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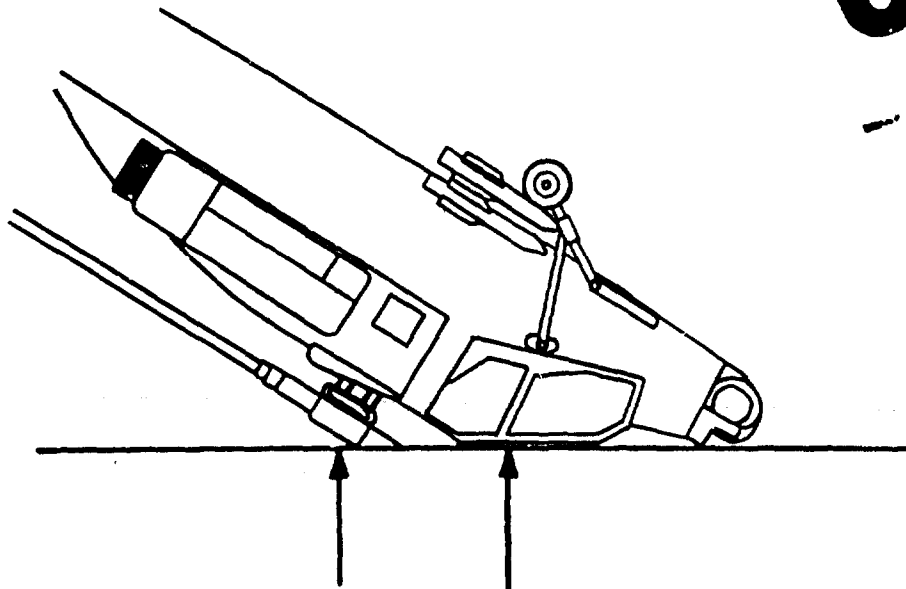
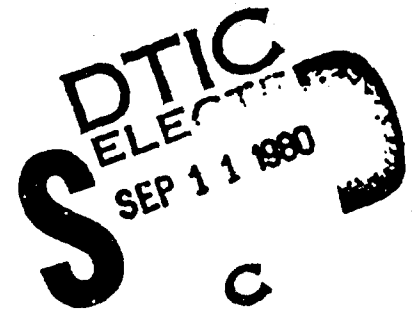
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**AIRCRAFT CRASH SURVIVAL DESIGN GUIDE
VOLUME III - AIRCRAFT STRUCTURAL CRASHWORTHINESS**

**SIMULA INC.
2223 SOUTH 48TH STREET
TEMPE, ARIZONA 85282**

AUGUST 1980

FINAL REPORT



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

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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 Report 71-22. This current edition consists of a consolidation of design criteria, concepts, and analytical techniques developed 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 interested personnel.

This document has been coordinated with USAAVRADCOM, the U. S. Army Safety Center, the U. S. Army Aeromedical Research Laboratory, 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. E. Bywaters, W. J. Nolan, and H. W. Holland of the Safety and Survivability Technical Area, Aeronautical Systems Division, Applied Technology Laboratory.

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

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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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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 III)~~ contains information on the design of aircraft structures and structural elements for improved crash survivability. Current requirements for structural design of U. S. Army aircraft pertaining to crashworthiness are discussed. Principles for crashworthy design are presented in detail for the landing gear and fuselage subject to a range of crash conditions, including impacts that are primarily longitudinal, vertical, or lateral in nature and those that involve more complicated dynamic conditions, such as rollover. Analytical methods for evaluating structural crashworthiness are described.

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PREFACE

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

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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.

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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 (AvSER) Division of the Flight Safety Foundation, Inc., 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 and other interested personnel. The document was to be a summary

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

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 Aircraft 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, accident information retrieval.

Volume III - Aircraft Structural Crashworthiness

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

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

Volume IV - Aircraft Seats, Restraints, Litters, and Padding

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 - Aircraft Postcrash Survival

Postcrash fire, ditching, emergency escape, crash locator beacons.

This volume (Volume III) contains information on aircraft structural crashworthiness. Following a general discussion of aircraft crashworthiness in Chapter 1, a number of terms commonly used in discussing the crash environment and aircraft structures are defined in Chapter 2. Chapter 3 presents a general discussion of aircraft types, principles for the design of crashworthy vehicles, and testing for evaluation of crashworthiness. Although Volume II discusses the crash environment in detail, a summary of information pertinent to aircraft structural design is presented in Chapter 4. Structural design and testing requirements for improved crashworthiness are described in Chapter 5. Principles and concepts for improving crashworthiness in aircraft structures are described in Chapter 6. Chapter 7 discusses analytical techniques for evaluating structural crashworthiness.

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 crashworthiness 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).
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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 Technologies 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 sufficiently 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 dictates 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 cannot absorb its share of the impact crash energy because of aircraft 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 performance on a component level only, and (2) requiring that the aircraft 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 requirements for seat and restraint systems are specified. All strength requirements presented in this volume are based on the crash environments described in Volume II. Testing requirements are based on ensuring compliance with strength and deformation 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, copilot, 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 during the development of completely new aircraft designs, the crashworthiness of existing aircraft can be significantly improved through retrofitting these aircraft with crashworthy components adhering to the design principles of this design

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.

guide. This can even be achieved while expanding the combat effectiveness of the aircraft. An example of this is the successful program to retrofit all U. S. Army helicopters with a crashworthy fuel system (Reference 15).

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 (as summarized in Figure 1) 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. Tradeoffs among the 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 of 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, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, November 1971, AD 739567.

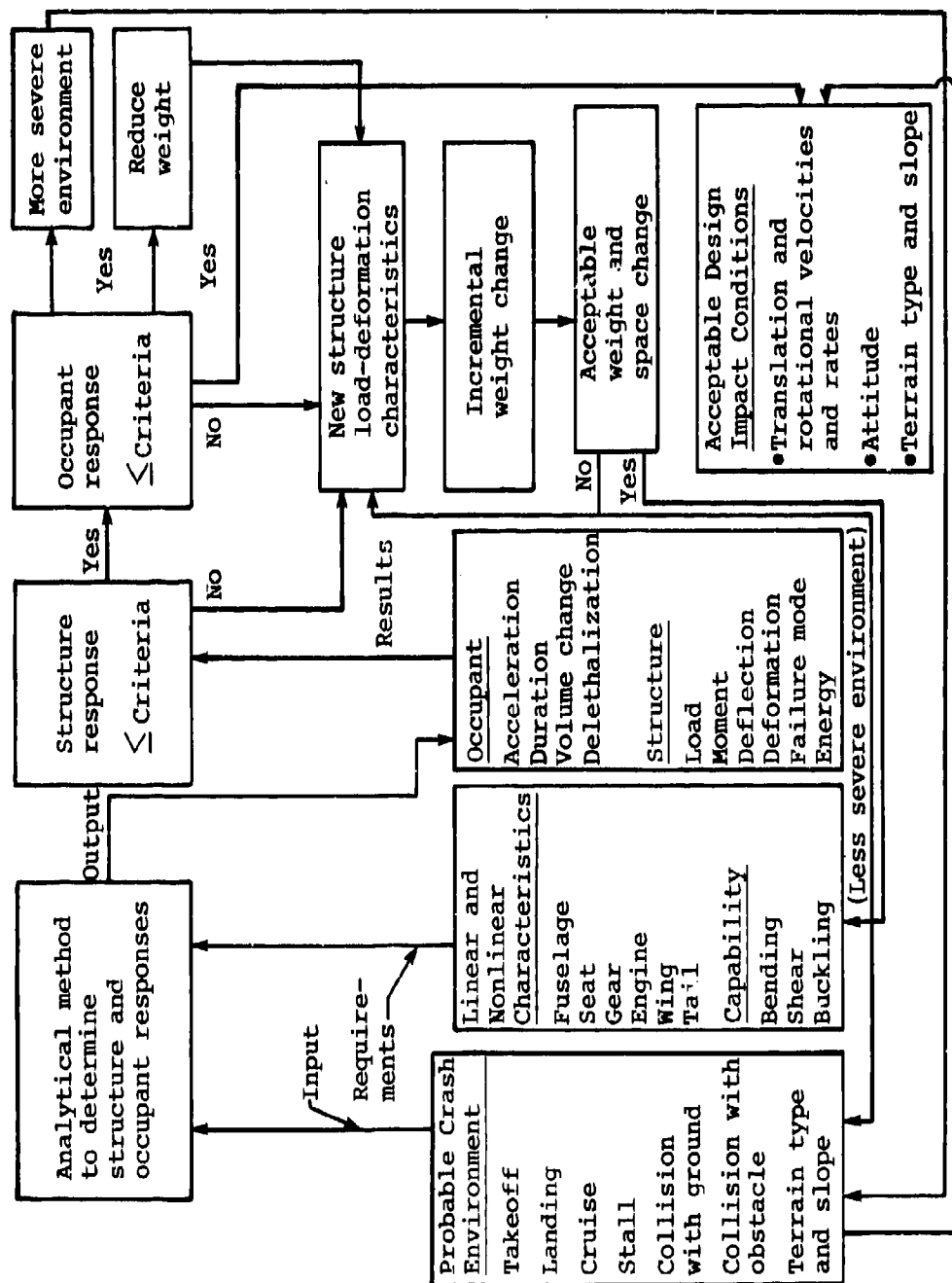


Figure 1. Procedure for evaluation of structural designs with respect to crashworthiness.

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 • Support of systems	• Landing gear • Controlled structural collapse	• Emergency egress • Occupant release from seats
• Single axis and combination of:	• Occupant support and protection	• Crashworthy energy-absorbing seats	• Door/exit opening
• Vertical impact	• Cargo containment and tiedown		• Accessibility of exits
• Longitudinal impact	• Support of landing gear loads	• Shedding of large mass items • Engines • Transmissions • Rotor heads • External stores • Tail boom (Shed items must not impact occupied areas)	• Minimization of postcrash fire hazards
• Lateral impact	• Space consistent with occupant strike envelope		• Fuel containment
• Postimpact	• Emergency exit structure		• Oil and hydraulic fluid containment
• Rollover			• Fuel modification
• Pitchover			• Ignition source control
• Nose plowing			• Reduce material flammability, smoke and toxicity

2. DEFINITIONS

2.1 AIRCRAFT COORDINATE SYSTEMS AND ATTITUDE PARAMETERS

- Aircraft Coordinates

Positive directions for velocity, acceleration, and force components and for pitch, roll, and yaw are illustrated in Figure 2. 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 2, with x, y, and z referring to the longitudinal, lateral, and vertical directions, respectively.

