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DESK REFERENCE GUIDE

CHAPTER 37

CRASHWORTHINESS

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SUBPART A: CRASHWORTHINESS - INVESTIGATING THE SURVIVAL ASPECTS OF GENERAL AVIATION ACCIDENTS

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SUBPART A - CRASHWORTHINESS - INVESTIGATING THE SURVIVAL ASPECTS OF GENERAL AVIATION ACCIDENTS

INTRODUCTION

From the safety viewpoint, aircraft accident investigation serves a two-fold purpose:

1. To determine all direct and indirect causes of the accident so that preventive steps may be taken.

2. To determine to what extent persons were unnecessarily injured or killed in potentially survivable crashes so that occupant protection criteria can be improved.

This text is aimed at you, the FAA inspector, who, in the process of an accident investigation, has to evaluate the survival aspects of the accident and complete all pertinent Supplements to the NTSB's Factual Report (Form 6120.4). Although you are not required to calculate crash forces and other impact parameters, the data you gather at the scene form the basis for subsequent crash injury analyses. Therefore, your understanding of the reasons for certain measurements and estimates adds immeasurably to the accuracy and validity of the data you provide.

An additional advantage of understanding what goes on during the dynamic (crash kinematic) phase of an accident is its applicability to emergency landing situations. An inspector who understands the protective role of energy-absorbing aircraft structure and occupant restraint during a crash is in a better position to judge the effectiveness of emergency landing procedures and practices.

The purpose of this text is to provide some basic insight in crash kinematics without going too deeply into the underlying laws of physics. Once the basic concepts are understood, the ability to apply them in practice can best be developed by studying high-speed movies of crashes (aircraft and cars) and by exploiting every opportunity to correlate vehicular damage with impact severity and occupant injuries.

Depending on the circumstances, survival in general aviation accidents is predicated on three factors:

1. The occupants have to survive the impact.

2. The occupants have to evacuate the aircraft before conditions become intolerable as a result of fire, submersion, or other postcrash hazards.

3. The occupants have to survive post-accident environmental conditions until rescued.

Each of these three factors, in turn, is governed by specific criteria:

2. Timely Egress (Safe evacuation criteria)

   a. Adequate escape provisions
   b. Post-crash fire protection
   c. Fire fighting and rescue services

3. Post-Accident Survival Factors

   a. Role of ELT in locating wreckage
   b. Survival gear and survival skills
   c. Search and Rescue (SAR) considerations
   d. Prompt medical attention

The most important variable in the survival of light aircraft accidents is unquestionably impact survival. The complexity and interdependence of the five criteria that determine impact survivability make that aspect of the investigation also the most difficult. For that reason, the main emphasis in this text will be on the elements of impact survival in Section A. The investigative aspects of timely egress and post-accident survival will be summarized in Sections B and C.

An important consideration in judging impact survivability is the fact that the survival or non-survival of one or more occupants is not necessarily a valid criterion. The survivability of the impact has to be evaluated independently of the injury experience. It is the contrast between survivable impact conditions and fatal injuries that requires an investigation and that leads to improvements in crash safety provisions. In that regard, the investigator may be confronted with three levels of impact severity and three reactions to hitting the ground.

1. Non-survivable impact - Cockpit/cabin structure is destroyed by impact. In rare cases, an occupant may be thrown clear onto soft terrain from a disintegrating aircraft and survive. Such survival does not classify the impact as survivable and a crash injury study would have little or no benefit.

2. Survivable impact - Cockpit/cabin structure remains relatively intact and the forces experienced by the occupants did not exceed or should not have exceeded the survivable limits of human G-tolerance. Such an impact is classified as survivable even if some or all occupants were fatally injured. The investigator makes his greatest contribution to crash safety by documenting the reasons why aircraft occupants were fatally or seriously injured in survivable impacts.

3. Partly survivable impact - Survivable impact conditions exist in part of the cockpit/cabin structure as determined by aircraft attitude at impact, obstacles struck, etc. In such a case, the investigator has to document the reasons for the serious or fatal injuries of the occupants in the survivable areas.

4. Hit and Skid, Hit and Bounce or Hit and Stick - Hard ground and paved surfaces that prevent the digging in of aircraft structure produce extremely high vertical forces of short duration at impact but relatively low horizontal forces (aircraft skids to a stop over several seconds). Under similar impact conditions, a soft surface may result in lower vertical G-loads but the horizontal G-loads will increase correspondingly due to the "digging" effect, and sudden stoppage. These differences are known as "hit and skid," "hit and bounce," or "hit and stick."

SECTION A: IMPACT SURVIVAL

1. THE DYNAMICS OF IMPACT-VELOCITY, ACCELERATION AND G-FORCES

Velocity - Airspeed velocity refers to the distance traveled in a specified amount of time. Velocity is usually expressed as a vector quantity, the magnitude of which is airspeed and the direction of which is the flight path. Velocity can be represented as an arrow. The length of the arrow represents the airspeed, the direction of the arrow represents the direction of travel. Velocity can be broken down into horizontal and vertical components, as seen in Figure 1. In an aircraft crash, the impact velocity is specified by the speed and the "flight path angle."

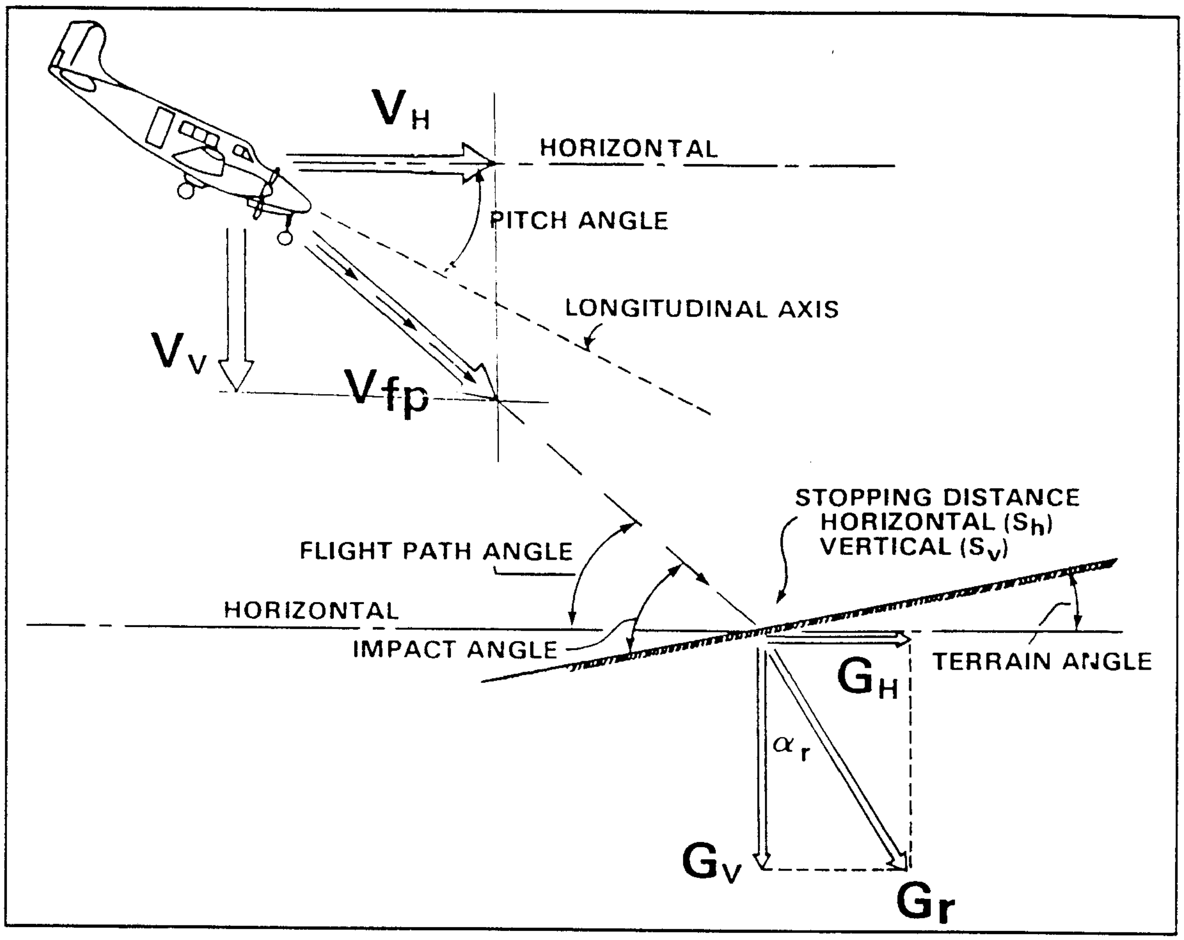


Figure 1. Vector Components at Crash Impact (from NTSB/SR-83-01)[1] include:

V_h = Horizontal Velocity

V_v = Vertical Velocity

V_{fp} = Velocity along flight path

S_h = Horizontal Stopping Distance (in feet)

G_h = Horizontal G-forces

G_v = Vertical G-forces

G_r = Resultant G-forces

S_v = Average Depth of Ground Scar (in feet)

There are several other angles of interest:

The terrain angle is the variation from horizontal. The impact angle is the angle between the path of flight and terrain at the impact site. The pitch angle, nose up or down, relative to the flight path, is the attitude of the aircraft at impact.

Yaw - The angle (nose left or right of flight path) must usually be determined by close examination of the wreckage. These may be different from the flight conditions if the aircraft hits trees or is otherwise maneuvered just prior to the crash. Roll angle at impact can usually be estimated by examining the wreckage.

Acceleration of Gravity and G-Units - The pull of gravity on earth is a familiar form of force. When we step on a weighing scale we measure this force in pounds. When the pull of gravity on a body is not resisted -- as in free fall -- gravity will cause an acceleration of 32 ft/sec/sec, if air resistance is disregarded. To be more precise and use scientific notation, this value is also written as 32.2 ft/sec^2.) Acceleration is a change in velocity over a period of time. This means that, in:

1 second, the body or component will have a speed of 32 ft/sec; in

2 seconds, a speed of 64 ft/sec; and in

3 seconds, 96 ft/sec, etc.

Since the component is going faster all the time, it is said to be accelerating. The measure of average acceleration is the change in velocity divided by the time required to make the change:

$$\textit{Average Acceleration} = a = \frac{\textit{Velocity Change}}{\textit{Time It Took}}$$

Thus, for every second of free fall the velocity of the body increases by 32 ft/sec, in accordance with the following table:

As Time Increases	Velocity Changes	As Height of Fall Increases
0 seconds	0 ft/sec	0 ft
1	32	16
2	64	64
3	96	144
4	128	256
5	160	400

Table 1. Acceleration of a free-falling body

A free-falling human body reaches its terminal velocity when the accelerating force of gravity equals the body's drag; this occurs at about 176 ft/sec (= 120 mph). The same is true for the various components of an inflight breakup sequence or a midair collision. Thus, generally, most aircraft components and occupants falling from above 400 feet altitude hit the ground at approximately 120 mph vertical speed.

Acceleration and velocity are measured with length dimensions of feet (or meters) instead of miles, and time dimensions of seconds instead of hours.

The dimensions of acceleration are:

$$a = \frac{V}{T} = \frac{\frac{FT}{SEC}}{SEC} = \frac{FT}{SEC} \times \frac{1}{SEC} = \frac{FT}{SEC^2}$$

Although the units for measuring acceleration are in $\frac{FEET}{SEC^2}$ ($\frac{or\ METERS}{SEC^2}$), it is convenient to speak of acceleration in terms of "G's."

Since gravity can manifest itself as a force and as an acceleration, it is customary to use the following symbols to differentiate between the two:

g = Acceleration of Gravity = 32 FT/SECSUP2 = Earth Gravitational Constant

G = the non-dimensional unit of acceleration V deceleration. This G-unit is a dimensionless number that expresses the ratio between any acceleration (a) and the acceleration of gravity (g). The FT/SEC² in the numerator cancel out with the FT/SEC² in the denominator (∈ what is called dimensionalanalysis.)

$$G = \frac{a}{g} = \frac{Any\ Acceleration}{32\ FT/SEC^2} = \frac{FT/SEC^2}{FT/SEC^2}$$

Example: An ejection seat accelerates its occupant up the seat rails at 480 ft/sec². What G's are experienced?

$$G = \frac{a}{g} = \frac{480}{32} = 15\ G's$$

The magnitude of an acceleration can be expressed in terms of G's by using the relationship of force (F) and weight (W). Using dimensional analysis again, the term pounds (lb) in both the numerator and denominator cancel each other out, leaving G as a dimensionless number (value).

$$G = \frac{F}{W} = \frac{Force\ Applied}{Weight\ (or\ Mass)} = \frac{lb}{lb}$$

Referring to the ejection seat example above, we can express the acceleration up the seat rails, assuming friction is zero, as follows:

$$G = \frac{6000\ LB.\ Rocket\ Motor\ Force}{400\ LB.\ Seat\ and\ Occupant\ Weight} = 15\ G's$$

In practical terms, this means that the individual is subjected to a force 15 times the force of gravity. Note that rocket motor powered ejection seats burn more uniformly and produce fewer back injuries than the older ballistic charge powered early ejection seats.

The symbol G can be used to identify:

1. The strength of a seat - A 9 G seat has the static strength to withstand a pull of 9 x 170 = 1530 lbs. (One hundred seventy pounds has been used as standard occupant weight in the civilian aviation community. The United States Air Force uses a 250 pound man/seat system as its standard seated occupant weight). These 9 G values are only a static load in pounds of force and are incorrectly called "G-loads."

2. A flight maneuver load - A 2 G turn doubles the load factor on the wings, but is a sustained (long duration) G-load and not part of this discussion.

3. An acceleration - A 15 G ejection seat firing can be expressed as an acceleration as follows:

$$a = G \times g = 15 \times 32 = 480\ FT/SEC^2$$

4. A crash force - When an aircraft occupant is subject to a 10-G deceleration, he exerts a crash force of 10 times his own weight on the seat/restraint system.

Let us further define force in terms of aerodynamics and Sir Isaac Newton's laws of motion. The four forces acting on an aircraft in flight are thrust, drag, lift and weight measured in "pounds of force." A force is defined as a push or pull exerted on a body.

a. Newton's First Law of Motion states that: "If no outside force acts on a body (an aircraft) it will continue at rest or will continue to move along a straight line (flight path) with constant velocity." For example, an aircraft in cruise flight moves along a straight line.

b. Newton's Second Law of Motion states: "The acceleration (deceleration) of a body (aircraft) is directly proportional to the unbalanced force acting upon it and is inversely proportional to the mass of the body (aircraft)." Parts of an aircraft which has broken up in flight or been involved in a midair collision will fall to earth with a force proportional to their weight and drag, while being accelerated by the pull of gravity. A crash landing in a plowed field has a deceleration directly proportional to the amount of dirt (unbalanced force) being displaced in the ground scar. That is to say, the more dirt, the higher the G-force, the shorter the stopping distance, and the greater the G's. The soil and rocks displaced by the impact represents the ground's resistance (the unbalanced force) acting against the aircraft at impact.

c. Newton's Third Law of Motion states: "To every action, there is an equal and opposite reaction." When an aircraft hits the ground with a force of 10G's (action), the ground pushes back on the aircraft with an equal opposite force (the reaction) of 10 G's. The forces experienced by seated occupants may be greater than the G-loads on the floor structure due to several variables such as: restraint system elongation, human body dynamics, and time lag. This is called Dynamic Overshoot and will be discussed later.

Acceleration (or, in its negative form, deceleration) is the rate of change in velocity. Since velocity is a vector quantity with magnitude and direction, a moving body is subject to an acceleration when there is a change in its speed or its direction. The occupants of an earth-orbiting spacecraft experience weightlessness because the centrifugal force (the constant change in direction) of the orbiting craft balances the gravitational pull of the earth; this is definitely not a case of operating in zero-gravity conditions, but of balanced forces.

The effects of acceleration are to increase the force acting on a system according to a well-known law of physics:

$$F(Force) = M(Mass) \times a(Acceleration)$$

Before the FAA adopted "dynamic seat testing requirements" in 1988, the formula, F = M x a, was used to define "static seat testing" procedures. Prior to 1988, using this procedure, a weight equal to the weight of an average 170 pound man (the mass) was multiplied by a load factor (the acceleration) to obtain a force (really a static load) which had to be carried by the seat without failure. Since this load factor roughly corresponded to the acceleration term in the law, the result was incorrectly called a "G force." (See Table 2.)

Static Test Requirements	Load Factor times		Passenger Weight equals Static Load or Force		
9 G's Forward	9	x	170 Lbs.	=	1530 lb.
4.5 G's Forward	4.5	x	170 Lbs.	=	780 lb.
1.5 G's Lateral	1.5	x	170 Lbs.	=	255 lb.

Table 2. The old static load requirements (prior to the adoption of the newer dynamic seat testing requirements for FAR Part 23 aircraft).

2. THE DECELERATION PROCESS

A moving body has a certain amount of energy, depending on its mass and velocity. It is called kinetic energy. (The Greek word kinetikos meaning "to move" forms the root of kinetic.) The NTSB has a special accident reporting form, Supplement II to the basic NTSB Form 6120.4, to be used by the investigator to describe the last few precious seconds of flight. The form is entitled the Crash Kinematics Supplement and allows the investigator to describe the aircraft attitude at impact. Kinematics is a branch of physics involved with the study of a body (an aircraft) in motion. Page 3 of Supplement I requires the investigator to draw a two-view drawing (plan and profile views) of the wreckage site, including ground scars, trees and utility poles/wires. These wreckage diagrams and pitch, roll and yaw attitudes describe the Crash Kinematics of the accident and help the reader understand the kinetic energy that was absorbed at ground impact.

