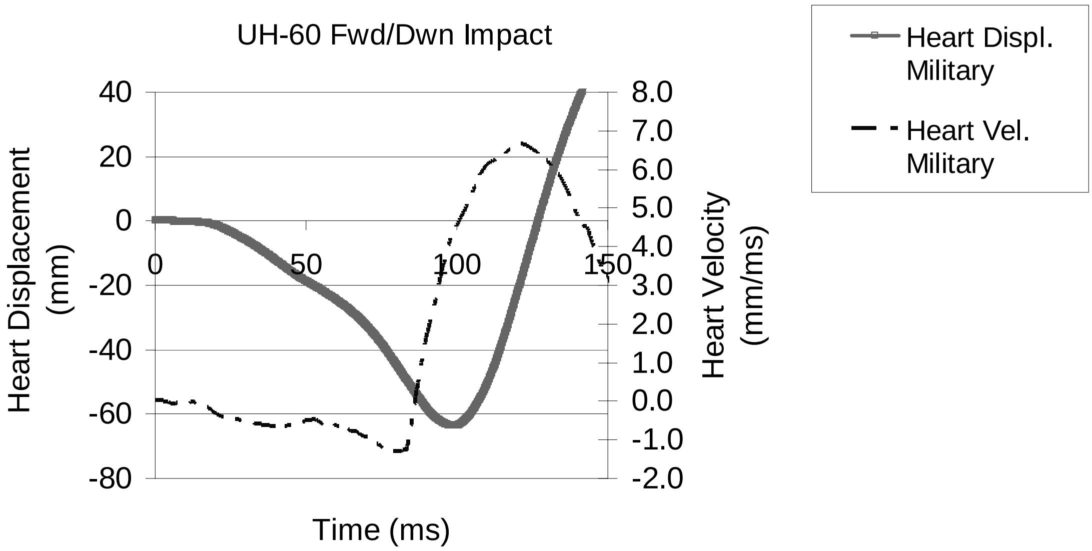


Figure C 2. HAI Model Response for UH-60 Fwd/Dwn Impact

YAH-63 Crash Test Impact

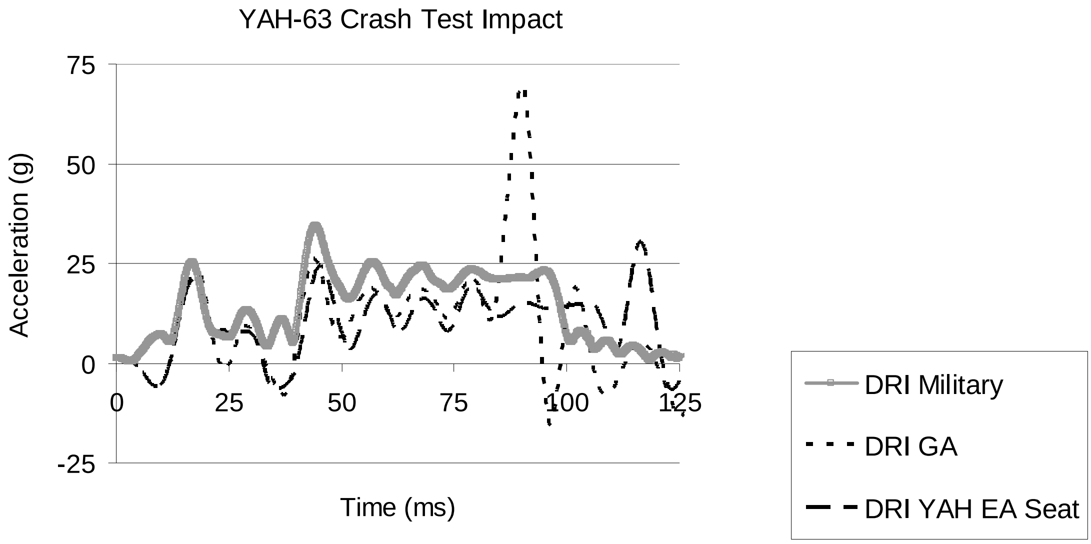


Figure C 3. DRI for YAH-63 Crash Test Impact

Sikorsky ACAP Crash Test Impact

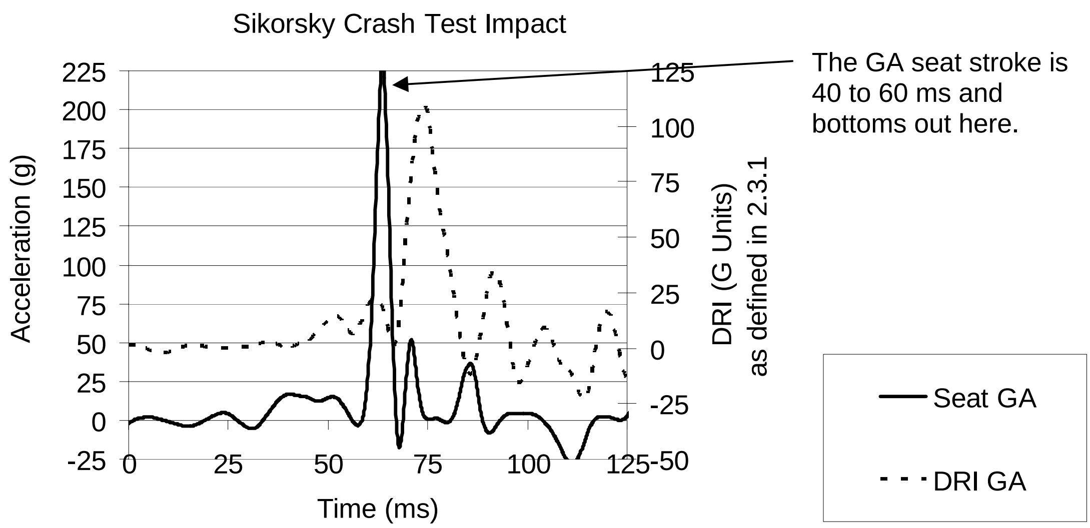


Figure C 4. Seat Acceleration and DRI for Sikorsky Crash Test Impact

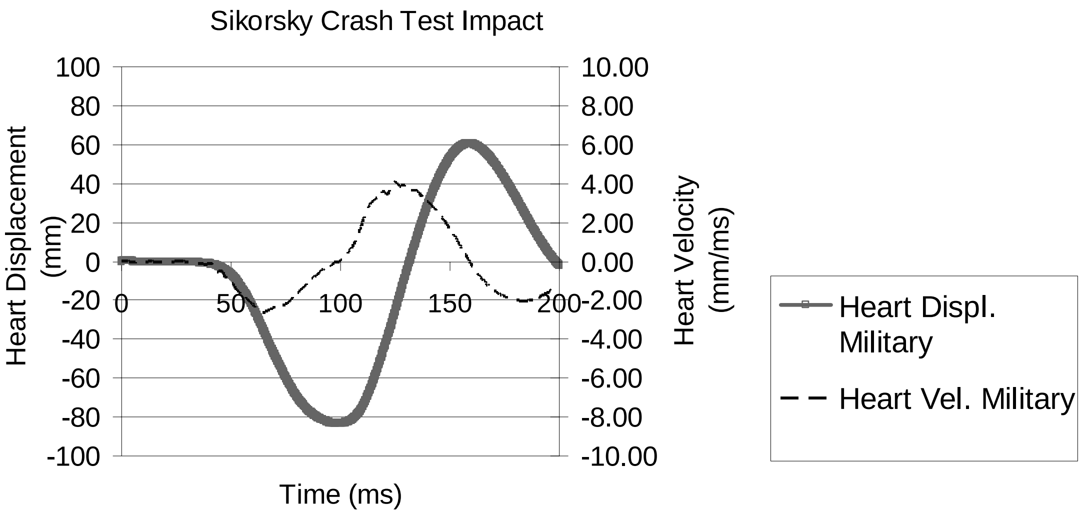


Figure C 5. HAI Model Response for Sikorsky Crash Test Impact

Comparative Model Results

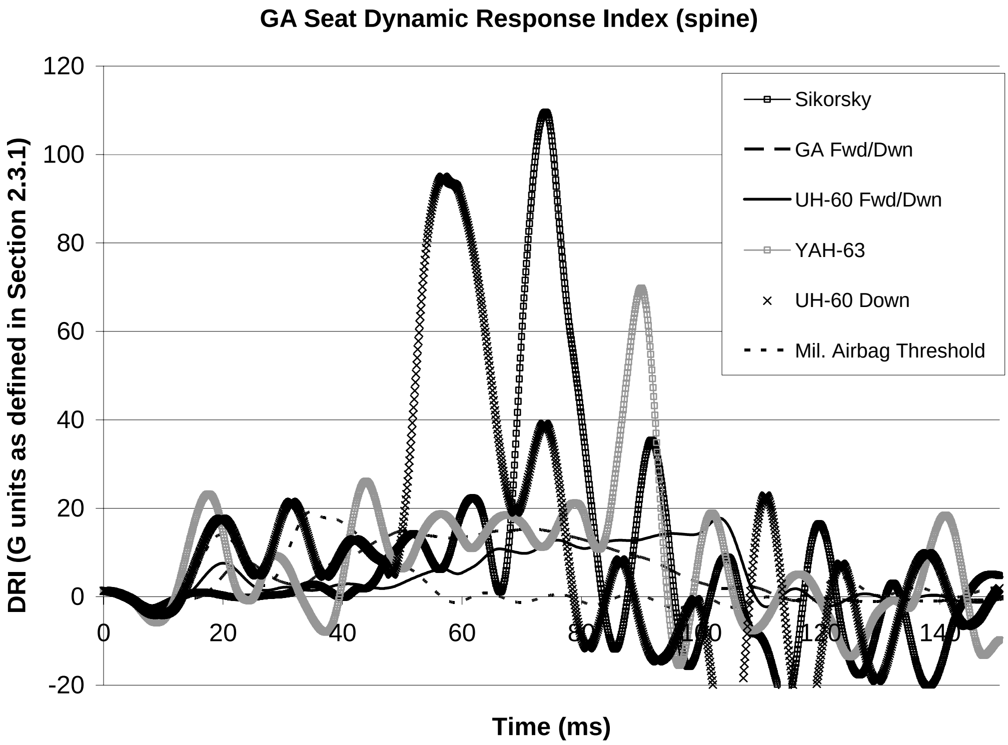


Figure C 6. GA Seat Dynamic Response Index for 6 Impacts

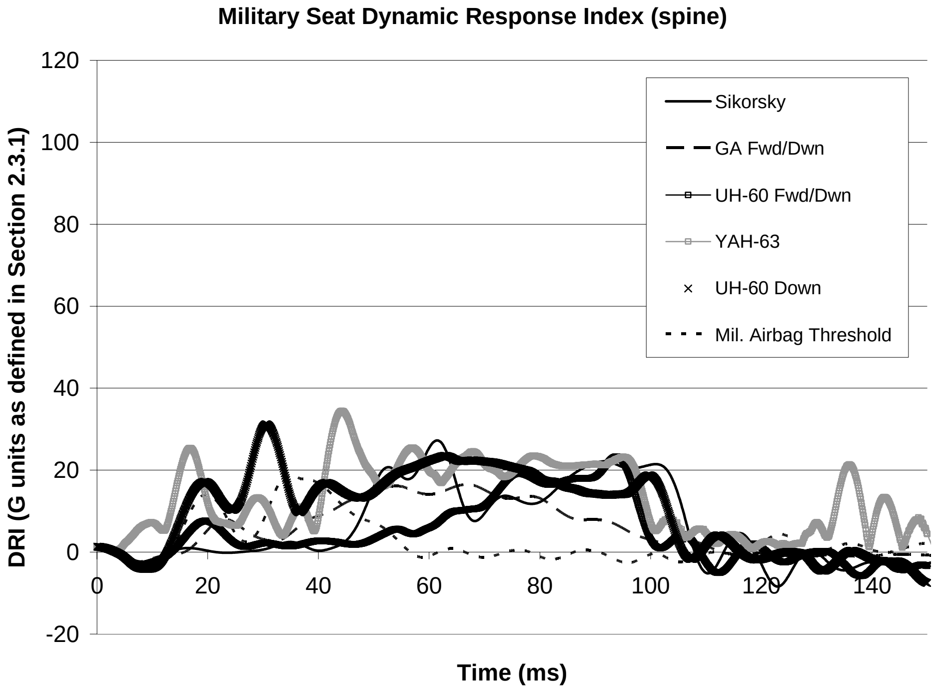


Figure C 7. Military Seat Dynamic Response Index for 6 Impacts

Figure C8 compares the calculated GA seat heart displacement for the six impacts cases. The arrows indicate inflection points where the seat bottomed out for the UH-60 Down and YAH-63 impacts. The Sikorsky seat also bottomed out, but the inflection point was not pronounced due to the high acceleration slope of the impact.