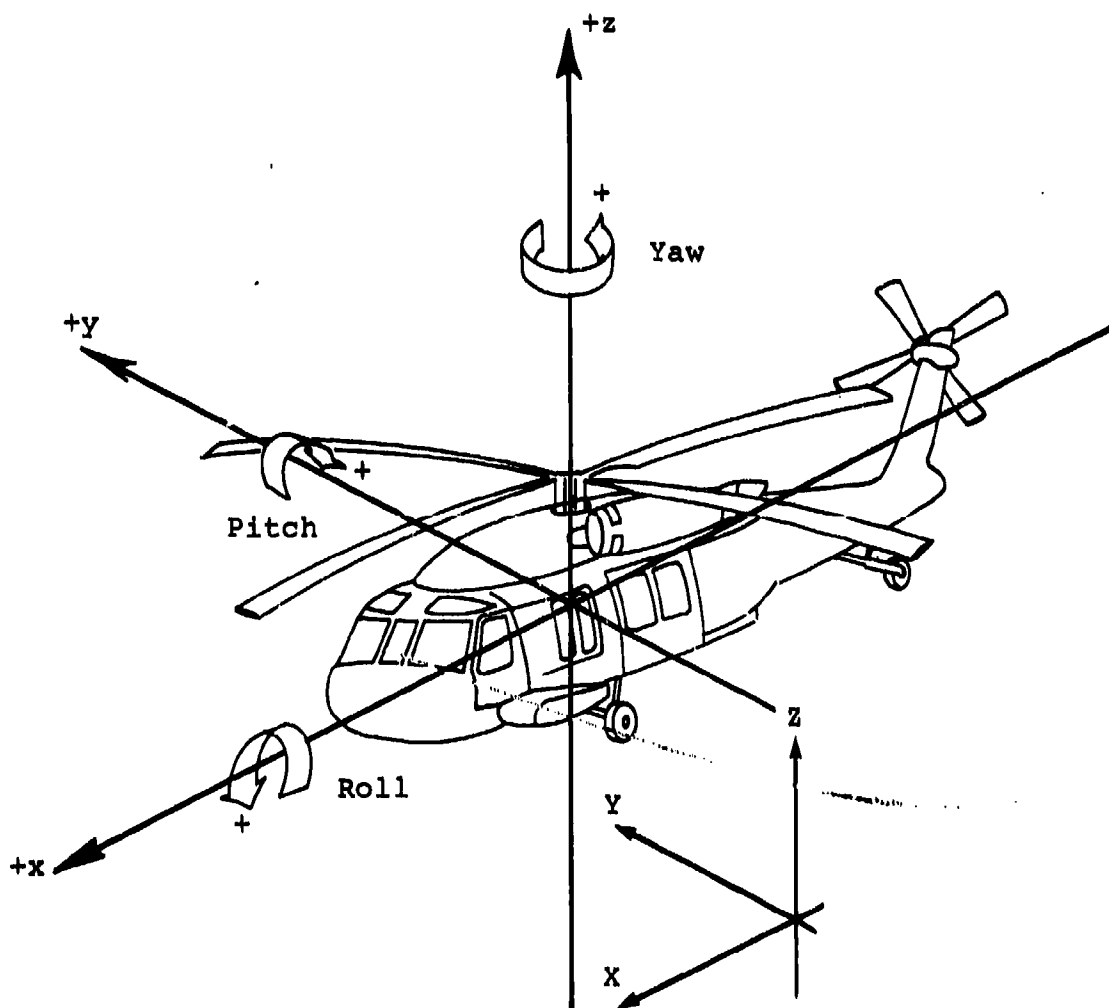


Figure 2. Aircraft coordinates and attitude directions.

However, care must be exercised when analyzing ground impact cases where structural failure occurs, aircraft geometry changes, and reaction loading at the ground plane takes place. In the simulation of such impacts, it is often necessary to use more than one set of reference axes, including the earth-fixed system shown in Figure 2 as X, Y, Z.

- Flight Path Angle

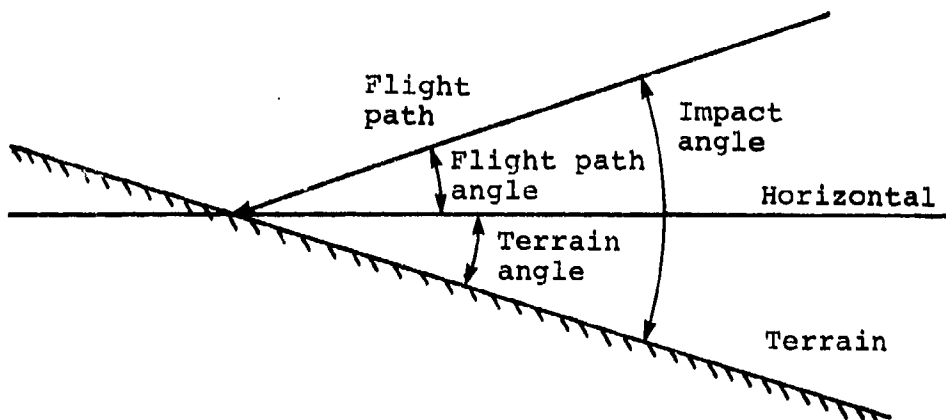
The angle between the aircraft flight path and the horizontal at the moment of impact. The algebraic sign of the Flight Path Angle is positive if the aircraft is moving downward immediately prior to impact. The sign is negative if impact occurs while the aircraft is moving upward.

- Terrain Angle

The angle between the impact surface and the horizontal, measured in a vertical plane. The algebraic sign of the Terrain Angle is positive when the direction of flight is uphill, and negative when the direction of flight is downhill.

- Impact Angle

The angle between the flight path and the terrain, measured in a vertical plane. The impact angle is the algebraic sum of the flight path angle plus the terrain angle.



- Attitude at Impact

The aircraft attitude in degrees at the moment of initial impact. The attitude at impact is stated in degrees of pitch, yaw, and roll (see Figure 2).

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/sec²). 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/sec².

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 are incurred, not necessarily the initial impact. For the acceleration pulse shown in Figure 3, the major impact should be considered ended at time t_2 . Elastic recovery in the structure will tend to reverse the direction of the aircraft velocity prior to t_2 . Should the velocity actually reverse, its direction 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.

- Longitudinal Velocity Change

The decrease in velocity during the major impact measured along the longitudinal (roll) axis of the aircraft. 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 would experience a longitudinal velocity change of 65 ft/sec during this impact.

- Vertical Velocity Change

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

- Lateral Velocity Change

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

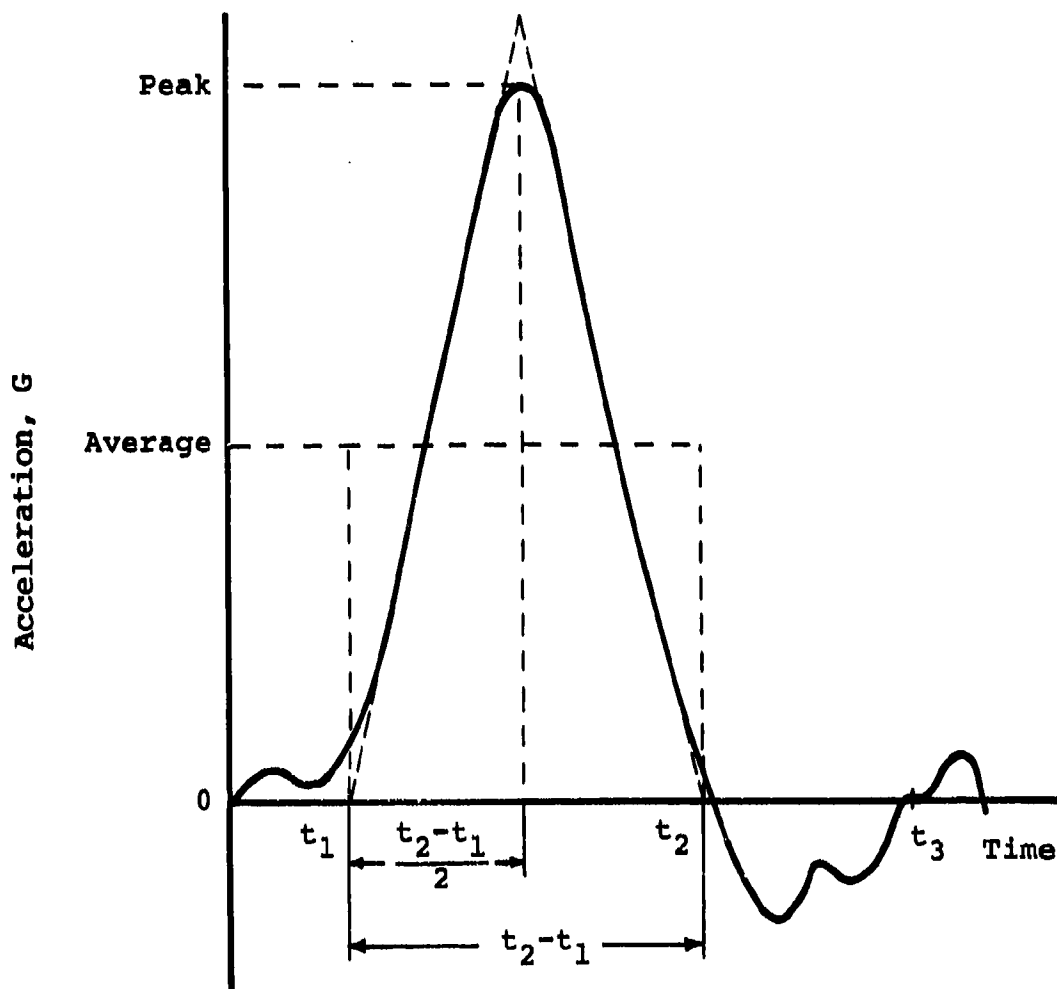


Figure 3. Typical aircraft floor acceleration pulse.

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 factor, when multiplied by a weight, produces a force 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 aircraft, parallel to the aircraft longitudinal (roll) axis.

- Aftward Load

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

- Downward Load

Loading in a downward direction parallel to the vertical (yaw) axis of the aircraft.

- Upward Load

Loading in an upward direction parallel to the vertical (yaw) axis of the aircraft.

- Lateral Load

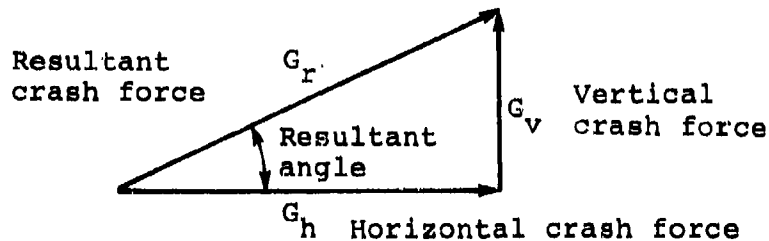
Loading in a direction parallel to the lateral (pitch) axis of the aircraft.