The kinetic energy (K.E.) of a body represents its potential ability to do work because of its motion. A hammer with a certain mass, moving at a certain velocity can do a certain amount of work on a nail. The energy required to drive the nail a certain distance into the wood is determined by the resisting force. The distance the nail is driven into the wood represents work done. The work done plus the heat and friction (resistance of the wood absorbing energy) equals the total energy of the hammer. If the wood is hard, a weak nail may be deformed or crushed. In either case, the hammer's energy is converted into work done on the nail and the wood, plus heat and friction.

The hammer-and-nail example is used because that familiar process closely resembles the energy-dissipating process in a crash. The only difference is that the aircraft not only functions as the hammer, but as the nail, in that the first structure to impact an obstacle is driven by the K.E. of the aircraft's mass behind the structure. The wood represents the ground and the nail hole represents the ground scars, trees and utility poles damaged.

Laws of Physics Crash impact forces will always obey the laws of physics. An understanding of the dynamics of impact requires familiarity with some basic physics concepts:

$$Mass = \frac{Weight}{gravity} = \frac{W}{G} = \frac{Pounds}{Feet/SEC^2}$$

Momentum is the mass (M) of an aircraft times its velocity (V) acting in one direction. (Momentum is a vector quantity; that is, it has magnitude and direction.)

$$Momentum = M \times V$$

If you double the speed of impact, you double its momentum at which it hits the ground, but you quadruple (four times) its Kinetic Energy. (The velocity is squared in the Kinetic Energy equation below.) That is why we land into the wind--to keep the Ground Speed (GS) as low as possible!

$$Kinetic\ Energy = \frac{1}{2}\frac{W}{g} \times V^2 = \frac{1}{2} M \times V^2$$

The K.E. of a moving object is half its mass (M) times the velocity (V) squared. That energy can be used to perform work in accordance with:

$$Work = F \times S$$

Work is done when a force (F) is acting on an object over a certain distance (S). Work and K.E. are both expressed in foot-pounds.

Stopping Distance on the Runway - Applying these two formulas to the deceleration process, it is apparent that an aircraft comes to a stop when the work done by a stopping force over a certain distance has dissipated all kinetic energy. That conclusion leads to this basic equation:

$$1/2\ M \times V^2 = F \times S$$

What this means is that an aircraft of a certain mass (M) moving at a certain velocity (V, in ft/sec) can be brought to a stop by an infinite number of combinations of stopping force (F, in pounds) and stopping distance (S, in feet). The difference between a normal landing and a crash is simply a matter of the magnitude of stopping force; the shorter the stopping distance, the larger the force.

Since velocity is a squared factor in the K.E. formula, it has a great determining effect on any stopping process. This can be shown by comparing landing distances at different landing speeds: 48 and 68 knots (groundspeed). Assuming similar aircraft weights and braking action in both cases, the two stopping distances will vary as the ratio of the square of the velocities.

$$\frac{Stopping\ Distance\ at\ 48\ knots}{Stopping\ Distance\ at\ 68\ knots} = \frac{48^2}{68^2} = \frac{2304\ Feet}{4624\ Feet} \approx 1/2\ the\ distance$$

Therefore, the stopping distance at a groundspeed of 68 knots is more than twice the stopping distance at 48 knots. This demonstrates vividly how much a difference a landing into a 10 knot headwind would make compared to a downwind landing, for an aircraft with a touch down speed of 58 knots (IAS).

Kinetic Energy During the Crash - Since kinetic energy is determined by groundspeed, wind direction also influences the destructive energy that has to be dissipated during a crash or forced landing.

The following illustrations of the importance of speed in determining the destructiveness of the crash energy are based on the squared velocity term of the formula $KE = \frac{1}{2} M \times V^2$.

If the stall speed is 58 knots, then the groundspeed in a full stall crash or off-airport landing in a no-wind condition will be GS = 58K. Into a 10K headwind, the GS=48K, but crashing with a 10K tailwind will produce a 68K GS. Thus, when comparing the ratios of the two Kinetic Energies, we square the Ground Speed into the headwind and compare it to the squared GS with a tail wind. Again, we discover that the ratio is twice the KE when crash landing with a tail wind. Thus, approximately twice the destructive energy exists at a crash site when attempting a downwind emergency (crash) landing, in an aircraft that has a 58k stall speed at touchdown for any given weight (mass) of aircraft.

$$\textit{Kinetic Energy at } 48 \textit{ knots} = 48^2 = 2304$$
$$\textit{Kinetic Energy at } 68 \textit{ knots} = 68^2 = 4624$$

The moral: always crash into the wind to minimize destructive crash energy.

When speed doubles, the K.E. is quadrupled, and four times the destructive crash energy has to be absorbed by the ground, the aircraft and its occupants. The same is true in your car! The ratios of the respective Kinetic Energies remain four to one regardless of the weight of the car or aircraft.

$$V_1 = 50k; \quad (50k)^2 = 2{,}500$$
$$V_2 = 100k; \quad (100k)^2 = 10{,}000 \textit{ a ratio of } 4 \textit{ to } 1$$

In your car, an impact at 70 mph is four times as severe as one at 35 mph.

$$V_1 = 35mph; \quad (35mph)^2 = 1225$$
$$V_2 = 70mph; \quad (70mph)^2 = 4{,}900, \textit{ a ratio of } 4 \textit{ to } 1$$

The basic deceleration formula $1/2\ M \times V^2 = F \times S$ can be converted for practical use into one that expresses the decelerative force directly in G units. (Its derivation is given in the footnote below.)

Formula Derivation:

$$1/2\ MV^2 = FS$$

$$1/2\ MV^2 = MaS \ (F = Ma)$$

$$1/2\ V^2 = aS$$

$$a = \frac{V^2}{2S}$$

$$a = \frac{V^2}{2S}$$

$$Gg = \frac{V^2}{2S} \ (G = \underline{a};\ a = Gg$$

$$G = \frac{V^2}{2gS}$$

$$G = \frac{V^2}{64S} \ (g = 32)$$

When the speed is expressed in mph instead of feet per second, use 0.034 as a constant:
When the speed is expressed in knots instead of feet per second, use 0.045 as a constant:

$$G = \frac{V^2}{64 \times S}$$

In other words, when an aircraft comes to a stop during a linear deceleration, the average number of G's is found by dividing the square of the velocity (in ft/sec) by 64 times the stopping distance (S) in feet. (Section D, page 43 presents G-calculations for a "Hit and Bounce" impact when the aircraft retains some velocity after the initial deceleration.)

$$G = 0.034 \frac{(mph)^2}{S}$$

$$G = 0.045 \frac{(knts)^2}{S}$$

The G-nomographs in Figure 2a and 2b are based on the last two formulas. The examples in the graphs deal with aircraft that skid to a stop in 20 feet while traveling at 100 mph (Figure 2a) and at 100 kts (Figure 2b). The resultant average decelerations are 17 and 22 G's respectively. Figure 2c provides graphs to convert velocity in knots and miles per hour into velocity in feet per second for your convenience.

Normal Operations - The last two G-formulas can also be used for calculations of normal braking situations. For example, an aircraft landing at a ground speed of 90 mph or 90 knots is brought to a stop in 1320 feet with constant braking action. What is the average rate of deceleration in G's?

$$90 \; mph \; case: \quad G = 0.034 \frac{(90)^2}{1320} = 0.207G$$

$$90 \; knots \; case: \quad G = 0.045 \frac{(90)^2}{1320} = 0.276G$$

In summary, the results are what we expected. We found a higher G level during braking from 90 knots since 90k is considerably faster than 90 mph.

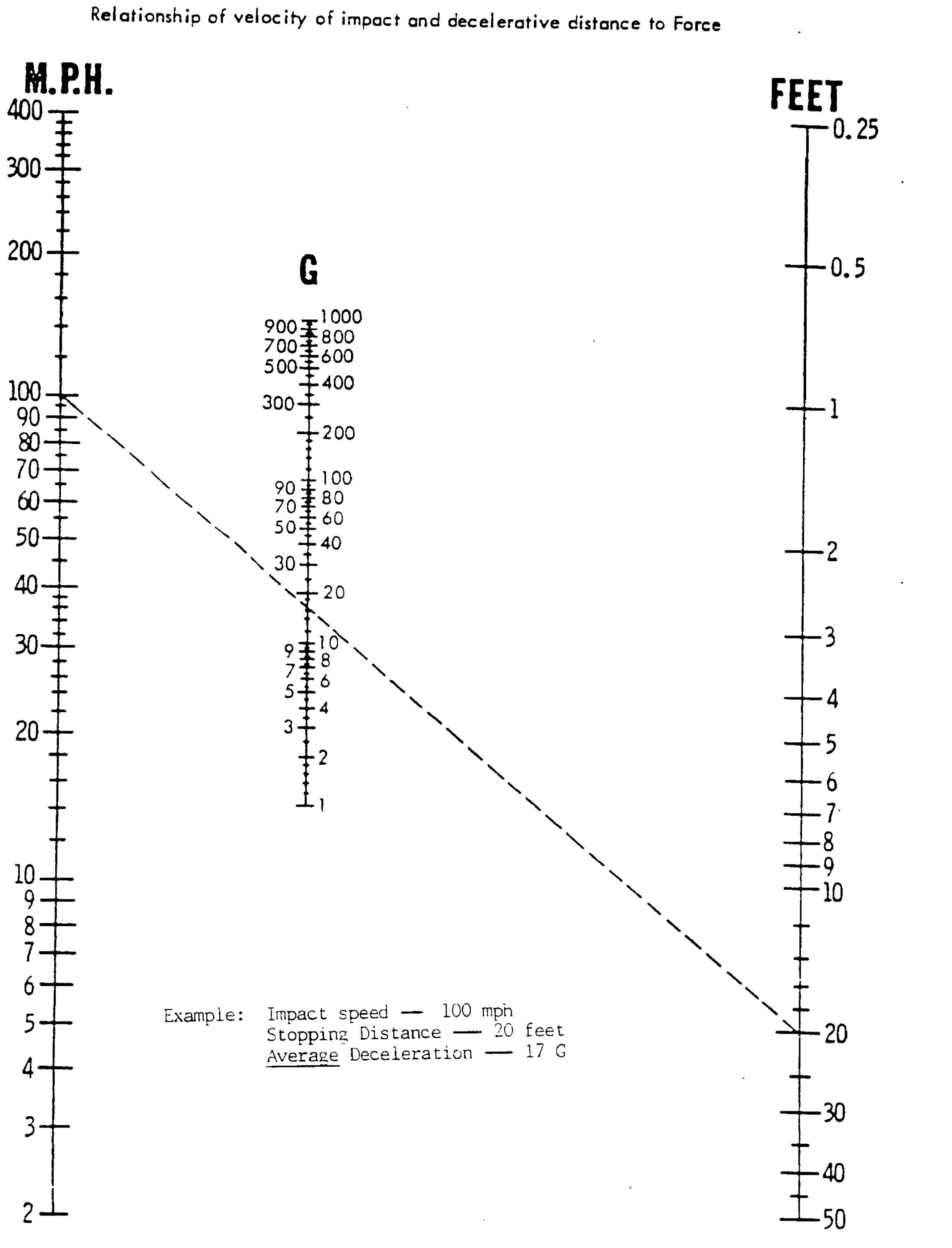


Figure 2a. Draw a dotted line from the estimated **ground speed** to the value of the measured ground scar to obtain a rough estimate of the G-forces when the **ground speed** is in miles per hour.(2)

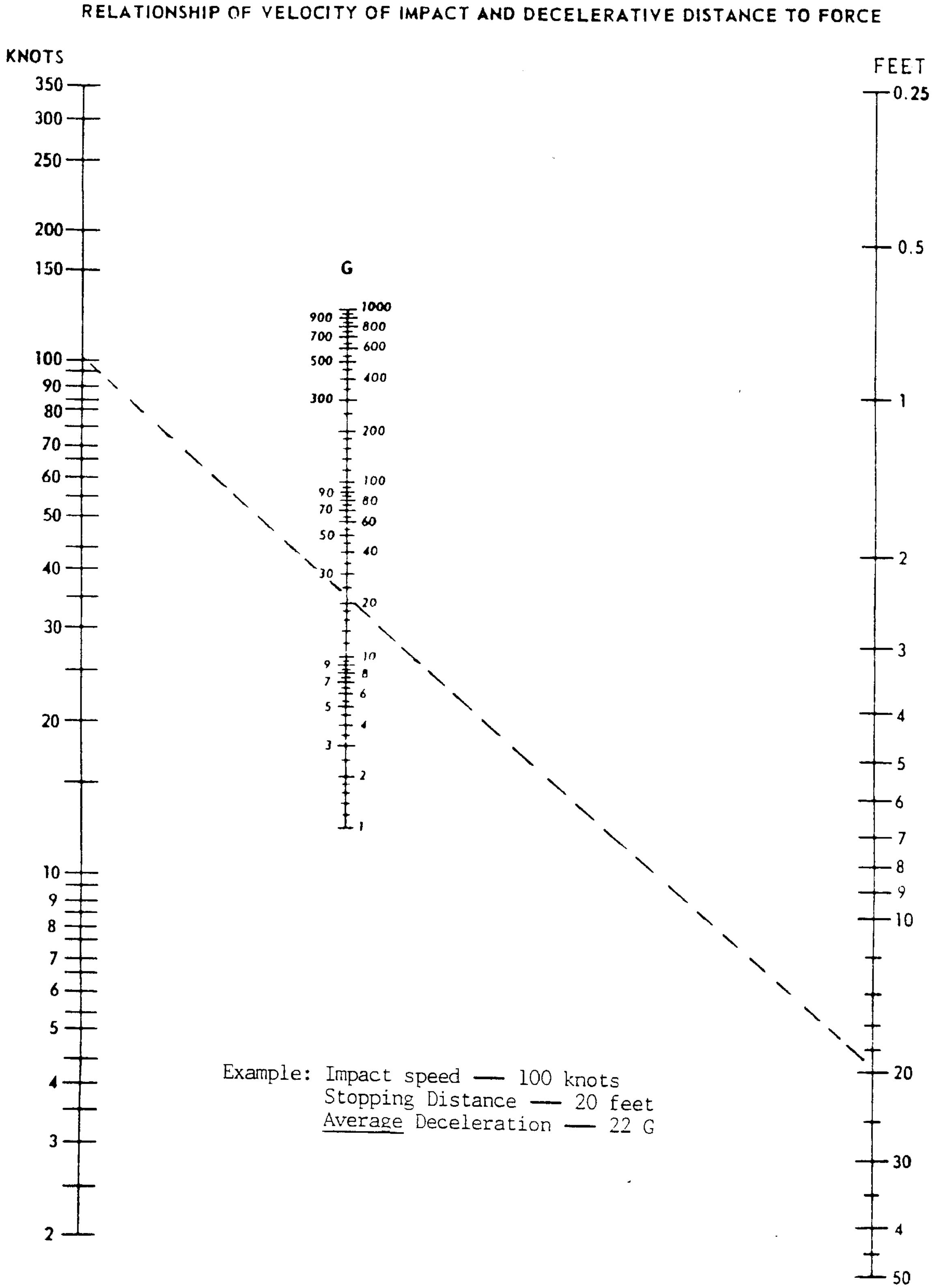
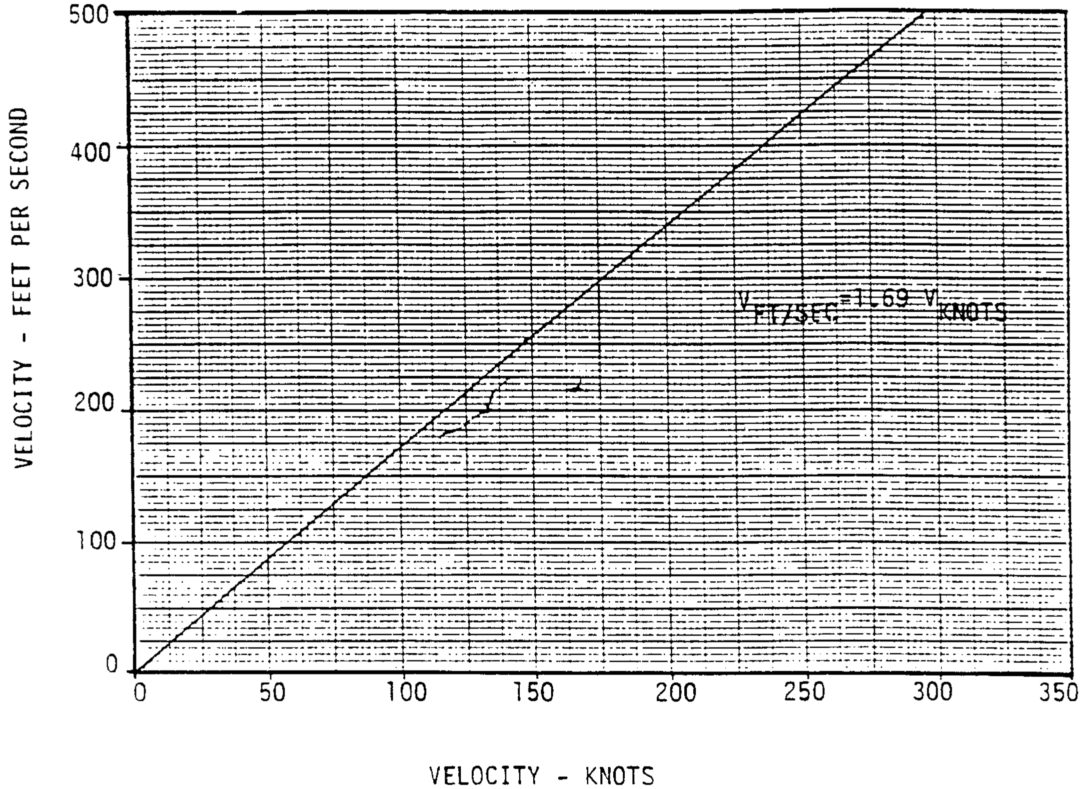