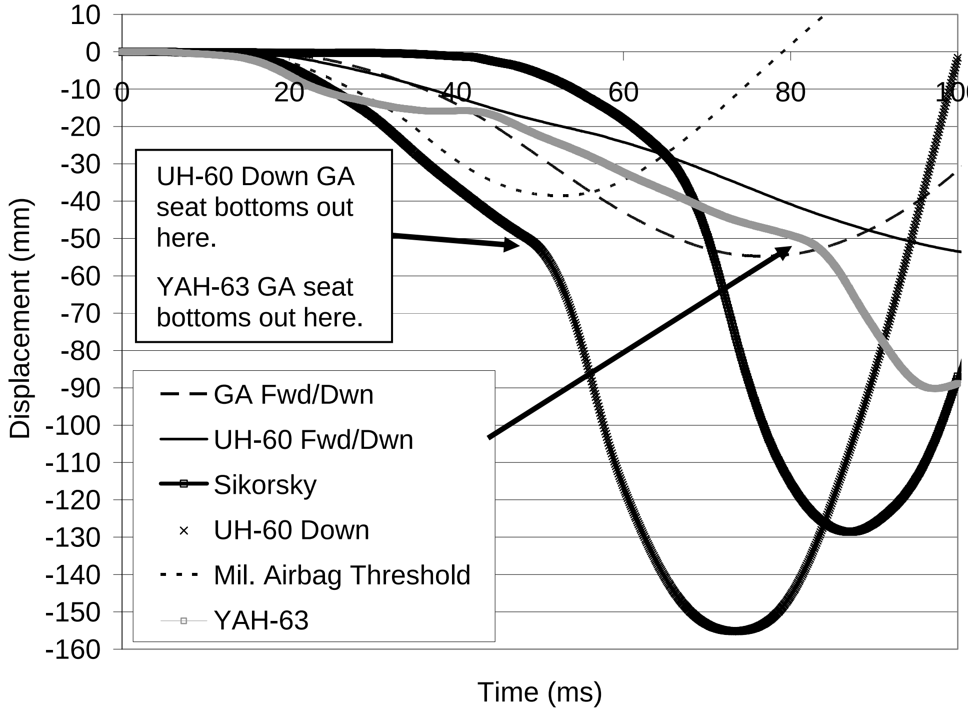


Figure C 8. GA Seat Heart Model Displacement for 6 Impact Conditions

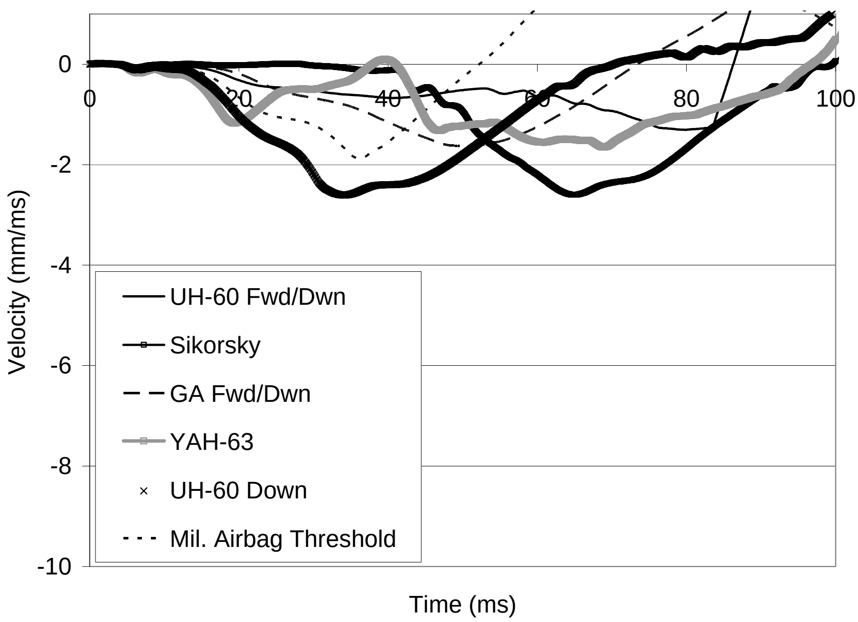


Figure C 9 Heart Model Velocity for 6 Impact Conditions and Two Seat Types

Appendix D: Accident Studies and USAARL Database Survey

Accident Studies Factual Reports:

Probable Cause Report SEA86FA033

National Transportation Safety Board
Washington, DC 20594

Printed on : 1/10/2009 10:29:34 PM

Brief of Accident

Adopted

SEA86FA033 File No. 2093	12/29/1985	DES MOINES, WA	Aircraft Reg No. N1152T	Time (Local): 18:13 PST

Make/Model: Mooney / M20K
Engine Make/Model: Continental / TSIO-360-GB
Aircraft Damage: Destroyed
Number of Engines: 1
Operating Certificate(s): None
Type of Flight Operation: Personal
Reg. Flight Conducted Under: Part 91: General Aviation

	Fatal	Serious	Minor/None
Crew	1	0	0
Pass	3	0	0

Last Depart. Point: HILLSBORO, OR
Destination: SEATLE, WA
Airport Proximity: Off Airport/Airstrip

Condition of Light: Night/Dark
Weather Info Src: Weather Observation Facility
Basic Weather: Instrument Conditions
Lowest Ceiling: 300 Ft. AGL, Broken
Visibility: 1.00 SM
Wind Dir/Speed: 260 / 004 Kts
Temperature (°C): 5
Precip/Obscuration:

Pilot-in-Command Age: 31

Certificate(s)/Rating(s)
Private; Single-engine Land

Instrument Ratings
None

Flight Time (Hours)
Total All Aircraft: 341
Last 90 Days: 3
Total Make/Model: 36
Total Instrument Time: 43

THE WEATHER BRIEFER INFORMED THE PILOT THAT VFR WAS NOT RECOMMENDED DUE TO CURRENT/FORECAST CONDTIONS. THE NON INSTRUMENT RATED PILOT THEN FILED A VFR FLIGHT PLAN RESPONDING THAT HE WAS IFR RATED AND WOULD FILE INFLIGHT IF NECESSARY. WITNESSES REPORTED OBSERVING THE AIRCRAFT CRUISING NORTHBOUND OVER I-5 AT A MODERATE SPEED AND LOW ALTITUDE BENEATH THE CLOUDS. WEATHER CONDITIONS IN THE VICINITY OF THE ACCIDENT SITE WERE DESCRIBED AS 300 FOOT CEILING AND 1 MILE VISIBILITY. DARK NIGHT CONDITIONS EXISTED WHEN THE AIRCRAFT STRUCK POWER LINE 75 FEET ABOVE THE I-5 MEDIAN AND 6 NAUTICAL MILES SOUTH OF THE DESTINATION AIRPORT. IN SPITE OF DETERIORATING WEATHER CONDITIONS THE PILOT MADE NO ATTEMPT TO DIVERT ALONG HIS ROUTE OF FLIGHT TO A MORE FAVORABLE DESTINATION. AN ENTRY REFERRING TO 'SCUD FLYING' WAS NOTED IN THE PILOT'S LOGBOOK.

SEA86FA033 File No. 2093	12/29/1985	DES MOINES, WA	Aircraft Reg No. N1152T	Time (Local): 18:13 PST

Occurrence #1: IN FLIGHT COLLISION WITH OBJECT
Phase of Operation: CRUISE - NORMAL

Findings
1. (C) PREFLIGHT BRIEFING SERVICE - DISREGARDED - PILOT IN COMMAND
2. (F) OVERCONFIDENCE IN PERSONAL ABILITY - PILOT IN COMMAND
3. (C) IN-FLIGHT PLANNING/DECISION - IMPROPER - PILOT IN COMMAND
4. (F) LACK OF RECENT EXPERIENCE - PILOT IN COMMAND
5. (F) WEATHER CONDITION - LOW CEILING
6. (F) LIGHT CONDITION - DARK NIGHT
7. (F) OBJECT - WIRE,TRANSMISSION

Occurrence #2: IN FLIGHT COLLISION WITH TERRAIN/WATER
Phase of Operation: DESCENT - UNCONTROLLED

Occurrence #3: IN FLIGHT COLLISION WITH TERRAIN/WATER
Phase of Operation: DESCENT - UNCONTROLLED

Findings Legend: (C) = Cause, (F) = Factor

The National Transportation Safety Board determines the probable cause(s) of this accident as follows.

Probable Cause Report ATL89FA035

National Transportation Safety Board
Washington, DC 20594

Printed on : 1/10/2009 10:39:29 PM

Brief of Accident

Adopted 01/24/1990

ATL89FA035 File No. 2103	11/14/1988	MOHAWK, TN	Aircraft Reg No. N9575F	Time (Local): 12:17 EST

Make/Model: Hughes / 269C
Engine Make/Model: Lycoming / HI0-360-D1A
Aircraft Damage: Destroyed
Number of Engines: 1
Operating Certificate(s): None
Type of Flight Operation: Instructional
Reg. Flight Conducted Under: Part 91: General Aviation

	Fatal	Serious	Minor/None
Crew	2	0	0
Pass	0	0	0

Last Depart. Point: MORRISTOWN, TN
Destination: Local Flight
Airport Proximity: Off Airport/Airstrip

Condition of Light: Day
Weather Info Src: Witness
Basic Weather: Visual Conditions
Lowest Ceiling: None
Visibility: 10.00 SM
Wind Dir/Speed:
Temperature (°C): 13
Precip/Obscuration:

Pilot-in-Command Age: 41

Certificate(s)/Rating(s)
Flight Instructor; Commercial; Gyroplane; Helicopter

Instrument Ratings
None

Flight Time (Hours)

Total All Aircraft: 756
Last 90 Days: 107
Total Make/Model: 604
Total Instrument Time: UnK/Nr

THE HELICOPTER HAD LANDED AT A PRIVATE AIRSTRIP AND THE INSTRUCTOR DEPLANED. THE DUAL STUDENT REMAINED IN THE HELICOPTER WITH THE ENGINE RUNNING. THE CFI REBOARDED AND THE STUDENT MADE THE TAKEOFF. LATER, ON DOWNWIND IN TRAFFIC PATTERN, A WITNESS REPORTED A LOUD NOISE FROM THE ENGINE. THE MAIN ROTOR WAS OBSERVED TO SLOW NOTICEABLY AND THE HELICOPTER ENTERED A VERY STEEP DESCENT, IMPACTING THE GROUND ABOUT 1,000 FEET SOUTH OF THE RUNWAY. THE ENGINE ROD BOLTS ON THE NUMBER FOUR CYLINDER HAD FRACTURED. EXAMINATION OF THE FLIGHT CONTROLS REVEALED NO EVIDENCE OF PREIMPACT FAILURE. ONE OF THE ROD BOLTS WAS METALLURGICALLY EXAMINED AND SHOWED CRACKING THROUGH 25 PERCENT OF THE BOLT. THE FATIGUE WAS ATTRIBUTED TO INSUFFICIENT PRELOAD ON THE BOLT. THE ENGINE HAD 813 HRS SINCE A MAJOR OVERHAUL AND 36 HRS SINCE ANNUAL INSPECTION.

ATL89FA035 File No. 2103	11/14/1988	MOHAWK, TN	Aircraft Reg No. N9575F	Time (Local): 12:17 EST

Occurrence #1: LOSS OF ENGINE POWER(TOTAL) - MECH FAILURE/MALF
Phase of Operation: APPROACH - VFR PATTERN - DOWNWIND

Findings
1. (C) ENGINE ASSEMBLY,CONNECTING ROD BOLT - FATIGUE
2. (C) MAINTENANCE,OVERHAUL - INADEQUATE - OTHER MAINTENANCE PERSONNEL
3. (C) ENGINE ASSEMBLY,PISTON - BURNED
4. (F) MAINTENANCE,100-HOUR INSPECTION - INADEQUATE - COMPANY MAINTENANCE PERSONNEL

Occurrence #2: FORCED LANDING
Phase of Operation: DESCENT - EMERGENCY

Occurrence #3: LOSS OF CONTROL - IN FLIGHT
Phase of Operation: DESCENT - EMERGENCY

Occurrence #4: IN FLIGHT COLLISION WITH TERRAIN/WATER
Phase of Operation: DESCENT - UNCONTROLLED

Findings
5. (C) AUTOROTATION - DELAYED
6. (C) ROTOR RPM - NOT MAINTAINED - PILOT IN COMMAND(CFI)

Findings Legend: (C) = Cause, (F) = Factor

The National Transportation Safety Board determines the probable cause(s) of this accident as follows.