- Combined Load

Loading consisting of components in more than one of the directions described in Section 2.1.

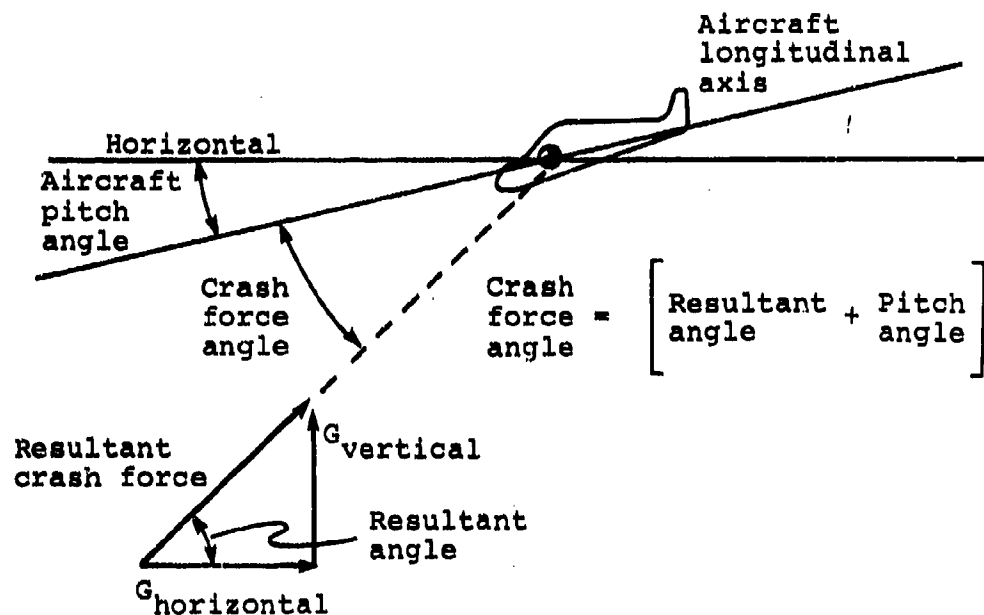
- Crash Force Resultant

The geometric sum of horizontal and vertical crash forces: horizontal and vertical velocity components at impact, and horizontal and vertical stopping distances. The Crash Force Resultant is fully defined by determination of both its magnitude and its direction. The algebraic sign of the resultant crash force angle is positive when the line of action of the resultant is above the horizontal, and negative if the line of action is below the horizontal.



- Crash Force Angle

The angle between the resultant crash force and the longitudinal axis of the aircraft. For impacts with little lateral component of force, the crash force angle is the algebraic sum of the crash force resultant angle plus the aircraft pitch angle.



2.5 DYNAMICS TERMS

- Rebound

Rapid return toward the original position upon release or rapid reduction of the deforming load, usually associated with elastic deformation.

- Dynamic Overshoot

The amplification of decelerative force on cargo or personnel above the floor 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). Transmissibilities maximize at resonant frequencies and may increase acceleration amplitude 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 4 (Reference 16). Terminology used throughout this guide is compatible with the NATO terms as illustrated.

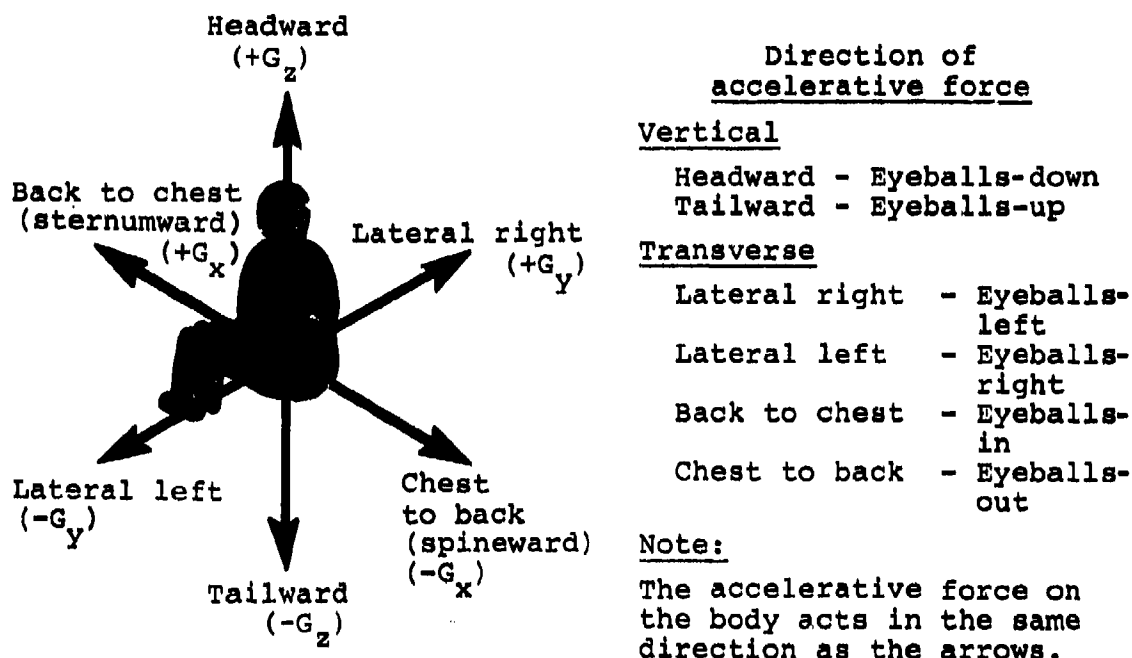


Figure 4. Terminology for directions of forces on the body.

● Anthropomorphic Dummy

A device designed and fabricated to represent not only the appearance of humans but also the mass distribution, joint locations, motions, geometrical similarities 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 response 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.

16. Gell, C. F., TABLE OF EQUIVALENTS FOR ACCELERATION TERMINOLOGY, Aerospace Medicine, Vol. 32, No. 12, December 1961, pp. 1109-1111.

- 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 probability for survival without major injury. As used in 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 the individual 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 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 localized 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.

2.8 STRUCTURAL TERMS

- Airframe Structural Crashworthiness

The ability of an airframe structure to maintain a protective shell around occupants during a crash and

to minimize 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.

- Strain

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

- 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 function.

- 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 a energy-absorbing device or structure divided by its weight. SEA is usually presented in inch-pounds per pound.

- Bottoming

With respect to energy-absorbing structure, bottoming is a condition in which the deforming structure or material becomes compacted and the load increases rapidly with very little increased deformation.

- Bulkhead

A structural partition extending upwards from the floor and dividing the aircraft into separate compartments. Seats can be mounted to bulkheads instead of the floor if sufficient strength is provided.

- Basic Structural Design Gross Weight (BSDGW)

The structural design gross weight is cited in the MIL-STD-1374, Part I, "Group Weight Statement-Dimensional and Structural Data", and is further explained in the detail system specification for the aircraft.

3. GENERAL DESIGN CONSIDERATIONS

3.1 AIRCRAFT TYPES - THEIR MISSIONS AND DESIGN RESTRAINTS

The mission of Army aviation is to augment the capability of the Army to conduct prompt and sustained combat incident to operations on land.

Army aviation supports the Army's ground combat function in the following areas:

- Command, Control, and Communications. Army aviation support includes courier and liaison missions, control of vehicular columns, message drop and pickup, command and control of airmobile operations, wire laying, and radio relay.
- Intelligence. Army aviation is an important means of gathering intelligence. It provides aerial "eyes" over the battlefield and conducts missions in support of aerial survey operations, aerial radiological survey, and target acquisition.
- Mobility. By airlifting troops and combat equipment, Army aviation provides an additional means of maneuver to the ground commander. Using Army aviation's airmobile capability, weapons may be emplaced rapidly and troops may be carried quickly over obstacles.
- Firepower. Army aviation, which provides aerial adjustment of indirect fires, is expanding the use of Army aircraft as weapon platforms to fill the gap between the support provided by conventional ground fire support and close air support.
- Combat Service Support. Army aviation supports logistical operations by providing delivery of troops and equipment and evacuation of casualties and damaged equipment within the Army combat zone.

3.1.1 Helicopters

The U. S. Army inventory of helicopters can be divided into five types by mission:

- | | |
|--------------------|-----------------|
| ● Observation (OH) | ● Cargo (CH) |
| ● Attack (AH) | ● Training (TH) |
| ● Utility (UH) | |

Figures 5, 6, and 7 show side elevations for typical helicopters to indicate comparative sizes and layouts. When considering a design for occupant protection, it becomes apparent that each type of helicopter poses different problems. The size, proximity of occupied areas to the ground impact plane, distribution of mass items and external stores, and the location of transparencies and cutouts for exits combine to provide the designer with major challenges in the efficient allocation of primary structure.

Figure 8 shows a helicopter whose design considered the parameters listed above. Notations indicate several major design features that must be incorporated into a primary structural matrix to satisfy the crashworthiness requirements of MIL-STD-1290(AV) (Reference 1).

3.1.2 Fixed-Wing Aircraft

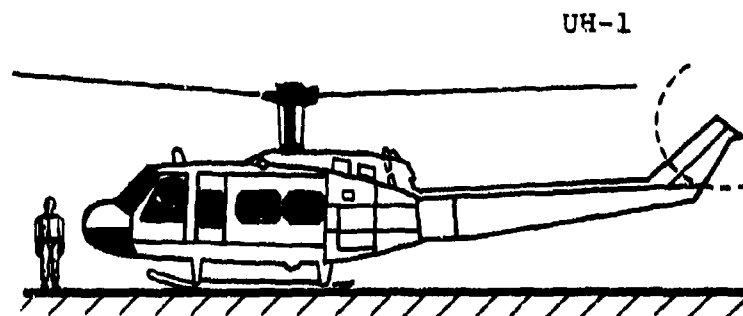
Side elevations of these aircraft types are shown in Figure 9. All, except for the OV-1, are military versions of commercial aircraft. The maximum capacity of any listed aircraft is a crew of two, with 20 passengers.