Figure 2b. Draw a dotted line from the estimated **ground speed** to the value of the measured ground scar to obtain a rough estimate of the G-forces when the **ground speed** is in knots.[2]



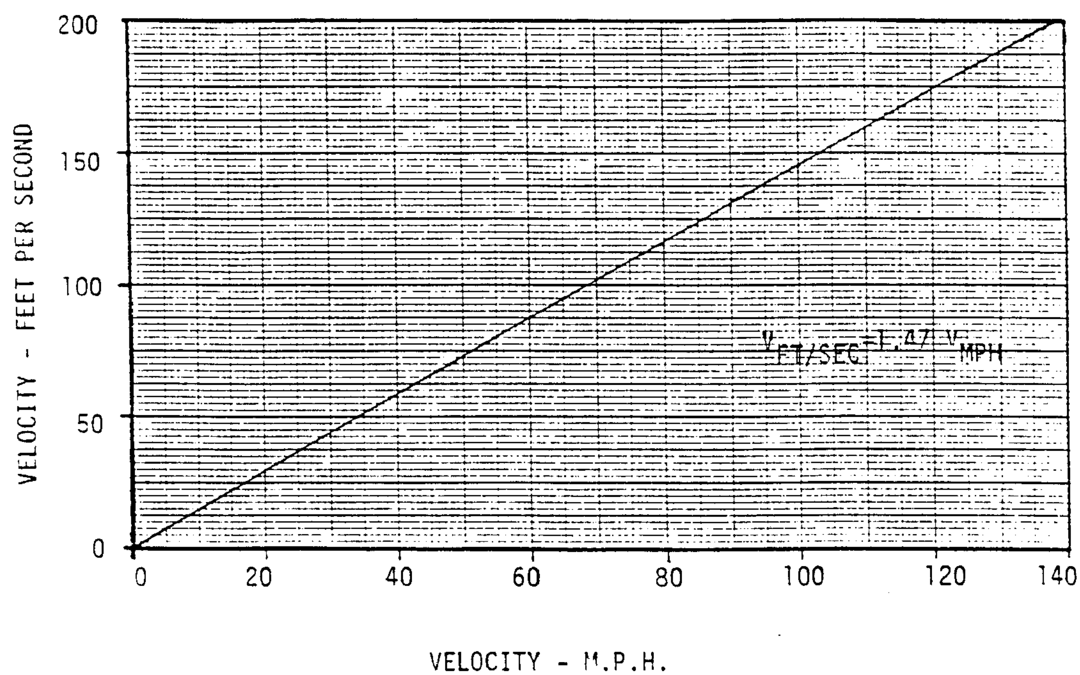


Figure 2c. Graphs to convert velocity in miles per hour and knots to velocity in feet per second when using equations where g-units are in ft/sec.[2]

3. HUMAN TOLERANCE TO PROLONGED G'S

Tolerance to Prolonged G's

As a living organism, the human body functions optimally under 1G conditions. Any deviation from that standard may cause problems, ranging from discomfort to death. The most common form in which aircraft occupants are exposed to changes in G-level are turbulence, aircraft maneuvers, and aerobatics. The accelerations associated with these events are usually the result of a change in the direction of motion in the aircraft rather than a change in speed. (Remember, velocity has both magnitude and direction.) The normally-seated occupant experiences these accelerative forces in a direction parallel to his spine. When the accelerative force acts in seat-to-head direction, the inertia reaction of the body, including vital organs like the brain and heart are in the opposite direction (head-to-foot); this is called positive G. An inverted loop imposes negative G's that increase the blood pressure in the easily-damaged capillaries that supply blood to the brain and eyes.

The G's produced by routine aircraft operations are considered prolonged G's because they affect the body long enough to cause functional disturbances, especially in the form of diminished blood circulation to the head. The human body has a very limited tolerance to this type acceleration. During a pull-up maneuver of about 4 G's the untrained pilot without a G-suit may successively experience gray-out, loss of peripheral vision (tunnel vision) and complete blackout due to diminished blood circulation to the eyes. At higher G-levels, he may become unconscious (cerebral failure). Some modern jet fighters (USAF's F-16) are so maneuverable and allow such a high G build-up that certain accidents have already been attributed to pilot's loss of consciousness. The regaining of consciousness is followed by a period of disorientation; this may create a critical situation at low altitude. The phenomenon is called GLOC: G-induced loss of consciousness.

Prolonged G forces that act perpendicular to the spine (Transverse G's) are easier to tolerate since they put less stress on the circulatory system, i.e., the G-forces act perpendicular to the flow of blood to the brain. For a prone or supine person, that tolerance is about 15 G's for several seconds; this is the position of astronauts during launch and re-entry.

For practical purposes, it is sufficient to remember that any acceleration lasting longer than one to two seconds allows sufficient time for circulatory and other physiological disturbances. The effects of prolonged G's may play a role in accident causation. As far as the crash injury mechanism is concerned, these prolonged G-disturbances can be disregarded.

Tolerance to Abrupt G's

Abrupt G's, such as those in a crash deceleration, are of such short duration (approximately 0.10 seconds or less) that there is no time for the manifestation of the effects typical during exposure to prolonged G's (longer than 1-2 seconds). Sudden stoppage imposes a shock load that threatens the structural integrity of the aircraft as well as the physical integrity of the occupants.

The principal variables that govern the human tolerance to impact deceleration are:

1. The magnitude and duration of the deceleration

2. The rate at which these decelerations reach their peak (rate of onset) as shown by the steepness (slope) of the G - vs - time graph. (See Figure 3.)

3. Body orientation and the manner in which the decelerative force is applied to the body (load distribution) as determined by seat and restraint system.

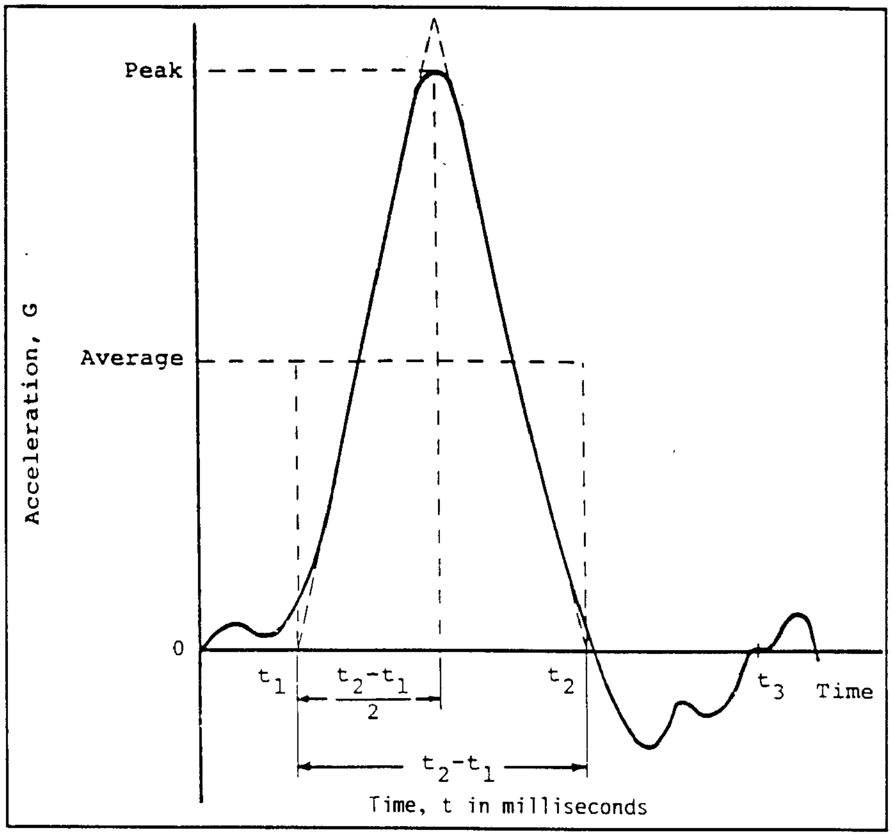


Figure 3. Typical shape of a plot of G's versus time, showing the crash event beginning at time t_1, ending at t_2 with smaller second impact beginning at t_3. The peak G occurs at exactly 1/2 the time interval. The average G is approximately 1/2 the peak G, but the most severe injuries occur during the top half of the peak (called the G-spike).[3]

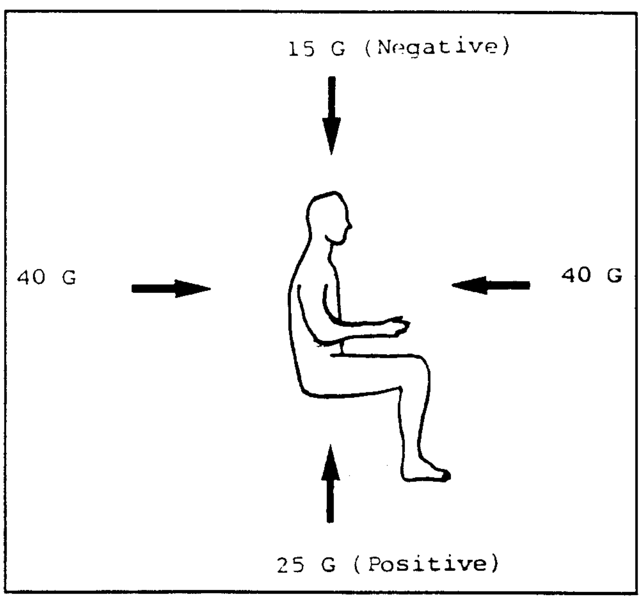


Figure 4. Upper levels of abrupt G forces and directions of application that have been voluntarily tolerated by human subjects in tests without injury when properly restrained.[3]

The terminology used in the next two pages is based on the direction of displacement of the body and body contents in reaction to a decelerative force. The "eyeballs-out" or "eyeballs-in" terms refer to the direction the eyeballs would tend to move in relationship to the direction of the applied force. Because the eyeball is essentially a liquid (vitreous humor) surrounded by a thin muscle, the watery mass of the eyeball reacts in the direction opposite the applied force. In other words, it tends to deflect out of shape and remain where it is as the force is applied to the body. Thus, the eyeball illustrates Newton's Third Law of Motion: "For every action, there is an equal and opposite reaction. In actuality, the whole watery mass of the body obeys Newton's Third Law and slumps or deforms in the direction opposite the applied force acting on the body.

A crash deceleration typically produces a combination of positive G's (eyeballs-down) and transverse G's (eyeballs-out) because the velocity along the flightpath has a horizontal and a vertical component in most cases. For occupants of aft-facing seats the transverse G's will be eyeballs-in.

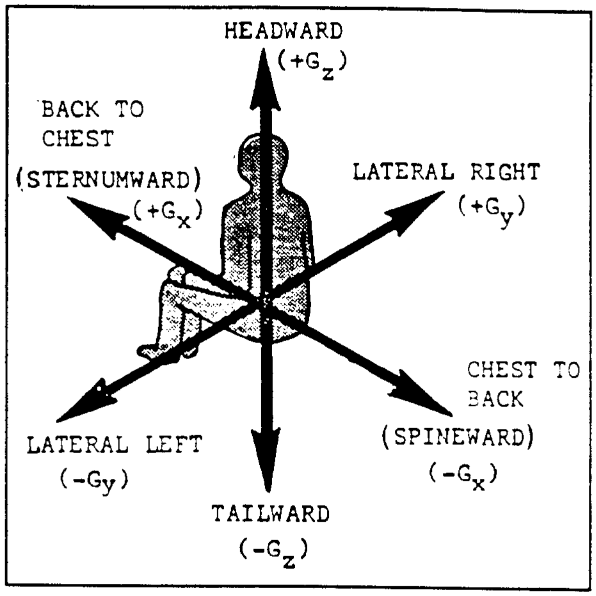


Figure 5. Decelerative forces on the body.
Note: The accelerative force of the crash is acting on the body in the direction of the arrows. Refer to Table 3.[3]

Direction of Applied Force	Direction of Body's Reaction	Human Limits*
Vertical (Parallel to Spine):		
Positive (Headward) + G_z	Eyeballs - down	20G
Negative (Tailward) - G_z	Eyeballs - up	15G
Transverse (Perpendicular to the Spine):		
Lateral right	Eyeballs - left	20G
Lateral left	Eyeballs - right	20G
Back to chest	Eyeballs - in	45G
Chest to back	Eyeballs - out	45G
* The values shown for human limits are approximate and represent no serious injury.		

Table 3. Directions of forces action on the body and the equal and opposite reactions of soft tissue (from USARTL-TR-79-22)[3].

ACCELERATION LIMITS

TYPE OF G	DIRECTION OF BODY MOVEMENT	AIRCRAFT MANEUVER	EXPERIMENTAL HUMAN EXPOSURES (MAXIMUM)	PHYSIOLOGICAL LIMITS HUMAN
POSITIVE (Eyeballs Down)	Head to Foot	Pull Out or Tight Turn	8 G for 15 Sec	Blackout to Unconsciousness
			4.5 G for 5 Min with G. Suit	Pain in Legs and Blackout
		Controlled Escape Deceleration	15 G for 1.75 Sec	Unconsciousness
		Ejection Escape (Upward)	20 G for 0.1 Sec with Face Curtain - Arm Rest	Skeletal Damage (Spine)
NEGATIVE (Eyeballs Up)	Foot to Head	Push Over	4.5 G for 5 Sec	Subjective Pain
			3 G for 32 Sec with Special Helmet	Fullness of Neck and Head Bradycardia
		Ejection Escape (Downward)	10 G for 0.1 Sec with Leg Support	Pain
TRANSVERSE (Eyeballs In)	Chest to Back	Catapult Launching	5 G for 2 Sec	No Damage
		Escape Decelera- tion or Higher Launching Stress	3 G for 9 Min 31 Sec Lying Flat	Monotony and Giddiness
			15 G for 5 Sec	Surface Petechial Hemor- rhage & Pain in Chest
		Crash (Facing Aft)	55 G for 0.01 Sec 35 G for 0.12 Sec	Skeletal Damage
TRANSVERSE PRONE (Eyeballs Out)	Back to Chest	Arrested Landing	5 G for 2 Sec	No Damage
		Escape Decelera- tion or Higher Landing Stress	15 G for 5 Sec Special Chest & Leg Support	Surface Petechial Hemor- rhage & Pain in Chest
		Crash (Facing Forward)	60 G for 0.01 Sec w/Special Harness 38 G for 0.12 Sec w/Special Harness	Skeletal Damage
FLUCTUATING POSITIVE	Alternating Positive and Transverse	Uncontrolled Aircraft "Jostle"	1.5 to 6.5 G for 20 Sec Combined w/72° Pitch and Roll	Additional Support Req'd Other Than Conventional Lap Belt & Shoulder Harness
CYCLIC	Alternating Positive Transverse Prone Negative Transverse Supine	Uncontrolled Escape Device "Tumbling"	No Human Experimentation Due to Severe Damage in Animal Exposures	

NOTE: G Refers to the force on the body in multiples of the body weight. Wearing G-Suit increases Human Tolerance to Blackout and Fatigue. The types of G, Transverse-Lateral and Fluctuating Negative have not been studied and are not listed in this chart.

Table 4. Acceleration Limits of Human Tolerance. Table 4 shows the limits of human test subject to acceleration (decelerations during the crash event) (from U.S. Navy's Aviation Medical Acceleration Laboratory).[4]

4. CRASH INJURIES: HOW THE BODY REACTS TO CRASH FORCES

Injuries produced by a violent stopping process fall in two broad categories:

1. Contact injuries which result from the body's striking, or being struck by, another object, and

2. Decelerative injuries which occur as a direct result of the shock loads on the body.

In the more severe accident, a combination of both types of injury mechanism will often be found.

Contact Injuries - The most prevalent form of contact injury involves bodily impact against solid objects within the occupant's striking range in the cockpit, cabin (or car/truck). Occasionally, occupants may be struck by a loose or dislodged object; these cases are self-explanatory and require no further elaboration.