Probable Cause Report AND95FA073

National Transportation Safety Board
Washington, DC 20594

Printed on : 1/10/2009 10:35:07 PM

Brief of Accident

Adopted 01/29/1996

ANC95FA073 File No. 1000	05/08/1995	CHUGIAK, AK	Aircraft Reg No. N825PK	Time (Local): 09:05 ADT

Make/Model: Piper / PA-18
Engine Make/Model: Lycoming / O-320-A2B
Aircraft Damage: Destroyed
Number of Engines: 1
Operating Certificate(s): None
Type of Flight Operation: Personal
Reg. Flight Conducted Under: Part 91: General Aviation

	Fatal	Serious	Minor/None
Crew	1	0	0
Pass	1	0	0

Last Depart. Point: ANCHORAGE, AK
Destination: Local Flight
Airport Proximity: Off Airport/Airstrip

Condition of Light: Day
Weather Info Src: Weather Observation Facility
Basic Weather: Visual Conditions
Lowest Ceiling: 7000 Ft. AGL, Broken
Visibility: 50.00 SM
Wind Dir/Speed: Calm
Temperature (°C): 7
Precip/Obscuration:

Pilot-in-Command Age: 52

Certificate(s)/Rating(s)
Commercial; Single-engine Land; Single-engine Sea

Instrument Ratings
Airplane

Flight Time (Hours)

Total All Aircraft: 3000
Last 90 Days: Unk/Nr
Total Make/Model: Unk/Nr
Total Instrument Time: UnK/Nr

AFTER DEPARTING ON A ROUND-ROBIN, THE PILOT CONTACTED THE LOCAL AUTOMATED FLIGHT SERVICE STATION (AFSS) AND AIR-FILED A VFR FLIGHT PLAN. THE AFSS REQUESTED A PILOT REPORT ABOUT THE WEATHER CONDITIONS. THE PILOT REPORTED A SMOOTH RIDE. ABOUT ELEVEN MILES NORTH OF THE LAST RADIO CONTACT POINT, THE AIRPLANE COLLIDED WITH MOUNTAINOUS TERRAIN IN A NOSE DOWN ATTITUDE. THE PROPELLER RECEIVED MINOR DAMAGE. THE ENGINE RECEIVED EXTENSIVE FIRE DAMAGE. NO ENGINE MALFUNCTION WAS NOTED DURING A POSTACCIDENT ENGINE EXAMINATION. AN AIRMET WAS IN EFFECT WHICH STATED 'COOK INLET AND SUSITNA VALLEY...OCCASIONAL MODERATE TURBULENCE BELOW 9,000 FEET WITH ISOLATED SEVERE WITHIN 5,000 FEET ABOVE THE GROUND, ESPECIALLY THROUGH CHANNELED TERRAIN. CONTINUING BEYOND 1200.' SEARCH AIRCRAFT ALSO ENCOUNTERED MODERATE TO SEVERE TURBULENCE.

ANC95FA073 File No. 1000	05/08/1995	CHUGIAK, AK	Aircraft Reg No. N825PK	Time (Local): 09:05 ADT

Occurrence #1: IN FLIGHT ENCOUNTER WITH WEATHER
Phase of Operation: CRUISE

Findings
1. (F) PREFLIGHT PLANNING/PREPARATION - INADEQUATE - PILOT IN COMMAND
2. (F) WEATHER CONDITION - TURBULENCE

Occurrence #2: LOSS OF CONTROL - IN FLIGHT
Phase of Operation: CRUISE

Findings
3. (C) AIRSPEED(VS) - NOT MAINTAINED - PILOT IN COMMAND
4. STALL - INADVERTENT - PILOT IN COMMAND

Occurrence #3: IN FLIGHT COLLISION WITH TERRAIN/WATER
Phase of Operation: DESCENT - UNCONTROLLED

Findings
5. TERRAIN CONDITION - MOUNTAINOUS/HILLY

Findings Legend: (C) = Cause, (F) = Factor

The National Transportation Safety Board determines the probable cause(s) of this accident as follows.
THE PILOT'S FAILURE TO MAINTAIN ADEQUATE AIRSPEED RESULTING IN AN INADVERTENT STALL. THE PILOT'S FAILURE TO OBTAIN A WEATHER BRIEFING AND AN ENCOUNTER WITH TURBULENCE WERE FACTORS IN THE ACCIDENT.

Table D 1 Accidents from 1977 to 2005 with HAI, Aircraft Type and Recorded Pre-Impact Air Speed

Case [1]	Aircraft	Air-Speed (knots) [2]	Vertical Speed (ft/min) [2]	Vertical Airspeed Component (knots) [3]	Horizontal Airspeed Component (knots) [3]
19770302002	CH47C	68	150	0.2	67.8
19770720004	T 42A	NR	NR	0	0
19770901001	OH58A	8	3600	0	8
19771211001	OH58A	82	150up	0.2	81.8
19780104005	UH 1H	38	150	0.7	37.3
19780303002	OH58A	22	750	6.5	15.5
19780920001	OH58A	68	150up	31.6	36.4
19811215008 *1*	OH58A	68	150up	1.3	66.7
19811215008 *1*	OH58A	68	150up	1.3	66.7
19820904001	UH 1V	52	150	0.1	51.9
19831018001	UH60A	40	0	0	40
19831019004 *2*	U 8F	160	5058	44.9	115.1
19831114010 *3*	UH 1H	50	5700	32.7	17.3
19840202002 *4*	UH60A	20	450up	1.3	18.7
19840615001	UH1H	NR	NR	NR	NR
19841107002	OH58C	55	100	0	55
19841117001 *5*	AH 1G	120	0	3.6	116.4
19841212001 *6*	U 21A	120	0	0	120
19850215001	JPAH 1S	100	2100	41.3	58.7
19860117001	OH58C	85	0	0	85
19860225001	OH58A	80	100	0.6	79.4
19860409001 *7*	CH47D	90	0	0	90
19860409001 *7*	FAH 1S	90	0	0	90
19860612001 *8*	AH 1F	50	500	0	50
19860922001	RG 8A	53	1100	0	53
19880308001	UH60A	76	0	0	76
19890615001 *9*	OH58C	70	0	0	70
19891017001 *10*	AH64A	10	100	0.1	9.9
19891130001	OH58C	80	0	0	80
19900724002	CH47D	NR	NR	NR	NR
19901029001	AH64A	100	50	0	100
19910904001 *11*	OH 6A	90	NR	0	90
19930222001	MH 6C	110	0	0	110
19930313001 *12*	UH 1H	80	0	0	80
19931216005	OH58C	50	4300	46.6	3.4
19940418001	OH58	NR	NR	NR	NR
19960414001	OH58DI	NR	NR	0	0
19960618001	UH60L	20	0	0	20
20010212001 *13*	UH60L	30	500	12.4	17.6
20010326001	RC12K	130	6000	97.5	32.5
20011009001	AH64A	90	200	2.2	87.8
20020222001 *14*	MH47E	158	1107	12	146
20021211001 *15*	UH60A	89	300up	0.7	88.3
20030608001	AH64A	80	NR up	Nr	nr
20040622001	AH64D	75	1193	24.7	50.3
20050128001 *16*	OH58DR	50	20	0.4	49.6

Notes:

1. Accident case code is: Year, month, day, 3 digit sequence. The Italic number represents accidents with multiple aircraft. Numbers 1 and 7 are repeated as Aortic injury occurred in both aircraft.
2. NR: Value Not Recorded
3. Components Calculated from Airspeed and Flightpath Angle

Table D 2 Accidents from 1977 to 2005 with Aortic Injury, Aircraft Type and Recorded Flight Path and Occupant Duty Station with HAI

Case [1]	Flight-Path (deg.) [2]	Pitch (deg.) (-) Down (+) Up [2]	Roll (deg.) (-) Left (+) Right [2]	Yaw (deg.) (-) Left (+) Right [2]	Occupant Duty Station With HAI [3]
19770302002	3	-3	-8	0	FE
19770720004	NR	NR	NR	NR	P, G
19770901001	3	-8	+8	0	P
19771211001	3 up	+3	-3	0	FE
19780104005	8	-8	+3	0	P, FE
19780303002	33	+38	-3	0	P
19780920001	43up	-3	+3	0	P
19811215008 *1*	8 up	-13	+3	0	P, P
19811215008 *1*	8 up	-13	+3	0	P
19820904001	3	-3	-3	0	P, P
19831018001	0	0	0	0	P, FE
19831019004 *2*	32	+5	0	0	P, P
19831114010 *3*	54	+0	0	0	P, FE
19840202002 *4*	15up	+10	0	0	FE,PA(x4)
19840615001	NR	NR	NR	NR	P, FE, G
19841107002	1up	-5	0	0	PA
19841117001 *5*	10	0	0	0	P, P, U
19841212001 *6*	0	0	0	0	P, P, PA(x2)
19850215001	40	-40	+40	0	P, P
19860117001	0	0	0	0	P
19860225001	5	+20	-60	0	P
19860409001 *7*	0	0	0	0	P, FE(x2), PA(x2)
19860409001 *7*	0	0	0	0	P
19860612001 *8*	0	+20	-45	0	P, P
19860922001	0	+10	-45	0	P, P
19880308001	0	+7	+26	0	P
19890615001 *9*	0	0	0	0	P, PA
19891017001 *10*	5	+10	0	0	P, P
19891130001	0	0	+65	90	P
19900724002	NR	0	NR	-180	P, FE
19901029001	1	-1	+2	-10	P, P
19910904001 *11*	NR	-3	0	0	P, P
19930222001	0	-3	0	0	P
19930313001 *12*	0	0	0	0	FE
19931216005	75	0	-75	0	P
19940418001	NR	(U)40	-60	NR	P
19960414001	NR	NR	NR	0	P, P
19960618001	0	+15	0	0	P, G
20010212001 *13*	40	+20	+40	0	P, P, FE(x2), PA(x2)
20010326001	60	-25	-45	-10	P, P
20011009001	9	+1	0	0	P
20020222001 *14*	16	-16	+16	0	P, P, FE
20021211001 *15*	5 up	+5	0	0	P, FE(x2)
20030608001	NR up	0	0	140	P, P
20040622001	35 up	+4	+2	0	P
20050128001 *16*	5 up	+5	0	0	P, P, U

Notes:

1. Accident case code is: Year, month, day, 3 digit sequence. The Italic number represents accidents with multiple aircraft. Numbers 1 and 7 are repeated as Aortic injury occurred in both aircraft.
2. NR: Value Not Recorded
3. FE: Flight Engineer, G: Gunner, P: Pilot, PA: Passenger, U: Unidentified

Table D 3Aortic or Heart Injury Accident Cases with Recorded Impact Data and Number of Occupants with HAI

Case [1]	Aircraft Type	lat g [2]	long g [2]	vert g [2]	Total Occupants [3]	Occupants With HAI
19831018001	UH60A	NR	NR	+99	5	2
19831019004	U 8F	-2	+99	-99	4	2
19831114010	UH 1H	+15	-35	-74	3	2
19840202002	UH60A	20	0	+15	11	5
19840615001	UH1H	0	0	-56	3	3
19841107002	OH58C	0	+20	-5	U	1
19841117001	AH 1G	+30	+80	99	3	3
19841212001	U 21A	+40	+99	-20	5	4
19850215001	JPAH 1S	+29	-33	-99	U	2
19860117001	OH58C	-79	(-)12	0	6	1
19860225001	OH58A	-30	+99	+30	3	1
19860409001	CH47D	-22	+65	+18	6	5
19860409001	FAH 1S	+14	+77	+99	4	1
19860612001	AH 1F	+76	+34	-54	3	2
19860922001	RG 8A	-8	-35	-18	3	2
19880308001	UH60A	+5	-10	-80	19	1
19890615001	OH58C	-35	-77	-62	4	2
19891017001	AH64A	+91	+37	+33	2	2
19891130001	OH58C	+91	+82	+3	3	1
19900724002	CH47D	0	-50	-2	U	2
19901029001	AH64A	+21	+99	+30	2	2
19910904001	OH 6A	0	-90	0	2	2
19930222001	MH 6C	+57	+99	+14	U	1
19930313001	UH 1H	+17	+18	+97	U	1
19930313001	UH 1H	-22	+14	-62	U	1
19931216005	OH58C	+78	-56	NR	2	1
19940418001	OH58C	+3	+2	+20	2	1
19960414001	OH58DI	+50	-20	-99	4	2
19960618001	UH60L	+3	+4	+22	6	1
20010212001	UH60L	0	+29	-100	17	6
20010326001	RC12K	-10	+200	-31	U	2
20011009001	AH64A	+4	-10	+5	U	1
20020222001	MH47E	0	+128	-5	10	3
20021211001	UH60A	0	+200	-5	5	3
20030608001	AH64A	NR	NR	+97	2	2
20040622001	AH64D	0	0	+200	U	1
20050128001	OH58DR	+1	+50	+100	2	3

Notes:

1. Accident case code is: Year, month, day, 3 digit sequence. Italic number represents accident with multiple aircraft.
2. Directions (-) Left/Aft/Down; (+) Right/Fore/Up; NR-Not Recorded
3. Unknown

