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AIRCRAFT CRASH SURVIVAL DESIGN GUIDE
VOLUME IV – AIRCRAFT SEATS, RESTRAINTS, LITTERS, AND PADDING
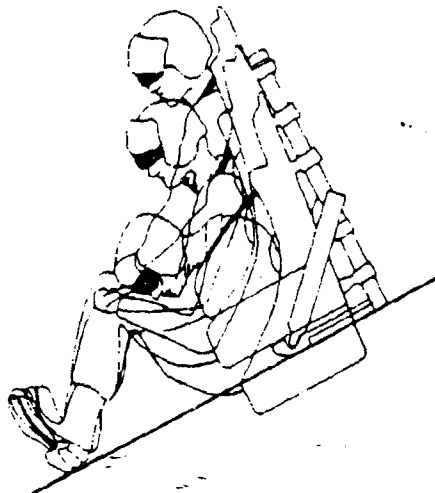
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FINAL REPORT

PREPARED FOR
APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
FORT EUSTIS, VIRGINIA 23604

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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This revised edition of the Crash Survival Design Guide was
prepared for the Applied Technology Laboratory by Simula, Inc.,
under the terms of Contract DAAJ02-77-C-0021. The original
Crash Survival Design Guide was published in 1967 as USAAVLABS
Technical Report 67-22 and subsequent revisions were published
as USAAVLABS Technical Report 70-22 and USAAMRDL Technical Re-
port 71-22. This current edition consists of a consolidation
of design criteria, concepts, and analytical techniques devel-
oped through research programs sponsored by this Laboratory
over the past 20 years into one report suitable for use as a
designer's guide by aircraft design engineers and other inter-
ested personnel.

This document has been coordinated with USAAVRADCOM, the U. S.
Army Safety Center, the U. S. Army Aeromedical Research Labor-
atory, and several other Government agencies active in aircraft
crashworthiness research and development.

The technical monitors for this program were Messrs. G. T.
Singley III, R. F. Bywaters, W. J. Nolan, and H. W. Holland of
the Safety and Survivability Technical Area, Aeronautical Sys-
tems Division, Applied Technology Laboratory.

Comments or suggestions pertaining to this Design Guide will
be welcomed by this Laboratory.

NOTE: This is a revised edition of the Crash Survival Desi
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         previous editions are obsolete and should be destroyed

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This five-volume document has been assembled to assist design engineers in understanding the problems associated with the development of crashworthy U. S. Army aircraft. Contained herein are not only a collection of available information and data pertinent to aircraft crashworthiness but suggested design conditions and criteria as well. The five volumes of the Aircraft Crash Survival Design Guide cover the following topics:

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20. (Continued)

Volume I - Design Criteria and Checklists;
Volume II - Aircraft Crash Environment and Human Tolerance;
Volume III - Aircraft Structural Crashworthiness;
Volume IV - Aircraft Seats, Restraints, Litters, and Padding;
Volume V - Aircraft Postcrash Survival.

This volume (Volume IV) contains information on aircraft seats, litters, personnel restraint systems, and hazards in the occupant's immediate environment. Requirements for design of seats, litters, and restraint systems are discussed, as well as design principles for meeting these requirements and testing for verification that the systems perform as desired. Energy-absorbing devices for use in seats are described, as are various types of cushions. Delethalization of cockpit and cabin interiors is discussed, including the use of protective padding and the design of controls for prevention of injury. Finally, computerized methods of analysis for evaluation of seats, restraints, and the occupant's immediate environment are presented.

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PREFACE

This report was prepared for the Safety and Survivability Technical Area of the Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, by Simula Inc. under Contract DAAJ02-77-C-0021, initiated in September 1977. The Department of the Army Project Number is 1L162209AH76. This guide is a revision of USAAMRDL Technical Report 71-22, Crash Survival Design Guide, published October 1971.

A major portion of the data contained herein was taken from U. S. Army-sponsored research in aircraft crashworthiness conducted from 1960 to 1979. Acknowledgment is extended to the U. S. Air Force, the Federal Aviation Administration, NASA, and the U. S. Navy for their research in crash survival. Appreciation is extended to the following organizations for providing accident case histories leading to the establishment of the impact conditions in aircraft accidents:

- U. S. Army Safety Center (USASC), Fort Rucker, Alabama.

- Civil Aeronautics Board, Washington, D. C.

- U. S. Naval Safety Center, Norfolk, Virginia.

- U. S. Air Force Inspection and Safety Center, Norton Air Force Base, California.

Additional credit is due the many authors, individual companies, and organizations listed in the bibliographies for their contributions to the field. The contributions of the following authors to previous editions of the Crash Survival Design Guide are most noteworthy:

D. F. Carroll, R. L. Cook, S. P. Desjardins, J. K. Drummond, J. L. Haley, Jr., A. D. Harper, H. G. C. Henneberger, N. B. Johnson, G. Kourouklis, W. H. Reed, S. H. Robertson, L. M. Shaw, Dr. J. W. Turnbow, and L. W. T. Weinberg.

This volume has been prepared by S. P. Desjardins and Dr. D. H. Laananen of Simula Inc. M. J. Reilly of the Boeing Vertol Company provided recommendations for sections dealing with troop and gunner seats, and P. A. Rakszawski contributed to the chapter on protective padding.

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INTRODUCTION

For many years, emphasis in aircraft accident investigation was placed on determining the cause of the accident. Very little effort was expended on the crash survival aspects of aviation safety. However, it became apparent through detailed studies of accident investigation reports that significant improvements in crash survival could be made if consideration were given in the initial aircraft design to the following factors that influence survivability:

1. Crashworthiness of Aircraft Structure - The ability of the aircraft structure to maintain living space for occupants throughout a crash.

2. Tiedown Chain Strength - The strength of the linkage preventing occupant, cargo, or equipment from breaking free and becoming missiles during a crash sequence.

3. Occupant Acceleration Environment - The intensity and duration of accelerations experienced by occupants (with tiedown assumed intact) during a crash.

4. Occupant Environment Hazards - Barriers, projections, and loose equipment in the immediate vicinity of the occupant that may cause contact injuries.

5. Postcrash Hazards - The threat to occupant survival posed by fire, drowning, exposure, etc., following the impact sequence.

Early in 1960, the U. S. Army Transportation Research Command* initiated a long-range program to study all aspects of aircraft safety and survivability. Through a series of contracts with the Aviation Safety Engineering and Research Division (AvSER) of the Flight Safety Foundation, the problems associated with occupant survival in aircraft crashes were studied to determine specific relationships among crash forces, structural failures, crash fires, and injuries. A series of reports covering this effort was prepared and distributed by the U. S. Army, beginning in 1960. In October 1965, a special project initiated by the U. S. Army consolidated the design criteria presented in these reports into one technical document suitable for use as a designer's guide by aircraft design engineers

*Now the Applied Technology Laboratory, Research and Technology Laboratories of the U. S. Army Aviation Research and Development Command (AVRADCOM).

and other interested personnel. The document was to be a summary of the current state of the art in crash survival design, using not only data generated under Army contracts, but also information collected from other agencies and organizations. The Crash Survival Design Guide, first published in 1967, realized this goal.

Since its initial publication, the Design Guide has been revised several times to incorporate the results of continuing research in crashworthiness technology. The last revision, published in 1971, was the basis for the criteria contained in the Army's military standard dealing with aircraft crashworthiness, MIL-STD-1290(AV), "Light Fixed- and Rotary-Wing Aircraft Crashworthiness" (Reference 1). This current revision, the fourth, contains the most comprehensive treatment of all aspects of aircraft crash survival now documented. It can be used as a general text to establish a basic understanding of the crash environment and the techniques that can be employed to improve chances for survival. It also contains design criteria and checklists on many aspects of crash survival and thus can be used as a source of design requirements.

The current edition of the Crash Survival Design Guide is published in five volumes. Volume titles and general subjects included in each volume are as follows:

Volume I - Design Criteria and Checklists

    Pertinent criteria extracted from Volumes II through V, presented in the same order in which they appear in those volumes.

Volume II - Aircraft Crash Environment and Human Tolerance

    Crash environment, human tolerance to impact, military anthropometric data, occupant environment, test dummies.

Volume III - Aircraft Structural Crashworthiness

    Crash load estimation, structural response, fuselage and landing gear requirements, rotor requirements, ancillary equipment, cargo restraints, structural modeling.

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1. Military Standard, MIL-STD-1290(AV), LIGHT FIXED- AND ROTARY-WING AIRCRAFT CRASHWORTHINESS, Department of Defense, Washington, D. C., 25 January 1974.

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Volume IV - <u>Aircraft Seats, Restraints, Litters, and Padding</u>

> Operational and crash environment, energy absorption, seat design, litter requirements, restraint system design, occupant/restraint system/seat modeling, delethalization of cockpit and cabin interiors.

Volume V - <u>Aircraft Postcrash Survival</u>

> Postcrash fire, ditching, emergency escape, crash locator beacons, retrieval of accident information.

This volume (Volume IV) contains information on aircraft seats, litters, personnel restraint systems, and hazards in the occupant's immediate environment. Following a general discussion of aircraft crashworthiness in Chapter 1, a number of terms commonly used in discussing the crash environment, seats, and occupant protection are defined in Chapter 2. Chapter 3 presents design considerations for aircraft seats, and Chapter 4, principles for crashworthy seat design. Energy absorption is discussed in Chapter 5. Principles for cushion and restraint system design are presented in Chapters 6 and 7, and strength and deformation requirements for seats and litters are stated in Chapters 8 and 9, respectively. Cockpit delethalization, including protective padding, is discussed in Chapter 10.

1. BACKGROUND DISCUSSION

The overall objective of designing for crashworthiness is to eliminate unnecessary injuries and fatalities in relatively mild impacts. A crashworthy aircraft also reduces aircraft crash impact damage. By minimizing personnel and material losses due to crash impact, crashworthiness conserves resources, is a positive morale factor, and improves the combat effectiveness of the fleet. Results from analyses and research during the past several years have shown that the relatively small cost in dollars and weight of including crashworthy features is a wise investment (References 2 through 13). Consequently, new generation aircraft are being procured to stringent, yet practical requirements for crashworthiness.

To provide as much occupant protection as possible, a systems approach to crashworthiness must be followed. Every available subsystem must be considered in order to maximize the protection afforded to vehicle occupants. When an aircraft impacts

2. ENGINEERING ANALYSIS OF CRASH INJURY IN ARMY OH-58 AIRCRAFT, USASC Technical Report, U. S. Army Safety Center, Fort Rucker, Alabama, to be published.

3. ENGINEERING ANALYSIS OF CRASH INJURY IN ARMY CH-47 AIRCRAFT, USAAAVS Technical Report 78-4, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama, June 1978.

4. ENGINEERING ANALYSIS OF CRASH INJURY IN ARMY AH-1 AIRCRAFT, USAAAVS Technical Report 78-3, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama, March 1978.

5. Carnell, B. L., CRASHWORTHINESS DESIGN FEATURES FOR ADVANCED UTILITY HELICOPTERS, in Aircraft Crashworthiness, K. Saczalski, et al., eds., University Press of Virginia, Charlottesville, Virginia, 1975, pp. 51-64.

6. Bainbridge, M. E., Reilly, M. J., and Gonsalves, J. E., CRASHWORTHINESS OF THE BOEING VERTOL UTTAS, in Aircraft Crashworthiness, K. Saczalski, et al., eds., University Press of Virginia, Charlottesville, Virginia, 1975, pp. 65-82.

7. Rich, M. J., INVESTIGATION OF ADVANCED HELICOPTER STRUCTURAL DESIGNS, Volume I, ADVANCED STRUCTURAL COMPONENT DESIGN CONCEPT STUDY, Sikorsky Aircraft, Division of United Technology Corporation; USAAMRDL Technical Report 75-59A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1976, AD A026246.

the ground, deformation of the ground absorbs some energy. This is an uncontrolled variable since the quality of the impacted surface usually cannot be selected by the pilot. If the aircraft lands on an appropriate surface in an appropriate attitude, the landing gear can be used to absorb a significant amount of the impact energy. After stroking of the gear, crushing of the fuselage contributes to the total energy-absorption process. The fuselage must also maintain a protective shell around the occupant, so the crushing must take place outside the protective shell. The functions of the seat and restraint system are to restrain the occupant within the protective shell during the crash sequence and to provide additional energy-absorbing stroke to further reduce occupant decelerative loading to within human tolerance limits. The structure and components immediately surrounding the occupant must also be considered. Weapon sights, cyclic controls, glare shields, instrument panels, armor panels, and aircraft structure must be delethalized if they lie within the strike envelope of the occupant.

8. Hoffstedt, D. J., and Swatton, S., ADVANCED HELICOPTER STRUCTURAL DESIGN INVESTIGATION, The Boeing Vertol Company; USAAMRDL Technical Report 75-56A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, March 1976, AD A024662.

9. Hicks, J. E., AN ANALYSIS OF LIFECYCLE ACCIDENT COSTS FOR THE ADVANCED SCOUT HELICOPTER, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama, January 1977.

10. McDermott, J. M., and Vega, E., THE EFFECTS OF LATEST MILITARY CRITERIA ON THE STRUCTURAL WEIGHT OF THE HUGHES ADVANCED ATTACK HELICOPTER YAH-64, Journal of the American Helicopter Society, Vol. 23, No. 4, October 1978, pp. 2-9.

11. Haley, J. L., Jr., CRASHWORTHINESS VERSUS COST: A STUDY OF ARMY ROTARY WING AIRCRAFT ACCIDENTS IN PERIOD JANUARY 1970 THROUGH DECEMBER 1971, paper presented at the Aircraft Crashworthiness Symposium, University of Cincinnati, Cincinnati, Ohio, October 1975.

12. Hicks, J. E., ECONOMIC BENEFITS OF UTILITY AIRCRAFT CRASHWORTHINESS, USAAAVS Technical Report 76-2, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama, July 1976.

13. THE ECONOMIC BENEFITS OF CRASHWORTHINESS AND FLIGHT SAFETY DESIGN FEATURES IN ATTACK HELICOPTERS, USAAAVS Technical Report 77-2, U. S. Army Agency for Aviation Safety, Fort Rucker, Alabama, June 1977.

Ideally, it would seem most efficient to simply specify human
tolerance requirements and an array of vehicle crash impact
conditions and then develop the helicopter as a crashworthy
system with a mixture of those crashworthy features that are
most efficient for the particular helicopter being designed.
Unfortunately, the validated structural and/or human tolerance
analytical techniques needed to perform and evaluate such a
maximum design freedom approach to achieving crashworthiness
are not available. Furthermore, testing complete aircraft suf-
ficiently early in the development cycle to permit evaluation
of system concepts in time to permit design changes based on
the test results is not practical. The systems approach dic-
tates that the designer consider probable crash conditions
wherein all subsystems cannot perform their desired functions;
for example, an impact situation in which the landing gear can-
not absorb its share of the impact crash energy because of air-
craft attitude at impact. Therefore, to achieve the overall
goal, minimum levels of crash protection are recommended for
the various individual subsystems. A balance must be struck
between the two extremes of: (1) defining necessary perform-
ance on a component level only, and (2) requiring that the air-
craft system be designed for an array of impact conditions
with no component design and test criteria.

Current helicopter crashworthiness criteria require that a new
aircraft be designed as a system to meet the vehicle impact
design conditions recommended in Volume II; however, minimum
criteria are also specified for a few crash critical components.
For example, strengths and minimum crash energy-absorption re-
quirements for seats and restraint systems are specified. All
strength requirements presented in this volume are based on the
crash environments described in Volume II. Testing require-
ments are based on ensuring compliance with strength and defor-
mation requirements. Mandatory minimum crashworthiness design
criteria for U. S. Army light fixed- and rotary-wing aircraft
are stated in MIL-STD-1290(AV) (Reference 1). All pilot, co-
pilot, observer, and student seats in either rotary- or light
fixed-wing aircraft should conform to the requirements of
MIL-S-58095(AV) (Reference 14).

Although much higher levels of crashworthiness can be achieved
in completely new aircraft designs, the crashworthiness of
existing aircraft can be significantly improved through retro-
fitting these aircraft with crashworthy components adhering to
the design principles of this design guide. This can even be

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14. Military Specification, MIL-S-58095(AV), SEAT SYSTEM:
    CRASHWORTHY, NON-EJECTION, AIRCREW, GENERAL SPECIFICATION
    FOR, Department of Defense, Washington, D. C., 27 August
    1971.

achieved while expanding the combat effectiveness of the aircraft. Examples of this are the successful program to retrofit all U. S. Army helicopters with crashworthy fuel systems (Reference 15), and the U. S. Navy program to retrofit the CH-46 with crashworthy armored crewseats (Reference 16).

In an initial assessment, the definition of an adequate crashworthy structure may appear to be a relatively simple matter. In fact, many influencing parameters must be considered before an optimum design can be finalized. A complete systems approach must be employed to include all influencing parameters concerned with the design, manufacture, overall performance, and economic restraint on the aircraft in meeting mission requirements. Trade-offs between the affecting parameters must be made in order to arrive at a final design that most closely meets the customer's specified requirements. It must be remembered that for each type cf aircraft, different emphasis will be placed in the parameter mix. Table 1 summarizes major crashworthiness criteria that must be considered during the preliminary design definition phase.

15. Cook, R. L., and Goebel, D. E., EVALUATION OF THE UH-1D/H HELICOPTER CRASHWORTHY FUEL SYSTEM IN A CRASH ENVIRONMENT, Dynamic Science Division of Marshall Industries; USAAMRDL Technical Report 71-47, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, November 1971.

16. Domzalski, L. P., et al., U. S. NAVY DEVELOPMENTS IN CRASHWORTHY SEATING, Naval Air Development Center; Proceedings 1978 SAFE Symposium, Survival and Flight Equipment Association, Canoga Park, California, October 1978.

TABLE 1. CRASHWORTHINESS CRITERIA FOR THE PRELIMINARY DESIGN PROCESS

Crash scenarios	Primary structure	Energy absorption	Postcrash requirements
• MIL-STD-1290(AV) defines predominant impact conditions	• Support of large mass items	• Landing gear	• Emergency egress
• Single axis and combination of:	• Support of systems	• Controlled structural collapse	• Occupant release from seats
• Vertical impact	• Occupant support and protection	• Crashworthy energy-absorbing seats	• Door/exit opening
• Longitudinal impact	• Cargo containment and tiedown	• Shedding of large mass items	• Accessibility of exits

• Lateral impact	• Support of landing gear loads	• Engines
		  • Transmissions
		  • Rotor heads
		  • External stores
		  • Tail boom
			• Minimization of fire potential

• Postimpact
  • Rollover
  • Pitchover
  • Nose plowing
	• Space consistent with occupant strike envelope	(Shed items must not impact occupied areas)	• Crashworthy fuel systems

	• Emergency exit structure	• Impacted surface (soft ground etc.)	• Low-flammability hydraulic fluid
			• Nonsparking materials in areas of potential ground contact.

2. DEFINITIONS

2.1 AIRCRAFT COORDINATE SYSTEMS AND ATTITUDE PARAMETERS

Positive directions for velocity, acceleration, and force components and for pitch, roll, and yaw are illustrated in Figure 1. When referring to an aircraft in any flight attitude, it is standard practice to use a basic set of orthogonal axes as shown in Figure 1, with x, y, and z referring to the longitudinal, lateral, and vertical directions, respectively.
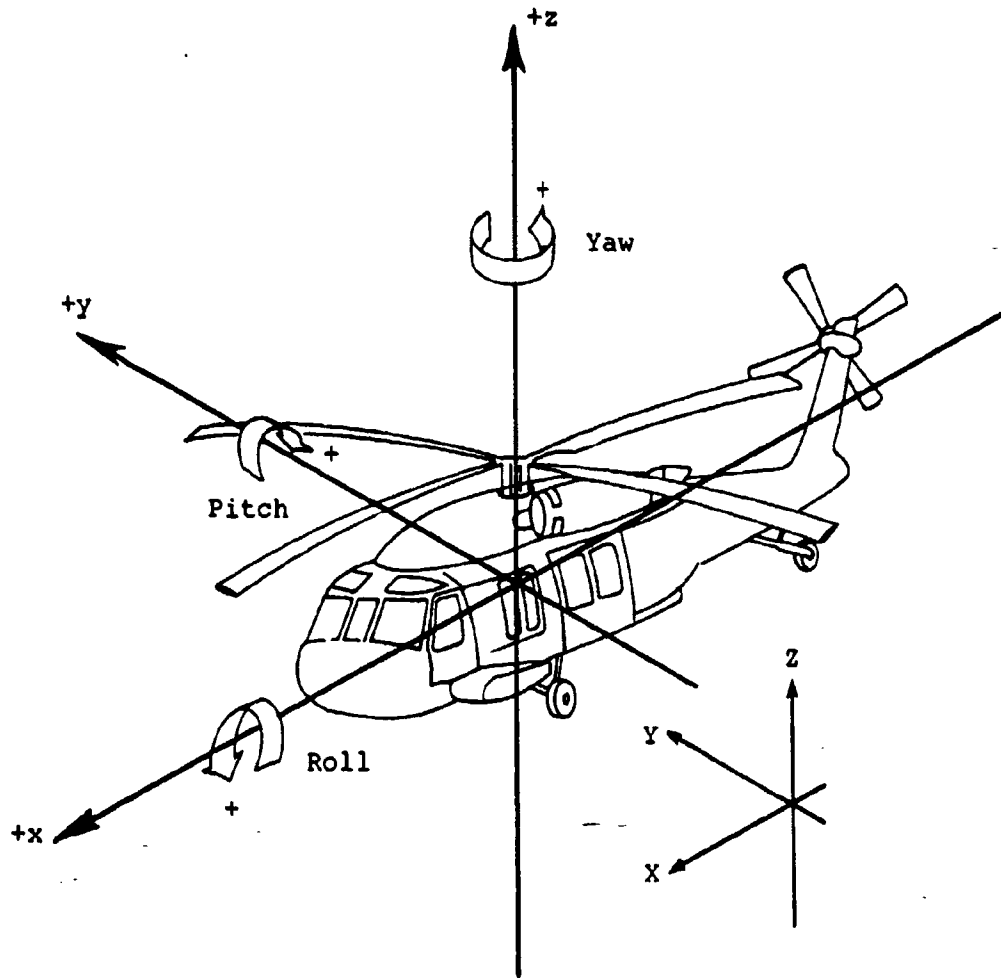
Figure 1. Aircraft coordinates and attitude directions.

2.2 ACCELERATION-RELATED TERMS

● **Acceleration**

The rate of change of velocity. An acceleration is required to produce any velocity change, whether in magnitude or in direction. Acceleration may produce either an increase or a decrease in velocity. There are two basic types of acceleration: linear, which changes translational velocity, and angular (or rotational), which changes angular (or rotational) velocity. With respect to the crash environment, unless otherwise specified, all acceleration values are those at a point approximately at the center of the floor of the fuselage.

● **Deceleration**

Acceleration which produces a decrease in velocity.

● **Abrupt Accelerations**

Accelerations of short duration primarily associated with crash impacts, ejection seat shocks, capsule impacts, etc. One second is generally accepted as the dividing point between abrupt and prolonged accelerations. Within the extremely short duration range of abrupt accelerations (0.2 sec and below), the effects on the human body are limited to mechanical overloading (skeletal and soft tissue stresses), there being insufficient time for functional disturbances due to fluid shifts.

● **The Term G**

The ratio of a particular acceleration to the acceleration due to gravitational attraction at sea level (32.2 ft/sec^2). In accordance with common practice, this report will refer to accelerations measured in G. To illustrate, it is customarily understood that 5 G represents an acceleration of 5 x 32.2, or 161 ft/sec^2.

2.3 VELOCITY-RELATED TERMS

● **Velocity Change in Major Impact (Δv)**

The decrease in velocity of the airframe during the major impact, expressed in feet per second. The major impact is the one in which the highest forces

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are incurred, not necessarily the initial impact.
For the acceleration pulse shown in Figure 2, the
major impact should be considered ended at time t_2.
Elastic recovery in the structure will tend to re-
verse the direction of aircraft velocity prior to
t_2. Should the velocity actually reverse, its di-
rection must be considered in computing the velocity
change. For example, an aircraft impacting downward
with a vertical velocity component of 30 ft/sec and
rebounding with an upward component of 5 ft/sec
should be considered to experience a velocity change

$$\Delta v = 30 - (-5) = 35 \text{ ft/sec}$$

during the major impact. The velocity change during
impact is further explained in Section 7.2 of Volume
III.

● Longitudinal Velocity Change

The decrease in velocity during the major impact mea-
sured along the longitudinal (roll) axis of the air-
craft. The velocity may or may not reach zero during
the major impact. For example, an aircraft impacting
the ground at a forward velocity of 100 ft/sec and
slowing to 35 ft/sec before rebounding into the air
would experience a longitudinal velocity change of
65 ft/sec during this impact.

● Vertical Velocity Change

The decrease in velocity during the major impact mea-
sured along the vertical (yaw) axis of the aircraft.
The vertical velocity generally reaches zero during
the major impact.

● Lateral Velocity Change

The decrease in velocity during the major impact mea-
sured along the lateral (pitch) axis of the aircraft.

2.4 FORCE TERMS

● Load Factor

A crash force can be expressed as a multiple of the
weight of an object being accelerated. A load fac-
tor, when multiplied by a weight, produces a force

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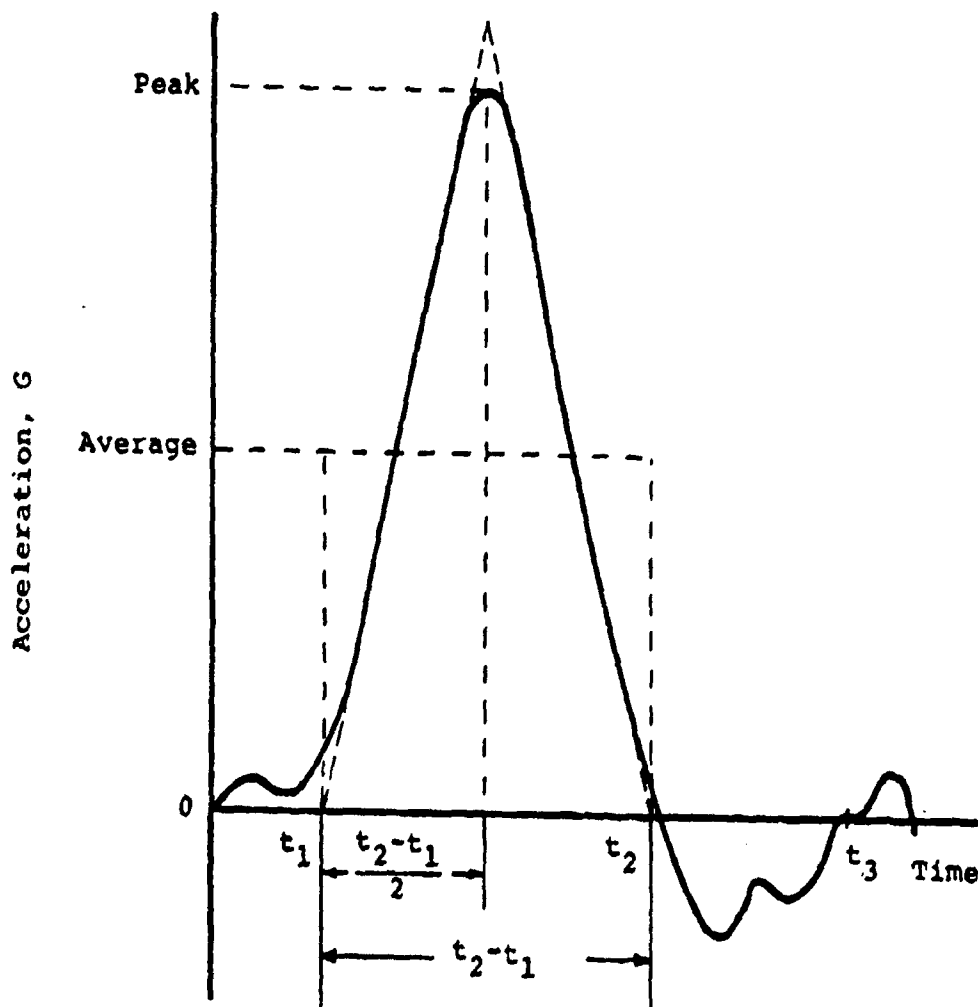
Figure 2. Typical aircraft floor acceleration pulse.

which can be used to establish static strength (see
Static Strength). Load factor is expressed in units
of G.

● Forward Load

Loading in a direction toward the nose of the air-
craft, parallel to the aircraft longitudinal (roll)
axis.

- **Aftward Load**

  Loading in a direction toward the tail of the air-
  craft, parallel to the aircraft longitudinal (roll)
  axis.

- **Downward Load**

  Loading in a downward direction parallel to the ver-
  tical (yaw) axis of the aircraft.

- **Upward Load**

  Loading in an upward direction parallel to the verti-
  cal (yaw) axis of the aircraft.

- **Lateral Load**

  Loading in a direction parallel to the lateral (pitch)
  axis of the aircraft.

- **Combined Load**

  Loading consisting of components in more than one of
  the directions described in Section 2.2.

2.5 DYNAMICS TERMS

- **Rebound**

  Rapid return toward the original position upon re-
  lease or rapid reduction of the deforming load, usu-
  ally associated with elastic deformation.

- **Dynamic Overshoot**

  The amplification of decelerative force on cargo or
  personnel above the input decelerative force (ratio
  of output to input). This amplification is a result
  of the dynamic response of the system.

- **Transmissibility**

  The amplification of a steady state vibrational input
  amplitude (ratio of output to input). Transmissibil-
  ities maximize at resonant frequencies and may pro-
  duce motion and acceleration amplification similar to
  dynamic overshoot.

2.6 CRASH SURVIVABILITY TERMS

- **Survivable Accident**

  An accident in which the forces transmitted to the occupant through the seat and restraint system 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 for the occupants throughout the crash sequence.

- **Survival Envelope**

  The range of impact conditions--including magnitude and direction of pulses and duration of forces occurring in an aircraft accident--wherein the occupiable area of the aircraft remains substantially intact, both during and following the impact, and the forces transmitted to the occupants do not exceed the limits of human tolerance when current state-of-the-art restraint systems are used.

  It should be noted that, where the occupiable volume is altered appreciably through _elastic_ deformation during the impact phase, survivable conditions may not have existed in an accident that, from postcrash inspection, outwardly appeared to be survivable.

2.7 OCCUPANT-RELATED TERMS

- **Human Body Coordinates**

  In order to minimize the confusion sometimes created by the terminology used to describe the directions of forces applied to the body, a group of NATO scientists compiled the accelerative terminology table of equivalents shown in Figure 3 (Reference 17). Terminology used throughout this guide is compatible with the NATO terms as illustrated.

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17. Gell, C. F., TABLE OF EQUIVALENTS FOR ACCELERATION TERMI-
     NOLOGY, _Aerospace Medicine_, Vol. 32, No. 12, December
     1961, pp. 1109-1111.

Headward
$(+G_z)$

Back to chest
(sternumward)
$(+G_x)$

Lateral right
$(+G_y)$

Lateral left
$(-G_y)$

Chest
to back
(spineward)
$(-G_x)$
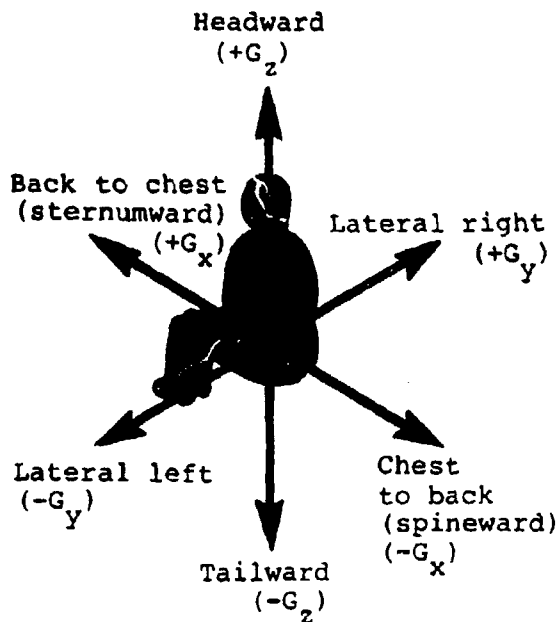
Tailward
$(-G_z)$

Direction of
accelerative force

Vertical

Headward - Eyeballs-down
Tailward - Eyeballs-up

Transverse

Lateral right	- Eyeballs-left
Lateral left	- Eyeballs-right
Back to chest	- Eyeballs-in
Chest to back	- Eyeballs-out

Note:

The accelerative force on
the body acts in the same
direction as the arrows.

Figure 3. Terminology for directions of forces on
the body. (From Reference 17)

- **Anthropomorphic Dummy**

    A device designed and fabricated to represent not
    only the appearance of humans but also the mass dis-
    tribution, joint locations, motions, geometrical sim-
    ilarities such as flesh thickness and load/deflection
    properties, and relevant skeletal configurations such
    as iliac crests, ischial tuberosities, rib cages,
    etc. Attempts are also made to simulate human re-
    sponse of major structural assemblages such as
    thorax, spinal column, neck, etc.- The dummy is
    strapped into seats or litters and used to simulate
    a human occupant in dynamic tests.

- **Human Tolerance**

    For the purposes of this document, human tolerance
    is defined as a selected array of parameters that
    describe a condition of decelerative loading for
    which it is believed there is a reasonable probabil-
    ity for survival without major injury. As used in

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this volume, designing for the limits of human tolerance refers to providing design features that will maintain these conditions at or below their tolerable levels to enable the occupant to survive the given crash environment.

Obviously, the tolerance of the human body to crash environments is a function of many variables including the unique characteristics of each person as well as the loading variables. The loads applied to the body include decelerative loads imposed by seats and restraint systems as well as localized forces due to impact with surrounding structures. Tolerable magnitudes of the decelerative loads depend on the direction of the load, the orientation of the body, and the means of applying the load. For example, the critical nature of loads parallel to the occupant's spine manifests itself in any of a number of types of spinal fractures, but typically the fracture is an anterior wedge, or compressive failure of the front surface of a vertebra. Forces perpendicular to the occupant's spine can produce spinal fracture through shear failures or from hyperflexion resulting, for example, from jackknife bending over a lap belt-only restraint. The lap belt might inflict injuries to the internal organs if it is not retained on the pelvic girdle but is allowed to exert its force above the iliac crests in the soft stomach region. Excessive rotational or linear acceleration of the head can produce concussion. Further, skull fracture can result from head impact with surrounding structure. Therefore, tolerance is a function of the method of occupant restraint as well as the characteristics of the specific occupant. Refer to Chapter 4 of Volume II for a more detailed discussion of human tolerance.

- Submarining

  Rotation of the hips under and about the lap belt as a result of a forward inertial load exerted by deceleration of the thighs and lower legs, accompanied by lap belt slippage up and over the iliac crests. Lap belt slippage up and over the iliac crests can be a direct result of the upward loading of the shoulder harness straps at the center of the lap belt.

- Effective Weight

  The portion of occupant weight supported by the seat with the occupant seated in a normal flight position.

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This is considered to be 80 percent of the occupant weight since the weight of the feet, lower legs, and part of the thighs is carried directly by the floor through the feet.

- **Iliac Crest Bone**

  The upper, anterior portion of the pelvic (hip) bone. These "inverted saddle" bones are spaced laterally about 1 ft apart; the lower abdomen rests between these crest bones.

- **Lap Belt Tiedown Strap (also Negative-G Strap, Crotch Strap)**

  Strap used to prevent the tensile force in shoulder straps from pulling the lap belt up when the restrained subject is exposed to $-G_x$ (eyeballs-out) acceleration.

2.8 SEATING GEOMETRY (SEE FIGURE 4 FROM REFERENCE 18)

- **Design Eye Position**

  A reference datum point based on the eye location that permits the specified vision envelope required by MIL-STD-850 (Reference 19), allows for slouch, and is the datum point from which the aircraft station geometry is constructed. The design eye position is a fixed point in the crew station, and remains constant for pilots of all stature via appropriate seat adjustment.

- **Horizontal Vision Line**

  A reference line passing through the design eye position parallel to the true horizontal and normal cruise position.

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18. Military Standard, MIL-STD-1333, AIRCREW STATION GEOMETRY FOR MILITARY AIRCRAFT, Department of Defense, Washington, D. C.

19. Military Standard, MIL-STD-850, AIRCREW STATION VISION REQUIREMENTS FOR MILITARY AIRCRAFT, Department of Defense, Washington, D. C.
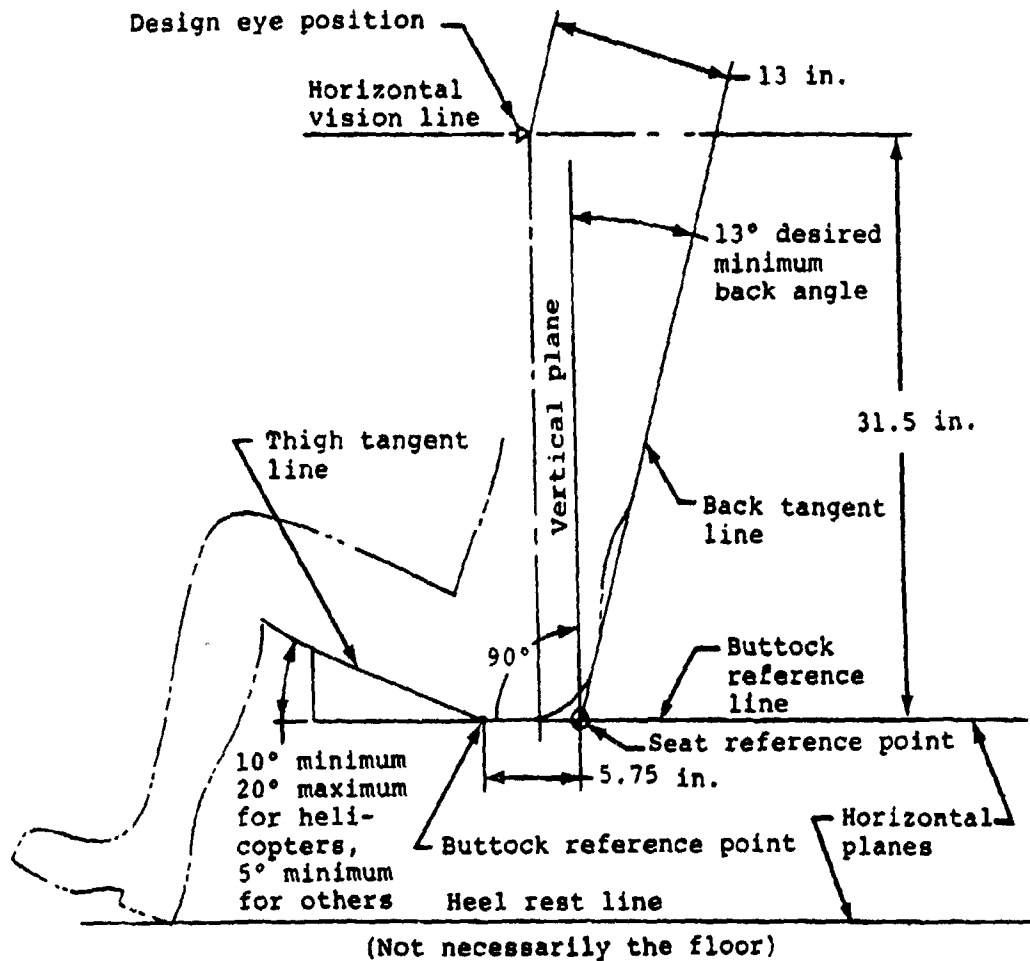
Figure 4. Seating geometry. (From Reference 18)

● __Back Tangent Line__

A straight line in the midplane of the seat passing
tangent to the curvatures of a seat occupant's back
-when leaning back and naturally compressing the back
cushion. The seat back tangent line is positioned
13 in. behind the design eye position measured along
a perpendicular to the seat back tangent line.

● __Buttock Reference Line__

A line in the midplane of the seat parallel to the
horizontal vision line and tangent to the lowermost
natural protrusion of a selected size of occupant
sitting on the seat cushion.

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- **Seat Reference Point (SRP)**

  The intersection of the back tangent line and the buttock reference line. The seat geometry and location are based on the SRP.

- **Buttock Reference Point**

  A point 5.75 in. forward of the seat reference point on the buttock reference line. This point defines the approximate bottom of an ischial tuberosity, thus, representing the lowest point on the pelvic structure and the point that will support the most load during downward vertical loading.

- **Heel Rest Line**

  The reference line parallel to the horizontal vision line passing under the tangent to the lovest point on the heel in the normal operational position, not necessarily coincidental with the floor line.

STRUCTURAL TERMS

- **Airframe Structural Crashworthiness**

  The ability of an airframe structure to maintain a protective shell around occupants during a crash and to minimize magnitudes of accelerations applied to the occupiable portion of the aircraft during crash impacts.

- **Structural Integrity**

  The ability of a structure to sustain crash loads without collapse, failure, or deformation of sufficient magnitude to: (1) cause injury to personnel, or (2) prevent the structure from performing as intended.

- **Static Strength**

  The maximum static load that can be sustained by a structure, often expressed as a load factor in terms of G (see Load Factor, Section 2.4).

- **Strain**

  The ratio of change in length to the original length of a loaded component.

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- Collapse

  Plastic deformation of structure to the point of loss
  of useful load-carrying ability. Although normally
  considered detrimental, in certain cases collapse can
  prove beneficial as a significant energy-absorbing
  process, maintaining structural integrity.

- Failure

  Loss of load-carrying capability, usually referring
  to structural linkage rupture.

- Limit Load

  In a structure, limit load refers to the load the
  structure will carry before yielding. Similarly, in
  an energy-absorbing device, it represents the load
  at which the device deforms in performing its func-
  tion.

- Load Limiter, Load-Limiting Device, or Energy
  Absorber

  These are interchangeable names of devices used to
  limit the load in a structure to a preselected value.
  These devices absorb energy by providing a resistive
  force applied over a deformation distance without
  significant elastic rebound.

- Specific Energy Absorbed (SEA)

  The energy absorbed by an energy-absorbing device or
  structure divided by its weight. SEA is usually pre-
  sented in inch-pounds per pound.

- Bottoming

  The exhaustion of available stroking distance accom-
  panied by an increase in force, e.g., a seat strok-
  ing in the vertical direction exhausts the available
  distance and impacts the floor.

- Bulkhead

  A structural partition extending upwards from the
  floor and dividing the aircraft into separate com-
  partments. Seats can be mounted to bulkheads in-
  stead of the floor if sufficient strength is pro-
  vided.

3. PRIMARY DESIGN CONSIDERATIONS

3.1 INTRODUCTION

Occupant protection and survival in aircraft accidents should
be a primary consideration in the design, development, and
testing of aircraft seats and litters. All operational re-
quirements as specified in other design guides should also be
met. Adequate occupant protection requires that both seats
and litters be retained generally in their original positions
within the aircraft throughout any survivable accident. In
addition, the seat should provide an integral means of crash
load attenuation, and the occupant's strike envelope should be
delethalized.

3.2 OPERATIONAL ENVIRONMENT

Several environmental and operational factors other than those
associated with crashworthiness affect the design of an ade-
quate seating system. Because of their importance in overall
design, these factors are mentioned briefly prior to the more
detailed presentation of information concerning crashworthi-
ness.

3.2.1 Comfort

The comfort of an aircraft seat is a safety-of-flight factor
rather than a crash-safety-design factor. An uncomfortable
seat can induce pilot fatigue in a short period of time. Pilot
fatigue is an indirect cause of aircraft accidents. Comfort
is thus of primary concern and must not be unduly compromised
to achieve crash safety.

Comfort is influenced by several factors, including the vibra-
tional environment. Adequate comfort also involves maintenance
of adequate body angles and load distributions. Therefore,
thigh tangent angles and seat back angles are influential in
body comfort. If the back angle is less than 13 degrees, the
occupant's back will be required to counteract too much forward
moment resulting from the weight of the body acting through
centers of gravity forward of the spinal column. As the back
angle is increased beyond 13 degrees, the center of gravity is
moved back and the moment is reduced, which provides for much
greater comfort. If the thigh tangent angle is too low, too
much effort will be required to maintain the lateral orienta-
tion of the legs. If the cushion supports the lateral position
of the legs, comfort will be improved. Also, increasing the
thigh tangent angle seems to rotate the pelvis to the rear,
effectively moving the center of gravity aft and providing a
rearward moment in the pelvis that reduces the forward moment

on the spine. A thigh tangent angle of 5 to 20 degrees is required by MIL-STD-1333 (Reference 17); however, it is recommended here that tangent angles greater than 10 degrees be used to maximize comfort and to reduce submarining tendencies.

Another aspect of comfort includes the width of the seat. Too narrow a seat can exert lateral forces on the sides of the body or force the body to be held forward out of the constraints of the seat bucket, again increasing discomfort. Maximum seat widths should be provided consistent with the space available in the aircraft, including consideration for the volume around the seat needed for lateral deflection during crash stroking and for items such as the collective control. Typically, the seat pan is required to be at least 18 in. wide with human factors specialists requesting 20 and compromising at 19 in. This dimension need not be restrictive if proper consideration is given to providing sufficient room for the seat during the initial design of the surrounding aircraft structure.

The surface upon which the occupant sits has a major influence on comfort. The function of this surface is to spread the contact load over the largest possible area, thereby decreasing high pressure points and preventing restriction of blood flow in these areas. In the past, this has been accomplished by nets or by extremely thick, soft cushions. Although such solutions provided comfort for prolonged flights, this practice is no longer acceptable since the low spring rates of these nets or cushions make them extremely hazardous in crash situations. The low spring rates allow large relative velocities to build up between the occupant and the airframe or seat during the imposition of decelerative loads and increase the hazard to the occupant. Thus, the cushion must provide adequate distribution of loads but not allow excessive motion during crash loading.

Another aspect of comfort is thermal ventilation. The thermal ventilation requirement for seat cushions is particularly important in hot, humid climates. The close contact between the buttocks or the back and the interfacing cushions can result in an elevation of temperatures coincident with collection of moisture through perspiration. Provisions should be made for air circulation to carry the hot, humid air out of this interface area, or thermal comfort will be inadequate.

3.2.2 Seat Adjustments

Passenger seats are not usually adjustable; however, in most cases, adjustment is mandatory for crewseats. First, the cockpit and crew station have been designed for a particular eye position. This eye position is associated with the size of a

50th-percentile male occupant; consequently, occupants of
smaller or larger stature may not be located efficiently if
seat adjustment is not provided. Theoretically, the seat ad-
justment enables each occupant to adjust his eye position to
the optimum point. Typically, a ±2.5-in. vertical adjustment
from the neutral seat reference position is required to account
for this variation in occupant size. Plus or minus 2.5 in. of
fore-and-aft adjustment is also required to permit the desired
repositioning of the eye and for locating the occupant at the
proper distance from controls, pedals, etc. Of course, human
factors should be considered in the design of adjustments.
Adjustment mechanisms should be easily found, easy to use, and
required adjustment motions should be precise, allowing the
occupant to easily get into the most comfortable position with-
out a great deal of distraction. Further, there should be an
efficient verification that the seat is firmly locked into the
chosen position.

3.2.3 Vibration Damping

By its basic nature, the helicopter includes a great number of
vibration sources, primarily as a result of the relatively
great number of moving parts. Typical critical frequencies
include the multiples associated with numbers of blades and
rotor speed. Critical conditions are located at multiples of
the main rotor speed; for example, one, two, four, and eight
per revolution. On four-bladed main rotors, the four-per-
revolution frequency is typically between 18 and 20 Hz. This
driving frequency will be present constantly during cruise;
therefore, it is highly desirable that the resonant frequency
of the seat, both empty and occupied, fall outside the 18- to
20-Hz frequency range. Other frequencies, such as eight per
revolution, can also be a problem. For startup and shutdown
conditions, the resonant frequency of the seat should be high
(not lie in the range of 2 to 25 Hz), and considering the
eight-per-revolution frequency it would be desirable to keep
the natural frequency above 40 Hz.

Seat vibrational problems are often difficult to solve because
the predetermined size and general structure of the seat seem
to control the occupied seat natural frequency rather than the
design options that lie within the limits of weight and cost.
However, the occupied seat natural frequency must be considered
since seat vibration can be very distracting to the occupant,
for example, in the lateral direction where the thighs touch
the sides of the bucket.

Stiffening of the structure is extremely costly in weight; how-
ever, in certain situations it may be the only viable solution

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to the problem. Dampers that can be added to the seating system normally consist of sprung and damped masses. Usually these mechanisms are very heavy and resorting to their use is not acceptable in a production aircraft. Isolation of the seat components by dash pots or elastomeric bearings may provide possible solutions to this problem.

To summarize, consideration must be given to the vibrational characteristics of the seat as associated with the vibrational environment produced in the specific aircraft for which the seat is being designed.

3.3 CRASH ENVIRONMENT

3.3.1 Dynamics and Kinematics

When an aircraft crashes, any number of loading combinations can be imposed on the seat. This is true for rotary- or fixed-wing aircraft. It would not be useful to try to identify each and every loading combination; however, studies that have been completed indicate combinations of loadings that must be dealt with in the design of the seat and restraint system. For example, the stall-spin accident typical of light fixed-wing aircraft can produce high lateral loadings, the resultant of which can be oriented in any direction in the longitudinal-lateral or yaw plane. Studies of helicopter crashes show very high incidences of side impacts or rollover after impact for some classes of helicopters (Reference 20).

As an example of the dynamics and kinematics of an aircraft crash, consider one of the new generation helicopters crashing in a nose-up, or flare orientation. The tail boom may strike the ground first, followed by rotation of the aircraft around a pitch axis, then, by impact of the fuselage. The gear will strike the ground, and, if it is a wheeled landing gear, the tires will begin to flatten, absorbing a small amount of energy. When the rim contacts the ground, the wheel may fail as the lower oleo strut begins stroking. After completion of the lower oleo stroke, the second stage will begin, and energy-absorbing stroke will continue until the fuselage impacts the ground. If the ground is relatively soft, the ground will deform under the loading of the wheels and absorb some energy. As the fuselage impacts, the softer ground will deform again while the fuselage structure is deforming. As the fuselage structure deforms, additional energy is absorbed. At this

20. Haley, J. L., ANALYSIS OF EXISTING HELICOPTER STRUCTURES TO DETERMINE DIRECT IMPACT SURVIVAL PROBLEMS, U. S. Army Board for Aviation Accident Research, Fort Rucker, Alabama, 1971.

point in the sequence, the loads can achieve the significant magnitudes required to initiate energy-absorbing stroke of the seat. The landing gear are designed to stroke at a lower load than that required to activate the vertical energy-absorbing system in the seats; thus, stroking of the gear will occur prior to vertical stroking of the seat. This will typically result in energy-absorbing stroke of the gear followed by an increase in fuselage loading when the fuselage impacts the ground and begins to crush. During some part of the crash sequence, the seat and fuselage may be stroking together. The decelerative loads may increase and the fuselage will eventually be stopped. Depending on the conditions of the particular crash, the seat may go on stroking, until it either absorbs the residual energy of the supported mass or bottoms at the end of its stroke. Thus, the seat may be the last item in the load path of interest to remain in motion during the crash sequence.

One important point here can be used to advantage by the seat designer. In a crash with combined loading, extremely high longitudinal or lateral loads can be applied to the seat after stroking of the energy-absorbing gear and during fuselage crushing. However, once the fuselage has come to a stop, crash loading is no longer exerted on the seat, and it may continue its stroke until either the residual energy or the seat stroke is expended. This can be important to the designer. For example, consider a seat design that includes only vertical energy-absorbing stroke. The seat is not required to withstand the high combined loads throughout its complete vertical stroke, only that portion of the stroke while the lateral/longitudinal crash loading is applied.

For those aircraft using wells, or depressions, in the floor under the seat to provide for increased stroke distance beyond the distance available between the seat pan and the floor, the seat must be guided sufficiently to clear the sidewalls of the well to utilize that additional distance. In a seat with a low lateral spring rate, the seat may move laterally to the point where it no longer lines up with the well under the seat pan during the application of the longitudinal/lateral loading. If the longitudinal/lateral loading is removed soon enough, the seat may be able to return to alignment and still stroke into the well under the seat. However, this occurs only if the longitudinal/lateral loading (in certain cases) has produced elastic, rather than plastic, deformation. If the deformation has been plastic, removal of the load will not cause the seat to return to its original over-the-well position but will allow it to continue its vertical stroke in the deflected configuration. On the other hand, if the elastic deformation is not damped sufficiently, or if the distance above the well

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is not sufficient, the rebound of the seat may carry it beyond the well on the other side without sufficient time to return to center as it goes through the floor plane. These motions can be considered during seat design and development phases to minimize a seat's weight while providing the crashworthy performance desired.

Several factors should be considered during the design of a seat that uses a well to increase available stroke. First, as much clearance as possible should be left between the outside of the seat pan and the inside of the well. This will allow for considerable deflection from the no-load position without creating impact or interference hazards. The next consideration is that the seat be made as stiff as possible in the lateral direction to limit the extent of deflection without imposing too high a weight penalty. Designing a seat with energy-absorbing stroke in the lateral direction may compromise the all-important vertical stroke. Usually, the confines around a pilot/copilot seat, which consist primarily of collective controls and consoles, do not permit sufficient lateral motion of the seat to avoid hazardous interference with the vertical stroke. Since the vertical stroke is the only required energy-absorbing stroke, its blockage will significantly degrade the degree of seat crashworthiness. Additionally, recent studies indicate a high frequency of thorax and head injuries (Reference 21). Allowing the seat to move either laterally or longitudinally any more than necessary could increase the risk of head or chest impact on surrounding structure.

One could infer from the above discussion that energy-absorbing strokes in the lateral or longitudinal directions are not desirable and serve to increase the overall hazard to the occupant. However, this general statement cannot be made, as the degree of hazard or benefit will depend on the configuration of the specific aircraft and the location of the seat within the aircraft. In certain aircraft, space will be available for seats that stroke in more than just the vertical direction, and, when it is available, it may be advantageous to include it in the system design.

Because of the cabin location of troop seats, they typically have a less lethal area surrounding them than crewseats, and

21. Singley, G. T., III, and Desjardins, S. P., CRASHWORTHY HELICOPTER SEATS AND OCCUPANT RESTRAINT SYSTEMS, in Operational Helicopter Aviation Medicine, AGARD Conference Proceedings No. 255, North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, Neuilly sur Seine, France, May 1978.

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do not have to stroke into wells. Troop seats are typically
load limiting in the longitudinal and lateral as well as verti-
cal directions. This three-dimensional load limiting reduces
occupant decelerative loading and the crash loads on the seat
structure in the transverse direction in comparison to a
vertical-only load-limiting seat. Lower loading of the seat
allows a lighter seat design. In the case of a side-facing
seat, load limiting along the seat's lateral axis is necessary
if the occupant decelerative loading during the specified air-
craft forward crash impact conditions of Volume II is to be
kept within human tolerance limits for lateral decelerations.

In reviewing the dynamics and kinematics of crashing aircraft,
it becomes quite apparent that all combinations of orientations,
loading, and load directions can exist. (Volume II presents
a detailed discussion of crash impact dynamics and kinematics.)
It should also be remembered that the seat is designed to ab-
sorb only a portion of the crash energy required to decelerate
the occupant in a tolerable environment. There are numerous
crash orientations in which the aircraft has a lateral compo-
nent of impact velocity, whether it results from a lateral
drift of the aircraft or from its attitude at impact. These
components of velocity can produce high lateral loading of gear,
which, in some cases, may simply break off before absorbing
significant energy. Consider, for example, the case of an air-
craft impacting the ground with a high roll angle. Loss of
gear will result in the aircraft fuselage impacting the ground
without the reduction in energy normally attributed to stroking
of the gear. Therefore, systems analyses must take this factor
into account. As an example of the possible dangers, it might
be decided that landing gear should absorb all the crash energy
associated with the 42-ft/sec vertical impact; therefore, seat
stroking would not be required. The results of applying this
logic to hardware would seriously reduce the overall crash-
worthiness of the aircraft in those crashes where the full en-
ergy absorption of the gear could not be realized. Therefore,
seats should contain the minimum energy-absorbing stroke de-
fined in this document, regardless of the energy-absorption
capacity of the gear.

After a helicopter crashes, the rotating main rotor may strike
the ground or other obstacles and roll the helicopter onto its
side. Because of the high center of gravity, the helicopter
may roll over without any added lateral impulse from the main
rotor blades after gear failure. In any case, the kinematics
of crashed helicopters can be quite complex and violent, and
the helicopter may come to rest in any orientation. Because
of these kinematics, loads are specified in all directions for
seats. This subject will be covered in more depth later in
this volume; however, the crash kinematics of these aircraft

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demand strength requirements in all directions, including up-
ward and aftward. In this regard, it should be remembered that
the seat may have used a significant portion of its available
vertical stroking distance during the major impact. If the
aircraft should then follow through with a flip, or land on
its back, the system should maintain the seat near its final
stroked position rather than allowing the seat to return to
its original position. Upward travel could be extremely haz-
ardous if the roof of the fuselage were severely crushed and
the occupant were free to travel unrestrained back toward his
initial position. Severe head and/or neck injuries could re-
sult.

In summary, it must be remembered that, to produce a crash-
worthy design, systems analyses must consider likely combina-
tions of loadings, including potential losses of energy-
absorbing structure, such as landing gear.

3.3.2 Design Conditions and Envelopes

The design impact conditions for light fixed- and rotary-wing
aircraft are presented in Volume II and are repeated here in
Table 2. All seats, restraint systems, and litters should be
designed for these impact velocities and provide the desired
performance in the design crash environments.

TABLE 2. SUMMARY OF DESIGN CONDITIONS
FOR ROTARY- AND LIGHT FIXED-
WING AIRCRAFT

Impact Direction	Velocity change (ft/sec)
Longitudinal	50
Vertical	42
Lateral*	25
Lateral**	30

*Light fixed-wing, attack, and cargo
 helicopters.
**Other helicopters.

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3.3.3 Structural Distortion

Structural distortion of the airframe and its resulting loading of the seat must be considered in the design stages. For example, a ceiling-mounted seat may experience lower loads than a floor-mounted seat because of the distortion or deflection of the roof and supporting walls. However, additional stroke distance may be required due to the inefficiency of the stroke provided by distortion of the airframe as compared to that provided by a load-limited seat. The effective stroke of a seat considered to be rigidly attached (no energy absorbers between the seat and roof) to the roof also must be considered. If the seat pan is 12 in. from the floor of the aircraft and the roof of the aircraft is expected to distort downward on the order of 12 in., careful consideration must be given to eliminating rebound rather than increasing total stroke, which could result in bottoming. In the practical case, the roof probably distorts something less than the distance between the seat pan and the floor of the aircraft; therefore, energy-absorbing stroke should be provided in the seat to maximize usage of the available space. A systems analysis should be applied to this situation to establish the correct combination of variables.

A considerable amount of the downward motion of an aircraft ceiling may be elastic. It would be advantageous to eliminate the rebound from this elastic distortion from the occupant and seat. Consideration could be given to a device that allowed vertical downward motion of the seat but restrained it from following the roof during its elastic rebound. It is possible to think in terms of an energy-absorbing device under the seat, connected to the floor, that resists motion in both the downward and upward directions. This would allow only partial return of the seat resisted by the energy-absorbing system. Another alternative would be to provide energy absorbers between the seat and the roof that would stroke when the roof returned to its equilibrium height. Again, a device that locks the seat in its lowest position would be required with this concept. Adequate support of the ceiling to support the applied loads with low deflections eliminates the problems mentioned. Efficient use of ceiling-mounted seats can be achieved in these aircraft.

A major consideration in providing crashworthy seating systems is the possibility of a local distortion in the part of the aircraft to which the seat is attached. For example, a floor-mounted seat may have to withstand severe distortions as a result of underfloor and floor deformations caused by impact forces. If the aircraft crashes on uneven ground or encounters rocks or stumps, distortions of the underfloor structure can occur. The seat structure or seat attachment to the floor

should be adequate to permit these distortions without producing failure of the seat structure or its attaching mechanisms. It should be noted that the forces causing this distortion cannot be resisted by the seat structure. In other words, it is not feasible to build a seat strong enough, if rigid, to maintain the attachment to the aircraft in these situations. The crash loads causing the distortion will, in most cases, exceed any strength that can be designed into the seat, thus, producing failures if not adequately accounted for in the design.

Likewise, distortion of bulkheads in bulkhead-mounted seats presents the same type of problem. It is apparent that local distortion of a bulkhead usually will not be of the magnitude of the distortions that can occur in the floor structure of an aircraft. Rocks and stumps can produce extremely large local deformations of structures upon which floor-mounted seats are mounted. However, rocks and stumps normally will not be involved in distortion of bulkheads and bulkhead structure. Consequently, the distortion requirements for seat mountings on bulkheads are less severe. A recent search of USASC crash records identified no known cases of bulkhead-mounted seat loss due to bulkhead distortion or fracture of attaching structure.

It is expected that sidewalls will deform more than transverse bulkheads, although they would not be as susceptible to rocks and stumps as floors. The deformation would usually be one of the wall buckling outward near the floor and changing the lateral and vertical relationships between attachment points. However, it should be remembered that in helicopters, sidewall-mounted seats are not usually pilot or copilot seats and therefore, are usually not of the stiffness that would create a problem in the environment described. For some fixed-wing aircraft, though, this may not be the case. For these cases, the aircraft/seat interface should be designed to be compatible by allowing flexibility in the seat, in the attachments, in stiffening the sidewall of the aircraft, or by simply not attaching rigid seats to sidewalls. Floor, bulkhead, and sideward warpage requirements are presented in Section 4.4.5, Joint Deformation.

3.4 APPLICABILITY OF CRITERIA

The recommendations in this volume will apply to all categories of U. S. Army aircraft. Those recommendations having application to a specific class or category of aircraft only will be so indicated by the text.

3.5 ACCEPTANCE CRITERIA

In addition to operational requirements specified in other design guide documents, seats and litter systems should be designed to provide occupant protection under crash conditions as specified in Volume II. Appropriate stress analyses, tests, and operational requirements outlined in this volume should be met by every seat, restraint, litter system, and by the cockpit and cabin interior prior to acceptance.

3.6 SELECTION CRITERIA

Crashworthy seats, restraint systems, litter systems, and cockpit and cabin materials should be evaluated on the basis of the occupant protection provided, and on their anticipated reliability and serviceability under the operational and potential crash conditions expected.

4. DESIGN PRINCIPLES FOR SEATS AND LITTERS

4.1 INTRODUCTION

There are several types of Army aircraft seating systems: pilot, copilot, crew chief, gunner, observer, student, medical attendant, troop, and passenger. Cockpit seats are typically forward-facing; however, cabin seats may face in any direction. Most are single-place seats, but in a few aircraft, two-, three-, and four-occupant cabin seats are provided. A single occupant seat is the preferred configuration in order to avoid situations where the energy-absorbing systems of multi-unit seats are rendered ineffective due to less than full occupancy (insufficient weight to activate the energy-absorbing mechanisms at loads within human tolerance limits). To the maximum extent practical, seats should be interchangeable to enable standardization. It is desirable that all seats face in the same direction so that the seat backs protect occupants from loose equipment which can become flying projectiles during crash impact.

The rearward-facing seat is optimal for providing maximum support and contact area in longitudinal impacts. The only critical impact sequence for the rearward-facing seat is one that involves a severe lateral component that allows sideward movement of the occupant prior to application of the longitudinal or vertical pulse. However, lateral torso movement can be prevented by use of an adequate restraint system of much lighter weight than that required for other seat orientations. When practical, the rearward-facing seat should be used.

Those crew members required to face forward in the conduct of their duties can be afforded adequate protection by the use of a restraint system consisting of shoulder straps, a lap belt, and a lap belt tiedown strap as discussed in Chapter 7. The lap-belt-only restraint is undesirable, as noted in the human tolerance section of Volume II. If all forward-facing passengers are provided with adequate upper- and lower-torso restraint, forward-facing seats are acceptable as a second choice to rearward-facing seats. If a single, diagonal, upper-torso restraint is used, it should be placed over the outboard shoulder of the occupants to provide restraint against lateral protrusion of the occupant outside the aircraft or impact with the sidewall.

Previously, side-facing seats have been provided with lap belt restraint only. This arrangement is considered completely inadequate for providing crash protection. Even with the addition of a shoulder harness or diagonal chest strap, the tolerance to abrupt acceleration is minimal. The use of side-facing

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seats is least desirable from the crash safety standpoint; however, when no reasonable alternative to their use exists, adequate restraint must be provided. If a single, diagonal, upper-torso restraint is used, it should be placed over the forward-facing shoulder (relative to the aircraft).

4.2 LITTERS AND THEIR ORIENTATION

The supine position of a litter patient is ideal for resisting vertical impacts. The contact area is the maximum possible, and the decelerative forces act transversely to the body. For existing litters, the major problem occurs as a result of impact forces in the lateral/longitudinal plane. The relatively flat litter surface makes it difficult to provide an adequate restraint harness to resist these loads. The current practice of wrapping two lengths of webbing around the litter offers a degree of restraint oriented transversely to the body, but only frictional forces prevent the body from sliding off the litter in the lengthwise direction.

Litters should be installed laterally to provide more positive restraint for expected combined crash forces. A lateral litter orientation also will prevent the litter from becoming completely detached from its current supports as occurs in a longitudinal orientation explained in Reference 22. The litter must withstand all of the environments previously described for the seats.

4.3 MATERIALS

Designers should select materials that offer the best strength-to-weight ratios while still maintaining sufficient ductility to prevent brittle failures. The guidelines in this section will alert the designer to certain material properties that can contribute to improved structural designs. These properties include ultimate strength, elongation, and energy-absorbing capabilities. The standard method for selecting materials using elastic analysis is adequate for most conditions in the working life of an article. For crashworthiness, however, only one application of the maximum load is expected, and the behavior of the material beyond the yield point generally is important.

22. Weinberg, L. W. T., AIRCRAFT LITTER RETENTION SYSTEM DE-
    SIGN CRITERIA, Aviation Crash Injury Research (AvCIR), Di-
    vision of Flight Safety Foundation, Inc.; USAAVLABS Tech-
    nical Report 66-27, U. S. Army Aviation Materiel Labora-
    tories, Fort Eustis, Virginia, April 1966, AD 632457.