Contact injuries produced by violent movement of the body are best understood when seen in terms of the so-called "second collision." According to Radar Nader, this term was first used by Sergeant Elmer Paul, an Indiana state policeman who looked at the impact of the vehicle itself as the first collision.[5] Since unrestrained occupants continue to travel at the vehicle's original speed until they collide with their rapidly decelerating structural environment, it is apparent that their collision occurs subsequent to the vehicle's impact. Thus, the second collision inside the vehicle is the most significant producer of contact injuries of unrestrained or poorly/partially restrained occupants.[6]

That the second collision may cause fatal trauma even at moderate speeds can be illustrated with the kinematics of an unrestrained child in a car that makes an emergency stop. The car is traveling at 5 mph when the driver "stomps" on the brakes. The child standing on the front seat is propelled head-first into the windshield. Assuming that the car - and the windshield - have come to a stop by the time the child's head collides with the windshield, the head impact occurs at the car's original speed: 5 mph. A stopping distance (0.1 foot) will be used; this consists of the deflection of the windshield plus skull deformation. The decelerative force on the child's head, expressed in G's, can be found using the formula on page 9 as follows:

$$G = \frac{.034(mph)^2}{.1} = .034(5)^2 = 8.5G$$

If the child weighs 40 pounds, this means that a force of 8.5 x 40 = 340 pounds was pressing against the child's head. Depending on the manner in which the blow is distributed over the skull, this would be a very serious or fatal injury. If a sharp object is involved, such as a rearview mirror, the skull may be penetrated. Certainly, the child's neck and spinal column would receive a very serious injury.

Jackknifing, Flailing, and Submarining Injuries - Any time an occupant's body does not fully participate in a vehicle's deceleration, a differential velocity will develop between the unrestrained parts of the body and the internal structure of the vehicle. This law of physics explains the limited protection of a lap belt only for the adult occupants of front seat in cars and aircraft. During a forward deceleration, they will jackknife over the lap belt; this will bring their head - perhaps even their upper torso - within striking range of the instrument panel and other structure. In other words, the lap belt acts as a fulcrum around which the body extremities gain angular momentum, rotating the upper torso forward and downward. The flailing extremities, including the head, will strike the instrument panel and/or the door post/window frame.

The striking range of the flailing head, hands and feet is shown in Figure 6. Note the forward displacement of the hips with regard to the seat back during jackknifing over the lap belt. Flailing and jackknifing are major sources of injury with lap-belt-only restraint. This situation is aggravated when the lap belts are not worn tight over the pelvic bone or when the seat cushion is compressed during impact causing the lap belt to slip off the bony pelvic structure and ride up into the soft tissue of the lower abdomen. This is known as submarining. If the body jackknifes around a raised lap belt, the bending of the body does not occur at its natural joint at the hip, but in the lower spine. Such hyper-flexion can easily cause spinal injuries.

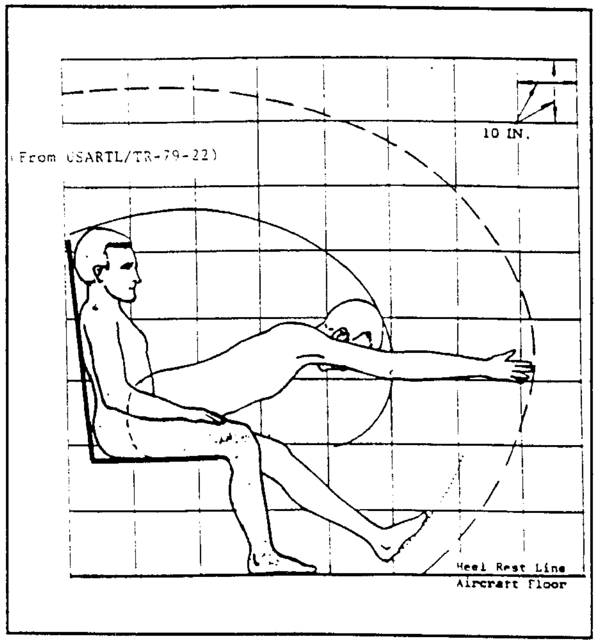
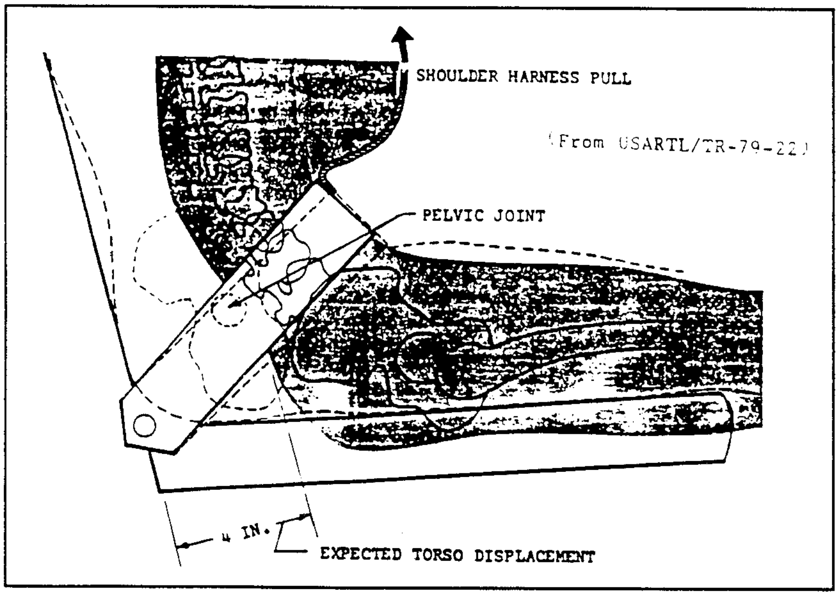


Figure 6. Occupant's strike zone of lap-belt only restraint system (from USARTL/TR79-22)[(3)]. G-forces will throw the occupant into the "brace position" unless the brace position recommended by the airlines is assumed prior to the crash impact.



The impact of the lap belt itself into the soft abdomen (Figure 7) may cause typical submarining injuries involving liver, spleen, bladder and other organs and tissues. Use of a shoulder harness minimizes jackknifing but internal injuries can still occur where the lap belt rides up.[(3)]

Figure 7. Pelvis rotation and "submarining" caused by high longitudinal forces combined with moderate vertical forces can occur even with shoulder harnesses unless 5-point restraint system anti-submarining crotch straps) are utilized (from USARTL/TR-79-22).[(3)] Note the compression fractures occurring on the spinal column of the shaded torso.

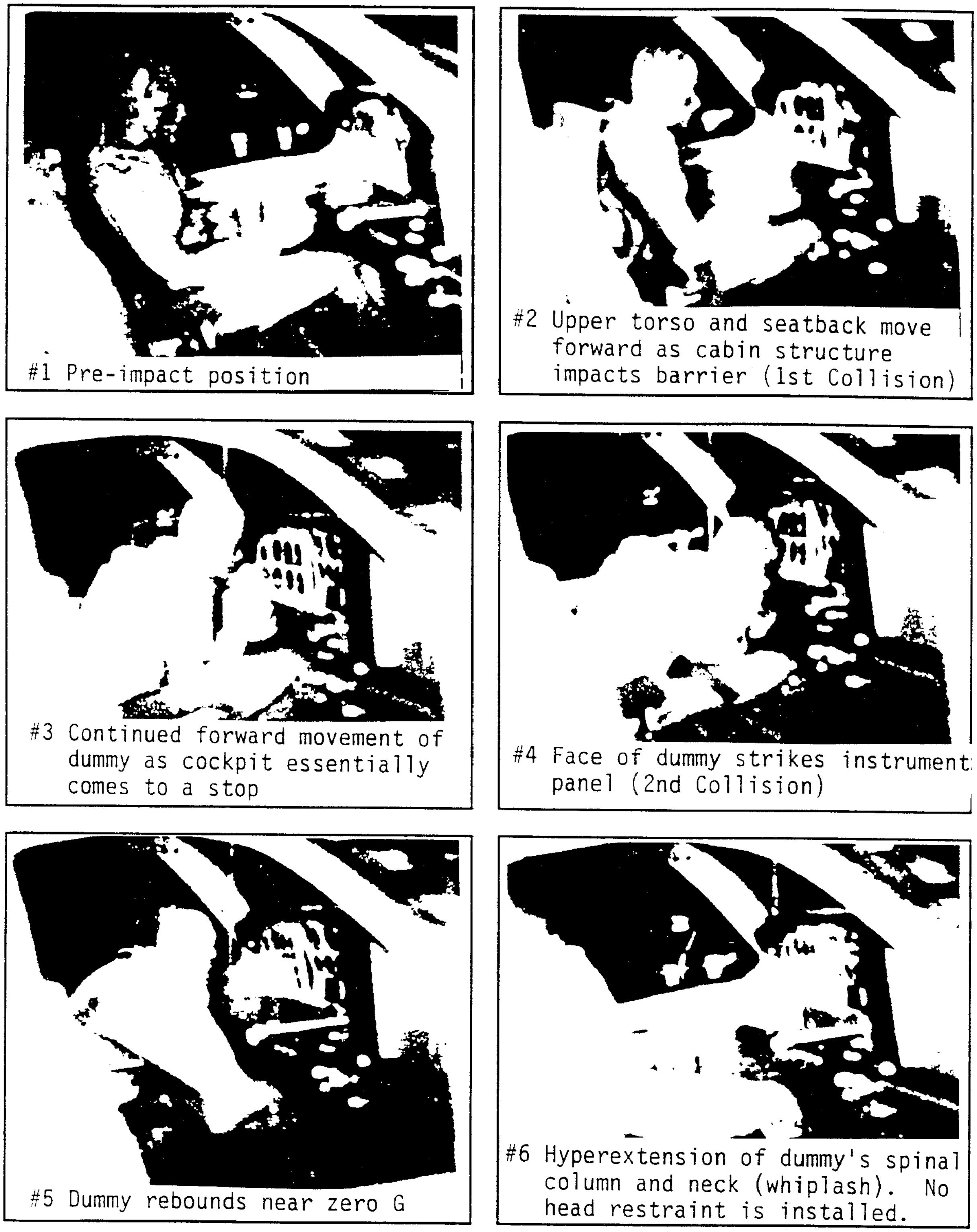


Figure 8. High-speed photographs of jackknifing action on a dummy, restrained by a well-secured lap belt without a shoulder harness in a typical general aviation cockpit during a crash test at 9.5 G and 35 feet per second velocity change. The total duration of this sequence is about 300 milliseconds (0.3 secs).[7]

Correlation of Injuries to Objects Causing Injuries -

The investigator should always attempt to correlate contact injuries to the particular object or structure involved, except in cases of extreme traumatic injuries. It would be misleading to evaluate which objects are within striking range of a particular occupant's head by strapping a person of the same height in a similar aircraft and simulating the jackknifing. The inertia effects of impact have to be taken into account by placing that person several inches forward of the normally seated position. Such forward displacement is governed by the following phenomena that take place during the dynamic phase of a crash:

1. The stretching of the lap belt and/or shoulder harness webbing. (The tightness or looseness adjustment of the belt by the user is an unknown variable.)

2. The "give" and elasticity in the seat structure and its attachments into the floor and the buckling of the cabin floor structure.

3. The compression of the body where it contacts the belts.

4. The compression of the seat bottom cushion and/or seat pan deflection/distortion..

5. The stretch in the upper torso as it rotates around the lap belt or lap belt/shoulder harness combination and the subsequent hyperextension which is discussed below.

It should be noted that jackknifing during a severe forward deceleration may cause crushing injuries of the chest when the chest impacts the thighs and knees, the seat in front, or the control column.

Decelerative Injuries (G Force Shock Loads to the Body)

In contrast with second-collision injuries, decelerative injuries occur as a direct result of the principal impact shock transmitted to the occupant through the floor, seat and restraint system. The injuries generally involve the skeletal structure and/or body organs; there is seldom external evidence of the severity of these internal injuries. Examples: compression fractures of the spine, ruptured liver, and transection of the aorta from the heart. Decelerative injuries suggest that the principal deceleration as experienced by the occupant exceeded the non-injurious limits of human G-tolerance expressed in Tables 3 and 4.

To understand the mechanism of this type injury, the human body should be viewed as a relatively rigid structural container (the skeleton) in which the various body organs are elastically suspended, similar to a laboratory spring-mass system. When the whole body is subject to the violent agitation of impact, there is a pronounced interaction between the body organs, depending on their mass and the damping characteristics of their elastic support (spring) suspension. The crash pulse may cause differential decelerations of the various internal organs resulting in stretching, tearing and shearing; excessive pressure may burst fluid-filled tissues and organs. (See the discussion of the "third impact" under the following Section 5, "Seats and Restraint Systems.")

Hyperextension of the cervical spine (whiplash injury) also falls in the category of decelerative injuries. (See sixth photo of Figure 8.) It is common to see this type of injury due to occupant rebound into the seat back without adequate head restraint. Remember to examine the head restraint for proper height and impact damage (bending), keeping in mind that it is not a "head rest," but part of the seat restraint system.

Crash Injury Correlations

The first objective in a crash injury investigation is to determine to what extent aircraft occupants were injured or killed in a potentially survivable accident. The data gained in that process support the second objective: improved occupant protection design criteria. For these reasons, it is essential to correlate injuries with the decelerative forces involved and the structures within the occupants' striking range.

To obtain the necessary medical information, the investigator has to work closely with the flight surgeon, county coroner, Aviation Medical Examiner (AME), and/or pathologist. Their active participation in the injury correlation process must be solicited.

Autopsy reports, hospital records and emergency services documentation provide reliable injury data. Such injuries include: (a) head-concussion, skull fracture, or internal hemorrhaging; (b) neck-fracture; (c) chest-crushed, punctured lung, or rib fracture; (d) spinal column-fracture, pinched nerve or severed spinal column; (e) limbs-fractures, cuts, or tearing of ligaments, muscle and tendons; (f) thermal injuries-burns, vascular damage or asphyxiation; and (g) drowning.

When there is doubt about which front seat occupant was handling the flight controls, the difference in injuries sustained by the hands and feet of the two occupants may sometimes provide vital clues, such as broken thumbs on the person whose hands were on the controls. Similarity of injuries, especially with regard to trauma to the thumbs, may indicate that both crew members had their hands on the yokes. Shoe and rudder pedal damage and broken foot and ankle bones may indicate attempts to move foot rudder or anti-torque controls prior to impact.

Summary:

The injury pattern in general aviation accidents has been documented for several decades and has remained virtually unchanged. In a 1952 study[8], engineer and World War I fighter pilot Hugh DeHaven found the following pattern in 800 survivors of light aircraft accidents who were restrained by a lap belt only. The percentages indicate the frequency of involvement of the body areas involved:

Head	31.6%
Lower Extremities	28.8
Upper Extremities	15.2
Upper Torso	11.4
Lower Torso	6.7
Spine	6.5

One of the conclusions reached by De Haven was that a "positive relationship exists between the frequency of injuries and the distance of damaged body areas from the safety belt." Since head injury is the most common cause of death in otherwise survivable accidents, it is apparent that the use of a properly designed and installed shoulder harness is the most effective method to reduce the frequency of serious and fatal injuries in general aviation. (Recent research on this subject by the NTSB is discussed under Seat and Restraint Systems in the following section.)

5. SEATS & RESTRAINT SYSTEMS

Early Seat Belts - In the early days of aviation, people thought the only purpose of seat belts was to keep pilots from separating from their planes during inverted flight. Circa 1935, Hugh DeHaven became interested in human survival factors, including seat belt use, after he barely survived a plane crash wearing only a lap belt. His efforts led to the establishment of a crash injury research program at Cornell University Medical College. Dr. Bertil Aldman, a Swedish anesthesiologist, and Nils Bohlin, a safety engineer from the Volvo Automobile Company invented the three-point safety belt system, which became increasingly important to aviation safety.

Cockpit & Cabin Environment - Aircraft can provide an even more hostile environment than automobile interiors during a crash. Impact speeds can be greater, and vertical, as well as horizontal, movement may be expected. As Sir Isaac Newton showed 300 years ago, doubling the speed of impact increases the severity of effects four-fold. Furthermore, for a light aircraft the deceleration time, or the time required to come to a complete halt after encountering an obstruction, such as a tree, is quite short, because of the relatively small mass of a light plane. This rapid deceleration imparts a violent, whiplike motion to the torso and head when a person is restrained only by a lap belt.[9]

During a crash deceleration, the unrestrained upper body will tend to flail around the lap belt, resulting in one or more secondary impacts against the control wheel, instrument panel, door post, or anything else within range. In the case of backseat passengers, obstructions could include seatbacks, sidewalls, ceiling panels, and other passengers.

Under most conditions -- even if there is time for forewarning of an impending crash -- the forces are so great that it is impossible to restrain the upper body's motion by bracing against any adjacent structure with one's arms. The head and torso injuries that result are often fatal.

Seat Belts and Shoulder Harnesses - In aircraft, as in automobiles, a small obstruction-free "living space" surrounds each occupant. In an accident, as long as one remains properly restrained within this space, the probability of surviving and escaping serious injury is quite good. (See Figure 9.) The immediate improvement in crash survival resulting from military use of the combined lap belt/shoulder harness equipment eventually led to its adoption in the cockpit of civilian air carriers. In 1977, a rule change of FAR 91.33 required crew member seats of general aviation aircraft manufactured after July 18, 1978, to have approved shoulder harnesses. By 1985, this requirement was extended to all forward-facing seats in light airplanes manufactured after December 12, 1986. Additionally, FAR 91.14 made pilots in command responsible for crew member and passenger usage of shoulder harnesses, wherever they are available, during takeoff and landing.