Table D 4 Injury Listings for Occupants in HAI Accidents

Pax Seq	Case	Duty	Injury Sev.	Body Part	Injury Type	Body Aspect	Cause Subject	Cause Action	Cause Qual.
1	19770302 002	FE	F	Heart	Hern. / Rupture	Body	U	U	U
1	19770720 004	P	F	Heart	Laceration	Body	U	U	U
2		GU	F	Heart	Hern. / Rupture	Body	U	U	U
1	19770901 001	P	F	Aorta	Hern. / Rupture	Body	U	U	U
1	19771211 001	FE	F	Aorta	Hern. / Rupture	Body	U	U	U
1	19780104 005	P	F	Heart	Hern. / Rupture	Body	U	U	U
2		FE	F	Aorta	Laceration	Body	U	U	U
1	19780303 002	P	F	Heart	Hemorrhage	Body	U	U	U
1	19780920 001	P	F	Aorta	Laceration	Body	U	U	U
1	19811215 008	P	F	Heart	Laceration	Body	U	U	U
2		P	F	Heart	Laceration		U	U	U
3		P	F	Heart	Laceration	Body	U	U	U
1	19820904 001	P	F	Aorta	Laceration	Body	U	U	U
				Heart	Hern. / Rupture	Body	U	U	U
1		P	F	Aorta, Heart	Laceration	Body	U	U	U
				Heart	Laceration	Body	U	U	U
1	19831018 001	P	F	Chest	Crushed		U	U	U
				Clavicle	Simple Closed		U	U	U
				Kidney	Contusion		U	U	U
				Vertebra T5	Fracture		U	U	U
				WRIST	Fracture		U	U	U
2		PA		U	U	U	U	U	U
3		GU	F	Arm	Simple Closed		U	U	U
				Chest	Crushed		U	U	U
4		P	F	Chest	Crushed		U	U	U
					Mult Fatal Inj		U	U	U
				Heart	Penetration		U	U	U
				Pelvis	Simple Closed		U	U	U
				Vertebra T12	Compresion		U	U	U
5		FE	F	Aorta	Transection	Central Int	Impact	U	U
				Shoulder	Simple Closed		Impact	U	U
				Skull	Crushed	Multiple	Impact	U	U
				Trunk	Laceration	Multiple	Impact	U	U
				Vertebra C3	Fracture	Body Part	Impact	U	U
				Vertebra T5	Fracture	Body Part	Impact	U	U
				Vertebra T6	Fracture	Body Part	Impact	U	U
1	19831019 004	PA		U	U	U	U	U	U
2		PA	F	Body	Burn (4th deg)	Body	Fuel Tanks	Ignited	Fuel
				Liungs	Edema		Fuel Tanks	Ignited	Fuel
				Trachea	Burns	Body Part	Fuel Tanks	Ignited	Fuel
3		P	F	Aorta	Laceration	Sup, Cranal, upper	Impact	U	U
				Brain	Avulsion	Body Part	U	U	U
				Chest	Mult Fatal Inj	Body	Impact	U	U
				Heart	Crushed	Body Part	Impact	U	U
				Lungs	Laceration	Multiple	Impact	U	U
				Ribs	Crushed		Impact	U	U
				Skull	Crushed	Multiple	U	U	U

4		P	F	Aorta	Laceration	Central Int	Impact	U	U
				Body	Burn (4th deg)	Body	Fuel Tanks	Ignited	Fuel
				Brain	Transection	Int, Causal, Lower	Impact	U	U
				Chest	Mult Fatal Inj	Body	Impact	U	U
				LUNGS	Hemo-Pneumothorax		Impact	U	U
				Pelvis	Amputation		Impact	U	U
				Skull	Mult Fatal Inj	Int, Causal, Lower	Impact	U	U
1	19831114 010	U							
2		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Brain	Contusion	Central Int	Impact	Exceeded	Human/Dsn limit
				DIAPHRAGM	Hern. / Rupture	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				Heart	Hern. / Rupture	Central Int	Impact	Exceeded	Human/Dsn limit
				Skull	Linear	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				SPLEEN	Hern. / Rupture	Central Int	Impact	Exceeded	Human/Dsn limit
3		FE	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Heart	Hern. / Rupture	Central Int	Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Central Int	External Objects	Penetrated	Occ Space
				Skull	Linear	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Spinal Cord	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				VERTEBRA (UNQ)	Fracture	Central Int	Impact	Exceeded	Human/Dsn limit
1	19840202 002	PA	F	Aorta	Transection	Central Int	Restraint	BROKE	Exc Motion
				HAND (UNQ)	Fracture		U	U	U
				LIVER	Laceration	Central Int	Restraint	BROKE	Exc Motion
				Pelvis	Fracture	Multiple	U	U	U
				Ribs/Sides	Fracture		Cargo	Crushed	U
				Skull	Fracture	Multiple	Restraint	BROKE	Exc Motion
				VERTEBRA C3	Fracture		Restraint	BROKE	Exc Motion
2		PA	TD	Brain	Contusion		Restraint	NOT USED	U
				Ribs/Sides	OBLIQUE		Restraint	NOT USED	U
				SPLEEN	Laceration	Body Part	Restraint	NOT USED	U
				TEMPORAL	Crushed		Restraint	NOT USED	U
3		P	TD	ANKLE	Joint Sprain	U	U	U	U
				Brain	Contusion		HELMET	allowed	Exc Loading
				HIP	Contusion		Restraint	allowed	Exc Loading
				Shoulder	Contusion		Restraint	allowed	Exc Loading
4		P	LW	Brain	Contusion		HELMET	allowed	Exc Loading
					Hemorrhage		Int Objects	Displaced	> 12 inch
				Chest, NFS	Contusion		Restraint	Asorbed	Exc Loading
					Pneumothorax		Uppr Torso Rest.	BROKE	U

				HAND (UNQ)	Simple Closed		AIRCRAFT	allowed	Exc Loading
5		FE	F	Aorta	Hern. / Rupture	Central Int	Body	Flailed	Outside A/C
				Chest, NFS	Hemothorax		Body	Flailed	Outside A/C
				Kidney	Contusion		Body	Flailed	Outside A/C
				Leg Lower	Transverse		Body	Flailed	Outside A/C
				LUNGS	Contusion		Body	Flailed	Outside A/C
				Mult. Bones, Basilar	Linear		Body	Flailed	Outside A/C
				SPLEEN	Laceration	Body Part	Body	Flailed	Outside A/C
6		PA	LW	ANKLE	Simple Closed		Restraint	NOT USED	U
				Brain	Concussion	Body Part	Restraint	NOT USED	U
				Chest	Pneumothorax		Restraint	NOT USED	U
				Heart	Contusion	Body Part	Restraint	NOT USED	U
				Leg Lower	Simple Closed		Restraint	NOT USED	U
				Ribs/Sides	Transverse		Restraint	NOT USED	U
				STERNUM	Transverse	Central Int	Restraint	NOT USED	U
7		PA	LW	EYES	Hemorrhage		U	U	U
				FACE (UNQ)	Laceration	Multiple	Body	Flailed	Excessive
				LOWER EXTREMITIES (UNQ)	Dislocation		Restraint	NOT USED	U
				Pelvis	Fracture		Restraint	NOT USED	U
8		PA	F	Aorta	Transection	Central Int	U	U	U
				Chest, NFS	Hemothorax		Body	Flailed	Excessive
				Ribs/Sides	Fracture		U	U	U
				SCALP	Laceration	Posterior, Dorsal	U	U	U
				SPLEEN	Laceration	Central Int	U	U	U
9		PA	F	Aorta	Transection	Central Int	U	U	U
				Brain	Laceration	Multiple	Body	Flailed	Excessive
				Chest, NFS	Hemothorax		Body	Flailed	Excessive
				Lower Leg	Fracture		U	U	U
				Ribs/Sides	Fracture		Cargo	Crushed	U
				Skull	Crushed	Multiple	Body	Flailed	Excessive
10		PA	LW	Abdomen	Contusion	Int, Causal, Lower	AIRCRAFT	allowed	Exc Loading
				Chest	Contusion		Restraint	BROKE	U
				SCALP	Laceration		Restraint	BROKE	U
11		U		U	U	U	U	U	U
1	19840615 001			U	U	U	U	U	U
	19841107 002	PA	LW	Heart	Contusion		AIRCRAFT	allowed	Exc Loading
1	19841117 001	P	F	Brain	Contusion	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Chest, NFS	Fracture		Impact	Exceeded	Human/Dsn limit
				Heart	Contusion	Multiple	Impact	Exceeded	Human/Dsn limit
				LUNGS	Contusion	Multiple	Impact	Exceeded	Human/Dsn limit
				Mult. Bones, Basilar	Fracture	Multiple	Impact	Exceeded	Human/Dsn limit

				Mult. Bones, Calvarium	Fracture		Impact	Exceeded	Human/Dsn limit
				TRACHEA	Fracture	Ant. Ventral Frnt	Impact	U	Longitudinal
2		P	F	Aorta	Avulsion	Central Int	Impact	Exceeded	Human/Dsn limit
				Brain	Int. Injury	Multiple	Impact	Exceeded	Human/Dsn limit
				DIAPHRAGM	Hern. / Rupture		Impact	Exceeded	Human/Dsn limit
				Heart	Hern. / Rupture		Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration		Impact	Exceeded	Human/Dsn limit
				Mult. Bones, face	Fracture	Multiple	Impact	Exceeded	Human/Dsn limit
				Skull	Fracture	Multiple	Impact	Exceeded	Human/Dsn limit
3		P		U	U	U	U	U	U
1	19841212 001	P	F	Abdomen	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
				Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Body	Burns, 4th deg	Body	Impact	Ignited	Fuel
				HEAD (UNQ)	DECAPITATION	Body Part	Impact	Exceeded	Human/Dsn limit
				Heart	Penetration	Multiple	Impact	Exceeded	Human/Dsn limit
				Mult. Bones	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
2		PA	F	Abdomen	Mult Fatal Inj	Multiple	Impact	Exceeded	Human/Dsn limit
				Aorta	Transection	Multiple	Impact	Exceeded	Human/Dsn limit
				Body	Burns, 4th deg	Multiple	Impact	Ignited	Fuel
				Heart	Penetration	Multiple	Impact	Exceeded	Human/Dsn limit
				Mult. Bones	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
3		P	F	Abdomen	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
				Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Body	Burns, 4th deg	Body	Impact	Ignited	Fuel
				HEAD (UNQ)	DECAPITATION	Body Part	Impact	Exceeded	Human/Dsn limit
				Heart	Penetration	Multiple	Impact	Exceeded	Human/Dsn limit
				Mult. Bones	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
4		P	F	Abdomen	Mult Fatal Inj	Multiple	Impact	Exceeded	Human/Dsn limit
				Body	Burns, 4th deg	Body	Impact	Ignited	Fuel
				Brain	Avulsion	Body Part	Impact	Exceeded	Human/Dsn limit
				Heart	Penetration	Multiple	Impact	Exceeded	Human/Dsn limit
				Mult. Bones	Mult Fatal Inj	Body	Impact	Exceeded	Human/Dsn limit
				Skull	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
5		PA		U	U	U	U	U	U
	19850215 001	P	F	Aorta	Transection	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
		P	F	Aorta	Avulsion	Central Int	Impact	Exceeded	Human/Dsn limit

				Heart	Contusion	Body Part	Impact	Exceeded	Human/Dsn limit
1	19860117 001	P	F	Brain	Hemorrhage	Sup. Cranial, uppr	Restraint	allowed	Exc Motion
				Mult. Bones, face	Fracture	Multiple	HELMET	allowed	Human/Dsn limit
				Skull	Crushed	Multiple	Restraint	allowed	Exc Motion
2		P	LW	Lower Leg	Laceration		DESIGN	allowed	Exc Motion
				Vertebra T8	Compression	Body Part	Impact	Exceeded	Human/Dsn limit
3		PA							
4		P	LW	Ribs/Sides	Simple Closed		Impact	Caused	Exc Motion
				SPLEEN	Hern. / Rupture	Central Int	Restraint	allowed	Exc Motion
5		FE	LW	Brain	Concussion		HELMET	NOT USED	PROPERLY
				DIAPHRAGM	Hern. / Rupture		Restraint	allowed	Exc Motion
				SPLEEN	Hern. / Rupture	Central Int	Restraint	allowed	Exc Motion
6		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				FOREHEAD	Laceration		Impact	Exceeded	Human/Dsn limit
				Pelvis	Transverse	Multiple	SEAT	BROKE	Exc Loading
				Ribs/Sides	Simple Closed		Uppr Torso Rest.	allowed	Exc Motion
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
1	19860225 001	FE	F	Chest, NFS	Hemothorax	Central Int	Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit
				LUNGS	Contusion		Impact	Exceeded	Human/Dsn limit
					Laceration		Impact	Exceeded	Human/Dsn limit
				Spinal Cord	Contusion	Multiple	Impact	Exceeded	Human/Dsn limit
					Hemorrhage	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				SPLEEN	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit
2		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Chest, NFS	Hemothorax		Ins. Panel	Penetrated	Occ Space
				LUNGS	Contusion		Ins. Panel	Penetrated	Occ Space
				Ribs/Sides	Fracture		Ins. Panel	Penetrated	Occ Space
				Spinal Cord	Contusion	Multiple	Impact	Exceeded	Human/Dsn limit
					Transection	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				VERTEBRA C6	OBLIQUE	Body Part	Impact	Exceeded	Human/Dsn limit
3		PA		U	U	U	U	U	U
1	19860409 001	PA		U	U	U	U	U	U
2		PA		U	U	U	U	U	U
3		P	F	Brain	Crushed	Body Part	MAIN ROTOR	Penetrated	Occ Space
				Kidney	Laceration		MAIN ROTOR	Penetrated	Occ Space
				LIVER	Crushed	Central Int	MAIN ROTOR	Penetrated	Occ Space
				Pelvis	Comminuted	Multiple	Restraint	Asorbed	Exc Loading