The degree of ductility needed in a seat's basic structural parts is highly dependent upon whether the seat structure is designed to absorb energy by the use of a separate lc.d-limiting device or whether large plastic deflections of the basic structure are required. As a general rule, a value of 10-percent elongation is a rough dividing line between ductile and nonductile materials. The 10-percent value is recommended as a minimum for use on all critical structural members of nonload-limited seats because the exact peak load is unpredictable due to pulse shape, dynamic response of the system, and velocity change. A minimum elongation of 5 percent in the principal loading direction is suggested for use on critical members of load-limited seats because the loads and strains are more predictable.

Castings are not recommended for use in primary load paths. In general, their quality is more difficult to verify and reproduce, and their ductility and fracture toughness are less than for forgings.

The effects of stress corrosion, (for example, selection of 7075 aluminum alloy in a T73 condition rather than T6), must be considered, as well as hydrogen embrittlement due to heat treating or various processing steps such as pickling (for example, 17-4PH stainless steel). In short, adherence to all the normal engineering design principles must prevail.

Flammability and toxicity retardation requirements are discussed in Volume V. Upholstery padding and other materials used in seats should meet the specified requirements.

4.4 STRUCTURAL CONNECTIONS

4.4.1 Bolted Connections

For the manufacture of basic aircraft structure, most aircraft companies recommend 15- and 25-percent margins of safety for shear and tensile bolts, respectively. These factors are intended to allow for misalignment of holes, stress concentrations, and fatigue. Fatigue is not generally a factor in the design of a seat or litter system fitting, since high loading of the fitting would be a one-time situation. Therefore, the safety factor for shear and tensile bolts located in load-limited portions of the seat where loads can be predicted accurately, can be reduced to 5 and 10 percent, respectively. Also, good aircraft engineering practice dictates that bolts less than 0.25 in. in diameter should not be used in tensile applications because of the ease with which these smaller bolts can be overtorqued. Because of the obvious advantages of structure being able to distort while maintaining load-carrying

ability, fasteners of maximum ductility for the application should always be selected. Where possible, fasteners such as bolts and pins should have a minimum elongation of 10 percent in the longitudinal and transverse directions.

4.4.2 Riveted Connections

The guidelines for riveted joints are presented in MIL-HDBK-5, and it is recommended that these guidelines be followed (Reference 23).

4.4.3 Welded Connections

Welded joints can be 100 percent efficient; however, the actual efficiency is dependent upon the skill of the welder, the process used, and the inspection procedures followed. Welded joints can be completely acceptable and even superior to bolted or riveted joints. However, strict inspection procedures should be used to ensure that welded joints are of good quality. Welded joints may result in stress concentrations and misaligned parts in a manner similar to bolted joints; therefore, the cross-sectional area of the basic material in the vicinity of a welded joint should be 10 percent greater than the area needed to sustain the design load. Welding processes are discussed in Military Specifications MIL-W-8604, -6873, -45205, and -8611; these specifications should be used as guides to ensure quality welding.

4.4.4 Seat Attachment

Cockpit seats are either bulkhead or floor mounted. Acceptable means of attaching seats to the cabin interior are listed below (refer to Section 3.3.3 for a discussion of ceiling-mounted seats and ceiling support stiffness):

1. Suspended from the ceiling with energy absorbers, and wall stabilized.

2. Suspended from the ceiling with energy absorbers, and floor stabilized.

3. Wall mounted with energy absorbers.

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23. Military Handbook, MIL-HDBK-5, METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES, Department of Defense, Washington, D. C.

4. Floor mounted with energy absorbers.

5. Ceiling and floor mounted (vertical energy absorbers above and below seat).

Suspension or mounting of all seats should not interfere with rapid ingress or egress. Braces, legs, cables, straps, and other structures should be designed to prevent snagging or tripping. Loops should not be formed when the restraint system is in the unbuckled position. Cabin seats must often be designed so that they may be quickly removed or folded and secured. Tools should not be required for this operation. The time required by one person to disconnect each single occupant seat should not exceed 20 sec. The time required by one person to disconnect multi-occupant seats should not exceed 20 sec multiplied by the number of occupants. All foldable seats should be capable of being folded, stowed, and secured or unstowed quickly and easily by one person in a period not to exceed 20 sec multiplied by the number of occupants.

4.4.5 Joint Deformation

Floor distortions as a result of impact can cause failure of the seat structure or tiedown connections in an aircraft crash (see Figure 5). A floor distortion can take the form of a bulge or dish in the floor surface between the seat tiedown connections. This produces a rotation of the seat relative to the floor surface, resulting in a connection failure if the deflection limits for the attachments are exceeded. A twisting or warping of the floor surface can also take place, producing distortion loads in the seat structure. Seat or connection failure can result from the additional loads imposed. The seat designer must anticipate possible floor bulging or warping and take appropriate measures in seat structural design to minimize the adverse effects.

For basically rigid seat structures that are distorted the critical design parameter appears to be the torsional rigidity of the seat pan, bucket, and/or structural members. If the torsional rigidity is low, only small forces are introduced. However, for stiff seat members, the warpage forces may produce a structural failure or impose a preload that, when coupled with crash inertial loads, results in failure. A high torsional rigidity in the seat pan may arise from integrating stiff lateral cross tubes between side trusses so that the tubes must also twist with the seat pan. Consequently, it may be desirable to connect the cross tubes to the seat pan in such a way that the seat pan is free to twist independently of the cross tubes or to design the crossmembers to be soft in torsion. Integrally armored crewseats are stiff and difficult to release
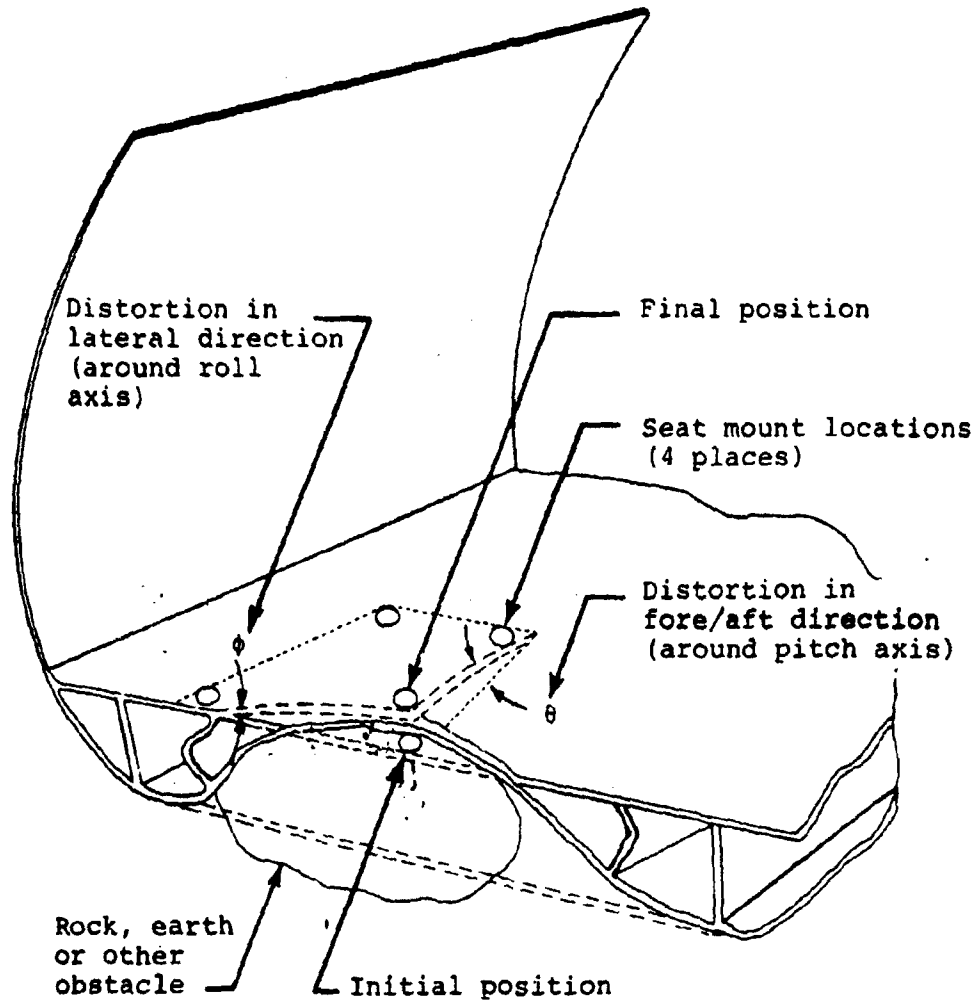
Figure 5.   Sketch illustrating buckling
or "dishing" formation.

from the support structure in order to permit distortion. One
method used successfully to solve this problem has been a three-
legged seat. The three support points can follow the floor
movement without distorting the seat structure because the seat
is free to tip (Reference 24).

24.   Desjardins, S. P., and Harrison, H., THE DESIGN, FABRICA-
      TION, AND TESTING OF AN INTEGRALLY ARMORED CRASHWORTHY
      CREWSEAT, Dynamic Science, Division of Marshall Indus-
      tries; USAAMRDL Technical Report 71-54, Eustis Director-
      ate, U. S. Army Air Mobility Research and Development
      Laboratory, Fort Eustis, Virginia, January 1972, AD 742733.

To prevent seat connection failures induced by floor dist   ion, structural joints should be capable of large angular displacements in all directions without failure. A seat designed properly for structurally integral load limiting would also satisfactorily accommodate floor buckling and warping under crash conditions. Figure 6 illustrates recommended limits of floor warping or buckling that must be withstood by all floor-mounted seat designs. The mounts should be capable of withstanding a ′ ⁰-degree warp of the floor, as well as a ±10-degree rotat .on ·.out a roll axis of a single track. The angles are based on distortions that have been noted in potentially survivable accidents.

With respect to the floor surface and to accommodate rotations that result from floor bulging, several design configurations may be considered. Two of these are presented below and are illustrated in Figure 7.

- A deliberate plastic hinge of sufficiently ductile material may be incorporated into the tiedown connection design. This plastic hinge would be required to permit yielding without failure up to a rotation angle that exceeds the maximum anticipated as a result of floor bulging. The hinge also would be required to carry the associated compressive, tensile, and shear loads in order to retain the seat while yielding in bending.

- A structural release such as a ball-and-socket joint may be used to permit relative rotation.

Other methods, such as a combination of a plastic hinge about one axis and rotation about an axle or pin oriented along a perpendicular axis, are acceptable also. The joint must be capable of sustaining large tension, compression, and shear forces during and after rotation.

The effect of not providing for relative seat leg-to-floor rotation can be illustrated by an actual example. The rear legs of a crewseat on early models of a U. S. Army helicopter were attached to a base frame with castings as illustrated in Figure 8. These castings failed repeatedly in accidents as a result of combined axial and bending stresses acting at the region of stress concentration. Studies showed that the seat could sustain a longitudinal decelerative force nearly twice as great when the bending moment at the juncture between the rear leg and the track fitting was removed.
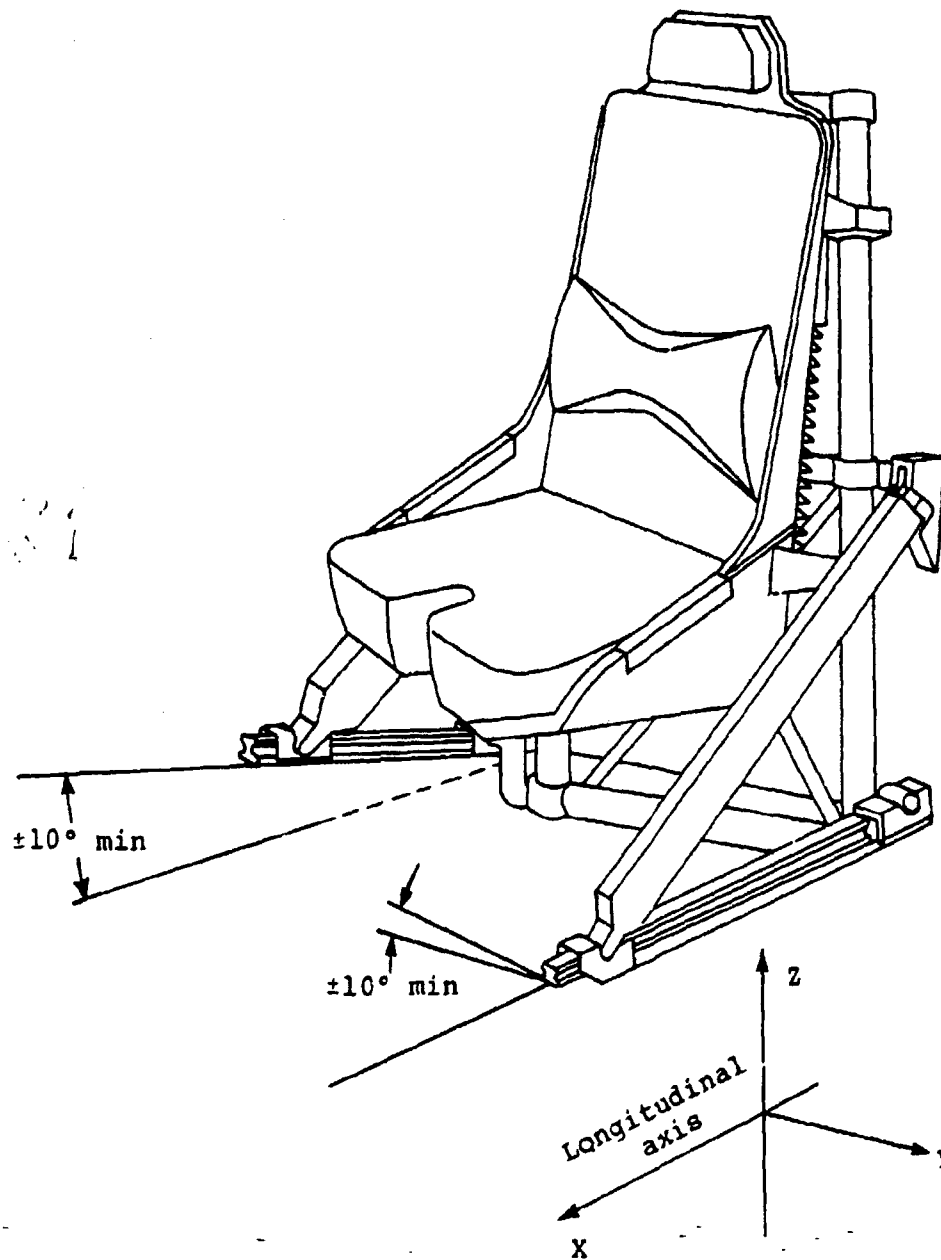
Figure 6. Static test floor warpage requirement to improve
the probability of seat retention in crashes.

This modification is illustrated in Figure 9. The moment was
relieved by cutting the corners off the casting so that only
the section around the center bolt remained. The joint was
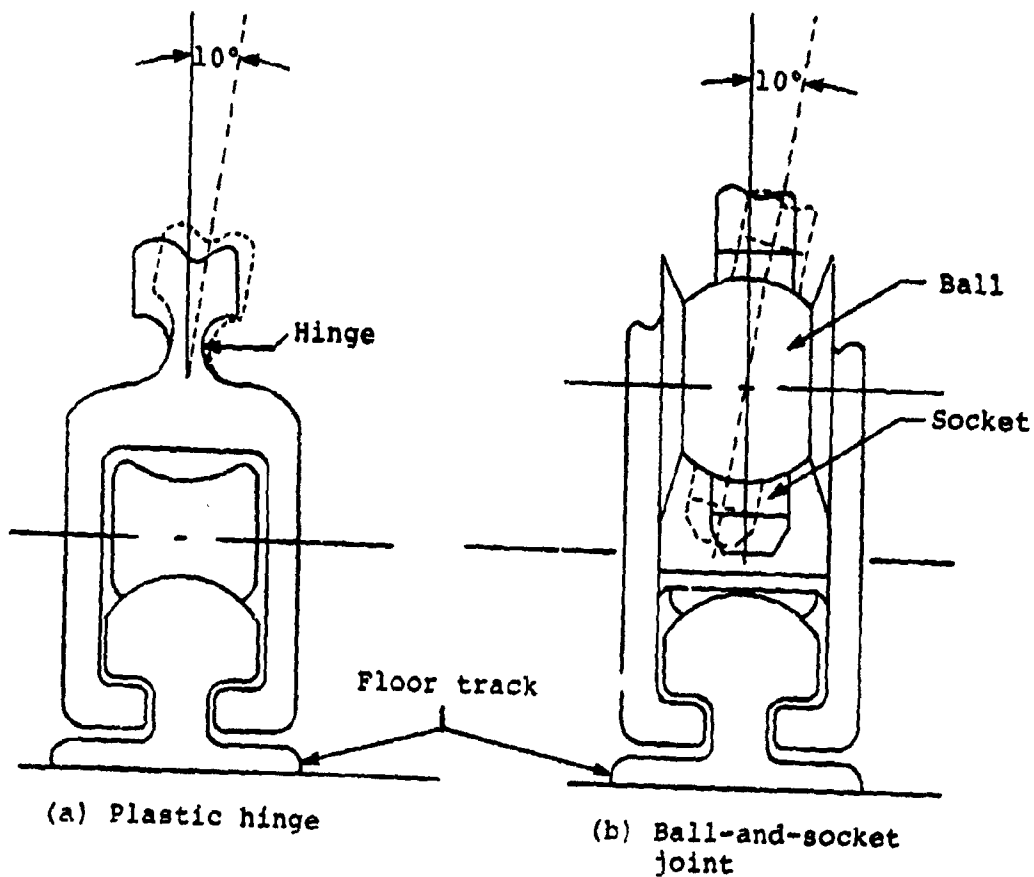
Figure 7. Concepts for release of floor-distortion-induced moments.

thereby changed from a fixed- to a pinned-end configuration. Subsequent tests showed improved load-carrying capacity.

Other methods of relieving torsion and moments include using spherical bearings and slotting holes through which bolts pass. For example, if a crossmember is required to move torsionally during floor warping, slots that relieve the loads can be provided for fasteners at end fittings. This is illustrated in Figure 10. Figure 11 illustrates an example of a fully-released joint acted on by two torsional loads and a moment.

The same general principles that apply for floor-mounted seats also apply for bulkhead-mounted seats except that the deflection and degree of warping of the bulkhead appear to be less than that of the floor. This is probably due to the bulkhead being less vulnerable to local planar distortion caused by

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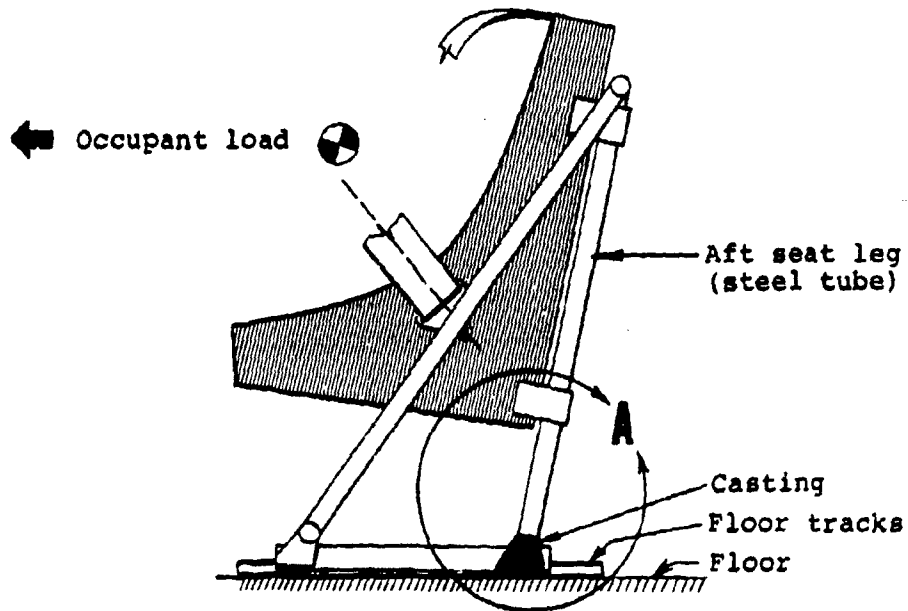
Figure 8. Aft seat leg casting attachment.

View **A** <u>Before</u> modification   View **A** <u>After</u> modification
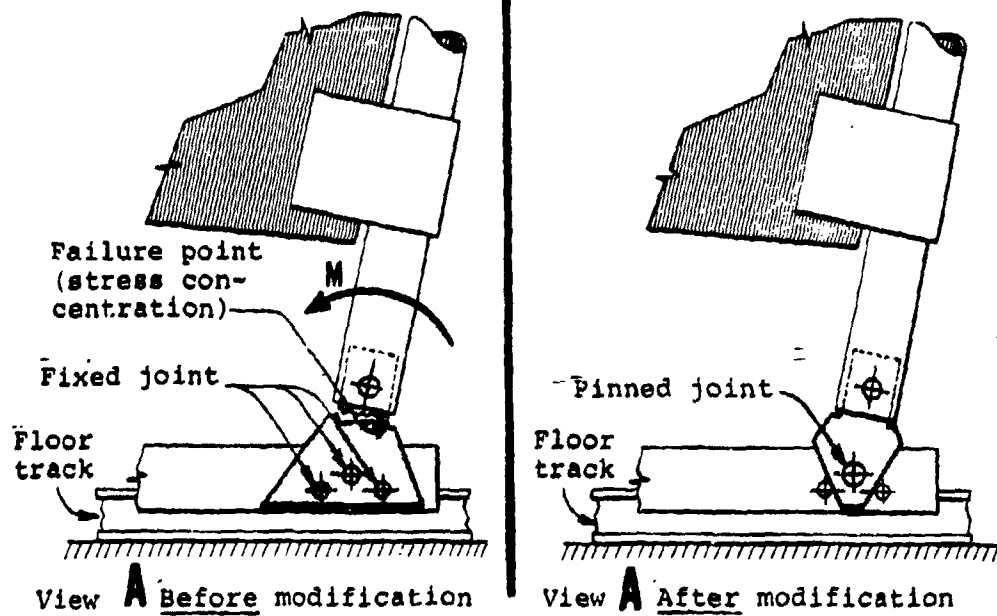
Figure 9. Aft seat leg casting attachment modification.

57
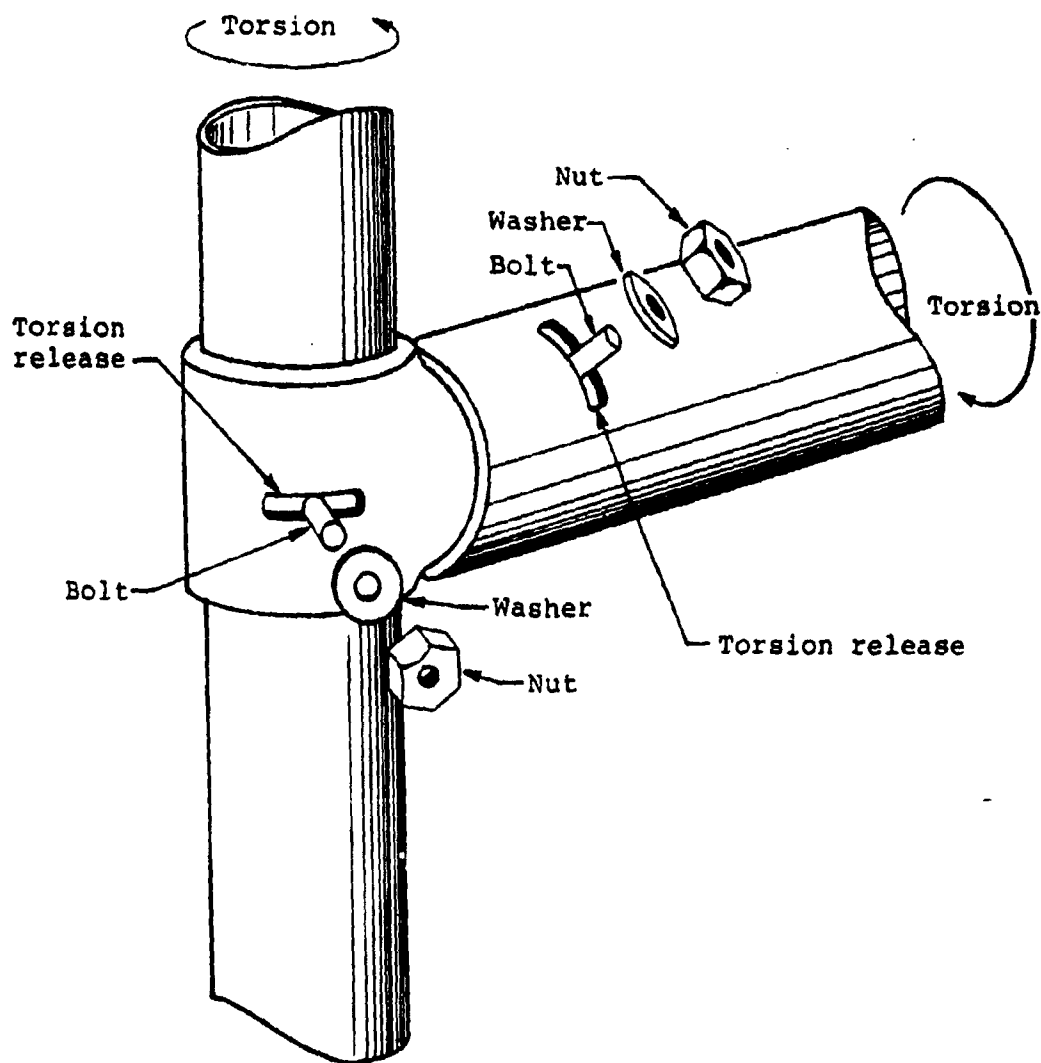
Figure 10. Torsional release of joints.

items such as rocks and stumps impacted by the underfloor
structure. A possible bulkhead distortion configuration is
shown in Figure 12. The recommended angular deflection re-
quirement for bulkhead-mounted seats is a 5-degree rotation in
the plane of the bulkhead. To accommodate local deformation,
each attachment of the seat to the bulkhead should be released
to permit ±10-degree rotations in any direction. One technique
for accomplishing this is with spherical bearings, as illus-
trated in Figure 13.

Sidewall-mounted seats require the same considerations as
bulkhead-mounted seats. As mentioned previously, the sidewalls
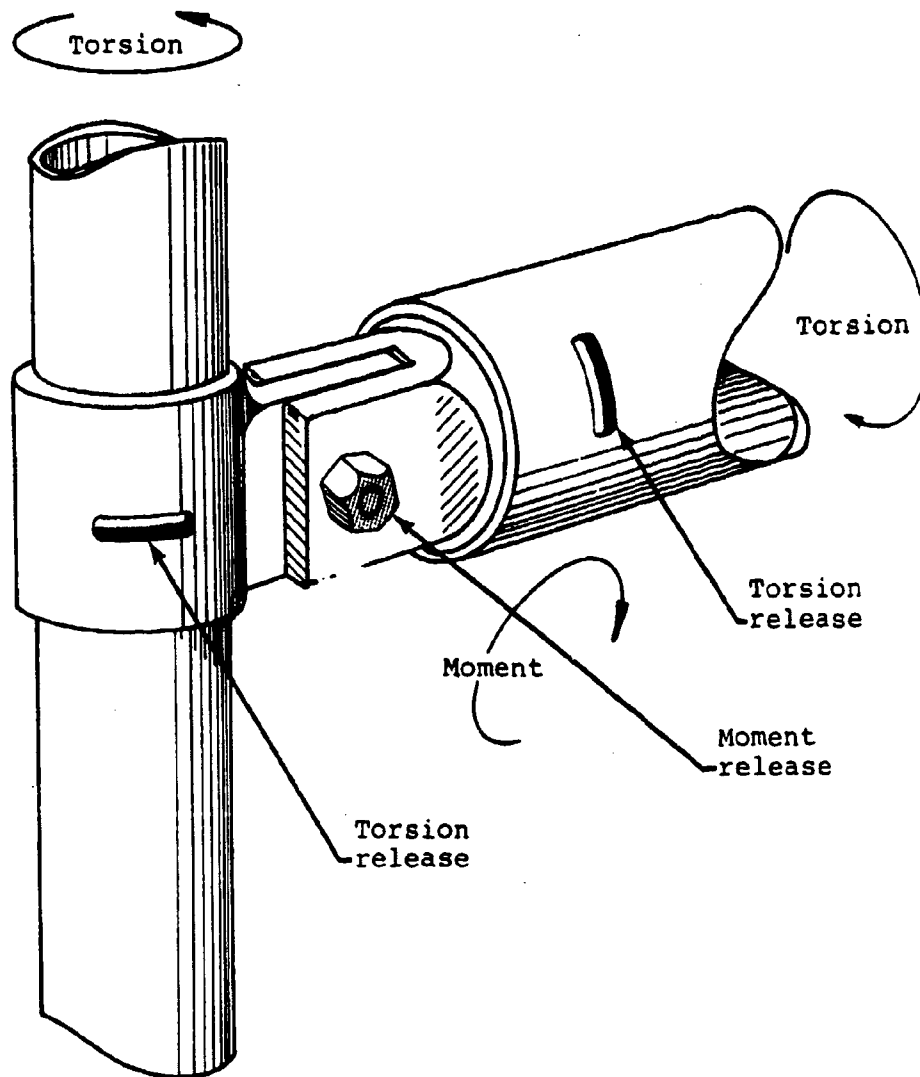
Figure 11. Fully released joint.

of aircraft tend to bow outboard during impacts with high vertical loading. Therefore, it is advisable that these seats be designed to accept relatively large distortions without failure. Although the angles are not known, it is expected that they may reach 25 degrees.

Seats that are mounted totally on the sidewall should not create a problem, as they will simply move with the sidewall. Extremely flexible seats also should be inherently immune from these problems. However, rigid seats mounted to both the floor

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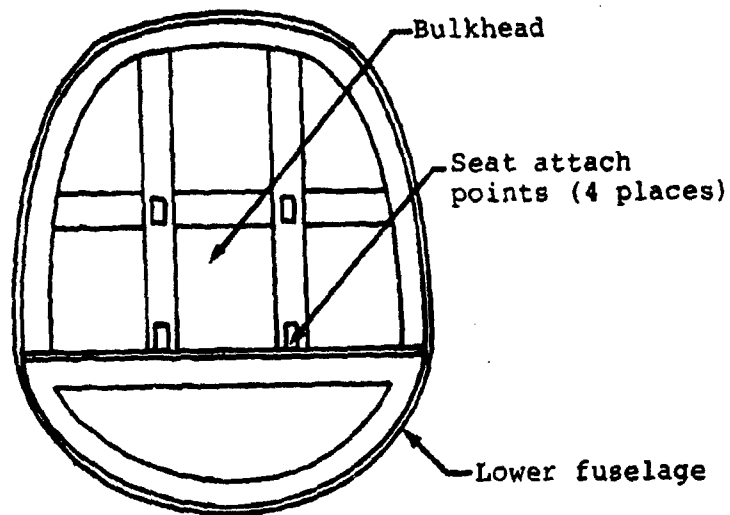
(a)   Initial configuration
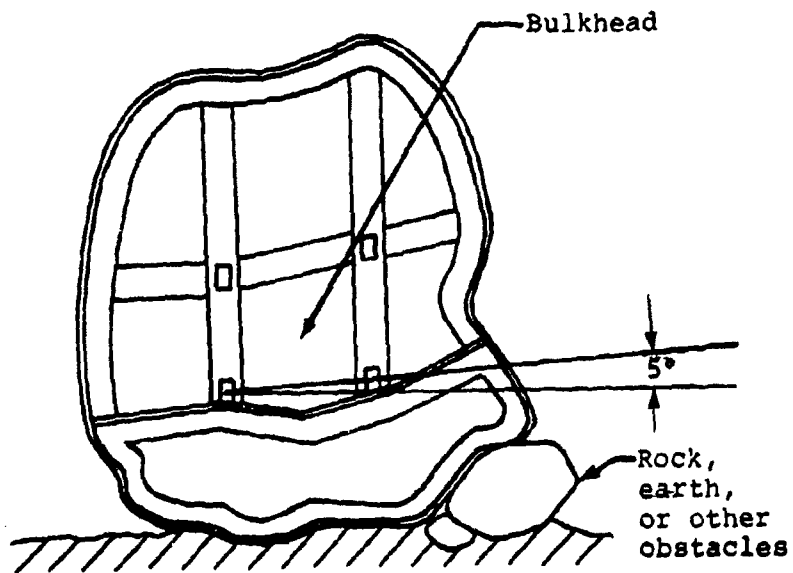
(b)   Postcrash configuration

Figure 12.   Bulkhead in-plane warping.

60
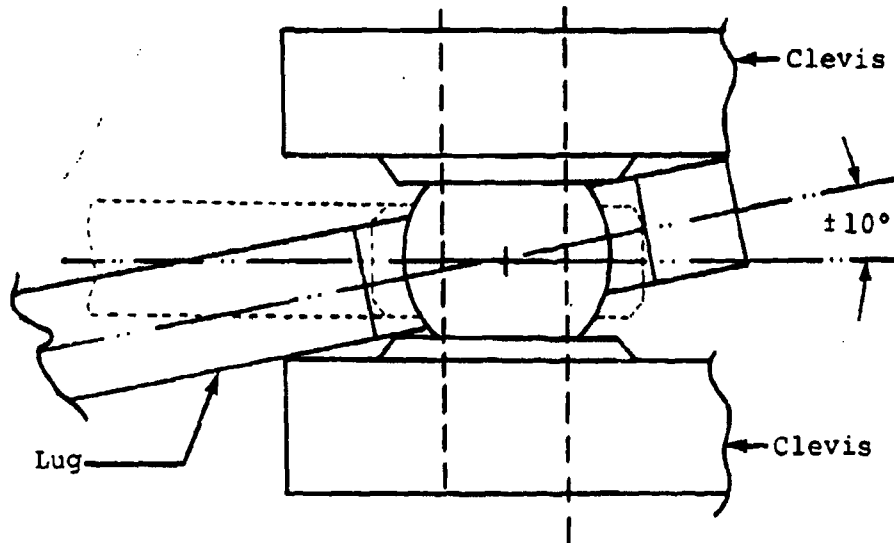
Figure 13. Universal release of a joint.

and the sidewall will require special design considerations. One way to provide the flexibility needed is to include releases such as pin joints, oriented to allow rotation around an aircraft roll axis. An example is shown in Figure 14. The attachments should be designed to permit the angle θ to reach 25 degrees at the maximum dynamic deflection.

The underfloor, bulkhead, or sidewall structure must be designed to be compatible with the seat. For example, the design of structural releases between the seat and the track may enable the seat to maintain its attachment during large floor deformations but may add to the torsional responsibilities of underfloor beams. If a large downward load is applied to the floor structure through a joint that does not carry moment (released), then the underfloor beams must resist any moment that may be developed without assistance from the seat structure. To illustrate, take the case of a seat strut attached through a release to the front floor track. During longitudinal loading in the forward direction, the strut is loaded in compression and applies a large downward load at the release. Any eccentricity between the load vector and the centroid of the underfloor beam will produce torsional loading around the beam's long axis. The beam must possess the capability to resist this torsional load through either its own torsional strength or that of its supporting structure.

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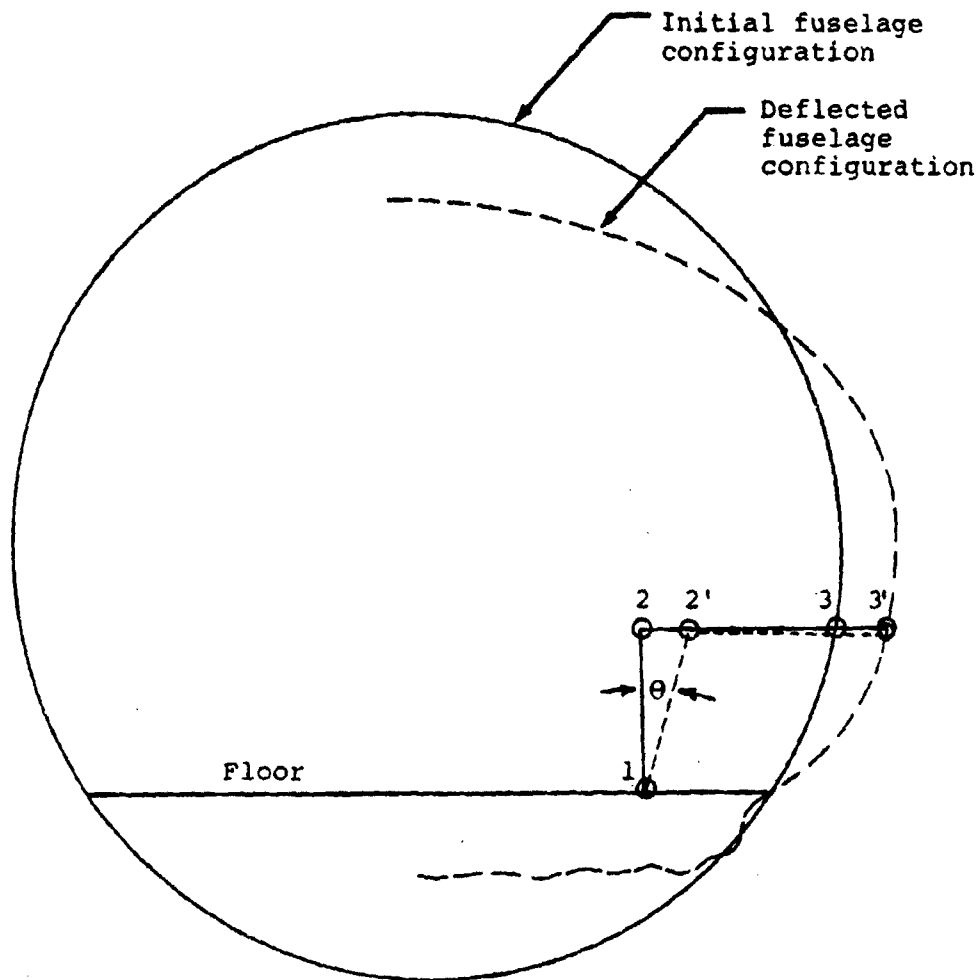
Figure 14. Pin joint releases oriented to allow rotation around an aircraft roll axis.

4.5 STRENGTH

4.5.1 General

An elastic stress analysis, as used in the design of airframes and aircraft components subjected to normal flight loads, is inadequate for the study of all the structure in a crash situation. For normal flight loads, keeping the stresses well below the material yield stress to avoid permanent deformation is necessary because of fatigue problems and, perhaps, other considerations. In a crash situation, however, where only one

application of maximum load is expected, fatigue is not a factor, and the final configuration of a structural component or its subsequent operational use need not be considered. Consequently, the load-carrying capacity of components deformed beyond the elastic limit should be considered in determining the ultimate seat strength. As a matter of fact, it is advisable for certain items in the load path to use the rupture strength as listed for many materials in MIL-HDBK-5 (Reference 23). The concepts of limit analysis or, in some circumstances, large deformation analysis, may be employed to make the best use of materials in certain components.

It may appear that the only difference between an elastic stress analysis and an ultimate strength analysis is that the former is more conservative. However, a more significant distinction is demonstrated by a comparison of two designs having the same maximum stresses for elastic behavior but decidedly different load-carrying capacities when the loads exceed the elastic limits. For example, consider the following two similar designs: (a) two simple beams spanning three supports and (b) a continuous beam spanning the same three supports, as illustrated in Figure 15.

(a) Two simple beams   (b) Continuous beam
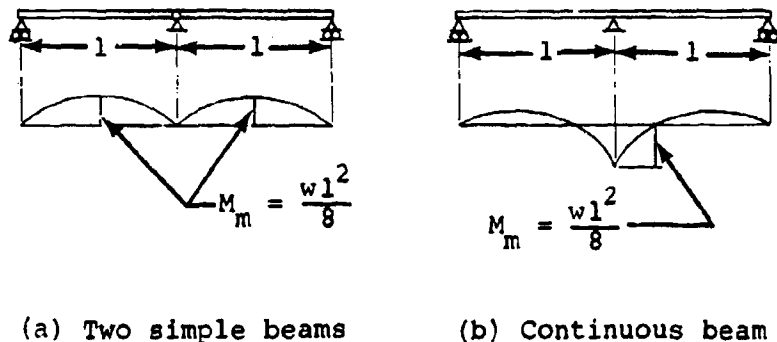
Figure 15.   Comparison of analysis methods
for simple beams.

For a uniformly distributed load, w, the bending moment diagrams are as shown (assuming elastic behavior). It is noted that in each case the maximum bending moment is $wl^2/8$ and each design has the same stress. There is a temptation to equate the designs from a strength viewpoint. However, considering design (a), if the load is gradually increased, the bending moment at the center of each span will eventually equal the moment resistance capability of the beam. For a ductile material, a yield hinge would form then at these maximum moment

points. Additional load could not be accepted without a mechanical collapse. This critical load would represent a realistic ultimate capacity for the beams. On the other hand, when a yield hinge occurs in design (b) under similar circumstances, it would occur at the middle support and, hence, not produce a collapsing mechanism. The load, w, could be further increased without collapse until a second set of yield hinges forms between the supports. Only then would collapse occur. It is intuitively evident, and may be demonstrated by analysis, that design (b) sustains a much greater ultimate load than does design (a), yet the difference is not discernible from elastic analysis. The design of an entire occupant retention system, ignoring inelastic postyield behavior, would result in components of varying ultimate strengths, some much stronger than others. The overdesigned components do not increase the strength of the system. It is desirable that all components work at the same allowable strength level just before failure.

A 1963 study of the restraint system used in three U. S. Army aircraft indicated that the strengthening of a few weak links in the tiedown chain improved the crash strength of these systems by a factor of 2 with only minor weight increases (References 25 through 27). A simple example of the benefit of strength analysis beyond the elastic limit is the improvement in the tiedown strength of the crewseat floor track in one of the three aircraft. In the existing arrangement, the seat leg may be positioned directly above a pair of seat track tiedown bolts (Figure 16). The elongation of the bolts prior to their failure would not be sufficient to permit bending in the floor track; thus, no appreciable load could be transmitted to the adjacent pair of bolts. To improve the ultimate strength of this connection, it was suggested that aluminum collars, which compress at a load slightly less than the breaking strength of

25. Haley, J. L., Jr., and Avery, J. P., Ph.D., PERSONAL RESTRAINT SYSTEMS STUDY - HC-1B VERTOL CHINOOK, AvCIR 62-26, Aviation Crash Injury Research (AvCIR), Division of Flight Safety Foundation, Inc., Phoenix, Arizona, November 1962.

26. Haley, J. L., Jr., and Avery J. P., Ph.D., PERSONAL RESTRAINT SYSTEMS STUDY - HU-1A AND HU-1B BELL IROQUOIS, AvCIR 62-27, Aviation Crash Injury Research (AvCIR), Division of Flight Safety Foundation, Inc., Phoenix, Arizona, December 1962.

27. Haley, J. L., Jr., and Avery, J. P., Ph.D., PERSONAL RESTRAINT SYSTEM STUDY - CV-2 DE HAVILLAND CARIBOU, AvCIR 62-16, Aviation Crash Injury Research (AvCIR), Division of Flight Safety Foundation, Inc., Phoenix, Arizona, April 1964.

Present attachment

Seat reaction — Leg stud

0.50 in. — Floor track

Leg stud

Proposed attachment

Leg stud

0.25 in.
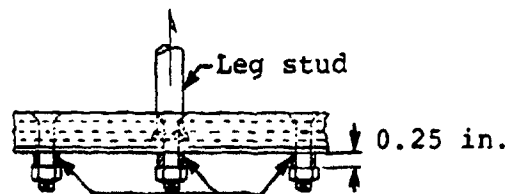
Aluminum collars added

Figure 16. Seat leg anchorage to floor track.

the bolt, be added beneath the nut. Thus, the collars would yield prior to failure of the center bolts and permit the track to bend and transmit some load to the adjacent bolts. This arrangement approximately doubled the ultimate tiedown strength of the floor track while adding a negligible amount of weight.

4.5.2 Limit Analysis Concepts

Where ductile materials are used, strain concentrations do not produce rupture prior to significant plastic deformation. If the geometric configuration of the structure permits only small elastic deflections, a rigid-plastic mathematical model may be used. This permits the use of a limit analysis, which assumes no deformation of structure until sufficient plastic hinges, plastic extensors, etc., exist to permit a geometrically admissible collapse mode.

Limit analysis is concerned with finding the critical load sufficient to cause plastic collapse with the physical requirements of static equilibrium, yield conditions for the materials,

and consistent geometry considerations. The principles of
limit analysis are well developed by a number of authors (References 28 and 29, for example). Two useful principles are
mentioned here: the upper and lower bound theorems. The upper
bound theorem for the limit load (collapse load for a rigid-plastic structure) states that the load associated with the
energy dissipated in plastic deformation will form an upper
bound for the limit load. The lower bound theorem, on the
other hand, states that the load associated with a statically
admissible stress distribution, which at no point exceeds the
yield conditions, forms a lower bound for the limit load. Use
of the upper and lower bound theorems to bracket the limit load
for a given structure makes it possible to obtain a realistic
evaluation of the structure's load-carrying capacity.

4.5.3 Large Deformation Analysis

If a structure contains elements that will permit large, stable elastic deformations when under load, the equilibrium of
the deformed state must be considered in evaluating ultimate
strength. For example, if a suitable attachment is made to a
thin flat sheet rigidly fixed at the edges so as to load the
sheet normal to the surface, a diaphragming action will occur.
The equilibrium and stress-strain (elastic-plastic) relations
for the deformed state would determine the load-carrying capacity. An example of this situation is a seat pan in which membrane rather than flexural stresses are important.

4.5.4 Strain Concentrations

Handbook stress concentration factors provide sufficiently accurate data to allow the designer to modify the structure in
the vicinity of stress concentrations. When large deformations at high load-carrying capacity are desired, as in energy-absorbing seats, these areas frequently become strain concentration points and rupture occurs, due to excessive strain, in
areas with little deformation and energy input. Large amounts
of energy can be absorbed in the structure only if large volumes

28. Beedle, L., PLASTIC DESIGN OF STEEL FRAMES, John Wiley
and Sons, New York, 1958.

29. Hodge, P. G., Jr., PLASTIC ANALYSIS OF STRUCTURES, McGraw-Hill Book Company, New York, 1959.

of material are strained uniformly. For further information on the subject, see pages 69-73 of Reference 30.

4.6   RESTRAINT SYSTEM ANCHORAGE

The design requirements for occupant restraint systems are presented in Chapter 7; however, the seat designer must consider the effect of the anchorage of the restraint system on the characteristics of the seat design. The restraint system should be anchored to the seat rather than to basic aircraft structure.

If the restraint system is anchored to basic aircraft structure, a desirable reduction of loads on the seat frame results; however, the restraint system must be designed to permit the energy-absorbing deformation of the seat during an impact. For example, if a load-limited seat strokes vertically and the seat belt is anchored to the floor, the loosening of the belt would permit the occupant to "submarine" under the belt or to move laterally. When the harness is anchored to the seat structure, the problem of maintaining a snug harness is reduced.

An advantage of attaching the shoulder harness to basic aircraft structure is the large reduction in overturning moment on the seat. To make this attachment acceptable, a simple load-limiting device might be incorporated into the shoulder harness anchorage to allow for longitudinal or vertical movement of the seat. On some aircraft, where room allows it, another option is to locate the anchor point far enough to the rear of the seat to allow vertical energy-absorbing stroke of the seat with only a rotation of the strap about the anchor point. If the distance is sufficiently large, the fore-and-aft motion resulting from the strap swinging in an arc can also be insignificant.

4.7   CRASH ENERGY ABSORPTION

4.7.1   General

The magnitude of a crash force is a function of the input velocity and the stopping distance. The stopping distance is controlled basically by the crushing of the airframe and landing gear in a given direction coupled with the gouging of the impact surface. The magnitude of the average deceleration of

30.   Turnbow, J. W., et al., AIRCRAFT PASSENGER-SEAT-SYSTEM RESPONSE TO IMPULSIVE LOADS, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc.; USAAVLABS Technical Report 67-17, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, August 1967, AD 661088.

a given point of the aircraft may be calculated from the following equation:

$$a = \frac{v_o^2 - v_f^2}{2S} \text{ or } \bar{G} = \frac{v_o^2 - v_f^2}{2gS} \quad (1)$$

where a = average deceleration, ft/sec^2

   $\bar{G}$ = average deceleration, G

   v_o = initial velocity, ft/sec

   v_f = final velocity, ft/sec

   g = acceleration due to gravity, 32.2 ft/sec^2

   S = total displacement of the point of the aircraft with respect to the ground, ft

It can be seen from the equation that the magnitude of the deceleration is inversely proportional to the stopping distance. In the case of a rigid structure impacting a nonyielding surface, the deceleration would be infinite. Some crushing of structure and soil educes or attenuates the deceleration to finite levels. Often, however, there is insufficient crushing to attenuate deceleration magnitudes to human tolerance levels. Tolerable levels can be achieved by increasing the stopping distance. The extra stopping distance may be provided by using: (1) additional crushable airframe structure, (2) energy-absorbing landing gear, (3) a seat design that possesses an energy-absorption mechanism(s) (load-limiting or controlled seat collapse), or (4) a combination of methods (1), (2), and (3).

The energy-absorption capability of a seat structure is also of considerable importance in evaluating the seat dynamic strength. Due to extension of the restraint harness, compressibility of the soft human tissue under the harness, penetration into the seat cushion, and relative movement of body parts, the occupant's center of gravity acquires a velocity relative to the airframe during an abrupt deceleration.

Depending upon the magnitude and duration of the deceleration pulse, as well as the nature of the connection between the occupant and the seat structure, the maximum relative velocity may be large. The seat structure, in order to perform its intended retention function, must then either (1) possess the capability of sustaining the maximum inertial force imposed by

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the deceleration of the occupant and the seat without collapse, or (2) possess sufficient energy-absorption capacity to reduce the occupant's relative velocity to zero before structural failure occurs. The first alternative may result in an excessive strength requirement because the input pulse shape and elasticity of the restraint system and cushion can result in significant dynamic overshoot. Computer simulation and experimental observation have shown that overshoot factors range from 1.2 to 2.0, necessitating a seat design strength requirement of 24 G to 40 G to accommodate an input floor pulse of 20 G.

The second alternative of using collapse behavior (load limiting) appears to offer the more practical approach to seat design. With this option, the seat structure would begin plastic deformation when the acceleration of the occupant and seat mass reaches a level corresponding to the critical structural load. The seat must absorb enough energy without failure to stop the motion of the occupant relative to the aircraft. Of course, this energy must be absorbed at force levels within human tolerance limits to provide the intended protective function.

In an attempt to eliminate common misconceptions regarding the role of energy-absorbing seats, a few introductory comments are made:

- The seat energy-absorbing system does <u>not</u> absorb all the ⁻gy associated with the impact velocity. The se⁻ ⁻⁻eriences the total velocity change; however, mo ⁻ the energy is absorbed by deforming earth, stroking landing gear, and deforming structure.

- The absorption of energy by the above processes produces the triangular-shaped deceleration versus time pulse used as the design input to the seat.

- The seat energy-absorbing stroke simply lengthens the stopping distance of the occupant by allowing energy-absorbing stroke of the seat to occur as the other energy-absorbing processes are nearing completion. In a crash in which the aircraft comes to rest in the major impact, much of the seat stroke can occur after complete deceleration of the aircraft fuselage. Thus, after the fuselage stops, the seat may continue to stroke until its kinetic energy has been exhausted.

- Disregarding dynamic response differences, the same stroke distance is required to decelerate any mass at a given deceleration magnitude. Therefore, lighter people do <u>not</u> require shorter strokes than heavier

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people for the same deceleration magnitudes. Of
course, loads required to decelerate occupants of
different weights at equal deceleration magnitudes
must vary with occupant weight.

- Consideration of the first comment explains why it
is detrimental to allow slack to develop in the re-
straint system or seat attachments. If the occupant
is allowed to continue to move with little or no
restraint through any significant portion of the
energy-absorbing process anywhere in the system (not
just in the seat and restraint system), a great deal
more stroke or, a much higher load, will be required
to decelerate the occupant. If the occupant moves
with little restriction until the fuselage stops mov-
ing, the occupant will then require the same stop-
ping distance as the fuselage to experience the same
G loads as the fuselage. Since this stroke is not
available, the loads would be high.

Aside from the seat structure, there are other areas within
the aircraft where energy absorption may find application.
Protective padding, generally a plastic foam, should be used
where structure is likely to be impacted by the occupant, par-
ticularly where head impact is likely. Deforming structure
such as sheet metal behind the foam also is helpful in such
items as instrument panels, glare screens, etc. Characteris-
tics that should aid in the selection of foams for such appli-
cations are discussed in Section 10.9. Also, energy-absorbing
webbing for restraint systems and litters is discussed in Sec-
tion 7.4.4.

4.7.2 Principle of Energy Absorption - Illustration

As an example of the energy-absorption allocations, rewrite
equation (1) for stopping distance as follows:

$$S = \frac{v_o^2 - v_f^2}{2g\bar{G}} \tag{2}$$

Assuming that v_o = 42 ft/sec, v_f = 0, and the average decelera-
tion produced by deforming terrain, flattening tires, stroking
energy-absorbing gear, and crushing fuselage is 10 G:

$$S = \frac{42^2}{(2)(32.2)(10)} = 2.73 \text{ ft} = 32.87 \text{ in.}$$

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This stroke is 2.73 times the minimum required for the seat;
however, the loads are well within human tolerance limits. If
the entire cumulative stroke could be accomplished at 11.5 G,
which is assumed to produce a deceleration environment toler-
able to humans in this direction, the total distance is

$$S = \frac{42^2}{(2)(32.2)(11.5)} = 2.38 \text{ ft} = 28.60 \text{ in.}$$

Obviously, 28.60 in. of stroke is impractical for a seat, so
the crash energy-absorption function must be a combination of
energy-absorbing landing gear, crushable airframe structure,
and seat energy absorption. The following example illustrates
how the seat and airframe (including the landing gear) combine
to limit decelerative loading of the occupant, assuming rigid
body mechanics, a triangular deceleration input pulse, and a
seat energy absorber load-deflection curve with the same rise
time as the input pulse and a constant limit load.

The triangular deceleration-time plot is an assumed, idealized
input to the system. In actual practice, the dynamic response
of the system as measured on any individual component does not
match this form because of the differing dynamic properties of
the components as discussed in Section 4.7.3.2.   The displace-
ment of the seat/occupant system relative to the airframe is
computed using the following notation:

Let G_m = maximum airframe deceleration in the vicinity of
          the seat attachment, G

      G_L = maximum seat/occupant system deceleration, G

      K = G_L/G_m, t_L/t_m (limited to 0.5 or less)

      t_m = time at maximum airframe deceleration (one-half in-
          put pulse duration), sec

      t_L = time to reach maximum system deceleration, sec

       t = time, sec

       v = velocity, ft/sec

      v_a = velocity of airframe at any time t, ft/sec

      v_s = velocity of seat/occupant system, ft/sec

v_L = common airframe and system velocity at $t = t_L$, ft/sec

v_o = initial impact velocity, ft/sec

g = acceleration due to gravity, ft/sec^2

a = airframe acceleration, ft/sec^2

a_s = seat/occupant acceleration, ft/sec^2

S = displacement, ft

S_a = airframe displacement, ft

S_s = seat/occupant system displacement, ft

The airframe acceleration in the interval $0 \leq t \leq t_m$ is given by

$$a = -G_m g t/t_m \qquad (3)$$

where the minus sign indicates a deceleration. The velocity during the same interval, starting from an initial value of v_o, can be found by integration of Equation (3)

$$v_a = v_o + \int_0^t a\, dt$$

$$= v_o - \int_0^t G_m g \left(\frac{t}{t_m}\right) dt$$

$$= v_o - \frac{G_m g t^2}{2 t_m} \qquad (4)$$

The airframe displacement at time t_m is then

$$S_a = \int_0^{t_m} v_a\, dt$$

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$$= \int_0^{t_m} (v_o - \frac{G_m g t^2}{2t_m}) dt$$

$$= v_o t_m - G_m g t_m^2/6 \tag{5}$$

For the interval $t_m < t \leq 2t_m$, the airframe acceleration is

$$a = -G_m g + G_m g(t - t_m)/t_m \tag{6}$$

and the velocity,

$$v_a = v_o - \frac{1}{2} G_m g t_m + \int_{t_m}^{t} a dt$$

$$= v_o + G_m g(t_m - 2t + \frac{t^2}{2t_m}) \tag{7}$$

so that, at $t = 2t_m$

$$v_a = v_o + G_m g(t_m - 4t_m + 2t_m)$$

$$= v_o - G_m g t_m \tag{8}$$

Since the peak deceleration G_m is that required to bring the aircraft to rest at time $2t_m$,

$$v_a = 0 = v_o - G_m g t_m$$

and

$$v_o = G_m g t_m \qquad (9)$$

The airframe displacement at $2t_m$ is then

$$S_a = v_o t_m - G_m g t_m^2/6 + \int_{t_m}^{2t_m} V_a dt$$

$$= v_o t_m - G_m g t_m^2/6$$

$$+ \int_{t_m}^{2t_m} [v_o + G_m g(t_m - 2t + \frac{t^2}{2t_m})]dt$$

$$= 2v_o t_m - G_m g t_m^2 \qquad (10)$$

Substituting Equation (9) into Equation (10) the total airframe displacement is

$$S_a = v_o t_m = G_m g t_m^2 \qquad (11)$$

The acceleration of the seat/occupant system matches that of the airframe for $0 \leq t \leq t_L$, where t_L is determined by the limiting deceleration G_L. Using Equations (4) and (5), the velocity and displacement of the seat at t_L can be found as follows:

$$v_s = v_o - \frac{G_m g t_L^2}{2t_m}$$

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$$S_s = \int_0^{t_L} (v_o - \frac{G_m g t_L^2}{2t_m}) dt$$

$$= v_o t_L - \frac{G_m g t_L^3}{6t_m} \tag{12}$$

For $t_r \leq t \leq t_f$ where t_f is the time when the seat/occupant system comes to rest

$$a_s = -G_L g \tag{13}$$

and the system velocity in this interval is given by

$$v_s = v_o - \frac{G_m g t_L^2}{2t_m} + \int_{t_L}^t a_S dt$$

$$= v_o - \frac{G_m g t_L^2}{2t_m} - G_L g(t - t_L) \tag{14}$$

Since $v_s = 0$ at $t = t_f$, Equation (14) can be used to find the final time t_f

$$0 = v_o - \frac{G_m g t_L^2}{2t_m} - G_L g t_f + G_L g t_L$$

Introducing the variable

$$K = G_L/G_m = t_L/t_m \tag{15}$$

the time t_f can be written

$$t_f = t_m(\frac{1}{K} + \frac{K}{2})$$ (16)

Using Equation (15) to substitute for t_L and G_L in Equations (12) and (14), the seat/occupant system displacement at t_f is found by

$$S_s = v_0 K t_m - \frac{G_m g K^3 t_m^2}{6} + \int_{Kt_m}^{t_f} (v_0 + \frac{K^2 G_m g t_m}{2} - K G_m g t) dt$$

$$S_s = G_m g \left[(1 + \frac{K^2}{2}) t_m t_f - \frac{K^3 t_m^2}{6} - \frac{K t_f^2}{2} \right]$$

$$= G_m g t_m^2 \left(\frac{1}{2K} + \frac{K}{2} - \frac{K^3}{24} \right)$$ (17)

The stroke distance required by the seat is the displacement of Equation (17) less that of the airframe, which is given by Equation (11):

$$\text{Stroke, } S = G_m g t_m^2 (\frac{1}{2K} + \frac{K}{2} - \frac{K^3}{24} - 1)$$ (18)

The above result also can be obtained geometrically, using the velocity and displacement curves shown in Figure 17. For further clarification, this somewhat simpler procedure is presented below.

The velocity of the airframe at time t is equal to the initial velocity plus the change in velocity from $t = 0$ to $t = t$,

$$v_t = v_0 + (a)\frac{t}{2}$$ (19)

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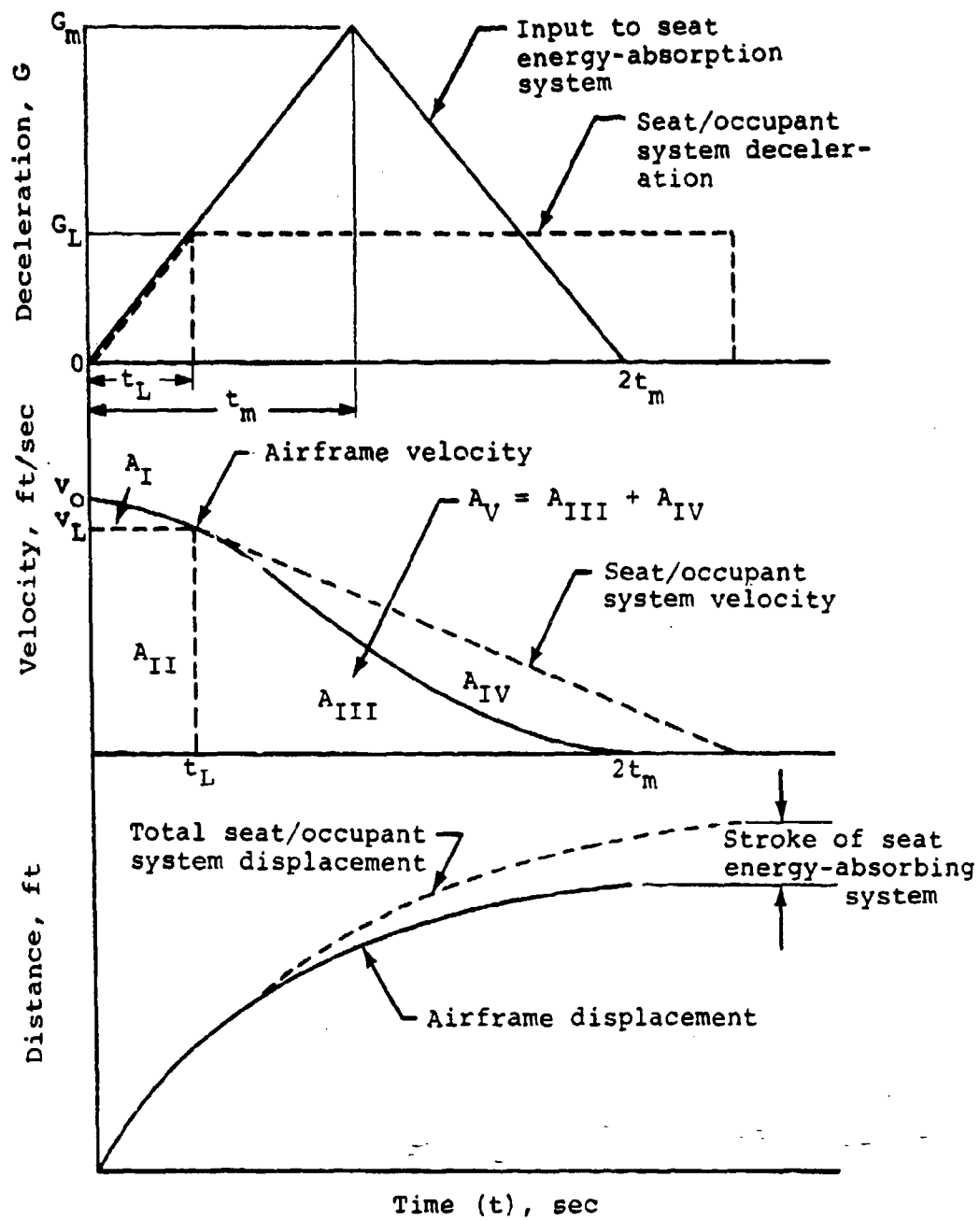
Figure 17. Deceleration-time, velocity-time, and distance-
time curves used in analysis of seat/occupant
displacement with respect to the airframe.

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Substituting the value of a from Equation (3),

$$v_t = v_o + \left[\frac{-G_m g t}{t_m}\right]\left(\frac{t}{2}\right)$$

$$v_t = v_o - \left[\frac{G_m g t^2}{2t_m}\right] \tag{20}$$

Now, assuming that the airframe comes to rest so that $v(t = 2t_m) = 0$, the total velocity change can be said to equal the initial velocity. Since this corresponds to the total area under the deceleration versus time curve,

$$v_o = G_m g t_m \tag{21}$$

Substituting Equation (21) into Equation (20) yields

$$v_t = G_m g t_m - \frac{G_m g t^2}{2t_m} \tag{22}$$

Using Equation (22), we can now compute the common velocity of the airframe and the system at time t_L,

$$v_L = G_m g t_m - \frac{G_m g t_L^2}{2t_m} \tag{23}$$

The change in velocity in the time interval t_L is

$$\Delta v = v_o - v_L \tag{24}$$

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Substituting Equations (21) and (23) into Equation (24) yields

$$\Delta v = G_m g t_m - (G_m g t_m - \frac{G_m g t_L^2}{2t_m})$$

$$\Delta v = \frac{G_m g t_L^2}{2t_m} \qquad (25)$$

The areas of interest in the velocity-versus-time graph in Figure 17 can be calculated now using the relationships just derived together with geometrical considerations.