3.2 APPLICABILITY OF CRITERIA

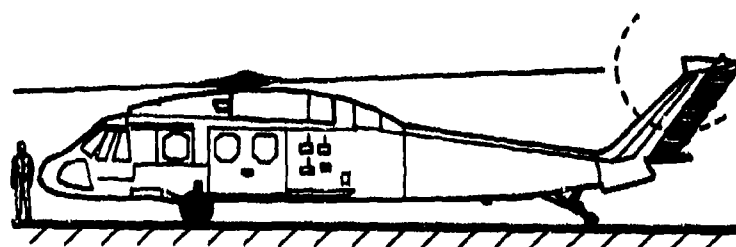
Information presented in this volume is generally applicable to all types and sizes of aircraft. The different operating characteristics and mission requirements of different aircraft types provide some likelihood of different crash conditions, which should be considered in designing for crashworthiness; however, experience in survivable accidents indicates that the impact environment--considering acceleration pulse shape, magnitude, and direction--is similar for all types of existing light fixed-wing and rotary-wing aircraft except for lateral impact. For lateral impacts, cargo and attack helicopters are grouped with fixed wing, while other helicopters appear to have a somewhat more severe environment. Where aircraft size or weight is an important factor, its effect is discussed. Whenever quantitative data concerning likely crash conditions or design requirements for improving crashworthiness in either existing or new aircraft are available, they are presented.

3.3 ACCEPTANCE OF STRUCTURES

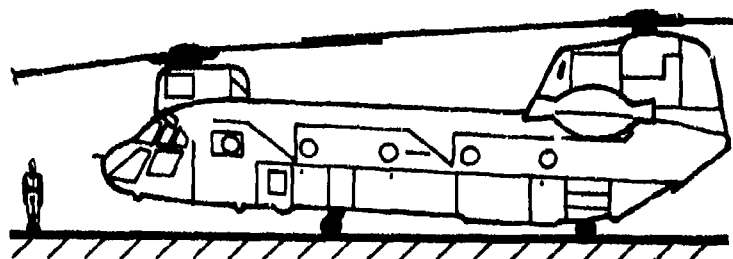
A standard airframe structure requirement has always been that the structure be capable of withstanding all loading conditions that may reasonably be expected to occur during any flight or ground handling operation. As understanding of various factors affecting airframe requirements, such as metal fatigue, has increased, the design criteria have been changed to reflect this



UH-60



CH-54



CH-54

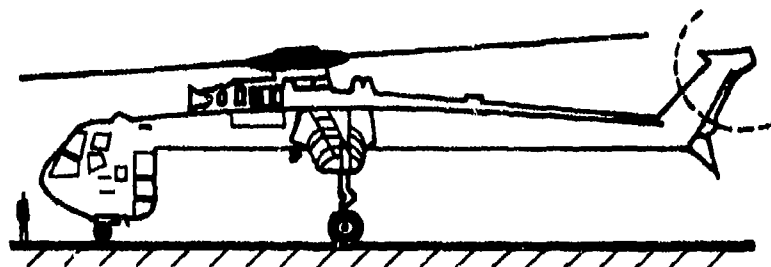


Figure 5. Side elevations of typical U. S. Army utility and cargo helicopters.

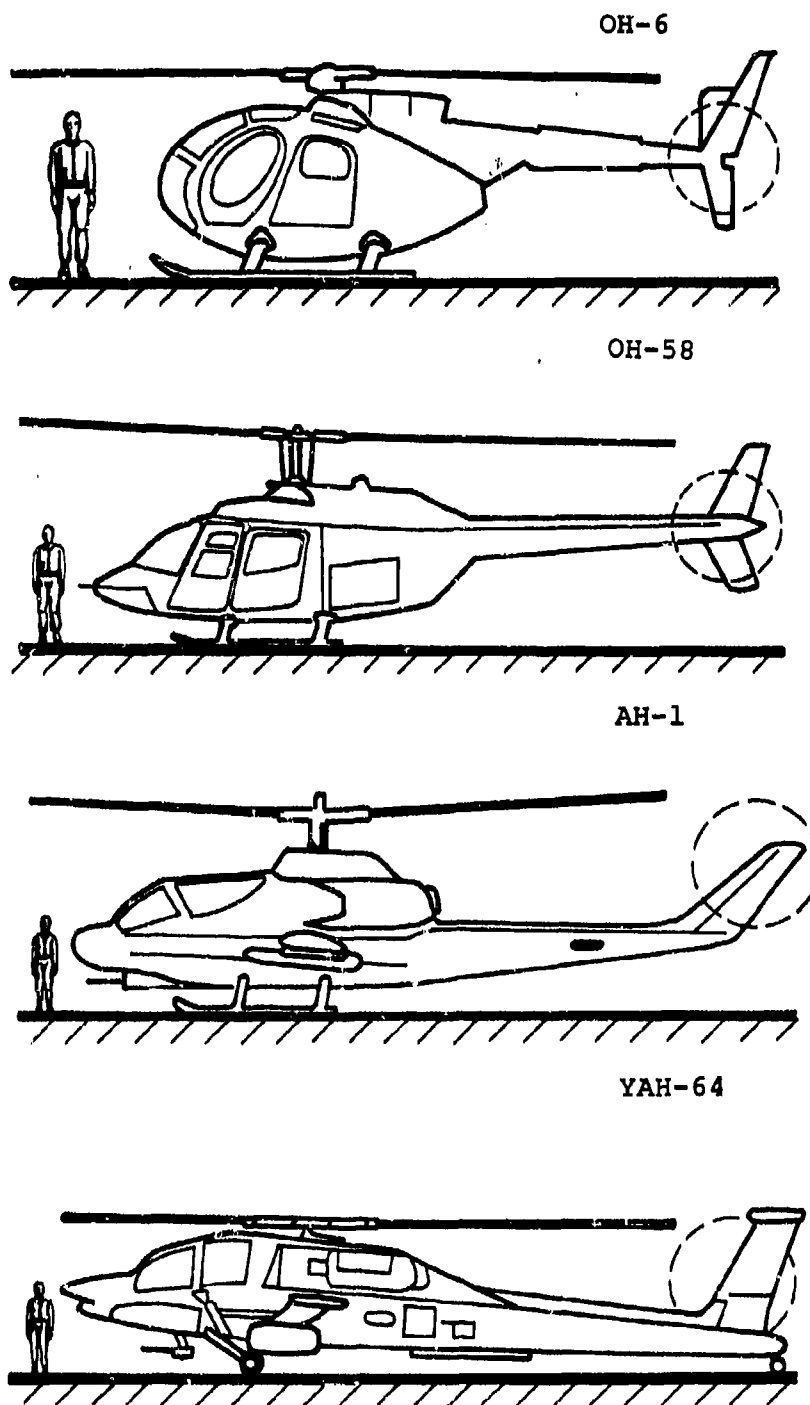


Figure 6. Side elevations of typical U. S. Army observation and attack helicopters.

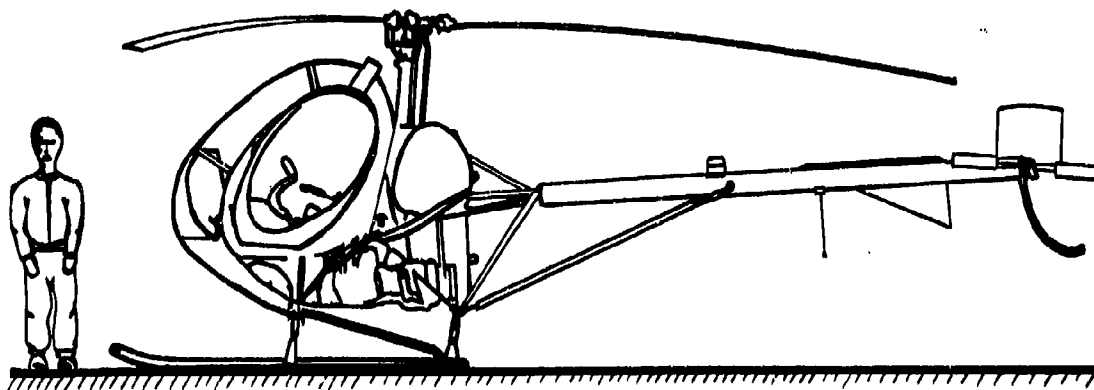


Figure 7. Side elevation of typical U. S. Army training helicopter.

new knowledge. Often, in designing aircraft structure, stringent requirements must be met even though it is understood that every available means will be used to avoid those design conditions. For example, aircraft are designed to withstand severe gust loads, even though it is never intended that they be deliberately flown into severe turbulence.

Both experience and reason indicate that as long as aircraft are flown, there will be accidents, and that these accidents will impose conditions that seriously threaten occupant survival. Although much effort will be directed toward avoiding crashes, acceptable aircraft structures should always provide the greatest possible degree of occupant protection from crash conditions. All available information should be considered in designing new aircraft structures to ensure that new designs will be acceptably crashworthy, as well as airworthy.

3.4 SELECTION OF STRUCTURES

The final design of a particular aircraft is the result of a series of compromises with respect to aerodynamics, strength, simplicity of fabrication, economics, etc. The additional requirement that crashworthiness become an important structural consideration will bring a need for further compromise and for good judgment in arriving at the compromise position. As more attention is directed toward airframe crashworthiness throughout the design stages, methods and techniques of construction will improve so that crashworthiness can be achieved without prohibitive weight and performance penalties.