Regardless of the additional protection that could be provided by proven design concepts, the non-availability or non-use of the standard shoulder harness remains the principal cause of avoidable death and injury in survivable impacts. According to an NTSB study [10,11]:

1. A potential 20 percent reduction in fatalities could be realized if all occupants of general aviation airplanes were to wear shoulder harnesses. (See Figure 9 for correct shoulder harness design and installation.)

2. Potentially, 88 percent of seriously injured occupants could be expected to incur significantly reduced injuries if shoulder harnesses were used.

3. Potentially, 34 percent of seriously injured occupants could be expected to have significantly reduced injuries if energy-absorbing seats were available.

The NTSB study also found that of 253 accident-involved occupants who had shoulder harnesses available, only 40 percent actually used them. And, shoulder harnesses were only installed on 40 percent of the total seating available. The net result was a 16 percent usage rate considering total seating capacity. This statistic indicates a poor understanding of the value of upper torso restraints on the part of both crew and passengers.

During a crash, the buckling and crushing of aircraft structure between the point of impact and the occupiable area (cockpit/cabin) absorbs energy of motion and reduces the magnitude of crash loads transmitted to the floor structure underneath the occupants. Thus, one of the first established principles of impact survival was that the occupants be firmly linked to the floor structure through their seat and restraint system. Subsequently, it was discovered that crew and passenger seat and restraint systems can be designed to reduce the loads transmitted from the floor to the seat occupants. It has been known for many years that crew and passenger seat and restraint systems can be designed to reduce the loads transmitted from the floor to the seat occupants by incorporating energy absorbing seat legs.

Restraint Improvements - During an elaborate general aviation crashworthiness study [1,10,11], the NTSB came to the conclusion that longitudinal (forward) decelerations of 30 to 35 G's in response to the impact G's can be survivable. With regard to vertical (downward) loads, the NTSB considered 25 to 30 G's in response to the impact G's to be non-lethal, "but the loads experienced by the occupants must be limited to a lower level to prevent crippling injuries to the back and neck."

Early in 1983, the FAA commissioned a special study group known as the General Aviation Safety Panel (GASP) made up of government and industry research scientists, engineers and accident investigators. Most major general aviation airframe manufacturers and seat, restraint systems and survival equipment subcontractors/suppliers were represented on the panel. Beginning in July 1983, the GASP held a series of meetings to explore general aviation crashworthiness issues. As a result of the meetings, the GASP forwarded a proposal to the FAA on May 2, 1984, that defined standards for seats and restraints. The stated goal was to prevent or reduce airplane crash injuries in a reasonable manner.

To ensure that the goal was met, panel members evaluated information presented by experts in such areas as accident investigation, crashworthy seat design, dynamic testing, manufacturing, crashworthiness, and human tolerance to vehicle crashes. The main objectives, in order of importance, were to (1) require dynamic testing that adequately represents an actual crash; (2) increase the strength of the seat and restraints; (3) require energy-absorbing seats to attenuate vertical loads; and (4) establish performance standards by which the tests could be evaluated.

Dynamic crash testing was proposed to ensure proper performance of crashworthy designs that operate in a dynamic environment. Some of the problem areas that are addressed by dynamic testing are dynamic overshoot, floor warping, and secondary head impacts. Dynamic testing also validates energy absorbing devices and defines occupant response in the restraint system.

The FAA adopted the seat/restraint dynamic testing requirements which the GASP recommended along with recommendations in other areas, such as fire survivability and flotation equipment improvements. The new dynamic seat testing requirements were adopted in 1988[12]. Several manufacturers adopted voluntary compliance for newly certified aircraft prior to the 1988 rule change.

Prior to the adoption of the GASP recommendations in 1988, the design requirements in FAR 23.561 were based on static conditions; that is, the manufacturer only had to show that the seat, its anchorage, and the restraint system could withstand steady static loads in the specified directions. (See Table 5.) For the discussion of 5-point restraint systems, turn to Section 6 where AG (agricultural) aircraft crashworthiness is discussed.

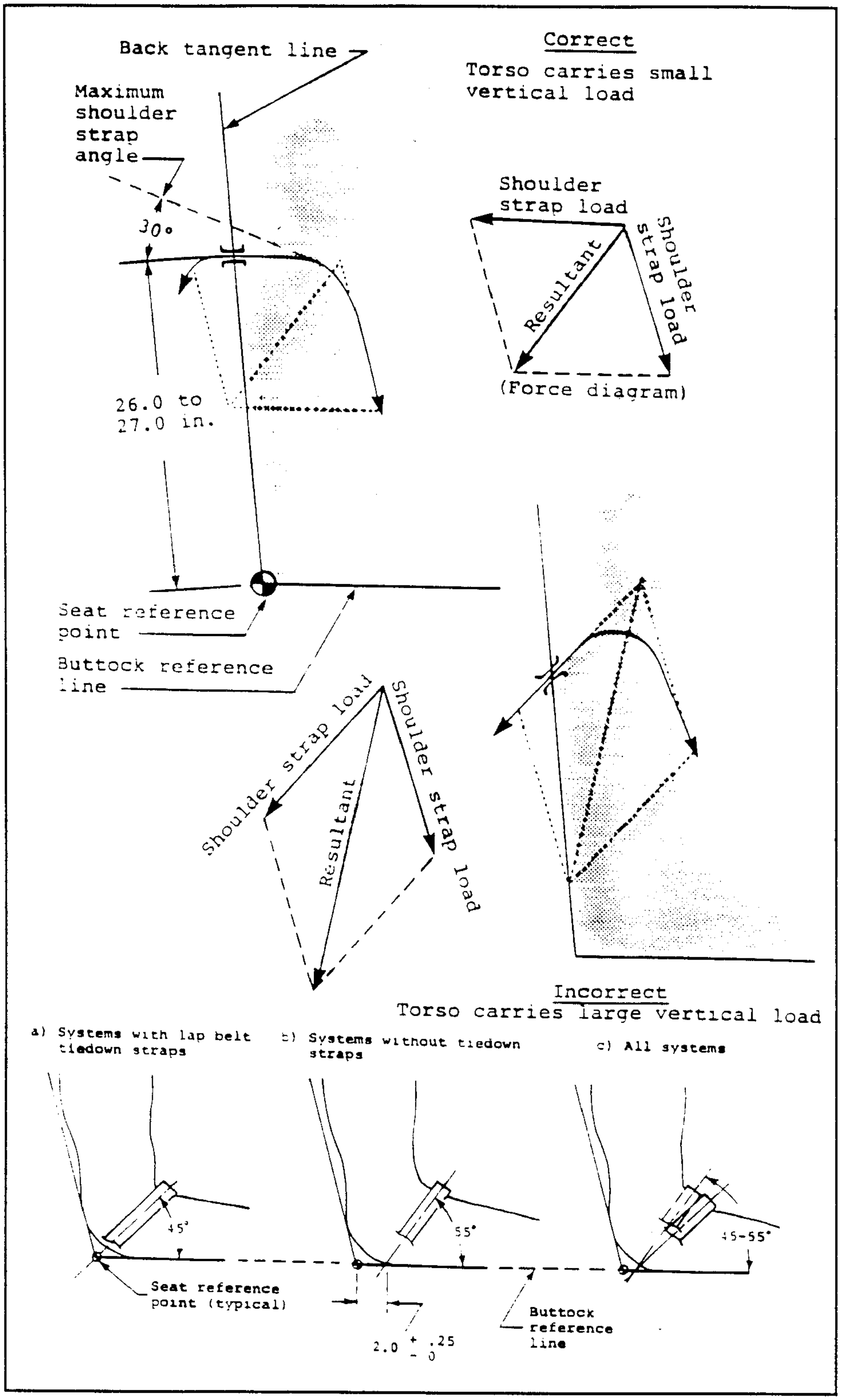


Figure 9. Shoulder harness and lap belt anchorage geometry (from USARTL/TR-79-22)[3]

Static Loads IAW Old FAR 23.561	Can be Survivable According to NTSB Study	New General Aviation Safety Panel (GASP) Seat Strength Adopted by FAA 08/15/88[12]
Downward 4.5 G's	25 - 30 G's	19 G's at 31 Ft/sec velocity change
Forward 9.0 G's	30 - 35 G's	26 G's at 42 Ft/sec velocity change
Lateral 1.5 G's	*	*
Upward 3.0 G's	*	*
	* Lateral and Upward seat strength will increase significantly on seats designed to the new "Dynamic" test requirements.	

Table 5. Comparison of old FAR 23 occupant protection criteria for "crash landing" conditions and the survivable G-tolerance established by the FAA, NTSB, and GASP. The illegal addition of extra weight (fire extinguishers, oxygen bottles, etc.) to the seat also lowers the protection.

Prior to 1988, the static strength of a seat/restraint system expressed in G's was based on an (average) occupant weight of 170 pounds (FAR 23.25). Therefore, a 9G seat was theoretically able to withstand a static pull of $9 \, X \, 170 = 1530$ pounds. This means that an occupant weighing 85 pounds would have been protected to $\frac{1530}{85} = 18 \; G's$ or a static load 18 times his body weight.

Occupants weighing more than 170 pounds had less than 9 G's protection, depending on the extent to which their weight exceeded the standard 170 pounds. At a weight of 255 pounds, an occupant was protected to $\frac{1530}{225} = 6 \; G's$.

In reality, a crash pulse excites dynamic responses (Figure 10) that may amplify the crash loads experienced by the occupant and, therefore, by the seat. The seat/restraint system with its occupant constitutes a mass-spring system with elastic characteristics that allow the development of differential velocity between occupant and floor, especially during a forward deceleration (eyeballs-out). When the amount of slack from a poorly adjusted restraint system is taken up and the belt and shoulder harness webbing elongates to its elastic limit, a severe jolt to the body will occur. This jolt will slow the occupant's velocity suddenly.[13]

Dynamic Overshoot - is one of the major causes of personal injury. (Refer to Figure 10.) This phenomenon can be best visualized by considering the static versus dynamic strength of a common string rated at 10 pounds and its reaction to a dynamic load. This string is able to support a weight of 10 pounds tied on to it during static conditions. However, when the same weight is dropped from a modest height, the inertia of the falling weight will exceed the load-carrying capability of the string, which will snap. Not having a tightly adjusted seat belt/shoulder harness combination and/or sitting on a deep spongy cushion will produce and/or amplify the Dynamic Overshoot and whiplash in a similar manner. In an aircraft accident, the occupant's deceleration may reach a peak well above that of the floor structure as a result of dynamic overshoot.

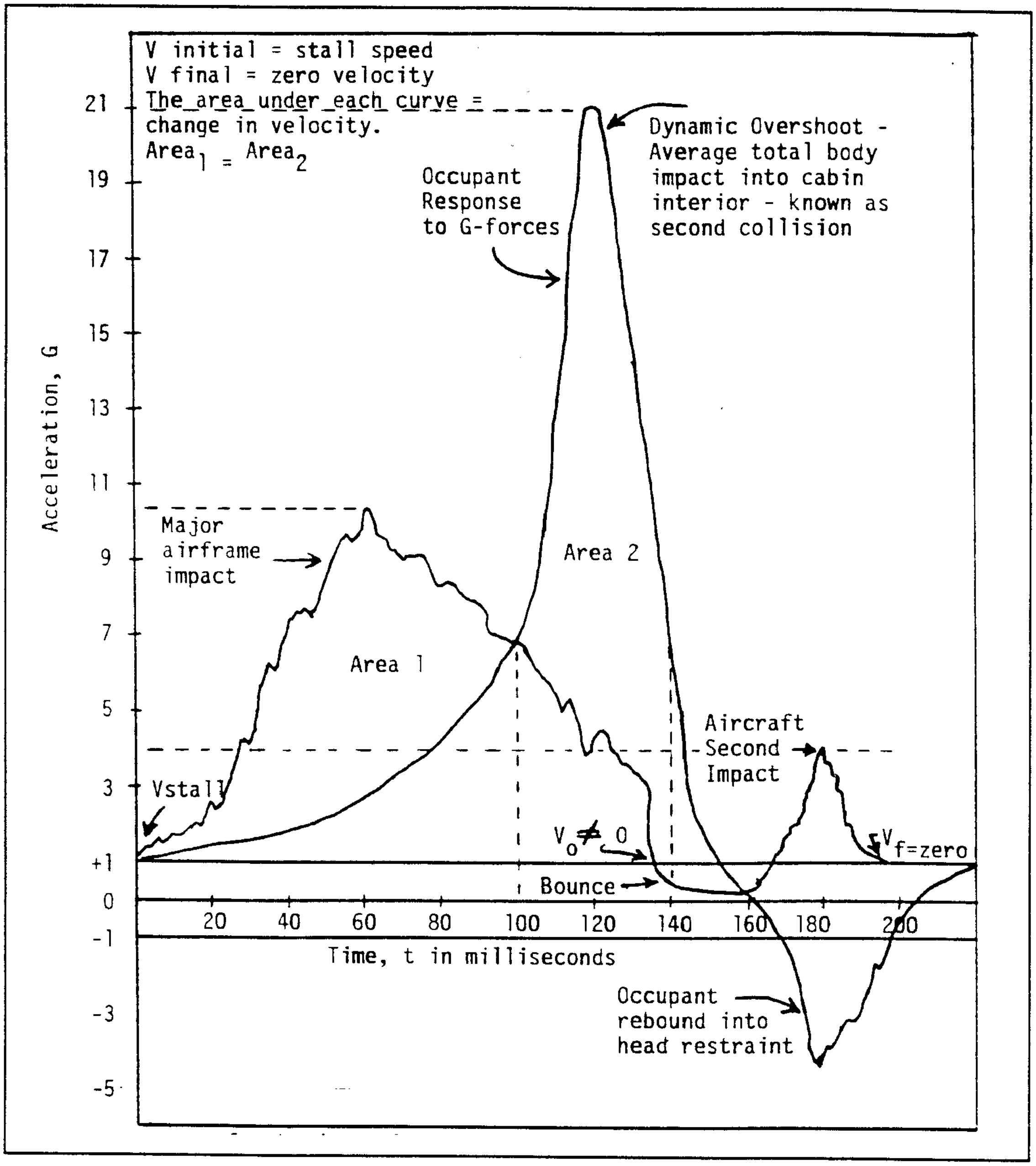


Figure 10. Typical General Aviation horizontal G versus time plot of the crash loads on cabin structure. Superimposed on the graph is the resulting occupant response. The time delay before the occupant curve rises at its maximum rate of onset (slope) is due to the stretching of the nylon or dacron restraint system, the compression of the seat cushion and the elasticity of the human body. Note that once the stretching and soft tissue deformation has taken place, the G-forces on the man-seat system peak much higher than those on the aircraft cabin structure. This is called "dynamic overshoot," which is the period of time, measured in milliseconds, when injury exposure is highest, often referred to as the "second-collision hazard." Refer back to the Figure 8 photos sequence, photos #3 and #4 (facial impact) and photo #6 (rebound and sequence of Figure 8: #3 and #4 (Facial impact) and #6 (rebound and hyperextension/whiplash).

Energy Absorption - An energy absorber system is like a one-time shock absorber between the occupant and the airplane. Energy absorption design criteria can be used to reduce crash injury. Another term for energy absorption is "load-limiting." In a load-limiting/energy absorbing system, the seat, restraint, or interior of the aircraft will deform at a load just below the load which causes injury to the body. As the system deforms, it moves according to some established design principle, but does not fail catastrophically. The crash load is maintained at a survivable level throughout the crash duration and the resulting seat displacement. There is little rebound. If such load limiting can be designed into a seat/restraint system, much of the crash energy can be absorbed by the system, rather than the occupant, thus, reducing injury.

The damaging and injurious effects of dynamic overshoot can be alleviated by applying load limiting concepts (energy absorbers) in the design of seat and restraint systems. This design feature involves the controlled crushing or elongation of components in the seat system while maintaining the integrity of the seat/restraint system. Scientists, engineers and accident investigators call this "controlled plastic deformation." The deformation takes place in the plastic region of the stress-strain curve. (See the Metallurgy Section, Chapter 39.)

This type of built-in energy absorption is especially important to protect the occupant against excessive vertical G's. In most small aircraft, there is considerable less crushable (energy absorbing) structure under the floor than in front of the occupants. The U.S. Army relies on energy absorbers to limit the level of the major vertical crash pulse which is transmitted to the occupants to approximately 14.5 G's in the Blackhawk and other Army helicopters. Piper and Cessna have used an S-tube with an internal coil spring design as an effective load limiter (energy absorber) in single engine aircraft designed during the 1980's. The weight penalty is very small and the benefit is significant.

Second Collision - Time and distance are the two factors that affect the energy transferred to the occupants during a crash. The concept is to let the vehicle absorb as much of the crash energy as possible by crushing, while transferring as little energy as possible to the occupants. Airframe and seat energy absorption has the benefit of extending the time of the first impact. Referring back to "Contact Injuries" previously discussed in Section 4, you will remember that jackknifing, flailing and submarining are the causes of many second collision injuries. Also refer back to Figures 6, 7, and 8. Second collision injuries also result from facial/head impact with the rearward crushing of the firewall and instrument panel and collapsing of the cabin roof.

Third Collision - There is a third impact that is recently getting special attention. It involves the body's organs as they strike its skeletal structure. Of particular interest is the brain and skull combination. Our brains are wonderfully equipped to withstand the thumping of everyday life. The surrounding cerebrospinal fluid acts as a shock absorber when we walk or change directions or even fall down. But extreme stresses, say a sudden encounter with part of an aircraft cockpit, can devastate the brain.