Recognizing that the curve describing the velocity of the airframe consists of the two parabolic segments shown in Figure 18, connected at time t_m, it can be seen that A_I is the area under a parabola of base t_L and height Δv. Therefore,

$$A_I = \frac{2}{3} \left(\frac{G_m g t_L^2}{2t_m} \right) t_L = \frac{G_m g t_L^3}{3t_m} \qquad (26)$$
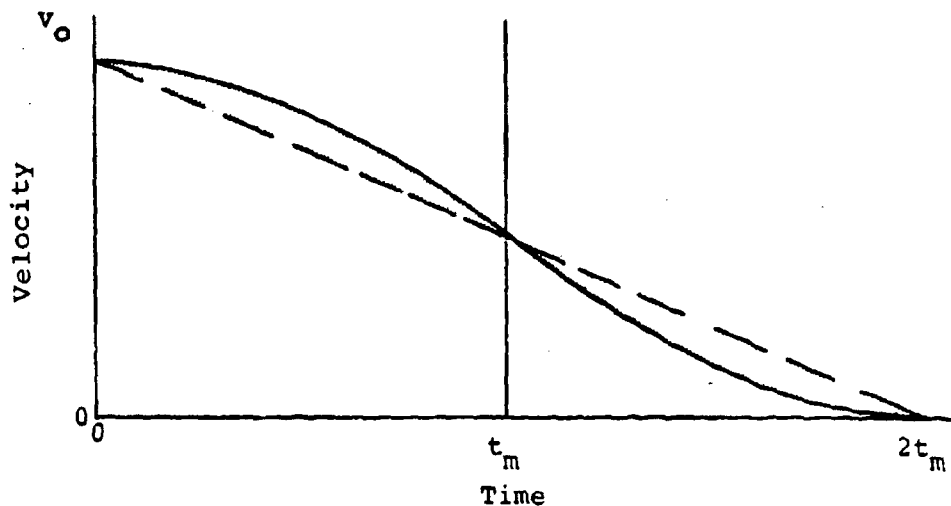
Figure 18. Airframe velocity-time curve.

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Area A_{II} is simply a rectangle of base t_L and height v_L, so that

$$A_{II} = t_L \left(G_m g t_m - \frac{G_m g t_L^2}{2t_m} \right) = G_m g t_L t_m - \frac{G_m g t_L^3}{2t_m} \qquad (27)$$

Since the system is undergoing a constant deceleration beginning at t_L, area A_V can be represented by the relationship

$$A_V = \frac{v_L^2}{2G_L g}$$

Substituting from Equation (23) and noting that $G_L = KG_m$,

$$A_V = \left(G_m g t_m - \frac{G_m g t_L^2}{2t_m} \right)^2 \frac{1}{2KG_m g} \qquad (28)$$

The area sought as representing the energy-absorption stroke of the seat is A_{IV}. In order to solve for this area, A_{III} must first be established. A_{III} can be determined by noting that, due to the triangular shape of the acceleration pulse, the airframe velocity curve consists of two parabolic segments meeting at the midpoint of the curve, as shown in Figure 18.

If a straight line is constructed joining v_o and $2t_m$, the two shaded areas bounded by the curve and the line can be shown to be equal since they are both areas between parabolic curves described by the same basic equation and a secant. The total area under the curve can then be said to be the same as the area of the triangle formed by the coordinate axes and line connecting v_o and $2t_m$. Therefore,

$$A_I + A_{II} + A_{III} = (\frac{v_o}{2}) 2t_m = v_o t_m = G_m g t_m^2 \qquad (29)$$

and

$$A_{IV} = (A_I + A_{II} + A_V) - (A_I + A_{II} + A_{III}) \qquad (30)$$

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Substituting from Equations (26), (27), (28), and (29) yields

$$A_{IV} = \frac{G_m g t_L^3}{3t_m} + G_m g t_L t_m - \frac{G_m g t_L^3}{2t_m} +$$

$$\left(G_m g t_m - \frac{G_m g t_L^2}{2t_m} \right)^2 \frac{1}{2KG_m g} - G_m g t_m^2$$

Simplification and substitution of Kt_m for t_L yields

$$A_{IV} = S = G_m g t_m^2 \left(\frac{K}{2} + \frac{1}{2K} - \frac{K^3}{24} - 1 \right) \qquad (31)$$

which is the same as Equation (18).

As an example, consider a triangular pulse representing a change in velocity of 42 ft/sec with

$$G_m = 48 \text{ G}$$

$$t_m = 0.027 \text{ sec}$$

$$K = \frac{11.5}{48} = 0.24$$

The required stroke is then

$$\text{Stroke} = (48)(386)(0.027)^2 \left(\frac{0.24}{2} + \frac{1}{2(0.24)} - \frac{(0.24)^3}{24} - 1 \right)$$

$$= 16.25 \text{ in.}$$

Test data show this stroke to be less than that required. Much of this difference can be attributed to system inefficiencies. It has been found in tests that an efficiency of approximately

80 percent can be expected from a rod-bending sled decelerator and a wire-bending seat load limiter (References 31 and 32). Therefore, correcting the calculated distance yields 16.25/0.8 = 20.31 in. It must be realized that 20.31 in. is probably a valid stroke for systems with little or no friction, such as ceiling-mounted troop seats. For seats guided by sliding or rolling components, friction adds to the resistive force, thus producing an apparent increase in efficiency. However, in general, large frictional resistance is not desirable because of the variation of the net resistive force and hence occupant decelerative loading as a function of loading direction. Review of the above indicates that the 12-in. minimum seat stroke required for the design pulse (used in the above calculations) is hardly adequate and should not be compromised unless other provisions are included to reduce the residual energy that the seat is required to absorb.

4.7.3 Dynamic Response

4.7.3.1 **Effective Weight:** The concept of effective weight has been used to account for masses supported by components other than the stroking portion of the seat; e.g., the seat occupant's lower legs supported by the floor during vertical loading. The effective weight of the occupant plus the weight of the movable portion of the seat is multiplied by the limit-load factor (G) during calculation of limit loads. The technique is not completely accurate physically because rigid bodies cannot adequately simulate the dynamic response of the real system. Seat designs should be dynamically analyzed and tested to establish their dynamic response and to demonstrate that they will provide the desired degree of occupant protection.

4.7.3.2 **Theoretical System Response:** A major design factor influencing the seat response is the movable seat mass. For very light seats, the gross response of the occupant can be estimated using the approximate mass of the occupant acting on the seat (80 percent when considering the vertical direction as discussed later in this chapter). However, when the seat

31.   Reilly, M. J., CRASHWORTHY, TROOP SEAT TESTING PROGRAM, The Boeing Vertol Company; USAAMRDL Technical Report 77-13, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1977, AD A048975.

32.   Reilly, M. J., CRASHWORTHY, HELICOPTER GUNNER SEAT TESTING PROGRAM, The Boeing Vertol Company; USARTL Technical Report 78-7, U. S. Army Research and Technology Laboratories, Fort Eustis, Virginia, February 1978, AD A054970.

mass increases to values typical of integrally armored crew-seats, interaction between the mass and spring properties of the seat and occupant can become significant. The occupant and seat components then realize sharp deceleration excursions, i.e., spikes.

The dynamics of the problem are illustrated in Figure 19, which presents the theoretical response of an integrally armored crew-seat and occupant to an input crash pulse as calculated by a digital computer analysis (described in Reference 24) and summarized in Section 4.8.6. The analysis simulates the occupant by three lumped masses representing the head, chest, and pelvis. The cushion and seat are represented by two additional masses. The five masses are connected by damped springs in the model.

The response curves for the seat structure, occupant pelvis, and chest are shown as functions of time for the indicated input excitation. The seat used was an energy-absorbing, integrally armored model set to stroke at 18 G (18 times the effective weight of the occupant plus movable seat). The armored seat bucket weighed 40.6 lb, and the energy absorber provided a trapezoidal force-versus-deformation characteristic. It can be seen that the dynamic response of the seat and segments of the body are not independent of one another and vary as the model springs load and unload.

Initially, the seat pan deceleration lags the input pulse as the springs representing the flesh and the cushion as well as the elastic spring of the seat structure are loaded. The stroking force of the energy absorber was sized for a deceleration of a particular mass, and the effective mass is not yet being applied to the seat structure because of the incomplete spring compression. Therefore, the seat pan deceleration exceeds the deceleration required to effect the force necessary to stroke the energy absorber. The seat pan deceleration approaches 43 G before the cushion and flesh springs compress to the point that significant deceleration of the pelvis begins. As deceleration of the pelvic mass increases, an increasing reaction force is applied in the downward direction on the seat pan. The seat pan deceleration decreases from 43 G to approximately 27 G as the effective mass is increased.

Because the input decelerative loading is still increasing and the chest inertial load has not yet been applied to the system, both the seat pan and the pelvic decelerations increase. As the spring representing the buttocks flesh and cushion bottoms out, the pelvic deceleration continues to increase, further
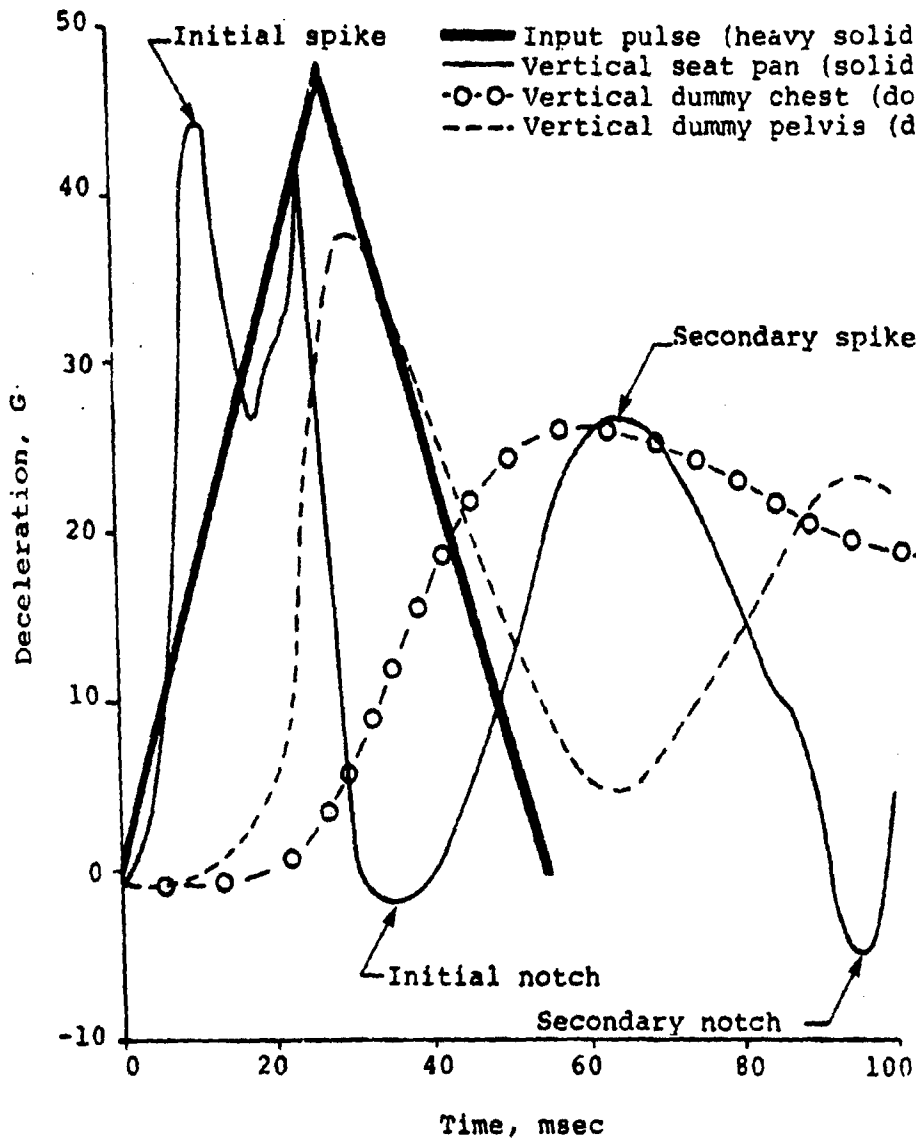
Figure 19. Deceleration versus time for various
components of seat and occupant.
(From Reference 24).

loading the seat pan and decreasing its deceleration. It can
be seen that the seat pan experiences a small acceleration
under the combined loading of the occupant's pelvis and chest.

As the chest deceleration increases, the decelerations of the
seat pan and the pelvis tend to normalize near the G level cor-
responding to the limit-load factor of the energy-absorbing
system.

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In summary, the limit load must be set at a load factor considerably below the tolerable level in order to limit the occupant response to a tolerable level, particularly for seats of high movable mass.

4.7.3.3 **Empirical System Response:** In the past few years, several programs were conducted in which crashworthy armored seats were dynamically tested (References 16, 24, and 33 through 35). These programs included drop tests in which the seats' response to decelerative loading in the vertical direction was measured. Two types of tests were conducted: in the first, the impact velocity vector was parallel, but in the opposite direction, to the loading and along the vertical axis of the seat, the yaw axis related to the aircraft (upward and perpendicular to the aircraft longitudinal axis), and in the second, the seat was pitched forward 30 degrees and rolled 10 degrees relative to the aircraft axis system. These dynamic tests demonstrated a characteristic deceleration-time history very similar to that theoretically predicted (see Figure 20). The characteristic shape has been evident in essentially all tests to date; however, the magnitudes of the spikes and notches vary. The characteristic shape of the seat pan deceleration-versus-time history includes a high initial spike followed by a deep notch that sometimes passes through zero and actually becomes an acceleration rather than a deceleration. This notch is followed by a second high spike followed by various waveforms, damping out and usually centering around the load factor used in sizing the energy-absorption system loads.

33. Mazelsky, B., A CRASHWORTHY ARMORED PILOT SEAT FOR HELICOPTERS, ARA Inc.; USAAVSCOM Technical Report 73-34 and Report No. NADC-74018-40, Joint Report issued by Naval Air Systems Command, Washington, D. C., and U. S. Army Aviation Systems Command, St. Louis, Missouri, January 1974, AD A007551.

34. Domzalski, L. P., and Singley, G. T., III, JOINT ARMY/NAVY TEST PROGRAM FOR UTTAS SEATING SYSTEMS, NADC-79229-60, Naval Air Development Center, Warminster, Pennsylvania, to be published.

35. Dummer, R. J., QUALIFICATION TEST REPORT 613-1787 COOL-QUALIFICATION TESTING OF ARMORED CRASHWORTHY AIRCREW SEAT RA-30525-1 (FOR SIKORSKY AIRCRAFT CONTRACT 576344), U. S. Army Contract No. DAAJ01-77-C-0001, Norton Company, Industrial Ceramics Division, Worcester, Massachusetts, revised January 1979.

Figure 20. Typical seat pan, dummy chest, and dummy pelvis response to vertical crash loading. (From Reference 34)

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The explanation of the characteristic waveform is associated with the inherent dynamic response of the seating system and its occupant. As explained previously, total coupling of the seat and its occupant is not achieved since the occupant consists of masses connected by body members, such as the spinal column and neck, which are not rigid.

Further, because the dummy is seated on simulated buttocks flesh and a comfort cushion, it is not rigidly connected to the seat pan. Since the energy-absorbing mechanism of the seat must be set for a given load (calculated by multiplying the effective weight of the occupant and movable part of the seat by the desired limit-load factor of 11.5 G), the actual deceleration measured on the seat pan will vary inversely to the coupled weight (w_t) according to the relationship $a = F/w_t$ where a represents the deceleration in G units, F, the load in pounds resisting the stroke of the seat, and w_t, the coupled weight in pounds. The term coupled, as used here, simply indicates that the applicable connecting springs are compressed sufficiently to result in the body segment being decelerated in phase at approximately the same rate as the seat pan (as would a rigidly attached mass).

A deceleration applied to the seat pan initially decelerates the movable seat mass only. Consequently, deceleration of the seat pan reaches a large magnitude as indicated by the initial spike in Figure 20. As the cushion and the simulated flesh on the buttocks compress, the deceleration of the pelvic mass increases. As the spinal column compresses, the deceleration of the chest increases. The deceleration of these masses increases as a result of the increased load in the connecting members. There is a spring constant involved when the connecting members are represented by springs. This constant defines the relationship between deflection and load; i.e., the further a spring is compressed, the larger the load required to compress it. The body segments react in the same way. Therefore, the greater the compression, the higher the load, and the higher the deceleration of the body segments.

As an illustration, consider Figures 21, 22, and 23. Comparing the figure of a seat occupant with a system of springs and masses, it can be seen that when the initial deceleration of the seat pan commences, the springs in the body are not compressed. The body and seat system have been under a 0-G environment during the drop. Therefore, the springs are totally unloaded as illustrated in Figure 21. This simply means that since the springs are not compressed when the deceleration first commences, large loads cannot immediately be applied to the body segments. As the pulse continues, the body segments
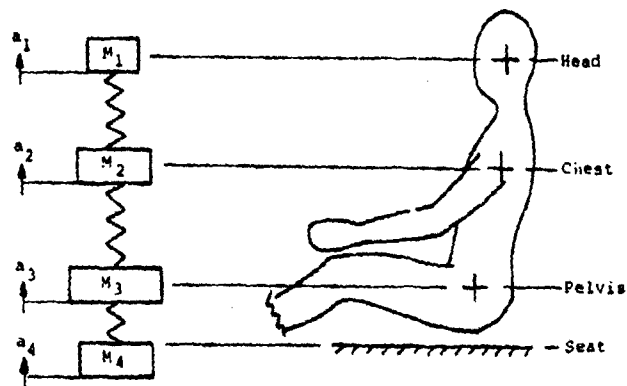
Figure 21.   Initial condition, no load.
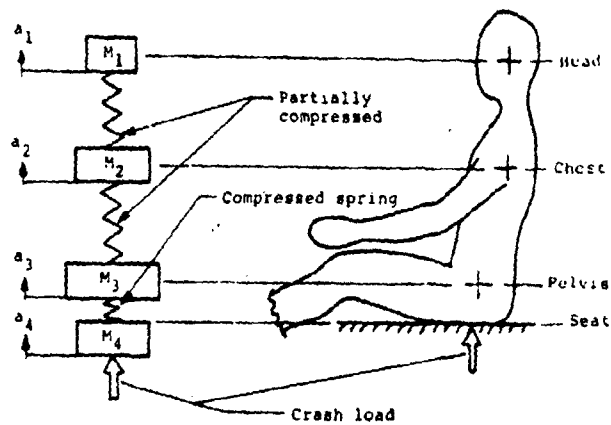
Figure 22.   Onset of deceleration load wherein pelvic
area is responding to deceleration load,
but the upper torso and head are not.
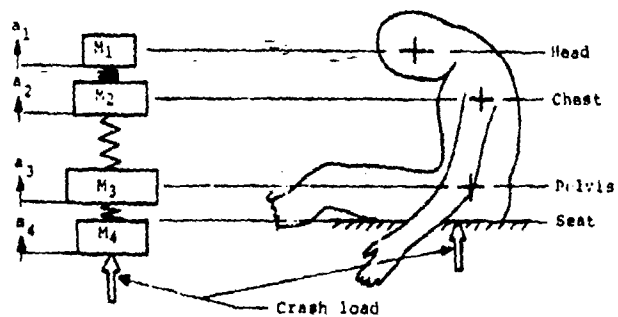
Figure 23.   High-deceleration load, springs compressed.

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continue to move under the resistive load of the partially com-
pressed springs, thus decelerating more slowly than the seat
and building up a velocity relative to the seat pan. Even-
tually the velocities of the body segments and the seat pan
must all approach a common value. This usually occurs later in
the sequence, after the secondary spike. In the interval, the
deceleration of the seat pan responds as a function of energy
absorber force, input pulse, seat and dummy weight, and spring
and damping characteristics.

Initially, the seat pan deceleration reaches a high value (ini-
tial spike). This occurs because the resistive force in the
energy-absorbing system is set at a given value considering
the weight of the movable portion of the seat and the occupant.
The seat pan is decelerated initially at a magnitude consistent
with the force of the energy-absorbing mechanism divided by
only the weight of the movable part of the seat, which is con-
siderably less than the design weight (the weight of the mov-
able portion of the seat and the effective weight of the occu-
pant). Thus, it is expected that the magnitude of initial seat
pan deceleration will always exceed the limit-load factor for
which the composite energy-absorbing system was designed.

Eventually, the cushion and buttocks springs are compressed,
and the pelvic mass loads into the seat pan (see Figure 22).
The increase of the coupled mass decreases the deceleration of
the seat pan from its initial peak. The seat pan deceleration
then decreases drastically as evidenced by the initial notch
in the deceleration-time history. At times, when the decelera-
tion actually turns into an acceleration, it simply means that
the mass of the pelvis is receiving a relatively high decelera-
tion and the reaction load is high enough to accelerate the
seat pan towards the aircraft floor. It is apparent that the
magnitude of this notch is a strong function of the spring rate
of the seat. Since the spine normally is still not compressed
significantly, it is not carrying high loads. This is evi-
denced by the small decelerations measured in the chest, which
is being supported by the spine.

Since this is a dynamically loaded spring system, the springs
associated with the buttocks and the cushion can overshoot as
they bottom out during the sequence and then unload again. The
unloading permits the seat pan deceleration to rise again to
the secondary spike on the trace. As the pelvis unloads, the
reaction load on the seat pan decreases and the seat pan decel-
eration spike can be extremely high. Note that the high decel-
eration of the seat pan does not necessarily correlate with the
high deceleration of the pelvis or chest. From the data re-
viewed, both analytical and empirical, it is generally the op-
posite; i.e., the unloading of the pelvis and/or the chest pro-
duces the spike in the seat pan deceleration.

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As the cushion and buttocks again load up and the pelvis deceleration increases, the high seat pan deceleration of the second spike is decreased. Also, the two characteristic deceleration spikes are usually followed by an increased compressive load in the spine and a buildup of deceleration of the chest. Eventually, the phasing of the decelerations of the various system segments begins to converge toward the average load factor for which the limit load of the energy-absorbing system was designed, as illustrated in Figure 23.

It is informative to note (see Figure 20), that the peak decelerations of the seat pan do not necessarily coincide with peak decelerations of the human occupant and, thus, are not necessarily hazardous to occupant safety. The Eiband human tolerance data of Section 4.3.3, Volume II, repeated here in Figure 24 for ease of reference, do not present information on the seat pan deceleration excursions from the average, or uniform acceleration experienced by the vehicle, and are therefore not informative on the subject. Again, this is an area presently being investigated under U. S. Army sponsorship. These criteria will be updated when additional data are available.

The response phenomena described above comprise the predictable response of the occupant/seat system to the input pulse. The high decelerations measured on the seat pan are not necessarily correlated with high decelerations of the occupant; however, this does not imply that the seat will provide the required protection. The entire deceleration history to which the occupant is exposed must be considered. As pointed out, low decelerations of the seat pan may be accompanied, and caused by, high loads imposed on the occupant. Thus, it is imperative that additional information relative to human tolerance to transient loading in the vertical direction be obtained and that the criteria for designing vertical energy attenuating systems for seats be refined and made more comprehensive. Several programs are now underway to expand knowledge in this area. As the data become available, criteria contained in this guide will be updated.

4.7.3.4 Tailoring of Energy Absorber: Results of analyses conducted under a U. S. Navy-sponsored program (Reference 36) indicated that the force-versus-deformation characteristic of the energy-absorbing system can be shaped to enable more efficient use of the stroke distance available. As yet, test data have not substantiated the analyses. However, proper tailoring

36. Carr, R. W., and Phillips, N. S., DEFINITION OF DESIGN CRITERIA FOR ENERGY ABSORPTION SYSTEMS, Beta Industries Incorporated; Report No. NADC-AC-7007, Naval Air Development Center, Warminster, Pennsylvania, 11 June 1970, AD 871040.
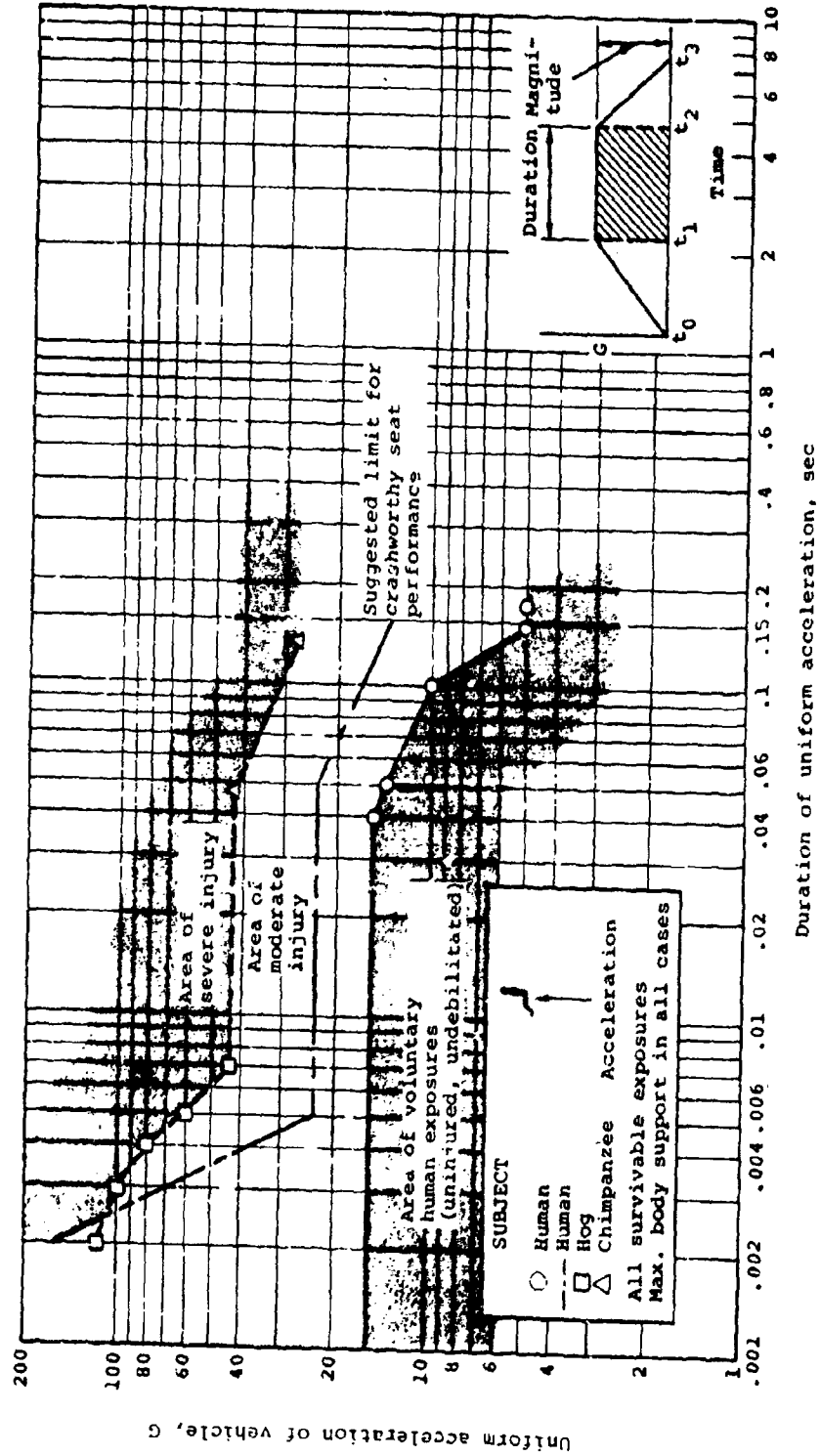
Figure 24. Duration and magnitude of headward acceleration endured by various subjects.

of the waveform should produce the potential for maximization
of the efficiency of a particular system. Research efforts
considering this approach are presently being sponsored by the
U. S. Army. Results should be available by 1981.

4.7.3.5 Adjustable Multiple Limit-Load Devices: Since stroke
distance is very limited in aircraft cabins and particularly
in aircraft cockpits, it is extremely important to maximize
the efficient use of the available distance. Energy absorbers
that stroke at a given limit load are sized for the effective
weight of the 50th-percentile occupant (by weight). This im-
plies that the majority of occupants will stroke at or near
the optimum load. Heavier people, however, will stroke at
a lower deceleration level and will require a longer stroke
than the average for which the system was designed, while the
lighter occupant will stroke at a higher deceleration and use
less of the available stroke. Obviously, the energy-absorption
load settings are not optimum for occupants whose weights lie
in the tails of the occupant weight distribution. If adjust-
ment of the limit load for the weight of the specific occupant
is possible, then the system can be optimized for the total
occupant weight distribution.

Variable limit-load energy absorbers can be controlled either
passively (requiring no action by the occupant) or actively
(requiring a conscious action by the occupant). The passive
device is more complicated and would require a considerably
more sophisticated system to control. It would have to be a
force/time integrating system, since the limit load of the en-
ergy absorber could not be a function of the dynamic loading
of the seat associated with occupants simply sitting down hard.
There is no doubt that this type of device could be developed;
but the cost and weight may be prohibitive, while an actively
controlled device should be neither overly complex nor costly.
To achieve most of the advantages offered by the system, the
load would not have to be infinitely adjustable but could be
applied in several increments. The occupant would simply turn
a dial or move a lever to a weight range best fitting his own
weight.

Previous studies (Reference 24) have indicated that a total
excursion of approximately 6 G results from using a single
limit load set for the 95th-percentile occupant weight. The
6-G excursion could be essentially eliminated with either type
of variable-load energy absorber. This would allow decelera-
tions of all occupants to be nearly identical and enable use
of essentially the same stroke distance for the same decelera-
tive loading and input crash severity for all occupant weights.

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Variable limit-load energy absorbers should therefore be incorporated in the vertical direction in all new crashworthy seating systems and retrofit should be considered for seating systems now in use that include stroking capabilities together with replaceable energy absorbers.

4.8 COMPUTERIZED METHODS OF ANALYSIS

4.8.1 General

Prediction of occupant and seat structure response to dynamic loading presents a complex engineering problem. The use of computer-aided design in these cases is essential, since the dynamic interaction of the occupant and the seat/restraint system is much too complex for analysis by manual techniques.

A number of dynamic models of the human body have been developed for use in crash survivability analysis. These models vary in complexity and possess from 1 to 40 degrees of freedom (References 37 through 54). One-dimensional models have been

37. Bacchetti, A. C., and Maltha, J., MADYMO - A GENERAL PURPOSE MATHEMATICAL DYNAMICAL MODEL FOR CRASH VICTIM SIMULATION, Report No. 753012-C, Instituut voor Wegtransportmiddelen, Netherlands 1978.

38. Bartz, J. L., DEVELOPMENT AND VALIDATION OF A COMPUTER SIMULATION OF A CRASH VICTIM IN THREE DIMENSIONS, Proceedings, Sixteenth Stapp Car Crash Conference, Society of Automotive Engineers, Inc., New York, 1972, pp. 105-127.

39. Danforth, J. P., and Randall, C. D., MODIFIED ROS OCCUPANT DYNAMICS SIMULATION USER MANUAL, Publication No. GMR-1254, General Motors Corporation Research Laboratory, Warren, Michigan, 1972.

40. Fleck, J. T., Butler, F. E., and Vogel, S. L., AN IMPROVED THREE DIMENSIONAL COMPUTER SIMULATION OF MOTOR VEHICLE CRASH VICTIMS, Final Technical Report No. ZO-5180-L-1 (in four volumes), Calspan Corporation, Buffalo, New York, 1974.

41. Furosho, H., Yokoya, K., and Fujiki, S., ANALYSIS OF OCCUPANT MOVEMENTS IN REAR-END COLLISION, Paper No. 13, in Safety Research Tour in the U.S.A. from the Viewpoint of Vehicle Dynamics, 1969.

42. Furosho, H., and Yokoya, K., ANALYSIS OF OCCUPANT'S MOVEMENT IN HEAD-ON COLLISION, Transactions of the Society of Automotive Engineers of Japan, No. 1, Tokyo, Japan, 1970, pp. 145-155.

used in prediction of human body response to an ejection seat
firing (References 55 through 57), which, if the body is tightly
restrained, can be approximated as a one-dimensional phenomenon.
However, a vehicle crash generally involves a horizontal compo-
nent of deceleration, which forces rotation of body segments
with respect to each other. If no lateral component of decel-
eration is present, a two-dimensional model will suffice, pro-
vided the restraint system is symmetrical. However, lateral

43. Glancy, J. J., and Larsen, S. E., USERS GUIDE FOR PROGRAM
    SIMULA, Report TDR No. 72-23, Dynamic Science, Division of
    Ultrasystems, Inc., Phoenix, Arizona, 1972.

44. Huston, R. L., Hessel, R., and Passerello, C., A THREE-
    DIMENSIONAL VEHICLE-MAN MODEL FOR COLLISION AND HIGH AC-
    CELERATION STUDIES, Paper No. 740275, presented at Auto-
    mobile Engineering Conference, Society of Automotive
    Engineers, Inc., Detroit, Michigan, 25 February - 1 March
    1974.

45. McHenry, R. R., ANALYSIS OF THE DYNAMICS OF AUTOMOBILE
    PASSENGER-RESTRAINT SYSTEMS, Proceedings, Seventh Stapp
    Car Conference, Society of Automotive Engineers, Inc.,
    New York, 1963, pp. 207-249.

46. Robbins, D. H., THREE-DIMENSIONAL SIMULATION OF ADVANCED
    AUTOMOTIVE RESTRAINT SYSTEMS, Paper No. 700421, In 1970
    International Automotive Safety Conference Compendium
    P-30, Society of Automotive Engineers, Inc., New York,
    1970.

47. Robbins, D. H., Bennett, R. O., Jr., and Bowman, B. M.,
    USER-ORIENTED MATHEMATICAL CRASH VICTIM SIMULATOR, Pro-
    ceedings, Sixteenth Stapp Car Crash Conference, Society of
    Automotive Engineers, Inc., New York, 1972, pp. 128-148.

48. Robbins, D. H., Bennett, R. O., and Roberts, R. L., HSRI
    TWO-DIMENSIONAL CRASH VICTIM SIMULATOR: ANALYSIS, VERI-
    FICATION, AND USER'S MANUAL, Final Report, Report No.
    HSRI-Bio-M-70-8, Highway Safety Research Institute, Uni-
    versity of Michigan, Ann Arbor, Michigan, 1970.

49. Robbins, D. H., Bowman, B. M., and Bennett, R. O., THE
    MVMA TWO-DIMENSIONAL CRASH VICTIM SIMULATIONS, Proceed-
    ings, Eighteenth Stapp Car Crash Conference, Society of
    Automotive Engineers, Inc., New York, 1974, pp. 657-678.

50. Segal, D. J., REVISED COMPUTER SIMULATION OF THE AUTOMO-
    BILE CRASH VICTIM, Report No. VJ-2759-V-2, Cornell Aero-
    nautical Laboratory, Inc., Buffalo, New York, 1971.

loading is common in helicopter accidents. Also, the diagonal shoulder belt used in some troop restraints is asymmetrical and may cause lateral motion of the occupant even in the absence of a lateral deceleration. Therefore, a model that is generally useful in restraint system evaluation must be capable of predicting three-dimensional motion, and several three-dimensional kinematic models, made up of interconnected rigid links, have been developed (References 38, 44, 47 and 53). Subsequent sections of this chapter describe the models of possible use to designers of seats and restraint systems.

4.8.2 Program SOM-LA

In 1972, the FAA initiated a program to provide a practical engineering tool for use in the design and evaluation of seats and restraint systems for light aircraft. This program incorporated a dynamic model of the human body combined with a

51. Segal, D. J., and McHenry, R. R., COMPUTER SIMULATION OF AUTOMOBILE CRASH VICTIM - REVISION, Report No. VJ-2492-1, Cornell Aeronautical Laboratory, Inc., Buffalo, New York, 1967.

52. Twigg, D. W., and Karnes, R. N., PROMETHEUS, A USER-ORIENTED PROGRAM FOR HUMAN CRASH DYNAMICS, Boeing Computer Services, Report No. BCS 4C038, Department of the Navy, Office of Naval Research, Washington, D. C., 1974.

53. Young, R. D., THREE-DIMENSIONAL MATHEMATICAL MODEL OF AN AUTOMOBILE PASSENGER, Research Report 140-2, Texas Transportation Institute, College Station, Texas, 1970.

54. Young, R. D., Ross, H. E., and Lammert, W. F., SIMULATION OF THE PEDESTRIAN DURING VEHICLE IMPACT, Paper No. 27, Proceedings, Third International Congress on Automotive Safety, Vol. II, Society of Automotive Engineers, Inc., New York, 1974.

55. Kroeger, W. J., INTERNAL VIBRATIONS EXCITED IN THE OPERATION OF PERSONNEL EMERGENCY ESCAPE CATAPULTS, Memorandum Report 340, Frankfort Arsenal Laboratory Division, Philadelphia, Pennsylvania, 1946.

56. Latham, W. F., A STUDY IN BODY BALLISTICS: SEAT EJECTION, Proceedings of Royal Society, London, England, 1957, B 147: 121-139.

57. Stech, E. L., and Payne, P. R., DYNAMIC MODELS OF THE HUMAN BODY, Frost Engineering Development Corp., AMRL Technical Report 66-157, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1969.

finite element model of the seat structure. The program is intended to provide the designer with a tool with which he can analyze the structural elements of the seat as well as evaluate the dynamic response of the occupant during a crash. The digital computer program based on this model is called SOM-LA (Seat/Occupant Model: Light Aircraft).

The aircraft occupant is modeled by twelve rigid mass segments with rotational springs and dampers at the joints. The segments represent the head, neck, upper torso, lower torso, upper arms, forearms, thighs, and lower legs, as shown in Figure 25. Each of the torso joints possesses three rotational degrees of freedom. The elbows, the knees, and the head-neck joint are hinge-type connections, each of which is allowed one additional degree of freedom. In total, the occupant model possesses 29 degrees of freedom.

Rotations at the body joints are resisted by torsional springs and dampers, whose characteristics depend on user selection of human or dummy occupant.

External forces are applied to the body segments by the seat cushions, the floor, the belt restraint system, and an optional inflatable restraint. The four available restraint system configurations consist of a lap belt alone or combined with a single diagonal belt over either shoulder, or a double shoulder belt. A lap belt tiedown strap may be used with the double shoulder belt system. The restraint loads are transmitted to the occupant through ellipsoidal surfaces to the upper and lower torso segments; and, the points of application depend on current belt geometry. The capability of the belts to move relative to the torso surfaces allows simulation of submarining under the lap belt as well as prediction of the lateral motion which may result with a single diagonal shoulder belt.

For calculation of external forces exerted on the occupant by the seat cushions and restraint system, and for prediction of impact between the occupant and the aircraft interior, 24 surfaces are defined on the body. These surfaces are ellipsoids, spheres, and cylinders, as shown in Figure 26.

The user may select either a finite element model of the seat structure or a rigid seat representation. The latter can include nonlinear translational and rotational stiffness elements for simulation of an energy-absorbing seat as shown in Figure 27. The bucket is assumed rigid, and frame elasticity is modeled by the torsional spring.

The program has been run on CDC 6600, Univac 1108, and IBM 370 systems. Input data include force-deflection information for

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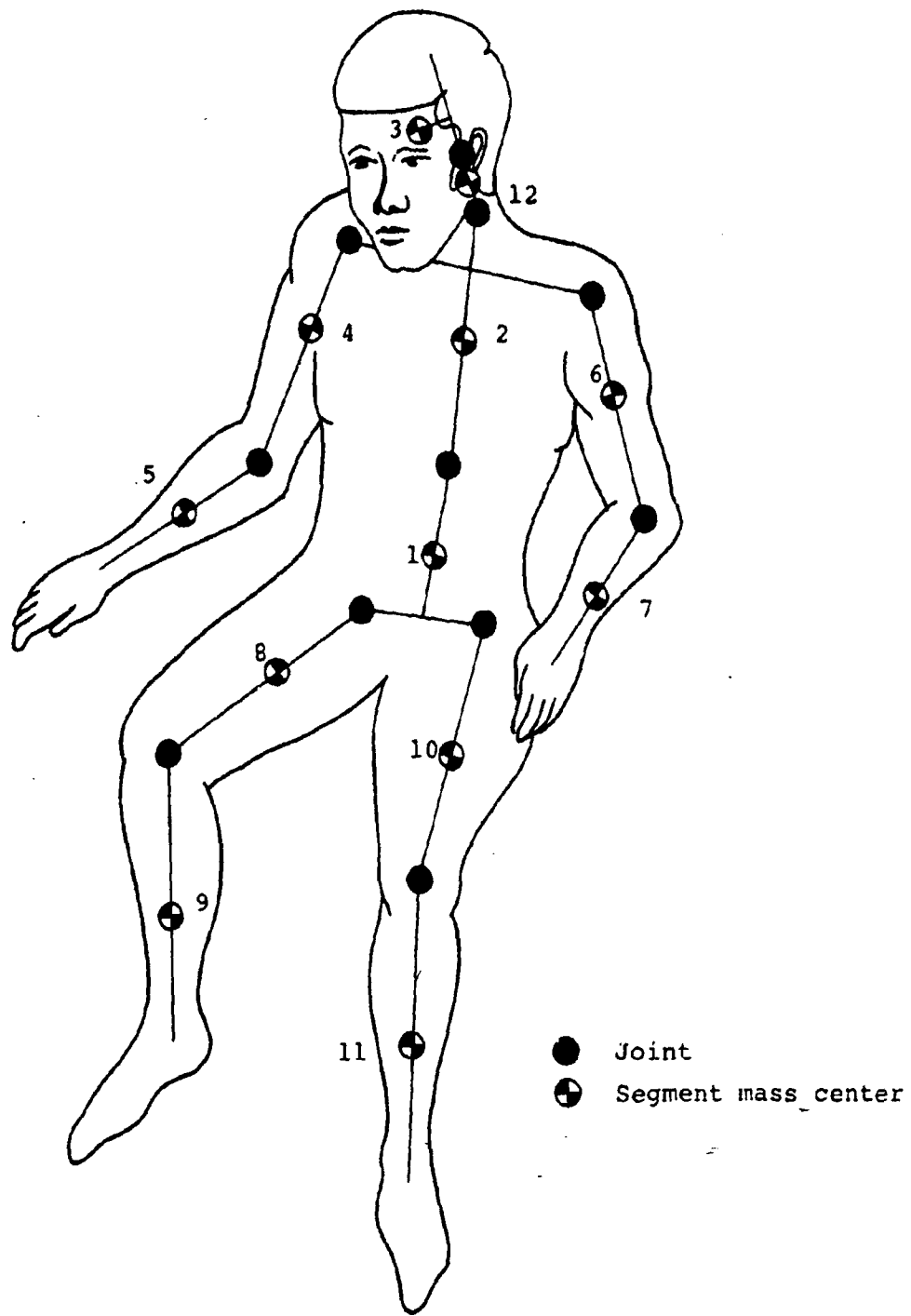
Figure 25.   Twelve-segment occupant model.
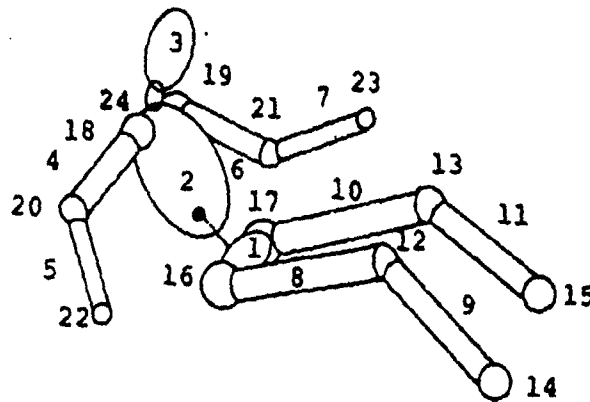
Figure 26. Occupant model contact surfaces.
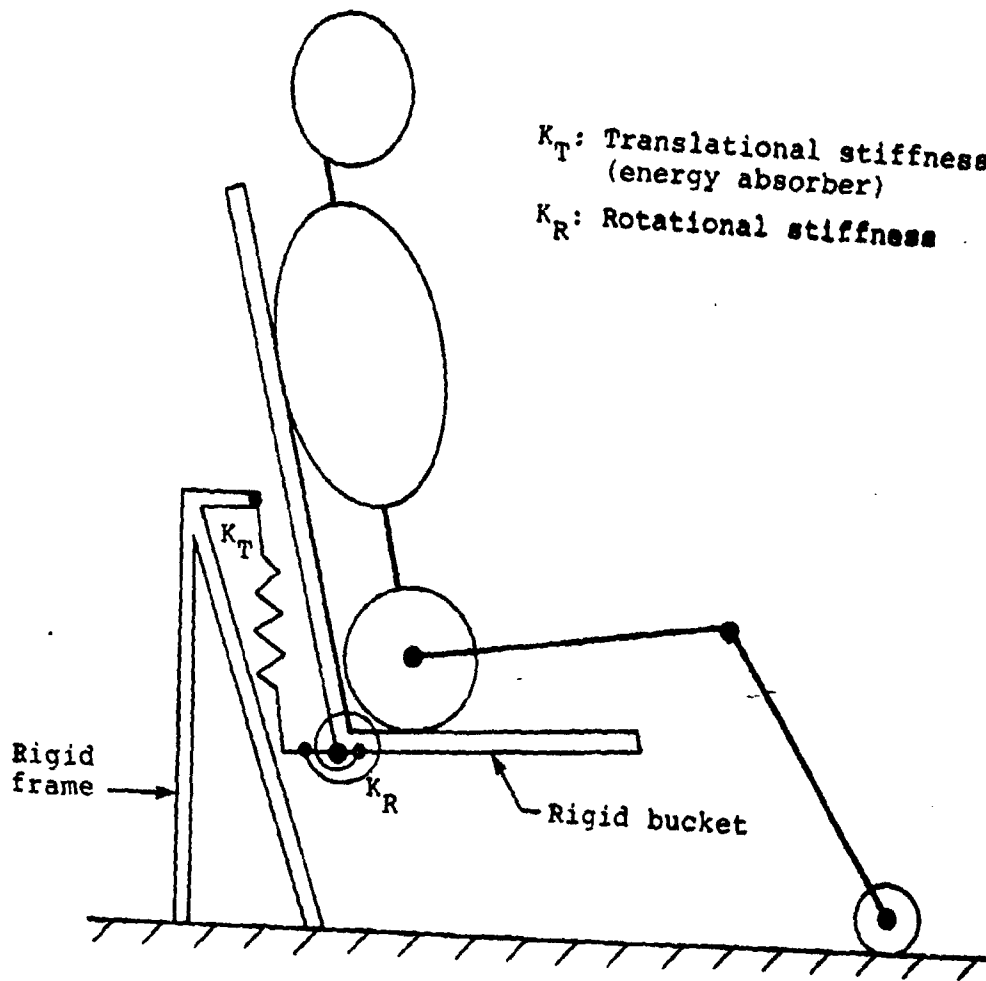
Figure 27. SOM-LA energy-absorbing seat model.

the cushions and belts; crash conditions, in terms of intial velocity and attitude and time variations of six acceleration components; occupant description; seat design data; and, if the prediction of impact with the aircraft interior is desired, a description of the cabin surfaces. Output data include time histories of occupant segment positions, velocities, and accelerations; restraint system loads; seat deflections and forces; details of contact between the occupant and the aircraft interior; and several measures of injury severity. The injury criteria used in the program are all computed from segment accelerations. The dynamic response index (DRI) provides an indication of the probability of spinal injury due to a vertical acceleration parallel to the spine. The Severity Index is calculated for the chest and head, and the Head Injury Criterion of Federal Motor Vehicle Safety Standard 208 is also computed.

This original model is described in Reference 58. Since its publication, a number of modifications to the model have been made to improve simulation quality and to provide increased capability and additional desirable output. In that interim, an extensive testing program was initiated by the FAA Civil Aeromedical Institute (CAMI) to provide data for validation of the model. Work on model improvement and validation is continuing, as described most recently in Reference 59.

4.8.3 Calspan Corporation - CVS

Probably the most sophisticated biomechanical model of the human body intended for crash simulation is the Calspan Corporation Crash Victim Simulator (CVS). Originally reported on in 1972 (Reference 38), the program includes a body dynamics model with 40 degress of freedom and a contact model that generates forces from contact with vehicle surfaces. The extensive validation effort has included the following experiments:

58. Laananen, D. H., DEVELOPMENT OF A SCIENTIFIC BASIS FOR ANALYSIS OF AIRCRAFT SEATING SYSTEMS, Dynamic Science, Division of Ultrasystems, Inc.; Report No. FAA-RD-74-130, U. S. Department of Transportation, Federal Aviation Administration, Washington, D. C., 1975, AD A004306.

59. Chandler, R. F., and Laananen, D. H., SEAT/OCCUPANT CRASH DYNAMIC ANALYSIS VALIDATION TEST PROGRAM, Paper No. 790590, presented at Business Aircraft Meeting, Society of Automotive Engineers, Inc., Wichita, Kansas, April 1979.

- Static bench tests with a spherical membrane and spherical contact surfaces to validate the air bag shape and contact force algorithm.

- Pendulum tests with a dummy torso form restrained and decelerated with an air bag to further validate this algorithm.

- Tests with instrumented anthropomorphic dummies on an impact sled at 20 and 30 mi/h with both belt and air bag restraints, in which both planar and non-planar dummy responses were produced.

- A head-on, laterally offset, car-to-car crash test, with the primary vehicle containing two instrumented anthropomorphic dummies.

A graphics display model provides rather sophisticated three-dimensional views of occupant response, as shown in Figure 28. Present capabilities of the program, a user manual, and a description of its validation are presented in Reference 40.
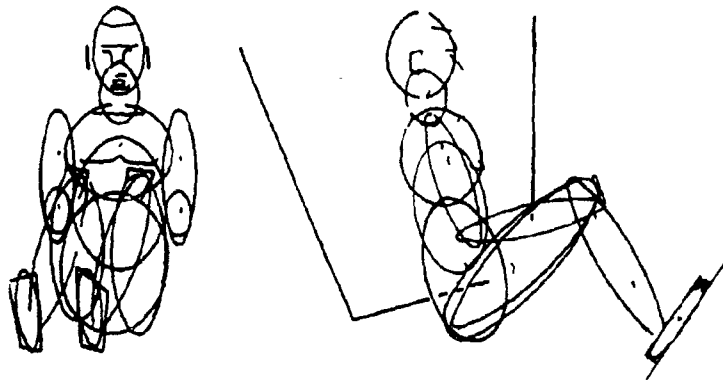
Figure 28. CVS graphics display model.

4.8.4 PROMETHEUS

In 1972, Boeing Computer Services began work on modification of a two-dimensional occupant model called SIMULA, which had been developed earlier by Dynamic Science, Inc. and Arizona State University. Their final product, which includes interactive, user-oriented capabilities, is called PROMETHEUS (Reference 52).

PROMETHEUS simulates a crash victim with either a two-dimensional, seven-link, side-facing mathematical model, shown in Figure 29(a), restrained by a seat belt and shoulder harness, or an eleven-link, forward-facing, unrestrained model, shown in Figure 29(b). A nonlinear finite element model of the impacting structure is incorporated. A new, fast differential equation solver was developed for the program to efficiently compute the transient response of the finite element vehicle structure and rigid-link occupant in a crash situation. The program is an interactive, user-controlled system designed for the rapid analysis/data edit/reanalysis cycles necessary for efficient parametric studies. PROMETHEUS input aids include free-field data input and an on-line data edit capability. Output provides user-selected time history and occupant configuration plots, as well as abbreviated output lists for rapid scan of results. The program operates on the CDC 6600 computer in either a batch or an interactive mode.

● Joint   ● Joint
▽ Point mass   ◪ Distributed mass
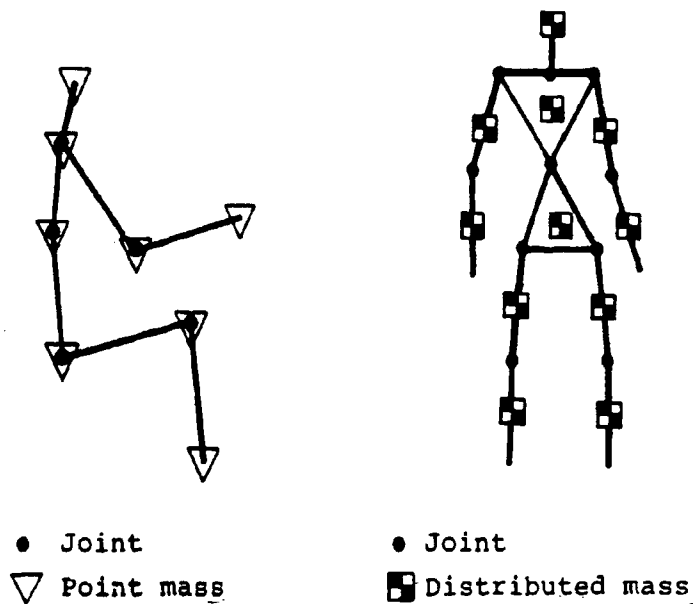
(a) Side-facing model   (b) Forward-facing model.

Figure 29.   PROMETHEUS occupant model.

4.8.5 Air Force Head-Spine Model

Under the sponsorship of the U. S. Air Force Aeromedical Research Laboratory, a three-dimensional, discrete model of the human spine, torso, and head was developed for the purpose of evaluating mechanical response in pilot ejection. It was developed in sufficient generality to be applicable to other body response problems, such as occupant response in aircraft crash and arbitrary loads on the head-spine system. There are no restrictions on the distribution of direction of applied loads, so a wide variety of situations can be treated. The model is described in Reference 60.

The anatomy is modeled by a collection of rigid bodies, which represent skeletal segments such as the vertebrae, pelvis, head, and ribs, interconnected by deformable elements, which represent ligaments, cartilageneous joints, viscera, and connective tissues. Techniques for representing other aspects of the ejection environment, such as harnesses and the seat geometry, are included. The model is valid for large displacements of the spine and treats material nonlinearities. The elements of the model are illustrated in Figure 30.

The basic model is modular in format, so that components may be omitted or replaced by simplified representations. Thus, while the complete model is rather complex and involves substantial computational effort, various simplified models that are quite effective in duplicating the response of the complete model within a range of conditions are available. Three methods of solution are available for the analysis: direct integration in time by either an explicit, central difference method; by an implicit, trapezoidal method; or by a frequency analysis method.

A variety of conditions have been simulated, including different rates of onset, ejection at angles, effects of lumbar curvature, and eccentric head loadings. It has been shown that large initial curvatures and perfectly vertical acceleration loadings result in substantial flexural response of the spine, which cause large bending moments. It has been further shown that the combination of the spine's low flexural stiffness, initial curvature, and mass eccentricity are such that stability cannot be maintained in a 10-G ejection without restraints or spine-torso-musculature interaction.

60. Belytschko, T., Schirver, L., and Schultz, A., A MODEL FOR ANALYTIC INVESTIGATION OF THREE-DIMENSIONAL HEAD-SPINE DYNAMICS - FINAL REPORT, University of Illinois at Chicago Circle; AMRL Technical Report 76-10, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, April 1976, AD A025911.
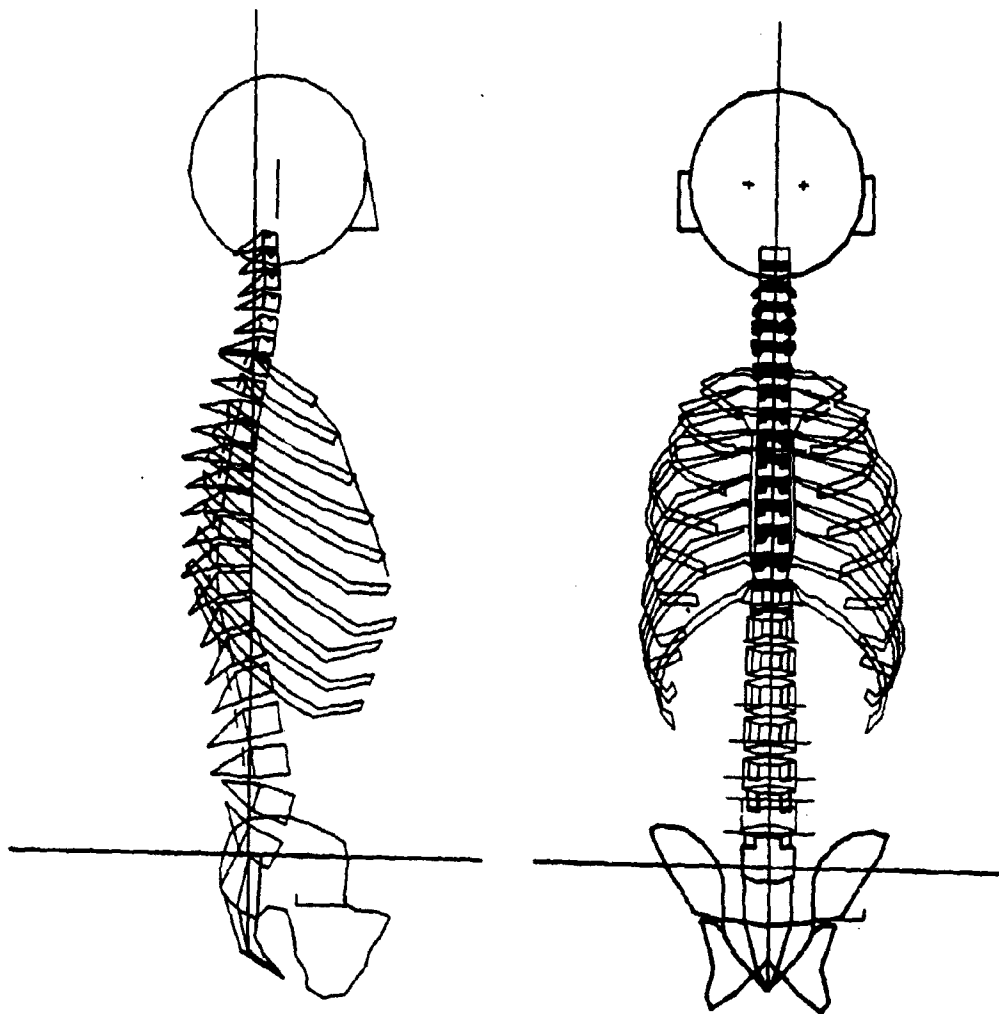
Figure 30.   Three-dimensional head-spine
model.   (From Reference 60)

The complete models were used mainly to study the effects of
the *rib cage* and viscera on spinal response.   The flexural
stiffness of the torso is increased substantially by a visceral
model, even though it has no inherent flexural stiffness.   In
addition, the viscera provide significant reductions in the
axial loads.

4.8.6   One-Dimensional Seat/Occupant Models

Although a three-dimensional simulation should *be* used for com-
plete prediction of aircraft occupant dynamics in investigating

restraint system properties or cockpit configurations to eliminate secondary impact hazards, the more simple one-dimensional models also may be useful in crashworthy seat analysis. For example, a model such as that illustrated in Figure 31 provides an economical means of optimizing energy absorber characteristics, which would be simulated by spring K_1. Energy absorber force-deflection characteristics might be varied while searching for the most favorable occupant response, evidenced by a minimum of spinal deflection, head acceleration, etc. The most notable difficulty with the use of such a model lies in obtaining valid occupant properties, i.e., masses and spring characteristics. One such model that has been used in seat evaluation is described in Reference 61.

Another widely known one-dimensional model is used to compute the Dynamic Response Index (DRI). The DRI is a predictor of spinal injury due to $+G_z$ acceleration, and is based on the response of a single-degree-of-freedom model as described in detail in Volume II.

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61. Auyer, W., and Turnbow, J., A STUDY OF THE DYNAMIC RESPONSE OF A DAMPED, MULTI-DEGREE OF FREEDOM, SPRING-MASS SYSTEM WHICH SIMULATES A SEAT, SEAT CUSHION, AND SEAT OCCUPANT SUBJECTED TO A VERTICAL IMPACT ACCELERATION, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc. (unpublished report).
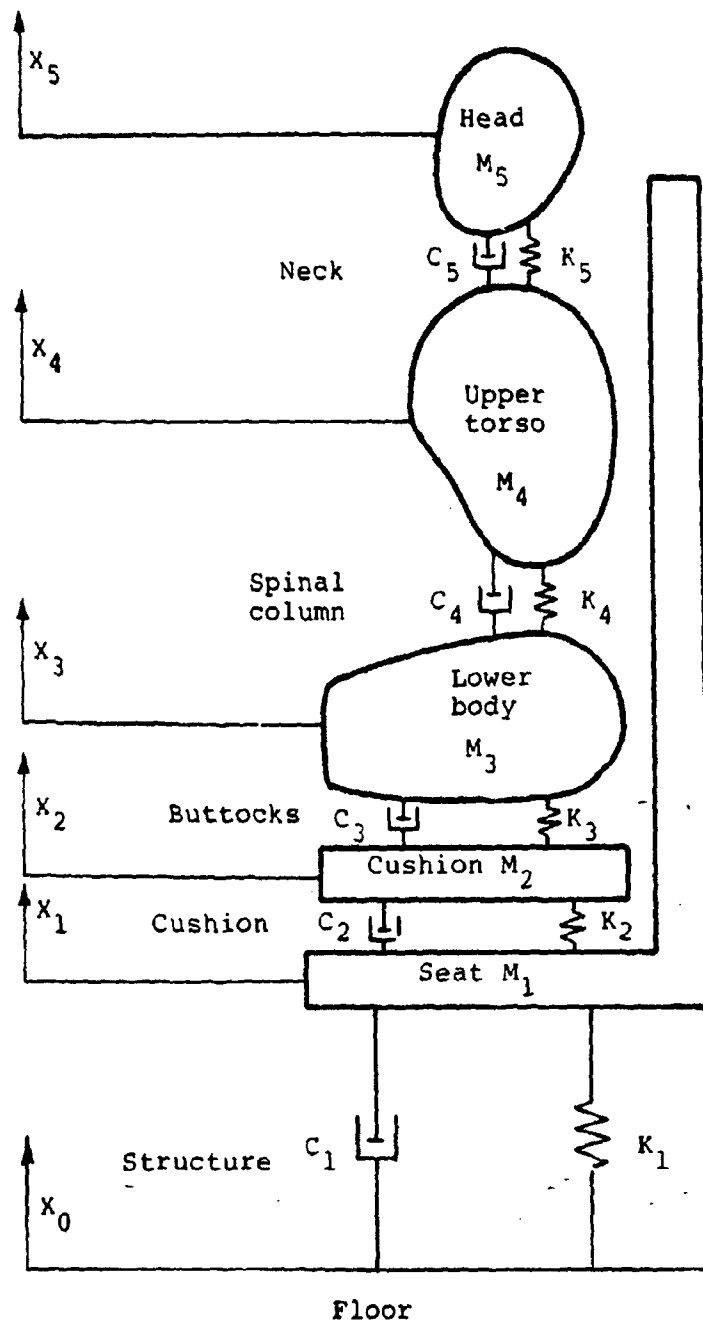
Figure 31. Lumped-parameter model of seat, seat cushion, and occupant.

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5. ENERGY-ABSORBING DEVICES

5.1 INTRODUCTION

A multitude of devices for absorbing energy and limiting loads
have been proposed, developed, and tested. As demonstrated
earlier, the kinetic energy of a moving mass can be absorbed
by applying a force over a distance; this is the primary mech-
anism for absorbing crash energy. The larger the distance
through which the force acts, the lower the average load on
the mass. Energy-absorbing mechanisms in aircraft structures
which transmit crash forces to the occupant should stroke at
loads tolerable to humans and should provide stroke distances
consistent with these loads and with the energy to be absorbed.

Past experience has shown that plastic deformation of material,
primarily metal, results in a reasonably efficient energy-
absorbing process. Consequently, most load-limiting or energy-
absorbing devices use that principle.

Desirable features of energy absorbers are as follows:

- The device should provide a predictable force-versus-
  deformation trace.

- The rapid loading rate expected in crashes should
  not cause unexpected changes in the force-versus-
  deformation characteristic of the device.

- The assembly in which the device is used should have
  the ability to sustain tension and compression.
  (This might be provided by one or more energy ab-
  sorbers, or by the basic structure itself, depending
  on the system design.)

- The device should be as light and small as possible.

- The specific energy absorption (SEA) should be high.

- The device should be economical.

- The device should be capable of being relied upon to
  perform satisfactorily throughout the life of the
  aircraft (a minimum of 10 years or 8000 flight hours)
  without requiring maintenance.

- The device should not be affected by vibration, dust,
  dirt, or other environmental effects. It should be
  protected from corrosion.

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- The device(s) should decelerate the occupant in the most efficient manner possible while maintaining the loading environment within the limits of human tolerance.

The discussion that follows refers to load limiters as separate devices. This is not meant to imply that load limiters must be separable devices at the exclusion of the integral design concept wherein the structure itself is designed to collapse in a controlled and predictable fashion. Rather, the discussion is present d in this way to simplify portrayal of different methods of absorbing energy and limiting loads.

Research on simple, compact, load-limiting devices has been conducted by the Government and by private industry. These data are recorded in References 62 through 70. A brief discussion of some of the more common energy-absorption devices and concepts applicable to seats is presented in the following text and in Table 3.

62. Ezra, A., and Fay, R. J., AN ASSESSMENT OF ENERGY ABSORBING DEVICES FOR PROSPECTIVE USE IN AIRCRAFT IMPACT SITUATIONS, in Dynamic Response of Structures, G. Herrmann and N. Perrone, eds., Pergammon Press, Elmsford, New York, 1972, pp. 225-246.

63. Reilly, M. J., CRASHWORTHY TROOᑫ SᴊAT INVESTIGATION, The Boeing Vertol Company; USAAMRDL Technical Report 74-93, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1974, AD/A-007090.

64. Kroell, C. K., A SIMPLE, EFFICIENT, ONE SHOT ENERGY ABSORBER, Reprint from Bulletin No. 30, Shock, Vibration, and Associated Environments, Part III, General Motors Research Laboratory, Warren, Michigan, February 1962.

65. Guist, L. R., and Marble, D. P., PREDICTION OF THE INVERSION LOAD OF A CIRCULAR TUBE, NASA Technical Note D-3622, Ames Research Center, Moffett Field, California, June 16, 1966.

66. Haley, J. L., Klemme, R. E., and Turnbow, J. W., TEST AND EVALUATION OF 1000-4000 POUND LOAD-LIMITING DEVICES, Dynamic Science, AvSER Facility, Report M69-2, for U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, February 1969.