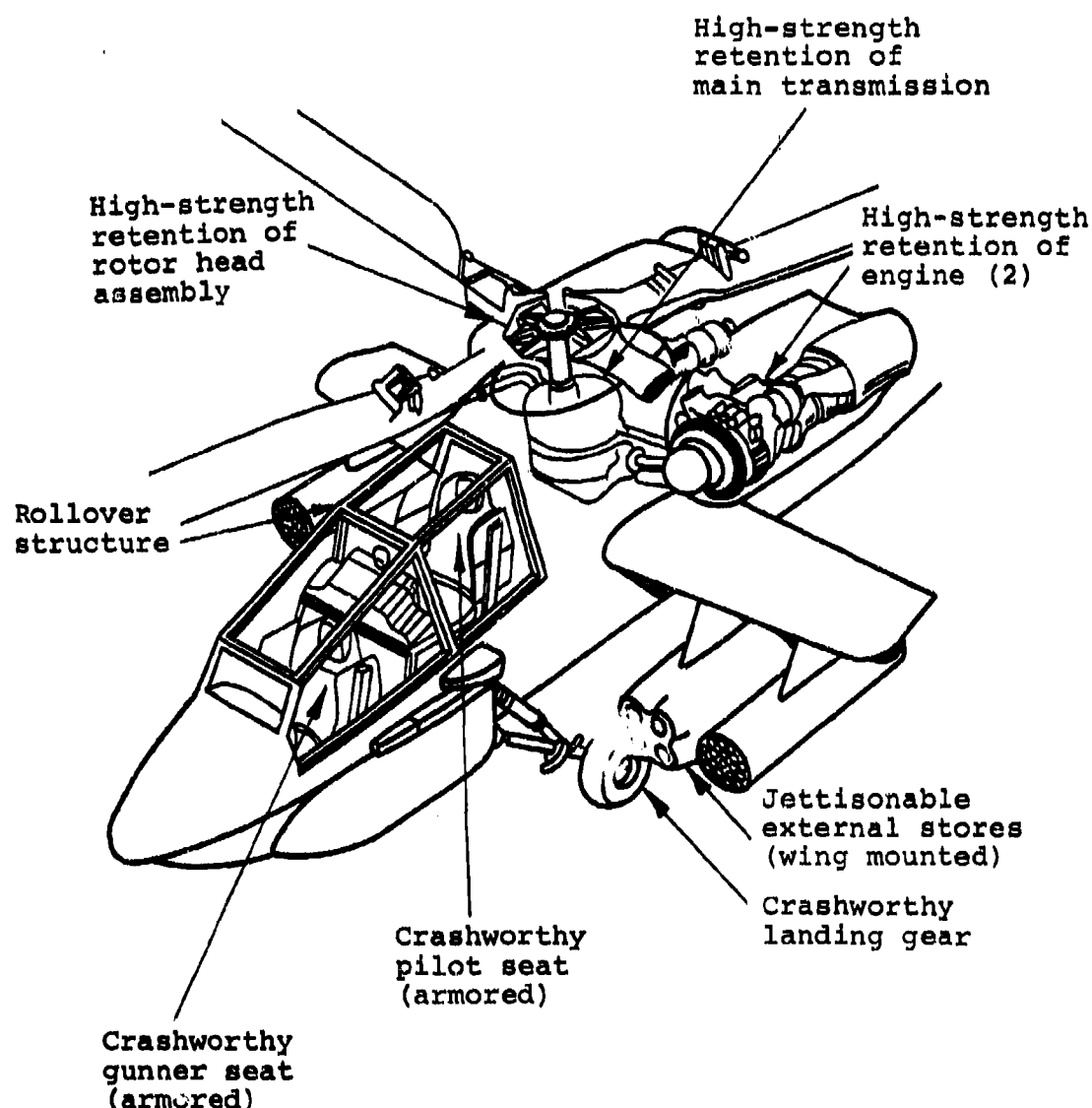


Figure 8. Selected helicopter crashworthy features.

When there is a choice between two designs which both adequately meet normal structural requirements, then the design which offers better crash protection should be chosen. Often, the upgrading of crashworthiness will not result directly from an increase in strength. Consideration of the deformations which are likely to occur, and ensuring that several parallel load paths are available to keep the structure intact even though localized damage occurs, will also improve crashworthiness.

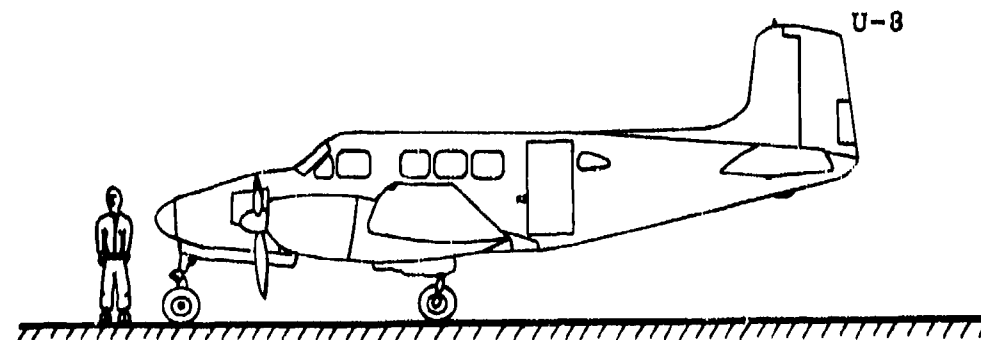
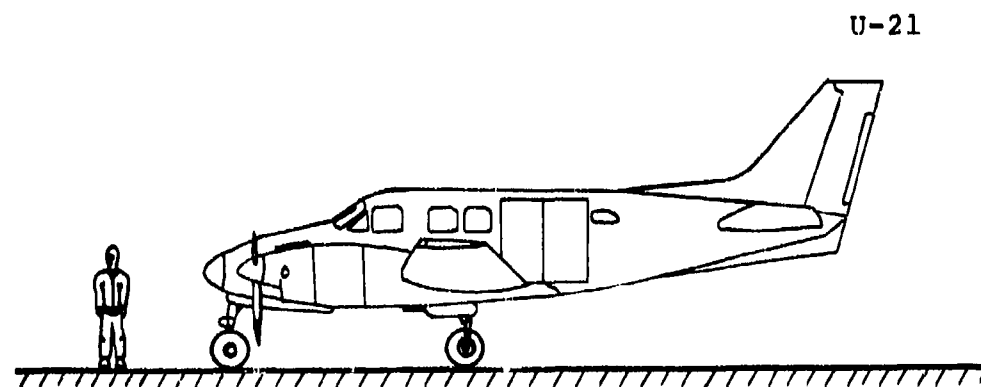
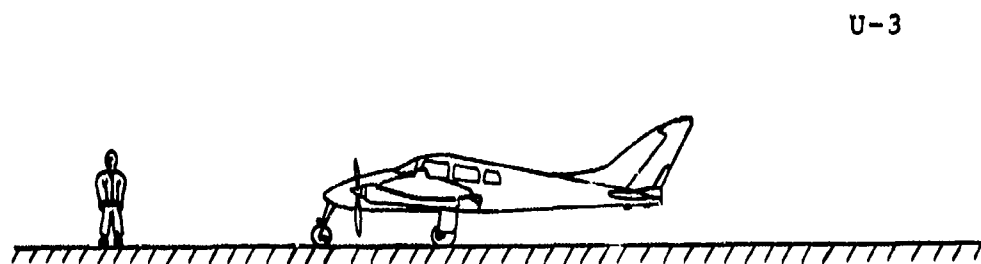
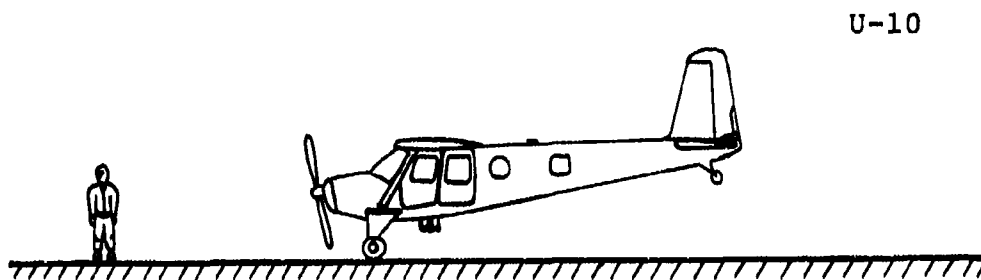
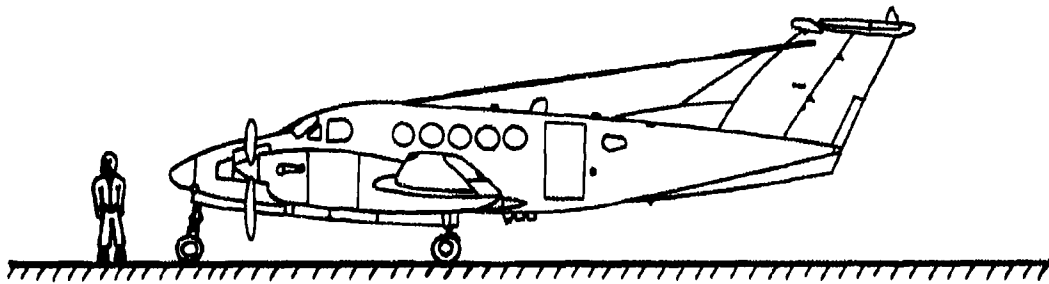
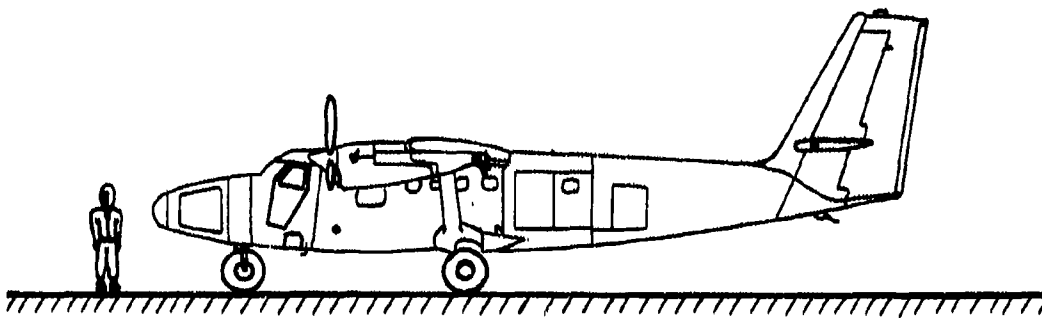


Figure 9. Side elevations of typical U. S. Army fixed-wing aircraft.

C-12



UV-18



OV-1

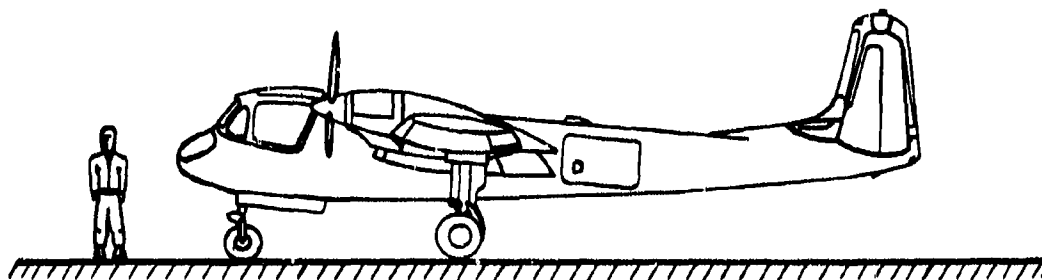


Figure 9 (contd). Side elevations of typical U. S. Army fixed-wing aircraft.

X
Excessively strong airframe structure is no more acceptable for crashworthiness than understrength structure. Not only will unnecessary strength impose a highly undesirable weight penalty, but also an excessively strong structure can develop high loads which may produce high accelerations of the aircraft during impact. These high-magnitude accelerations place severe demands upon occupant restraint systems. If these demands are not met, the extra structural strength can result in reduced survivability.