Because there is fluid space between the brain and the skull, on impact the brain can actually move with respect to the skull. It is that relative motion that is one of the key causes of brain injury. As the brain rocks forward and hits the front part of the skull, then sloshes backward, the frontal lobe, which is critically involved with judgment, self-restraint, and personality, is frequently bruised or lacerated. As the brain continues to move, pinpoint hemorrhages can occur and neurons may tear loose from each other. Then there are the bridging veins that lie atop the brain. They can stretch and even break. When these vessels tear, they leak blood into the area between the hard skull and the soft brain, under the canvaslike covering called the dura. Such a subdural hematoma, or blood clot, can kill within minutes.

Infant Restraints & Approved Car Seats - Careful selection of children's seats and proper use of seat belts are important, whether they are to be used in a car or an aircraft. It is critical to get the proper device for a child's size. Age doesn't have a lot to do with it, but size does. Making sure the device is used properly, that it is properly secured, and that the child is in it in the correct way are important also. The following points are made for accident investigators in the interest of safety of operations involving approved child restraint systems.

Never put a child under 18 months in a seated position facing forward using straps to hold the child rigidly within the seat. The reason is simple. On impact, there is a tremendous amount of force on the whole body to move forward. If the entire body is solidly anchored in the seat, there is one thing left to move -- the worst thing -- the head. Because a child's head is disproportionately heavy compared to its total body weight and its neck muscles are relatively weak, serious head and neck injuries can occur on impact.

Put a child up to two years in an infant restraint system that is rear-facing, so his or her body is fully supported by the back of the seat and the crash loads are distributed evenly by the body and head into the seatback. If a mother holds her child on her lap, she may feel in control, but this is one of the most dangerous positions for the child. If a car traveling at 30 mph stops over a distance of one block, anyone could hold a child. But if the car is stopping over a distance of five feet, it would be very difficult to hold the child. The force required to hold a child after impact in an aircraft could be as much as 16 times the weight of the child, or 16G's. A 20 pound child could require you to hold as much as 320 pounds to restrain him.

Five Do's and Don't's on Infant Restraint (from the Oklahoma State Department of Health) that apply to aircraft, as well as automobiles:

1. DON'T bundle the child and then try to buckle the shoulder harness. DO buckle the harness, then add extra blankets or covers.

2. DON'T place infant in a child restraint facing forward. DO face the child restraint backward. Baby must ride backward until he or she can sit up well and weighs 17-20 pounds. If the driver or pilot must supervise the infant, place the child restraint in the front seat.

3. DON'T recline an infant child restraint with adjustable tilt feature too far down. This could permit the infant to be forced out head first by frontal impact. DO check manufacturer's instructions for information on the safe degree of tilt.

4. DON'T fail to secure the child restraint system with a seat belt. Once again, the child could be forced out upon sudden impact. DO try another position in the car or a seat belt extender to lengthen the belt. If these do not work, use a different model which is fitted to the car and your aircraft before purchase.

5. DON'T neglect to use or tighten ALL harness or anchor straps. This could allow the child to be thrown out of the child restraint. DO snugly secure both harness and anchor straps.

A well-designed, properly adjusted seat restraint system should apply crash loads to the body in a proper, predictable manner so as to reduce injury.

The best seat/restraint systems support during a crash is one which distributes the crash loads over a maximum area of the body. The following is a listing of aircraft seat and restraint system designs ranked in descending order of crash protection offered, with side facing (bench or couch) designs being the worst style) because the human body has a low tolerance to lateral G forces).

1. High back, rear facing seat
2. Forward facing seat & airbag cushion
3. Forward facing seat & 5 point restraint system
4. Forward facing seat & lap belt, double shoulder belt restraint
5. Forward facing seat & lap belt, single diagonal torso belt.
6. Forward facing seat & lap belt
7. Side facing seat & lap belt with upper torso restraint
8. Side facing seat & lap belt only

Summary

In summary, crew and passenger seats can be designed to benefit from the energy-absorbing process by absorbing crash loads in a controlled manner and by distributing forces more evenly to the human body within human injury tolerance. The more the seat, seat pan, and minimum-rebound cushions absorb crash energy, the better the occupants' chances are of escaping serious or fatal decelerative injuries.

6. AIRFRAME CRASHWORTHINESS

The term crashworthiness refers, in general, to the capability of a vehicle to protect its occupants during a crash. The design concepts involved follow the general principles of packaging fragile goods for transit. The capacity of cockpit/cabin structure to serve as a protective container for the occupants depends to a large extent on its basic strength, the energy-absorbing characteristics of the structures between the probable points of impact and the occupiable area, and mass distribution. The validity of this concept has been proven for many years in the remarkably low fatality rate in serious accidents involving agricultural airplanes (cropdusters). Some of the design factors which contribute to the crashworthiness of this type aircraft:

a. Long nose section. More structure between occupant and probable point of impact (nose) means more energy absorbing structure ahead of the cockpit. Also, aft displacement of the engine will not immediately affect the cockpit.

b. Maximum payload weight below and forward of the cockpit; this reduces the chance of crushing inertia loads on the cockpit.

c. A sturdy, smooth keel that prevents abrupt deceleration as a result of the "plowing" effect in low angle or "mushing" type impacts on soft terrain ("Hit and Stick" impacts).

d. Strong roll-over structure to prevent crushing of upper cockpit structure. (Tubular steel rollbar cage.)

e. A 5-point seat/restraint system with a design strength that fully utilizes the structural protection offered by the cockpit. (Note: The crotch-strap of a 5-point restraint system counteracts the pull of the shoulder harness straps and keeps the lap belt in place. Without the fifth strap, the center-attached dual shoulder harnesses would pull up on the buckle and pull the lap belt off the pelvis bone and up into the soft abdominal tissue.)

Historically, the agricultural aircraft was an ideal candidate for the application of these design concepts. It is not only involved in one of the most hazardous forms of flying, but its operational performance is not materially affected by rigid adherence to the principles of crashworthy design. In most other forms of flying, the configuration of the aircraft is dictated by performance requirements, particularly speed and passenger-carrying capability. This means that even the most safety-conscious designer is limited in his options. Nevertheless, current technology indicates that crashworthiness features like the following can be incorporated within practical constraints of economic and operational limitations:

a. Occupant restraint systems, including shoulder harness, must be of adequate strength and comfortable to use. (Note: the front seat shoulder harness should have an inertia reel that remains locked once it has been activated by a crash pulse.)

b. Seats should be equipped with energy-absorbing features that maintain their occupant-restraint capability up to the point of collapse of the basic structure to which they are attached.

c. The most crashworthy passenger seats are aft-facing seats with high backrests (not merely forward facing seats turned around and mounted facing aft.

d. Non-injurious environment: no sharp objects or structures within striking range of the occupants and padding of the most likely head impact areas. (Delethalization.)

e. Fuel systems which are less likely to rupture and spill fuel. Breakaway, self-sealing fuel fittings should critical locations.

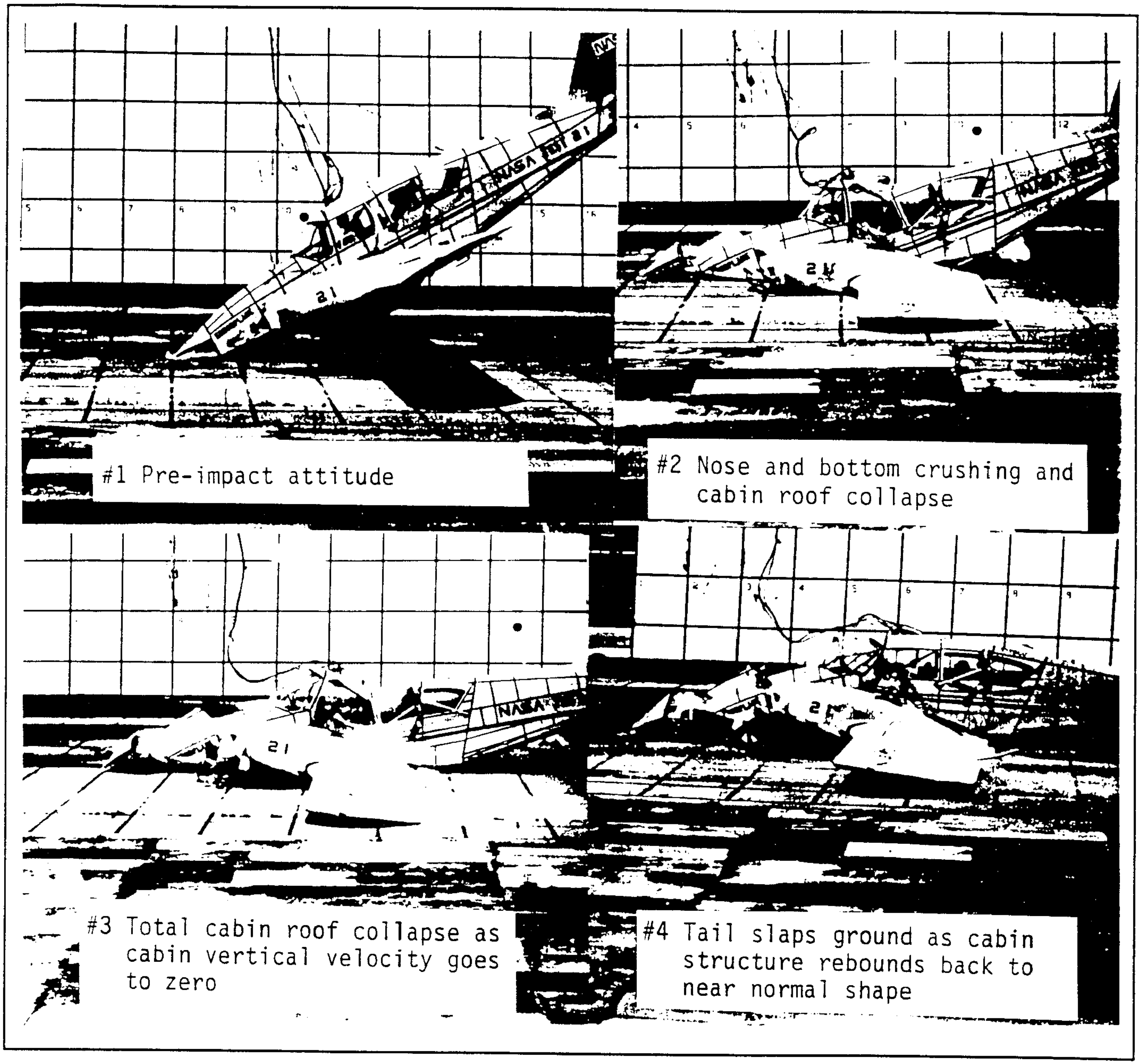


Figure 11. Piper Aztec crash test #21 at NASA's Langley Research Center, Hampton, Virginia.[14] Please note that the aircraft still has forward velocity as it "hits and skids" on this simulated runway (hard surface) after the vertical velocity goes to zero. Dummies are involved in their "second collision" with the instrument panel and the backs of the front seats. The rear dummy's head can be seen in the fourth photo rebounding (whiplash) into its head restraint.

Survivable Impact Most definitions of a survivable accident contain a provision that deals directly with the crashworthiness of cockpit/cabin structure. In the following NTSB definition, the portion dealing with structural crashworthiness is underlined:

> A survivable accident is one in which the forces transmitted to the occupant through the seat and restraint systems do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a livable volume is provided throughout the crash sequence.[10]

Actually, it would be more correct to consider this a definition of a survivable impact. As explained in the first section of this text, accident survival may involve more than just impact survival. For that reason, impact survivability and accident survivability become synonymous only when there are no post-impact complications such as fire, egress, rescue, and medical assistance problems.

Regardless of how the NTSB definition is interpreted, there is one notable exception to it. In some accidents the post-crash shape of the cockpit/cabin structure may suggest an adequate "livable volume" which, actually, did not exist during the dynamic phase of the accident. During such an impact the normal oval shape of the fuselage will be flattened (crushed) at the bottom resulting in a bowing out of the sides and a lowering of the cabin ceiling that reduces the livable space. (See Figure 11.) The roof may actually contact the tops of the seats, and then rebound by the time the wreckage comes to a stop. Timewise, the maximum downward deflection of the ceiling, or roof collapse, lags behind the peak vertical deceleration reaction. Roof collapse has an adverse impact on the proper functioning of ceiling or upper sidewall mounted or guided upper torso restraints, causing slack and allowing the occupants' head and torso to move further forward. This slack then contributes to rearward whiplash and spinal hyperextension.

The post-crash shape of the cockpit and cabin structure may be misleading as in this PA-32 Piper Saratoga flat spin accident. The bottom crushed upwards, and the nose crushed aft, pinning the pilot's feet on the rudder pedals, a situation commonly referred to as "feet entrapment." Note the crush-line (tight wrinkle) below the rudder pedals.

Next in the cabin deformation sequence, the cabin sidewalls bowed out, and the roof collapsed. A few milliseconds later, the roof rebounded, (the elastic portion of the stress-strain curve) somewhat to its post-accident condition. As the roof rebounded, the door posts and sidewalls rebounded inward, leaving some permanent deformation (plastic deformation on the stress-strain curve.

Figure 11. An example of misleading cockpit and cabin deformation in a PA-32 Piper Saratoga.

The moral: what you see as the investigator is less deformation that what the crew and passengers experienced!

Summary

To summarize, the investigator should always be aware that wreckage, as static evidence of a dynamic occurrence, can be misleading. During the principal impact, an aircraft compresses to reach its smallest dimensions. Subsequently, the structure rebounds and the spatial relationship between aircraft components and contents changes. When this phenomenon is not taken into account, it is often impossible to visualize or explain how certain components struck each other and to correlate contact injuries with the structure involved. (See case history in Appendix C.)

In high-wing aircraft, a considerable portion of the aircraft's weight is located above the cockpit/cabin. During a severe vertical deceleration, the crushing of the cockpit/cabin structure will be more extensive and there will be less rebound of this structure. (See Figure 12.)

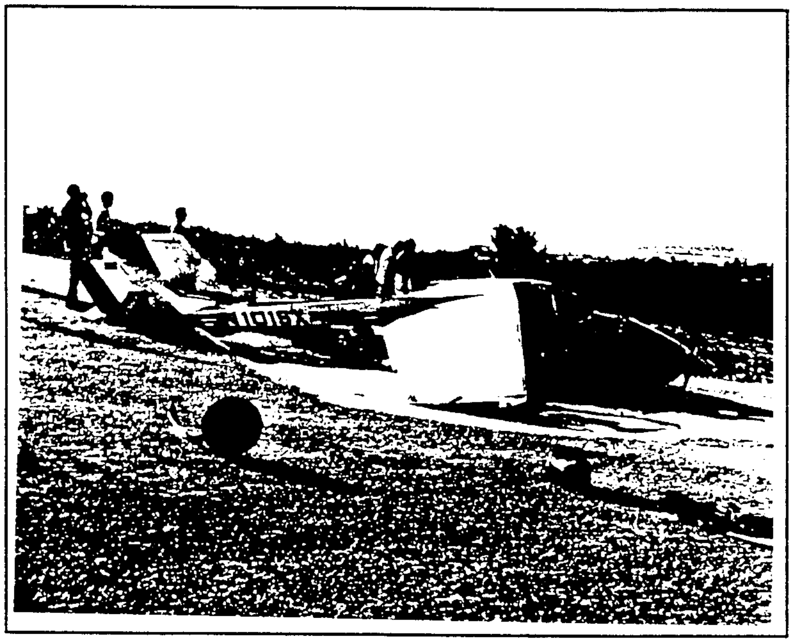


Figure 12. Crushing of the cockpit/cabin structure in a Cessna 337. The cabin roof of the Cessna 337 has significant permanent downward deformation or collapse illustrated in this photograph of its final resting position after initial impact overload of main landing gear strut seen in foreground.

SECTION B: TIMELY EGRESS - FIRE SURVIVABILITY

When an accident involves a post-crash fire, timely evacuation of the aircraft becomes a matter of life and death for the occupants who survived the impact. In 1980, the National Transportation Safety Board (NTSB) began to gather data for its General Aviation Crashworthiness Program. The investigative data provided the basis for a Safety Report on the survivability limits of modern general aviation airplane accidents; "General Aviation Crashworthiness Project: Phase Two - Impact Severity and Potential Injury Prevention in General Aviation Accidents," (NTSB/SR-85/01).[10]

In the less severe impacts, the fatality rates were greater when there was a fire. In the more severe impacts, the fatality rates were similar whether a fire was present or not. This suggests that, in the severe accidents, the crash force is the primary cause of death rather than the fire.

About 14 percent of the fatally injured occupants in fire accidents evaluated above could have survived had there been no fire. That translates to about a 4 percent yearly reduction in fatalities in all general aviation airplane crashes if post-crash fires were prevented in survivable crashes. Additionally, about 26 percent of the seriously injured occupants in accidents with fire could have been injured less severely had there been no fire which represents about a 6 percent yearly reduction in serious injuries.

The Safety Board believes that the predicted 4 percent reduction in fatalities by averting fires is an absolute minimum based on a conservative analysis of the accidents. The anticipated improvements through other FAA crashworthiness rule-making efforts, such as the addition of dynamically tested seat/shoulder harness systems and energy absorbing seats, may expand the survivable envelope of general aviation airplane accidents so that more occupants will survive the impact. These anticipated improvements will increase the number of crash survivors who will be exposed to post-crash fires. During the 1990s, FAA inspectors and NTSB investigators should carefully investigate general aviation accidents involving fire to determine if more individuals are surviving in the more severe (higher G) crashes only to receive fatal fire injuries.