TABLE 3. COMPARISON OF LOAD-LIMITING DEVICES FOR 1000-TO-4500-LB LOADS

Device description	Energy-absorption process	Operation sketch	Tension or compression	SEA[a] (ft-lb/lb)	Stroke-to-length ratio[b]	Long-term reliability	Ability to sustain rebound loads	Constant load level	Potential application
Strap/wire over die or roller	Metal bending and friction		T and C[c]	1200[d]	Good - T, Poor - C	Good to excellent	Zero to excellent[c]	Excellent	Seat strut or support
Inversion tube	Hoop tension/compression and bending		T and C	1800	Excel - T, Poor - C	Excellent	Excellent	Excellent	Seat support
Rolling torus	Cyclic compression and bending		T and C	1500	Good - T, Avg - C	Fair to good	Excellent	Good	Seat strut or support
Honeycomb compression	Buckling of membrane "columns"		C	2500-3500	Average	Good	Poor[e]	Fair	Seat strut or support
Basic metal tube or plate	Elongation of metal		T	3400-4500	Poor	Good to excellent	Poor[e]	Fair	Seat support
Basic stranded cable	Elongation of stainless steel		T	3000-4500	Poor	Excellent	Zero	Fair	Seat support or brace
Rod pull-through tube	Hoop tension and friction		T and C	600[f]	Good - T, Poor - C	Good	Poor	Good	Seat support
Tube flaring	Hoop tension, friction, and bending		C	700	Good to excellent	Good	Poor[e]	Fair	Seat strut
Tension pulley	Shear and bending of sheave housing		T	Unknown	Good	Good	Zero	Good	Seat support

(a) SEA is very dependent on materials and design. To be directly comparable the devices would need to be designed for the same application. The SEA values for the first three devices listed, those now being used in operational energy-absorbing seats, are reasonably comparable.

(b) In some cases, final length is significant; in other cases, initial length is significant.

(c) Simplest devices operate in tension (T) only; a recently developed troop seat strut is capable of tension (T) or compression (C) (Section 5.2).

(d) Specific energy measured for device that operates in tension or compression.

(e) This device could be rated higher if an integral rebound device were incorporated into the design.

(f) This value is based on the compressed tube device tested. This value could be doubled in a more efficient design.

In Table 3 Long-Term Reliability refers to the ability of the device to perform its function without benefit of maintenance throughout the life of the aircraft. The weight used in calculating SEA values includes the necessary end fittings required to apply the load except as noted.

Pertinent characteristics of each device listed in Table 3 are discussed in succeeding paragraphs. The concepts that have found use in actual seat designs are presented first.

5.2 WIRE OR STRAP BENDING

This device uses the force required to bend a metal wire or strap around a die or roller. It can be as simple as a steel wire threaded through a perforated plate or a wire wound around rollers. One characteristic that may be a problem with this device (as with all devices affected by or utilizing friction from metal-to-metal contact) is that an initial peak load higher than the normal stroking load is induced. This initial load increase can be reduced or eliminated by providing initial slack in the wire when passing it over the rollers. These devices, by themselves, do not have the ability to sustain compressive loads. However, by anchoring both ends of the wire and attaching the seat bucket to the rollers, compressive as well as tensile loads can be sustained.

67. Rich, M. J., VULNERABILITY AND CRASHWORTHINESS IN THE DE-SIGN OF ROTARY-WING VEHICLE STRUCTURES, Paper No. 680673, presented at Aeronautic and Space Engineering and Manufacturing Meeting at Los Angeles, Society of Automotive Engineers, Inc., New York, October 1968.

68. Bendix Products Aerospace Division, ENERGY ABSORBING CHAR-ACTERISTICS OF CRUSHABLE ALUMINUM STRUCTURES IN A SPACE ENVIRONMENT, Report No. SPP-65-107 (NASA-CR-65096), prepared for NASA Manned Spacecraft Center, Houston, Texas, July 1965.

69. McGehee, J. R., A PRELIMINARY EXPERIMENTAL INVESTIGATION OF AN ENERGY-ABSORPTION PROCESS EMPLOYING FRANGIBLE METAL TUBING, NASA Technical Note D-1477, National Aeronautics and Space Administration, Washington, D. C., October 1962.

70. Schwartz, M., DYNAMIC TESTING OF ENERGY-ATTENUATING DE-VICES, NADC Report No. AC-6905, Naval Air Development Center, Warminster, Pennsylvania, October 1969.

Two variations of the wire-bending device have been developed
and used in the ceiling- and floor-mounted troop seat illus-
trated in Figure 32. The two tension-type devices at the top
of the troop seat are shown in greater detail in Figure 33.
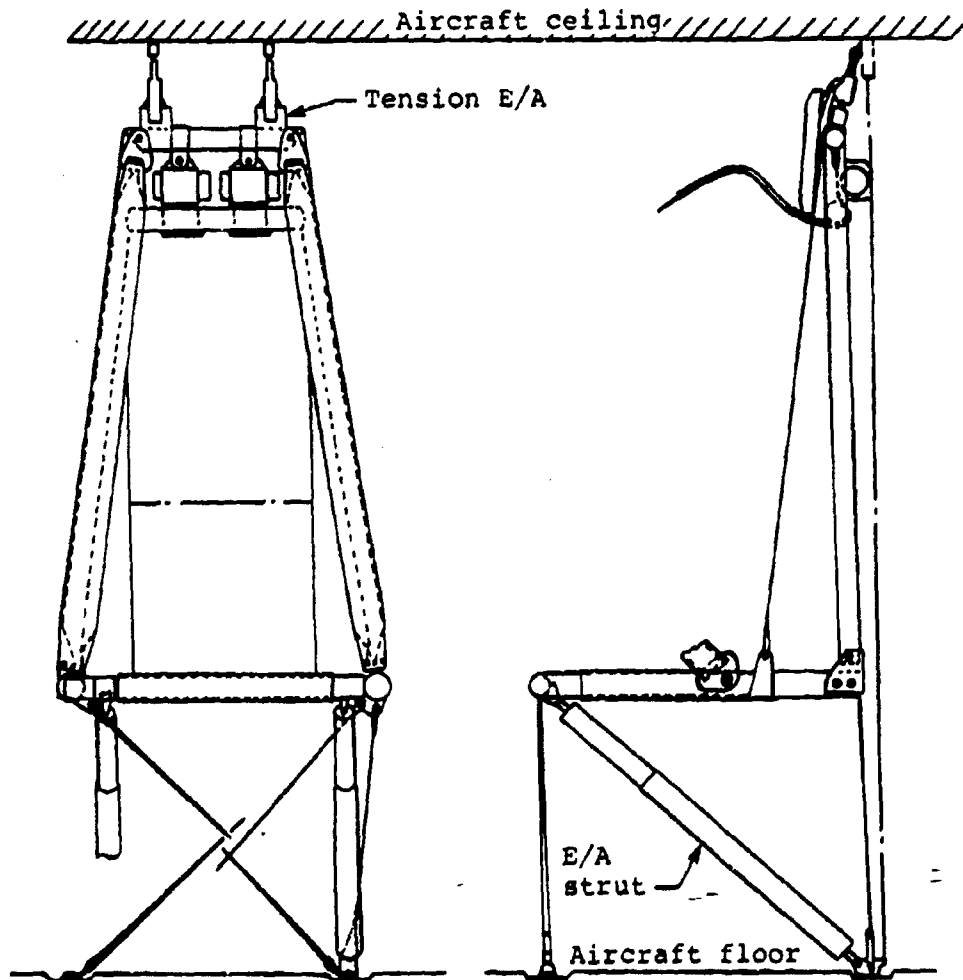
Figure 32. Crashworthy troop seat. (From Reference 63)

In the analysis of energy absorbers for the troop seat, re-
ported in Reference 63, wire of varying diameter was investi-
gated in order to produce a notched force-deflection curve as
recommended in Reference 36. It was concluded that the notched

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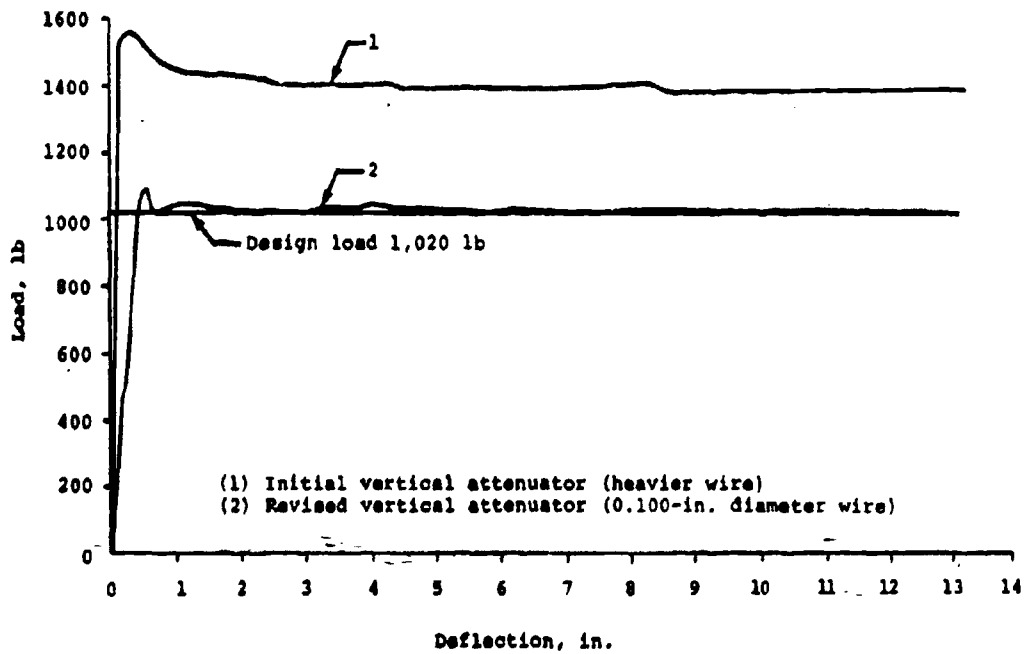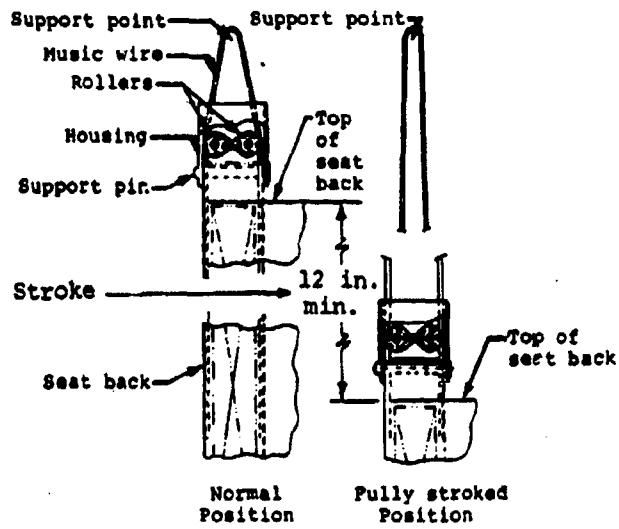
Figure 33. Troop seat tension energy absorber including characteristics for two wire diameters.

force-deflection curve was not suitable for lightweight troop seats due to the sensitivity of the system response to location of the notch in the load-versus-deflection characteristic. A fixed location for the notch was not compatible with the various dynamic response phasing resulting from the wide range of troop and equipment weights. The trapezoidal force-deflection curve produced by the constant limit-load device, although not as efficient theoretically and ideally as the notched curve for a specific dynamic condition, appeared to be more tolerant of the wide range of seat occupant weights. Figure 33 shows the force-deflection characteristics of the device that were measured for two different wire diameters.

The other variation of the wire-bending energy absorber used in the above mentioned troop seat, and shown in Figure 34, is capable of functioning in tension or compression. The device is contained in two telescoping aluminum tubes. A cap is placed on the inner end of the inner tube. Music wire of 0.100-in. diameter, in the shape of a hairpin, is looped through the cap, and the two free ends are secured to a stud in the outer end of the inner tube. A trolley consisting of three rollers sandwiched between two plates bends the wire as the trolley moves back or forth on the wire. The trolley is pinned to the outer tube, and a slot is provided in the inner tube to allow passage of the pin connecting the two.

5.3 INVERSION TUBE

This device uses the force required to invert (to turn inside-out or outside-in) a length of metal tubing. The concept was developed by an American automobile manufacturing company for incorporation into steering columns to produce controlled collapse loads (see Reference 64). No real disadvantages have been noted in experimental tests to date except with those loaded in compression. In dynamic tests of troop seats (Reference 71) using these devices in compression, there was a tendency for the outer and inner tubes to misalign, which resulted in failure and crippling of the inner tube. However, this problem can be solved by using an internal guide to keep the initial eccentricity from developing. It is possible that atmospheric corrosion could occur in the closed space between the inner and outer tube walls, especially in the bend radius. It has been suggested that this potential problem might be solved by injecting a low-density, closed-cell plastic foam into the small volume between the inner and outer tube walls

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71. Singley, G. T., III, FULL SCALE CRASH TESTING OF A CH-47C HELICOPTER, paper presented at 32nd Annual National V/STOL Forum, American Helicopter Society, Washington, D. C., May 1976.
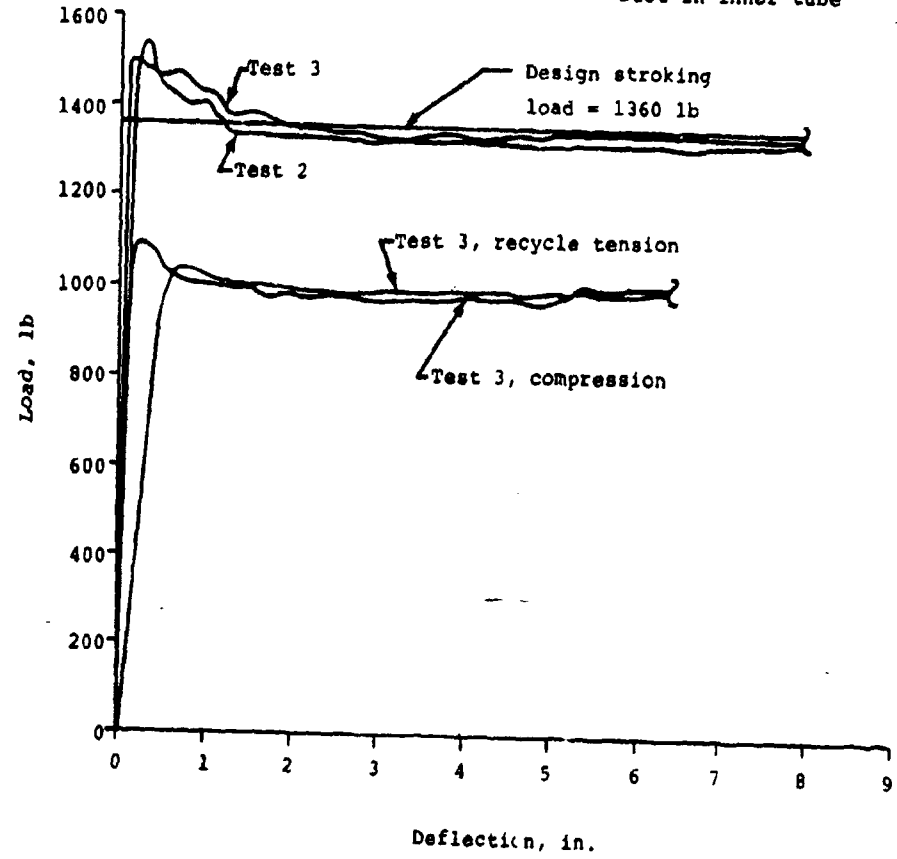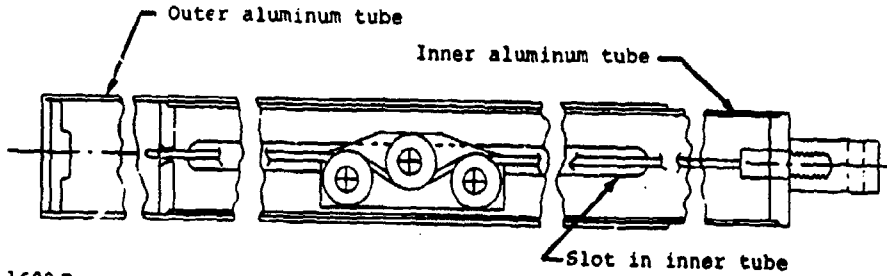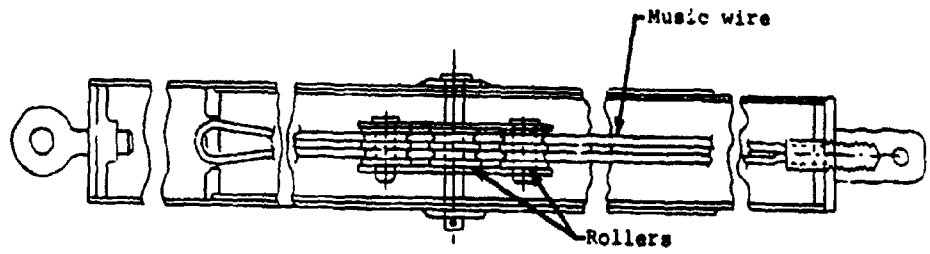
Figure 34. Tubular strut wire-bending energy absorber with force-deflection curves. (From Reference 31)

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to prevent moisture penetration of this area. Also, the tubes could be plated and/or coated to protect them from corrosion.

The materials used so far in inversion tubes have been 3003-H14 aluminum and mild steel, as described in References 64 through 66. It is possible that an annealed, higher strength alloy steel, such as 4130 or stainless steel, could yield even higher specific energy values than those shown in Table 3. However, the aluminum devices that are in use are both compact and lightweight.

Figure 35 illustrates a specific design concept of the inversion tube energy absorbers (Reference 72). The load-deflection curves are also shown for nine devices, three of which were subjected to fatigue testing and three to both environmental and fatigue testing. The traces are essentially flat for the entire stroke distance after the initial peak.

Typical load-deformation information for tubes made from 3003-H14 aluminum is presented in Figure 36. These curves show the variation in the load-deformation curve for a total of 12 dynamic test specimens and 2 static test specimens. Note that the peak dynamic load is about 1300 lb while the minimum dynamic load is about 1010 lb. This 25-percent variation is higher than the variation now being experienced at equivalant loading rates in operational systems. Posttest examination of the specimens showing 15- to 25-percent load increases indicated that the inverting tube had been scrubbing the inner wall of the loading tube due to asymmetric loading in the jig; therefore, friction probably caused some of the load increase. Figure 36 shows clearly that the inverting load remains essentially constant during the stroke (Reference 64).

5.4 ROLLING TORUS

Early versions of this energy absorber consisted of a number of torus elements located in the annular space between two telescoping cylinders. Modification of this concept has resulted in the substitution of a continuous helix of stainless steel wire for the toroidal elements. The interference fit between the cylinders and tori, or wire, causes the wire to roll when axial loads are applied. The cyclic plastic deformation of the rolling tori or wire helix and elastic deformation of the tubes effect the energy absorption. The cylinders remain intact and do not plastically deform when subjected to

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72. Desjardins, S. P., et al., CRASHWORTHY ARMORED CREWSEAT FOR THE UH-60A BLACK HAWK, paper presented at 35th Annual National Forum, American Helicopter Society, Washington, D. C., May 1979.

Thin-walled aluminum
roll tube (3003-H14)

Unstroked

Outer tube

Partially stroked

Plastically
deforming
region

	Three devices previously fatigue tested	Three devices previously environmentally and fatigue tested	Three new devices used as control group
	———— S/N 1002	▲▲▲ S/N 1005	▽▽▽ S/N 1008
	·············· S/N 1003	—··— S/N 1006	—··— S/N 1009
	·········· S/N 1004	▼▼▼ S/N 1007	——— S/N 1010

Stroke, in.
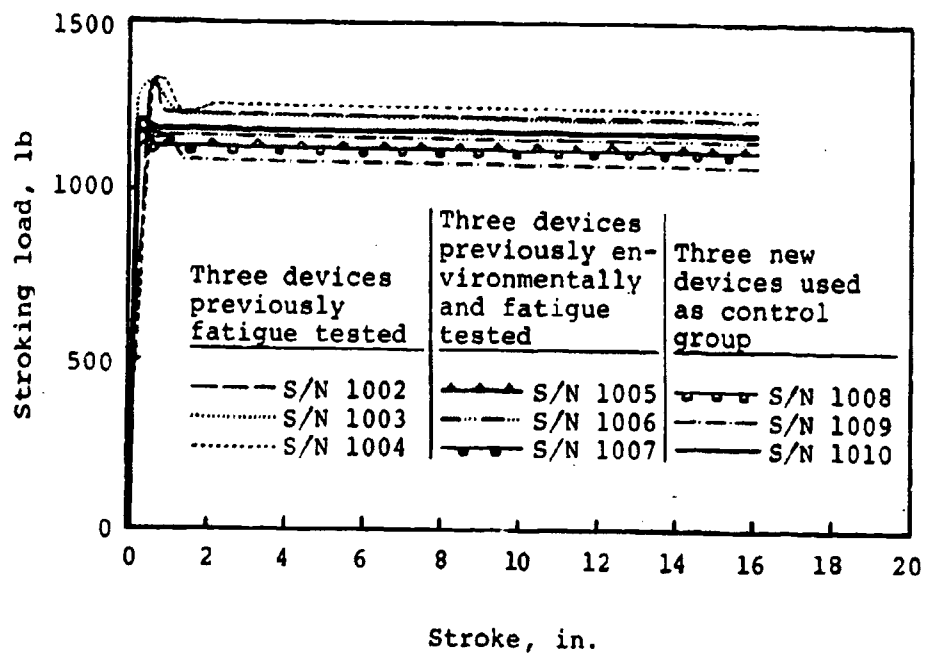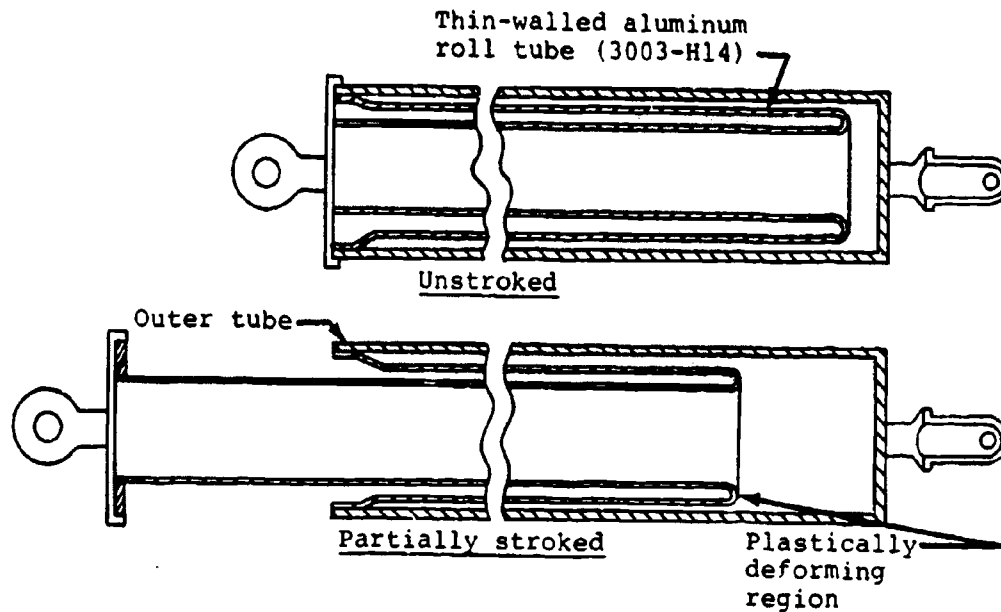
Figure 35. Inversion tube concept with typical
force-deflection characteristic.

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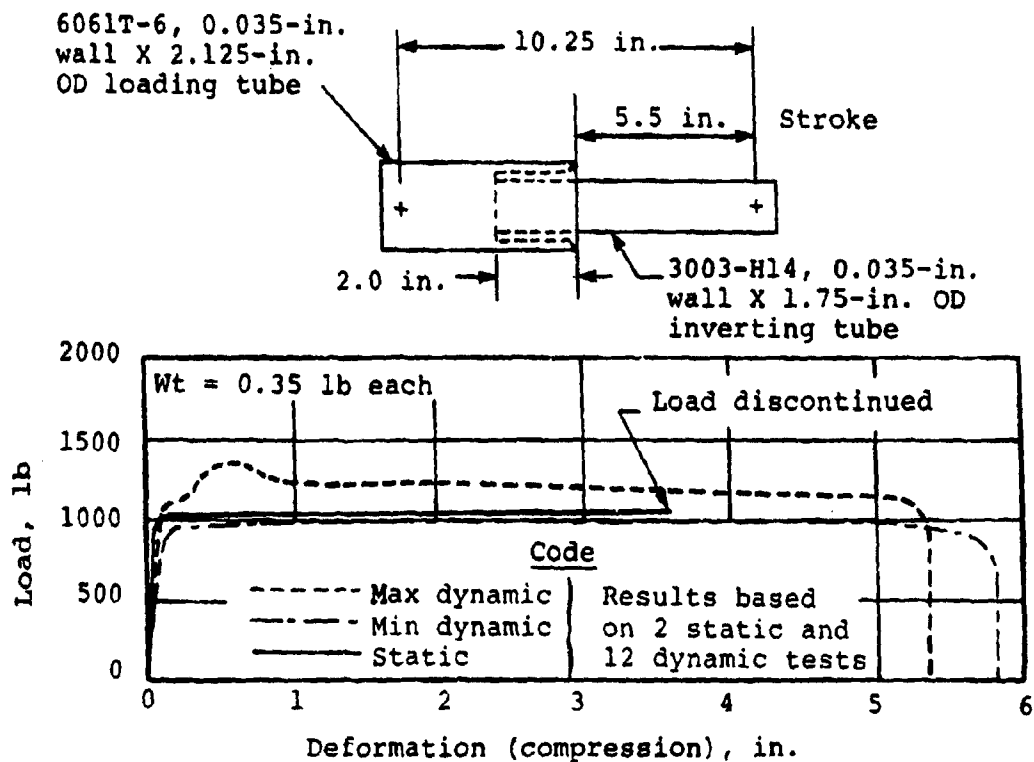
Figure 36. Comparison of dynamic and static load-
deformation curves for inversion tubes.

impact loading. The impact force is transmitted through the
tubes to the tori or wire helix. Dynamic testing of these de-
vices is reported in Reference 70.

The load limiters using wire as the working medium (Figure 37)
are normally made with cylinders that range from 1 to 2 in. in
diameter with a wall thickness of approximately 0.035 in. The
wire ranges between 0.030 and 0.035 in. in diameter and is of
300 series stainless steel. These bidirectional devices may be
used repeatedly several times until fatigue failure of the wire
occurs. The recent investigation of a lighter weight aluminum
energy absorber of this type is documented in Reference 73.

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73. Mazelsky, B., INVESTIGATION OF AN ALUMINUM ROLLING HELIX
CRASH ENERGY ABSORBER, ARA, Inc.; USAAMRDL Technical Re-
port 77-8, Eustis Directorate, U. S. Army Air Mobility
Research and Development Laboratory, Fort Eustis, Vir-
ginia, May 1977, AD A042084.
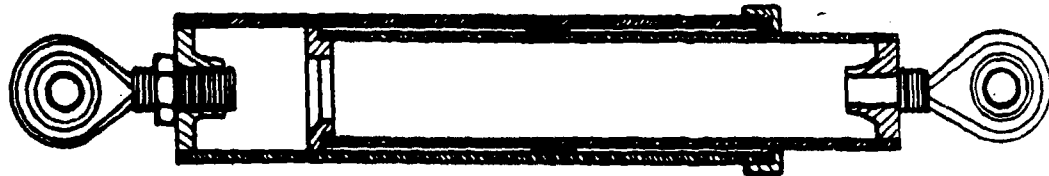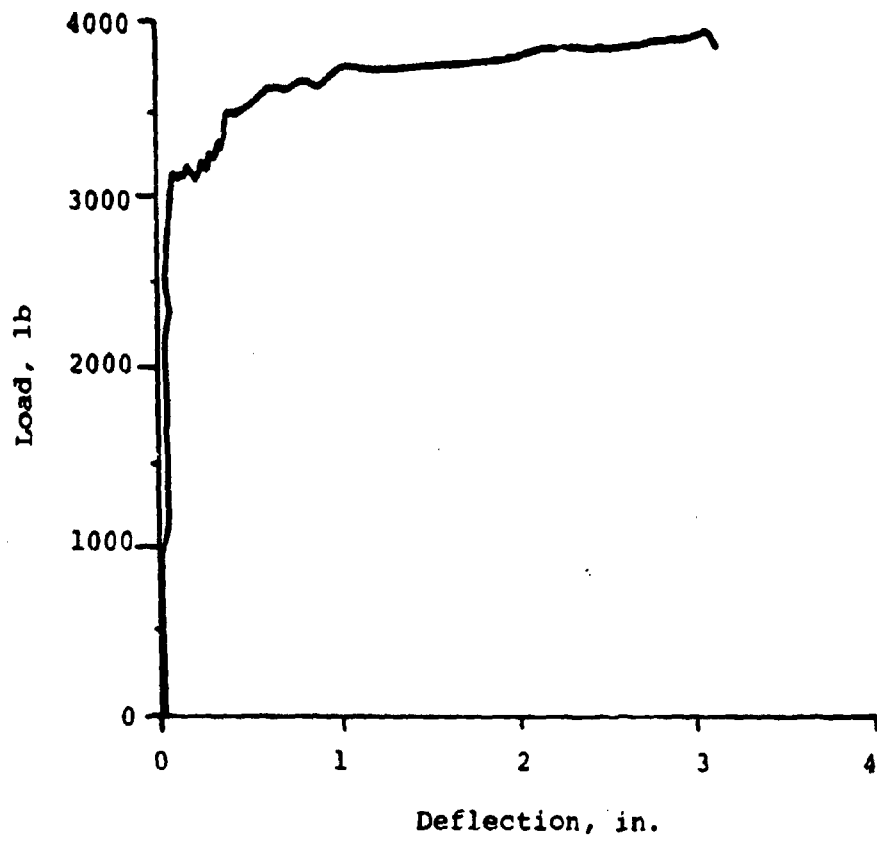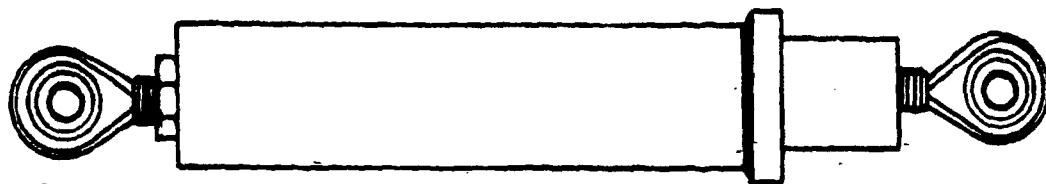
Figure 37. Rolling torus energy absorber.

Devices of this type can be single or multiple staged. The multiple-staged energy absorbers include three tubes with helices of wire between the walls of the outer tube and the center tube, and between the center tube and the inner tube. In operation, one helix of wire is rolled to the end of its stroke and then the second stage is initiated and rolled. Staged energy absorbers provide increased stroke distance without an appreciable increase in prestroked envelope.

The device produces a somewhat jagged load-versus-deformation characteristic as can be seen in Figure 37. Further, the interference contact between the tori and the cylinders, the closed spaces between the tube walls, and the spaces between the wire wraps are prime areas for corrosion. This potential should be considered during the development, test, and usage of this device. The long-term effects on performance of the interference fit between the wire and the tubes is another area for concern.

Seats with energy-absorbing mechanisms utilizing this device are now in use in a modified U. S. Marine helicopter (Reference 16) and in a utility helicopter developed for Iran.

5.5 CRUSHING HONEYCOMB

This device uses the force required to crush or deform a column of low-density material. In order to provide sufficient column stability and transverse load resistance, it appears that most applications will require a telescoping cover to give additional bending strength. Table 3 shows this device to be above average in all categories with the exception of rebound load ability. Rebound load capacity could probably be added by the incorporation of a suitable mechanism that allows movement in only one direction.

This device, besides being used on seats, is used as a load limiter in the main landing gears of some helicopters. In these applications, the crushable material is installed above the oleo piston as outlined in Reference 67. The energy-absorption ability of these devices has been responsible for preventing major structural damage to several aircraft in severe accidents.

To date, the best crushable material for use in this type of device appears to be corrugated aluminum foil backed by flat foil, cemented at the nodal points as illustrated in Figure 38. Further research information on the development of crushable aluminum columns may be found in Reference 68.
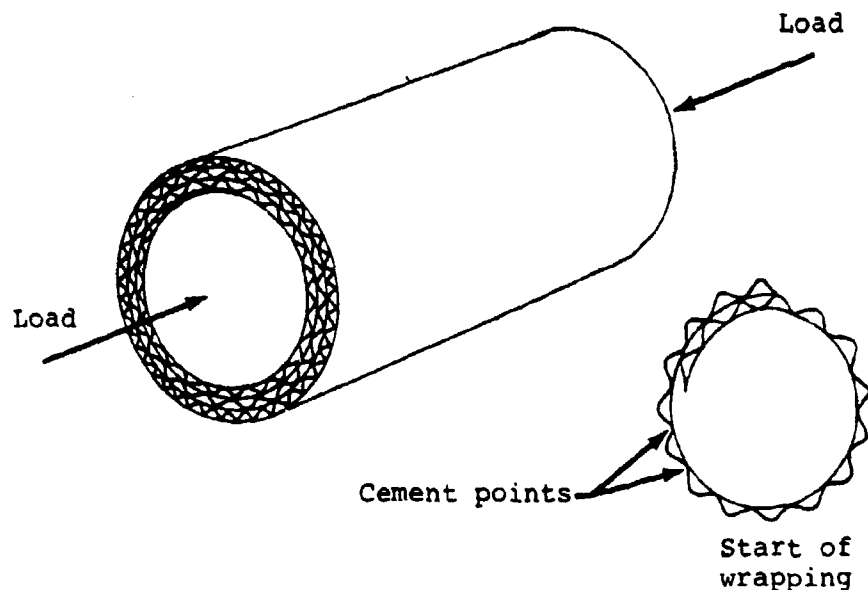
Figure 38. Illustration of corrugated aluminum foil formed into annular column.

5.6 EXTENSION OF BASIC METAL TUBE OR FLAT STRAP

This concept uses the inherent plasticity of certain ductile metals which elongate under a relatively constant force. The primary problem with this device is strain concentration at the end connections. Research to date indicates that annealed stainless steel in the AISI 300 series is least susceptible to strain concentrations because of its excellent ductility (45 to 50 percent).

The flat strap device was evaluated for use as a vertical load limiter for a pilot's seat by the U. S. Naval Aircraft and Crew Systems Technology Directorate, now part of the U. S. Naval Air Development Center and was found to perform satisfactorily (Reference 74). Since a flat strap sustains only minimum compressive loads, a separate rebound device would be necessary for application in personnel seats.-

The thin-walled tube will perform in much the same manner as the flat strap, and it has the advantage of sustaining higher

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74. Woodward, C. C., et al., INVESTIGATION, DESIGN AND DEVEL-
OPMENT OF AN F7U-3 EJECTION SEAT ENERGY ABSORPTION SYSTEM
FOR REDUCTION OF CRASH FORCE LOADS, NADC Report ACEL-335,
Naval Air Development Center, Warminster, Pennsylvania,
June 1957.

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compressive loads; although this capability is still inadequate.
It is desirable that the tube elongate throughout its length
rather than locally; for example, at the end attachments. A
successful method of achieving nearly uniform elongation is the
use of a low-modulus bonding agent between the tube and the ap-
propriate end fitting (see Reference 66).

Typical load-elongation characteristics of a 0.02-in. wall by
0.50-in.-diameter stainless steel tube are illustrated in Fig-
ure 39.
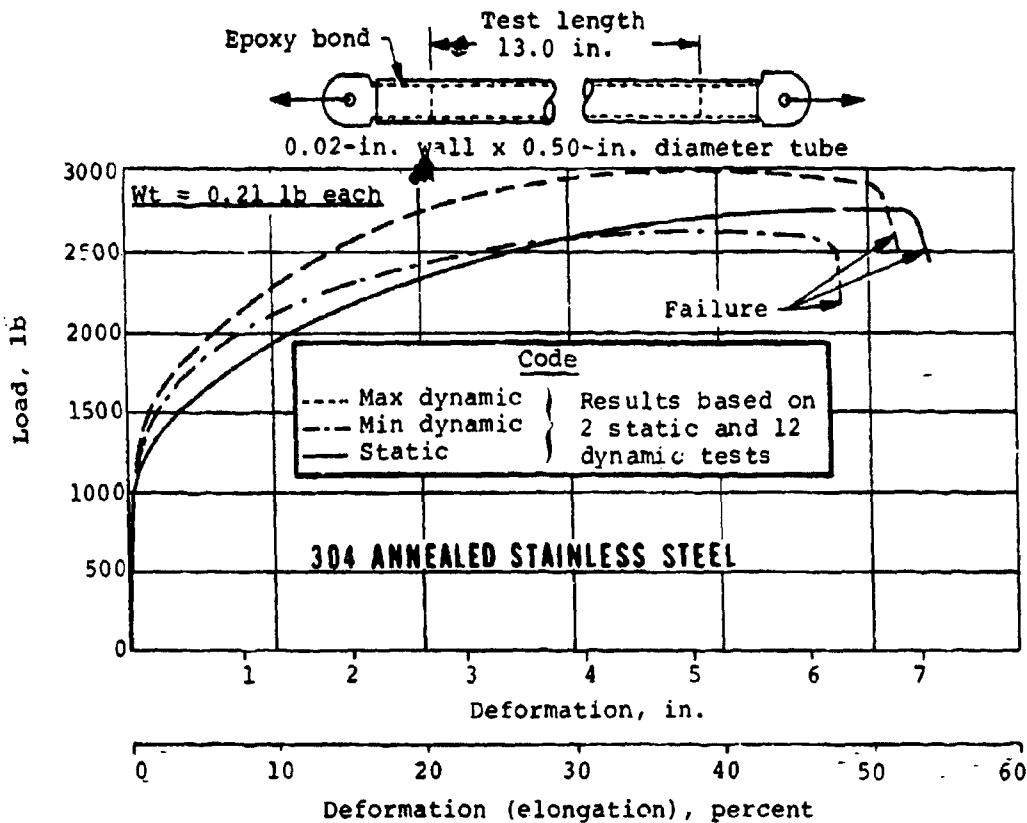
Figure 39.   Comparison of dynamic and static load-elongation
curves for stainless steel tubes.

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5.7 ELONGATION OF BASIC STRANDED CABLE

This device has the same characteristics as the basic metal tube or flat strap; however, the flexibility of a cable obviously has advantages for some load-limiter applications. The cable end fittings are capable of sustaining the ultimate load of the cable under static and dynamic conditions. This device appears to be most applicable to bracing lightweight seats, such as troop and gunner seats.

5.8 ROD PULL-THROUGH TUBE

This device uses the force required to expand the diameter of a tube as a hardened, oversized rod or tube is drawn through it, or to compress an inner rod or tube as it is drawn through a die. The force required to overcome friction also contributes to the energy absorbed by this device; however, dependence on friction to maintain a uniform load is unpredictable. The frictional resistance of the device tested in Reference 66 (a compression tube device with a rigid outer cylinder) was reduced by lubrication, but the device exhibited an initial peak load as indicated by point A in Figure 40.

It can be seen in Figure 40 that the stroke of this device was limited to 4 in. and that the failure load was about three times the stroking (sustained) load. Thus, the tested device had a safety factor of at least 3 to 1 built into it, and this fact partially accounted for the poor specific energy rating shown in Table 3. It can be seen in the figure that the maximum variation in the stroking load was from 1300 to 1600 lb, or about 21 percent.

5.9 TUBE FLARING

This device simultaneously uses the forces required to expand the diameter of a tube to the failure point and to bend the tube walls through 90 degrees. The tube wall either shatters into fragments or rolls up into spirals around the periphery of the tube, as illustrated in Figure 41. A review of Reference 69 indicates that the above processes are sensitive to the ratio of the wall thickness to the die radius; and that ratios of less than 0.3 are likely to result in a rolling process, while ratios of greater than 0.4 are likely to result in the fragmentation on the basis of tests using 2024-T3 aluminum tubes.

This concept has been evaluated for an experimental crewseat by the U. S. Naval Aircraft and Crew Systems Technology Directorate, now part of the U. S. Naval Air Development Center, as described in Reference 70. The device was used as the vertical

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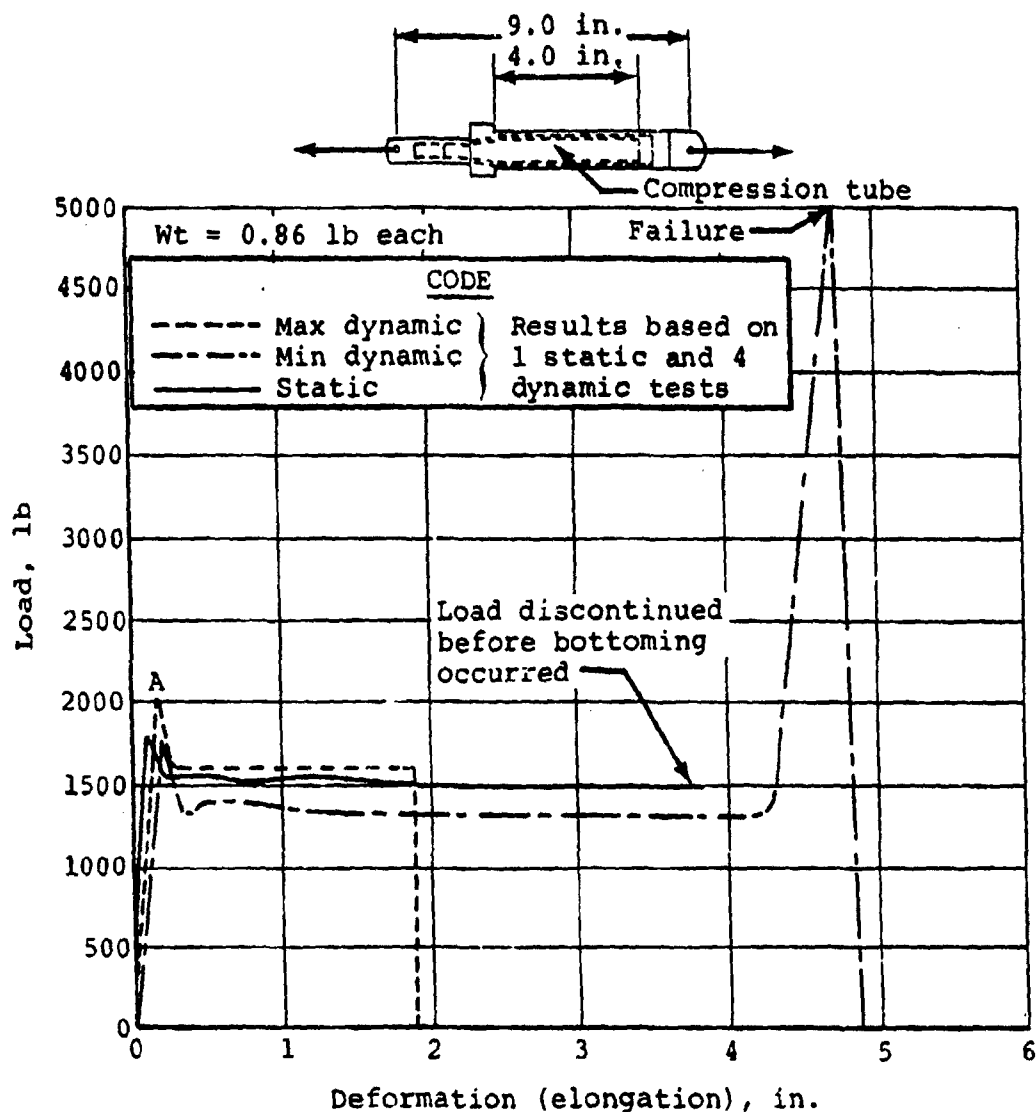
Figure 40. Comparison of dynamic and static load-deformation curves for compression tubes.

energy absorber in the seat. The device also was used as the vertical load limiter for an experimental troop seat, as described in Reference 63.

The device cannot sustain rebound forces because only a minimum rebound resistance is provided by friction between the tube and the forming die. However, a mechanism was installed in the forming die to grip the tube against rebound movement.

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| Forming die | Fragmentation | Rolling |
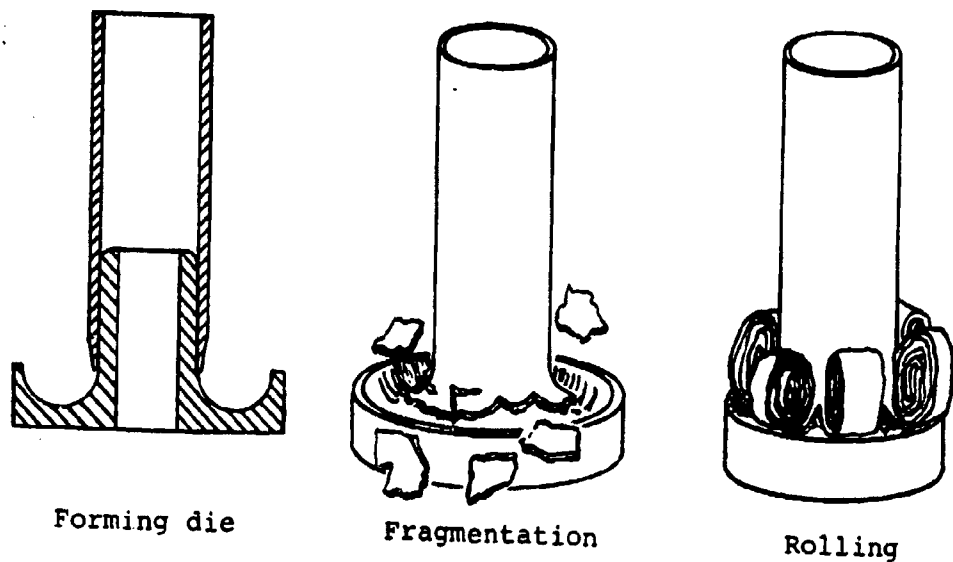
Figure 41. Illustration of fragmentation and rolling-
processes in tube-flaring device.

5.10 TENSION PULLEY

The tension-pulley load limiter shown in Figure 42 requires
that the pulley casing be literally split open as the pulley
rotates. The plastic deformation of the casing material ef-
fects the energy absorption. As the name implies, the device
is unidirectional and operates under tensile loading only. It
has been used in cargo restraint systems and energy-absorbing
troop seats, as described in Reference 75.

5.11 SELECTION OF AN OPTIMUM LOAD LIMITER

An optimum load-limiting system cannot be selected on the basis
of the data presented above. The data should be used as guide-
lines with due consideration to the requirements for each spe-
cific application.

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75. Turnbow, J. W., Robertson, S. H., and Carroll, D. F., DY-
     NAMIC TEST OF AN EXPERIMENTAL TROOP SEAT INSTALLATION IN
     AN H-21 HELICOPTER, Aviation Crash Injury Research (AvCIR),
     Division of Flight Safety Foundation, Inc.; TRECOM Tech-
     nical Report 63-62, U. S. Army Aviation Materiel Labora-
     tories, Fort Eustis, Virginia, November 1963.
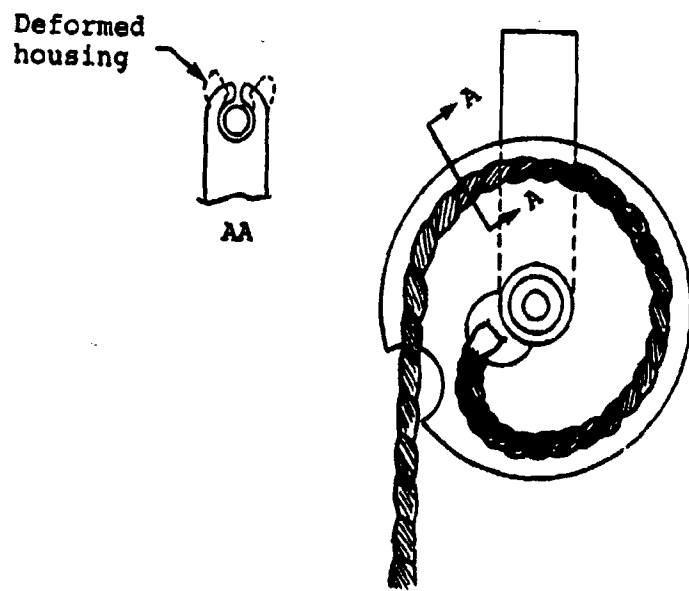
Figure 42. Tension-pulley load limiter.

6. SEAT CUSHIONS

6.1 INTRODUCTION

The seat bottom and back with which the occupant is in constant
contact should be designed for comfort and durability. Suffi-
cient clearance between fabric backs and bottoms or sufficient
cushion thickness of the appropriate material stiffness should
be provided to preclude body contact with the seat structure
when subjected to either the specified operational or crash
loads. Seat bottoms made of fabric should be provided with
means of tightening to compensate for sagging in use. The con-
flicting requirements of long-term comfort-versus-crash safety
considerations have made this a difficult design area.

For seat cushions, the problem is one of developing a compro-
mise design that will provide both acceptable comfort and
safety. In the past, the comfort requirement was met by pro-
viding very thick, soft, foam cushions that allowed the oc-
cupant to sink in deeply, thereby producing a contour and
spreading the load around the person's buttocks so as to de-
crease local high pressure and eliminate point loading. This
approach provided both immediate and long-term comfort. A
method of providing thermal comfort was to force air through
the cushion, or to use stretched net cushions, which provided
contouring and load spreading as well as the free passage of
air. The passage of air allows the evaporation of sweat and,
thus, achieves the desired cooling effect.

Crash-safety considerations require a minimal thickness of foam
to minimize or eliminate vertical motion of the pelvis during
high vertical loadings. This requirement conflicts with the
method chosen for providing pressure comfort described in the
previous paragraph, and constitutes a problem that must be
solved to provide an acceptable cushion.

One approach producing the desired compromise between crash
safety and comfort uses a cushion base with a contour that
matches the universal buttocks configuration as closely as pos-
sible. This wraparound configuration spreads the load and de-
creases localized pressure without resorting to soft foams.
Additional comfort layers of foam can then be added to the base,
and the cushion base can be equipped with slots or holes which
allow for fore-and-aft passage of air to provide the desired
cooling. A layer of rate-sensitive foam can be used on top of
the base to provide a contour transition softer than the base.
This layer must either be open celled, or holes must be pro-
vided to allow for vertical movement of air. A layer of soft,
open-celled foam can be used on top of the rate-sensitive foam
to provide the initial comfort material and to also provide

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vertical and horizontal air motion. The entire cushion can be covered with a fire-retardant, open, nylon material to provide for wear and abrasion resistance.

The total thickness of the compressed cushion at the buttock reference point should be minimized and can be limited to between 0.5 and 0.75 in. of thickness. This cushion probably permits not more than 3/8 in. of vertical motion of the pelvic structure (ischial tuberosities) from the 1-G loaded position to the full vertical crash-loaded position.

Other methods of achieving the desired effect are available. One is to include the basic provisions just described but to achieve the thermal effect plus some loading comfort by the use of special coverings such as lamb's wool. This type of cover uses the lamb's skin with a small depth of combed and clipped wool on the occupant interface surface. These covers need holes cut through the leather to allow free passage of air for cooling as previously discussed.

To meet the required crashworthy characteristics, the optimum aircraft seat cushion will:

- Be extremely lightweight.

- Possess flotation capabilities.

- Be nonflammable.

- Be nontoxic; will not give off fumes when burned, charred, or melted.

- Be tough and wear resistant.

- Be easily changeable.

- Provide comfort by distributing the load and reducing or eliminating load concentrations.

- Provide thermal comfort through ventilation.

- Provide little or no rebound under crash loading.

- Allow an absolute minimum of motion during crash loading.

6.2 REQUIREMENTS

For seats of light movable weight (less than 30 lb), cushions should be used for comfort only. The maximum uncompressed

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thickness for a properly contoured cushion should be 1-1/2 in., unless it can be shown through analysis or through dynamic tests that the cushion design and material properties produce a beneficial (reduced force transmissibility) result.

For seats of greater movable weight, such as integrally armored seats, every effort should be made to design a cushion that minimizes relative motion between the occupant and the seat and that acts as a shock damper between the occupant and the heavy seat mass. Viscoelastic and loading-rate-sensitive materials, such as discussed previously, can be used to accomplish this goal. Again, dynamic analysis and/or testing should be conducted to demonstrate that the cushion design produces a desirable system result over the operational and crash environmental range of interest.

6.3 ENERGY-ABSORBING CUSHIONS

The use of load-limiting cushions in lieu of load-limiting seats is undesirable for two reasons:

- The downward movement of the torso into a crushable seat cushion produces slack in the restraint harness. This slack could allow injury during subsequent longitudinal or lateral acceleration in forward-facing seats by contributing to dynamic overshoot and/or by allowing the lap belt to move upward into the soft portion of the abdomen. For an aft-facing seat, this slack is not as significant for longitudinal accelerations but applies to the lateral direction.

- A crushable cushion does not make optimum use of the available stroke distance since space must be allowed for the crushed material. A crushable cushion can be only approximately 75 percent as efficient as a mechanical load-limited system that allows the seat to stroke completely to the floor.

Crushable cushions are impractical in rotary- and light fixed-wing aircraft because of the long stroke distance required to attenuate the high vertical loads present in the 95th-percentile crashes. The only justifiable use of energy-absorbing cushions instead of load-limited seats might be in retrofit circumstances where, because of limitations in existing aircraft, another alternative does not exist (see Reference 76 for further information on energy-absorbing cushions).

76. DYNAMIC TEST OF CRUSHABLE SEAT CUSHIONS, AvSER Report M67-6, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc., Phoenix, Arizona, August 1967.

Recent research has indicated that foams can be used more economically than honeycombs without reduction in performance. Foams are much easier to form and are less costly than metallic honeycomb materials and are therefore recommended for this use.

6.4 NET-TYPE CUSHIONS

This type of cushion serves the same purpose as the filled cushion; however, a net material is stretched over a contoured seat frame, and the body is supported by diaphragm action in the net rather than by deformation of a compressible material. The net-type cushion might more properly be called a net support. If a net support is used in the seat, its rebound characteristics should be capable of limiting the return movement from the point of maximum deformation to 1-1/2 in. Net supports should not increase the probability of occupant submarining or dynamic overshoot. The net elastic-stretch limitation might be achieved by including a stiffer net, such as a steel or aluminum woven material under the net support.

6.5 OTHER CUSHIONS

In most cases the back cushion will not play a significant role in the crash dynamics; however, it will influence comfort and can influence the injury tolerance of the spine. The cushion should be of a lightweight foam material or net. The foam can be a standard furniture type that meets the other requirements listed in Section 6.2. Lumbar supports, particularly those that are adjustable by the occupant, are desirable for comfort and for safety reasons. A firm lumbar support that holds the lumbar spine forward in extension increases the tolerance to $+G_z$ loading.

6.6 HEADRESTS

A headrest should be provided for occupant head/neck whiplash protection. Headrest cushions are used only to cushion head impact and prevent whiplash injury due to backward flexure of the neck. The cushioning effect can be provided by a thin pad and a deformable headrest or a thicker cushion on a more rigid headrest. For the thicker cushion, the provisions of Section 10.9 should be applied and at least 1.5 in. of cushion should be provided if possible within the space limitations of the application.

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7. DESIGN PRINCIPLES FOR PERSONNEL RESTRAINT SYSTEMS

7.1 INTRODUCTION

Crash injury accident statistics indicate that failure of personnel restraint harnesses has been a frequent cause of injuries and fatalities in U. S. Army aircraft accidents. This is unfortunate because body restraint is relatively easy to control. Adequate restraint in a crash can mean the difference between life and death, since evacuation from a burning or sinking aircraft is considerably improved if no prior injury or debilitation has occurred. It is the intent of this section to provide general criteria and guidelines for the design of personnel restraint systems to reduce injury or debilitation in a crash situation. Design criteria for cargo restraint systems are presented in Volume III.

Restraint harnesses for personnel should provide the restraint necessary to prevent injuries to all aircraft occupants in crash conditions approaching the upper limits of survivability. Appropriate strength analysis and tests as described in Section 8.5 should be conducted to ensure that a restraint system is acceptable.

Numerous methods of restraining the human body have been proposed, investigated, and used. Some of these have proven to be exceptionally good, and some have left much to be desired. However, there are certain qualities that a harness should possess if it is to be used routinely for military flights. These desirable qualities are listed below:

- Comfortable and light in weight.

- Easy for the occupant to put on and take off even in the dark.

- Contain a single-point release system, easy to operate with one (either) hand since a debilitated person might have difficulty in releasing more than one buckle with a specific hand. Also, it should be protected from inadvertent release, e.g., caused by the buckle being struck by the cyclic control or by inertial loading.

- Provide personnel with freedom of movement to operate the aircraft controls. This requirement necessitates the use of an inertia reel in conjunction with the shoulder harness.

- Provide sufficient restraint in all directions to prevent injury due to decelerative forces in a potentially survivable crash.

- Webbing should provide a maximum area, consistent with weight and comfort, for force distribution in the upper torso and pelvic regions and should be of low elongation under load to minimize dynamic overshoot.

7.2 TYPES OF SYSTEMS

7.2.1 Aircrew Systems

The existing military lap belt and shoulder harness configuration with a center tiedown strap as shown in Figure 43 is the minimum acceptable harness for use by U. S. Army pilots. The lap belt tiedown strap resists the upward pull of the shoulder straps and prevents the belt's displacement into abdominal tissue. The tiedown strap is comfortable to wear since it does not contact the pelvis, and it is narrow enough within limits of acceptable strength so that little leg rubbing is encountered by the wearer during antitorque or rudder pedal operation.

The configuration shown in Figure 44 provides improved lateral restraint due to the addition of the reflected shoulder straps. This system, which resulted from the investigation reported in Reference 77, consists of one dual-spool inertia reel or two separate inertia reels with two reflected straps, a shoulder harness collar assembly, a lap belt assembly including retractors, and a buckle assembly. The buckle assembly consists of a single-point release buckle permanently attached to the tiedown strap. The tiedown strap consists of a fixed-length strap for any specific seat and cushion design, and an anchor fitting that connects the strap to the seat pan beneath the seat cushion. The left- and right-hand lap belts, connected at the single-point release buckle, are attached to the seat or aircraft structure through automatic lock/unlock retractors.

The shoulder harness collar assembly consists of a pad in the form of a collar fitting around the crewman's neck, over which the shoulder harness straps are routed. The lower shoulder

77. Carr, R. W., and Desjardins, S. P., AIRCREW RESTRAINT SYSTEM - DESIGN CRITERIA EVALUATION, Dynamic Science, Division of Ultrasystems, Inc.; USAAMRDL Technical Report 75-2, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1975, AD A009059.

Item identity

1. Buckle assembly
   A. Single-point release buckle
   B. Tiedown strap
   C. Tiedown anchor
2. Lap belt assembly
   A. Lap belt
   B. Adjuster
3. Shoulder harness assembly
   A. Inertia reel
   B. Inertia reel strap
   C. Lower shoulder strap
   D. Adjuster

Forward
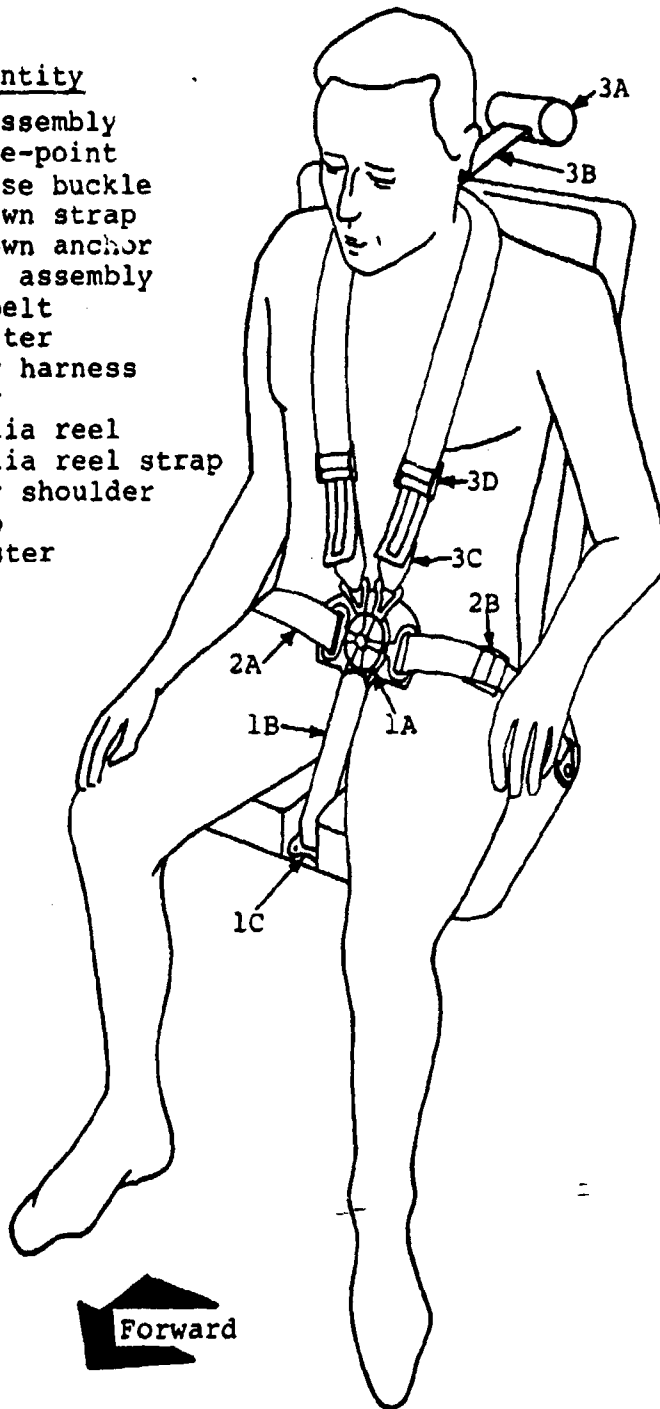
Figure 43.   Basic aircrew restraint system.

Item identity

1. Buckle assembly
   A. Single-point
      release buckle
   B. Tiedown strap
   C. Tiedown anchor
2. Lap belt assembly
   A. Lap belt
   B. Retractor
3. Shoulder harness
   collar assembly
   A. Pad
   B. Roller fitting
   C. Adjuster
   D. Lower shoulder strap
4. Inertia reel assembly
   A. Reflected strap
   B. Anchor

Forward
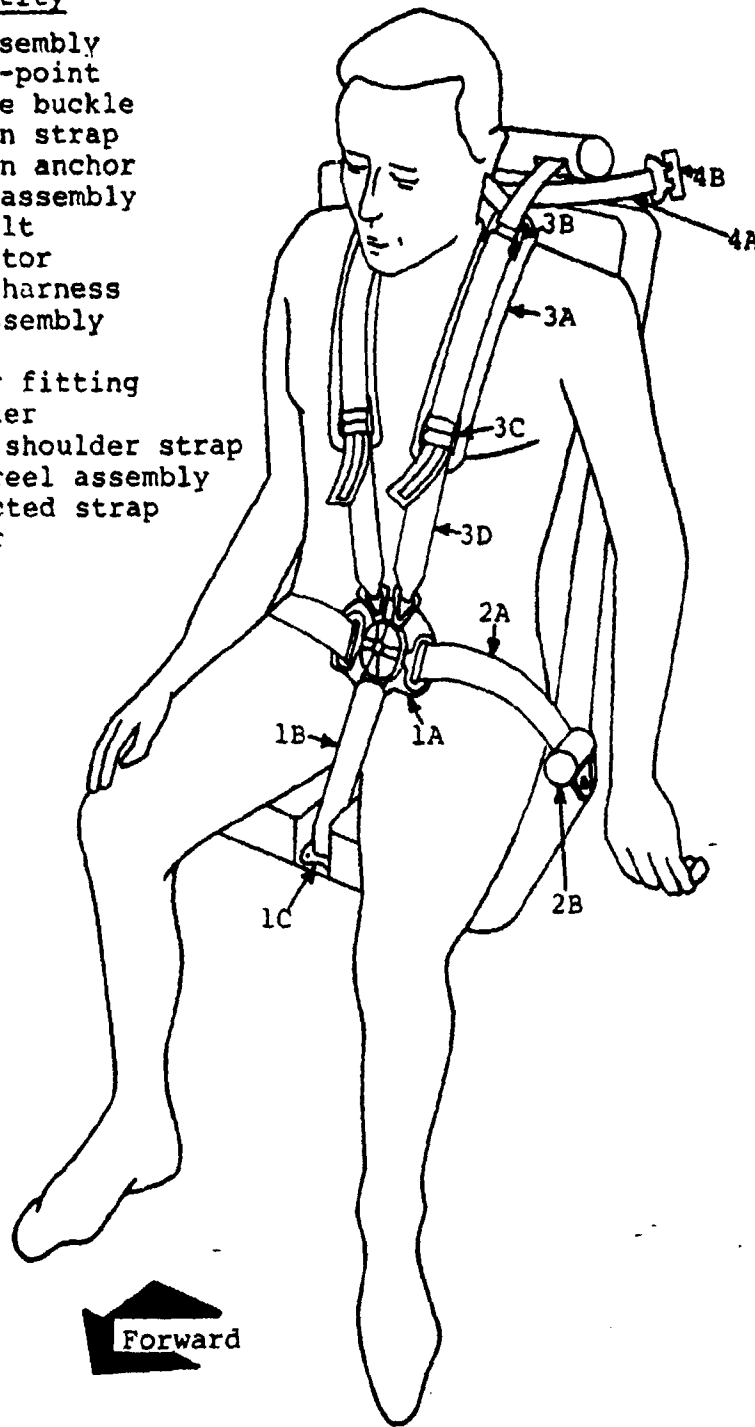
Figure 44. Aircrew restraint system, including
             reflected shoulder straps.

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straps connect to the bottom of the collar assembly through the adjusters. The reflected straps pass through the roller fittings at the top of the collar. Each reflected strap is extended forward from an inertia reel, looped through the roller fitting, and then directed rearward to the opposite side of the seat back. These straps are attached to the seat through anchor fittings on the reflected ends and through inertia reels at the other end. The lap belt straps, tiedown strap, and lower shoulder straps are all connected at the single-point release buckle. Details of the hardware in these systems are discussed in Section 7.5.