				Skull	Crushed	Body Part	HELMET	Asorbed	Exc Loading
				SPLEEN	Crushed	Central Int	MAIN ROTOR	Penetrated	Occ Space
				TRUNK (UNQ)	Laceration	Central Int	MAIN ROTOR	Penetrated	Occ Space
4		P	F	Aorta	Transection	Central Int	SEAT	allowed	Exc Loading
				Body	Burns, 4th deg	Int, Causal, Lower	Impact	INJURED	Fuel
				Chest, NFS	Hemothorax		Uppr Torso Rest.	allowed	Exc Motion
				LIVER	Laceration	Central Int	Impact	Collapsed	Occ Space
				SPLEEN	Laceration	Central Int	Impact	Collapsed	Occ Space
				TRACHE A	INTAKE, NFS	Body Part	Impact	Ignited	Fuel
				Vertebra T3	Dislocation	Body Part	Uppr Torso Rest.	allowed	Exc Motion
5		PA	F	Aorta	Transection	Central Int	SEAT	Asorbed	Exc Loading
				Brain	Hemorrhage	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
					Transection		Impact	Exceeded	Human/Dsn limit
				Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Central Int	AIRCRAFT	Asorbed	Exc Loading
				OCCIPIT AL	Hern. / Rupture	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
				SPLEEN	Laceration	Central Int	AIRCRAFT	Asorbed	Exc Loading
6		FE	F	Aorta	Transection	Central Int	SEAT	allowed	Exc Loading
				Brain	Hemorrhage	Multiple	HELMET	Asorbed	Exc Loading
					Crushed	Body Part	HELMET	Asorbed	Exc Loading
				Heart	Laceration		Monkey Harn	allowed	Exc Motion
				LIVER	Laceration	Central Int	Monkey Harn	allowed	Exc Motion
				PANCRE AS	Laceration	Central Int	Monkey Harn	allowed	Exc Motion
				Skull	Crushed	Body Part	Helmet	Asorbed	Exc Loading
7		P	F	Aorta	Transection	Central Int	Body	Asorbed	Exc Loading
				ARM LOWER, NFS	Simple Closed		Impact	Collapsed	Occ Space
				Brain	Transection	Int, Causal, Lower	Body	Flailed	Excessive
				DIAPHRA GM	Laceration		Impact	Collapsed	Occ Space
				Heart	Laceration		Body	Flailed	Excessive
				LIVER	Laceration	Central Int	Impact	Collapsed	Occ Space
				Skull	Transverse	Body Part	Helmet	Asorbed	Exc Loading
8		FE	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Chest	Hemothorax		Impact	Caused	Exc Motion
				LEG UPPER, NEC	Comminuted		Body	Flailed	Excessive
				Mult.	Transverse	Sup.	Helmet	Asorbed	Exc

				Bones, Basilar		Cranial, uppr			Loading
9		PA	F	Aorta	Transection	Central Int	SEAT	Asorbed	Exc Loading
				Chest	Hemothorax		Impact	Exceeded	Human/Dsn limit
				Lower Leg	Comminuted		Body	Flailed	Excessive
				LEG UPPER, NEC	Compound		Body	Flailed	Excessive
				LUNGS	Pneumothorax		Impact	Exceeded	Human/Dsn limit
				Pelvis	Comminuted	Multiple	Impact	Exceeded	Human/Dsn limit
10		P	F	Brain	Transection	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Clavicle	Simple Closed		Restraint	Asorbed	Exc Loading
				LIVER	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
				Mult. Bones, Basilar	Transverse	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
				Upper Extr.	Contusion	Multiple	Impact	Exceeded	Human/Dsn limit
				VERTEB RA C6	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
	19860409 001	PA	F	Aorta	Transection	Central Int	SEAT	Asorbed	Exc Loading
				Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
		P	F	Aorta	Transection	Central Int	SEAT	allowed	Exc Loading
		FE	F	Aorta	Transection	Central Int	SEAT	allowed	Exc Loading
				Heart	Laceration		Monkey Harn	allowed	Exc Motion
		P	F	Aorta	Transection	Central Int	Body	Asorbed	Exc Loading
				Heart	Laceration		Body	Flailed	Excessive
		FE	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
		PA	F	Aorta	Transection	Central Int	SEAT	Asorbed	Exc Loading
1	19860612 001	P	F	Aorta	Laceration	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Brain	Transection	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
					Hemorrhage	Body Part	HELMET	Asorbed	Exc Loading
				Clavicle	Fracture		Uppr Torso Rest.	Asorbed	Exc Loading
				LUNGS	Contusion		Impact	Exceeded	Human/Dsn limit
					Hemothorax		Impact	Exceeded	Human/Dsn limit
				NECK, NFS	Hern. / Rupture	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
2		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				LUNGS	Contusion		Impact	Exceeded	Human/Dsn limit
					Hemothorax		Impact	Exceeded	Human/Dsn limit
				Mult. Bones, Basilar	Transverse	Multiple	HELMET	Asorbed	Exc Loading

				NECK, NFS	Crushed	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
				Pelvis	Comminuted		Impact	Exceeded	Human/Dsn limit
				STERNUM	Transverse	Central Int	Uppr Torso Rest.	allowed	Exc Motion
3		PA						U	U
1	19860922 001	PA						U	U
2		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
				Brain	INJURY, NFS	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Chest, NFS	Hemothorax		Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
				LUNGS	Laceration		Impact	Exceeded	Human/Dsn limit
				Ribs/Sides	Crushed	Multiple	Impact	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	HELMET	Displaced	IMPROPERLY
3		P	F	Aorta	Penetration	Central Int	Impact	Exceeded	Human/Dsn limit
				Brain	INJURY, NFS	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Chest, NFS	Hemothorax		Impact	Exceeded	Human/Dsn limit
				Lower Leg	Comminuted		Impact	BUCKLED	Occ Space
					Fracture		Impact	BUCKLED	Occ Space
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
				SPLEEN	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
1	19880308 001	P	F	U	U	U	U	U	U
2		P	F	U	U	U	U	U	U
3		PA	F	U	U	U	U	U	U
4		PA	F	U	U	U	U	U	U
5		PA	F	U	U	U	U	U	U
6		PA	F	U	U	U	U	U	U
7		PA	F	U	U	U	U	U	U
8		PA	F	U	U	U	U	U	U
9		FW	F	U	U	U	U	U	U
10		PA	F	U	U	U	U	U	U
11		PA	F	U	U	U	U	U	U
12		PA	F	U	U	U	U	U	U
13		PA	F	U	U	U	U	U	U
14		PA		U	U	U	U	U	U
15		PA		U	U	U	U	U	U
16		P	F	Brain	Laceration	Multiple	HELMET	Asorbed	Exc Loading
				LUNGS	Contusion	Central Int	Impact	Crushed	Occ Space
				Ribs/Sides	Crushed	Multiple	Impact	Crushed	Occ Space
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
17		PA	F	Body	Mult Injuries	Central Int	Impact	Crushed	Occ Space
				Vertebra T1	Dislocation	Posterior, Dorsal	Impact	Caused	Exc Motion
18		FE	F	Body	Mult Injuries	Central Int	Impact	Crushed	Occ Space
19		P	F	Body	Mult Injuries	Central Int	Impact	Crushed	Occ Space
				Brain	Laceration	Multiple	HELMET	Asorbed	Exc Loading
				Heart	Laceration	Central Int	Impact	Crushed	Occ Space
				LUNGS	Laceration		Impact	Crushed	Occ Space
				Ribs/Side	Crushed	Multiple	Impact	Crushed	Occ Space

				s					
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
				VERTEBRA	Fracture	Posterior, Dorsal	Impact	Caused	Exc Motion
1	19890615001	P	F	Brain	Laceration	Multiple	HELMET	Asorbed	Exc Loading
				Chest, NFS	Hemothorax		Impact	Crushed	Occ Space
				HAND, NFS	OBLIQUE		Impact	Crushed	Occ Space
				Lower Leg	Fracture		Impact	Crushed	Occ Space
				LUNGS	Laceration		Impact	Crushed	Occ Space
				Ribs/Sides	Crushed		Impact	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
2		PA						U	U
3		PA	F	ABDOMEN, NEC	Laceration	Central Int	SEAT	Asorbed	Exc Loading
				Aorta	Transection	Central Int	Restraint	Asorbed	Exc Loading
				Brain	Laceration	Multiple	HELMET	Asorbed	Exc Loading
				Heart	Laceration	Multiple	Impact	Crushed	Occ Space
				LUNGS	Laceration		Impact	Crushed	Occ Space
				Skull	Comminuted	Multiple	HELMET	Asorbed	Exc Loading
				Vertebra T3	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
4		P	F	Brain	Laceration	Multiple	HELMET	Asorbed	Exc Loading
				Heart	Laceration	Multiple	Impact	Crushed	Occ Space
				LIVER	Laceration	Multiple	Impact	Crushed	Occ Space
				LUNGS	Laceration		Impact	Crushed	Occ Space
				Ribs/Sides	Crushed		Impact	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
				SPLEEN	Laceration	Multiple	Impact	Crushed	Occ Space
1	19891017001	P	F	Brain	Transection	Int, Causal, Lower	Body	PROVIDED	JAGGED EDGES
				Heart	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Multiple	Body	PROVIDED	JAGGED EDGES
				Pelvis	Comminuted	Multiple	Impact	Crushed	Occ Space
				Ribs/Sides	Simple Closed	Multiple	Impact	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	Impact	Exceeded	Human/Dsn limit
2		P	F	Aorta	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
				Heart	Hern. / Rupture	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				Ribs/Sides	Simple Closed	Multiple	Impact	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	Impact	Exceeded	Human/Dsn limit
				Spinal Cord	Transection	Body Part	Body	PROVIDED	JAGGED EDGES
				Vertebra T1	Transverse	Body Part	Impact	Exceeded	Human/Dsn limit
1	19891130001	P	F	Aorta	Hemorrhage	Sup. Cranial, uppr	Body	Asorbed	Exc Loading
				Body	Fracture	Body	Impact	Collapsed	Occ Space
				Heart	Int. Injury	Body Part	Body	Asorbed	Exc

									Loading
				Mult. Bones, Calvarium	Compound	Ant. Ventral Frnt	NIGHT VISION DEVICE(S)	Asorbed	Exc Loading
				Pelvis	Hemorrhage	Central Int	Impact	Collapsed	Occ Space
				SPLEEN	Laceration	Body Part	Body	Asorbed	Exc Loading
2		PA	LW	ANKLE	Simple Closed		Body	Flailed	Excessive
				ARM UPPER, NFS	Compound		Body	Flailed	Excessive
				HEAD (UNQ)	Contusion	Multiple	HELMET	Asorbed	Exc Loading
				Shoulder	Simple Closed		Body	Displaced	Excessive
				Upper Extr.	Contusion		Impact	Collapsed	Occ Space
3		PA		U	U	U	U	U	U
1	19900724 002	P	F	Heart	Contusion	Body	Impact	Caused	Exc Loading
		FE	F	Heart	Contusion	Multiple	Impact	Caused	Exc Motion
1	19901029 001	P	F	Aorta	Transection	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Multiple	Restraint	allowed	Exc Motion
				LUNGS	Laceration		STRUCTURE	Displaced	Occ Space
				Mult. Bones, face	Fracture	Multiple	HELMET	Asorbed	Exc Loading
				Pelvis	Fracture	Multiple	SEAT	Exceeded	Human/Dsn limit
				Vertebra T1	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
2		P	F	Abdomen	Int. Injury	Multiple	Restraint	allowed	Exc Motion
				Heart	Laceration		Restraint	allowed	Exc Motion
				LUNGS	Hemothorax		Restraint	allowed	Exc Motion
				Pelvis	Fracture	Multiple	SEAT	Exceeded	Human/Dsn limit
				Skull	Crushed	Multiple	HELMET	Exceeded	Exc Loading
				VERTEBRA C1	Dislocation	Body Part	STRUCTURE	Displaced	Occ Space
				Vertebra T3	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
1	19910904 001	P	F	Abdomen	Mult Fatal Inj	Multiple	Impact	Exceeded	Human/Dsn limit
				Aorta	Transection	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				FACE, NFS	Fracture	Ant. Ventral Frnt	NIGHT VISION DEVICE(S)	Caused	Exc Loading
				Heart	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit
				LUNGS	Laceration		Impact	Exceeded	Human/Dsn limit
				Mult. Bones, Basilar	Linear	Multiple	HELMET	Asorbed	Exc Loading
				Pelvis	Linear	Multiple	Restraint	Asorbed	Exc Loading
2		P	F	Abdomen	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit
				Aorta	Transection	Multiple	Impact	Exceeded	Human/Dsn limit
				FACE, NFS	Fracture	Ant. Ventral Frnt	NIGHT VISION DEVICE(S)	Caused	Exc Loading
				LUNGS	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit

				Pelvis	Crushed	Ant. Ventral Frnt	Restraint	Asorbed	Exc Loading
				Skull	Crushed	Multiple	HELMET	Asorbed	Exc Loading
				VERTEB RA C3	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
1	19930222 001	P	F	Heart	Hern. / Rupture	Body Part	Uppr Torso Rest.	NOT USED	PROPERL Y
1	19930313 001	FE	F	Heart	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
							Restraint	allowed	Exc Motion
		P	F	Heart	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
1	19931216 005	PA	F	Leg Lower	Simple Closed		Body	Flailed	Excessive
					Simple Closed		Body	Flailed	Excessive
				LIVER	Laceration	Ant. Ventral Frnt	Body	Asorbed	Exc Loading
				Mult. Bones, Basilar	Transverse	Multiple	Impact	Exceeded	Human/Dsn limit
				Pelvis	Simple Closed	Multiple	Impact	Exceeded	Human/Dsn limit
				Vertebra T1	Comminuted	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
2		P	F	Aorta	Laceration	Multiple	Body	Asorbed	Exc Loading
				Brain	Hemorrhage		Impact	Exceeded	Human/Dsn limit
				LIVER	Laceration	Ant. Ventral Frnt	Body	Asorbed	Exc Loading
				Mult. Bones, Basilar	Transverse	Multiple	Impact	Exceeded	Human/Dsn limit
				Pelvis	Fracture	Multiple	Impact	Exceeded	Human/Dsn limit
				SPLEEN	Laceration	Body	Body	Asorbed	Exc Loading
1	19940418 001								
1	19960414 001	P	F	Heart	Laceration	Other	Occ. Space	Crushed	> 12 inch
				Skull	Crushed	Body Part	Occ. Space	Crushed	> 12 inch
				VENA CAVA	Laceration	Sup. Cranial, uppr	Occ. Space	Crushed	> 12 inch
2		P	F	Aorta	Transection		Impact	Exceeded	Human/Dsn limit
				Heart	Laceration	Other	Occ. Space	Crushed	> 12 inch
				Skull	Crushed	Body Part	Occ. Space	Crushed	> 12 inch
3		P	M	Arm lower	Laceration	Ant. Ventral Frnt	U	U	U
				CHIN	Laceration	Ant. Ventral Frnt	U	U	U
				EYES	Abrasions	Ant. Ventral Frnt	U	U	U
4		P	F	Arm lower	Amputation	Body Part	MAIN ROTOR	Penetrated	Occ Space
				Body	4th degree	Body	Fuel Tanks	RUPTURE D	Other
				LIVER	Laceration	Central Int	MAIN ROTOR	Penetrated	Occ Space
1	19960618 001	G	M	FACE, NFS	Laceration	Sup. Cranial, uppr	Body	Inj. outside A/C	Inad. Clearance

2		G	M	Arm lower	Laceration	Int, Causal, Lower	Body	Inj. outside A/C	Inad. Clearance
3		G	M	Abdomen	Contusion	Ant. Ventral Frnt	Body	Inj. outside A/C	Inad. Clearance
4		PA	LW	Body	Laceration	Body	Body	Not Rest.	Other
5		G	F	LUNGS	Asphyxiation	Central Int	Body	INJURED	Outside A/C
6		PA	TD	Arm Uppr	Simple Closed	Body Part	Body	INJURED	Outside A/C
				BLADDER	Hern. / Rupture	Central Int	Body	INJURED	Outside A/C
				Chest	Pneumothorax	Body Part	Body	INJURED	Outside A/C
				HEAD (UNQ)	Comminuted	Body Part	Body	INJURED	Outside A/C
				LIVER	Laceration	Central Int	Body	INJURED	Outside A/C
				Pelvis	Simple Closed	Body Part	Body	INJURED	Outside A/C
7		PA	LW	LUNGS	Contusion	Central Int	Body	Not Rest.	Other
				STERNUM	Fracture	Sup. Cranial, uppr	Body	Not Rest.	Other
8		FE	LW	Lower Leg	Comminuted	Sup. Cranial, uppr	SEAT	Collapsed	IMPROPERLY
					Simple Closed		SEAT	Collapsed	IMPROPERLY
9		PA	F	Pelvis	Crushed	Body Part	Roof	Collapsed	> 12 inch
				VERTEBRA C2	Fracture	Body Part	Roof	Collapsed	> 12 inch
10		PA	LW	ABDOMEN, NEC	Laceration	Body	Body	Not Rest.	Other
11		G	LW	HEAD (UNQ)	Concussion	Sup. Cranial, uppr	Body	Inj. outside A/C	Inad. Clearance
12		G	LW	HEAD (UNQ)	Abrasions	Body	Body	Inj. outside A/C	Inad. Clearance
13		PA	LW	Body	Contusion	Body	Body	Not Rest.	Other
14		FE	LW	ORBIT	Contusion	Int, Causal, Lower	HELMET	Displaced	Excessive
				SPLEEN	Hern. / Rupture	Sup. Cranial, uppr	Restraint	Failed to Att.	Exc Loading
15		PA	LW	SCAPULA	Simple Closed	Body Part	Body	Not Rest.	Other
				Vertebra T4	BLOWOUT	Body Part	Impact	Exceeded	Human/Dsn limit
16		P	LW	Vertebra L1	Compression	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
17		PA	LW	HEAD (UNQ)	Concussion	Body Part	Body	Not Rest.	Other
18		PA	LW	BACK (UNQ)	Contusion	Posterior, Dorsal	Body	Not Rest.	Other
				Vertebra T7	Compression	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
19		PA	LW	HEAD (UNQ)	Concussion	Body Part	Body	Not Rest.	Other
20		P	LW	BACK (UNQ)	Strianed	Body	STRUCTURE	Collapsed	> 12 inch
				Vertebra T11	CHIP	Int, Causal, Lower	STRUCTURE	Collapsed	> 12 inch
21		PA	LW	ANKLE	Fracture	Body Part	Body	Not Rest.	Other
22		G	F	Aorta	Hern. / Rupture	Sup. Cranial, uppr	Body	Crushed	Outside A/C
23		PA	LW	HEAD (UNQ)	Concussion	Body Part	Body	Not Rest.	Other
				TRUNK	Laceration	Body	Body	Not Rest.	Other

				(UNQ)					
24		PA	LW	LUNGS	Hemo- Pneumothorax	Central Int	Body	Not Rest.	Other
				SCAPUL A	Fracture	Body Part	Body	Not Rest.	Other
25		PA	LW	Leg Uppr	Comminuted	Body Part	Body	Not Rest.	Other
26		PA	LW	Skull	Fracture	Int, Causal, Lower	Body	Not Rest.	Other
27		P	F	Aorta	Penetration	Body Part	Impact	Exceeded	Human/Dsn limit
				Skull	Transverse	Int, Causal, Lower	SEAT	Displaced	Longitudinal
				Vertebra T12	Compression	Ant. Ventral Frnt	Impact	Exceeded	Human/Dsn limit
				Vertebra, Lumbar	Compression	Ant. Ventral Frnt	Impact	Exceeded	Human/Dsn limit
28		PA	F	Lungs	Laceration	Posterior, Dorsal	Roof	Collapsed	> 12 inch
				Ribs/Side s	Fracture	Body Part	Roof	Collapsed	> 12 inch
29		PA	LW	BLADDE R	Hern. / Rupture	Body Part	Body	Not Rest.	Other
				LUNGS	Pneumothorax	Central Int	Body	Not Rest.	Other
				Pelvis	Fracture	Body Part	Body	Not Rest.	Other
30		PA	LW	Arm Lower	Fracture	Superior, Cranal, upper	Body	Not Rest.	Other
				ELBOW	Fracture	Body Part	Body	Not Rest.	Other
				Leg Lower	Fracture	Superior, Cranal, upper	Body	Not Rest.	Other
31		PA	LW	FACE (UNQ)	Laceration	Body Part	Body	Not Rest.	Other
				FOOT (UNQ)	Fracture	Body Part	Body	Not Rest.	Other
				Pelvis	Fracture	Body Part	Body	Not Rest.	Other
32		FE	LW	Body	Abrasions	Body	Body	Flailed	Excessive
				Leg uppr	Penetration	Anteriro, Ventral, Front	Body	Flailed	Excessive
				Pelvis	Fracture	Body Part	Body	Flailed	Excessive
33		PA	LW	NECK, NFS	Fracture	Central Int	Body	Not Rest.	Other
34		FE	LW	ARM LOWER (UNQ)	Laceration	Anterior, Ventral, Front	STRUCTU RE	Collapsed	> 12 inch
				Ribs/Side s	Fracture	Multiple	Restraint	allowed	Exc Motion
				Vertebra L2	Compression	Int, Causal, Lower	SEAT	Collapsed	IMPROPER LY
35		P	LW	Leg uppr	Penetration	Posterior, Dorsal	Body	Flailed	Excessive
				Vertebra L3	Compression	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Vertebra L4	Compression	Int, Causal, Lower	Impact	Exceeded	Human/Dsn limit
				Zygoma/ Malar	Fracture	Anterior, Ventral, Front	Body	Flailed	Excessive
36		PA	F	Abdomen	Penetration	Posterior, Dorsal	Roof	Collapsed	> 12 inch
				Diaphrag m	Hern. / Rupture	Body	Roof	Collapsed	> 12 inch

				Pelvis	Crushed	Body Part	Roof	Collapsed	> 12 inch
37		PA	LW	Leg uppr	Fracture	Body Part	Body	INJURED	Outside A/C
38		PA	LW	Arm uppr	Simple Closed	Supperior, Cranial, Upper	Body	Not Rest.	Other
				Intestines	Hern. / Rupture	Central Int	Body	Not Rest.	Other
				Trunk	Laceration	Body	Body	Not Rest.	Other
1	20010212 001	PA	F	Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
		FE	F	Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
		PA	F	Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
		FE	F	Aorta	Transection	Central Int	Impact	Caused	Exc Loading
				Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
		P	F	Aorta	Transection	Central Int	Impact	Exceeded	Human/Dsn limit
		P	F	Heart	Laceration	Central Int	Impact	Exceeded	Human/Dsn limit
1	20010326 001	P	F	Aorta	Transection	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
		P	F	Aorta	Transection	Sup. Cranial, uppr	Impact	Exceeded	Human/Dsn limit
1	20011009 001	P	F	Heart	Laceration	Other	Body	Asorbed	Exc Loading
					Laceration	Ant. Ventral Frnt	Body	Asorbed	Exc Loading
1	20020222 001	FE	F	Brain	Hemorrhage	Multiple	HELMET	Failed to Att.	Exc Loading
					Hern. / Rupture		HELMET	Failed to Att.	Exc Loading
				Intestines	Contusion	Body Part	Body	Asorbed	Exc Loading
				LIVER	Laceration	Body Part	Body	Asorbed	Exc Loading
				Pelvis	Fracture	Ant. Ventral Frnt	Body	Asorbed	Exc Loading
				Ribs/Sides	Fracture	Body	Body	Asorbed	Exc Loading
2		FE	F	Aorta	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
				Anto-Occipal	Dislocation	Body Part	Body	Flailed	Excessive
				Lower Extrem.	Compound	Other	Body	Asorbed	Exc Loading
				Pelvis	Laceration	Other	Body	Asorbed	Exc Loading
							Impact	Exceeded	Human/Dsn limit
				Spinal Cord	Transection	Body Part	Body	Flailed	Excessive
				TRUNK (UNQ)	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
3		S	M					U	
4		P	F	HEAD (UNQ)	Contusion	Posterior, Dorsal	Body	Flailed	Excessive
				Heart	Hern. / Rupture	Anterior, Ventral, Front	Impact	Exceeded	Human/Dsn limit
				LUNGS	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
				Other	Laceration	Multiple	Impact	Exceeded	Human/Dsn limit
				Pelvis	Hemorrhage	Int,	Body	Asorbed	Exc