Evacuation

The available escape time from a burning small aircraft can be extremely limited due to factors such as:

1. Proximity of fuel tanks to occupiable area
2. Limited resistance of fuselage to heat and fire
3. Ease of ignition of the fuel used and the rate of flame propagation

In determining to what extent a post-crash fire was responsible for fatalities, the investigator has to develop information in the following areas:

1. The ability of the occupants to evacuate the aircraft. (Did they survive the impact? Were they injured, incapacitated, trapped? Were their body dimensions compatible with emergency exits? Were they familiar with the location and operation of exits? What were their ages and physical condition?) Thorough post-mortem examinations are essential to differentiate between impact fatalities and fire fatalities and to determine if the real cause of the fatality was incapacitation as a result of impact injury.

2. The escape potential of the aircraft. (Consider number, size and ease of operating exits. The elapsed time, if any, between when the aircraft came to rest and when fire engulfed the fuselage.)

3. The effectiveness of post-crash fire fighting and rescue activities. (Investigate the distance from the crash site, response time, and the quality of equipment, protective clothing, and training methods.)

Crash Resistance Limits to Fuel Systems

Accident investigations have shown that fuel lines and fittings are likely to break in survivable crashes. Given that fact, fuel systems should be designed so that the locations of the breaks and separations are dictated by design in order to minimize fuel spillage. For example, if an engine is displaced during a crash, the fuel lines are likely to break regardless of the load generated in the crash. With a properly designed system, the location of the break can be controlled, such as by incorporating a self-sealing breakaway fitting as the weakest link in the line. When the self-sealing fitting breaks, both ends of the line are sealed, preventing a fuel spill.

Fuel tank design is the one area where crash severity is an important design consideration. Fuel tanks containing large masses of fuel are affected directly by the acceleration loads. To prevent spillage during a crash, fuel tanks would have to be able to withstand large acceleration loads and to resist penetration. The U.S. Army "Crash Survival Design Guide," Volume V, is the best source of information on this subject[3]. It is recognized that Volume V is primarily directed to helicopter design, but many of the concepts are applicable equally to general aviation airplanes.

Fuel Spillage

When the post-crash condition of the wreckage permits it, the investigator should determine where fuel spillage first occurred and its ignition source. This is especially significant when there are reasons to suspect that an in-flight fire preceded the ground impact sequence. **Another approach is to carefully look for fuel spillage or potential fuel spillage (broken lines or fittings) in accidents when there is little or no fire.**

In case of a controlled water landing (ditching), timely egress has an urgency similar to that in case of a post-crash fire and requires similar investigative emphasis on the capability of the occupants to exit the aircraft and the escape potential of the aircraft. Postmortems are necessary to differentiate between death due to impact and drowning. **Each exit should be carefully checked to see if crash forces have rendered them inoperable. Many exits will be bound or jammed in their door frames.**

Earlier it was stated that impact survival may not be the most critical variable in large aircraft. There have been several accidents involving jet transports in which the deceleration levels were nil or negligible but numerous passengers died as a result of smoke inhalation and fire. On 11 August 1985, a British Airtours B-737 crew rejected the take-off at Manchester, England, following an engine failure and brought the aircraft to a normal stop. The top burner can on number 1 engine came apart, penetrated the casing, and ruptured a wing fuel tank and a severe fire ensued. (See Figure 13.)

Figure 13. British Airtours B-737 after an external fire on the left side burned through the fuselage, gutted the interior, and burned out the crown (top) of the fuselage. Many passengers in the aft cabin were trapped by toxic smoke after the fire melted the left side cabin windows, which allowed the aft cabin to quickly become nonsurvivable.

SECTION C: POST ACCIDENT SURVIVAL

Many general aviation accidents occur in remote areas and without the benefit of a flight plan or communication with ATC. Therefore, occupants who passed the first two hurdles of accident survival (impact survival and timely egress) may still be facing a third one: post-accident survival until help arrives or until they can find help. It is not necessarily a "crash" that may threaten survival. Depending on the nature of the terrain, the climate, and the occupants' preparedness, even a forced landing without aircraft damage could result in deaths due to exposure, starvation, wandering away from the crash site, encounters with bears or snakes, etc.

Post-accident survival problems are most likely to occur when an aircraft goes down without eye witnesses, radio messages, or radar traces. In such a case, the emergency locator transmitter (ELT) becomes a crucial element in pinpointing the accident location and in starting the rescue efforts. The manner in which the ELT served - or failed to serve - its intended purpose should be fully explored and documented.[15]

By determining to what extent and for which reasons survivors died during the post-accident phase, the inspector gains insight in some of the basic shortcomings in pre-flight preparations. The inspector's findings will be used effectively to better educate and regulate the public about post-crash environmental hazards. Special attention should be paid to:

1. Protective clothing, appropriate for climate and terrain
2. Survival gear, including food, liquids, knife and matches
3. Signalling devices and methods used
4. Emergency medical supplies and first aid training
5. Caliber of leadership before rescue was effected
6. Presence of wild animals that may have eaten human remains

In ditchings, the following factors should be considered:

1. Water temperature and wind conditions
2. Proximity to land and water depth
3. Physical condition and age of occupants and their ability to swim
4. Availability of life vests and other water survival equipment
5. Whether the ditching was made into the swells, with the swells, or on a diagonal to the swells
6. Whether an S.O.S. was broadcast on 121.5 or 245 frequency
7. Whether the ditching was made with or without flaps
8. Who opened the doors/hatches and who exited first and last

9. An approximate time when crew and passengers donned life jackets and/or deployed life rafts

10. An approximate time the aircraft remained afloat

The Role of Pilot Technique

The FAA inspector who becomes involved in accident investigation is in an ideal position to judge the adequacy of current emergency training practices and standards. Insight in the manner in which non-essential (=non-occupiable) parts of the aircraft can be sacrificed to protect the occupants during an emergency landing under unfavorable conditions will assist him in improving the caliber of emergency training in his district. Further guidance on this subject can be found in a 1972 NTSB special study[9] which deals with emergency landing techniques in light aircraft. The emphasis on the role of pilot technique is apparent in that study's table of contents.

SECTION D : PRACTICAL APPLICATIONS

FAA Order 8020.11A, Sections _____ and _____ and NTSB Form 6120.4, Supplements I through N explain when a crash injury investigation is to be conducted and provide a format for the collection of data. Since the majority of general aviation accidents is subject to a small-scale investigation, this means that the investigator in charge often has a dual task: collecting pertinent evidence for accident-cause determination, as well as crash injury correlation. In such cases, both investigations should be conducted concurrently during the on-scene phase. Considerable time can be saved, for example, by using the examination of the cockpit to combine the documentation of the operational evidence (instrument readings, trim settings, etc.) with the documentation of the crashworthiness aspects (condition of seats, restraint systems, injury producing objects, etc.).

The NTSB forms dealing with the collection of crash data (Supplements I through N) are largely self-explanatory. Nevertheless, it may be helpful to review some of the critical entries on Supplement I: Crash Kinematics. (Definitions of most of the terms used in that Supplement are listed in Appendix A. Appendix B presents conversion factors and useful formulas. Appendix C contains the index of terms. Appendix D contains an interesting case history.)

Aircraft Attitude

The airplane's attitude at principal impact, in conjunction with flight path angle and terrain angle gives the investigator the impact angle. The impact angle (refer back to Figure 1) has a significant effect on impact survivability since it determines the direction of load application on the occupants. A useful measurement in that regard is the so-called crush line.

According to the NTSB[1], a crush line is formed as a result of the airframe being crushed against a surface and leaving a distinctive flattened area on the airframe. The crush line can be identified by small, tight wrinkles in the skin, or by deformation of the airframe surfaces around spars, longerons, or stringers. Points representing the edges of the damaged areas are plotted on airplane drawings or photographs and straight lines are drawn between these points. The impact attitude can be visualized by relating the crush line to the impact surface. (See Figures 14 and 15). The rotation required to fit the crush line on the impacted surface determines the aircraft's pitch, roll and yaw at impact relative to that surface. Correcting for surface slope will relate these attitudes to the horizontal.

Speed at Impact

The violence of the stopping process during a crash is governed by impact velocity and stopping distance (structural crushing plus ground scars). The most critical of these is a reliable estimate of impact velocity since velocity is a squared factor in the G-formula. Even small errors have a large effect on the results of the calculations.

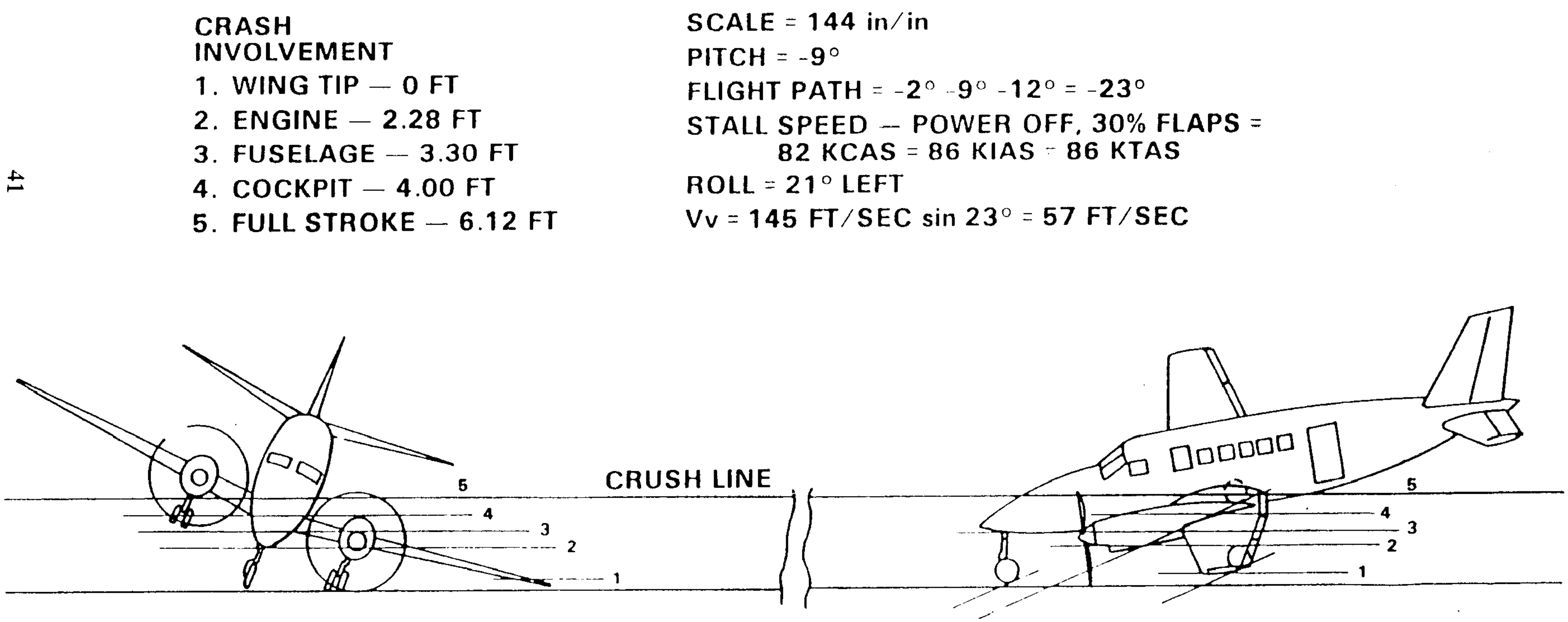
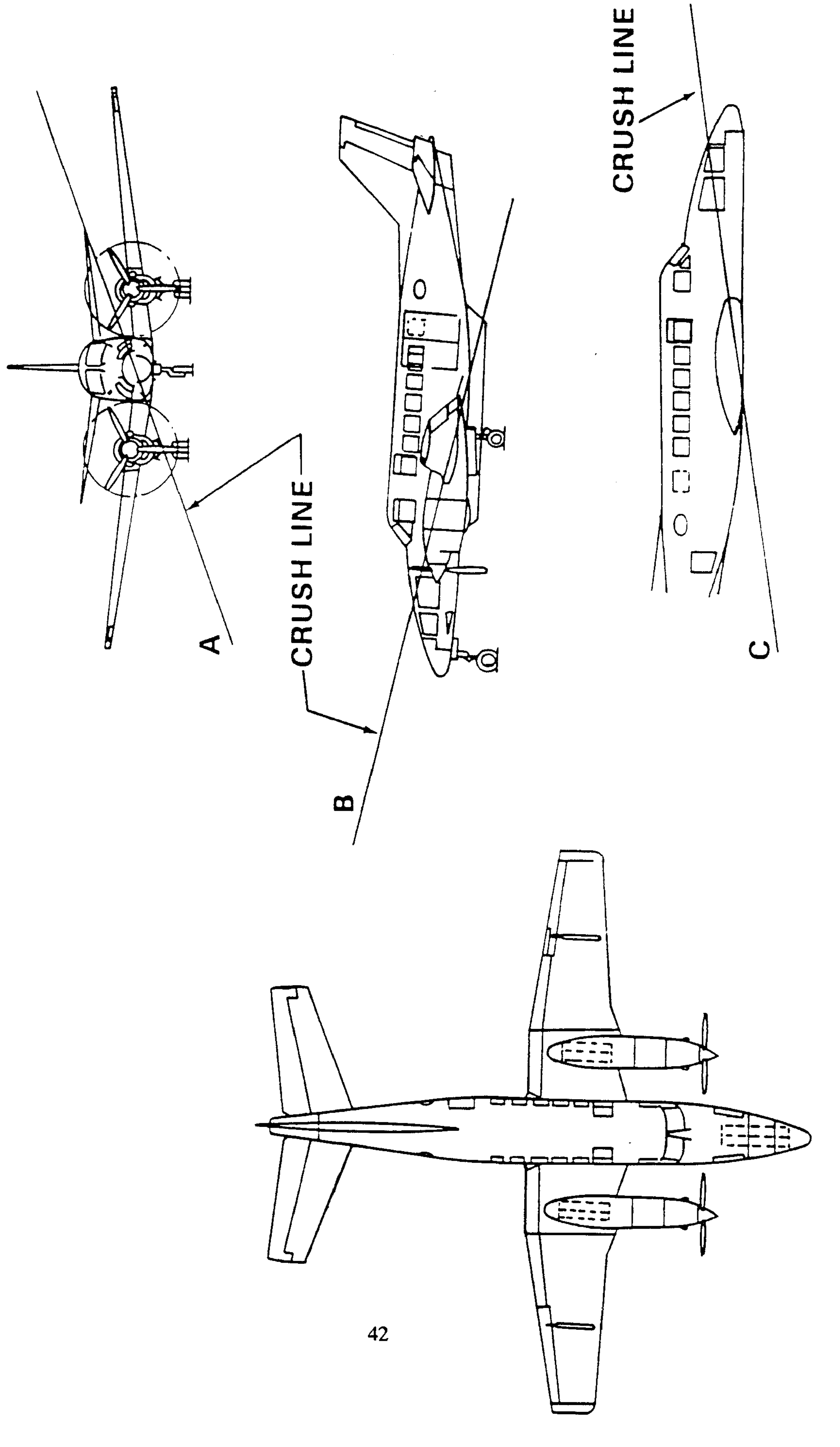


Figure 14. Beechcraft B 99 visualization (from NTSB/SR-83-01)[1]



(From NTSB/SR-83/01)

Figure 15. Three-view drawing showing crush line (from NTSB/SR-83-01)[1]

Item #5 in NTSB Form 6120.4, Supplement I (Crash Kinematics) asks for the investigator's estimate of "Airspeed at Impact." Actually, the aircraft's kinetic energy depends on groundspeed. This means that the surface wind at the impact site should be taken into account by the investigator. Since the wind information is not entered in this Supplement, but in the basic Form 6120.4 (Items 192 and 193), the investigator should not make allowance for the wind in his estimate of "Airspeed at Impact." If you wish to make some G calculations of your own, you should work with your best estimate of groundspeed.

If an aircraft does not lose all forward velocity during the principal impact, it may bounce or slide to a stop "Hit and Bounce" or "Hit and Skid." If the terrain is relatively firm and the damaged aircraft has no surfaces that cause "plowing," that portion of the deceleration process is negligible from the impact survival viewpoint. In that case, the G-formula ($G = .034 \frac{mph^2}{S}$) cannot be applied because the aircraft's velocity was not reduced to zero at principal impact. Although NTSB Supplement I does not address that situation, it is of interest to the investigator to know how the crash injury analyst treats it. The latter estimates the aircraft's remaining speed (exit velocity) as it bounces/emerges from the principal impact area and uses a modified G-formula:

$$G = \frac{V^2 - Vo^2}{64\ S} \quad (Using\ ft/\text{sec})$$

$$G = 0.034\ \frac{V^2 - Vo^2}{S} \quad (Using\ mph)$$

$$G = 0.045\ \frac{V^2 - Vo^2}{S} \quad (Using\ knots)$$

V = *Initial velocity (ft/sec, mph,or knots)*

V_o = *Exit velocity on the bounce (ft/sec, mph, or knots)*

S = *Deceleration distance during principal impact. (Always in feet.)*

Stopping Distance

The stopping distance in a crash always refers to the distance over which the cockpit/cabin (occupiable area) decelerated during the principal impact phase. The pertinent data blocks on NTSB Form 6120.4, Supplement I require three measurements:

Block #11. Principal Impact Ground Scar Length

Block #12. Principal Impact Ground Scar Depth

Block #20. Fuselage crush

Fuselage crush refers to the "foreshortening" or compressive buckling of the structure as a result of impact. The decrease in the aircraft's structural dimensions (deformation) should be measured horizontally and vertically, relative to the aircraft's longitudinal axis. Adding the horizontal fuselage crush to the length of the ground scar yields the horizontal stopping distance (S_h). The vertical stopping distance (S_v) is obtained by adding the depth of the ground scar to the vertical crushing distance of the belly of the fuselage.