7.2.2 Troop Systems

Considerations in the selection of a troop or passenger seat restraint system are different from those for an aircrew system. First of all, the seat may face forward, sideward, or aftward. Secondly, the restraint system must be capable of being attached and removed quickly in an operational environment by troops encumbered by varying types and quantities of equipment. Also, whereas a pilot probably uses the restraint system in his aircraft so frequently that its use becomes a matter of habit, troops and passengers can be expected to be unfamiliar with the system. The effects of this lack of familiarity would probably become more pronounced in a combat situation when the risk involved in not using the restraint system becomes even higher. Therefore, hardware should be uncomplicated and, if possible, resemble the familiar, such as automotive hardware. Finally, the need to quickly remove and stow the seats requires compact and lightweight restraint systems.

For the aft-facing passenger, the need for a tiedown strap is negligible, since the seat back will provide the primary restraint; however, the shoulder harness should be retained as part of the restraint system to provide adequate support in crashes that produce significant lateral loads.

It is difficult to provide adequate restraint for side-facing passengers with a lap belt and shoulder harness alone. Leg restraint would also be preferred; however, leg restraints are generally not practical because of operational requirements, which necessitate the side-facing seats in Army aircraft. A reflected shoulder strap and side belt strap offers a compromise solution; however, they too have met with resistance because of weight and cost considerations. The belt side straps, extending from the lap belt high on the thigh to the seat pan forward of the lap belt anchor, help to hold the belt in place over the pelvic region as well as provide more area to resist the pressure from the pelvis. The reflected shoulder strap provides improved upper torso restraint.

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Two systems that resulted from the investigation reported in Reference 78 are shown in Figure 45. The Type II troop restraint system was designed to mount on a forward-facing or aft-facing troop seat and consists of a two-strap shoulder harness and a lap belt assembly. The two shoulder straps are attached to two single inertia reels. They extend forward and down over the occupant's upper torso and are connected into the single-point release, lift-lever buckle. The lap belt assembly includes left- and right-hand belts, with adjusters, that are connected together at the lap belt buckle. The Type I troop restraint system was designed to mount on a side-facing troop seat and differs from the Type II restraint by having a single shoulder strap that passes diagonally across the occupant's upper torso. It should pass over the shoulder closest to the nose of the aircraft. If the Type I system is used in either a forward- or aft-facing seat, the diagonal shoulder strap should pass over the outboard shoulder to restrain the occupant from protruding outside the aircraft during lateral loading.

7.2.3 Crew Chief and Door/Window Gunner Systems

Restraint systems for crew chiefs and door/window gunners are similar to troop systems; however, they must allow the crewmember to move out of the seat to perform duties such as maneuvering the gun or observing tail rotor clearance while landing in unprepared areas. The system should restrain the occupant to the seat the instant he returns to the seat and provide adequate restraint during a crash. The system should maintain the lap belt buckle in the proper relationship to the gunner, preventing the shoulder straps from pulling it up or the lap belt from pulling it sideways. Such a system has been described in Reference 79 and is shown in Figure 46. It consists of a lap belt with inertia reels on each side of the seat and two shoulder straps connected in an inverted-Y arrangment to a single inertia reel strap. The lap belt with thigh strap attachment is easy to put on and prevents the lap belt from riding up during operation of the gun. The lap belt is plugged into the two seat pan inertia reels when the crewmember is to

78. Carr, R. W., HELICOPTER TROOP/PASSENGER RESTRAINT SYSTEMS DESIGN CRITERIA EVALUATION, Dynamic Science, Division of Ultrasystems, Inc.; USAAMRDL Technical Report 75-10, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1975, AD A012270.

79. Reilly, M. J., CRASHWORTHY HELICOPTER GUNNER'S SEAT INVESTIGATION, The Boeing Vertol Company; USAAMRDL Technical Report 74-98, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1975, AD A005563.
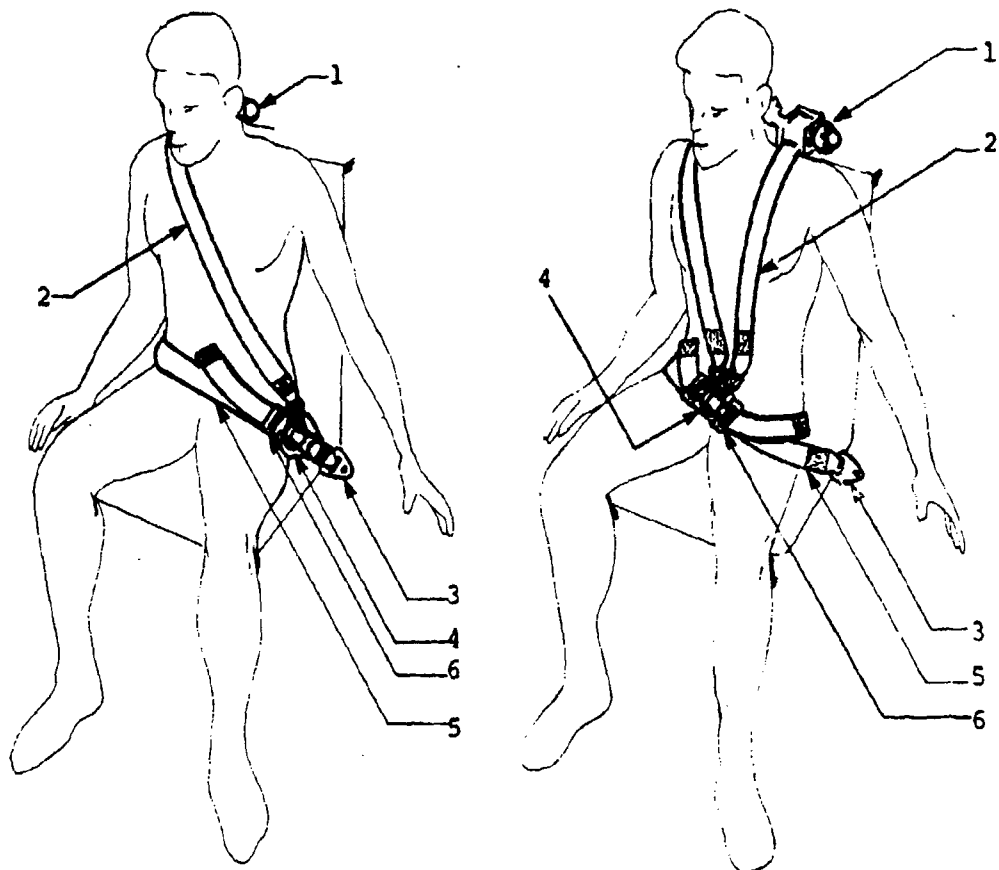
Type I   Type II

<u>Item identity</u>

1. Inertia reel
2. Shoulder strap
3. Lap belt anchor
4. Buckle with shoulder strap connection
5. Lap belt
6. Adjuster/fitting

Figure 45. Aircraft troop/passenger restraint systems.
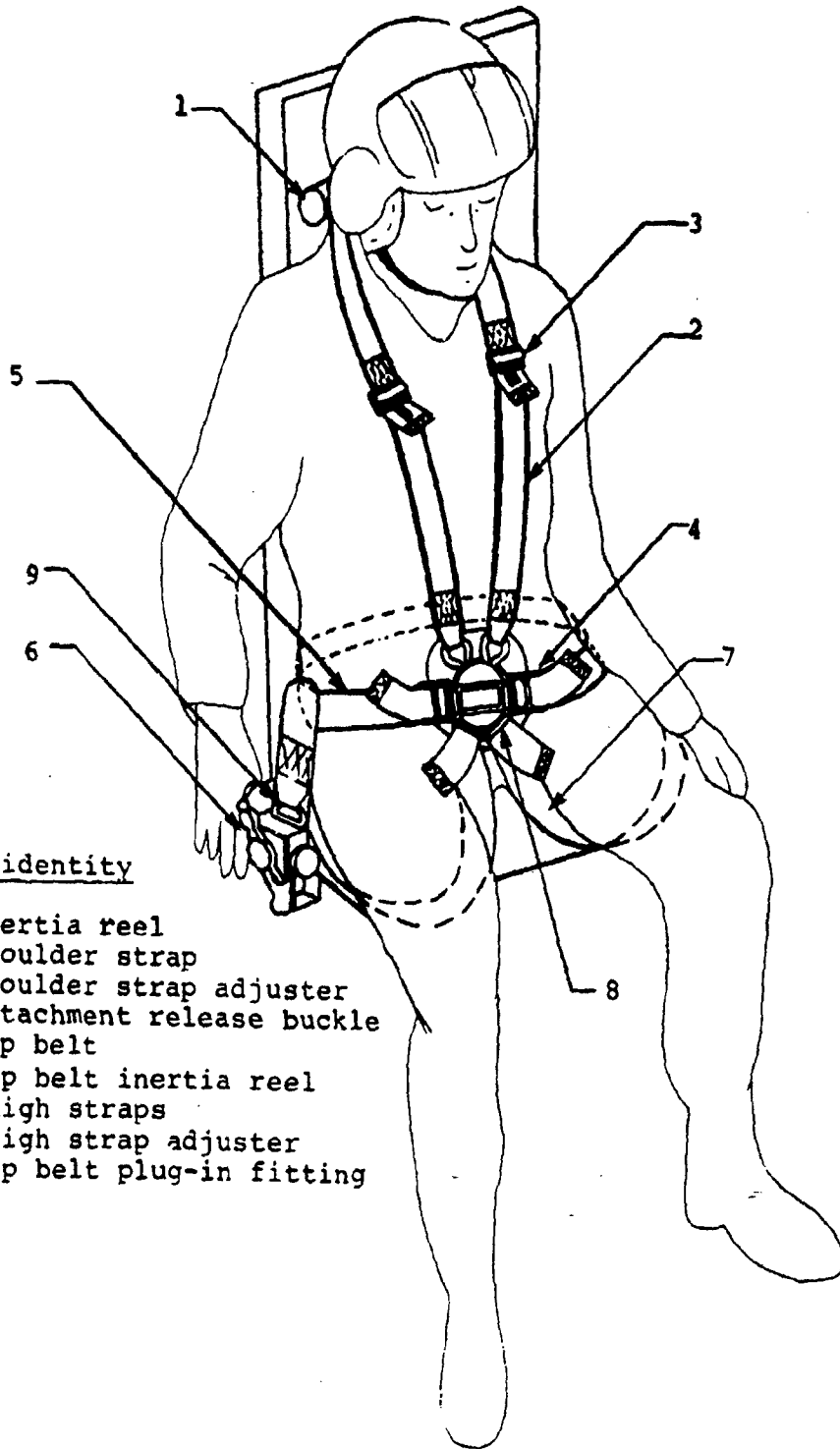
Item identity

1. Inertia reel
2. Shoulder strap
3. Shoulder strap adjuster
4. Attachment release buckle
5. Lap belt
6. Lap belt inertia reel
7. Thigh straps
8. Thigh strap adjuster
9. Lap belt plug-in fitting

Figure 46. Gunner restraint system. (From Reference 79)

be seated or standing in front of the seat. The shoulder harness and lap belt with thigh straps may serve as a "monkey harness" when the crewmember disconnects the two lap belt plug-in fittings from the inertia reels. The resultant configuration permits the crewmember more extensive travel within the cabin while still being connected to the shoulder harness inertia reel, thereby restraining the crewmember from falling out of the aircraft.

7.2.4 Inflatable Systems

An automatically inflatable body and head restraint system for helicopter crewmen has been jointly developed and tested by the Naval Air Development Center and the Applied Technology Laboratory. As illustrated in Figure 47, this system provides increased crash protection because it provides automatic pretensioning that forces the occupant back in his seat, thereby reducing dynamic overshoot and reducing strap loading on the wearer when the inflated restraint is compressed during the crash. The concentration of strap loads on the body are reduced because of the increased bearing surface provided when the restraint is inflated, and both head rotation and the possibility of whiplash-induced trauma are also thus reduced.

Although more complex and costly than conventional belt systems, such a system may be justified because of its occupant protection potential. Development of the system and results of testing are documented in References 80 and 81.

7.3 GENERAL DESIGN CRITERIA

7.3.1 Comfort

Comfort must not be compromised by crash-survival requirements for obvious reasons. For example, a lap belt with an adjustment fitting located directly over the iliac crest bone would provide a constant source of irritation that would result in eventual fatigue to the wearer. The main comfort consideration for restraint harnesses is the absence of rigid hardware

80. Schulman, M., and McElhenney, J., INFLATABLE BODY AND HEAD RESTRAINT, NADC-77176-40, Naval Air Systems Command, Department of the Navy, Washington, D. C., September 1977, AD A046477.

81. Singley, G. T., III, TEST AND EVALUATION OF IMPROVED AIRCRAFT RESTRAINT SYSTEMS FOR COMBAT HELICOPTERS, Paper No. A.18, presented at NATO/AGARD Aerospace Medical Panel, Aerospace Specialist's Meeting on Aircrew and Survivability, North Atlantic Treaty Organization, Bodo, Norway, May 20-23, 1980.

Inflated

Normal
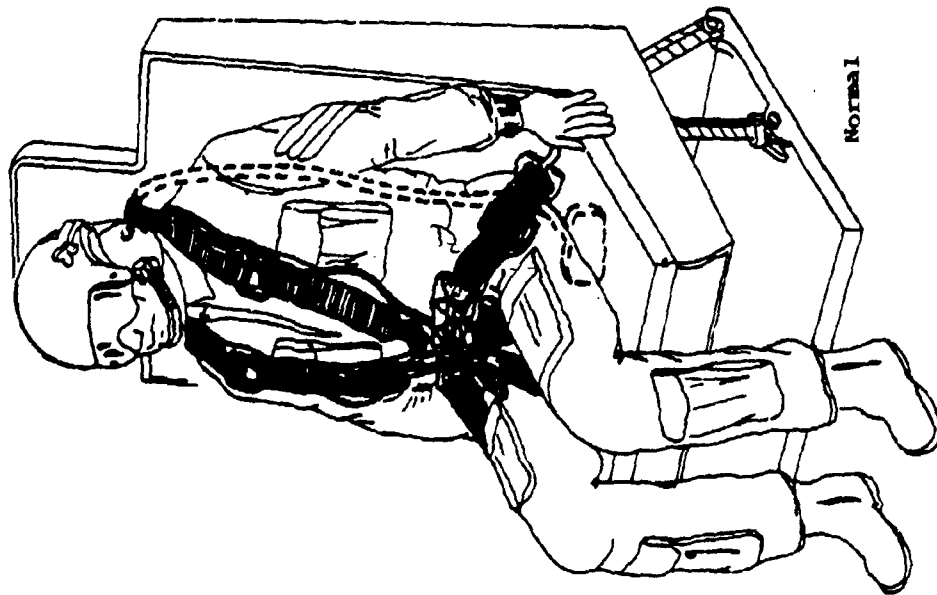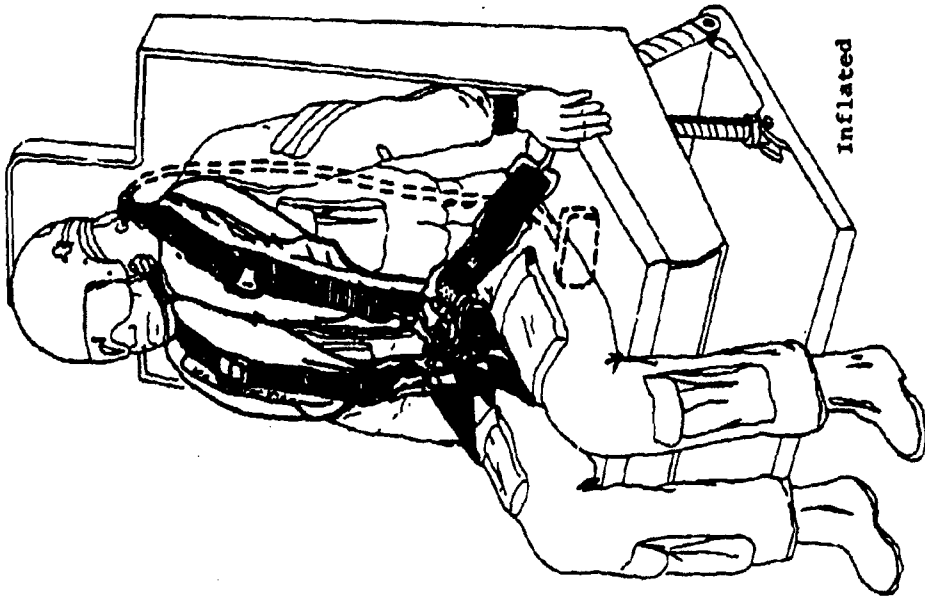
Figure 47. Inflatable body and head restraint. (From Reference 80)

located over bony portions of the torso. Also, webbing that
is too wide or too stiff could cause discomfort.

7.3.2 Emergency Release Requirements

From a crash survival point of view, it is mandatory that a
shoulder harness/lap belt combination have a single point of
release that can be operated by one (either) hand to make it
easier for debilitated occupants to quickly free themselves
from their harnessing in a severe crash because of the dangers
of postcrash fire or sinking in water. The force required to
release the harness with only one finger should fall between
20 and 30 lb on the basis of existing requirements for mili-
tary harnesses. An excessive force could hinder rapid emer-
gency release, while a light force could cause inadvertent re-
lease. Further, the release should be possible with the weight
of the occupant hanging in the restraint system after exper-
iencing the full crash loads. This will guarantee that the
occupant can release the system after a severe survivable crash
even when inverted in a loaded restraint system. The release
forces for the inverted case should be minimized and, in any
case, should not exceed 50 lb applied with only one finger. It
should be possible to produce the torque necessary to release
rotary buckles by applying a load at a single point on the
handle as described above.

In restraint systems other than the Type I of Figure 45, if a
lift latch or similar type buckle is used, the restraint system
design should ensure that the latch lifts from left to right on
all installations. This will reduce the possibility of reverse
installations and their resultant hazard.

The release device must either have the capability to with-
stand the bending moments associated with deflections and mo-
tions during loading, or it should contain features that allow
the fittings to align themselves with the loads, thereby reduc-
ing or eliminating the moments. If belt loading direction is
such as to cause the strap to bunch up in the end of a slot,
failure can occur through initiation of edge tear. As a re-
sult of an investigation of restraint system design criteria
reported in Reference 77, the fitting angles illustrated in
Figure 48 are recommended.

Eliminating fitting rotation in the flat plane of the buckle
during loading may prove to be difficult in lightweight sys-
tems. If the integrity of the attachment of the fitting within
the buckle can be compromised by rotation, then rotation must
be completely eliminated. Experience has shown that it is
better to design the attachment of the fitting within the

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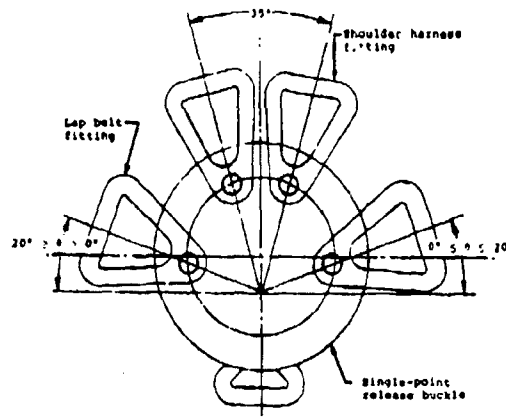
Figure 48. Buckle fitting attachment and motion angles.

buckle to be insensitive to rotation, i.e., a round pin in a
round hole, rather than a flat-faced dog which must seat on a
flat face of a slot, than to rely on restraining the fitting
against rotation. In the latter case, a small amount of rota-
tion can cause point loading of a corner of the dog against
one end of the slot. The point loading can easily increase
the stress applied at the contact point to i_s ultimate bear-
ing strength. This will result in metal deformation and the
formation of a sloped surface which then can act to cam open
the attachment mechanism.

Further, the release mechanism (buckle) should be protected
against accidental opening. Neither decelerative loading of
components nor contact with aircraft controls such as cyclic
controls should open the device. It was mentioned earlier in
this volume that required cockpit dimensions should be re-
viewed. It appears that the occupant can be placed too close
to the cyclic control in helicopters and that a fully retracted
cyclic head can contact the buckle. The buckle release mech-
anism should be protected against inadvertent release either
during operation or in a crash. It should be emphasized that,
if contact between the cyclic control and the buckle is pos-
sible in an operational mode, a considerable overlap can exist
during crash loading when the restraint system is deformed for-
ward several inches.

7.3.3 Lap Belt Anchorage

The anchorage points for the lap belt can be located either on
the seat bucket or on the basic aircraft structure. If the an-
chorage is located on basic aircraft structure, the movement
of the seat under the action of load-limiting devices must be

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considered to ensure that the lap belt restraint remains effective regardless of seat position. If the seat includes longitudinal load limiting, attachment of the lap belt to the basic structure will not be practical because then most of the forward load will be carried to the aircraft structure through the belt rather than through the seat. In such a case careful consideration must be given to the belt strength since the belt must restrain the motion of the seat, as well as the occupant.

The lap belt should be anchored to provide optimum restraint for the lower torso when subjected to eyeballs-out ($-G_x$) forces. One of the anchorage variables which has an influence on restraint optimization is the location of the lap belt anchorage in the fore-and-aft direction. The important characteristic is the angle in a vertical fore-and-aft plane between a projection of the lap belt centerline and the buttock reference line, or plane. This angle defines the geometrical relationship between the longitudinal and vertical components of the belt load. A small angle provides an efficient path for supporting longitudinal loads while a large angle provides an efficient system for supporting large vertical loads. Thus, for supporting large forward-directed loads, a small angle would be desirable, but for reacting the large vertical loads imposed on the lap belt by the loaded shoulder harness a large angle is required. The compromise for location of the anchorage must consider all the variables including the tendency for the occupant to submarine under the lap belt. In an accident with high combined vertical and longitudinal impact forces the restrained body will tend to sink down into the seat (where the magnitude of the displacement depends on cushion properties) and almost simultaneously be forced forward. This movement is illustrated in Figure 49. If the lap belt angle is too small the belt can tend to slip over the iliac crests of the pelvic bone, allowing the pelvis to rotate under the belt. The inertial load of the hips and thighs tend to pull, or submarine, the lower torso under the belt. Lower torso restraint is then accomplished through lap belt loading of the soft abdominal portions of the body, possibly causing visceral injury in addition to the spinal injury illustrated in Figure 49.

To counteract the tendency for submarining the lap belt angle can be increased; however, the load in the belt increases for a given torso deceleration because of the smaller longitudinal loading component available to restrain the occupant. Further, additional forward motion is allowed because of the increased deflection of the webbing caused by the increased loading and the greater forward rotation of the lap belt. However, as the webbing is loaded, it presses down into the thighs of the occupant and minimizes the possibility of submarining by picking

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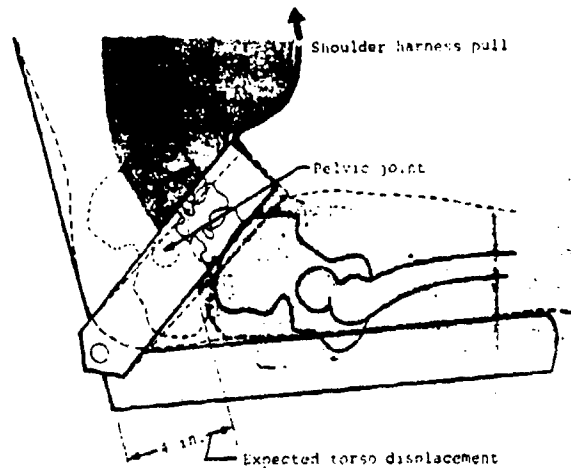
Figure 49. Pelvic rotation and submarining caused by
high longitudinal forces combined with
moderate vertical forces.

up the longitudinal component of restraint load required to
bring the system into equilibrium.

In order to avoid the increased possibility of both spinal and
abdominal injury, a properly designed restraint system should
not allow submarining to occur. Still, an efficient angle
should be maintained to limit the forward motion of the occu-
pant.

Comfort is another concern in lap belt anchor location. A pi-
lot must raise and lower his thighs during operation of rudder
pedals or antitorque pedals. If the lap belt anchor is too far
forward, the lap belt will pass over the pilot's thighs forward
of the crease between the thighs and the pelvis and thus may
interfere with vertical leg motion. It is important, there-
fore, to position the lap belt anchorage so that it provides
optimum restraint while not interfering with the pilot's oper-
ational tasks. A forward location of the anchor does not neg-
atively influence the comfort of passengers since passengers
are not required to perform operations with their legs.

In order to accomplish these objectives, the vertical angle
between the lap belt centerline and the buttock reference line
as installed on the 50th-percentile occupant should not be less
than 45 degrees and should not exce   5 degrees, as shown in
Figure 50(a). Further. it is der   ule to locate the anchor
point at or below the buttock r   ence line for comfort and

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a) All systems   b) Systems with lap belt   c) Systems without tiedown
                    tiedown straps   straps
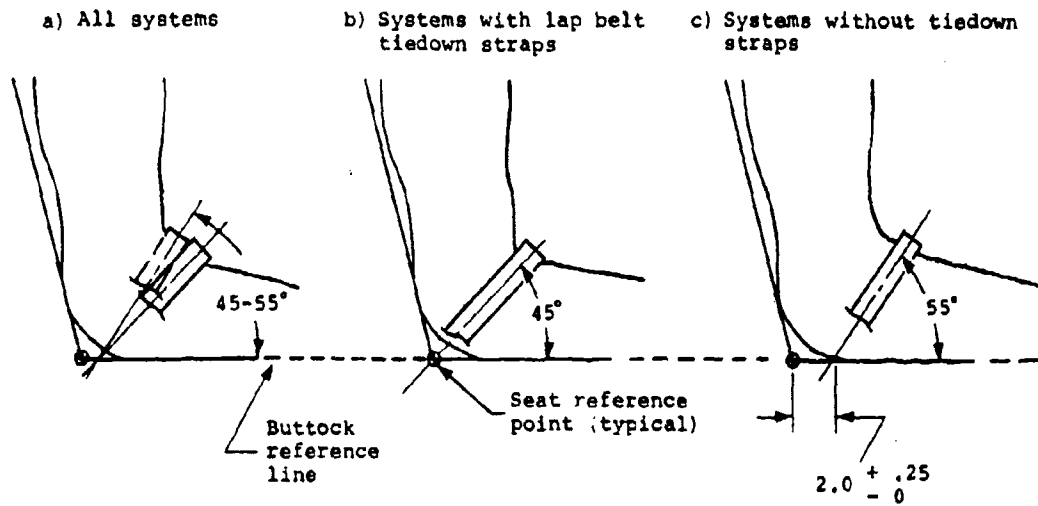
Figure 50. Lap belt anchorage geometry.

performance. If the anchor point must be located above the buttock reference line, as on most armored seats, the anchor point should be positioned to ensure that the belt angle lies within the desired 45- to 55-degree range. For a system having a lap belt tiedown strap to counteract the upward force of the shoulder harness (e.g., in pilot seats), the lap belt anchors should be positioned so that the centerline of the lap belt passes through the seat reference point as shown in Figure 50(b). If the restraint system does not have a tiedown strap (e.g., in passenger seats), the lap belt anchor should be positioned so that the belt centerline passes through the buttock reference line 2 to 2-1/4 in. forward of the seat reference point as shown in Figure 50(c). This position provides sufficient vertical load components to help counteract the upward force of the shoulder straps. For positioning anchors that do not fall on the buttock reference line, the angle between the lap belt centerline and the buttock reference line can be assumed to be 45 degrees for systems with tiedown straps and 55 degrees for those without.

Submarining can be reduced by ensuring that the lap belt is tight, as shown in studies reported in Reference 82. Thus,

82. Roberts, V. L., and Robbins, D. H., MULTIDIMENSIONAL MATHEMATICAL MODELING OF OCCUPANT DYNAMICS UNDER CRASH CONDITIONS, Paper No. 690248, Society of Automotive Engineers, Inc., New York, January 1969.

care should be taken to train occupants to tighten the lap belt to the maximum consistent with comfort and to not loosen the belt anytime during flight.

For seats that limit lateral motion of the occupant with structure, such as in armored seats, the anchorage point and hardware should possess sufficient flexibility and strength to sustain design belt loads when the belt is deflected laterally toward the center of the seat through an angle of up to 60 degrees from a vertical position. The side motion of fittings on other seats should also be capable of supporting design loads with the lap belt deflected laterally away from the center of the seat through an angle up to 45 degrees from the vertical. These recommendations are made to ensure that lateral loading on the torso will not result in lap belt anchorage failure.

7.3.4 Shoulder Harness Anchorage

The shoulder harness or inertia reel anchorage can be located either on the seat back structure or on the basic aircraft structure. In placing the inertia reel, strap routing and possible reel interference with structure during seat adjustment or energy-absorbing stroke of the seat must be considered. Location of the anchorage on the basic aircraft structure will relieve a large portion of the overturning moment applied to the seat in longitudinal loading; however, due consideration must be given to the effect of seat bucket movement in load-limited seats. Vertical movement of the seat pan can be provided for by placing the inertia reel aft of the seat back shoulder strap guide a sufficient distance so that seat vertical movement will change the horizontal position and the angle of the straps very little.

Shoulder straps should pass over the shoulders in a plane perpendicular to the back tangent line or at any upward (from shoulders to pull-off point) angle not to exceed 30 degrees, as illustrated in the upper-left sketch in Figure 51.

Any installation that causes the straps to pass over the shoulders at an angle below the horizontal adds additional compressive force to the seat occupant's spine as shown in the lower sketch of Figure 51. A shoulder harness pull-off point at least 26 in. above the buttock reference line is needed to ensure that the straps do not apply an excessive downward load on the spine of a 95th-percentile occupant.

The shoulder harness anchorage or guide at the top of the seat back should permit no more than 0.5-in. lateral movement (slot no more than 0.5 in. wider than strap) to ensure that the seat occupant is properly restrained laterally. The guide should provide smooth transitions to the slot. The transition contour

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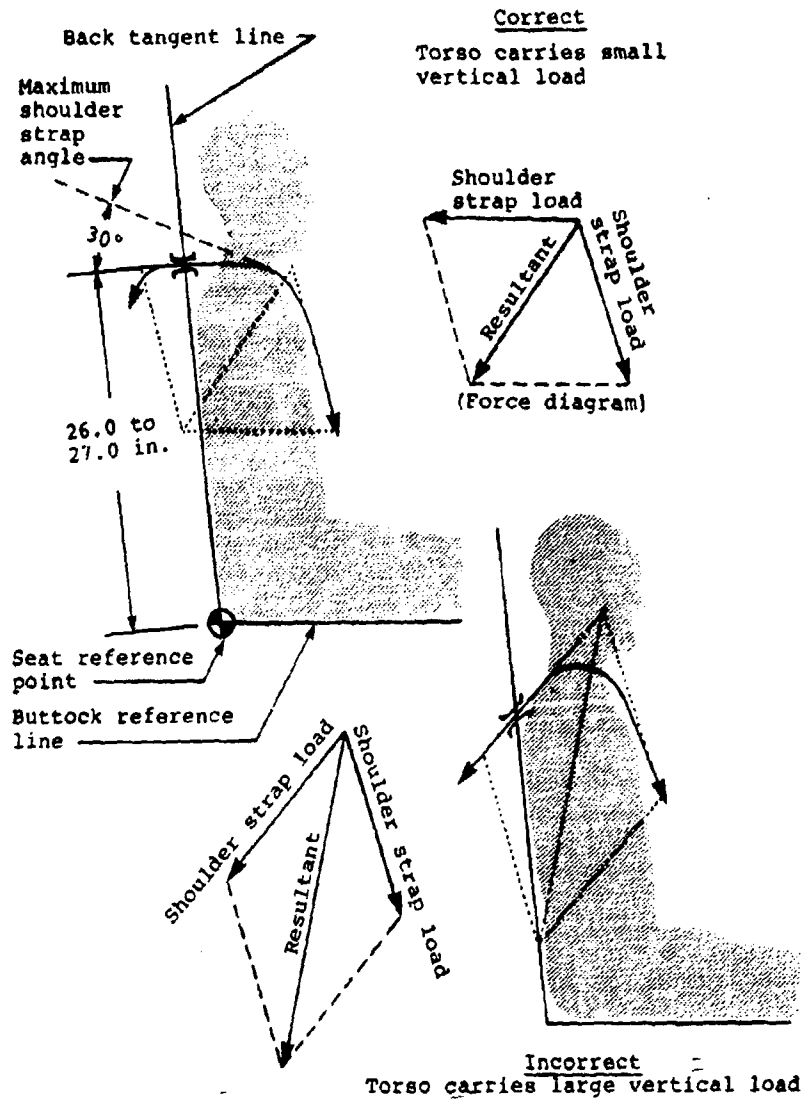
Figure 51. Shoulder harness anchorage geometry.

should be of a radius no less than 0.25 in. and should extend
completely around the periphery of the slot to minimize edge
wear on the strap and reduce the possibility of webbing failure
due to contact with sharp edges under high loading.

7.3.5 Lap Belt Tiedown Strap Anchorage

When the upper body is thrown forward against the shoulder
straps, an upward pull is exe' _ on the lap belt. If a lap

belt tiedown strap is not being used, the tendency is for the belt to be pulled up off of the iliac crests and into the soft solar plexus area, causing injury to abdominal viscera as previously shown in Figure 49. A tiedown strap attached to the center of the lap belt will prevent the upward belt movement. It is recommended that the tiedown strap be located on the seat pan centerline at a point 14 to 15 in. forward of the seat back. For shorter seat pans, the anchor must be placed as far forward as possible.

7.3.6 Adjustment Hardware

Adjusters must carry the full design load of the restraint system subassembly, of which they are a part, without slipping or crushing the webbing between items such as locking cams and the opposite locking surface. In extremely highly loaded applications, this may require that the strap be doubled in a manner that requires the adjuster to carry only half of the strap assembly load. The force required to adjust the length of webbing should not exceed 30 lb in accordance with existing military requirements for harnesses. Insofar as possible, all adjustments should be easily made with one (either) hand. Adjustment motions should be toward the single-point release buckle.

7.3.7 Location of Adjustment and Release Hardware

This hardware must not be located directly over hard points of the skeletal structure, such as the iliac crests of the pelvis or the collarbones. The lap belt length adjusters should be located either at the center of the belt near the release buckle or at the side of the hips below the iliac crests, preferably the latter. The shoulder strap adjusters should be located as low on the chest as possible in order to avoid concentrated pressure on the collarbones.

7.3.8 Webbing Width and Thickness Requirements

Selection of the optimum webbing width for a lap belt and shoulder harness must be based on two conflicting requirements: (1) maximum width for lowest pressure and (2) minimum width for maximum comfort and minimum hardware weight. Webbing requirements are discussed in detail in Section 7.4.

7.3.9 Hardware Materials

All materials used for the attachment of webbing (release buckles, anchorages, and length adjusters) should be ductile enough to deform locally, particularly at stress concentration points. Ductility in restraint harness hardware is not as critical when energy-absorbing provisions are incorporated into

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the seat, because the maximum loading of the system is limited. Thus, it would be possible to specify low-ductility materials on load-limited seats and to specify high-ductility, moderate-strength materials on nonload-limited seats. Such a specification could possibly lead to the inadvertent installation of low-ductility harness fittings on rigid, nonload-limited seats. For example, it is known that 20-G-strength shoulder straps have been mistakenly installed in place of 40-G straps. To prevent such a possibility, it is concluded that, wherever applicable, all harness fittings should be made of equivalent high-ductility materials to ensure their interchangeability. A minimum elongation value of 10 percent (as determined by standard tensile test specimens) is recommended for all metal harness-fitting materials. The 10-percent elongation value can be achieved with copper-base aluminum alloys, low-carbon steels, and stainless steel. There are obviously some components that, for operational purposes, rely on hardness. These components should be designed to perform their necessary function but be made from materials as nearly immune as possible to brittle failures.

7.3.10 Structural Connections

7.3.10.1 Bolted Connections: Safety margins of 15 and 25 percent for shear and tensile bolts, respectively, are recommended by most aircraft companies for the manufacture of basic aircraft structure. These margins are intended to allow for misalignment of holes, stress concentrations, and fatigue strength reductions; however, the bolt's fatigue strength is not a factor for a one-time maximum loading as occurs in a crash. Thus, it is concluded that the safety margins for shear and tensile bolts in restraint systems can be reduced to 5 and 10 percent, respectively.

Good aircraft engineering practice also dictates that bolts less than 0.25 in. in diameter should not be used in tensile applications because of the ease with which these smaller bolts can be overtorqued. Wherever possible the bolts should be designed for shear rather than tension.

7.3.10.2 Riveted Connections: Riveted joint design guidelines are presented in MIL-HDBK-5, "Metallic Materials and Elements for Aerospace Vehicle Structures" (Reference 23). This handbook is recommended as a guide for restraint system hardware design.

7.3.10.3 Welded Connections: Welded joints can be 100 percent efficient; however, they may be only 50 percent efficient, depending upon the skill of the welder. Since welded joints can be completely acceptable and in some cases superior to

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bolted or riveted joints, it is not reasonable to prevent the use of this type of joint if strict inspection procedures are used to ensure that all welded joints are adequate. Welding processes are discussed in Military Specifications MIL-W-8604, -6873, -45205, and -8611. These specifications should be used as guides to ensure quality welding.

Welded joints may contain stress concentration points and misaligned parts in a manner similar to bolted joints; therefore, the cross-sectional area of the basic material in a welded joint should be 10 percent greater than the area needed to sustain the design ultimate load.

7.3.10.4 **Plastic Strength Analysis:** Plastic analysis methods should be used for strength determination wherever applicable in order to obtain maximum-strength hardware at the lowest possible weight. Plastic analysis makes maximum use of the strain energy available in ductile metals. References 28 and 29 cover this subject.

7.4 WEBBING AND ATTACHMENTS

7.4.1 Properties

The maximum load to be sustained by restraint harnesses can be determined by a review of seat load-deflection requirements (Chapter 8). The curves shown there include the effects of dynamic overshoot loads. The maximum load shown is 35 G for the cockpit seat, where the seat structure provides for little elongation. The required load is reduced as the deformation is increased. Although the restraint harness could be designed to varying loads in accordance with the energy-absorber G level used in the seat, it is believed to be more practical and fool proof to design a single-strength restraint harness that can be interchanged with all seats of similar configuration and orientation. The main advantage of a single-strength harness would be the assurance that it could be interchanged between load-limited seats and nonload-limited seats without fear that an understrength harness might be installed. On this premise, the design strength of all forward-facing and side-facing restraint harnesses should be equal to or greater than the strength of the cockpit seats because the higher design strength of the cockpit seats would govern. At first, this solution might seem to be too conservative because of the lower load levels required for cabin seats; however, closer scrutiny indicates that the assymmetrical nature of the forces on the harness in the side-facing seats could result in loads just as high as those experienced in the forward-facing cockpit harness for a more symmetrical loading.

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The distribution of the total load on the various harness components is not easily determined; however, these forces have been fairly well approximated by theoretical calculations and by experimental test data. The test data have been obtained from tests on restrained 95th-percentile anthropomorphic dummies under a variety of test conditions. The maximum design loads for the various harness components attached on the seat are listed in Table 4. These loads may appear to be higher than necessary to offer restraint on a 35-G seat for a 222-lb occupant; however, these loads allow for (1) torso variations, (2) asymmetric loadings, and (3) a safety factor to ensure that the harness does not fail before the seat fails.

TABLE 4. RESTRAINT HARNESS COMPONENTS LOAD-ELONGATION DESIGN AND TEST REQUIREMENTS (MIL-S-58095(AV))

Harness components	Minimum load (lb)[a]	Maximum elongation (design goal) (in.)[b]
Inertia reel strap(s)	6000[c]	1.5[e]
Shoulder harness strap(s)	4000[d]	1.5[e]
Lap belt	4000	2.0
Lap belt tiedown strap	4500	0.5

NOTES: (a) Applied in straight tension.
(b) Total length of harness component tested must be the same as when installed on the seat and adjusted for a 95th-percentile clothed occupant.
(c) This represents the total load from all shoulder straps. A single diagonal shoulder strap should carry 6000 lb.
(d) This represents the minimum load that one of two shoulder straps should carry.
(e) This applies only to the shoulder harness and inertia reel strap outside the reel (exclusive of the webbing wound on the spool of the inertia reel).

It will be noticed that the inertia reel strap is required to carry 6000 lb when the inertia reel itself is designed to carry only 4000 lb. Since no inertia reel spool failures have occurred, and since combinations of shoulder strap loads exceeding 6000 lb have been measured, it must be assumed that the loads in the straps are reduced through friction with the body and guide slots to no more than 4000 lb at the reel.

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The elongation of all webbing used in the harness must be mini-
mized to decrease overshoot. Dynamic tests conducted with an-
thropomorphic dummies and several tests with cadavers indicate
that a total elongation greater than about 1.5 in. will result
in an overshoot load that is more than 25 percent above input
peak loads at the floor. The load and deformation requirements
indicated for seats in Chapter 8 are based on the use of a re-
straint harness that elongates only 1.5 in. away from the seat
back. Torso compression and "normal" harness slack, however,
account for another 2 in. (at a 35-G load). Therefore, the
total torso movement away from the seat back is about 3.5 in.
The value of 1.5 in. for harness elongation is less than half
of the total torso movement. A lower value would not be rea-
sonable unless the normal harness slack and tissue deformation
are also reduced. Table 4 shows that the shoulder strap elon-
gation is restricted to 1.5 in., while the lap belt is re-
stricted to 2.0 in. of total end-to-end stretch or 1.0 in. of
loop elongation. Restraint systems for the new generation of
Army helicopters use a low-elongation polyester webbing, the
characteristics of which are listed in Table 5.

TABLE 5. RESTRAINT WEBBING CHARACTERISTICS

Restraint system component	Nominal webbing width (in.)	Webbing thickness (in.)	Minimum breaking strength (lb)	Elongation* (percent)
Inertia reel	1-3/4	0.057	6980	6.9 @ 3000 lb
Shoulder straps	2	0.057	7800	7.6 @ 4000 lb
Lap belt	2-1/4	0.057	8880	7.8 @ 4000 lb
Lap belt tiedown strap	1-3/4	0.057	6980	6.9 @ 3000 lb

*Based on 10-in. gage length.

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Dynamic testing of polyester webbing has demonstrated the dynamic elongation to be approximately 60 to 75 percent of the static elongation under the same load, as illustrated in Figure 52 (References 63 and 83).

7.4.2 Width and Thickness Requirements

Selection of the optimum webbing width for a lap belt and shoulder harness must be based on two conflicting requirements: (1) maximum width for lowest pressure and (2) minimum width for maximum comfort and minimum hardware weight. The widths specified in Table 6 are believed to be a good compromise between these conflicting requirements. All webbing used for restraint harness must be thick enough to ensure that the webbing does not fold or crease to form a "rope" or present a thin sharp edge under high loading that will cause damage to soft tissue. Such damage is more likely to occur in the neck region during a lateral loading or, in the pelvic region during a forward loading. Although requirements based on early investigations using nylon webbing specified a minimum thickness of 0.090 in., it has since been determined that state-of-the-art webbing materials must be thinner in order to achieve the desired low elongation. No significant problem of injuries caused by the thin webbing has been observed with this low-elongation webbing which has seen extensive automotive use. Therefore, based on currently available materials, a minimum thickness of 0.055 in. is considered acceptable.

7.4.3 Webbing Attachment Methods

7.4.3.1 Stitched Joints: The strength and reliability of stitched seams must be ensured by using the best known cord sizes and stitch patterns for a specified webbing type. The stitch patterns and cord sizes used in existing high-strength military restraint webbings appear to provide good performance. The basic stitch pattern used in these harnesses is a "W-W" configuration for single-lapped joints. Research by the U. S. Naval Aerospace Recovery Facility (NARF) at El Centro, California, has reaffirmed the adequacy of basic "W-W" stitch patterns; however, the research also revealed that a larger-size cord with fewer stitches per-inch gave superior performance to the No. 4 MIL-T-7807 cord currently being used. On the basis of this research, the 50-lb strength No. 6 cord at 4-1/2 to 5

83. Kourouklis, G., Glancy, J. L., and Desjardins, S. P., THE DESIGN, DEVELOPMENT, AND TESTING OF AN AIRCRAFT RESTRAINT SYSTEM FOR ARMY AIRCRAFT, Dynamic Science, Division of Ultrasystems, Inc.; USAAMRDL Technical Report 72-26, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1972, AD 746631.
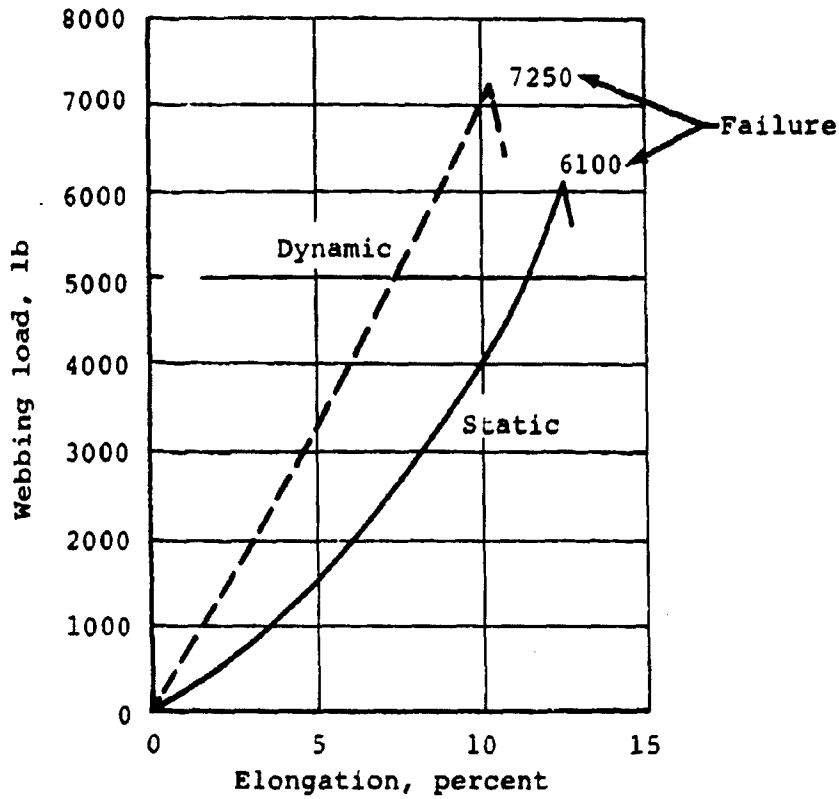
Figure 52. Load elongation characteristics for
MIL-W-25361 (Type II) polyester
webbing for static and rapid loading
rates.

TABLE 6. MINIMUM WEBBING WIDTH REQUIREMENTS

Webbing identity	Minimum width (in.)
Lap belt	2-1/4*
Shoulder strap	2.0
Tiedown strap	1.5

*A greater width (up to 4 in.) or pad is de-
sirable in the center abdominal area.

stitches per inch is recommended, as illustrated in Figure 53, for use on MIL-W-25361 webbings. Also, the heavier cord can be expected to provide better resistance to sunlight degradation and abrasion. The use of the 50-lb cord and an 80-percent efficiency results in a minimum strength of 160 lb/in. (4 stitches x 50 lb/stitch x 80 percent) for a single-lapped joint or 320 lb/in. for a looped joint. Thus, the total stitch length needed can be determined by the total required load.
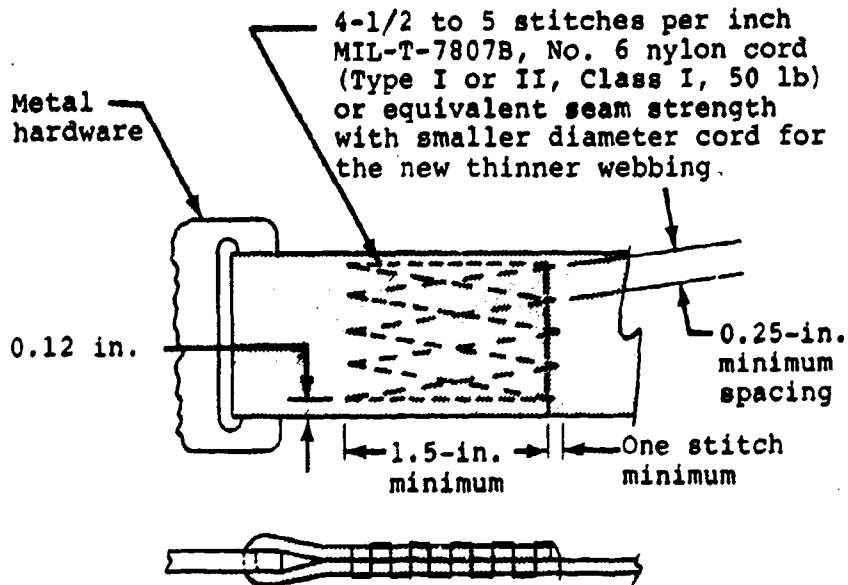
Figure 53. Stitch pattern and cord size.

It has been shown recently that the heavier thread is not compatible with the new low-elongation polyester webbing (Reference 84). For these webbings, a smaller diameter cord offers the advantages of reduced webbing fiber damage and the ability to be used with automatic sewing machines and is therefore acceptable.

The strength of stitched joints can be expected to decrease with age because of normal weather exposure and because of the normal dust and grit collection between the webbing surfaces. The grit and dust can gradually abrade the cords over a period of time. The use of a 30-percent increase in the total stitch length required is recommended to offset the normal aging

84. Farris, L., HIGH STRENGTH STITCHING FOR AIRCRAFT PERSONNEL RESTRAINT SYSTEMS, Pacific Scientific Co.; Proceedings, 1978 SAFE Symposium, Survival and Flight Equipment Association, Canoga Park, California, October 1978.

strength decrease as well as the possible abrasion strength decrease. Covering the stitched joints with cloth to provide wear protection for the cords is also recommended.

An example of establishing the total seam length is given:

Assume: A single-lapped joint, 50-lb cord strength, with a 4000-lb joint load.

Then, the minimum stitch strength is

$$(50)(4)(0.80) = 160 \text{ lb/in.}$$

and the minimum seam length is

$$\frac{4000}{160} = 25 \text{ in.}$$

Therefore, the total seam length is

$$(25)(1.3) = 32.5 \text{ in.}$$

The total seam length is achieved through placing many short lengths in a rather small area. Several patterns have been developed and tested; however, the W-W as described below is still preferred. The size of the overlapped and stitched area should be minimized to reduce weight, reduce the stiffened section of the webbing, and provide more room between fittings for adjustment.

Unpublished data from comparative tests of five stitch patterns performed by NARF indicated better performance of two new stitch patterns over the basic W-W pattern. The data from this research are reported here with permission of NARF.

The five stitch patterns tested are shown in Figure 54. These patterns were sewn in Types XIII and XXII of MIL-W-4088 nylon webbing used for parachutes. Three samples of each stitch pattern were tested. Table 7 shows the results of the first test series. Because of the low number of total stitches, the results were inconclusive, and a second test series was performed. Patterns 2 and 5 were eliminated from the second series. Table 8 shows the results of the second test series. It relates the performance of the two stitch patterns, 1 and

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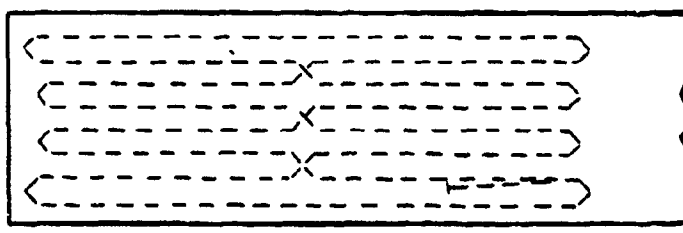
Pattern 1

5 Stitches/inch

Pattern 2
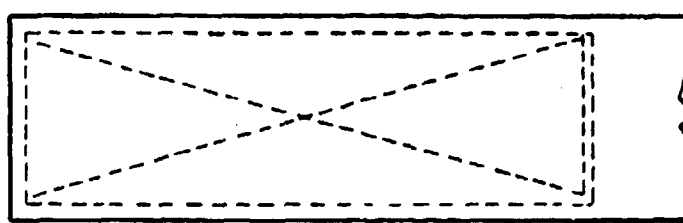
7 Stitches/inch

Pattern 3
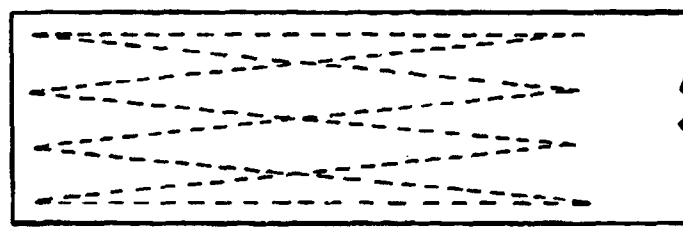
5 Stitches/inch

Pattern 4
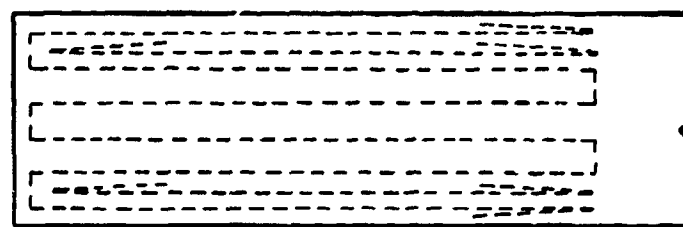
5 Stitches/inch

Pattern 5
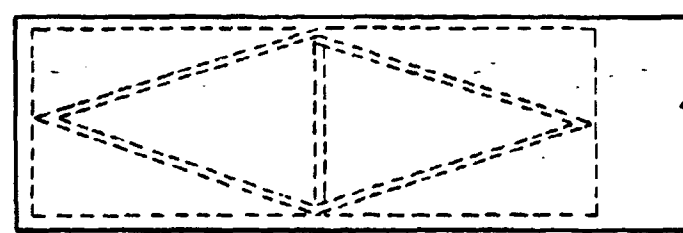
5 Stitches/inch

Figure 54.   Stitch patterns tested.

TABLE 7. BREAKING STRENGTH OF STITCH PATTERNS (TEST SERIES ONE)

	Sample no.	Webbing and stitch type									
		A-1[a]	A-2[a]	A-3[a]	A-4[a]	A-5[a]	B-1[a]	B-2[a]	B-3[a]	B-4[a]	B-5[a]
	1	4835	5040	5645[b]	4975	5150	5450	5960	5430	5315	5550
Breaking strength (lb)	2	4675	4640[b]	5680[b]	4880	4935	5420	5780	5620	4650	5420
	3	4545	5060[b]	5190[b]	4740	4500	5710	5695	5665	5570	5120
Average breaking strength (ABS) (lb)		4685	4913	5505	4865	4862	5527	5812	5572	5178	5363
ABS/ABS for pattern 3		0.851	0.892	1.00	0.884	0.883	0.992	1.04	1.00	0.929	0.963
Approximate total stitches		200	190	190	190	180	200	190	190	190	180
ABS/stitch (lb)		23.43	25.86	28.97	25.61	27.01	27.64	30.59	29.33	27.25	29.79
ABS/stitch/ABS for Pattern 3		0.809	0.893	1.00	0.884	0.932	0.942	1.04	1.00	0.929	1.02

(a) A designates MIL-W-4088 Type XIII nylon webbing.
    B designates MIL-W-4088 Type XXII nylon webbing.
    Numerals 1, 2, 3, 4, and 5 designate stitch patterns as shown in Figure 54.
(b) Webbing broke.

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TABLE 8. BREAKING STRENGTH OF STITCH PATTERNS (TEST SERIES TWO)

	Sample no.	Webbing and stitch type					
		A-1[a]	A-3[a]	A-4[a]	B-1[a]	B-3[a]	B-4[a]
	1	4400	4410	4540[b]	6340	6420	6215
Breaking strength (lb)	2	4710	4740	5080	6480	6490	6060
	3	4820	4360	4870	7200	6500	6070
Average breaking strength (ABS) (lb)		4643	4503	4830	6673	6470	6115
ABS/ABS for pattern 3		1.03	1.00	1.07	1.03	1.00	0.945
Approximate total stitches		260	270	270	260	270	270
ABS/stitch (lb)		17.86	16.68	17.89	25.67	23.96	22.65
ABS/stitch/ABS for pattern 3		1.07	1.00	1.07	1.07	1.00	0.945

(a) A designates MIL-W-4088 Type XIII nylon webbing.
   B designates MIL-W-4088 Type XXII nylon webbing.
   Numerials 1, 3, and 4 designate stitch patterns as shown in Figure 54.
(b) Jaw separation 20-in. minimum. All other tests at 2-in. minimum.

4, to the performance of pattern 3, the W-W pattern, for the two different types of webbing. Stitch patterns 1 and 4 exhibited better strength properties than pattern 3 (W-W) when Type XIII webbing was used. Pattern 4 did not perform as well when Type XXII webbing was used, while pattern 1 again indicated better strength characteristics than did pattern 3.

The W-W stitch pattern as shown in Figure 53 is still recommended until more conclusive information on these or other stitch patterns becomes available.

7.4.3.2 Webbing Wrap Radius: The wrap radius is the radius of the fitting over which the webbing is wrapped at buckles, anchorages, and adjusters, as illustrated in Figure 55. Detailed information on just how small this radius can be before the strength of the webbing is affected is not available; however, the 0.062-in. minimum radius shown is based upon the geometry of existing high-strength restraint harnesses. This radius should be carried around the ends of the slot as shown in Figure 55 to preclude edge cutting of webbing if the webbing should be loaded against the slot end.
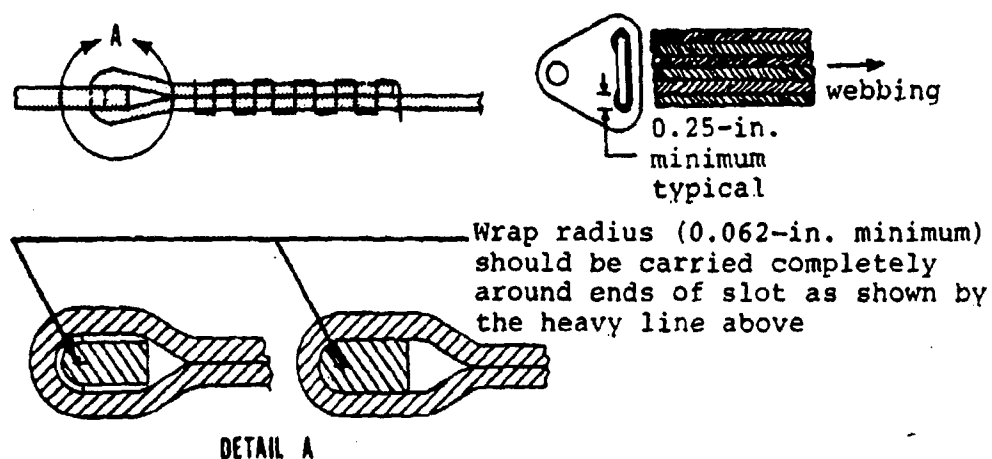
Figure 55. Wrap radius for webbing joints.

7.4.3.3 Hardware-to-Webbing Folds: A possible method of reducing fitting width at anchorage, buckle, or adjuster fittings is to fold the webbing as shown in Figure 56. This reduces the weight and size of attachment fittings; however, it can also cause premature webbing failure because of the compressive force applied by the top layer of webbing to the lower against the fitting slot edge. If this technique is to be used, tests to demonstrate integrity are recommended. Also, for configurations that require two load paths, such as lap belts, where an adjuster cannot hold the required 4000-lb load, the webbing is looped through a full-width slot which halves the load in each strap. An adjuster is then included in one strap. Adjustment requires that the webbing be freely drawn through the fitting, a requirement that folded webbing cannot meet.

7.4.3.4 Surface Roughness of Fittings: A surface roughness of no more than RMS-32 is recommended to prevent fraying of the webbing due to frequency of movement over the metal.

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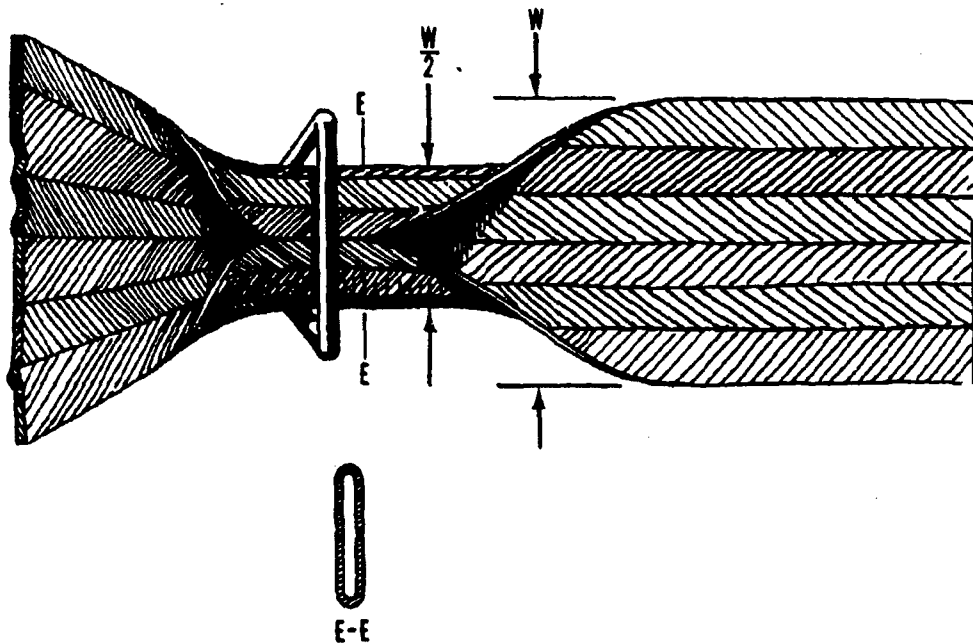
Figure 56. Webbing fold at metal hardware attachment.

7.4.4 Energy-Absorbing Webbing

Energy-absorbing restraint system webbing has been considered for limiting loads on the occupant. The potential advantages of energy-absorbing webbing are: (1) reduction of maximum load exerted by the webbing on the occupant and (2) reduction of the amount of elastic energy stored in the webbing. Webbings of this type have been developed and are described briefly here for information purposes. They are not recommended for use in seating systems for the reasons presented below.

The principle of energy absorption for the first webbing material depends on a core wrap of fiberglass that breaks at a design load; then, the outer cover of nylon wrap takes over the loading, gripping the fiberglass until it breaks again. The construction of the webbing varies, depending on the type of force-versus-percent-of-elongation curve desired. For this webbing, the general shape for the force-versus-elongation curve includes a linear elastic region followed by a region of constant force.

The construction of the second type of energy-absorbing webbing differs greatly from the first. It is made of polyester,

and the energy absorption is produced by the filaments themselves. The polyester filaments are heat shrunk from their original sizes; and they do not return to the shrunk dimensions after the load application. This has the effect of plastic deformation; and this property provides the energy-absorption capability of the material. The general shape for the force-versus-elongation curve for this webbing is a constant rate in pounds per inch which makes inefficient use of stroke distance.

A third type of energy-absorbing webbing material has been evaluated for parachute applications at the U. S. Naval Aerospace Recovery Facility. The material is made by stitching together two pieces of webbing. The two pieces of webbing separate (peel) at a constant load by breaking the stitches holding them together. The constant breaking force can be varied by increasing or decreasing the number of stitches. Because of its construction, the material does not appear to be suitable for use in aircrew restraint systems.

Because of other considerations, including primarily the increased potential for secondary impacts of occupants, energy-absorbing webbing is not recommended for use in seating systems. The limited room available in aircraft requires that the strike envelope be minimized. Therefore, the use of the lowest elongation available is specified.