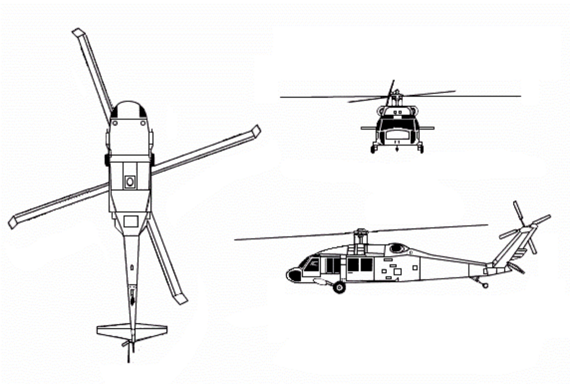
						Causal, Lower			Loading
					Fracture	Other	Body	Asorbed	Exc Loading
				SPLEEN	Laceration	Body Part	Impact	Exceeded	Human/Dsn limit
5		P	F	Aorta	Laceration	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				Body	Contusion	Body	Impact	Caused	Other
				LUNGS	DROWNED	Body Part	AIRCRAFT	Other	Other
				PARIETAL	Hemorrhage	Body	Body	Asorbed	Exc Loading
				Ribs/Sides	Fracture	Body	Impact	Caused	Other
				Vertebra T3	Compression	Body Part	Impact	Caused	Other
6		FE	M						
7		S		LUNGS	DROWNED	Body Part	AIRCRAFT	Other	Other
8		PA	F	LIVER	Laceration	Body Part	Body	Asorbed	Exc Loading
				LUNGS	DROWNED	Body Part	AIRCRAFT	Other	Other
					Laceration	Body Part	Body	Asorbed	Exc Loading
				Pelvis	Fracture		Body	Asorbed	Exc Loading
					Laceration	Int, Causal, Lower	Body	Asorbed	Exc Loading
					Fracture	Body Part	Body	Asorbed	Exc Loading
9		PA	F	BACK (UNQ)	Hemorrhage	Body	Body	Asorbed	Exc Loading
				FRONTAL	Fracture	Anterior, Ventral, Front	HELMET	Failed to Attenuate	Exc Loading
					Fracture	Body Part	HELMET	Falied to Attenuate	Exc Loading
				LUNGS	Drowned	Body Part	AIRCRAFT	Other	Other
				Pelvis	Fracture	Body Part	Body	Asorbed	Exc Loading
10		FE	F	LUNGS	Drowned	Body Part	AIRCRAFT	Other	Other
				Pelvis	Fracture	Other	Impact	Exceeded	Human/Dsn limit
				Vertebra c7	Fracture	UNKNOWN	Body	Flailed	Excessive
1	20021211001	P	F	Aorta	Laceration	UNKNOWN	Impact	Exceeded	Human/Dsn limit
				Anto-Occipal	Fracture	Central Int	Impact	Exceeded	Human/Dsn limit
				Heart	Contusion	Anterior, Ventral, Front	Impact	Exceeded	Human/Dsn limit
				Mult Bones, Basilar	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
2		P	F	Lower Extrem.	Comminuted	Body	Impact	Exceeded	Human/Dsn limit
				Ribs/Sides	FLAIL Chest	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				Skull	BLOWOUT	Superion, Cranial, Upper	Impact	Exceeded	Human/Dsn limit
				Vertebra	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
3		FE	F	Aorta	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
				Body	4th degree	Body	Impact	Ignited	Fuel
				Pelvis	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
				Skull	Comminuted	Body Part	Impact	Exceeded	Human/Dsn

									limit
4		FE	F	Aorta	Laceration	Posterior, Dorsal	Impact	Exceeded	Human/Dsn limit
				Anto-Occipal	Fracture	UNKNOWN	Impact	Exceeded	Human/Dsn limit
				Pelvis	Fracture	Anterior, Ventral, Front	Impact	Exceeded	Human/Dsn limit
				Skull	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
				Vertebra	Transection	Body Part	Impact	Exceeded	Human/Dsn limit
5		GU	F	Anto-Occipal	Fracture	Body Part	Impact	Exceeded	Human/Dsn limit
				Lower Extrem.	Comminuted	Body Part	Impact	Exceeded	Ins. Loads
				Pelvis	Fracture	Body Part	Impact	Exceeded	Ins. Loads
				Skull	Fracture	Body Part	Impact	Exceeded	Ins. Loads
1	20030608 001	P	F	Aorta	Transection	Body Part	AIRCRAFT	Exceeded	Human/Dsn limit
				Atanto-Occipal	Fracture	Body Part	MAIN ROTOR	Penetrated	Occ Space
				Head	Decapitation	Superion, Cranial, Upper	MAIN ROTOR	Penetrated	Occ Space
				Heart	Laceration	Other	AIRCRAFT	Exceeded	Human/Dsn limit
2		P	F	Aorta	Transection	Body Part	AIRCRAFT	Exceeded	Human/Dsn limit
				Heart	Laceration	Other	AIRCRAFT	Exceeded	Human/Dsn limit
				Skull	stellate	Int, Causal, Lower	AIRCRAFT	Exceeded	Human/Dsn limit
					stellate	Multiple	AIRCRAFT	Exceeded	Human/Dsn limit
1	20040622 001	P	F	Heart	Laceration	Central Int	Body	Exceeded	Human/Dsn limit
1	20050128 001	P	F	Aorta	Transection	Central Int	Impact	Collapsed	Occ Space
				LUNGS	Hemothorax	Central Int	Impact	Collapsed	Occ Space
				Skull	Crushed		Impact	Collapsed	Occ Space
2		P	F	Aorta	Transection	Central Int	Impact	Collapsed	Occ Space
				Heart	Laceration	Superion, Cranial, Upper	Impact	Collapsed	Occ Space
				Skull	Crushed		Impact	Collapsed	Occ Space

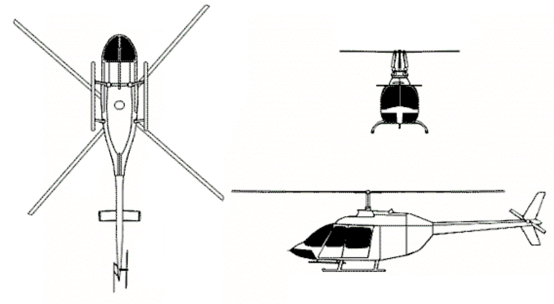
Table D5: Aircraft Types Recorded in Injury Listings.

Notes:
Information gathered from internet websites:
http://www.combataircraft.com
http://en.wikipedia.org/wiki/List_of_military_aircraft_of_the_United_States
http://www.fas.org/irp/program/collect/guardrail.htm
http://www.globalsecurity.org/intell/systems/rg-8.htm

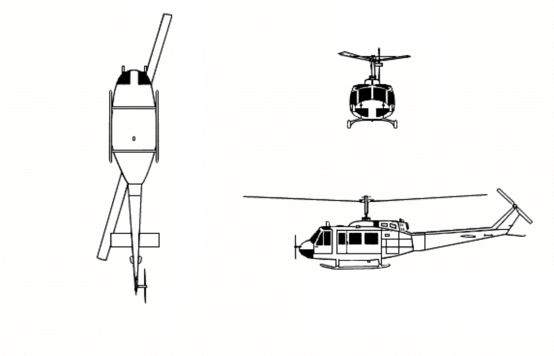
Notations:
MTOW: Maximum Take-Off Weight
General Aircraft Designations (Designations do not always follow the code)
Modified Mission Symbols (First Letter)
A: Attack, C: Cargo, F: Fighter, R: Reconnaissance, T: Training, U : Utility
Vehicle Type Symbol (Second Letter)
H: Helicopter, G: Glider



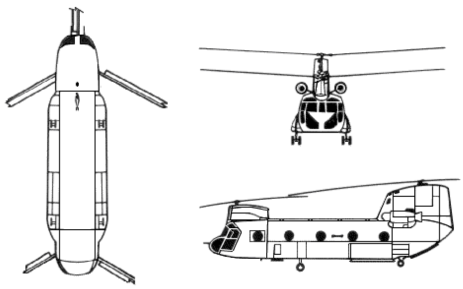
Sikorsky UH-60 Blackhawk
Length 19.76m, Height 5.13m, Empty Weight 4,819 kg, MTOW 11,113kg



Bell OH-58A/C Kiowa, and OH-58D Kiowa Warrior (illustrated)
OH-58A: Length 9.81m, Height 2.92m, Empty Weight 704kg, MTOW 1,049kg
OH-58D: Length 12.39m, Height 2.29m, Empty Weight 1,490kg, MTOW 2,495kg

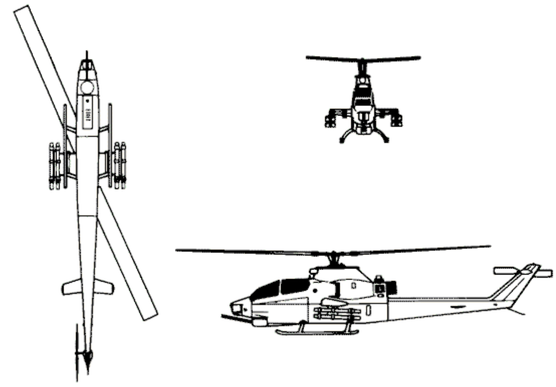


Bell UH-1D/H/V Huey
Length 17.4m, Height 4.4m, Empty Weight 2,365kg, MTOW 4,310kg

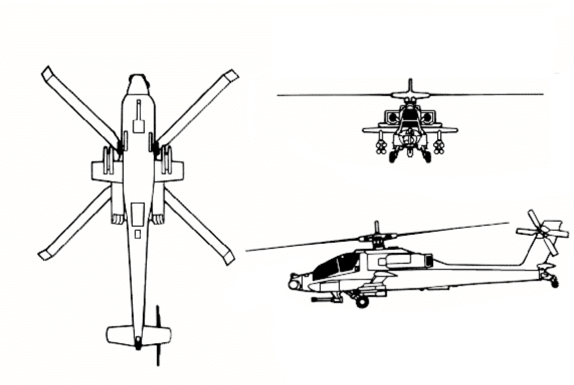


Boeing CH-47 C/D, MH-47-E Chinook

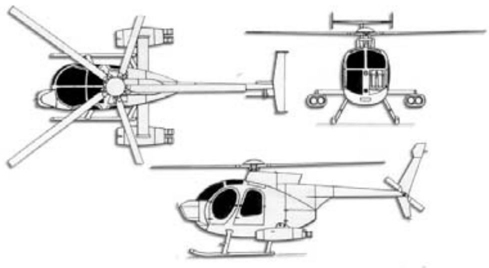
Length 30.1m, Height 5.7m, Empty Weight 10,185kg, MTOW 22,680kg



Bell AH-1 F/G Cobra
Length 13.6m, Height 4.1m, Empty Weight 2,993kg, MTOW 4,500kg

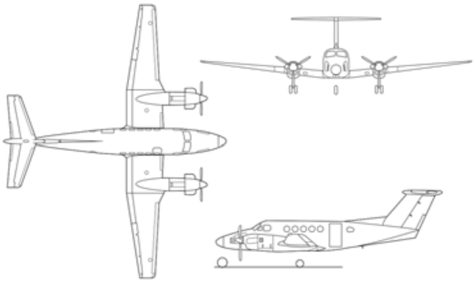


Boeing AH-64 A Apache (Illustrated) and D Longbow
Length 17.73m, Height 3.87m, Empty Weight 5,165kg, MTOW 9,525kg



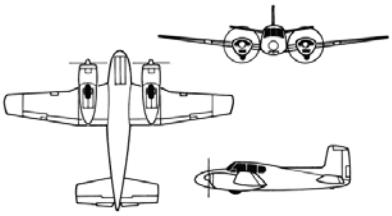
Hughes OH-6 A Cayuse, MH-6C, (updated Boeing MD500 Defender version pictured)
Length 9.4 to 9.8m, Height 2.6 to 3.4m, Empty Weight 572 to 896kg, MTOW 1,361 to 1,610kg

Beechcraft T-42 Cochise
Length 8.5m, Height 2.9m, Empty Weight 1,467kg, MTOW 2,312



Beechcraft U-21A, RC-12 Guardrail, (King Air B200)
Length 13.34m, Height 4.57m, Empty Weight 3,500kg, MTOW 5,670kg

RC-12 K, Modified Beechcraft King Air (www.fas.org/irp/program/collect/guardrail.htm)
Federation of American Scientists, Intelligence Resource Program



Beechcraft U-8F Seminole
Length 9.61m, Height 3.51m, Empty Weight 2,270kg, MTOW 3,311kg

Condor Schweizer RG-8A / SA2-37B
Length 8.79m, Height NA, Empty Weight 1,156kg, Gross Weight 1,950kg
(www.globalsecurity.org/intell/systems/rg-8.htm)

Appendix E: Analysis and Discussion

Simulation Response and Aircraft Impact Parameter Correlation Table

The aircraft impact parameters of Peak Acceleration, Impact Slope, and Velocity Change (Impact Delta V) and the simulation responses of Peak DRI, Peak Seat Acceleration, Peak Heart Acceleration, and Peak Heart Velocity have been put in correlation table given in table E-1.