Structures which have insufficient strength, on the other hand, can permit occupant injuries due to loss of the protective shell.

3.5 TESTING

The present-day state of the art in analysis of structural behavior under crash impact conditions is such that accurate prediction of location and modes of collapse and failure and prediction of impact forces, accelerations, and deformations are not possible. For this reason, the use of full-scale dynamic crash testing to complement and substantiate analytic determination of airframe behavior is highly recommended. Such crash tests should be conducted under conditions similar to a severe survivable crash which could be expected to occur in service. When full-scale crash tests are conducted, test results should be carefully studied to provide information for design improvement and for background to improve future designs. During the development of new aircraft, testing should be conducted to demonstrate that the required design strengths are met.

In many instances, static and/or dynamic testing of only one component of the structure is necessary for validating certain aspects of crashworthiness of the aircraft; however, full-scale tests of the complete aircraft are recommended for proof of compliance for fuselage and related structures such as landing gear, engines, transmissions, and seat tiedown provisions.

4. CRASH ENVIRONMENT

4.1 INTRODUCTION

Aircraft impact conditions can vary considerably depending on the vehicle's attitude and velocity components, and on the characteristics of the impacted terrain.

A statistical analysis of accident data, summarized in Volume II, was used to define velocity changes occurring in the major impact for the 95th-percentile potentially survivable crashes. In addition, estimates of acceleration pulses experienced at the cabin floor level near the center of gravity of the aircraft were made for use in the definition of seat-occupant and cargo design environments. The data were obtained from investigations of light fixed- and rotary-wing aircraft accidents from 1960 to 1965 and from 1971 to 1976. The aircraft involved did not contain crashworthy structures, energy-absorbing seats, or crashworthy landing gear, thereby tending to increase occupant injury potential due to high accelerations at the floor plane in conjunction with seat collapse or breakaway. These data are summarized in Table 2.

The resultant velocity change for combined longitudinal, vertical, and lateral components of the 95th-percentile survivable accident of rotary- and light fixed-wing aircraft does not exceed 50 ft/sec. The vertical or lateral components do not exceed their individual 95th-percentile values, i.e., 42 ft/sec vertically, and 25 and 30 ft/sec laterally for light fixed-wing aircraft and attack and cargo helicopters, and for other helicopters, respectively.

Since deceleration loads are a function of the strength of the structure, a systems analysis should be performed to establish the distribution of energy-absorbing properties to the gear, fuselage, seats, etc. For new aircraft, the elements can then be designed to provide the required optimum properties. For older aircraft, certain elements in the chain cannot be changed; thus those that can be changed should be designed to make up for the deficient elements. For these older aircraft, which have not been subjected to a systems analysis, and for those in which certain key energy-absorbing elements, such as landing gear, might be lost before the element has absorbed its allotment of the crash energy, standard design environments have been established. These design environments are defined in terms of triangular acceleration pulses having the required peak accelerations, durations, and velocity changes and are presented in Table 2. For the situations described above,

TABLE 2. SUMMARY OF CRASH IMPACT CONDITIONS FOR HELICOPTERS AND LIGHT FIXED-WING AIRCRAFT DESIGN

Impact direction (aircraft axes)	Velocity change, Δv (ft/sec)	Peak acceleration (G)	Pulse duration, Δt (sec)	Comments
Longitudinal (Cockpit)	50	30	0.104	Triangular deceleration pulse: 
Longitudinal (Cabin)	50	24	0.130	
Vertical	42	48	0.054	
Lateral	25 ^a	16	0.097	Δt calculated from known or assumed values for G_{peak} and Δv : $\Delta t = \frac{2(\Delta v)}{g G_{peak}}$
	30 ^b	18	0.104	

- a) Light fixed-wing aircraft, attack and cargo helicopters.
b) Other helicopters.

these pulses should be used for the design of restraint systems, seats, cargo restraint, and other items inside the aircraft.

Certainly in the case of retrofit, the maximum crashworthiness possible within the restraints of the existing hardware should be provided. This may mean that a less severe design environment might be necessary for the achievement of maximum crashworthiness in a practical vehicle.

Figure 10 shows plots of combined longitudinal, lateral, and vertical velocity changes for helicopters to be used in determining intermediate velocity change components. For light fixed-wing aircraft and cargo and attack helicopters, Figure 10(b) will still be correct, but (c) and (d) must be altered for a lateral velocity change of 25 ft/sec instead of 30 ft/sec.

Figure 10(a) represents a three-dimensional display of the resultant velocity changes defined in 10(b), 10(c), and 10(d). In general, the three components are related by the equation

$$v_x^2 + v_y^2 + v_z^2 = v_R^2 \quad (1)$$

where v_x = longitudinal velocity change, ft/sec

v_y = lateral velocity change, ft/sec

v_z = vertical velocity change, ft/sec

v_R = resultant velocity change, ft/sec

and the axes are those illustrated in Figure 2. The curves terminate at 15 degrees above the x-y plane of the aircraft.

As mentioned in Section 5.3.1.4, impact accelerations for design of the overhead structure have been determined. However, these conditions are intended for aircraft inverting after impact, not those impacting in an inverted attitude. Therefore, no design velocity changes are presented here for impact on the upper parts of the aircraft.

It should be remembered that human survival is determined by acceleration magnitudes, durations, and rates of acceleration change actually experienced by the body, rather than by the aircraft velocity change. The preceding values for velocity change limitations act only as a guide for establishing crash energy content. A combination of structure, landing gear, and seat that allows a long stroking distance to absorb energy may well provide survival capability in crashes with velocity changes in excess of those shown.

The velocity change, acceleration, and pulse duration are useful in defining occupant impact loading environments in a crash sequence. However, other structural factors that can influence human survival in a crash impact must also be considered:

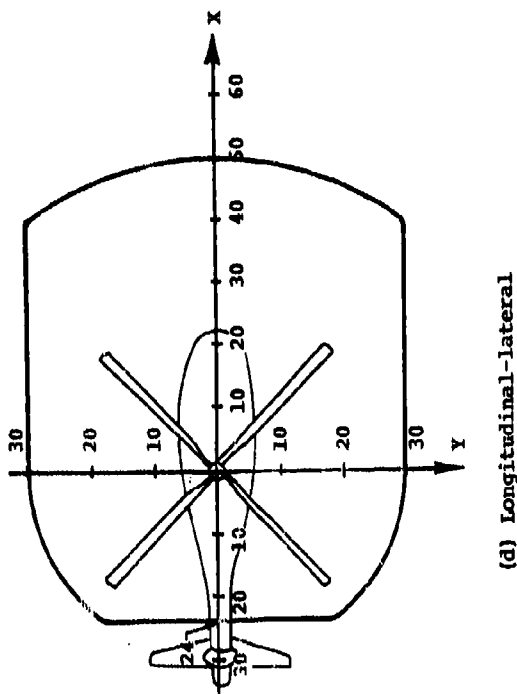
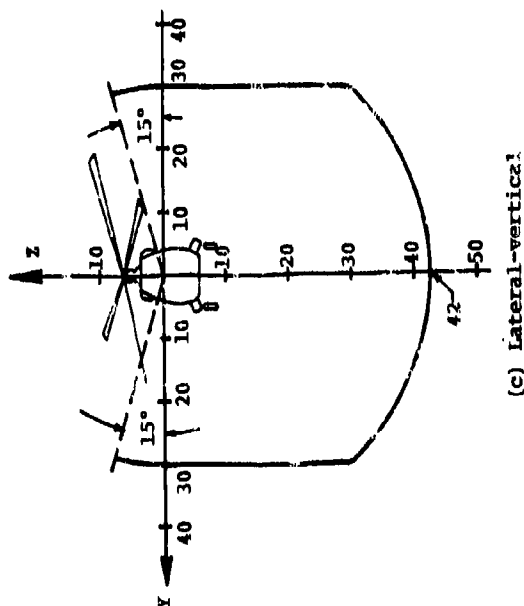
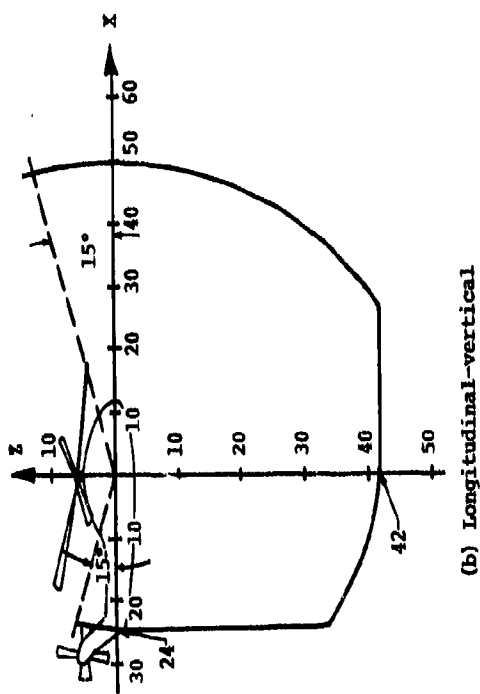
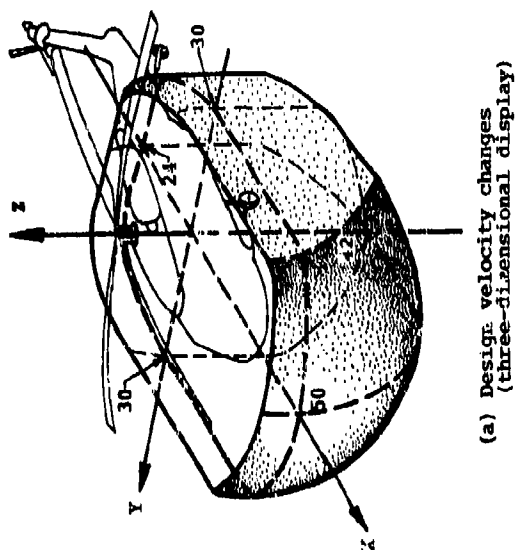


Figure 10. Design velocity change - off-axis requirements.

- Structural collapse and support of large mass items.
- Structural elastic deformation that may intrude into occupied areas.
- Structural penetration by aircraft components or external agents.
- Structural strength to ensure postcrash operation of emergency exits with adequate egress potential.
- Adequate structural strength to provide support for the seat and restraint system combination, as well as the landing gear.

Helicopters are often used in areas where fixed-wing aircraft cannot function and, of necessity, spend time maneuvering between obstacles at low forward velocities. Under such conditions, power failure at low altitude results in a predominantly vertical impact. Blade or fuselage impact with ground obstacles, such as overhead wires, trees, or buildings, can generate aircraft rotation with ground impacts occurring at roll attitudes as severe as 180 degrees; that is, completely inverted. (See Volume II, Section 3.4 for further information pertaining to helicopter attitude upon impact.)