A comprehensive sketch of the crash site (plan view and elevation view) is essential in any accident report. It provides the investigator the opportunity to show details of the crash kinematics the analyst needs for a valid crash injury correlation such as: obstacles struck, measurements of sliding and skipping distances, location and dimension of ground scars, etc. Photographs from the cardinal directions of the nose/cockpit/cabin wreckage add immeasurably to the value of the reported data.

The Final Analysis

Figure 16 shows schematically how the crash injury analyst uses the data obtained in the field to calculate the crash forces. He first resolves the aircraft's flight path velocity into its horizontal and vertical components. Knowing the stopping distances and impact velocities, he now uses the G-formula to calculate the horizontal and vertical crash pulses separately (G_h *and* G_v). If G_h *and* G_v occur during the same time, the crash pulses can then be combined to form the resultant crash pulse (G_r). In combination with the aircraft's attitude at principal impact, the resultant G (G_r) determines the magnitude and the direction of the total crash pulse that affected the occupiable area. This has a direct bearing on impact survivability.

Two considerations have to be used in the evaluation of crash loads:

1. The G-formula produces an average G-level. NASA crash tests, investigations, theories tested with math modeling and experience have shown that the peak G-load may be more than twice as high as the average G-level.

2. The vertical component of impact velocity usually becomes zero during principal impact. (No exit velocity.) The generally easy to measure vertical crush and ground scar depth, plus the known reduction of vertical velocity to zero, tend to give reliable indications of the vertical crash pulse. (G_v.)

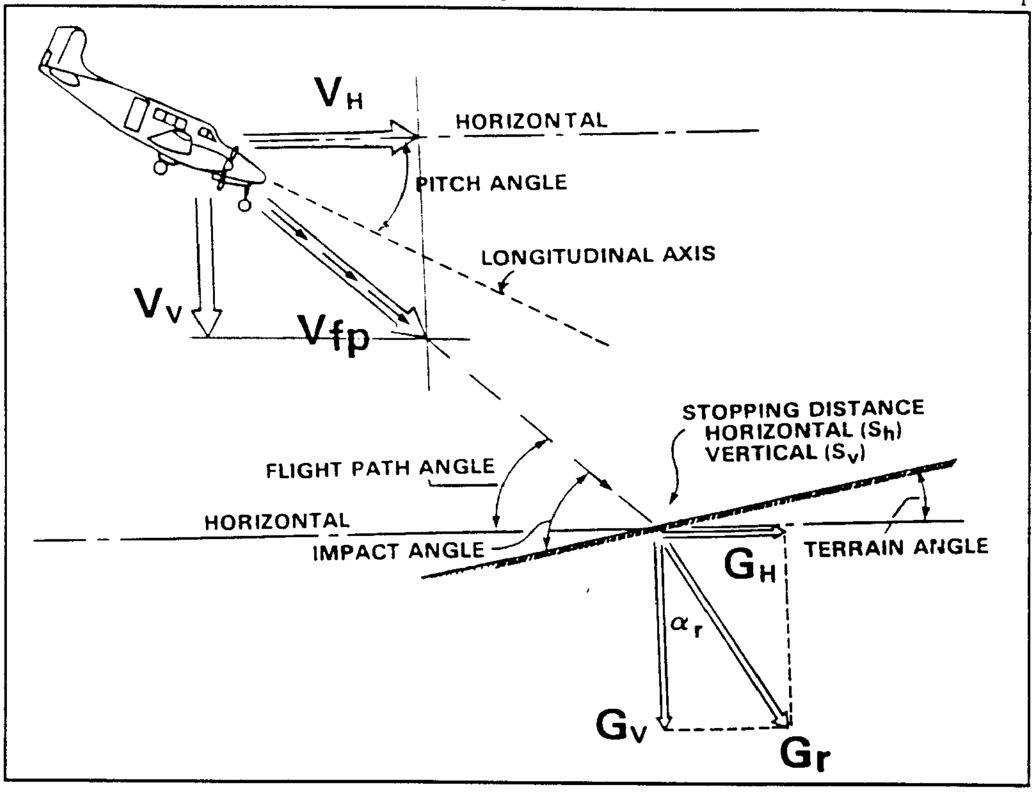


Figure 16. Vector Components at Crash Impact (from NTSB/SR-83-01)[1] include:

V_h = Horizontal Velocity	G_h = Horizontal G-forces
V_v = Vertical Velocity	G_v = Vertical G-forces
V_{fp} = Velocity along flight path	G_r = Resultant G-forces

Please note that Figures 1 and 16 are identical and should bring you back full circle to our stated purpose in the introduction. Crashworthiness investigations are conducted to determine to what extent persons were unnecessarily injured or killed in potentially survivable crashes so that lessons can be learned to enhance occupant protection can be enhanced through lessons learned during investigations.

Recommended Reading

Those who wish to develop a deeper understanding of crash safety in general aviation, including its evolution and current status, will find thorough documentation of that subject in the NTSB's three-part study: General Aviation Crashworthiness Project.[1,10,11]

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Appendix A

GLOSSARY OF TERMS[1]
(See Figures 1, 16 & 17)

Flight path — The path the aircraft follows in the air, regardless of aircraft attitude.

Flight path angle — The angle between the aircraft's flight path and the horizontal.

Terrain angle — The angle between the slope of the terrain and the horizontal.

Impact angle — The angle between flight path and terrain. (Algebraic sum of terrain angle and flight path angle.) When the aircraft strikes natural or man-made obstructions, the slope of the obstructing surface must be added to the flight path angle to arrive at the impact. angle.

Pitch angle — The angle, as seen from the side, between the longitudinal body axis of the aircraft and the horizontal.

Angle of attack — The difference between pitch angle and flight path angle.

Principal impact — The point in the crash sequence where the decelerative forces had their maximum effect on the cockpit/cabin enclosure and its occupants.

> Note: The principal impact is not necessarily the initial impact or the final impact. For example: an aircraft strikes a high tension line with its landing gear (initial impact); subsequently, it strikes the ground in uncontrolled flight (principal impact); it then slides to a stop against a tree (final impact).

Impact Speed: — Velocity of the aircraft at principal impact. Since kinetic energy depends on ground speed, the estimated airspeed should be corrected for the wind, if known. An aircraft in a flat spin has little or no forward airspeed,except wind drift (downwind). However, it does have a significant velocity downward due to the pull of gravity. Of course, the Air Speed Indicator would read zero, since there is no forward speed.

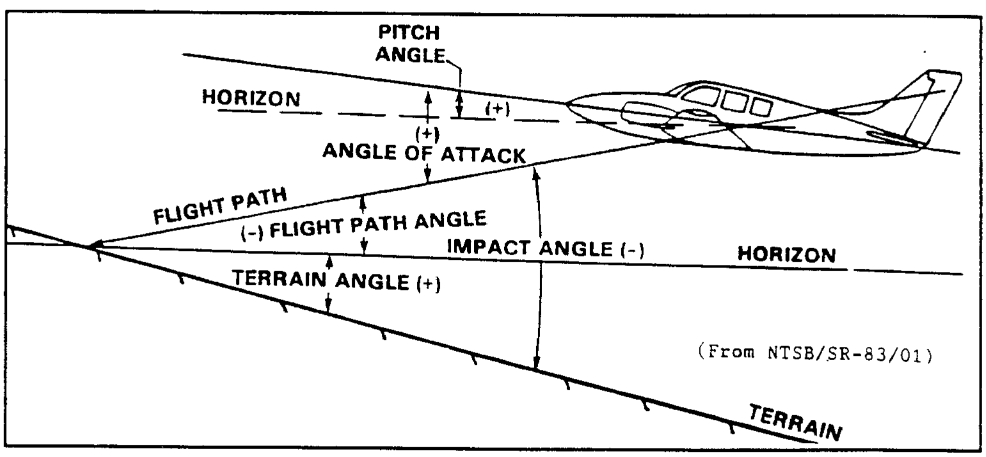

Figure 17. Relationship of definitions (from NTSB/SR-83-01).[1]

Appendix B

SPEED CONVERSION FACTORS

Feet per second *x* .592 = *Knots*
x .682 = *Miles per hour*
x 1.097 = *Kilometers per hour*

Knots *x* 1.689 = *Ft*/sec
x 1.152 = *Mph*
x 1.852 = *Kph*

Miles per hour *x* .869 = *Kts*
x 1.457 = *Ft*/sec
x 1.609 = *Kph*

Kilometers per hour *x* .911 = *Ft*/sec
x .621 = *Mph*
x .540 = *Kts*

Rule of thumb: 1000 *Ft/minute* =16.66 *Ft*/sec = 10 *Kts*

For example 1000 *Ft*/min = 16.66 *Ft*/sec = 10*K*

Time: 1 *second* = 1000 *milliseconds*

Appendix C

A CASE HISTORY

The Accident

On August 30, 1978, a Piper PA-31-350 (Navajo Chieftain) crashed in VFR conditions shortly after takeoff from the North Las Vegas Airport. Eyewitnesses observed a pitch attitude of 50° to 75° after liftoff followed by a "wingover" from about 400 feet above the ground and a steep nosedown descent. At impact the aircraft was in an almost level attitude. All 10 occupants of the charter flight were killed at impact. There was no fire.

The accident was attributed to a backed-out elevator down-stop bolt that limited down elevator travel to only 1-1/2° of a normal 20° range. As a result, the pilot could not control the noseup pitching tendency after liftoff. (The aircraft was about 236 pounds over the maximum allowable weight limit and the C.G. was about 0.9 in. inside the aft limit.)

Survival Aspects

The aircraft crashed on nearly level desert terrain with loose sandy soil to depth about 6 inches. During the principal impact, the aircraft's attitude was slightly pitched up, slightly rolled to the right, and slightly yawed to the left. Following the main impact, the aircraft bounced about 80 feet and came to rest about 90 feet from the initial impact point.

Based on the post-crash shape of the cockpit/cabin structure, the commonly used definition of a survivable accident would suggest that the presence of a "livable volume" implies survivable conditions. (See Figure 18.) Although relatively intact, cockpit/cabin structure in non-pressurized general aviation aircraft tends to indicate survivable impact conditions, severe impacts cause deviations from this rule as explained in Section A, Subsection 6, Airframe Crashworthiness.

In this accident, the post-crash measurements of the interior cabin at the main spar showed a 7 inch reduction in ceiling height and a 5 inch lateral expansion. According to the accident report, full-scale NASA tests with similar aircraft "showed that the actual change of ceiling height at impact was probably much greater than 7 inches, but the flexibility of the structure was such that little permanent compression remained."[(16)]

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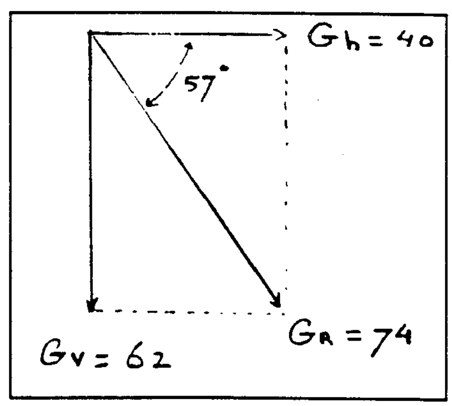
[16]National Aeronautics and Space Administration, Comparative Analysis of PA-31-350 Chieftan (N-44LV) Accident and NASA Crash Test Data (NASA Technical Memorandum 80102), October 1979.

Figure 18. First appearance of post-crash structures may be deceiving. In this accident, the Piper Navajo Chieftain struck the ground in a flat attitude at a high sinkrate at or below stall speed. All ten occupants received multiple fatal injuries; yet the cockpit/cabin structure appears relatively undamaged.

Figure 19. The magnitude of peak deceleration in the Piper Navajo Chieftain accident. When the vertical and longitudinal G vectors are combined, the resultant peak deceleration was 74 G applied at an angle of 57°. This is well outside the survivable limits of human G-tolerance.



Injury Patterns

What made the principal impact non-survivable was the magnitude of the peak deceleration. NASA crash tests, using similar impact parameters, showed that instrumented dummies in the third row of seats experienced the following G-loads with a pulse duration of about .06 seconds:

Vertical :	62 G's*	(See note below.)
Longitudinal :	40	
Lateral	15	

Note: These data measurements were dummy response values and were at least twice as much as the input G values. Dummy G's in response to the forces represent the Dynamic Overshoot of the body. (See text discussion in Section A, Subsections 4 and 5 and Figure 10.)

The next table shows the number of occupants who sustained the specified major injuries:

Major Injuries	Number of Occupants
Crushed Chest	10
Lower extremities fractures	10
Upper extremities fractures	9
Deep forehead lacerations	6
Abdominal organ damage	6
Fractured skull	5
Broken neck	4
Broken back	4
Fractured pelvis	2

The NTSB accident report and the Human Factors Group Chairman's Factual Report do not elaborate on the principal injury mechanism, except for the statement: "All occupants receiving crushing injuries to the chest, resulting in severe trauma to the heart.... Each occupant also received other potentially fatal injuries."[17] Considering the magnitude (74G) and direction of the crash force resultant, the extreme violence of the downward flailing of the upper torso would produce fatal decelerative injuries even without the interference of (folding) seat backs.

Appendix D

INDEX OF TERMS

TERM PAGE REFERENCE

FIELD INVESTIGATORS' GUIDE - CRASHWORTHINESS CHECKLIST

General

Determine early in the investigation if an FAA crashworthiness investigation is needed in accordance with IAW Order 8020.11A paragraph 206. Consider the following conditions in making this determination:

1. The pilot compartment or cabin or some occupiable portion remains relatively intact and the occupants were injured seriously by the surrounding structure or the failing of seats, occupant restraints, or cargo-restraint systems.

2. The aircraft structure was destroyed by impact and/or fire and any one occupant survived or should have survived.

3. Were the post-crash conditions tolerable (survivable)?

4. The hospital staff, Aviation Medical Examiner (AME), or coroner should determine to what extent aircraft occupants were injured (injury correlation).

Aircraft

When a crashworthiness investigation is undertaken, the following items, when pertinent, shall be investigated for inclusion in a crashworthiness paragraph of your report and documented with photographs and sketches if possible:

1. The approximate magnitude and direction of major impact forces.

2. The final ground trajectory of the aircraft.

3. The condition of the entire aircraft, including the interior and evidence of injuries to occupants as a result of failed components or detached objects. Include the progression of structural failure of the passenger compartment.

4. Any floor deformation and its relevance to any seat failures.

5. The number. location, type and condition of seats and restraint systems. Indicate the direction in which the seats were facing before and after impact.

6. The condition of cargo and other items of large mass. List all items that separated form the structure which may have injured passengers or crew. Relate failures to structural design.

7. Any design features, such as apparent inadequately padded seat backs, bulkhead reinforcing members, lower seat structure, etc. that may have contributed to injuries.

8. The evacuation procedures. Identify the exits used and the number of persons who used each exit.

9. If all exits were operable and usable from inside and outside.

10. If entry was made though any exit from outside by crash fire rescue or other rescuers.

FIELD INVESTIGATORS' GUIDE - CRASHWORTHINESS CHECKLIST

11. The performance of the emergency equipment, such as the emergency interior lighting systems, life rafts, life vests, etc.

12. If the emergency exit markings, both inside and outside, were adequate.

13. If any obstructions could or did restrict the use of any door or emergency exits.

14. The method used for directing the aircraft evacuation. Comment on the system's adequacy.

15. If evacuation from the inside or assistance from the outside was hampered by smoke, fire, etc.

16. If findings in the aircraft correlate with victim's injury patterns. (Consult the Aviation Medical Examiner (AME), medical examiner, or pathologist.)

Seats and Restraints

A seat-restraint system should be investigated based on the details of design and how it is worn. Crew and passengers' interviews should also be used to help determine how the restraints were being used.

1. Shoulder harness(es) should not pull the lap belt up the pelvis

2. Single diagonal shoulder belts should connect at the side of the occupant

3. Lap belts should pull down and back from the pelvic bone

4. Long restraint straps stretch more than short straps, allowing the occupant to experience second impact with the aircraft interior

5. Inertia reels may add slack to restraints (Slack increases injuries)

6. Inertia reels may not lock or may unlock prior to second impact

7. Seats should take moderate floor deformation without becoming detached

8. Seats should gradually deform under increasing loads to absorb energy

9. Forward facing seats should have headrests (head restraints) to reduce whiplash

10. Lap belts should have been worn tight

11. Upper torso belts should have been snug

12. Did the passengers assume a brace position?

13. Infants and small children should have been using special infant and child restraint seats.