Table E 1Selected Responses Correlated to Impact Parameters for GA Seat

Correlation Table GA Seat							
	Peak DRI	Peak Seat Accel.	Peak Heart Displ.	Peak Heart Vel.	Impact Peak Accel.	Impact Slope	Impact Delta V
Peak DRI	1.00						
Pk Seat Accel.	1.00	1.00					
Pk Heart Displ.	0.94	0.97	1.00				
Pk Heart Vel.	0.97	0.97	0.96	1.00			
Impact Pk Accel	0.92	0.89	0.77	0.82	1.00		
Impact Slope	0.82	0.78	0.60	0.67	0.88	1.00	
Impact Delta V	0.85	0.87	0.87	0.77	0.81	0.64	1.00
Correlation Table Military EA Seat							
Peak DRI	1.00						
Pk Seat Accel.	0.84	1.00					
Pk Heart Displ.	0.92	0.92	1.00				
Pk Heart Vel.	0.37	0.47	0.31	1.00			
Impact Pk Accel	0.70	0.87	0.79	0.64	1.00		
Impact Slope	0.44	0.63	0.52	0.63	0.92	1.00	
Impact Delta V	0.81	0.92	0.93	0.49	0.77	0.48	1.00

A research study of dynamic sled impact tests using seventeen cadavers exposed to lateral impacts was done by Cavanaugh (2005). In this study Cavanaugh related the occurrence of heart and aortic injury to spine and rib accelerations as given in figures E-1 and E-2.

Ex.

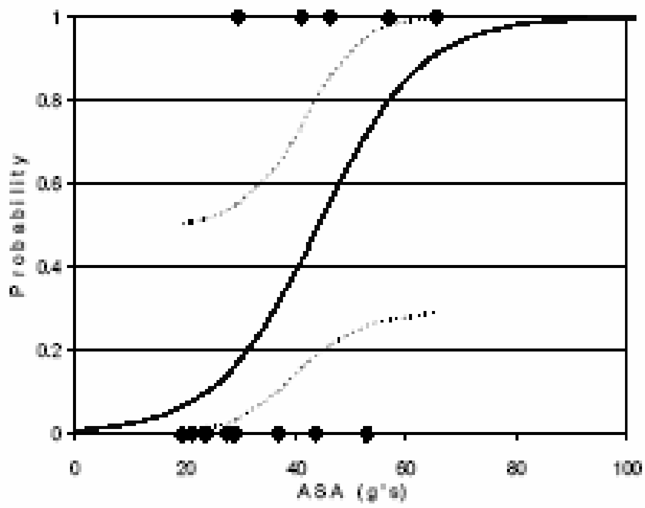


Figure 2a. Logist plot of probability of AIS 4 or higher to the aorta vs. ASA10 (Average Spine Acceleration, Chi square = 5.216, P = 0.0224)

Figure E 1 Cavanaugh (2005) Logist Plot of Aortic Injury to Average Spine Acceleration

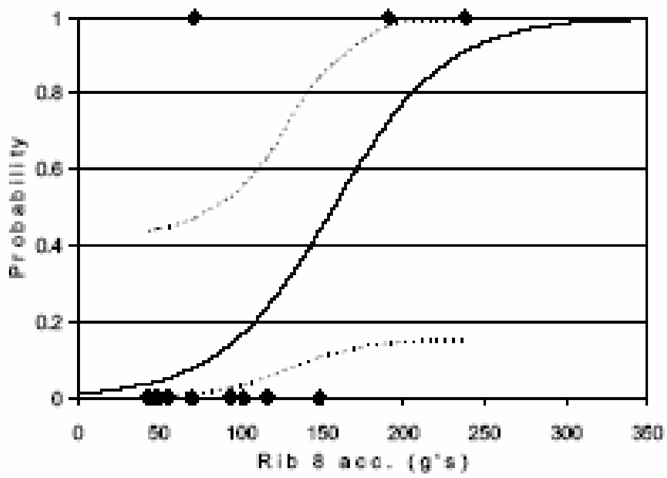


Figure 2c. Logist plot of probability of AIS 4 or higher to the aorta vs. right rib 8 acceleration (Chi square = 5.166, P = 0.0230)

Figure E 2 Cavanaugh (2005) Logist Plot of Aortic Injury to Rib Acceleration

The relationship between various model simulation responses and the aircraft impact parameters was evaluated to identify a means to measure potential injury according to the impact. Some of the relationships evaluated which were either not discussed in the body of the thesis or did not provide a good correlation are provided in figures E3 to Ex.

Dynamic Response Index:

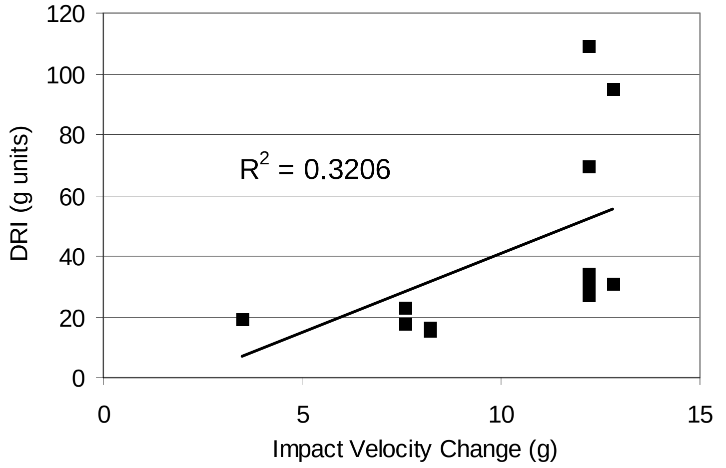


Figure E 3. DRI versus Aircraft Impact Velocity Change

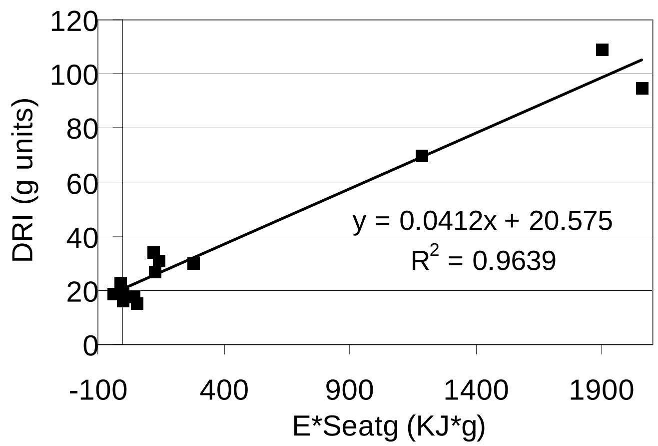


Figure E 4 DRI versus E*Seatg

Heart Displacement:

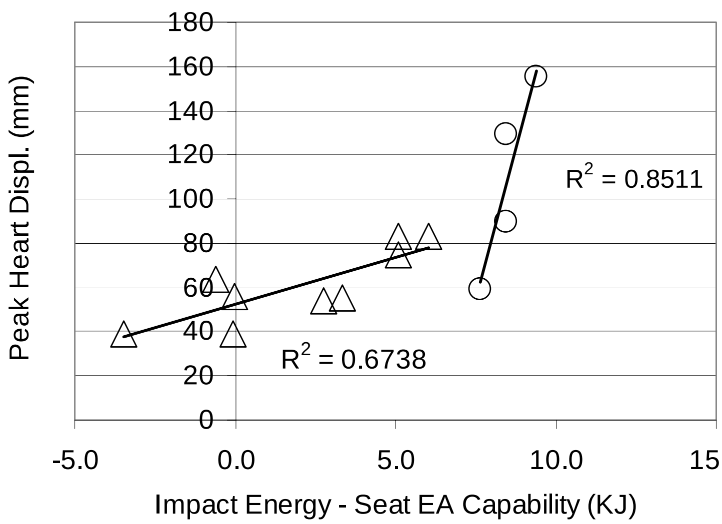


Figure E 5 Peak Heart Displacement versus (Impact Engergy – Seat EA Capability)

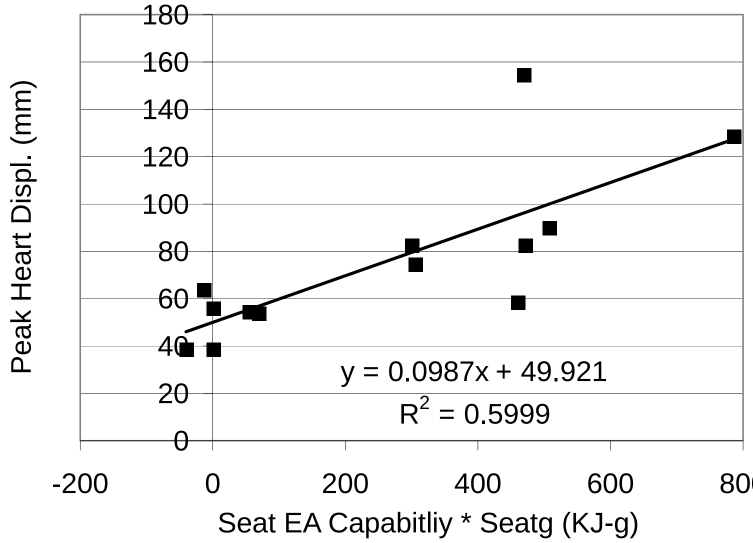


Figure E 6 Peak Heart Displacement versus (Seat EA Capability*Seat g)

Heart Velocity:

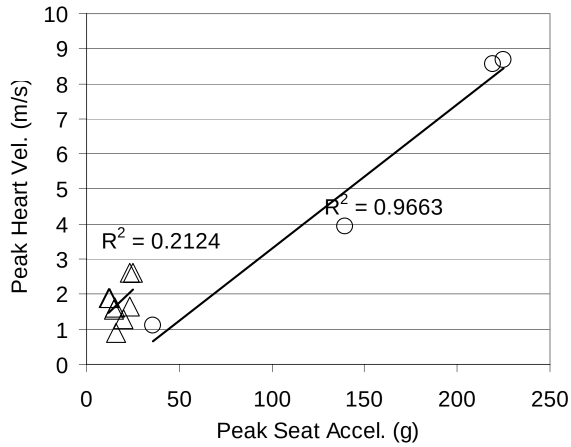


Figure E 7 Peak Heart Velocity versus Peak Seat Acceleration

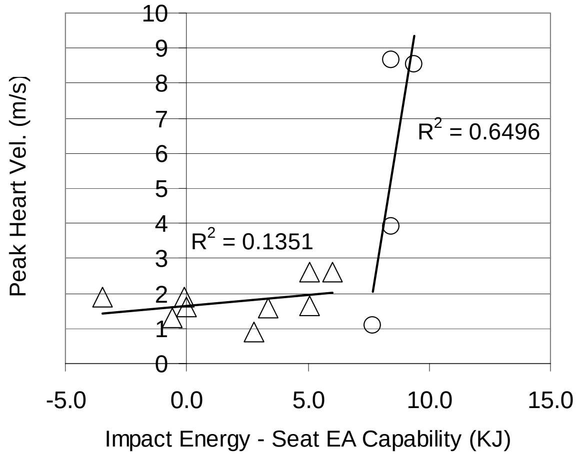


Figure E 8 Peak Heart Velocity versus (Impact Engergy – Seat EA Capability)

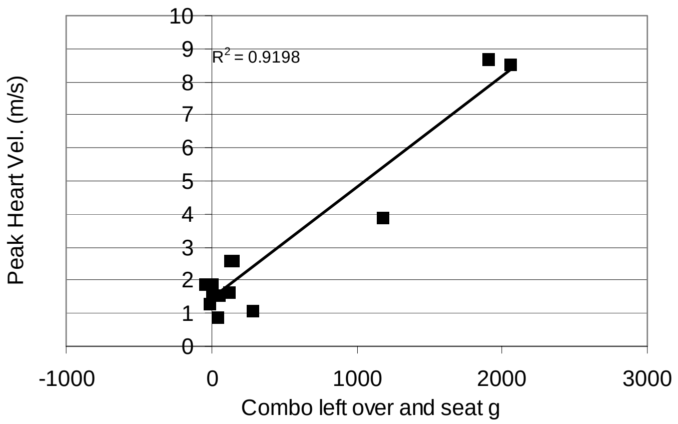


Figure E 9 Peak Heart Velocity versus (Left Over Seat EA Capability*Seat g)