7.5 RESTRAINT SYSTEM HARDWARE

7.5.1 General

The restraint system configured for use in a particular location in an aircraft will include various hardware selected on the basis of a trade-off among such factors as crashworthiness, weight, and cost. An aircrew system meeting the requirements of MIL-S-58095(AV) that has been developed is illustrated in Figure 57. The system shown in Figure 58, which is defined by a draft military specification (Reference 85), offers improved protection but is heavier and more expensive. For example, it includes two inertia reels for the reflected shoulder strap system, which reduces both lateral and forward motion. Its use may be warranted where space is a problem and strike envelopes need to be minimized. Also, this system's use of lap belt retractors rather than adjusters provides greater convenience in ingress, greater comfort by eliminating the adjuster, and greater crash safety by eliminating slack (preload held on the lap belt by torsional spring in retractor). The weight of the

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85. Proposed Draft Military Specification,
    RESTRAINT SYSTEM, AIRCREW, September 1974.
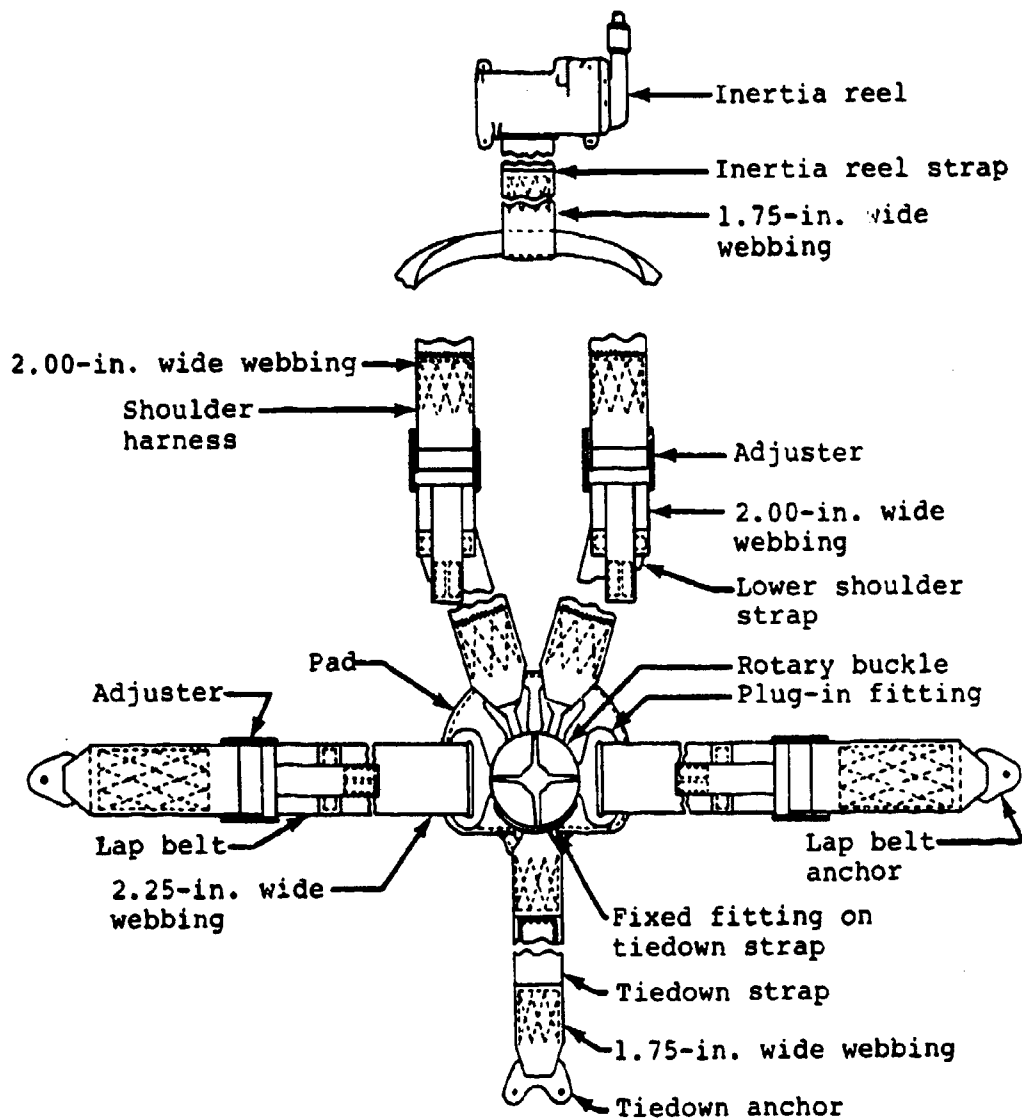
Figure 57. Aircrew restraint system.

system shown in Figure 57 is 5.50 lb and that of the system in Figure 58, 8.50 lb, with the difference due mostly to the additional inertia reel and the two lap belt retractors of the latter system.

The various hardware components involved in a state-of-the-art restraint system are described below. Information on production items is included where available.

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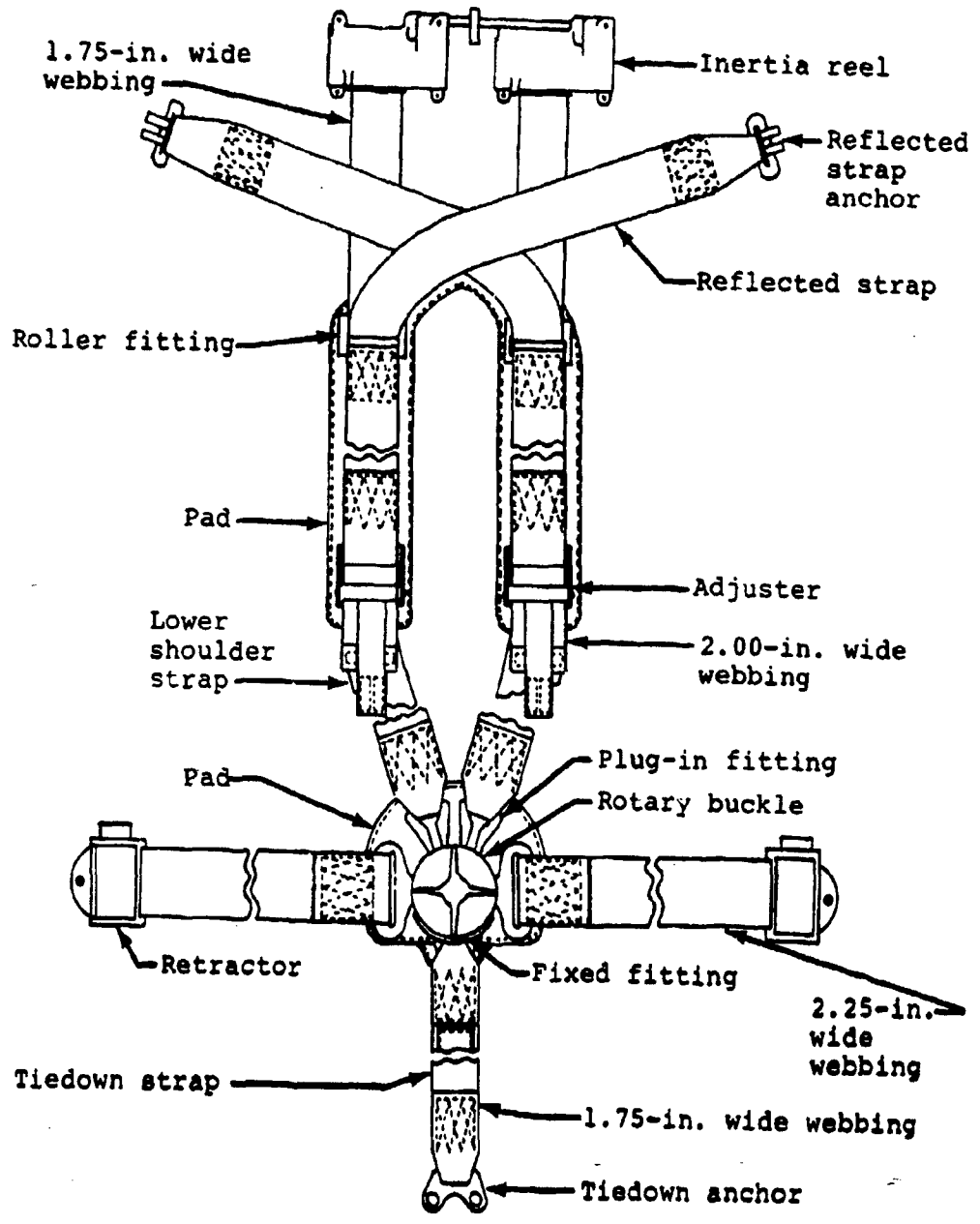
Figure 58. Reflected shoulder strap restraint
system. (From Reference 85)

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7.5.2 Buckles and Emergency Release

The buckle is of the single-point release type for all systems and provides positive release of all strap fittings (with the exception of the one to which it is permanently attached). These capabilities should help prevent entrapment of a wounded occupant.

7.5.2.1 Aircrew Restraint Buckle: To facilitate egress in emergencies, a rotary-release buckle provides the advantage of operation by a force applied in many directions. In one existing buckle, each fitting can be inserted and locked separately. When the release handle is rotated, springs move the fittings far enough so that none will reengage when the handle is released. This is an example of a desirable feature that will protect against a potential hazard created by a fitting relocking upon release of the handle. For example, if one lap belt fitting relocks, it could partially restrain the occupant as he attempts an emergency egress.

7.5.2.2 Troop/Passenger Restraint Buckle: The restraint systems recommend d for troop seat installations, as shown in Figure 45, include a single-point, lift-lever release buckle that is permanently attached to one of the lap belt straps. The lift-lever release mechanism replaces the rotary release here for the convenience of troops or passengers who, because of infrequent system use, might find it easier to use in emergencies since it resembles automotive hardware (References 63, 78, and 86). The design of such a buckle is described in Reference 78.

7.5.3 Adjustment Hardware

The lap belt-length adjusters are located either at the center of the lap belt near the attachment-release buckle or at the side of the hips of the occupant below the iliac crests of the pelvis. Shoulder strap adjusters are located as low on the chest area as possible to avoid a concentrated pressure over the collarbones of the seat occupant. It is possible for the seat occupant to make strap adjustments easily with either hand. A downward pull on the free end of the shoulder harness straps tightens the shoulder harness, and an upward pull on the free end of the lap belt straps tightens the lap belt.

86. Reilly, M. J., ENERGY ATTENUATING TROOP SEAT DEVELOPMENT, The Boeing Vertol Company; Report NADC-AC-7105 with Addendum NADC-73121-40, U. S. Naval Air Development Center, Aerospace Crew Equipment Department, Warminster, Pennsylvania, May 1971.

7.5.4 Inertia Reels, Control, and Installation

7.5.4.1 Inertia Reels and Controls: Inertia reels currently installed on the crewseats of U. S. Army aircraft are designed in accordance with the requirements in Reference 87. The design requirements specified in MIL-R-8236 are compatible with the other restraint harness requirements listed in this chapter, and it is recommended that the use of this specification be continued.

Some discussion of inertia reel function is included here to explain the two basic types of reels listed in MIL-R-8236. The basic function of the inertia reel is to give the crewmember full freedom of movement during normal operating conditions while automatically locking the shoulder harness during an abrupt deceleration.

The freedom of movemen... is obtained by spring-loading the reel cable or webbing to which the shoulder straps are attached. This allows the shoulder harnes to be extended without apparent restraint of the shoulders (only 6 lb at maximum extension). The reel will be constantly taking up any slack.

There are two basic types of MIL-R-8236 reels. The impact-sensitive type requires a 2- to 3-G impact on the inertia reel housing itself to lock automatically. Normal flight loads, including severe turbulence, will not activate this reel.

The rate-of-extension type reel, although mechanically different, serves the same purpose. Its automatic operation depends on the rate at which the inertia reel strap is reeled off, which makes it a function of the rate of upper torso displacement away from the seat back, regardless of direction. The automatic operation of this reel can be checked at any time by a jerk on the shoulder straps. The shoulder harness, after being locked automatically, reels up the slack in the strap every time the occupant bounces back toward the seat back. Eventually, the occupant will find himself firmly locked against the seat back.

A few words about the manual control lever will clear possible misconceptions about its use. Both types of reels have identical control levers, usually mounted under the seat pan, on the seat side, or at some other convenient location. The lever has two positions: manual and automatic. The manual position

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87. Military Specification, MIL-R-8236, REEL, SHOULDER HARNESS, INERTIA LOCK, Department of Defense, Washington, D. C.

permits the pilot to lock the reel if rough conditions are anticipated, or at any other time warranted. Normally, the control lever should be in the automatic position to allow the wearer to lean forward easily and reach all controls without first having to release the control lever. MIL-R-8236 requires that both reel types lock automatically before the occupant travels more than 0.5 in. during an emergency deceleration.

In addition to the MIL-R-8236-type reel, which has the function of preventing further strap extension, there are power-haulback reels, which rapidly retract slack to apply a tensile load to the belt. Generally, these systems, some of which use a basic MIL-R-8236 inertia reel, are powered by a gas generator and must be manually actuated prior to impact. Automatic actuation by an acceleration sensor is not recommended because human tolerance considerations limit the haul-back velocity. By the time the crash could be sensed, there would not be time to complete the haulback within tolerable accelerative limits.

7.5.4.2   **Inertia Reel Installation in Rotary- and Fixed-Wing Aircraft:**   Accident statistics indicate that rotary-wing aircraft frequently impact on their sides, or impact vertically with little longitudinal der   ration. Therefore, it is concluded that all rotary-win .. VTOL aircraft should incorporate the rate-of-extension .   . reel, because a unidirectional ($-G_x$) acceleration (needed .o actuate the impact type reel) might not be present in all rotary-wing or VTOL aircraft accidents.

On the other hand, the study of about 92 fixed-wing aircraft accidents, described in Volume II, revealed that only one accident occurred in which no longitudinal ($-G_x$) acceleration was present. On this basis, it is concluded that a unidirectional-(impact) type reel would be adequate for fixed-wing aircraft. However, it is recommended that the rate-of-extension type reel be used on all aircraft types to assure locking regardless of load direction.

The inertia reel may be anchored to the seat back structure or to the basic aircraft structure. The shoulder straps must be maintained at the correct angle with respect to the wearer's shoulder at all times as described in Section 7.3.4. If an anchorage to basic structure is used, consideration must be given to the possible seat bucket motion so that the shoulder strap angle or length does not change by a significant amount during energy-absorbing stroke. The reel should be mounted and the webbing routed so that the webbing does not bear on the reel housing. Excessive webbing loading of the housing can produce housing and/or webbing failure as the housing is not designed as a contact surface for loaded webbing.

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8. SEAT STRENGTH AND DEFORMATION REQUIREMENTS

8.1 INTRODUCTION

Previous sections of this volume have presented background in-
formation to aid in understanding the problems involved in de-
signing crashworthy seats and restraint systems. This chapter
presents specific design and test requirements for seat systems
and litter systems. Occupant sizes and weights to be used in
the design are defined, as are the required static design
strength-deformation relationships. Static tests to demon-
strate the adequacy of the system in all loading directions
are presented. Finally, dynamic test requirements, to demon-
strate that the seat systems, restraint systems, and litter
systems will provide the degree of protection desired, ar; also
defined. Successful completion of all static tests and dynamic
tests are required to demonstrate acceptability of a design.

In this chapter, the direction of applied loads are referred
to in terms of forward or aftward, lateral or vertical, and
upward or downward. These terms, together with aircraft and
occupant axes, are defined in Chapter 2, Definitions, and refer
to seat loading in directions consistent with the <u>aircraft
coordinate system</u>. Thus, a forward load on a forward-facing
seat is in the positive x direction with respect to both the
seat and the aircraft. If the seat is a side-facing seat, the
forward load would be applied to the seat in the plus-or-minus
y direction, depending on whether the seat faces right or left
respectively in the aircraft. For an aft-facing seat, the for-
ward load would be applied in the negative (-x) direction (to-
wards the back of the seat).

8.2 RECOMMENDED OCCUPANT WEIGHTS FOR SEAT DESIGN

It is recommended that the upper and lower limits of occupant
weights to be considered in seat design be based on the 95th
and 5th percentiles. Ideally, seat stroke limits should be
sized for the 95th-percentile occupant while the occupant ac-
celeration limits should be determined for the 5th percentile.
If this were done, the resistive forces would be tolerable
while the stroke lengths would also be adequate for all occu-
pants in the design range (5th through 95th percentile). How-
ever, in most situations sufficient stroke distance will not
be made available in the aircraft to permit using the ideal ap-
proach; therefore, compromises will have to be made. Specific
criteria for these cases are presented in this chapter and, for
the present, should be viewed as <u>minimum</u> state-of-the-art de-
sign goals.

8.2.1 Crewseats

The design weight should be based on the typical weight of the seated occupant, not the extremes. Although the weight of a 95th-percentile, combat-equipped aviator can be as high as 250 lb, it is believed that a majority of the flight hours logged in Army aircraft over the past 20 years have been noncombat hours. Consequently, it is probable that crewmembers will be lightly equipped. The restrictions placed on crewseats, including stroke length, control access, and seat armor, limit the flexibility of design options. If the crewseats were to be designed to protect occupants over the full range of weights (144 to 250 lb), a weight-sensitive energy-absorbing system would be mandatory. Thus, the typical aviator weight recommended for crewseat design should not include combat gear. Based on data of Reference 88, typical aviator weights are presented in Table 9.

TABLE 9. TYPICAL AVIATOR WEIGHTS

Item	95th-percentile weight (lb)	50th-percentile weight (lb)	5th-percentile weight (lb)
Aviator (Reference 88)	211.7	170.5	133.4
Clothing	3.1	3.1	3.1
Helmet	3.4	3.4	3.4
Boots	4.1	4.1	4.1
Total weight	222.3	181.1	144.0
Vertical effective weight	175.2	142.3	112.6

88. Churchill, E., et al., ANTHROPOMETRY OF U. S. ARMY AVIATORS 1970, Anthropology Research Project; USANL Technical Report 72-52-CE, U. S. Army Natick Laboratories, Natick, Massachusetts, December 1971, AD 743528.

Variable-load energy-absorbing systems are highly desirable to maximize efficiency and thus, protection in limited space. Therefore, they should be incorporated in seat designs whenever possible.

8.2.2 Troop and Gunner Seats

The same percentile range of occupant sizes should be considered for troop and gunner seat designs. A greater variation of clothing and equipment is used by troops than by aviators; troop seats should be designed to accommodate them. The 95th-percentile occupant should be considered heavily clothed and equipped, while the 5th-percentile occupant should be considered lightly clothed and equipped. Based on data contained in References 31, 32, 63, 79, and 89, the typical weights of seated troops in aircraft are shown in Table 10.

8.3 STRENGTH AND DEFORMATION

8.3.1 Forward Loads

In Section 4.7, it was shown that for a load-limited system there is a minimum displacement that must be achieved if the system is to remain in place during a given deceleration pulse. Actually, all systems are load limited, although not necessarily through original intent. The inherent load-deflection curve for any system imposes a definite limit on the system's ability to resist impulsive loading. The objective of intentionally load-limited seat systems is to make the best use of the space available for relative displacement of the seat and occupant with respect to the airframe, while maintaining loads on the occupant consistent with the type of restraint system used and the occupant's capacity to survive the loads imposed.

The basic data used in developing the seat design curves presented in Figure 59 were obtained through a computer simulation of the seat/occupant system (see Reference 25) and from the results of static and dynamic seat tests (References 31, 32, 63, and 79) using body blocks and anthropomorphic dummies, respectively. The computer simulation allowed the calculation of the seat displacement for given load-limiting values. The simulator included a realistic kinematic behavior of the occupant and the nonlinear effects of the restraint system. It is estimated that the requirements given in Figure 59 are not conservative for the input pulses selected for design purposes.

89. U. S. Army, THE BODY SIZE OF SOLDIERS - U. S. ARMY ANTHRO-POMETRY - 1966, USANL Technical Report 72-51-CE, U. S. Army Natick Laboratories, Natick, Massachusetts, December 1971, AD 743465.

TABLE 10. TROOP AND GUNNER WEIGHTS

Item	95th-percentile weight (lb)	50th-percentile weight (lb)	5th-percentile weight (lb)
Troop/Gunner weight (Reference 89)	201.9	156.3	126.3
Clothing (less boots)	3.0	3.0	3.0
Boots	4.0	4.0	4.0
Equipment	33.3	33.3	33.3
Total weight	242.2	196.6	166.6
Vertical effective weight clothed	163.9	127.4	103.4
Vertical effective weight equipped	197.2	160.7	136.7

These are a 30-G peak triangular pulse of 50-ft/sec velocity change in the cockpit and a 24-G peak with 50-ft/sec velocity change in the cabin area.

The static loads that the seat must withstand are obtained by multiplying the load factors (G) shown in Figure 59 by the sum of the total weight of the 95th-percentile crewmember or passenger plus the weight of the seat and any armor or equipment attached to or carried in the seat. For crewseats, the weight of combat gear is not included (see Section 8.2.1).

Longitudinal displacement of approximately 6 in. for cockpit seats and 12 in. for cabin seats measured at the seat reference point (the seat reference point may be projected to the outside of the seat pan for measurement convenience) is the practical limit for seats in existing Army aircraft. Since
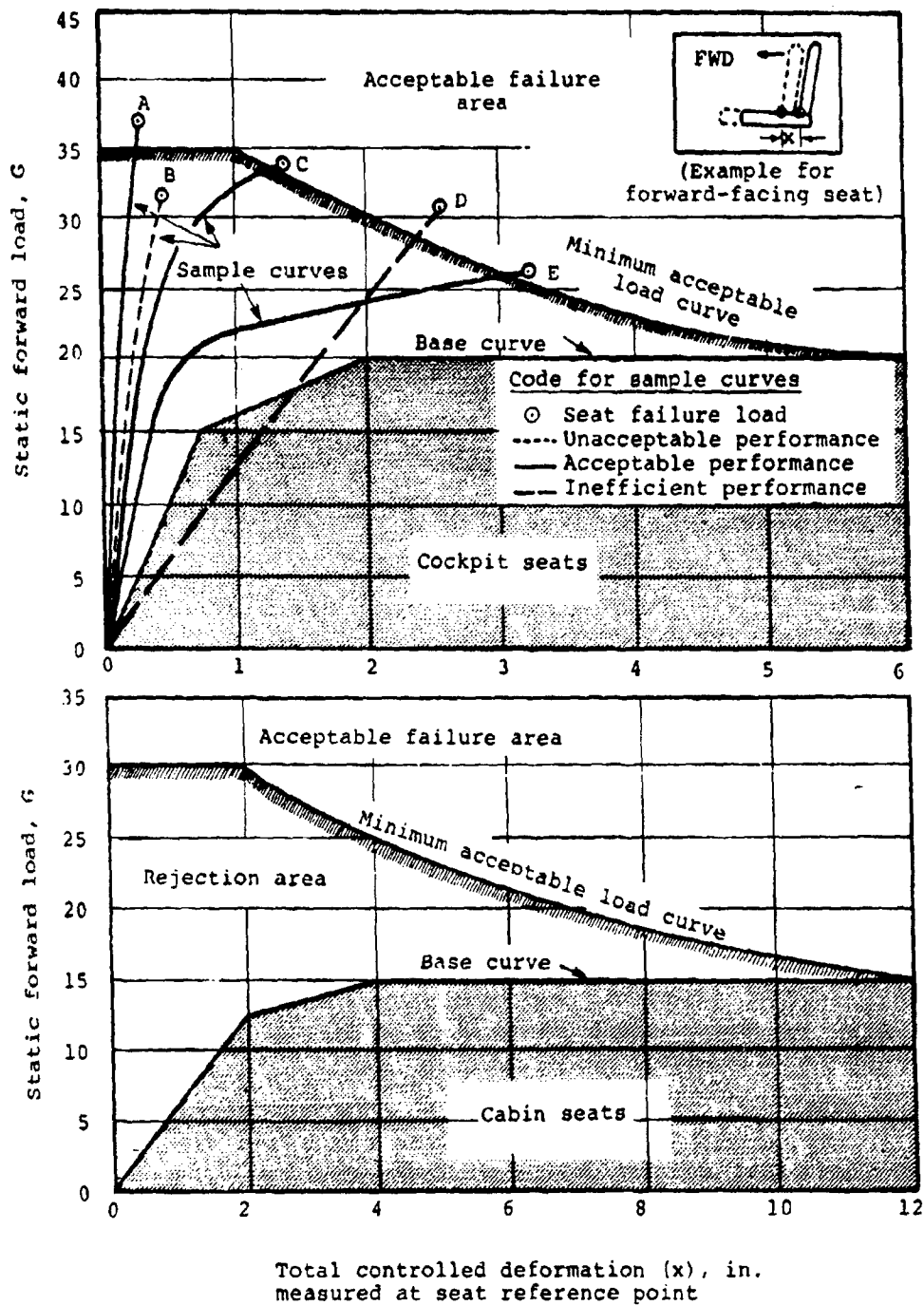
Figure 59. Seat forward load and deflection requirements
for all types of Army aircraft (forward design
pulse).

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there is typically more room available in cabins than in cockpits, the advantages of longer energy-absorbing strokes can usually be achieved. Longer strokes permit the absorption of equivalent energy at lower loads and thus can serve to reduce seat weight and increase the level of protection offered over a wider occupant weight range.

In viewing Figure 59, it can be seen that for cabin seats 12 in. of stroke enables the minimum limit load to be reduced to 15 G; whereas, for cockpit seats a 20-G minimum limit load is required with only 6 in. of stroke. The 15-G and 20-G minimum limit loads fix the G levels of the base curves for the cabin and cockpit seat respectively. The available stroke will be unique for each specific aircraft, and the energy-absorbing mechanisms in the seats should be compatible with the available stroke distances. If forward or sideward motion threatens to limit the effectiveness of the vertical energy attenuating system or increase the possibility of severe injury caused by secondary impact of the occupant with items in the aircraft, then energy-absorbing stroke in directions other than vertical should not be used. The 6 in. and 12 in. allowed by the curves of Figure 59 should be viewed as maximum distances which are subject to limitations of available space in each specific aircraft and location in the aircraft.

The initial slope of the cockpit seat base curve to 0.75 in. of deflection allows for elastic deformation consistent with a relatively rigid crewseat while the lighter weight and more flexible troop/gunner seat requires a lesser slope. The 30-G and 35-G upper cutoffs reflect consideration of human tolerance limits, load variations between cockpit and cabin locations, and practical limitations of seat weight and excessive airframe loading.

8.3.2 Use of Design Curves

To be acceptable, a seat design must have a characteristic load-deflection curve that rises to the left and above the base curves of Figure 59 and extends into the region beyond the upper curve. This discussion also applies to the lateral strength and deformation requirements discussed in Section 8.3.6. In Figure 59, curves A, C, and E are acceptable curves, but curve B is unacceptable because it does not reach the required ultimate strength. Curve D reveals inefficient use of seat deflection by intruding into the base area. The seat is deflecting at too low a load, thus absorbing less energy than it could.

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8.3.3 Aftward Loads

Large aftward loads seldom occur in fixed-wing aircraft accidents but may occur in rotary-wing accidents. A capability to withstand 12 G is recommended for aftward loads for all seats. This value will usually be automatically met by all seats meeting the forward load requirements. Occupant weight should be the total weight of the 95th-percentile crewmember or trooper as presented in Section 8.2.

8.3.4 Downward Loads

Human tolerance to vertical impact limits the acceptable forces in the vertical direction for all aircraft seats. The maximum allowable headward acceleration (parallel to the back tangent line) for seated occupants is on the order of 23 G for durations up to approximately 0.006 sec. Since most back tangent lines are oriented at a backward leaning angle of 13 degrees from the vertical aircraft axis, tolerance to vertical impact loads should be somewhat increased over the stated criteria. In spite of this, however, the 48-G design pulse imposes the requirement for energy absorption in the vertical direction by some form of load limiting. The vertical dynamic response of seat-occupant systems and, in particular, the effect of seat behavior on the occupant deceleration excursions, has not been sufficiently investigated to allow a full explanation of the effects of this phenomenon. The factors affecting the response of the seat and occupant and thus the final design of the load-limiting system include:

- Input pulse variables.

- Orientation of the occupant and seat relative to the resultant force vector.

- Effective occupant weight.

- Occupant spring rate and damping characteristics.

- Weight of the movable part of the seat.

- Spring rate and damping characteristics of the seat.

- Spring rate and damping characteristics of the cushion.

- Available stroke distance.

- Force-deflection characteristic of the energy-
  absorption system.

- Any external influences such as those caused by loads
  transmitted through dummy legs, or binding of the
  seat mechanism.

Army-sponsored research in these areas is currently underway
and results will be incorporated into this document when avail-
able.

The effective weight in the vertical direction of a seated oc-
cupant is approximately 80 percent of the occupant's total
weight because the lower extremities are partially supported
by the floor. The effective occupant weight may be determined
by summing the following:

- Eighty percent of the occupant's body weight.

- Eighty percent of the weight of the occupant's cloth-
  ing (less boots).

- One hundred percent of the weight of any equipment
  carried on the body above knee level. Combat gear
  is not included in the effective weight of the pilot
  or copilot (see Section 8.2.1).

The dynamic limit load for the load-limiting system should be
established by use of a load factor (G_r) of 11.5. The dynamic
limit load is determined by multiplying the summation of the
effective weight of the seat occupant, and of the movable or
stroking portion of the seat, by 11.5. The resulting dynamic
limit load includes the total force resisting the vertical
movement of the seat in a crash; the dynamic limit load of the
energy-absorption system, simple friction, friction due to
binding, etc. This requirement is difficult to satisfy with
a sliding guidance system because the frictional load varies
with contact load which, in turn, varies with the impact load
vector direction. A relatively friction-free rolling mechanism
or collapsible structure is therefore recommended.

The 11.5-G design criterion, taken from Reference 24 and modi-
fied to provide a tolerable deceleration of the 5th-percentile
occupant, considers the dynamic response of the seat and occu-
pant. The factor of 11.5 was established to limit the decel-
erative loading on the seat/occupant system to less than 23 G
for durations in excess of 0.006 sec (the tolerable level for
humans as interpreted from the Eiband data) in crashes that do
not exhaust the stroke of the seat.

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Crewseats should be designed to stroke a minimum distance of
12 in. when the seat is in the lowest position of the adjust-
ment range. This distance is needed to absorb the residual
energy associated with the vertical design pulse. Further, the
load-limiting system should be designed to stroke through the
full distance available including the vertical adjustment dis-
tance. Since a vertical adjustment of ±2-1/2 in. from neutral
is typically required by crewseat specifications, proper design
can provide up to 17 in. of stroke, depending on seat adjust-
ment position.

The minimum of 12 in. of stroke is recommended to provide the
minimum required level of protection. As illustrated later in
this section, even with 12 in. of stroke, heavier occupants in
more severe crashes will exhaust the available stroke distance
and bottom out. The following reasons point out the need for
obtaining the greatest possible energy-absorbing stroke from
the seat:

- It is easier to provide energy-absorbing stroke in
  the seat than in the fuselage or landing gear. The
  distance from the floor of the helicopter to the
  ground is usually specified either directly or im-
  plicitly by overall dimensional requirements.

- The energy-absorption capacity of the seat is much
  easier to demonstrate than that of the airframe, as
  the energy-absorption capacity of the airframe is
  difficult to predict and hardware is usually not
  available for testing in the early design phases of
  a new aircraft.

- Energy absorption assigned to landing gear can be
  lost depending on the type of terrain upon which
  the aircraft crashes; i.e., soft versus hard, as in
  marshes or water as opposed to a landing strip. Air-
  craft attitude at impact has a significant influence;
  also a relatively high roll angle, for instance,
  could render the landing gear energy-absorbing fea-
  ture inoperative.

- Based on the two previous points, the seat is a low-
  risk approach for providing energy-absorbing stroke.

- 12 in. of stroke has been shown to be practical in
  existing aircraft.

If it is absolutely impossible to obtain a minimum of 12 in.
of stroke, a lesser amount is acceptable, but in no case should
it be less than 7 in. The reduced stroke is acceptable for a

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retrofit application or for use in small aircraft in which it is simply impossible to find the space for a 12-in. stroke. In such cases a systems analysis is mandatory; the analysis must show that occupant protection is equivalent to the system in which the 12-in. stroke is available.

For retrofit applications, the maximum protection possible should be obtained in any component being modified, i.e., seats, gear, etc. Separate test criteria have been established for seats not having the required 12 in. of stroke and are presented in Section 8.6.3.2 of this document.

Energy-absorbing systems should be designed for 11.5 plus 1 G minus 0 G considering the effect of the dynamic loading rate. To obtain the static test loads, dynamic limit loads should be reduced by the amount due to rate sensitivity of the particular device used. Further, in the design of the system the desired total resistive load on the seat should be obtained by summing the resistive load provided by the energy-absorbing system and the resistive load resulting from friction and/or other mechanisms unique to the particular system. Thus, the resistive load of the energy-absorbing subsystem must be reduced from the load required to decelerate the seat by the amount of the other stroke-resisting variables.

If the energy-absorbing system is to provide only one force setting, the effective weight of the 50th-percentile occupant from Tables 9 and 10 should be used for sizing it in order to ensure a tolerable stroke for the majority of the occupants, not exceeding the stroke limitations of the seat. These weights are 142.3 and 160.7 lb for pilot/copilot and troop and gunner seats, respectively.

The following is an example of the calculations made for a seat designed to stroke under the decelerative load imposed by a 50th-percentile crewmember. The average deceleration and stroke of the 5th- and 95th-percentile seat occupants are approximated. First, using weights from Table 9, the 50th-percentile effective weight is calculated according to

$$Wt_{eff} = 0.80 \ (Wt_{50} + Wt_c) + Wt_h \qquad (35)$$

where Wt_{eff} = effective weight of 50th-percentile occupant, lb

Wt_{50} = nude weight of 5th-percentile occupant, lb

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Wt_c = weight of clothes, lb

Wt_h = weight of helmet, lb

Thus, Wt_{eff} = 0.80 (170.5 + 3.1) + 3.4

$\quad\quad\quad\quad\quad\quad$ = 142.3 lb

which is shown in Table 9 as the effective weight of the 50th-percentile crewmember. The effective weights for the 95th- and 5th-percentile aviators are 175.2 and 112.6, respectively.

Assuming a 60-lb movable seat weight, the total weights that the load-limiting system must be designed for are:

$\quad\quad\quad\quad$ 5th percentile: $\quad$ 172.6 lb

$\quad\quad\quad\quad$ 50th percentile: $\quad$ 202.3 lb

$\quad\quad\quad\quad$ 95th percentile: $\quad$ 235.2 lb

The 50th-percentile static limit load (L_L) is calculated as follows:

$$L_L = G_L \, Wt_{eff} = (11.5)\,(202.3) = 2326 \text{ lb}$$

The static load factors for the 95th- and 5th-percentile aviators are then

$$G_{L95th} = \frac{2326}{235.2} = 9.9$$

$$G_{L5th} = \frac{2326}{172.6} = 13.5$$

Seat deceleration spikes approaching 23 G could be expected for the seat occupied by a 5th-percentile aviator. Decelerations of this magnitude would not be expected to cause severe injury. Also, in more severe crashes, the stroke would exceed 12 in. for a seat occupied by the heavier percentiles. This would mean that the 95th-percentile vertical survivable crash could not be fully protected against in the seat adjusted-down position. With the seat in the neutral or up position, however, protection over the entire range might be provided (see Reference 24).

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For comparison, the same type of calculations for a system limit load sized for the 95th-percentile crewmember yields the following:

$$L_L = (11.5) \ (235.2) = 2705 \ \text{lb}$$

and

$$G_{L50th} = \frac{2705}{202.3} = 13.4$$

$$G_{L5th} = \frac{2705}{172.6} = 15.7$$

The entire population in the 5th- to the 95th-percentile weight range could be expected to receive deceleration spikes in excess of 23 G in seats in which the limit load was designed for the 95th-percentile occupant. Also, the natural distribution of occupant weights places the majority of aviator weights near the 50th percentile. It is therefore expected that more overall protection can be provided by sizing limit loads for the 50th-percentile rather than for a heavier occupant.

In order to use the stroke distance available at maximum efficiency, regardless of occupant weight, a variable-force load-limiting mechanism is desirable. With an infinitely variable force system, the deceleration levels can be maintained within acceptable limits (if the stroke is not exhausted) for the full range of occupant weights for either crew or troop seats while using equal stroke lengths for identical pulses. A compromise is possible for a seat design that uses a load-limiting device rather than collapsing structure. The device can be designed to produce two or more limit loads that can be selected by the seat occupant. An example of one such system is discussed in Reference 24. The selection would be made on the basis of aviator weight. For example, for a dual-limit-load device, the lowest load device might be established by using the weight of a 5th-percentile occupant. The second force might be designed for the weight of a 50th-percentile aviator. In operation then, the aviator would be required to select a limit load by movement of a lever or dial upon entering the seat.

It is recommended that at least a dual-level load limiter (preferably three or more levels) be used to provide maximum protection over the complete occupant weight range. As an illustration, consider the limit-load factors calculated on this page and on 181. With the limit load set for the

50th-percentile occupant weight, the calculated load factors were 9.9 for the 95th- and 13.5 for the 5th-percentile occupant weights. This produces a negative variation of 1.6 G for the heavy occupant and a positive variation of 2 G for the lighter occupant from the design factor of 11.5 G. If two load settings were possible, the variations could be halved producing 0.8-G and 1.0-G variations, respectively. An infinitely adjustable mechanism would reduce the variation to zero.

The interaction between the occupant and the movable seat masses increases with seat mass. Therefore, the movable seat mass should be minimized. For integrally armored seats, this mass is relatively high, varying between 60 and 120 lb. However, design in compliance with the criteria presented herein should provide the desired degree of protection. The criteria were derived primarily from studies of an inter 'ly armored seat prototype and projected to unarmored seats. The criteria are expected to be somewhat conservative for seats of very light (10 to 15 lb) movable sections.

Because troops do not have operational functions to perform and troop seats are not armored, more flexibility exists in troop seat design. Troop seats should be designed for the maximum stroke feasible to maximize protection over the large weight range represented by the fully equipped and lightly equipped occupant. It is recommended that the full 17-in. seat pan height normally considered desirable from the human engineering standpoint be used for energy-absorbing stroke. It is further recommended, as a minimum, that the limit load of the system be sized using the 11.5-G load factor and the effective weight of the 50th-percentile heavily equipped occupant (160.7 lb). Variable-level load limiters sized as discussed previously are also desirable for troop seats.

8.3.5 Upward Loads

A capability to withstand a minimum upward load of 8 G is recommended for all aircraft seats. Occupant weight should be that of the 95th-percentile crewmember or trooper as presented in Section 8.2.

8.3.6 Lateral Loads and Deformation

The lateral load and deformation requirements for forward- and aft-facing seats are presented in Figure 60. Two curves are presented. One is for light fixed-wing aircraft and attack and cargo helicopters, while the other is for other rotary-wing aircraft. The deflections of the seat are to be measured by recording the motions of the seat reference point. Occupant weight should be as stated in Section 8.2 and should be that of the 95th-percentile aircrew member or trooper.
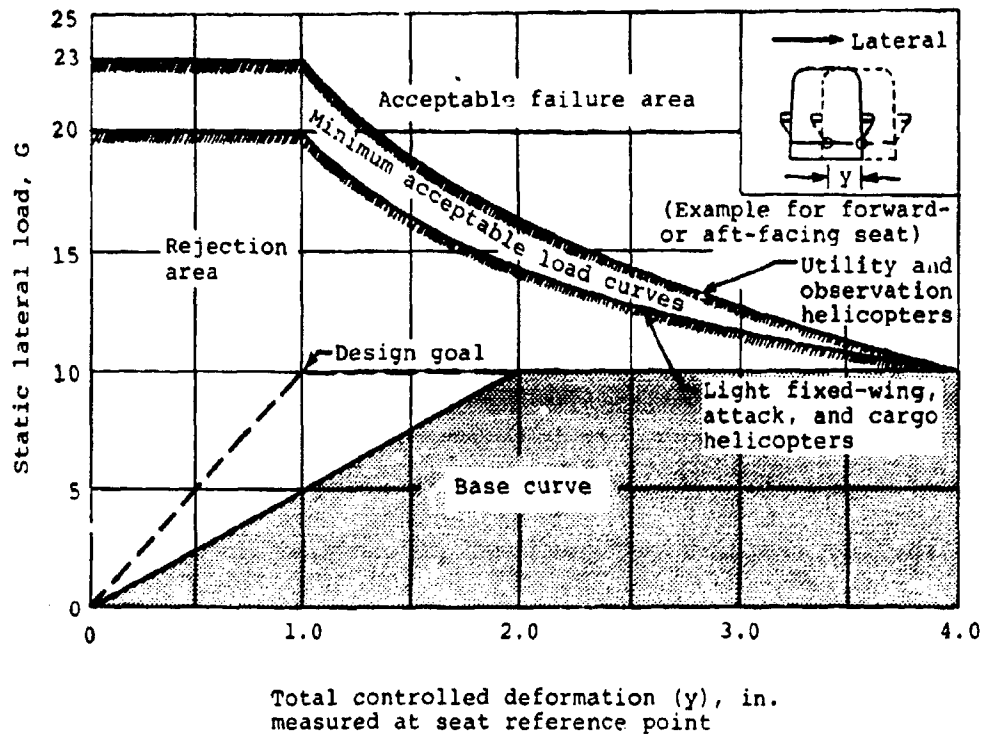
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Figure 60. Lateral seat load and deformation requirements
for all types of Army aircraft.

Lateral loading in the forward direction (aircraft reference
system) on side-facing seats should be the same as for forward-
loading (Figure 59) except load limiting should be employed.

For crewseats, the lateral deflection should be minimized; how-
ever, it is doubtful if any great stiffness can be achieved in
lightweight hardware. As a matter of interest, many new ar-
mored buckets are made from Kevlar, a very tough and strong ma-
terial in tension. Its resin-starved condition (required for
good ballistic protection properties) leaves it with a rather
low flexural modulus, particularly after the seat has had other
loads imposed. The material is also rather rate sensitive
(stiff under high loading rates, soft under low rates). For
this reason, it is believed adequate, as a design goal, to at-
tempt to limit the initial deflection to 1 in. with a 2-in. re-
quirement. Because of the possible loading rate sensitivity
of the seat materials, it is considered acceptable to demon-
strate compliance by analysis of test data. This analysis
might include adjustment of the static test data by use of mea-
sured or known deflection and load data from dynamic tests.

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Further, in cases where wells are provided under the seats to increase the available stroke distance, the deformation should be elastic. This may allow the seat to realign itself with the well prior to entry after the lateral and longitudinal loads are relieved, as explained in Chapter 4.

8.4 OTHER SEATS

The requirements presented for crewseats and troop and gunner seats also apply to passenger seats and any other seat installed in the aircraft for any purpose. Unique seats installed for special uses are not to be exempt.

8.5 PERSONNEL RESTRAINT HARNESS TESTING

The restraint harnesses are to be statically and dynamically tested along with the seat and/or structure to which they are attached as noted in Chapter 7. However, the lap belt, shoulder straps, and tiedown straps, including all hardware in the load path, should be statically tested separately to ensure that all components possess adequate strength and to determine elongation. The strength and elongation test requirements of restraint system subassemblies are specified in Table 4.

Specific component tests, including operational tests, are detailed in a draft military specification (Reference 85). However, all components and subassemblies should be statically load tested. Each subassembly should be tested to its full design load to demonstrate its adequacy. Elongation characteristics should be measured to document these data for comparison with requirements and use in systems analyses.

8.6 STRUCTURAL TEST REQUIREMENTS

Both static and dynamic tests are recommended. Dynamic tests of aircraft seats have shown that individual components capable of maintaining the design loads often fail when tested in combination with other components. This could be a result of inaccurate analyses. However, it is recommended that all seat and litter systems be tested as complete units. This is not to imply that component tests are not useful. Component tests can be extremely useful and should be used wherever possible to verify required strengths. This practice is particularly valid where finite-element analyses have been used to accurately predict distribution of loads in redundant structures.

Upon acceptance of prototype systems tested under both static and dynamic conditions, no further tests should be required except for quality assurance. Major structural design changes in the basic seat system will require static retesting of the

new system to ensure that no loss in strength has been caused by the design changes. If the changes could affect the energy-absorbing, or stroking, performance of the seat, additional dynamic tests should also be conducted. Major structural design changes are those changes involving principal load-carrying members such as floor, bulkhead, or ceiling tiedown fittings, structural links or assemblies, seat legs, or energy-absorbing systems. Minor changes, such as in ancillary fittings, can be accepted without a structural test. A significant weight increase, however, such as the addition of personnel or seat armor, would require additional testing. In summary, changes that increase loading, decrease strength, produce significant changes in load distribution, or affect the stroking mechanism will require retesting.

All testing is to be conducted with the seat cushions in place and, for seats with adjustments, the seats should be in the full-up and full-aft positions unless another position is shown to be more critical.

If desired, dynamic tests may be substituted for static tests; however, loading in all principal directions are required. Alternate dynamic tests are presented in Section 8.6.1.9.

8.6.1 Static Test Requirements

8.6.1.1 General: The purpose of the static tests is to demonstrate that the seat has the strengths and other properties required to provide the desired performance in all the principal loading directions. Static testing enables basic properties to be ascertained for known loads applied at a slow enough rate so that seat response can be observed. Successful completion of the static tests does not guarantee passing the dynamic tests, but it improves the chances. Weaknesses can be identified and corrected prior to conduct of the ultimate dynamic tests. Also, due to the loading rate sensitivity of materials, load distributions may be different in dynamic tests than they are in static tests. Certain structures, statically soft, may react as stiffer members under dynamic loading, and thus, pick up more of the load than when the system was loaded statically. Because of these reasons and because of dynamic overshoot, a margin of safety has been added to the ultimate static load factor on the design curves as compared to the peak accelerations of the dynamic design pulses. It is recommended that this margin not be sacrificed for reduced weight.

Table 11 presents the static test requirements for complete seat units. The tests required include a series of unidirectional tests to determine basic seat strengths along the major

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TABLE 11. SEAT DESIGN AND STATIC TEST REQUIREMENTS

Test ref. no.	Loading direction with respect to fuselage floor	Load required	Percentile occupant used in load determination	Load/deformation requirements[a,i]
1	Upward	8-G minimum	95	No requirement
2	Downward[b,d]	$11.5 \,^{+1.0}_{-0}$ G	50	See Section 8.3.4
3	Aftward	12-G minimum	95	No requirement
4	Forward	See Figure 59	95	See Figure 59
5	Combined			
	Forward [e,f]	See Figure 59	95	See Figure 59
	Downward[c]	$11.5 \,^{+2.0}_{-1.0}$ G	50	Same as Test 2[h]
	Lateral[f]	9-G minimum	95	No requirements
6	Lateral[g]	See Figure 60	95	See Figure 60

(a) The aircraft floor or bulkhead should be deformed as detailed in in Figures 61 and 62, simultaneously with, or prior to the conduct of all static tests and kept deformed throughout load application.

(b) If more than one load-limiter setting is provided, a representative sample of settings spanning the range of loads should be tested.

(c) If more than one load-limiter setting is provided, the highest load should be used.

(d) Subsequent to the stroking of the vertical energy-absorbing device, cockpit seats should carry a static load of 25 G, based on the effective weight of the 95th-percentile clothed and equipped occupant per Section 8.2 plus seat without loss of attachment to the basic structure except when the seat pan has stroked to and is supported by the floor.

(e) In the event that no load-limiting device is used in the forward direction, a 20-G load for cabin seats and a 25-G load for cockpit seats may be used for this combined loading.

(f) For seats employing vertical guides which could distort under combined loading and cause binding, the maximum forward and lateral loads should be reached prior to initiation of stroking. This sequence demonstrates whether the seat will stroke downward after transverse loads are applied.

(g) The lateral loads should be applied in the most critical direction. In the case of symmetrical seats, the loading direction is optional.

(h) Failure to meet the 11.5-G +2.0/-1.0-G static vertical load limit should not be cause for seat rejection if the seat vertical energy-absorbing system meets dynamic load requirements.

(i) Plastic deformation is permissible; however, structural integrity must be maintained.

axes. A combined loading test is also required to evaluate the seat performance under static conditions simulating the most severe, unsymmetrical loading condition anticipated. All static tests should be conducted under simultaneous conditions of floor buckling and warping as illustrated in Figure 61 or bulkhead warping as illustrated in Figure 62. The warping conditions must be introduced in the static test phase to evaluate completely the performance of the seat under the most severe requirements selected for design.

8.6.1.2 Unidirectional Tests: Where separate strength and deformation requirements have been specified in Table 11 for longitudinal, vertical, and lateral loading of seats, the loads should be applied separately. Seats must demonstrate no loss in structural integrity during these tests and should demonstrate acceptable energy-absorbing capacity.

8.6.1.3 Combined Loads: Seats must demonstrate no loss of structural integrity under conditions of combined loading as shown in Table 11 and should demonstrate ability to stroke in the vertical direction with the transverse loads applied.

8.6.1.4 Load Application Method: The static test loads are to be applied at the expected center-of-gravity location of the occupant or occupants of each seat. The loads should be applied through a body block (see Section 8.6.1.5) restrained in the seat with the restraint system. Figure 63 shows the location of the center of gravity that should be used as the initial static load application point for the seat occupant.

For the testing, the seat should be adjusted to its aftmost and full-up position. The loads calculated by multiplying the weight of the occupant and equipment plus the weight of the seat by the required load factor should be applied continuously, or in not more than 2-G increments while the load-deformation performance of the seat is recorded. Maximum loads need not be held for more than 1 sec. The maximum load reached, regardless of duration, is to be used to assess compliance.

On integrally armored crewseats, care should be taken to assure that the loads are applied proportionally to the proper assembly or test item to simulate the loads that would typically be carried by the restraint harness and the seat support structure. In other words, the portion of the load that could be expected to be restrained by the restraint harness should be applied to the body block as described above. The portion of the load representing inertial loading of the movable assembly should be applied separately at the center of gravity of the appropriate substructure through another provision. For example, a
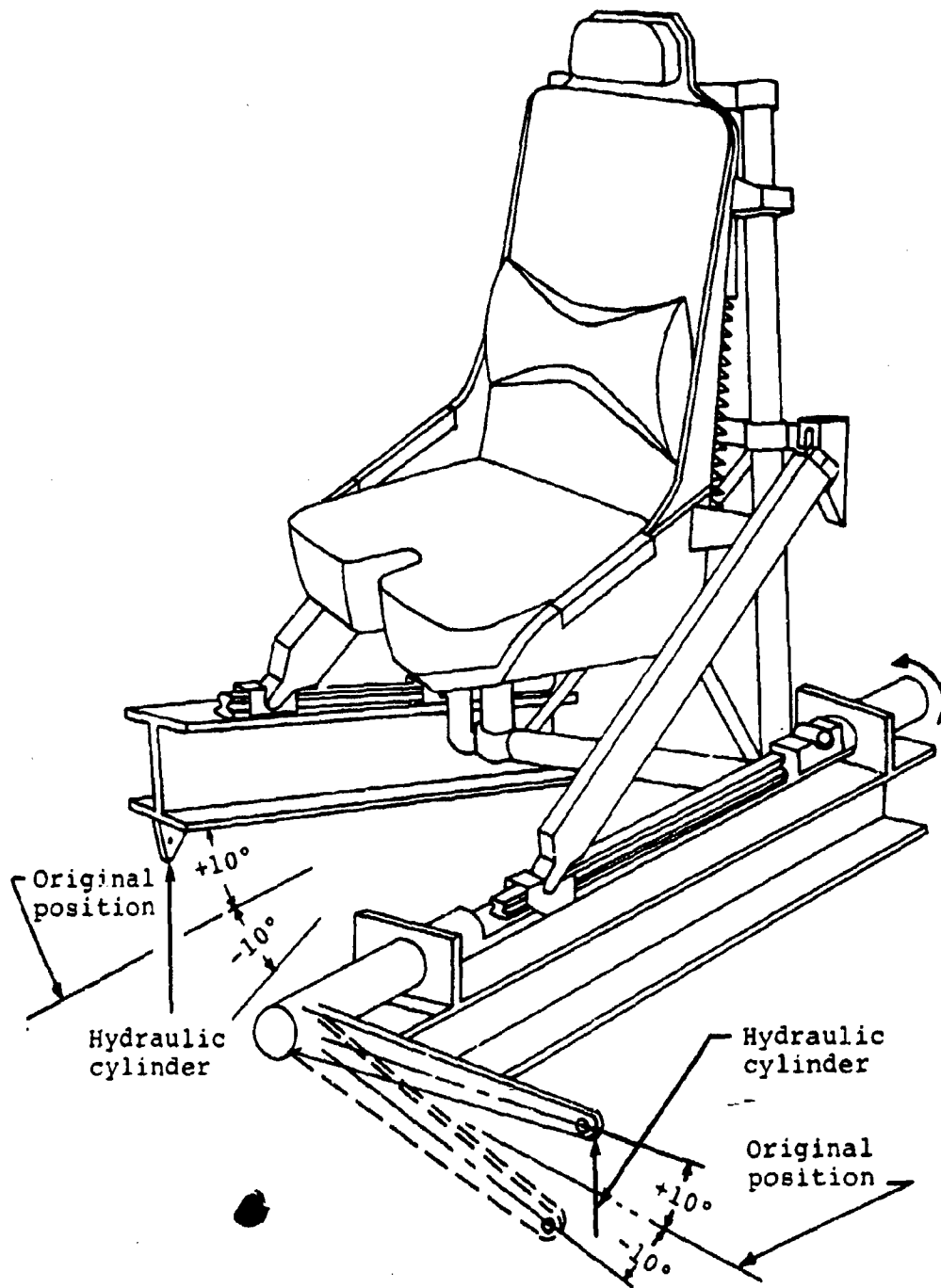
Figure 61. Suggested method of applying floor warping
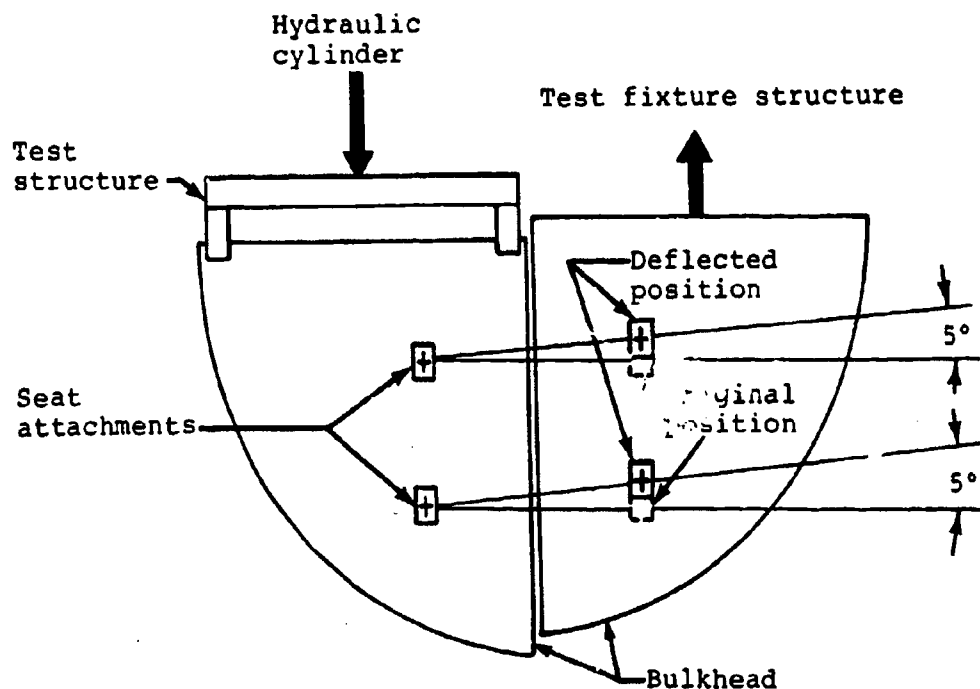for static testing of seats.

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Figure 62.   Suggested method of applying bulkhead
warping for static testing of seats.

lever to proportion the load between the body block and movable
section of the seat, and a sling to apply the appropriate por-
tion of the load to the bucket, can be used. For seats with
relatively heavy frames, the inertial load of the frame can be
applied separately at its appropriate center of gravity. This
technique, although adding complexity to the test setup, as-
sures that all components in the seat and restraint system as-
sembly have been tested to their approximate static design
loads and that, as far as a static test simulation can be ex-
tended, performance and structural adequacy have been demon-
strated. For lightweight seats (less than approximately 45 lb
for total seat and restraint system), the total load can be im-
posed on the body block.

8.6.1.5 Static Load Body Block: The static test loads must
be applied through a body block contoured to approximate a
95th-percentile occupant seated in a normal flying attitude.
The body block must contain shoulders, neck, and upper legs,
and provide for passage of a belt tiedown strap between the
legs. The upper legs should be contoured to simulate the flat-
tened and spread configuration of seated thighs and to allow
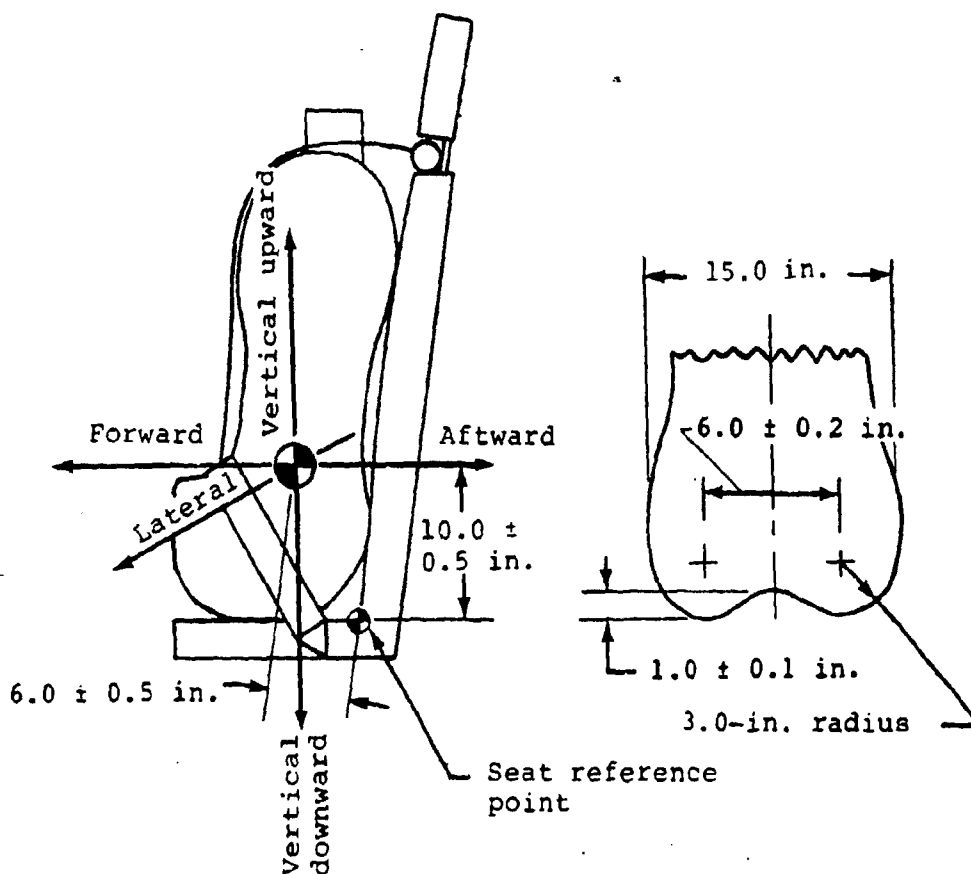the proper location of the buckle. Critical pelvis dimensions

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Figure 63. Static load application point and critical body block pelvis geometry.

are shown in Figure 63. Buttock contours must be provided to permit proper fit in a contoured seat pan. The leg stubs should be configured to permit proper seat pan loading as the body block rotates forward under longitudinal loading; i.e., the leg stubs should be only long enough to provide a surface to react the lap belt load. The side view of the buttocks should include an up-curved surface forward of the ischial tuberosities to allow the forward rotation of the body block while maintaining the primary contact between the ischial tuberosities and the seat pan through the cushions.

8.6.1.6 Deflection Measurements: Deflection should be measured as close to the seat reference point as possible to eliminate seat structure rotational deformation from influencing the test results. To simplify these measurements, the seat reference point can be projected to the outside of the seat pan or bucket.

Normally the restraint system will be attached to the seat. However, if a unique situation should develop in which the only option for increasing crashworthiness is to attach the system (lap belts and shoulder harness) to the basic aircraft structure rather than to the seat, certain factors should be considered. First, the forward and lateral deflection requirements of Figures 59 and 60 need not be considered because the restraint harness limits torso and seat deflection. Second, the vertical deflection of the seat pan still must be considered since the downward movement of the seat pan could cause excessive slack in the restraint harness, or the harness could limit the stroke of the seat, depending on where the restraint system is anchored. Neither of these conditions is acceptable in the design.

8.6.1.7 <u>Load Determination</u>: The total load required for all test directions, except vertical downward, is determined by multiplying the required load factor from Table 11 by the weight of the 95th-percentile clothed and equipped occupant from Table 9 or 10 (Section 8.2) plus the weight of each seat. The effective weight of the 50th-percentile occupant should be used to calculate vertical components of loading (Test Nos. 2 and 5 of Table 11) as discussed in Section 8.3.4; the effective weight of the 95th-percentile clothed and equipped occupant should be used for the bottomed test (Test No. 2(d) in Table 11). The weight of that portion of the seat that strokes with the load-limited portion of the seat must be added to occupant weight to determine the total required load in the vertical direction.

8.6.1.8 <u>Multiple Seats</u>: Multiple-occupancy seats should be fully occupied when tested. If it is determined that the most adverse loading condition occurs in other than full-occupancy situations, additional tests should be run for those conditions.

8.6.1.9 <u>Substitution of Dynamic For Static Tests</u>: It is recommended that static tests be conducted because of the advantages previously described. In summary, static tests are more economical to run than dynamic tests; because of their slow rate of load application, closer real-time observation of seat response to the loading is possible; and, static testing provides structural response information which is more comparable to the static analyses typically used in the development of present seat designs. In the future, when dynamic analysis becomes more reliable, this latter point will no longer apply. A significant consideration in static-versus-dynamic testing is the cost of the hardware. Static testing can be conducted with a minimum number of seats because the condition of the seat can be monitored and judgments made as to its acceptability for continued testing. If failures due to previous tests occur, parts can be replaced and the test economically rerun.
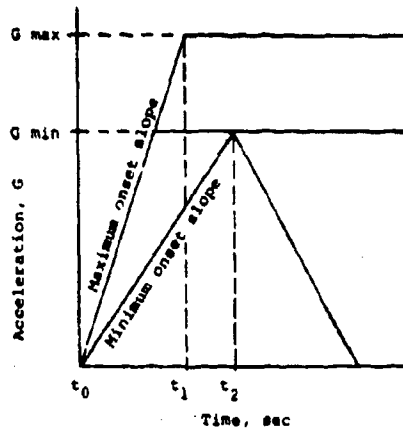
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If final acceptance decisions are based on dynamic tests alone, a considerably more rigorous dynamic test matrix is required to enable testing in all the principal loading directions. Dynamic tests are usually more expensive than static tests and the increased number of tests will also require additional hardware. If new hardware is not used for each test, the results may be inconclusive. If the seat passes the test, the results are acceptable; but if the seat fails the test, another test must be made since it will not be apparent whether the failure was due to damage inflicted during a previous test or due to a basic design or manufacturing flaw.

If for any reason, dynamic tests are substituted for the static tests previously described, then loading in all principal directions must be conducted. The dynamic test requirements are presented in Figure 64. These three tests must be conducted in addition to the two presented in Section 8.6.2, and all five must be passed. These tests are to be conducted in accordance with the same ground rules as those presented in Section 8.6.2 and are subject to the same testing parameters and evaluation procedures. Further, the static upload of 8 G and the static aftward loading of 12 G must be imposed and satisfactorily passed.

8.6.2 Dynamic Test Requirements

8.6.2.1 Dynamic Test Requirements for Seats Having at Least 12-in. of Vertical Stroke: All U. S. Army prototype seats should be dynamically tested to the two conditions specified in Figure 65. These test conditions were determined from the design velocity changes presented in Volume II. Test 1 is required to ensure that the vertical load-limiting provisions will perform satisfactorily under simultaneous forward and lateral loading conditions. Test 2 is required to ensure that the seat can resist the loads produced by the design pulse when applied simultaneously in the forward and lateral directions. A 50th-percentile anthropomorphic dummy complying with the Code of Federal Regulations, Title 49, Part 572 specification for dummies (Reference 90) should be used to simulate the seat-system occupant for Test 1. A 95th-percentile anthropomorphic dummy simulating as closely as possible the features of the 50th-percentile dummy described above should be used to simulate the seat-system occupant for Test 2. Total weight including instruments of these two test dummies should be:

90. U. S. Code of Federal Regulations, Title 49, Chapter 5, Part 572: ANTHROPOMORPHIC TEST DUMMY, Government Printing Office, Washington, D. C., (Rev.) 1978.

Test	Configuration	Parameter	Cockpit seats		Cabin seats	
			Qualification	R&D	Qualification	R&D
1	Dummy inertial load	t_1 sec	0.036	0.020	.050	.028
		t_2 sec	0.051	0.051	.074	.074
		G min	46	46	32	32
		G max	51	51	37	37
		Δv min, ft/sec	42	42	42	42
2a	Utility and observation helicopters Dummy inertial load	t_1 sec	0.062	0.036	.062	.036
		t_2 sec	0.104	0.104	.104	.104
		G min	16	16	16	16
		G max	21	21	21	21
		Δv min, ft/sec	30	30	30	30
2b	Light fixed-wing, cargo and attack helicopters Dummy inertial load	t_1 sec	0.057	0.033	.057	.033
		t_2 sec	0.100	0.100	.100	.100
		G min	14	14	14	14
		G max	19	19	19	19
		Δv min, ft/sec	25	25	25	25
3	Dummy inertial load	t_1 sec	0.066	0.038	.081	.046
		t_2 sec	0.100	0.100	.127	.127
		G min	28	28	22	22
		G max	33	33	27	27
		Δv min, ft/sec	50	50	50	50

Figure 64. Requirements of dynamic tests if substituted for static tests.
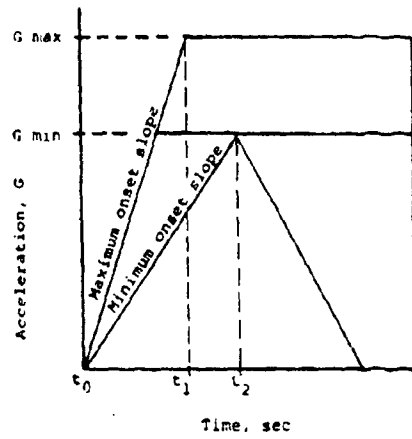
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Test	Configuration	Parameter	Cockpit seats		Cabin seats	
			Qualification	R&D	Qualification	R&D
1	Dummy inertial load, 30°, 10°	t_1 sec	0.043	0.024	0.059	0.034
		t_2 sec	0.061	0.061	0.087	0.087
		G min	46	46	32	32
		G max	51	51	37	37
		Δv min, ft/sec	50	50	50	50
2	30°, Dummy inertial load	t_1 sec	0.066	0.038	0.081	0.046
		t_2 sec	0.100	0.100	0.127	0.127
		G min	28	28	22	22
		G max	33	33	27	27
		Δv min, ft/sec	50	50	50	50

Figure 65.   Dynamic test requirements for qualification
and for research/development testing.

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50th percentile

> Pilot/Copilot = 181.1 lb
> Troop/Gunner = 196.6 lb

95th percentile

> Pilot/Copilot = 222.3 lb
> Troop/Gunner = 242.2 lb

Dynamic testing of multiple occupant seats should be performed with the maximum number of occupants specified for the test seat. Additional tests should be run if it is determined that the most adverse loading condition occurs in other than full-occupancy situations. For both tests of Figure 65, adjustable seats should be adjusted to the full-aft and up position of the adjustment range. Plastic deformation of the seat is permissible; however, structural integrity must be maintained in all tests. For Test 1, the seat should limit the acceleration as measured in the pelvis of the dummy to values which ensure that the 50th-percentile clothed seat-system occupant (see Section 8.2) will not experience vertical, $+G_z$, accelerations in excess of human tolerance as defined in Sections 4.3 and 4.8 of Volume II (see Figure 24 of this volume). The roll direction (10 degrees right or left) for Test 1 should be the more critical loading for the specific seat design.