Fixed-wing aircraft can impact with high vertical velocity if a stall occurs close to the ground plane with insufficient altitude to regain control. Impacts with a predominantly longitudinal velocity vector occur when aircraft are flown into inclined surfaces, mountains, ground obstacles, or when ground impact occurs with the aircraft in an extreme nose-down diving attitude. When an impact occurs with an obstacle located near the ground, i.e., overhead wires, trees, or buildings, the subsequent rotational motions can result in ground impact occurring at almost any attitude.

After the initial impact, subsequent aircraft decelerations, rotations, and secondary impacts are generally less severe for occupants. However, during this phase of the crash sequence, items such as rotor blades, transmission assemblies, engines, and external stores may become detached from the aircraft. These items may represent subsequent hazards if they impact occupied aircraft sections or cause postcrash fires by releasing flammable fluids in the presence of an ignition source. During the crash sequence, external agents that may penetrate occupied aircraft sections represent additional potential hazards; these include trees, ground equipment, metallic structures, etc.

Therefore, occupants must be protected not only from initial impact pulses, but also from secondary impacts, rotations, penetrations in critical sections, fire, and water hazards.

4.2 STRUCTURAL DAMAGE WHICH FREQUENTLY RESULTS IN OCCUPANT INJURY

Fixed-wing conventional aircraft and vertical takeoff and landing aircraft tend to experience similar structural loading for similar impact conditions, although the distribution of accident types may vary considerably between these two generic groups. The structural damage that produces occupant injury is generally the same for both types of aircraft. Structural damage in severe accidents cannot be avoided. However, improvements in airframe structure and optimization of element distribution can work to control the manner in which structural damage occurs so that a survivable environment is more likely to be maintained.

Usually, the structure that first contacts the impact surface is the first to begin to deform. This localized deformation continues until the kinetic energy of the aircraft is absorbed at low loads over relatively large distances, or until there is enough structure involved in the deformation to produce a significantly high decelerative force on the aircraft mass. If the quantity of kinetic energy to be absorbed is small, structural damage may be minor, and the aircraft may simply come to rest without endangering occupants. When the initial kinetic energy is high, there is a greater likelihood that structural damage will be severe and that forces will build up until total aircraft decelerative forces become large. Once these high decelerative forces are reached, buckling throughout the aircraft may occur. The protective shell is then compressed between the impact surface and masses aft or above the protective shell. It may become desirable to reduce the cabin deformation by allowing parts of the aircraft, such as wings and tail sections of fixed-wing aircraft, to break free from the cabin section during the impact. However, while this may reduce cabin deformation, it may produce no significant reduction of crash forces. This would mean that a higher acceleration level might be experienced within the cabin. The effects of mass reduction upon energy-absorption requirements for protective shell structure and its effects upon acceleration levels within the cabin are discussed further in Sections 6.6.5.5 and 7.2.5.

The following subsections define the general response of an aircraft for different impact conditions and injury-causing events that have frequently occurred.

4.2.1 Longitudinal (Crushing) Loads on Cockpit Structure

During longitudinal impact against soft earth, the aircraft nose structure is sometimes deformed in such a way that it forms a scoop that picks up earth as the aircraft slides along in contact with the impact surface. When this occurs, the scooped earth must be quickly accelerated to the velocity of the aircraft. This impulsive acceleration of the scooped-up earth mass produces momentary high forces that must be reacted by aircraft structure near the impact point. Often, the forward cockpit bulkhead must support this load, resulting in collapse of cockpit structure, entrapment of occupants, and injury to occupants' lower extremities. In addition, the high forces produce high aircraft accelerations, resulting in high loads on personnel and cargo restraint systems.

Sometimes in high-velocity accidents, the combination of nose structure crushing and friction between the structure and the terrain (particularly in "long-nose" aircraft) causes the forward structure to be pulled beneath the rest of the aircraft. This type of damage also causes rupture of the cockpit floor, and results in higher longitudinal acceleration than would be experienced if a smooth skid were maintained under the nose.

Longitudinal crushing also occurs during a crash in which a high angle of attack exists between the aircraft and the obstacle against which it crashes. This can result from a shallow-angle impact with terrain features such as a hillock or bank, or from a steep-flight angle impact with respect to relatively flat terrain. In these crashes, the aircraft nose usually crushes a sufficient distance to destroy the occupied section of the aircraft, thus providing a very poor chance for occupant survival.

4.2.2 Vertical (Crushing) Loads on Fuselage Shell

Collapse of the protective shell due to vertical loading often occurs in high-sink-rate accidents or rollover accidents. The collapse is often aggravated by the attachment of large masses to fuselage structure; these masses might be engines, transmissions, and rotor mechanisms in rotary-wing aircraft and high wings in fixed-wing aircraft. This damage results in loss of occupiable volume and crushing injuries or entrapment of occupants.

Also, if insufficient energy-absorbing structure is provided, or if the underfloor structure crushes only at excessively high loads, these high loads are transmitted to the occupants, resulting in compressive spinal and associated injuries.

4.2.3 Lateral (Crushing) Loads on Fuselage Shell

Lateral impact of utility helicopters occurs frequently and produces a hazardous environment. A 1971 study showed that over half of severe utility helicopter crashes result in roll-over or side impact (Reference 17). Eyewitnesses of crashes in which landing or hovering helicopters caught rotor blades on trees or other obstacles report that the helicopters tend to flip on their sides and rise to a height of approximately 15 ft before crashing. Since the sides of the fuselage are not usually designed for crash protection, severe injuries can result from relatively minor accidents.

Occupants are placed close to the sides of the fuselage, and often their restraint systems, such as lap belts used alone or with gunner tethers, are not adequate to restrain the occupants laterally. On many occasions, the doors have been removed previously or are lost during the crash. The occupant is then exposed to a variety of hazards, including being bodily ejected and crushed, having protruding body parts entrapped and mangled, or being violently impacted against the side of the fuselage. Injuries and fatalities then can result from crushing, dismemberment, loss of blood, excessive G loads, entrapment or debilitation, and exposure to fire and other postcrash hazards.

4.2.4 Transverse (Bending) Loads on Fuselage Shell

Rupture or collapse of the protective shell often occurs due to the high bending loads during rapid pitch change associated with longitudinal crashes at moderate-to-high impact angles. Rupture of the protective shell exposes occupants to injury through direct contact with the impact surface, contact with jagged metal, and loss of restraint. Miscellaneous equipment also may strike occupants after breakup of the aircraft.

4.2.5 Deformation (Buckling) of Floor Structure

Breakup of floor structure often indirectly accounts for occupant injury. In most aircraft, occupant and cargo restraint depends heavily upon the integrity of the floor structure. When this structure fails, restraint is lost. Often floor failure is caused by crushing of underfloor supporting structure. Localized damage is frequently caused when fuselage-mounted landing gear are driven into the floor structure.

17. Haloy, 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.

4.2.6 Landing Gear Penetration of Fuselage Shell

Landing gear failures often result in personnel injuries, either directly (as mentioned above) or indirectly, through fire exposure caused by rupture of ignitable fluid lines and tanks. Attention must be focused on a landing gear design and location that will prevent penetration into livable space or into any part of flammable fluid systems.

4.2.7 Helicopter Lateral Rollover

In helicopter accidents, rollover invariably causes the main rotor blades to strike the ground. This contact involves two potential hazards: displacement of the transmission and intrusion of blades into occupied areas.

Transmission displacement is controlled basically by the strength of its mounts. The problem has been found to be reduced in aircraft with fully articulated main rotor hubs, where the blades tend to destroy themselves without transferring excessively high crash loads to the transmission. However, a high inertia main rotor affords a pilot some additional margin during a powerless autorotation, thereby reducing the frequency and severity of accidents. The majority of Army helicopters have a high inertia main rotor, so it must be assumed that blade impact loads will be transferred to the transmission and reacted by its mounts.

Hazardous blade intrusion is minimized by using a combination of longitudinal and lateral beams in the cockpit overhead structure. The lateral beams can act to deflect the rotating blades while the longitudinal members provide a continuous support.

4.2.8 Rupture of Flammable Fluid Containers

Rupture of structure surrounding ignitable fluid containers or transfer lines is often an indirect cause of occupant injury as a result of postcrash fire. Structural members surrounding flexible (bag) fluid containers should not fracture in a manner that causes penetration of the container. Penetration resistance may also be improved by the use of a foam liner, as described in Section 6.6.5.8.

5. DESIGN REQUIREMENTS

5.1 INTRODUCTION

A crash can involve a wide range of dynamic conditions, from a simple unidirectional impact to a complex combination of rotational and multidirectional impact conditions. The current requirements for Army light fixed- and rotary-wing aircraft are summarized in Table 3. Any light aircraft designed to similar criteria would exhibit improvements in crashworthiness.

When a crash does occur, the service life of the aircraft is usually ended, and the only structural requirement is to provide occupant protection. In order to accomplish this, structure must be allowed to crush and deform in a controlled, predictable manner so that forces and accelerations imposed upon occupants will be minimized while still maintaining the protective shell. This means that any analysis for crashworthiness must consider the large deflections of structural members and joints as well as loading in the plastic range of stress. Excessively strong airframe structure is no more acceptable than understrength structure for crashworthiness. Not only will unnecessary strength result in an unacceptable weight penalty, but on impact, high G levels that compromise occupant survivability may be generated.

5.2 GENERAL REQUIREMENTS

Aircraft systems should be designed to prevent occupant fatalities and minimize the number and severity of occupant injuries during crash impacts of the severity of up to those defined in Chapter 4 while minimizing, to the maximum extent practical, aircraft damage. This should be achieved by selecting the most effective mix of the crashworthiness factors listed below and by complying with the detail requirements cited in Section 5.3.

Design impact velocity changes are presented in Table 2. These velocity changes are for the major impact, assumed to occur on a rigid surface and with a triangular acceleration-time pulse shape.