When determining compliance of the achieved test pulse with the dynamic test requirements of Figure 65 (or Figure 64, as described in Section 8.6.1.9):

1. Determine the maximum acceleration and construct the onset slope for the test pulse by the method explained in Section 8.6.3.

2. Compare the achieved onset and peak acceleration of the test pulse with those allowed and presented in Figure 65. The achieved onset slope should lie between the minimum and maximum onset slopes using the values of t_1 and t_2 listed in Figure 65 for the specific test conditions. The maximum acceleration should also fall between the upper and lower limits allowed.

3. Integrate the actual acceleration/time curve of the test pulse and establish the achieved velocity change. The velocity change achieved should be equal to or greater than that tabulated for the specific test conditions.

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8.6.2.2   Special Dynamic Test Requirements for Seats Having
Less Than 12 in. of Vertical Stroke: In the event that the
application of a systems approach permits the seat to have
less than 12-in. minimum vertical stroke, additional require-
ments are made of the dynamic testing. First, it would be de-
sirable to perform a full-scale crash test with the test speci-
men, including all assemblies involved in the energy-absorbing
process. This would include a section of the fuselage, land-
ing gear, and the seat or seats. This approach is totally ac-
ceptable for demonstrating the dynamic response and acceptabil-
ity of the system.

Since cost associated with the type of system testing described
above is usually prohibitive, a different approach is accept-
able. This approach includes dynamically testing the seat only,
as is done for systems with at least 12 in. of stroke, but mod-
ifying the input pulse to represent the energy-absorbing proc-
esses of the gear and fuselage. An example of such a modified
test pulse is presented in Figure 66. The initial plateau (t_1
to t_0') represents the acceleration-time history created by
stroking of the landing gear. The sharp increase in accelera-
tion at t_0' relates to fuselage impact, and the pulse beyond t_0'
represents the crushing of the stiffer fuselage section. The
velocity change under the pulse should be the same as identi-
fied for the particular crash force direction for other estab-
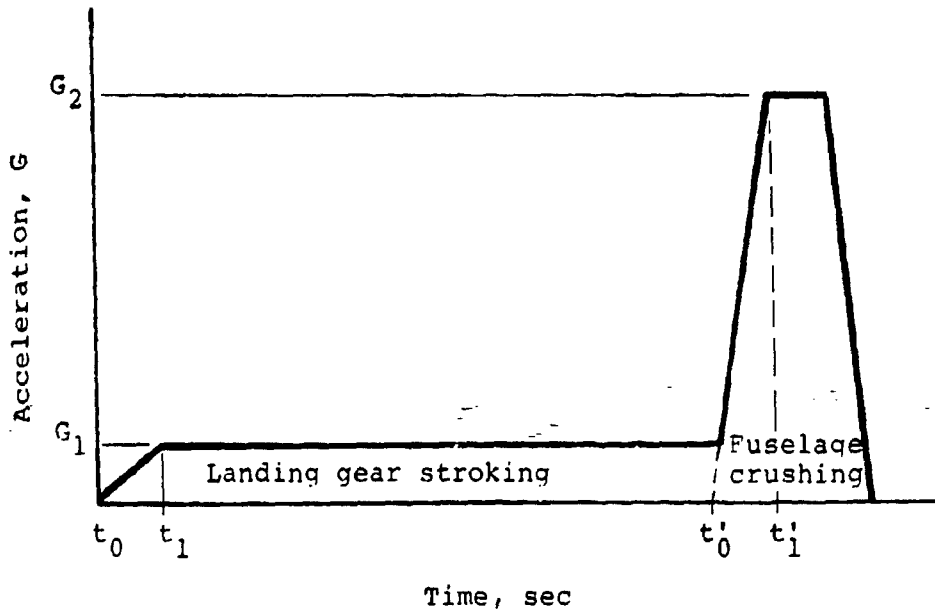lished tests (50 ft/sec for Test No. 1 or No. 2 of Figure 65).

Figure 66.   Example of input pulse for seats
having less than 12 in. of stroke.

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It will be difficult to determine accurate dynamic crush characteristics of the various portions of the system to enable establishment of a representative, and thus acceptable, test pulse. The best analytical techniques, supported by test data, should be used for determining the properties of the fuselage. Since drop tests of landing gear are required, a much more accurate approach exists for obtaining the landing gear influence on the pulse. Seat testing should await completion of landing gear tests so that the results can be used to establish the initial plateau (or other shape) between t_1 and t_0' of the input pulse.

Typically the landing gear will stroke at loads below those required to stroke the seat; therefore, much of the kinetic energy of the occupant and seat will be absorbed prior to fuselage impact. If the systems analysis is accurate, the energy-absorbing capacity of the seat will be sufficient to absorb the residual energy at limit loads tolerable to the occupant.

Since each system may display different characteristics, it is not appropriate to present in this document specific quantitative limits for use in evaluating the acceptability of the test pulse. However, the same general approach and tolerances already presented for the standard pulse apply and should be used. The technique described in Section 8.6.2.1 for establishing compliance with the required test pulse applies directly to the portion of the special test pulse following t_0'.

8.6.3 Data Acquisition and Reduction

Data acquisition and reduction should comply with the requirements of SAE J211 (Reference 91) for measurements of an anthropomorphic dummy, body accelerations, and structures.

Data should be presented in both analog and tabular form in compliance with the sign convention shown in Figure 4. Impact velocity should be determined and recorded for the test platform or vehicle. In the analysis of the data, velocity change should be computed through either electronic means or graphically with a planimeter by integrating the area under the measured acceleration-time trace.

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91. SAE Recommended Practice, SAE J211b, INSTRUMENTATION FOR IMPACT TESTS, SAE Handbook 1979, Part 2, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1979, pp. 34.117-34.118.

The method recommended for use in establishing the acceptabil-
ity of the pulse (see Section 8.6.2) and to determine other
parameters associated with the data is similar to that pre-
sented in MIL-S-9479(USAF); see Reference 92. Parameters such
as rise time, onset slope, and acceleration plateau duration
may be obtained using the following graphic approximation tech-
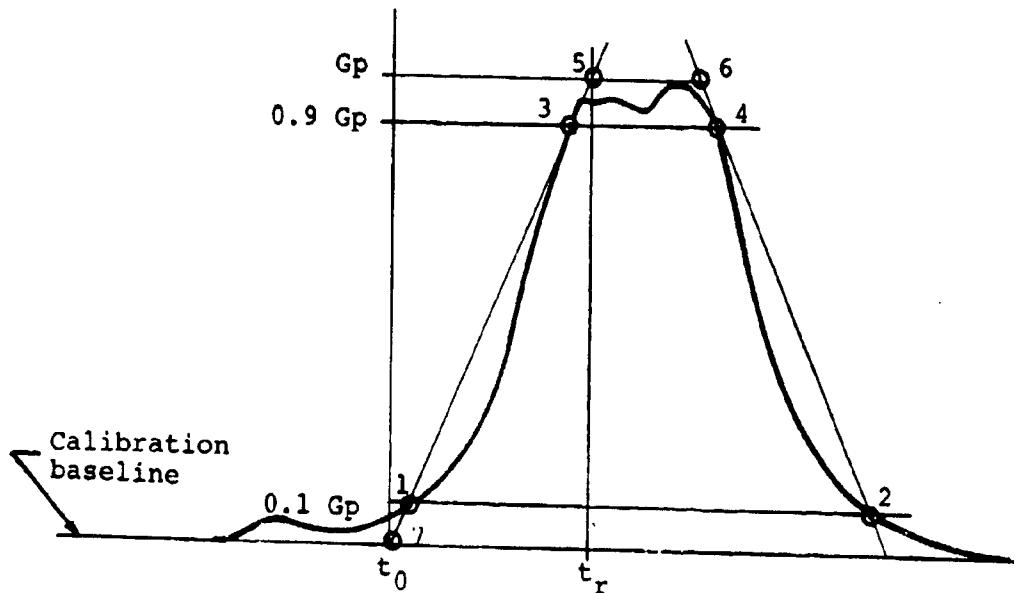nique as shown in Figure 67.

Figure 67. Graphic approximation example.
(From Reference 92)

- Locate the calibration baseline.

- Determine the maximum (G_p) acceleration magnitude.

- Construct a reference line parallel to the calibra-
tion baseline at a magnitude equal to 10 percent of
the peak acceleration (G_p). The first and last in-
tersections of this line with the acceleration-time
plot defines points 1 and 2.

92. Military Specification, MIL-S-9479, SEAT SYSTEM, UPWARD
EJECTION, AIRCRAFT, GENERAL SPECIFICATION FOR, Department
of Defense, Washington, D. C.

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- Construct a second reference line parallel to the calibration baseline at a magnitude equal to 90 percent of the peak acceleration. The first and last intersections of this line with the acceleration-time plot define points 3 and 4.

- Some logic and practical judgment may be required for selection of the first and last intersections depending on the noise, structural or electronic, apparent in the data. Significant tendencies are important, not noise.

- Construct the onset line defined by a straight line through points 1 and 3.

- If desired, construct the offset line defined by a straight line through points 2 and 4.

- If desired, construct a line parallel to the calibration baseline, through the peak acceleration. The time interval defined by the intersections of this line with the constructed onset and offset lines (points 5 and 6) is the plateau duration (Δt).

- Locate the intersection of the constructed onset line with the calibration baseline (point 7). The time interval defined by points 7 and 5 is the rise time (t_R). Referring to Figure 65, the rise time should be greater than t_1 but less than t_2 when determining compliance with dynamic test requirements. Point 7 is the initial time t_0 in Figure 65.

8.6.4 Seat Component Attachment

Since components that break free during a crash can become lethal missiles, it is recommended that attachment strengths be consistent with those specified for ancillary equipment (see Section 6.6.5.9, Volume III). Therefore, static attachment strengths for components, e.g., armored panels, should be as follows:

Downward:	50 G
Upward:	10 G
Forward:	35 G
Aftward:	15 G
Lateral:	25 G

These criteria may be somewhat conservative for load-limited seats; however, load limiting is mandatory in the vertical direction only. In light of the potential hazard, the strength requirements are considered justified.

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9. LITTER STRENGTH AND DEFORMATION REQUIREMENTS

9.1 INTRODUCTION

This chapter presents strength and deformation requirements
for litter systems. Aircraft systems are rather difficult to
design because of limitations including that of the strength
of existing litters and width of utility aircraft as compared
to the length of standard litters. The ultimate vertical
strength of existing litters with a 200-lb occupant and a total
system weight of 250 lb (see Section 9.2) is about 13 G. Since
the desired decelerative loads to be imposed on these litters
exceed 13 G, special techniques must be used to limit the de-
flection and to support some of the occupant load. A new
litter should be developed having the required strength to sup-
port loads in excess of 13 G, preferably 17 G, as presented as
a minimum in this chapter.

The other problem is associated with the length of the litter.
The width of the new Army utility helicopter does not allow
litters to be placed in the preferred lateral direction. The
lateral orientation is preferred because of the characteristics
of existing restraint systems used on litters which provide
more support when loaded laterally than when loaded longitu-
dinally. Since higher loads are more frequently seen in the
forward direction than in the lateral, it would be desirable
to orient the litters laterally in the aircraft. This is not
possible because the helicopter is not wide enough, so special
devices have been developed to permit loading the litters in a
lateral direction and then rotating the litters into a fore-
and-aft orientation inside the aircraft. Improved litter re-
straint systems are required to provide the desired support to
the supine occupant on litters oriented in the fore-and-aft di-
rection in these aircraft.

This chapter presents the design strength-deformation relation-
ships and testing requirements for aircraft litters and their
supports.

9.2 RECOMMENDED OCCUPANT WEIGHTS FOR LITTER DESIGN

The litter strength and deformation requirements defined below
are based on a 200-lb, 95th-percentile litter occupant with
20 lb of clothing and personal gear, a 10-lb splint or cast,
and 20 lb of litter and support bracket weight for a total
weight of 250 lb (the weight of a litter and patient as speci-
fied in MIL-A-8865 (ASG), Reference 93).

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93. Military Specification, MIL-A-8865, AIRPLANE STRENGTH AND
RIGIDITY MISCELLANEOUS LOADS, Department of Defense, Wash-
ington, D. C.

9.3 VERTICAL LOADS

9.3.1 Downward Loads

In the case of litter systems, human to‚erance is not the limiting case in the vertical direction. The loads would be applied in a transverse direction to the body of a litter occupant. However, design to the 45-G human tolerance level is impractical due to the strength requirements for litters and for the basic structure to support the litter systems.

Litters are either hung from the ceiling or supported at the floor. In either case, the input deceleration pulses are the same as for floor- or bulkhead-mounted seats (see Volume II). The use of ceiling-supported litters is limited by the strength of the overhead fuselage structure. The inefficiency of structural deformation of the ceiling of older aircraft requires additional energy-absorbing stroke to provide the protection desired. Litters should not be suspended from the overhead structure unless it is capable of sustaining, with minimum deformation, the downward loads from the tiers of litters. Therefore, in the design cf an efficient system, intentional load limiting should be related to the floor pulse.

The vertical strength and deformation requirements for a litter system are detailed in Figure 68. This curve is read in the identical manner as the seat load-deflection curve shown in Figure 59. The load factors in units of G are based on the summation of the weights of the occupant plus clothing, personal gear, splint or cast, and the weight of the litter and attachment brackets for a total of 250 lb as described in Section 9.2. The curve of Figure 68 is based on the assumption that 3 or 4 in. of vertical deflection will occur at the midpoint of the litter. In the unlikely event that a rigid litter is used, an additional 2 in. of deflection should be added to the curve. The deflection curve is limited to 6 in., because a larger deflection occurring on one corner of the litter due to an asymmetric loading could cause ejection of the litter occupant. A larger energy-absorbing stroke can be used effectively if a mechanism is included in the system to control the amount of tilt allowed. For example, a system mechanism could be designed that forced all four corners of the litter to stroke the same distance (within elastic limits) thus achieving this goal.

The additional problem associated with inadequate litter strength must be dealt with in the design of litter systems. The curve of Figure 68 assumes a litter capable of at least 17 G with a maximum of 25 G. If the existing litter is used, then a pan, net, or other device should be included under the
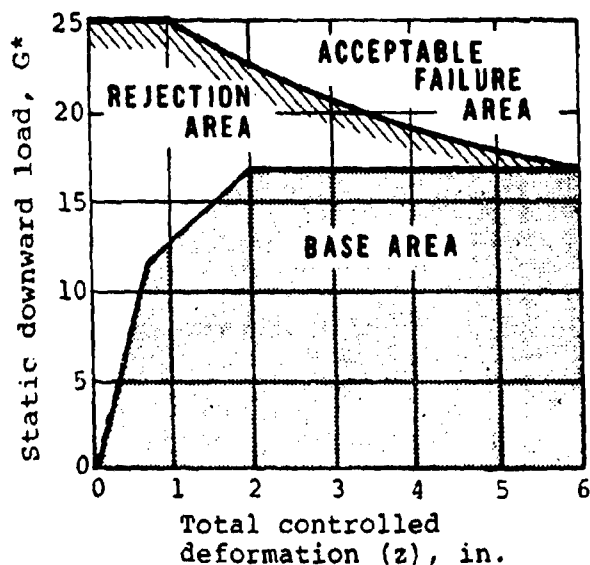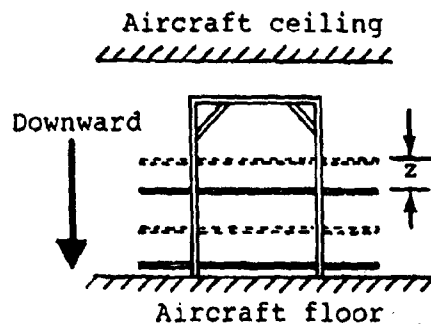
*G value based on 250-lb per litter
position.

Figure 68.   Litter downward load and
deflection requirements.

litter to catch and support the litter occupant if the litter
fails.   Actually the device should limit the deflection to a
value less than required to fail the litter and should stroke
with the litter.   If all of these provisions are included, i.e.,
a rigid new litter or old litter with supporting pan under-
neath, together with the tilt-limiting mechanism, then the
stroke can be extended to 12 in. at a 17-G limit-load factor.
The load-deformation curve of Figure 68 would be extended at
17 G to 12 in. of stroke.

Further background information on analysis and testing of helicopter litter systems can be found in Reference 22.

9.3.2 Upward Loads

All litter systems should be capable of withstanding a minimum upward load of 8 G.

9.4 LATERAL AND LONGITUDINAL LOADS

Litter systems for all aircraft should be designed to withstand the load and deformation requirements indicated in Figure 69 in all radials of the lateral/longitudinal plane. The litter lateral loads are made equal to the longitudinal loads because the litters may be oriented in either direction depending upon the aircraft.
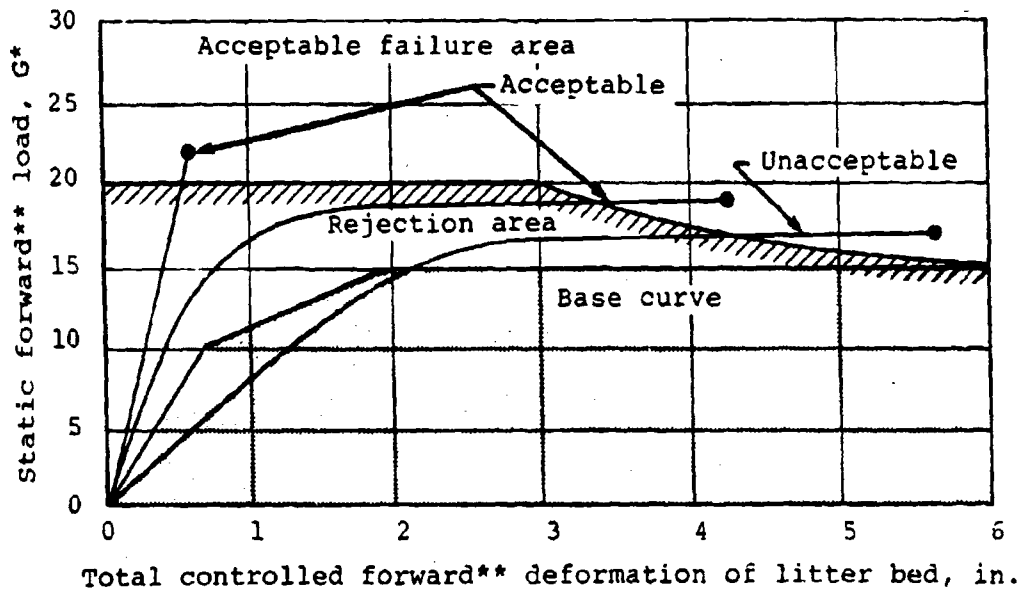
*G value based on 250-lb per litter position.

**Forward is the direction towards the nose of the aircraft regardless of litter orientation in the aircraft.

Figure 69. Litter forward or lateral load and deflection requirements for all types of Army aircraft.

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The 20-G acceptable load level indicated in Figure 69 is predicated on the tolerance to acceleration of an individual restrained by straps on existing "table top" litters. If litters and allied restraint harnesses are designed for improved crashworthiness, the 20-G load should be increased to 25 G.

Acceptable or nonacceptable load-deformation characteristics are read from Figure 69 in the identical manner as the readings from Figures 59 and 60 for seats. The deformation is measured with respect to the aircraft floor along the longitudinal axis toward the nose of the aircraft, regardless of litter orientation.

9.5 LITTER RESTRAINT HARNESS TESTING

The restraint used in existing military litters consists of two straps wrapped around the litter. These straps should withstand a straight tensile minimum load of 2000 lb (4000-lb loop strength). The maximum elongation should not be more than 3.0 in. under the straight pull (end-to-end) test on a minimum strap length of 48 in. Elongation is restricted for litter belts in order to minimize dynamic overshoot.

9.6 LITTER SYSTEM TEST REQUIREMENTS

9.6.1 Static Test Requirements

9.6.1.1 **General:** Table 12 presents the static test requirements for complete litter systems. Since previous studies have shown that existing litters will not withstand the loads as specified in this chapter, the assumption must be made that a litter of sufficient strength will be developed prior to implementing these recommendations. The tests required include a series of unidirectional tests to determine basic litter and attachment strengths in the major axes. Also, a combined loading test is required to evaluate the litter system performance under static conditions simulating a severe crash loading situation with loading components in multiple directions. Since the litter orientation can be either lateral or longitudinal, a single requirement is made for transverse loading in the horizontal plane (Test 5).

9.6.1.2 **Unidirectional Tests:** The test loads for forward, lateral, and downward loading of litter systems as presented in Table 12 should be applied separately.

9.6.1.3 **Combined Loads:** Litter systems must demonstrate no loss of system integrity under conditions of combined loads as specified in Table 12.

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TABLE 12. LITTER SYSTEM STATIC TEST REQUIREMENTS

Test ref. no.	Loading direction with respect to fuselage floor	Load required	Deformation requirements
1	Forward	See Figure 69	See Figure 69
2	Lateral	See Figure 69	See Figure 69
3	Downward	See Figure 68	See Figure 68
4	Upward	8 G	No requirement
5	Combined loading		
	Downward plus transverse load along any radial in the x, y plane of the aircraft	See Figure 68 See Figure 69	See Figure 68 See Figure 69

9.6.1.4 Point of Load Application: The loads should be applied through a body block that simulates a supine occupant.

9.6.1.4.1 Forward (Longitudinal) - Lateral Tests: For systems using the existing litter, a rigid simulated litter may be substituted for the actual litter. This will enable application of equal loads at all attachment points between the litter and the suspension system and allow testing of the suspension system. The rigid litter substitution does not apply if the litter has adequate strength to take the loads.

9.6.1.4.2 Downward and Upward Tests: Downward and upward loads may be applied to each vertical suspension point separately. If the suspension system has the tilt-limiting features, and the litter is adequate, then the load should be applied at the center of gravity of the body block.

9.6.1.5 Deflection Measurements: Downward, forward (longitudinal), and lateral deflections should be measured at the bracket attaching the litter to the suspension system.

9.6.1.6 Load Determination: The test load should be determined by multiplying the required load factor (G) as specified in Table 12 by 250 lb.

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9.6.2 Litter System Dynamic Test Requirements

A single test to evaluate the vertical load-limiting system is required. Litter systems with 95th-percentile anthropomorphic dummies and 30 lb (250-lb total) of additional weight in each litter should be subjected to a triangular acceleration pulse of 48-G peak and 0.054-sec duration (42-ft/sec velocity change).

The same test pulse tolerances, data, handling, and processing requirements as presented for the seats in Section 8.5 apply. At least three accelerometers should be placed in the dummy; one in the head, one in the chest, and one in the pelvic region. The instruments should be positioned to sense accelerations in the vertical directions (x axis of the supine occupant, z direction relative to the aircraft). The input acceleration-time pulse also should be measured. It is advisable to use redundant accelerometers to sense the input pulse to assure acquisition of the needed impact environment data.

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10. DELETHALIZATION OF COCKPIT AND CABIN INTERIORS

10.1 INTRODUCTION

The kinematics of body action associated with aircraft crash impacts are quite violent, even in accidents of moderate severity. The flailing of body parts is much more pronounced when the aircraft occupant is restrained in a seat with only a lap belt. However, even with a lap belt and a shoulder harness that are drawn up tightly, multidirectional flailing of the head, arms, and legs, and to a lesser extent, the lateral displacement of the upper torso within its restraint harnessing, is extensive. If it were possible to provide adequate space within the occupant's immediate environment, this flailing action of a fully restrained occupant would not be a particular problem. Since space for occupants is usually at a premium in aircraft, especially in cockpit areas, it is not feasible to remove structural parts of the aircraft sufficiently to keep the occupant from striking them. The only alternative is to design the occupant's immediate environment so that, when the body parts do flail and contact rigid and semi-rigid structures, injury potential is minimized.

An occupant who is even momentarily debilitated by having his head strike a sharp, unyielding structural object or by a leg injury can easily be prevented from rapidly evacuating the aircraft and may not survive a postcrash fire or a water landing. The importance of occupant environment designed for injury prevention, therefore, should be emphasized if optimum crash protection is to be ensured.

Several approaches are available to alleviate potential secondary impact problems. The most direct approach, which should be taken if practical, is to relocate the hazardous structure or object out of the occupant's reach. Such action is normally subject to tradeoffs between safety and operational or human engineering considerations. If relocation is not a viable alternative, the hazard might be reduced by mounting the offending structure on frangible or energy-absorbing supports and applying a padding material to distribute the contact force over a larger area.

10.2 OCCUPANT STRIKE ENVELOPES

10.2.1 Full Restraint

Body extremity strike envelopes are presented in Figures 70 through 72 for a 95th-percentile Army aviator wearing a restraint system that meets the requirements of MIL-S-58095(AV) (Reference 14). The restraint system consists of a lap belt,

10 in.

Heel rest line for cockpit.
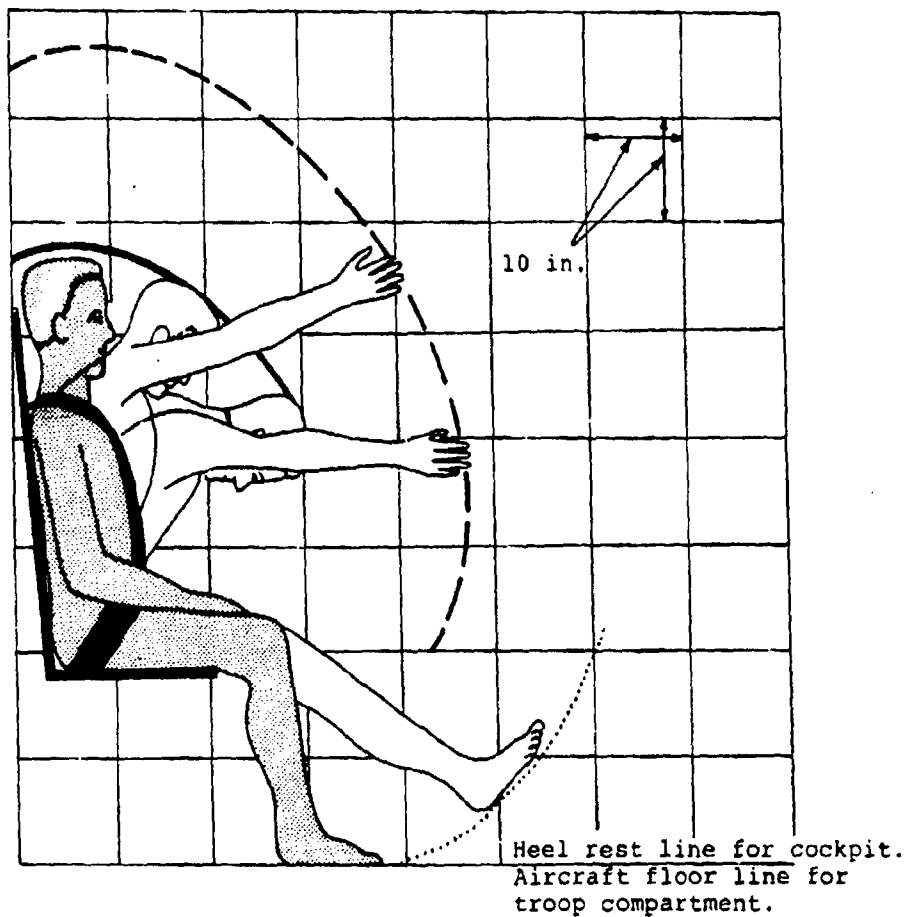Aircraft floor line for
troop compartment.

Figure 70.   Full-restraint extremity strike
envelope - side view.

lap belt tiedown strap, and two shoulder straps. The forward
motion shown in Figures 70 and 71 was obtained from a test
utilizing a 95th-percentile anthropomorphic dummy subjected to
a spineward (-G$_x$) acceleration of 30 G. The lateral motion is
based on an extrapolation of data from the same 30-G test. In
positions where an occupant is expected to wear a helmet, the
helmet dimensions must be added to the envelope of head motion.

10 in.
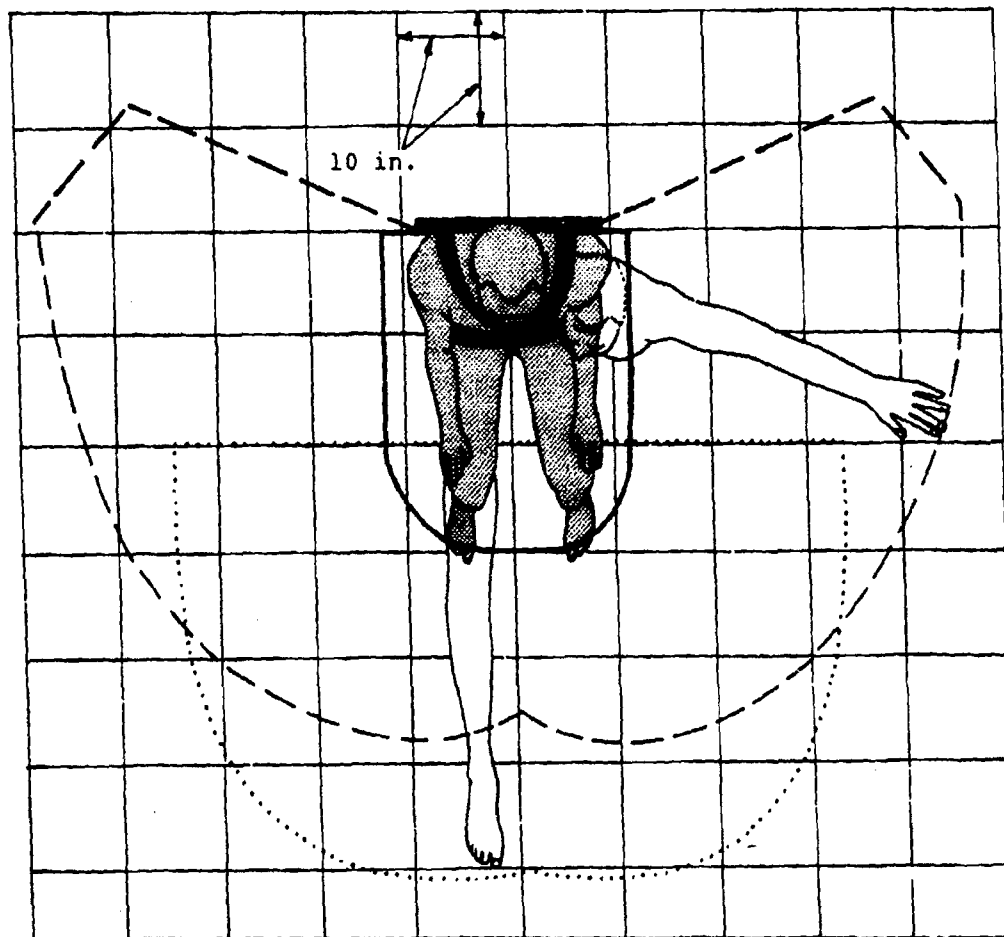
Figure 71. Full-restraint extremity strike
envelope - top view.

10.2.2 Lap Belt-Only Restraint

Although upper torso restraint is required in new Army air-
craft, strike envelopes for a 95th-percentile aviator wearing
lap belt-only restraint are presented in Figures 73 through 75
for possible use. They are based on 4-G accelerations and
4 in. of torso movement away from the seat laterally and for-
ward. In positions where an occupant is expected to wear a hel-
met, the helmet dimensions must be added to the envelope of
head motion.

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10 in

Heel rest line for cockpit.
Aircraft floor line for
troop compartment.
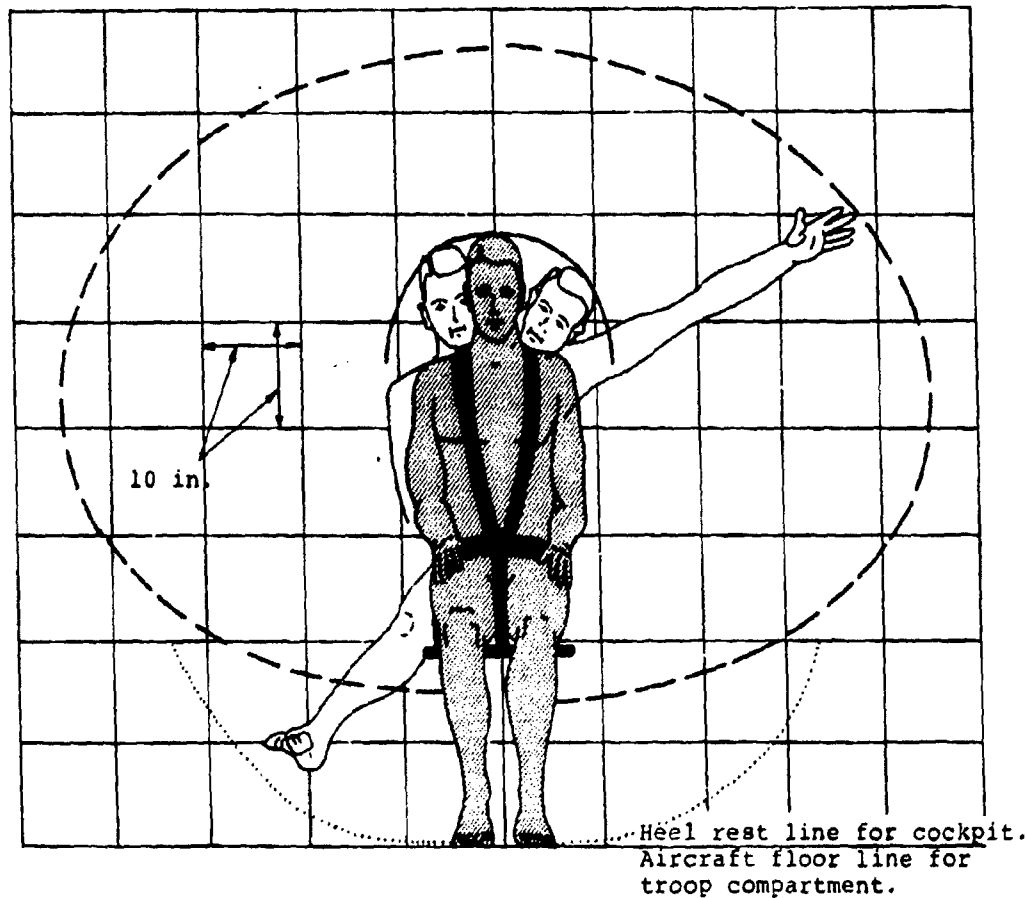
Figure 72.   Full-restraint extremity strike
envelope - front view.

10.2.3 Seat Orientation

The strike envelopes of Figures 70 through 75 apply to all seat
orientations.

10.3 ENVIRONMENTAL HAZARDS

10.3.1 Primary Hazards

The primary environmental hazards are those rigid or semirigid
structural members within the extremity envelope of the head
and chest. It can be seen in Figures 70 through 75 that the
strike envelopes allow considerable upper torso movement for
various seating and restraint configurations. Since the upper

10 in.

Heel rest line for cockpit.
Aircraft floor line for
troop compartment.
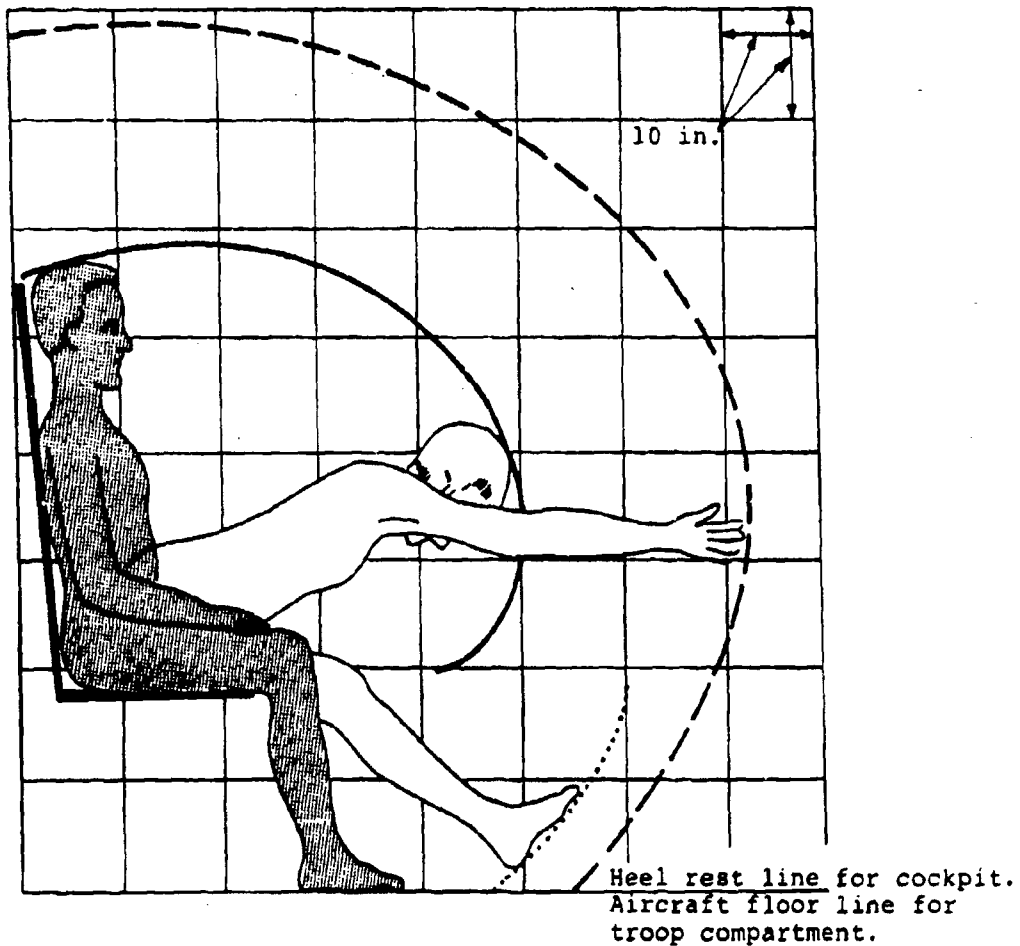
Figure 73.   Lap belt-only extremity strike
envelope - side view.

torso, and particularly the head, is the most vulnerable part
of the body, maximum protection must be provided within its
strike envelope.

10.3.2   Secondary Hazards

Secondary environmental hazards are those that could result in
trapping or injuring the lower extremities to the extent that
one's ability to rapidly escape would be compromised.   The
movement of unrestrained lower extremities in a crash impact is
not significantly influenced by method of body restraint.   Con-
sequently, even with an optimized body restraint system, those
areas within the lower extremity strike envelope must include
ample protective design.
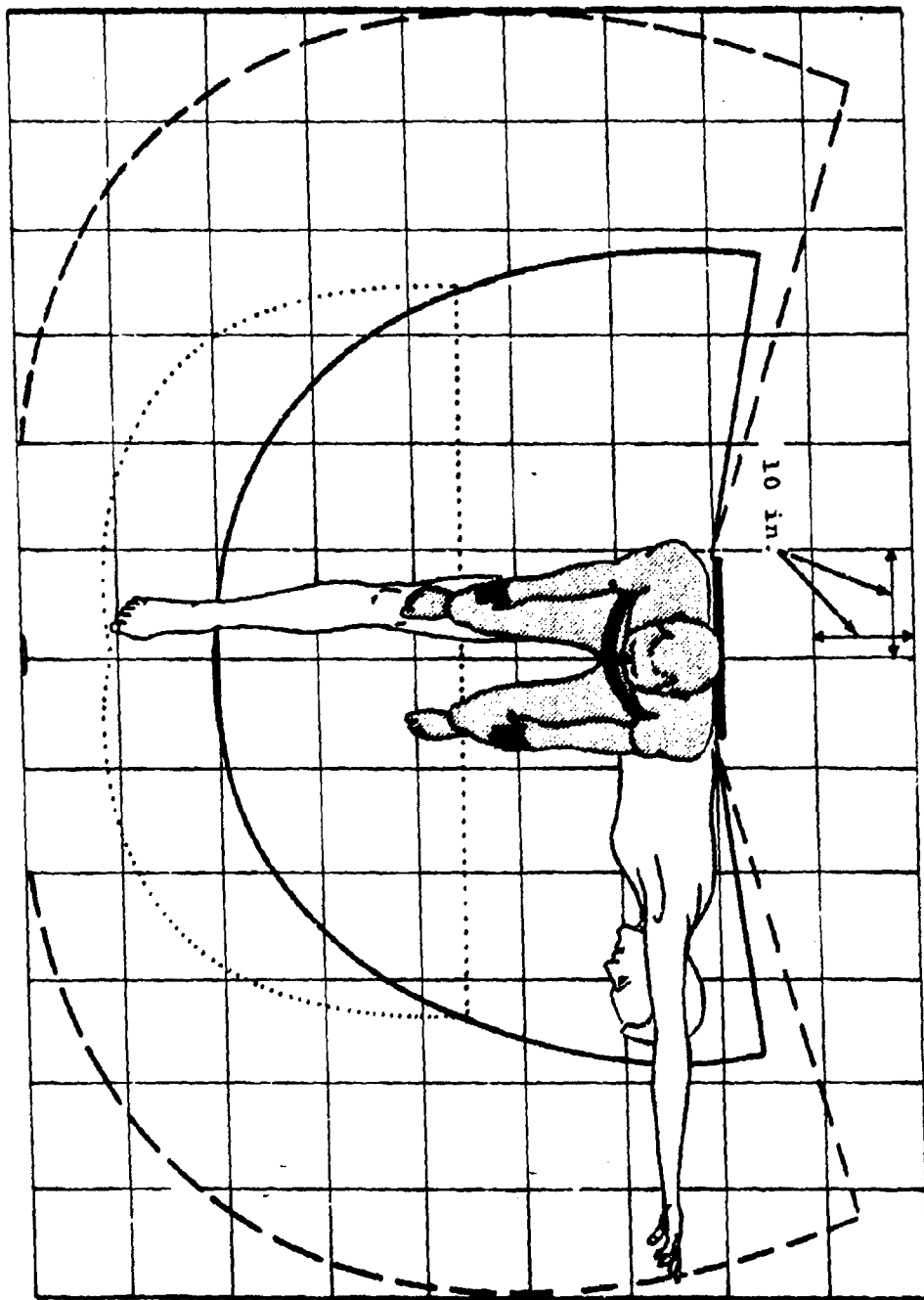
Figure 74. Lap belt-only extremity strike envelope - top view.

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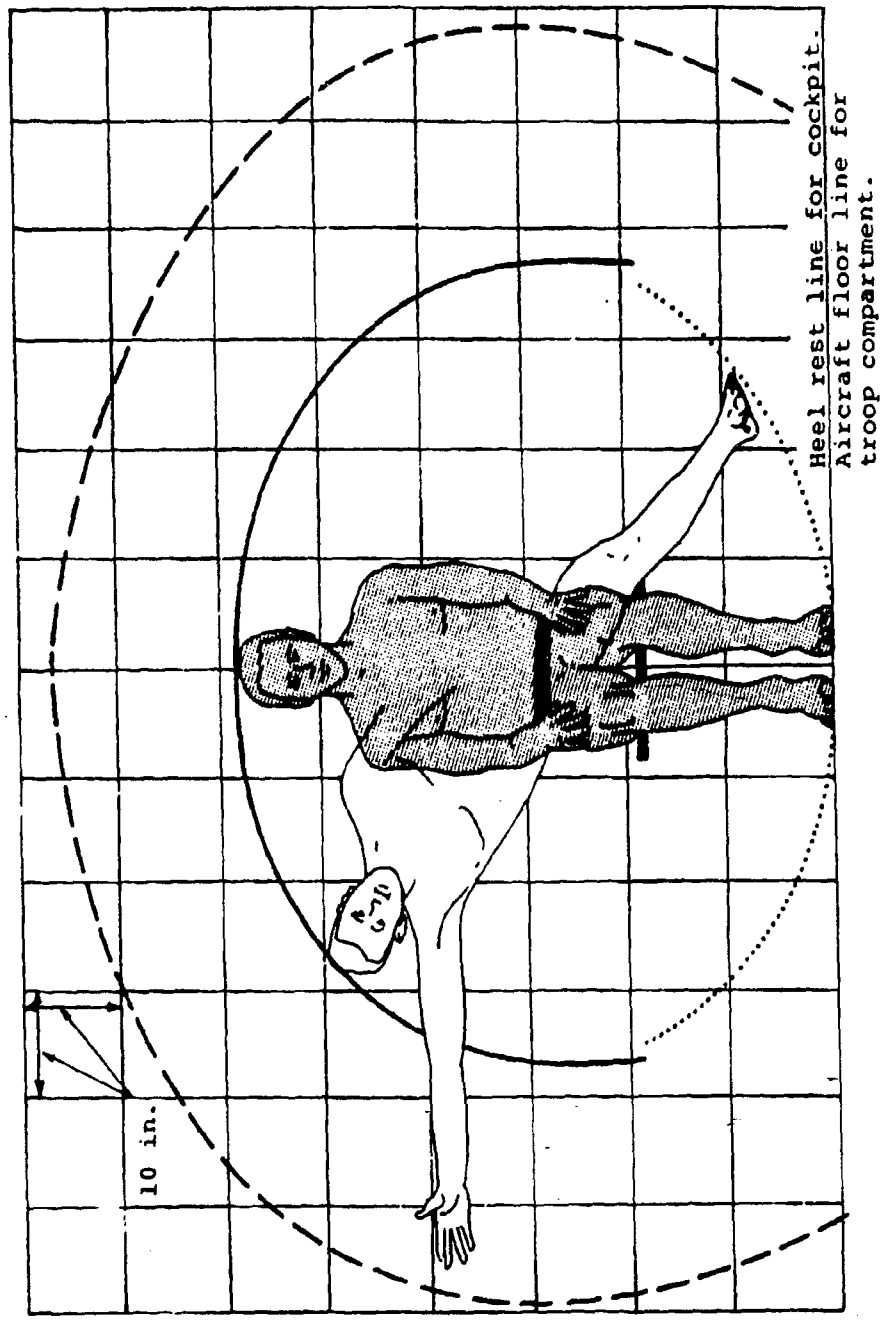
Figure 75. Lap belt-only extremity strike envelope - front view.

Heel rest line for cockpit.
Aircraft floor line for troop compartment.

10 in.

10.3.3 Tertiary Hazards

Tertiary environmental hazards are those rigid and semirigid structural members that could cause injury to flailing upper limbs to an extent that could reduce an occupant's ability to operate escape hatches or perform other essential tasks.

10.4 HEAD IMPACT HAZARDS

10.4.1 Geometry of Probable Head Impact Surfaces

Aircraft in the U. S. Army inventory in 1965 were examined to determine the kinds of contact hazards most commonly found (Reference 94). Typical hazards in the cockpit area included window and door frames, consoles, control columns, seat backs, electrical junction boxes, and instrument panels. Reference 94 presents further details of these impact hazards and a statistical analysis of head injuries in both civilian and military aircraft accidents. Contact hazards commonly found in aircraft cabin areas include window and door frames, seats, and fuselage structure. Use of suitable energy-absorbing padding materials, frangible breakaway panels, smooth contoured surfaces, or ductile materials in the typical hazard areas mentioned will reduce the injury potential of occupied areas.

10.4.2 Tolerance to Head Impacts

Protection of the head in the form of protective helmets and energy-absorbing structure and padding in the occupant's immediate environment is considered to be essential since, under certain circumstances, even the forces incurred in minor crash impacts could cause unacceptably high head impact velocities.

Tolerance levels for head impact are discussed in detail in Volume II, and the reader should refer there for an understanding of the problem. However, for the case of forehead impact on a flat surface, which is pertinent to the discussion of this section, the most widely accepted collection of tolerance data is represented in the tolerance curve of Figure 76. These data, resulting from impact tests conducted on animals and human cadavers at Wayne State University, demonstrate the contribution of both acceleration and pulse duration to the tolerance criterion.

94. Haley, J. L., Jr., et al., HELMET DESIGN CRITERIA FOR IMPROVED CRASH SURVIVAL, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc.; USAAVLABS Technical Report 65-44, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, January 1966, AD 628678.
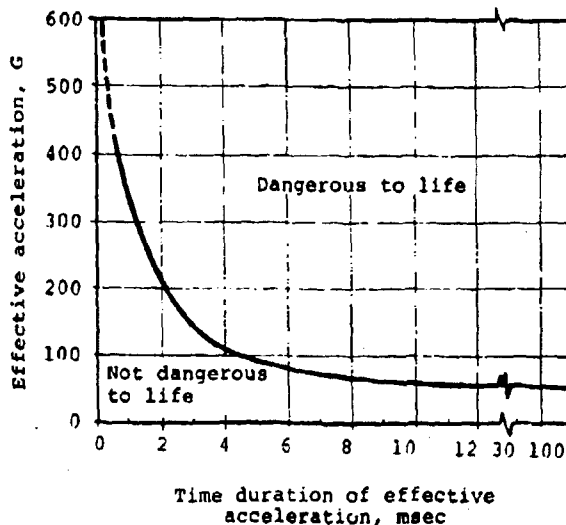
Figure 76. Wayne State Tolerance Curve for the human brain in forehead impacts against plane, unyielding surfaces. (From Reference 95)

10.4.3 Test Procedures

The simplest test procedure for evaluating the effectiveness of protective structure and padding in preventing serious head injury makes use of an instrumented headform. The headform, equipped with an accelerometer, can be propelled by a ram, dropped, or swung on a pendulum to impact the surface to be evaluated. The recommended procedure is described in SAE J921 (Reference 96). The measured acceleration pulse can be averaged for comparison with the Wayne State Tolerance Curve, or integrated to compute a Severity Index, as discussed in Section 4.4.1 of Volume II.

Figure 77 shows typical head velocities relative to the seat as measured on anthropomorphic dummies, cadavers, and live human subjects in dynamic seat tests. Various combinations

95. Patrick, L. M., Lissner, H. R., and Gurdjian, E. S., SURVIVAL BY DESIGN - HEAD PROTECTION, Proceedings, Seventh Stapp Car Crash Conference, Society of Automotive Engineers, Inc., New York, 1963.

96. SAE Recommended Practice, SAE J921b, MOTOR VEHICLE INSTRUMENT PANEL LABORATORY IMPACT TEST PROCEDURE - HEAD AREA, SAE Handbook, 1979, Part 2, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1979, pp. 34.133-34.134.
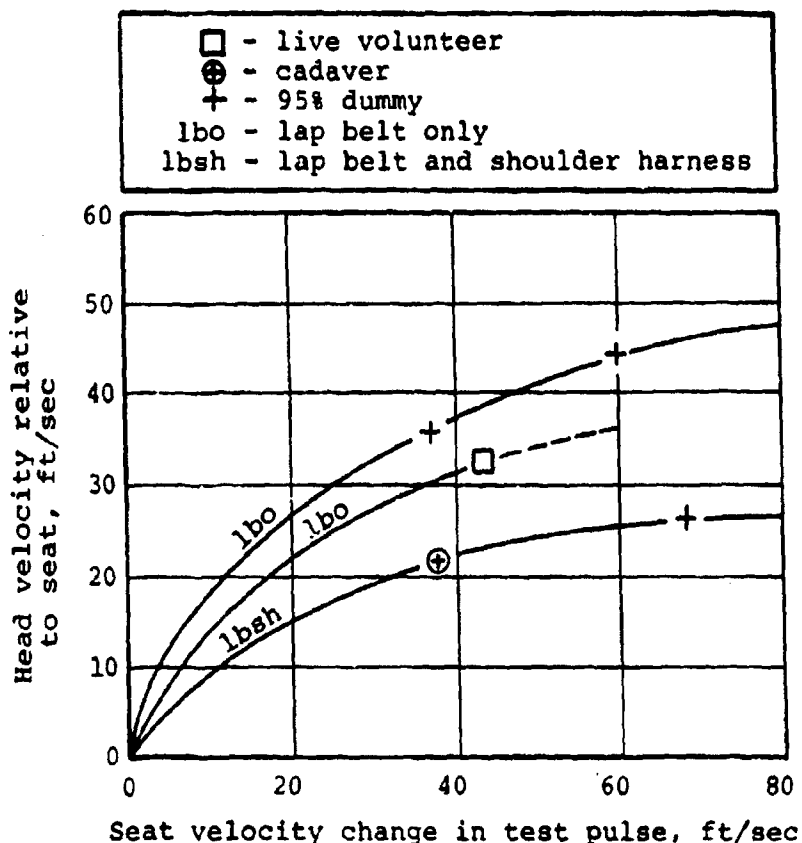
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Figure 77. Measured head velocities in sled tests with
anthropomorphic dummies and cadavers.

of occupant restraint were used and are so indicated on each
curve.

10.5 INSTRUMENT PANEL STRUCTURE PROXIMITY

Most aircraft cockpits are, of necessity, very compact. It is
necessary, for instance, for a pilot to be able to reach var-
ious controls on the instrument panel by leaning forward no
more than 18 in. (the extent of unlocked inertia reel exten-
sion). Consequently, instrument panels must be close enough
to be reached and seen easily. Unfortunately, this usually
requires that the instrument panel and its supporting struc-
ture be placed directly above the pilot's lower legs as they
rest normally on the rudder pedals. When a seated pilot is
exposed to $-G_x$ (eyeballs-out) accelerations in a crash, the

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lower limbs are abruptly extended longitudinally with some up-
ward velocity. In this process, the lower leg usually impacts
on the lower edge of the instrument panel. Depending on the
particular aircraft configuration, this contact can take place
from the kneecap down to the ankle. In view of the high ve-
locities associated with such flailing, disabling lower leg
injuries are common in accidents where high $-G_x$ forces are
present. It is essential that designers consider using suit-
able energy-absorbing padding materials, frangible breakaway
panels, or ductile panel materials for structure within the
lower leg strike envelope.

10.6 RUDDER PEDAL CONFIGURATION

In certain types of aircraft accidents, the pilot's feet remain
on the rudder pedals instead of flailing upward and outward.
If the rudder pedal is a simple, bar type of arrangement, the
heel may be forced under the pedal. When the body is exposed
to a combination of vertical (G_z eyeballs-down) and longitu-
dinal ($-G_x$ eyeballs-out) forces, pelvic rotation around the
lap belt will almost invariably occur unless a lap belt tie-
down strap is used. This pelvic rotation, which forces the
feet hard against the rudder pedals, can occur even though the
lap belt is drawn up tightly. A loose or slack lap belt aggra-
vates the tendency toward pelvic rotation. If the forces are
great enough, a badly injured or trapped foot can result.
Therefore, it is desirable to design the rudder pedals and sur-
rounding structure to prevent this from occurring. This is
usually done by providing a pedal capable of supporting both
the ball of the foot and the heel, and by providing a surround-
ing structure of sufficient strength to prevent crushing and
trapping of the lower limbs. The geometry required by MIL-STD-
1290(AV) (Reference 1) to prevent entrapment of feet is illus-
trated in Figure 78.

10.7 CONTROL COLUMNS

Control columns located in front of flight crew stations can
present a serious hazard to crewmembers if they fail at any
appreciable distance above the aircraft floor. Such a failure
often leaves a torn, jagged stump that can inflict serious in-
jury to a crewman should he be thrown against it during impact,
move into it as an energy-absorbing seat strokes, or come in
contact with it during egress after impact. It is recommended
that control columns be designed so that fracture due to the
occupant's striking the column will occur at a point no more
than 4 in. above the pivot point. The failure should occur in
the form of a clean break, leaving no jagged or torn edges.
Control columns that pass longitudinally through the instrument
panel are not recommended since these tend to impale the crew-
members in severe longitudinal impacts.
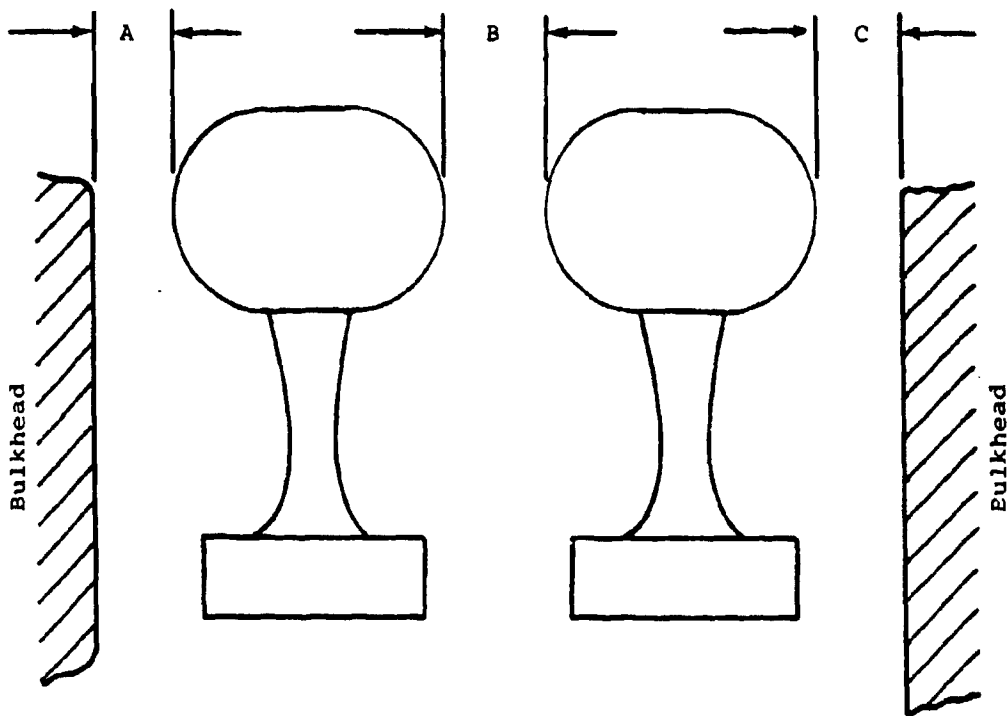
Dimensions A, B, and C must be either
less than 2 in. or more than 6 in.

Figure 78.   Antitorque, or rudder, pedal geometry
to prevent entrapment of feet.

10.8   SIGHTING AND VISIONIC SYSTEMS

Delethalization of the copilot/gunner (CPG) station of an at-
tack or scout helicopter equipped with a weapon sighting opti-
cal relay tube (ORT) can present a difficult design problem.
The copilot/gunner crewstation activities demand that the CPG
will be either in contact with the ORT eyepiece during hazard-
ous nap-of-the-earth (NOE) flight or close to the eyepiece when
sitting in the full upright, erect position.   Operational loca-
tion of the CPG head, when not looking in the ORT, may be as
little as 8.5 in. from the eyepiece.   Therefore, it can be ex-
pected that the CPG, when restrained by a MIL-S-58095(AV) re-
straint system, will contact the ORT eyepiece under nearly all
impacts over 4 G (see Figure 79).   Any deformation of the bulk-
head which would cause the ORT to move rearward will only fur-
ther ensure head contact.   Forward motion of the upper torso
after head contact with the ORT could cause spinal injury.

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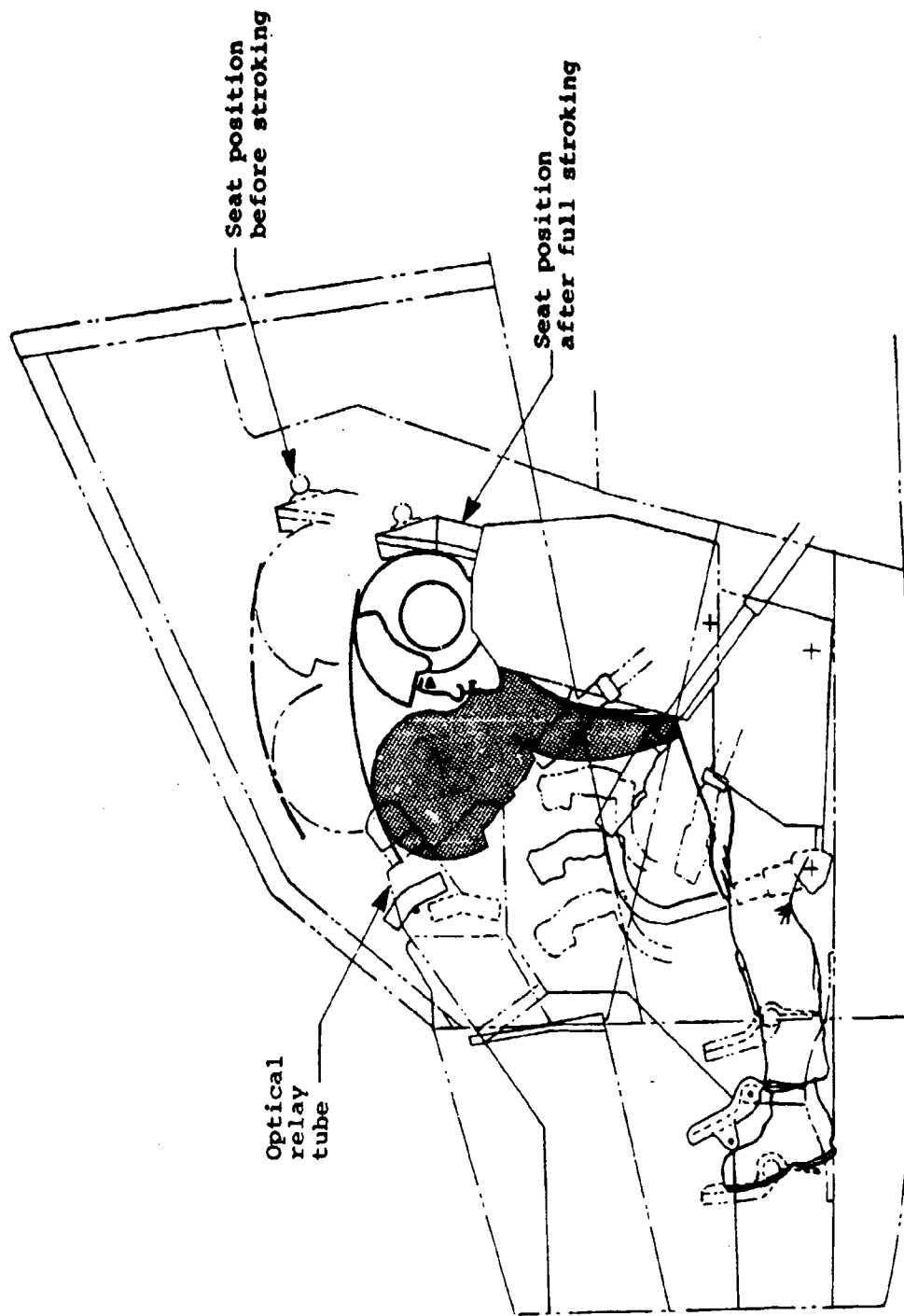
Figure 79. Pilot/gunner station occupant strike in-board profile 4-G impact.

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Under NOE conditions with the CPG looking through the ORT, it can be expected that no warning of impending impact will occur. Regardless, any courses of action taken by the CPG to hold himself erect will probably not help in keeping his head from striking the ORT due to head flailing and body stretch. Another factor that further decreases the distance between the head and the ORT eyepiece is the travel of the seat as it strokes under crash loads.

Possible ORT hazards to the lower extremities and the torso consist of the sharp unyielding lower structure of the ORT. In addition, the rudder pedals may be located adjacent to the ORT. During a crash, the potential displacement of the ORT may cause the CPG's legs to become entrapped. A summary of typical ORT crash hazards is presented in Table 13.

TABLE 13. POTENTIAL OPTICAL RELAY
TUBE CRASH HAZARDS

Hazard	Location of injury	Type of Injury	Cause
1	Head	Laceration, Fracture, Concussion	Head strikes ORT due to flailing forward and downward on impact
2	Head/Chest	Crushing, Avulsion, Fracture	Head/chest strikes ORT due to ORT displacing rearward
3	Head/Chest	Laceration, Crushing, Fracture	CPG seat displaces downward and forward during energy-absorbing stroke. Contact of the head/chest with sharp edges of franged ORT.
4	Arm	Laceration, Fracture	CPG arms flail forward on longitudinal impact
5	Lower torso	Avulsion, Laceration, Crushing, Fracture	ORT displaces rearward on longitudinal impact
6	Leg	Laceration, Fracture	CPG leg flails forward on longitudinal impact
7	Leg	Crushing	CPG leg trapped between aircraft structure and displacing ORT

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The cockpit should be designed to minimize the probability of the CPG head/neck striking the ORT and minimize injury if the CPG should strike the ORT, for both the "head-up" and "head-down" CPG positions. Some of the options available to the designer given this task are:

- <u>ORT Eyepiece Relocation</u> – Consideration should be given to reducing occupant strike hazards by moving the ORT further away from the CPG.

- <u>Restraint System</u> – The restraint system of Figure 44 would offer improved upper torso restraint, particularly when combined with the power-haulback inertia reel.

- <u>Inflatable Restraint</u> – Consideration should be given to an inflatable restraint system (see Section 7.2.4). This type of restraint harness can prevent injury to the CPG in both the erect and head-down position by reducing slack and increasing the surface area of the body over which the harness reacts.

- <u>Frangible/Breakaway Features</u> – ORT or ORT components designed to be frangible should break away at a total force not to exceed 500 lb. For the frangible ORT, this force should be applied along any direction of loading within the plane normal to the axis of the ORT, as well as along the axis of the ORT. Breakaway point(s) of the ORT should be outside the head strike envelope.

- <u>Collapsible Features</u> – If the ORT is designed to collapse in order to avoid injuring the CPG, the collapse load along the axis of the ORT should not exceed 500 lb. Figure 80 illustrates one crushable sight eyepiece concept (from Reference 97). Two advantages of the crushable sight eyepiece are that it is always available and, it should function regardless of head location. A helmet crash-absorber pad would attenuate crash loads to the helmet when available crushing is expended.

- <u>Power-Haulback Inertia Reel (PHBIR)</u> – On the basis of Air Force testing accomplished for the development of PHBIRs, the retraction time is 0.3 to

97. Fox, R., Kawa, M., and Sharp, E., DESIGNING CRASHWORTHINESS INTO THE YAH-63, paper presented at the Aircraft Crashworthiness Symposium, University of Cincinnati, Cincinnati, Ohio, October 1975.
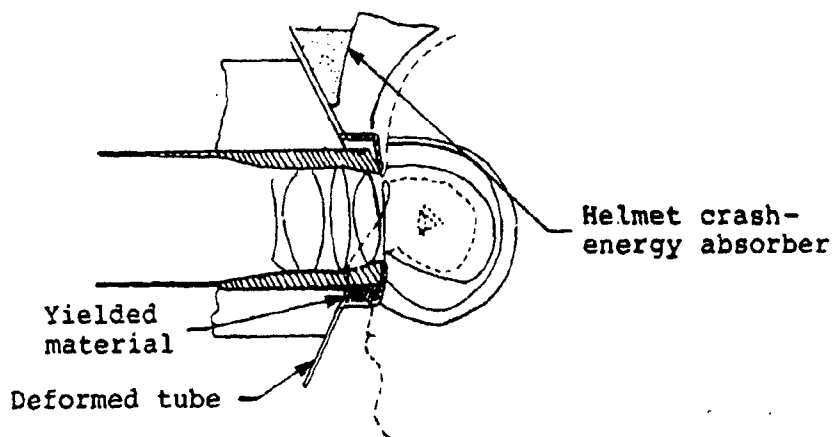
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Normal operation

Helmet crash-energy absorber

Crash energy-absorbing material

SPH-4 helmet reference

Pressure support area approximately 6 in.^{2}

Preloaded slip rings

Optical relay tube

Crush stroke

Inner contours of face mask

Outer contour face mask

20-MM eye relief

After crash stroke

Helmet crash-energy absorber

Yielded material
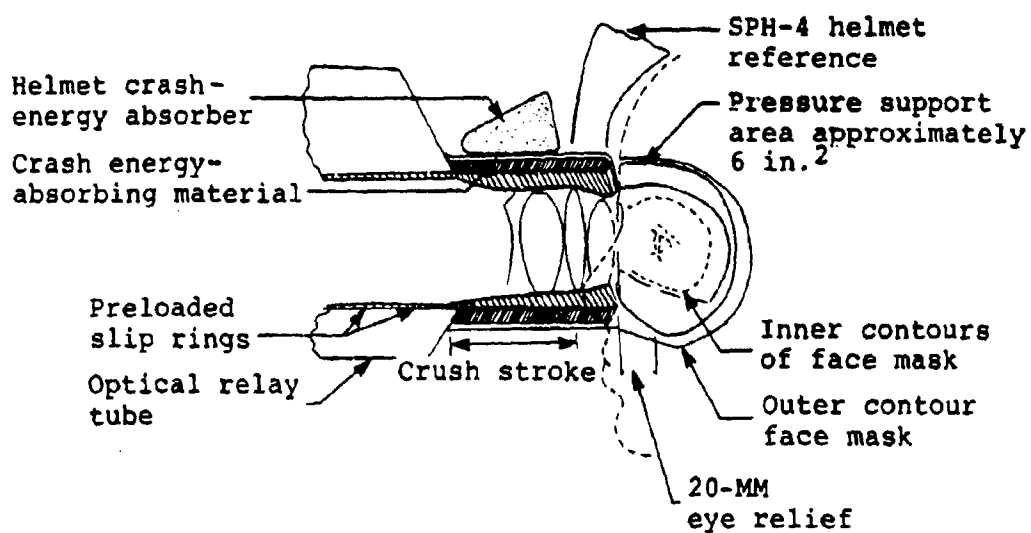
Deformed tube

Figure 80. Crushable eyepiece concept. (From Reference 97)

0.4 sec, which is too slow for effectiveness in most crashes. If this time were reduced, the retraction velocity of the torso would have to be increased considerably over the current limit of 9 ft/sec. A retraction velocity greater than this is not recommended due to the lack of human tolerance data on this type of loading. In a crash with a single pulse

of say 30-G peak and 50-ft/sec velocity change, the
retraction velocity should be approximately 25 ft/sec;
therefore, the known tolerance limits would be ex-
ceeded at the higher velocity. In summary, the PHBIR,
as currently qualified under both Air Force and Navy
military specifications, requires excessive time to
position the torso by crash sensing. To be fully
effective, the system should move the torso into po-
sition in approximately 0.06 sec, but the resulting
acceleration would exceed known human tolerance
limits. The primary crashworthiness advantage of the
PHBIR would be as a manually activated tightening de-
vice for the head-up CPG position; the PHBIR offers
only limited advantage for the head-down CPG position.

10.9 ENERGY-ABSORBING REQUIREMENTS
FOR COCKPIT AND CABIN INTERIORS

10.9.1 General

To minimize occupant injury, the acceleration experienced dur-
ing secondary impacts of the occupant with surrounding struc-
tures must be reduced to a tolerable level. The areas of con-
tact to be considered for energy absorption include instrument
panels, glare shields, other interior surfaces within the occu-
pant's strike envelope, and seat cushions. A padding material
should not only reduce the decelerative force exerted on an im-
pacting body segment, but should distribute the load in order
to produce a more uniform pressure of safe magnitude.

As an example of the need for an energy-absorbing system to
possess both these characteristics, consider the case of head
impact. Head injuries sustained from impact may be grouped in
two general categories. The first is skull fracture with its
inherent brain damage and danger to life. The second is in-
jury to facial tissue and bone structure with a lesser proba-
bility of brain damage.

A system that is to absorb the energy of an impacting head
should cushion the head to prevent skull fracture or penetra-
tion from protruding objects as a result of decelerative forces.
It should also distribute the forces-to minimize injury to tis-
sue and bone structure. The cushioning material used must ef-
fect low peak deceleration and low average stress. Figures 81
and 82, taken from Reference 98, indicate the impact behavior

98.   Lee, W. M., and Williams, B. M., CUSHIONING AND LOAD DIS-
      TRIBUTION PERFORMANCE OF PLASTIC FOAMS, Paper No. 700453,
      Society of Automotive Engineers, Inc., New York, May 1970.
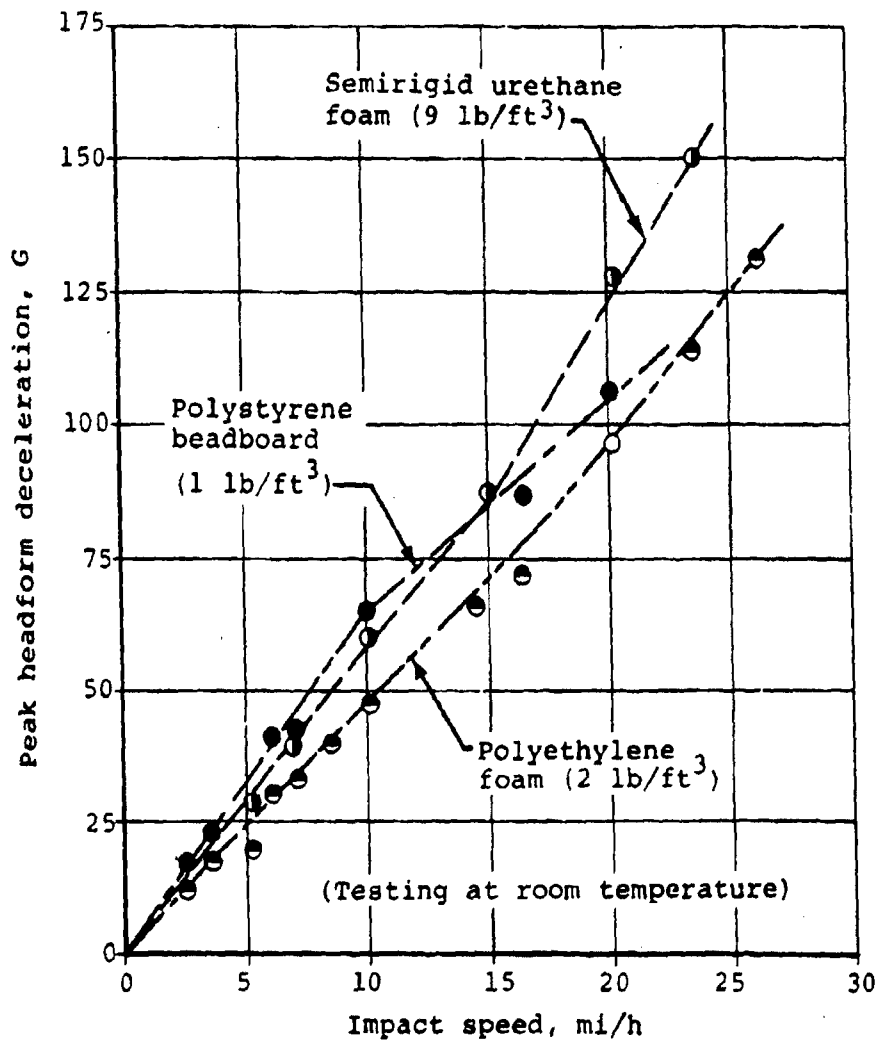
Figure 81. Impact behavior (headform deceleration versus speed) of three padding materials.

of three plastic foams. The foam sample specimens used to obtain these data were 6 in. thick to minimize any bottoming-out effect. Although the semirigid urethane appears to be a fair cushioning material, it does not distribute the load as well as the materials with which it is compared. A fair cushioning material is not necessarily an effective load distributor. Both criteria must be considered in the selection of a material that is to provide impact protection for the head.
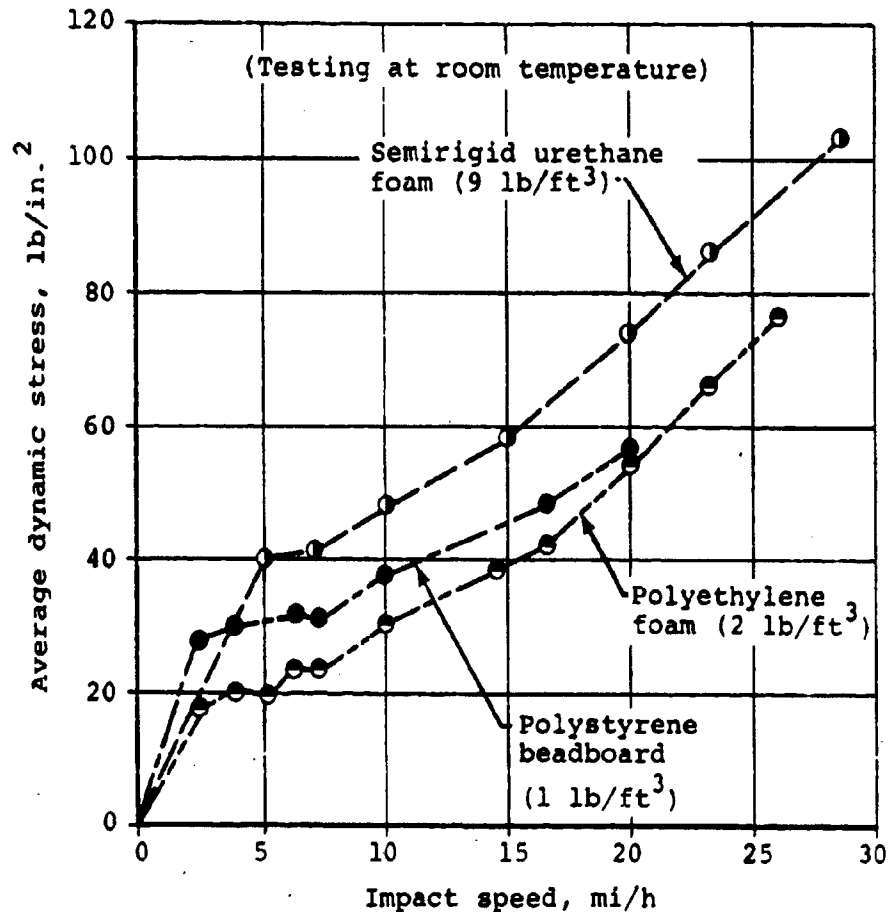
Figure 82. Impact behavior (average dynamic stress versus speed) of three padding materials.

In addition to protecting bone structure and facial tissue, the energy-absorbing system must also afford protection against intracranial lesions. Cerebral concussion, and the loss of consciousness which often accompanies it, may occur if the head is subjected to excessive decelerative forces. Mattingly, et al. (Reference 99), in discussing possible intracranial lesions and cerebral trauma including concussion, swelling, contusion, laceration, and hematoma, conclude that in order to prevent

99. Mattingly, T. E., et al., INVESTIGATION OF VIBRATION AND IMPACT PROTECTION OF THE HUMAN HEAD AND NECK, Northrop Corporate Laboratories; AMRL Technical Report 69-112, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, December 1969, AD 702124.

head injury, materials must be carefully selected to absorb and attenuate the energy of impact. The material must reduce the level of acceleration, the rate of onset, and the amount of energy transmitted to the head.

10.9.2 Types of Padding Materials and Properties

The most useful types of materials for energy-absorbing padding are plastic foams. A foamed plastic is usually totally unlike the same plastic in the solid: unlike in properties, in processing, and usually in applications. Three steps are involved in producing a cellular structure in a polymer: 1) preparation of polymeric material into a viscous liquid state, 2) introduction of fine bubbles of gas to produce expansion, and 3) solidification of the foamed plastic to stabilize the foamed structure. The particular process used in manufacturing foam materials has a direct effect on their properties and can result in products of the same chemical composition being very different in performance.

10.9.2.1 Material Form: The form in which the foam material is commercially available influences its adaptability to vehicle applications. Slab and molded foams are often used in the construction of instrument panels and seat systems. Differences in properties due to varying the form should be considered in the selection of a material. For example, Figure 83 shows the variation of minimum tensile strength versus product density for polyethylene foam in sheet and plank forms.

10.9.2.2 Classification of Foams: Foams can be described as flexible or rigid. A flexible foam recovers when deformed, whereas a rigid foam cannot sustain multiple impacts. Flexible foams are most widely used in situations where energy absorption is important.

Another method of classifying foams is open-cell or closed-cell. An open-cell foam contains individual cells that interconnect with the others, while in a closed-cell foam individual cells are completely enclosed by a wall of plastic.__

Plastic foam materials also can be classified according to their chemical composition. Several energy-absorbing plastic foams and some of their typical applications are listed in Table 14.

10.9.2.3 Material Properties: The selection of a foam material for vehicle energy-absorbing applications involves an evaluation of its processability; its mechanical, thermal, and
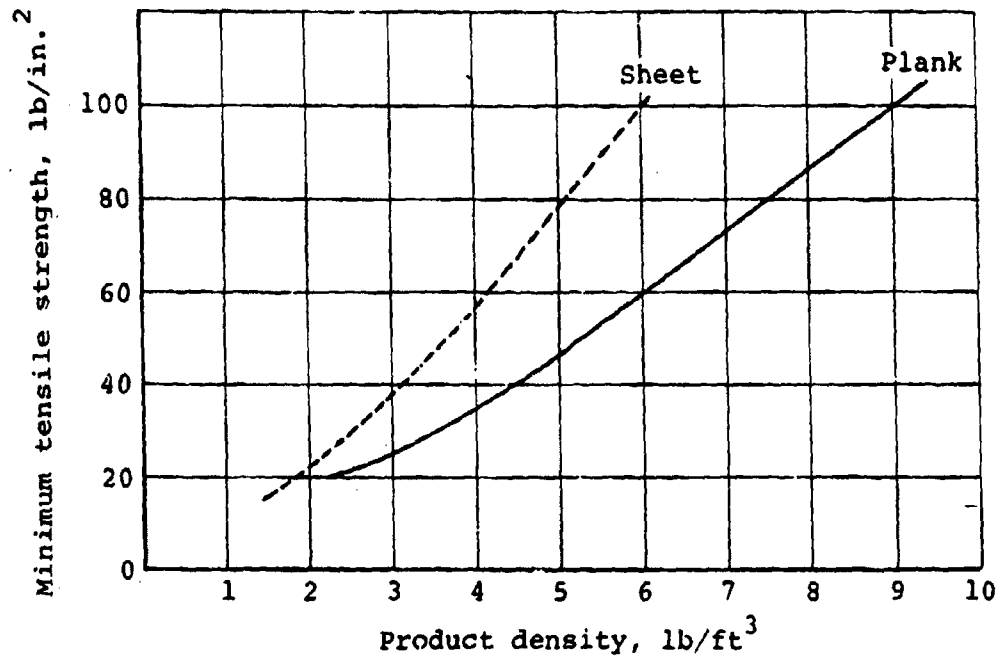
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Figure 83.   Minimum tensile strength versus product
             density for polyethylene sheet and plank.
             (From Reference 100)

chemical properties; as well as its cost. Along with the pri-
mary foam materials, the characteristics of adhesives and sur-
face coatings must be considered, particularly with respect to
emission of smoke and toxic vapors. The characteristics of
suitable materials for such use are listed below:

- Adaptability and ease of processing

- High energy dissipation

- Effective load distribution

- Low rebound

- Temperature insensitivity

- Low water absorption

100. Frados, J., PLASTICS ENGINEERING HANDBOOK OF THE SOCIETY
     OF THE PLASTICS INDUSTRY, INC., Van Nostrand Reinhold Co.,
     New York, 1976, pp. 499-567.

- Resistance to chemicals, oil, ultraviolet radiation, and sunlight

- Nontoxic, fume generation

- Favorable flammability rating

- Minimal smoke generation

- Durability and long life

- Cost competitive

- Aesthetic

TABLE 14. ENERGY-ABSORBING PLASTIC FOAMS
AND SOME TYPICAL APPLICATIONS

1. **Semirigid and flexible urethane foam**

Aircraft, automobile, and furniture seat cushions, safety padding, arm rests, sun visors, horn buttons, bedding, carpet underlay, packaging delicate products.

2. **Polyvinylchloride foam**

Crash padding in automobile head liners and sun visors, flooring, shoe soles and heels, automobile door panels, seating upholstery sealants, gaskets, bumperstock.

3. **Polystyrene foam**

Insulation, packaging.

4. **Expanded rubber**

Bus and subway seat cushions, truck and ship mattresses, gaskets, hose insulation.

5. **Polyester foam**

Short-run, custom-type seat cushioning.

6. **Polyolefin foam**

Packaging, gasketing, water sports equipment, rug underlay, athletic padding, antivibration padding.

Foam materials are most often characterized by the mechanical properties listed below, where it may be noted that several of the properties apply only to rigid or flexible foams. For

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example, compressive strength is not relevant in considering flexible foams. The compression-set test, on the other hand, applies only to flexible materials.

- Density
- Tensile strength
- Tensile modulus
- Compressive strength
- Compressive modulus
- Flexural strength
- Flexural modulus
- Tear strength
- Compression set
- Compression deflection
- Elongation
- Rebound
- Hardness
- Impact

Properties of possible interest in selection of a material for energy-absorbing applications are presented in Table 15 for several applicable materials (data taken from References 100 through 103).

101. ENSOLITE, Publication ASP 9997, Expanded Products Department, Uniroyal, Inc., Mishawaka, Indiana, 1977.

102. TEMPER FOAM, Form TF-20, Edmont-Wilson, Division of Becton, Dickenson and Co., Coshocton, Ohio, 1975.

103. Sundquist, D. J., POLYOLEFIN FOAMS, Monographs on Plastics, Vol. 1, Part 1, 1972, pp. 193-295.

TABLE 15. PROPERTIES OF SELECTED FLEXIBLE CELLULAR POLYMERS

Property	Polyvinyl Chloride with Nitrile Rubber (Uniroyal "Ensolite")[101]	Urethane (Edmont-Wilson "Temperfoam")[102]	Polystyrene[100]	Urethane (Mobay Chemical Co. "Cold-Cure Foam")[100]	Low-Density Polyethylene (Dow Chemical Co. "Ethafoam" and Furakawa Electric Co., Ltd. "Foamace")[103]
Density (lb/ft^3)	2.5 - 12.0	5.0	1.01 - 10.1	2.5 - 4.5	1.7 - 9.0
Tensile strength (psi)	30 - 150	19 - 51	20 - 250	10 - 14	20 - 100
Elongation (percent)	60 - 150	75 - 225		90 - 110	
Shrinkage (percent)	2.0 - 3.0			0.3 - 3.0	
Water absorption	0.1 lb/ft^2		0 - 2.0% by volume		0.1 - 0.5% by volume
Thermal conductivity (Btu/hr ft °F)	0.25 - 0.30		0.18 - 0.28		0.3 - 0.4
25% ILD (lb/50 in.^{2})		47 - 500		7 - 50[a]	
65% ILD (lb/50 in.^{2})		92 - 1070		25 - 160	
Rebound (percent)		5 - 10[b]		50 - 60	

(a) @ 20% ILD (indentation load deflection).
(b) Ball weight = 286 g, drop height = 20 in.

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10.9.3 Standard Test Methods

ASTM standard test procedures are widely used by manufacturers to specify various properties of a particular type of material. Table 16 summarizes ASTM test methods and specifications for flexible cellular plastics that provide a basis for comparison of materials. Here it may be noted that most ASTM tests involve simple tests, whereas the operational environment involves dynamic loading and more complex conditions.

In particular, ASTM D 1564-71 describes "Standard Methods of Testing Flexible Cellular Materials-Slab Urethane Foam" (Reference 104). Among other tests, there are compression-set and load-deflection tests. In the compression-set test, the method consists of deflecting the foam specimen under specified conditions of time and temperature and noting the reduction of specimen thickness after removal of the load. The compression device consists of two flat plates larger than the specimen.

In the load deflection test, one method consists of measuring the Indentation Load Deflection (ILD) value, which is the load necessary to produce a specified 25-percent or 65-percent indentation in the specimen under a 50-in.^{2} circular indenter foot. Acceptable deflection rates range from 1.0 to 15.0 in./min. A second method, which uses the same indenter, obtains the deflections under specified loads of 4.45, 111, and 222 N (1, 25, and 50 lb) during loading and 111 N during unloading. These deflections are reported as Indentation Residual Gage Load (IRGL) values. The latter method, which involves indentation to specified loads, is intended for use with seat cushion materials.

The above tests provide results that specify the material, but do not necessarily portray its performance under actual impact situations. A simple dynamic drop test, such as ASTM D1596-64 (1976), "Standard Test Method for Shock-Absorbing Characteristics of Package Cushioning Materials" (Reference 104), more closely simulates actual impact conditions. An acceleration-time curve is obtained by mounting a transducer on the dropping head. The parameters evaluated are peak deceleration and the dynamic set of the specimen. This method allows the test parameters to vary and yet is simple enough to ensure repeatability among different test facilities. In a drop test, the test parameters are: the drop height that determines the impact velocity, the weight and surface area of the impactor, and foam thickness.

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104. Lukens, R. P., et al., 1977 ANNUAL BOOK OF ASTM STANDARDS, American Society for Testing and Materials, Easton, Maryland, 1977, Parts 20, 38, 48.

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TABLE 16. SUMMARY OF ASTM TEST METHODS AND
          SPECIFICATIONS FOR FLEXIBLE
          CELLULAR PLASTICS (REFERENCES
          104 AND 105)

D1564-71*	Testing Flexible Cellular Materials-Slab Urethane Foam
D1667-76*	Specification for Flexible Cellular Materials - Vinyl Chloride Polymers and Copolymers (Closed-Cell Sponge)
D1565-76*	Specification for Flexible Cellular Materials - Vinyl Chloride Polymers and Copolymers (Open-Cell Foam)
D1055-69* (1975)	Specification for Flexible Cellular Materials - Latex Foam
D1056-73*	Specification for Flexible Cellular Materials - Sponge or Expanded Rubber
D3575-77	Testing Flexible Cellular Materials Made From Olefin Plastics
D1596-64* (1976)	Test for Shock-Absorbing Characteristics of Package Cushioning Materials
D2221-68* (1973)	Test for Creep Properties of Package Cushioning Materials
D1372-64* (1976)	Testing Package Cushioning Materials
D696-70*	Test for Coefficient of Linear Thermal Expansion of Plastics
E143-61* (1972)	Test for Shear Modulus at Room Temperature
D412-75*	Tests for Rubber Properties in Tension
D1433-76*	Test for Rate of Burning and/or Extent and Time of Burning of Flexible Thin Plastic Sheeting Supported on a 45-degree Incline
D1692-76	Test for Rate of Burning and/or Extent and Time of Burning of Cellular Plastics Using a Speciman Supported by a Horizontal Screen

*Indicates that the standard has been approved as
American National Standard by the American National
Standards Institute.

Other standard test procedures include SAE J815, "Load Deflection Testing of Urethane Foams for Automotive Seating," as described in Reference 106. This test points out the factors of interest in testing materials for vehicle seat cushions: the thickness of the padding under the average passenger load, a measurement that indicates the initial softness, and a measurement that indicates resiliency. SAE J815 determines load versus deflection by measuring the thickness of the padding under fixed loads· of 1 lb, 25 lb, and 50 lb with a circular indentor foot (see Reference 105).

Also, SAE J388, "Dynamic Flex Fatigue Test for Slab Urethane Foam" (Reference 107), describes procedures for evaluating the loss of thickness and the amount of structural breakdown of slab urethane foam seating materials. A test specimen is measured for thickness under a specified load and, subsequently, subjected simultaneously to compressive and shear deformation under a constant load for a specified number of cycles. In the constant load height measuring test, a flat, circular indenter foot of 50 in.^{2} with loads from 1.0 to 75.0 lb is deflected at rates from 2 to 8 in./min. The constant load dynamic fatigue apparatus uses rollers in a more complicated setup.

SAE J921, "Motor Vehicle Instrument Panel Laboratory Impact Test Procedure-Head Area," describes a test procedure for evaluating the head impact characteristics of such areas as instrument panels (Reference 96). An SAE J984 headform with an effective weight of 15.1 lb is impacted at specified positions. The parameters evaluated are the impact velocity, the acceleration-time history of the headform, and the start of impact, with optional measurement of the rebound velocity and the headform dynamic displacement.

105. ENCYCLOPEDIA OF POLYMER SCIENCE AND TECHNOLOGY - PLASTICS, RESINS, RUBBER, FIBERS, John Wiley and Sons, Inc., New York, 1965, Vol. 3, pp. 98-126.

106. SAE Recommended Practice, SAE J815, LOAD DEFLECTION TESTING OF URETHANE FOAMS FOR AUTOMOTIVE SEATING, SAE Handbook 1979, Part 2, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1979, p. 34.31.

107. SAE Recommended Practice, SAE J388, DYNAMIC FLEX FATIGUE TEST FOR SLAB POLYURETHANE FOAM, SAE Handbook, 1979, Part 2, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1979, pp. 34.28-34.30.

10.9.4 Research on Materials for Energy-Absorbing Applications

Static tests that deviate from ASTM test procedures and simple dynamic tests that are intended to grossly simulate crash conditions have been performed by manufacturers and users with different types of materials. Several of their approaches and their energy-absorption criteria are discussed below.

10.9.4.1 Acceptable Stress-Strain Characteristics: Haley, et al., have investigated design criteria for padding materials, as described in Reference 94. According to their conclusions, energy-absorbing materials with stress values between 40 and 80 lb/in.^{2} at 50 percent strain would offer reasonable survival potential for head impacts on flat surfaces at velocities of up to 20 ft/sec with a padding thickness of 1.5 in. More recent unpublished data gathered by the Army's Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, indicates that the above stress values are too high because the values were based on the compressive strength alone while it is probable that tensile stresses and shear stresses around the periphery of the compressed areas play a large role in the total force resisting compression. Regardless of the stress distribution in the padding material, the USAARL research has shown that the stress level should fall between 30 and 45 lb/in.^{2} for padding less than 1 in. thick and 20 to 30 lb/in.^{2} for padding greater than 1 in. thick in order to prevent peak G pulses from exceeding the tolerance values stated in Volume II. These crush strength values, as illustrated in Figure 84, are recommended. These levels are expected to prevent unconsciousness (within the limits of the crush depth) for head impacts. The lower stress level for the thicker padding is based on: (1) the average design decelerative level must be reduced as the depth of the padding and concomitant time duration are increased to meet the known tolerance limits stated in Volume II, and (2) a larger area of foam is crushed as the head sinks into the thicker pad.

Use of a padding as proposed in Figure 84, is intended to limit head peak G values to 160 for the thin pads and 120 G for the thicker padding.

The criteria of Figure 84 are to be satisfied by the padding material over the entire anticipated operating temperature range if the potential for survival is to be maintained. Practical considerations and risk analysis, however, may reduce the temperature range requirements. Figure 85, taken from Reference 108, indicates the temperature dependency of the stress-strain properties of a particular foam material. It illustrates the variation experienced by many padding materials

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108. PACKAGING WITH ETHAFOAM, Publication No. 172-221-10M-767, Dow Chemical Company, Midland, Michigan, revised 1966.
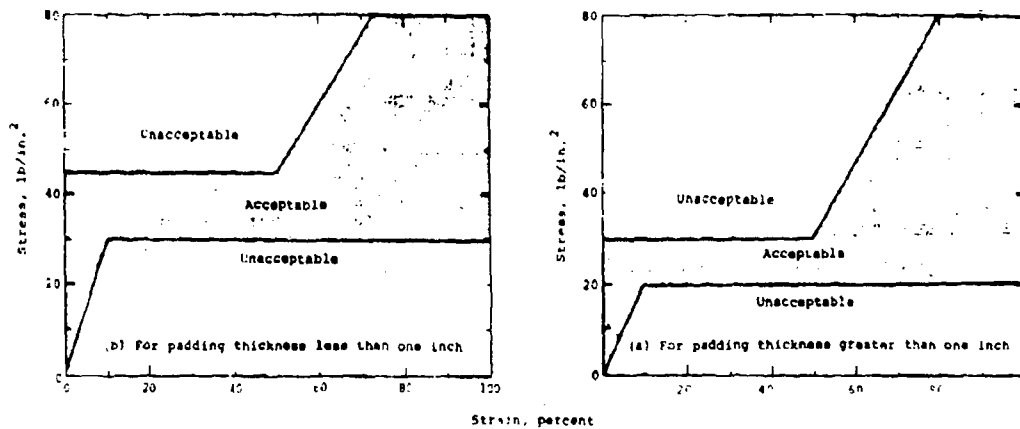
Figure 84. Recommended stress-strain properties for padding
material for head contact, with cushion thickness
of at least 1.5 in. (From Reference 94)

and indicates that temperature sensitivity must be considered
as a padding material selection criterion.

Stress-strain curves for a polyurethane-foamed plastic are
shown in Figure 86. The curves are taken from Reference 109
and indicate that a 6-in. thickness of the foam with a density
of 5 lb/ft^3 will satisfy the criteria of Figure 84 (superim-
posed as a crosshatched area) over at least part of the oper-
ational temperature range. The lowest impact velocity used to
obtain the data of Figure 86 was 50 ft/sec. A weight of 295 lb
impacting at this velocity requires the absorption of over
11,000 ft-lb of energy by the padding material. This require-
ment is obviously considerably more demanding than that of 90
ft-lb of energy at an impact velocity of 20 ft/sec, as de-
scribed above. Further work with variations of this foam may
yield a material that will satisfy the design criteria with a
thickness of 2 in. or less.

10.9.4.2 Bioengineering Approach to Material Evaluation:
Daniel investigated the injury-reducing functions of crash pad-
ding, considering strength of skull segments, as described in
Reference 110. He concluded that because the cranial vault

109. ENGINEERING DESIGN HANDBOOK, DESIGN FOR AIR TRANSPORT
AND AIRDROP OF MATERIAL, AMC Pamphlet No. 706-130, U. S.
Army Materiel Command, Washington, D. C., December 1967,
AD 830262.

110. Daniel, R. P., A BIO-ENGINEERING APPROACH TO CRASH PADDING,
Paper No. 680001, Society of Automotive Engineers, Inc.,
New York, 1968.

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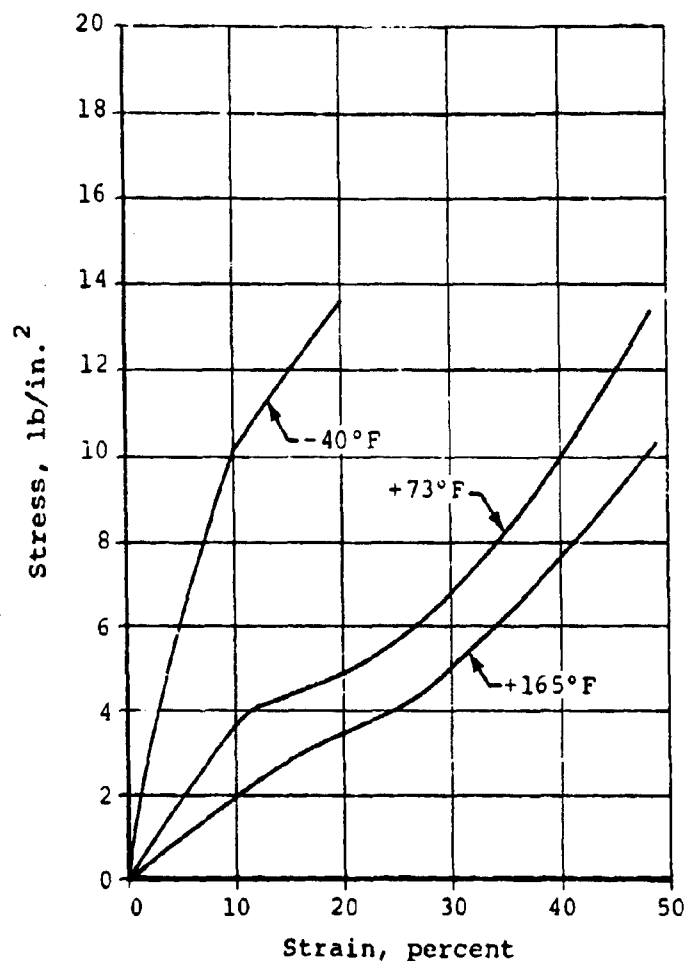
Figure 85. Stress-strain curves for polyethylene
foam. (From Reference 108)

(above the eyebrows) is strong under localized impact, padding
used for protection of this region has the primary function of
energy absorption to reduce the possibility of brain damage.

On the other hand, padding for facial protection should dis-
tribute the impact load over the weaker facial bones, and re-
quired energy absorption would be provided by the supporting
structure. His suggested evaluation criterion for energy-
absorbing materials, based on a program of 91 impact tests, is
illustrated in Figure 87. For any given material, plotting on
these curves the results of a test conducted according to the
given parameters would enable the determination of a material
"efficiency," where a 100-percent efficiency would correspond
to the deceleration achieved by an ideal square-wave energy

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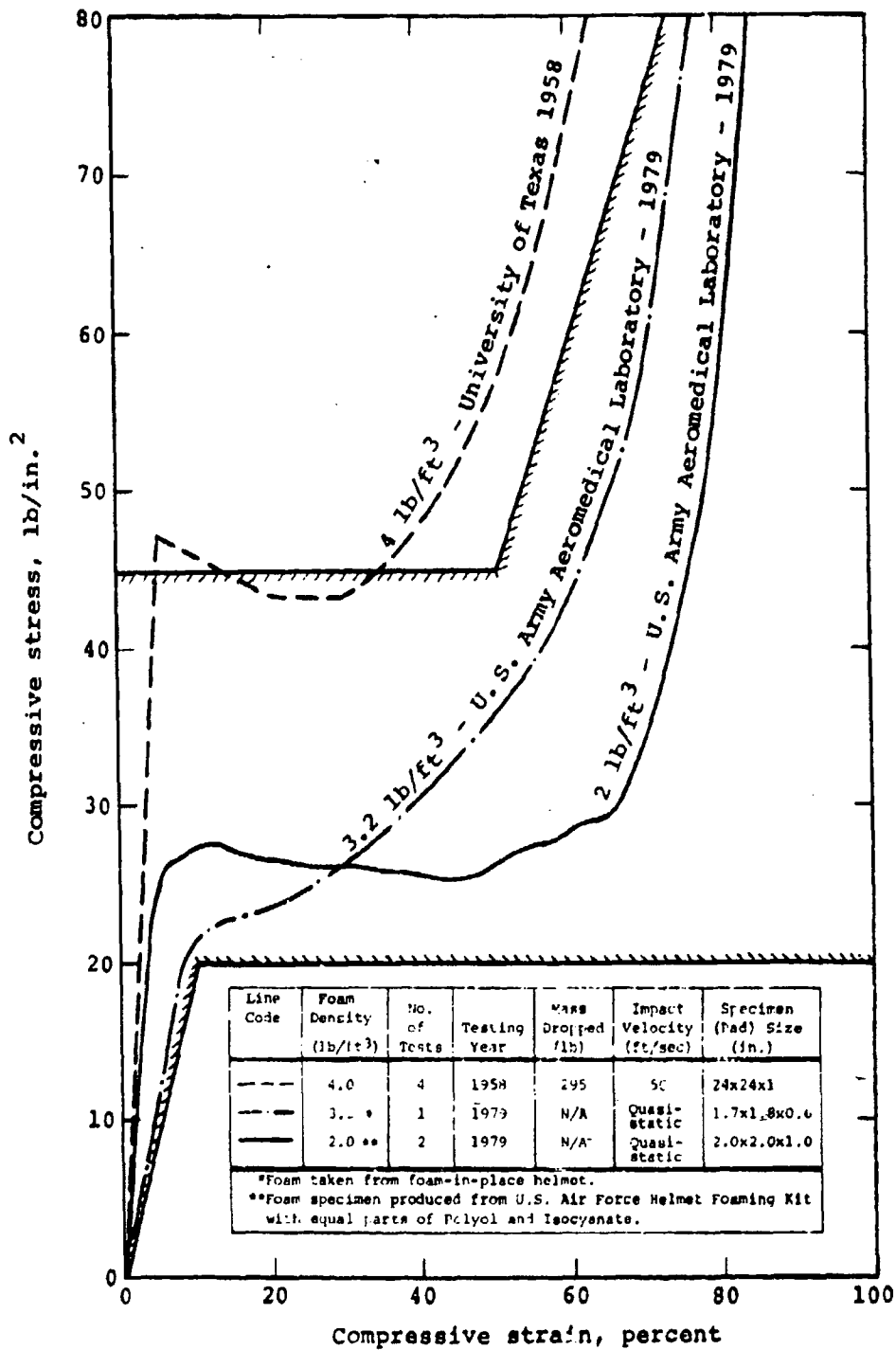
Figure 86. Effect of density on stress-strain curves
for polyurethane-foamed plastic.

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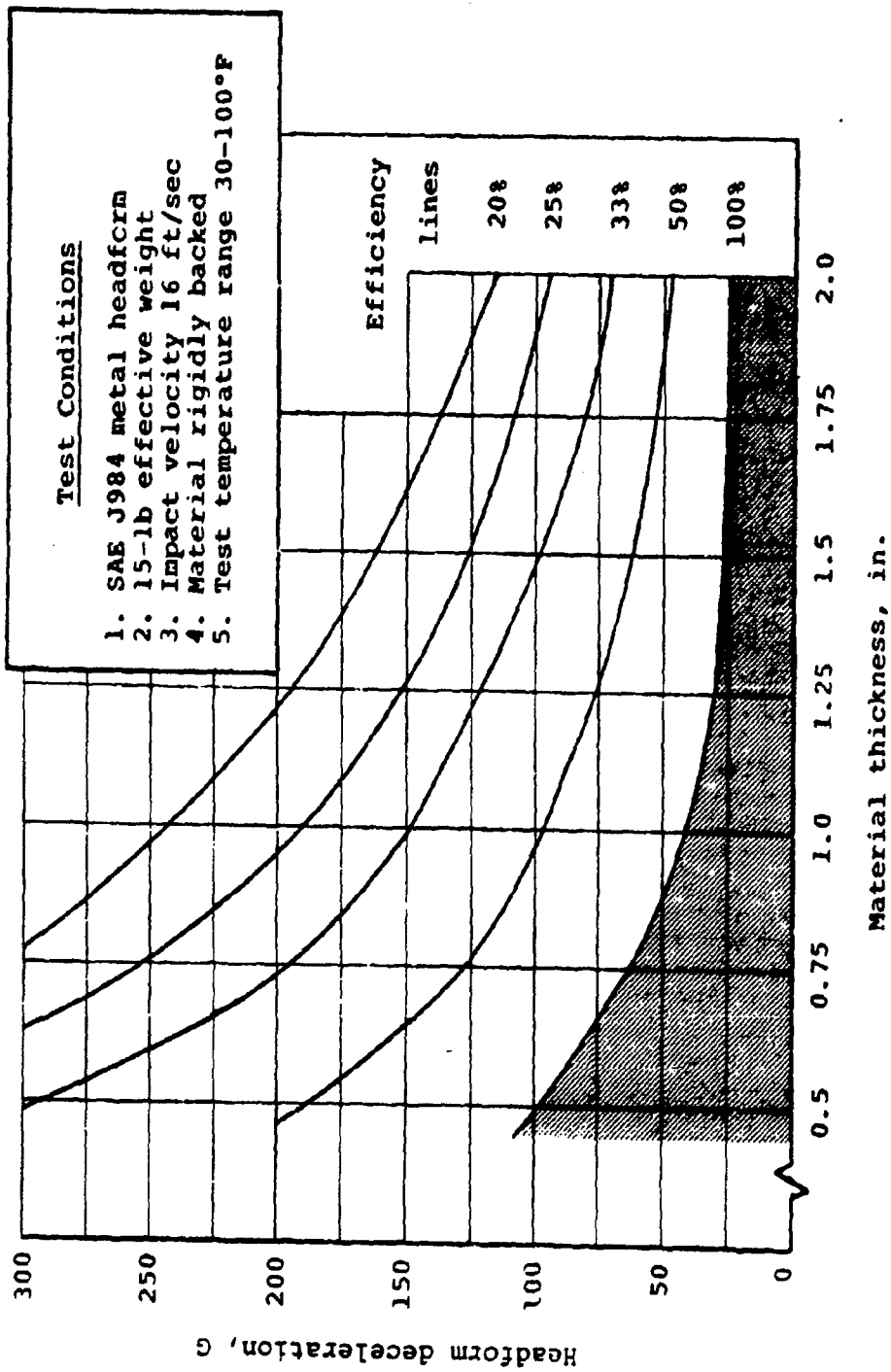
Figure 87. Evaluation criteria for energy-absorbing material. (From Reference 110)

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absorber of the given thickness. According to Daniels, energy-absorbing materials might be selected on the basis of maximum efficiency.

Evaluation criteria for load-distributing applications, which are illustrated in Figure 88, are based on the following assumptions:

- A load-distributing pad should permit the face to penetrate its surface relatively easily and then maintain a cushioning layer of foam between the base and the underlying structure during collapse of the understructure.

- The understructure should deform at close to the 80-G (1200 lb) face tolerance level expressed in both SAE J885 and Federal Motor Vehicle Safety Standard 201 (References 111 and 112, respectively).

10.9.4.3 <u>Energy-Absorbing Efficiency Calculations</u>: The energy-absorbing characteristics of foamed polymers were mathematically calculated by Rusch from low-speed experimental data for compressive strain and modulus (Reference 113). Materials were characterized by three parameters: energy-absorbing efficiency, impact energy per unit volume divided by foam modulus, and the maximum decelerating force per unit area divided by foam modulus.

An ideal energy absorber would provide a constant deceleration from an initial speed, v_i, for 100 percent of its thickness, h The maximum deceleration for an ideal absorber is then given by

$$d_{m_i} = v_i^2/2h$$

(36)

111. SAE Information Report, SAE J885, HUMAN TOLERANCE TO IMPACT CONDITIONS AS RELATED TO MOTOR VEHICLE DESIGN, <u>SAE Handbook 1979, Part 2</u>, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1979, pp. 34.114-34.117.

112. U. S. Code of Federal Regulations, Title 49, Part 571: MOTOR VEHICLE SAFETY STANDARDS, 201, OCCUPANT PROTECTION AND INTERIOR IMPACT, Government Printing Office, Washington, D. C., (Rev.) 1978.

113. Rusch, K. C., IMPACT ENERGY ABSORPTION BY FOAMED POLYMERS, <u>Journal of Cellular Plastics</u>, Vol. 7, No. 2, 1971, pp. 78-83.

Test Conditions

1. Flat face form
2. 37- to 40-lb effective weight
3. Impact velocity 22 ft/sec
4. Material rigidly backed
5. Test temperature 30-100°F
6. Sample size: 12 x 12 x 2 in.

NOTE: Assumes 80-G (1200 lb) face tolerance value. If this value changes, range of loads shown must change in the ratio of new value divided by 80-G value.
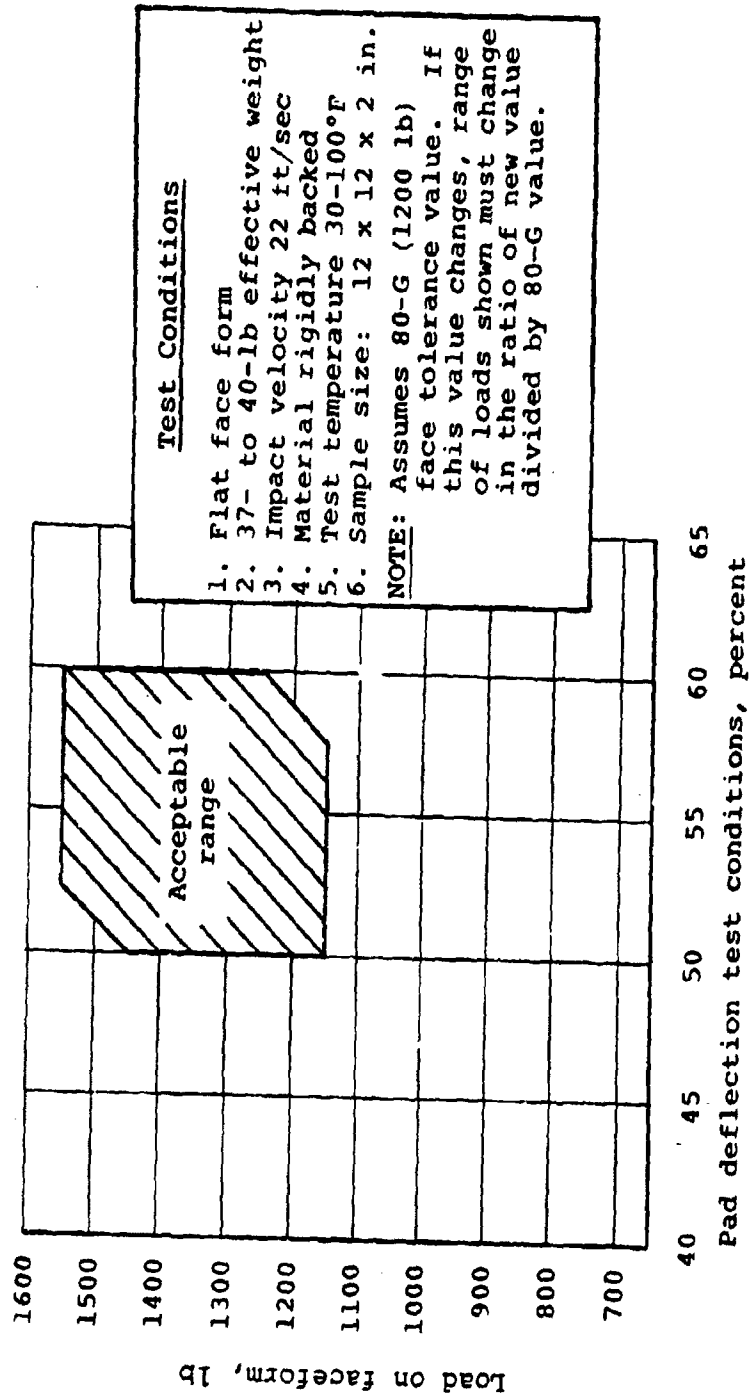
Figure 88. Load-distributing material evaluation criteria. (From Reference 110)

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The energy-absorbing efficiency, K, is defined as the inverse ratio of the maximum deceleration exhibited by a real material, d_m, to that for an ideal material of equivalent thickness, d_{mi}.

$$K = v_i^2/2hd_m \qquad (37)$$

Generally, K is expressed as a function of the impact velocity. At low v_i, the impact energy is small relative to the stiffness of the foam, the degree of penetration is small, and K is low. At high v_i, the impact energy is large relative to the stiffness, the impacting body "bottoms" on the understructure, and K is low. At some intermediate v_i, K exhibits a maximum. The optimum material is one for which: (1) the K versus v_i curve is as broad as possible, (2) K_{max} is close to unity, and (3) K_{max} occurs at the most probable v_i for the particular application.

On the basis of his calculations, Rusch stated the following conclusions: (1) the energy-absorbing characteristics of a brittle foam are superior to those of a ductile foam; (2) the optimum energy-absorbing foam has a large cell size, a narrow cell size distribution, and a minimum number of reinforcing membranes between the cells; and (3) foam composites offer no significant advantage over a single foam.

10.9.4.4 Composite Foam System: Brooks and Rey (Reference 114) found that a composite could be formed combining the high energy dissipation of polystyrene beaded foam with the load-distributing effects of semi-rigid urethane. Simple dynamic tests consisted of dropping a 6-1/2-in. diameter aluminum hemispherical headform weighing 15 lb at impact velocities up to 30 mi/h (44 ft/sec). As shown in Figure 89a, the urethane exhibits the lowest level of headform acceleration during impact. On the other hand, the polystyrene exhibits the lowest level of penetration as shown in Figure 89b. The urethane can be said to absorb the least amount of energy, as indicated by the highest rebound value in Figure 89c.

In small-scale static tests, 2-in. cubes were compressed to 70-percent deflection and then relaxed with an Instron testing machine at 2.0-in./min crosshead speed. Figure 89d shows the relative energy absorption of the three materials tested, indicating the composite foam as a compromise between polystyrene and semi-rigid urethane foam.

114. Brooks, J. D., and Rey, L. G., POLYSTYRENE-URETHANE COMPOSITE FOAM FOR CRASH PADDING APPLICATION, Limited Publication, Low Chemical of Canada, Sarnia, Ontario.
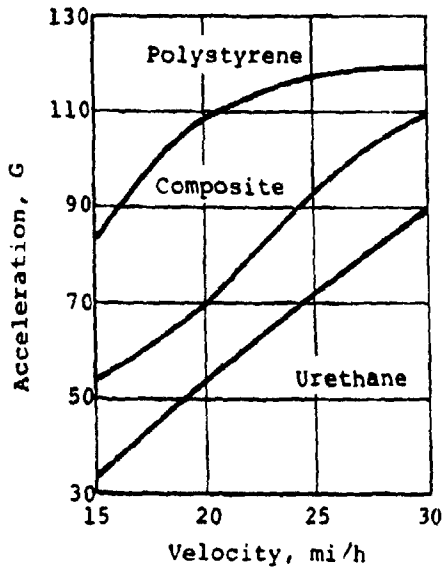
(a) Head form acceleration
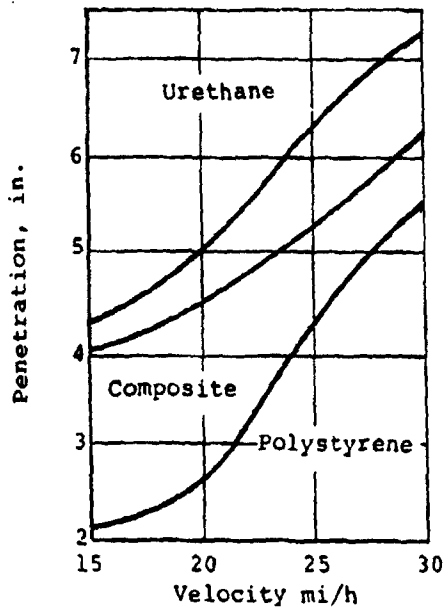
(b) Headform penetration
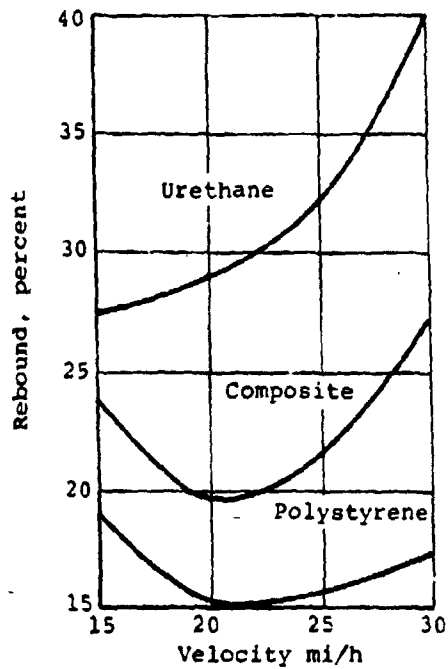
(c) Headform rebound
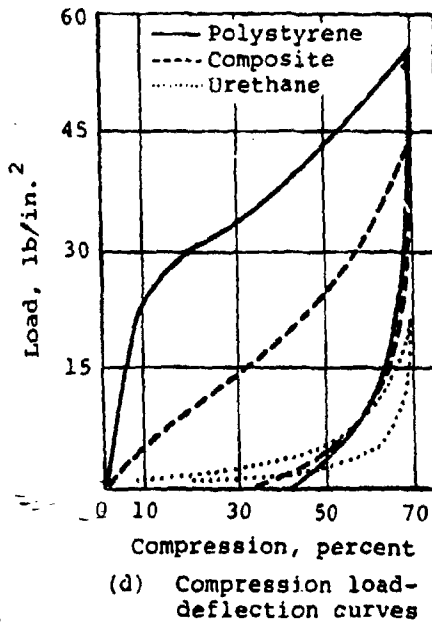
(d) Compression load-deflection curves

Figure 89. Response of composite foam, compared with urethane, and polystyrene. (From Reference 114)

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10.9.4.5 Specific Energy and Relative Energy-Absorption Ratio:
Reference 115 discusses performance parameters of Dow composite
foam in energy-absorbing applications. It was concluded that,
on the typical response curve for a compression test, where the
area contained within the hysteresis loop shown in Figure 90
is directly related to the energy absorbed, three performance
parameters can be defined: the specific energy absorbed at
maximum strain, the relative energy-absorption ratio, and the
maximum stress. The total energy absorbed at maximum strain is
the sum of areas A and B. When this total energy is expressed
in terms of a unit volume (or unit weight), the quantity be-
comes the specific energy absorption at maximum strain. The
ratio of area A to the sum is the relative energy-absorption
ratio, which is a measure of the amount of energy actually dis-
sipated during compression. In effect, it corrects the per-
formance parameter for the energy that is momentarily stored.
The maximum stress is usually the stress at maximum strain.
Exceptions to this occur when some rigid cellular materials are
compressed and a spike is observed during the initial stage of
compression. Maximum stress levels are directly related to the
deceleration that the impacting object sustains.
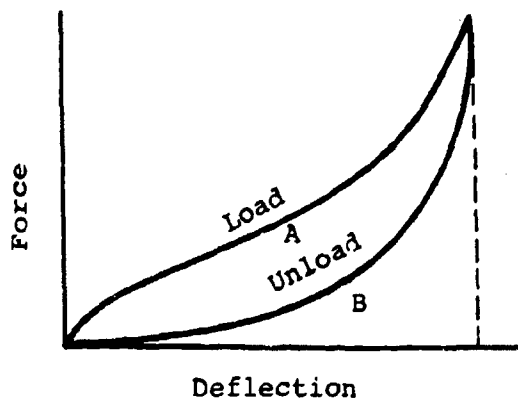
Figure 90. Typical response of plastic
            foam to compression test.

115. PERFORMANCE PARAMETERS OF DOW COMPOSITE FOAM IN ENERGY
     ABSORBING APPLICATIONS, Dow Chemical Company, Midland,
     Michigan.

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Melvin and Roberts (Reference 116) measured the specific energy absorbed and the relative energy-absorption ratio for the materials listed in Table 17 using three speeds: 20, 2000, and 13,000 in./min. Their results are summarized in Table 18 and Figure 91, from which they concluded that the majority of foams do not exhibit marked increases in properties with increasing test speed. The vinyl foams, which exhibit dramatic increases, are the exceptions.

TABLE 17. MATERIAL SUMMARY (FROM REFERENCE 116)

Material and code number	Density (lb/ft^3)	Specimen height (in.)	Initial strain rate (sec^{-1})		
			Speed 1	Speed 2	Speed 3
Polyethylene E-1	2.34	2	0.17	17	100
Polyethylene E-2	6.65	1.5	0.22	22	150
Polyethylene E-3	9.05	2	0.17	17	100
Polystyrene S-1	1.09	2	0.17	17	100
Polystyrene S-2	3.35	2	0.17	17	100
Polystyrene S-3 (pelletized)	1.21	2	0.17	17	100
Polyurethane U-1 (rigid)	1.53	2	0.17	17	100
Vinyl V-1	7.35	1	0.33	33	220
Vinyl V-2	7.25	1	0.33	33	220
Vinyl V-3	5.04	1	0.33	33	220
Cork C-1	11.5	1.5	0.22	22	150

116. Melvin, J. W., and Roberts, V. L., COMPRESSION OF CELLULAR PLASTICS AT HIGH STRAIN RATES, Journal of Cellular Plastics, March/April 1971, pp. 97-100.

TABLE 18. TEST RESULTS SUMMARY (FROM REFERENCE 116)

Material	Curve type	Average maximum stress, lb/in.^{2}			Average specific energy absorbed to maximum strain, in.-lb/in.^{3}			Average relative energy-absorption ratio	
		Speed 1	Speed 2	Speed 3	Speed 1	Speed 2	Speed 3	Speed 1	Speed 2
E-1	II	15.8	20.2	21.8	4.42	6.4	7.0	0.48	0.69
E-2	II	59.8	60.5	77.7	20.9	19.9	29.2	0.76	0.87
E-3	II	86.2	107.1	132.0	28.9	37.6	45.2	0.82	0.90
S-1	I	47.2	48.5	49.7	19.8	20.7	21.2	0.86	0.87
S-2	I	141.1	177.5	175.4	57.1	71.0	72.7	0.93	0.95
S-3	I	34.7	37.0	37.7	11.6	12.1	12.2	0.82	0.85
U-1	I*	36.8	41.2	42.0	13.2	13.0	14.0	0.97	0.98
V-1	II	18.7	34.0	49.0	4.2	9.6	14.0	0.39	0.66
V-2	II	22.9	43.5	60.3	5.9	13.6	18.3	0.50	0.70
V-3	II	24.6	44.2	55.9	7.2	16.3	20.4	0.62	0.75
C-1	I	364.5	382.8	445.3	124.3	152.6	171.2	0.87	0.87

NOTE: Speed 1 = 20 in./min, Speed 2 = 2000 in./min, and Speed 3 = 13,000 in./min

*Exhibited initial load spike.

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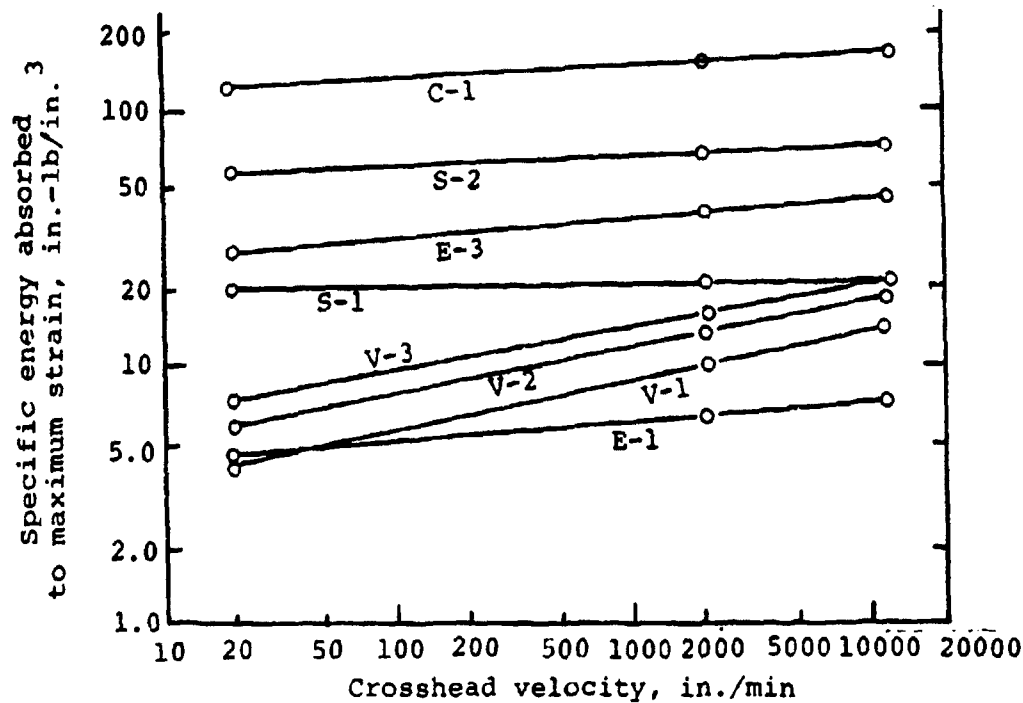
Figure 91. Specific energy absorbed to maximum
strain versus crosshead velocity.

10.9.4.6 **Dynamic Property Index:** Fan (Reference 117) developed techniques for simulating the force-penetration properties of viscoelastic materials based on results of pendulum impact tests on polyurethane foam. The dynamic force-penetration relationship of polyurethane can be approximated by a function of three variables: penetration-thickness ratio, sample thickness, and impact velocity. Fan suggested a criterion for energy absorption expressed as the dynamic-property index:

$$I = E_d/G_m \tag{38}$$

117. Fan, W. R. S., A SIMULATION OF THE DYNAMIC PROPERTIES OF
     ENERGY-ABSORBING MATERIALS, 1970 International Automobile
     Safety Conference Compendium, Society of Automotive Engineers, Inc., New York, 1970, pp. 1075-1083.

where   I = dynamic-property index of the material.

E_d = the amount of energy dissipation by the foam material during impact.

G_m = the maximum deceleration measured at the impactor during impact.

A high index value implies a high degree of effectiveness. The dynamic-property index of a material varies with the test conditions. The material rated as the most effective in a certain case is not necessarily the most effective material in other cases.

10.9.4.7 Dynamic Crushing Pressure: Furio and Gilbert (Reference 118) conducted a series of drop tests with low density (2 lb/ft³) urethane foam using a flat impactor weighing 729 lb at a drop height of 45 ft.

The dynamic crushing pressure, P_{cr}, which is the product of the weight of the impact mass and the acceleration divided by the impact area, is shown in Figure 92 as a function of temperature and velocity for two samples of identical dimensions. The increase in pressure with velocity is attributed to the fact that the entrapped gas must escape in order for the foam to collapse. Under dynamic loading, the gas cannot escape fast enough, and a higher pressure results.

10.9.5 Application of Padding Material

In the absence of data for extremity impacts, it is assumed that padding material that is suitable for head impact protection will be suitable also for protecting extremities. Extremity impacts are not likely to have the potentially severe effects of head impacts. It is suggested that areas within the extremity strike envelope having radii of 2 in. or less be padded and that such padding have a minimum thickness of 0.75 in.

Caution must be exercised in padding sharp edges and corners. Padding installed in a manner that allows it to be broken away from the corner or cut through by sharp edges offers no protection. It is recommended that edges and corners to be padded have a minimum radius of 0.5 in. prior to padding. A definite volume of the padding must be crushed to absorb the initial kinetic energy of the head and protective helmet.

118. Furio, A. J., Jr., and Gilbert, W. E., IMPACT TESTS OF URETHANE FOAM, Report No. NSRDC 4254, Naval Ship Research and Development Center, Bethesda, Maryland, January 1974, AD 775903.
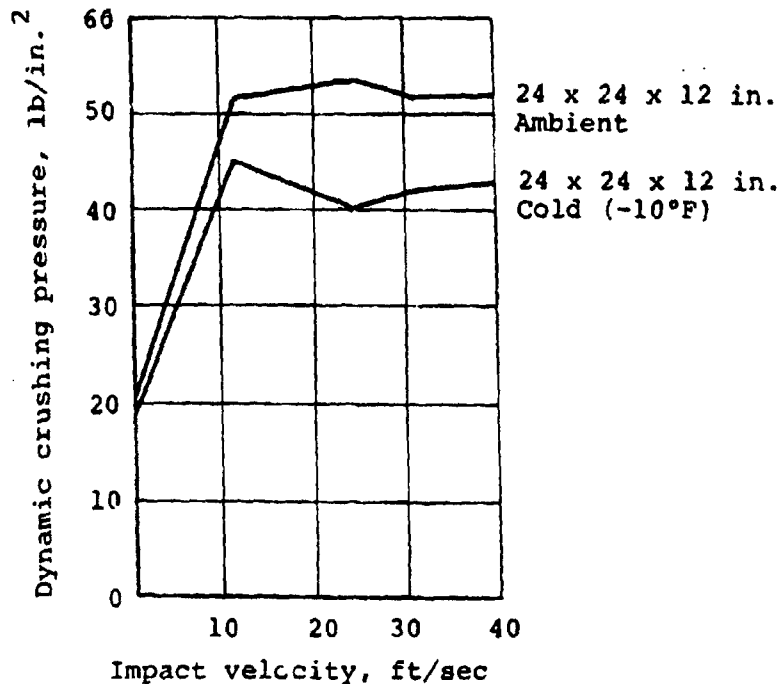
Figure 92.   Dynamic crushing pressure versus
             impact velocity for tests at two
             temperatures.

10.9.6 Ductile Materials

In cases where the use of padding material is impractical or
the thickness allowed is inadequate to provide the necessary
protection, ductile energy-absorbing materials or frangible
breakaway panels should be used where possible. Window and
door frames, control columns, electrical junction boxes, etc.,
should be designed with large radii (1 in. or more) rather than
with sharp edges and corners.

Swearingen concluded in Reference 119 that at impact velocities
of 30 ft/sec against rigid structure padded with materials even
6-in. thick, unconsciousness, concussion, and/or fatal head
injuries will be produced. Where possible, a combination of

119.   Swearingen, J. J., EVALUATIONS OF VARIOUS PADDING MATER-
       IALS FOR CRASH PROTECTION, FAA Technical Report AM 66-40,
       Federal Aviation Administration, Civil Aeromedical Insti-
       tute, Washington, D. C., December 1966, AD 647048.

deformable structure and padding material should be considered to absorb the impact energy and to adequately distribute the forces over the face. Surfaces to which this combination should be applied are instrument panels, seat backs, bulkheads, and any other structure the head may impact during the crash sequence.

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