Probability of occupant survival during crash impacts will be increased if proper attention is given to the following features that influence crash survivability during the initial design stages of the aircraft system:

- Airframe protective shell
- Tiedown strength
- Occupant acceleration environment

TABLE 3. PERFORMANCE REQUIREMENTS FOR STRUCTURAL CRASHWORTHINESS

Impact direction	Impacted surface	Velocity differential (ft/sec)	Vehicle attitude limits	Percentage volume reduction	Other requirements	Data source
Longitudinal	Rigid	20		No hazard to pilot/copilot	Does not impede postcrash egress	Volume II
		40		15 max. length reduction for pass./troop compartment	Inward buckling of side walls should not pose hazards	MIL-STD-1290 Volume II
Lateral	Rigid	30	±20° Yaw	15 max. width reduction	Lateral collapse of occupied areas not hazardous. No entrapment of limbs.	MIL-STD-1290 Volume II
Vertical	Rigid	42	+25°/-15° Pitch ±20° Roll	15 max. height red. in pass./troop compartment	G loads not injurious to occupants	MIL-STD-1290 Volume II
Resultant	Rigid	50	Combination	As above for various components	Max. velocity changes: long. = 50 ft/sec vert. = 42 ft/sec ^a lat. = 30 ft/sec ^b 25 ft/sec ^c	MIL-STD-1290 Volume II
Rollover	Earth	-	90° sideward or 180° inverted or any intermediate angle	Minimal (door hatches etc. assumed to be non-load carrying)	Forward fuselage buried to depth of 2 in. (inverted or on side). Load uniformly distributed over forward 25% of occupied fuselage length. Can sustain 4 G without injury to seated and restrained occupants. All loading directions between normal and parallel to skin to be considered.	MIL-STD-1290
Rollover (post-impact)	Rigid		Two 360° rolls (max.)	15 max. volume reduction (5% desired)		MIL-STD-1290
Earth plowing & scooping (longitudinal)	Earth	-	-	-	Preclude plowing when forward 25% of fuselage has uniformly applied vertical load of 10 G and rearward load of 4 G or the ditching loads of MIL-A-008865A, whichever is the greatest. Aircraft deceleration at normal G.W. for impact with no fuselage to ground contact. All other A/C structural parts, except blades, should be flight-worthy following crash.	MIL-STD-1290
Landing gear	Rigid	20	±10° Roll ±10° Pitch	None. Plastic deformation of gear and mounting system allowable		MIL-STD-1290
Landing gear	Sod	100 long. ^a 14 vert.	-5° Pitch ±10° Roll ±20° Yaw	15 max. volume reduction (5% desired)	No rollover, or if rollover occurs, two 360° rolls without fuselage crushing	MIL-STD-1290 Volume II

a) Light fixed-wing aircraft, attack and cargo helicopters.

b) Other helicopters.

c) Velocity at impact, not differential.

- Occupant environment hazards
- Postcrash hazards.

5.3 DETAIL REQUIREMENTS

5.3.1 Airframe Crashworthiness

The aircraft structure should provide a protective shell for vehicle occupants in crashes of the severity cited in Table 2; moreover, the structure should allow deformation in a controlled, predictable manner so that forces imposed upon the occupant will be minimized while still maintaining the protective shell. In structural areas where large structural deformations are anticipated, joints and attachments should be designed to withstand large angular deflections and/or large linear displacements without failure. All exterior surfaces and all structures which could be exposed to contact with the impact surface should be constructed of materials which characteristically resist sparking as a consequence of abrasion. Unless otherwise stated herein, the aircraft basic structural design gross weight (BSDGW) should be used for the vehicle weight in the analyses described below. Directions are assumed with respect to the aircraft (Figure 2) unless otherwise stated.

5.3.1.1 Longitudinal Impact

5.3.1.1.1 Impact Conditions: The basic airframe should be capable of impacting longitudinally into a rigid abutment or wall at a contact velocity of 15 ft/sec without crushing the pilot and copilot stations to an extent which would either preclude pilot and copilot evacuation of the aircraft or otherwise be hazardous to the life of the aircraft occupants. For such an impact, the engine(s), transmission, and rotor system for helicopters should remain intact and in place in the aircraft except for damage to the rotor blades. The basic airframe's capability to impact longitudinally into a rigid abutment or wall at a contact velocity of 40 ft/sec without reducing the length of the passenger/troop compartment by more than 15 percent shall be demonstrated analytically. Any consequent inward buckling of walls, floor, and/or roof should not be hazardous to the occupants and/or restrict their evacuation. The aircraft should also be designed to withstand impact as in a low angle, missed approach; the impact conditions of this type accident are illustrated in Figure 11. These impact conditions in plowed soil can result in a rollover, and rollovers can be critical for inward crushing and/or separation of the fuselage as shown by past experience. The volume of the cockpit for the occupied passenger/troop compartment should not be reduced by more than 15 percent (5 percent desired) for these conditions.

IMPACT CONDITIONS

1. Assume loose plowed soil
2. Aircraft pitch (β) = 5 degrees nose down
3. Aircraft roll (ϕ) = +10 degrees
4. Aircraft yaw (γ) = +20 degrees
5. Flight path angle (α) = 8 degrees
6. Impact airspeed = 60 knots

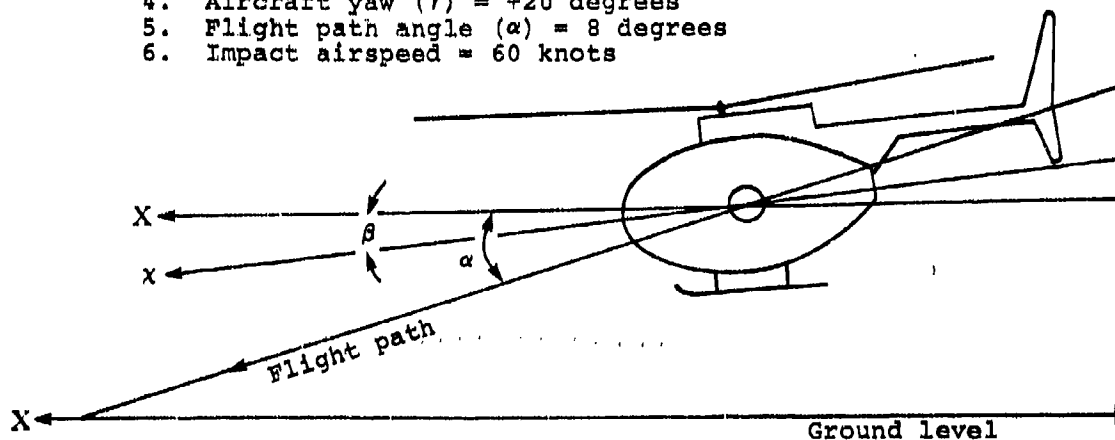


Figure 11. Low angle impact design conditions (simulated approach with antitorque loss under poor visibility).

Should the aircraft turn over, the fuselage container should maintain structural integrity for a minimum of two 360-degree rolls. The static loads to be considered for rollover analysis are described in Section 5.3.1.4.

5.3.1.1.2 Earth Scooping Effects: Design features for reducing the earth scooping effects encountered in longitudinal impacts should include the following:

- Provide a large, relatively flat surface in those areas which could otherwise gouge or plow, thereby increasing the aircraft's tendency to slide over the impact terrain.
- Minimize inward buckling of the fuselage nose or engine nacelle for the purpose of maintaining skid surface integrity.
- The nose section should be designed to preclude any earth plowing and scooping tendency when the forward 25 percent of the fuselage has a uniformly applied local upward load of 10 G and an aft load of 4 G, as shown in Figure 12.

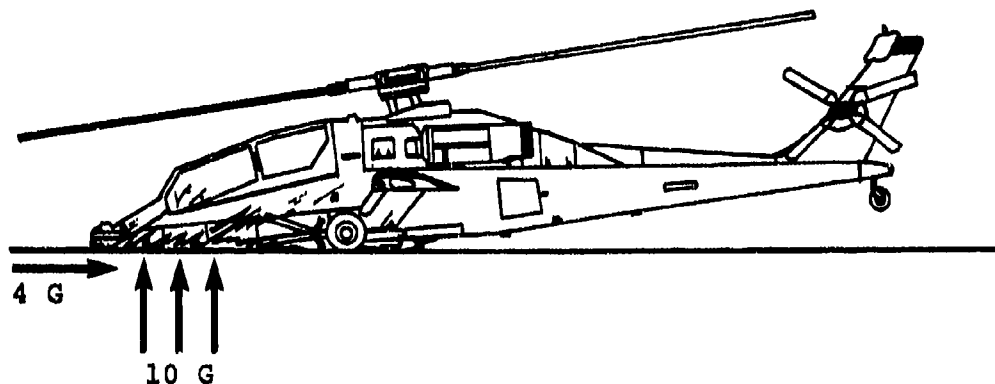


Figure 12. Nose section design conditions.

5.3.1.1.3 Buckling Effects: To minimize hazards to personnel created by buckling of the structure, the aircraft should be designed to:

- Provide sufficient strength of structure to prevent bending or buckling failure of the fuselage.
- Position personnel away from likely fuselage fracture areas.
- Have the fuselage buckle outward, if at all possible, rather than inward into living space when its collapse strength has been exceeded.
- Include cargo tiedowns that will restrain cargo should fuselage bending failure occur.

5.3.1.1.4 Floor: The floor structure should possess sufficient strength to carry, without failure, loads applied by the occupants and cargo restraint systems in impacts of the severity cited in Table 2.

5.3.1.2 Vertical Impact

5.3.1.2.1 Impact Conditions: The aircraft should possess the capability to withstand an impact velocity of 42 ft/sec vertically, with respect to the ground, without reducing the height of the cockpit and passenger/troop compartments by more than 15 percent and/or causing the occupants to experience injurious accelerative loading. For this analysis, the aircraft orientation (attitude) upon impact should be any attitude within +25/-15-degrees pitch and +20-degrees roll.

5.3.1.2.2 Design Application: Design applications for accomplishing the above goal should include the following:

- To the greatest extent feasible, locate massive items in lower fuselage locations rather than in upper fuselage locations.
- Increase cockpit and cabin vertical strength and stiffness to prevent the structure from crushing occupants.
- Provide crash-force attenuating structure beneath cockpit/cabin flooring.
- Provide load-limiting landing gear capable of absorbing as much of the crash energy as practical.

5.3.1.3 Lateral Impact: The aircraft should have the capability to withstand lateral impacts into a rigid barrier/wall of 25 ft/sec for light fixed-wing and cargo and attack helicopters and 30 ft/sec for other rotary-wing aircraft without reducing the width of occupied areas by more than 15 percent or permitting the lateral collapse of occupiable portions of the aircraft to an extent that would be hazardous to life. Precaution should be taken during design of the vehicle to minimize the chance of the occupant or his extremities being trapped between the structure and any impacting surfaces following failure of doors, canopies, or hatches.

5.3.1.4 Rollover Impacts: The aircraft should be designed to resist an earth impact loading as occurs when the aircraft strikes the ground in either a 90-degree (sideward) or 180-degree (inverted) attitude. A rollover accident should not cause an injury due to structural intrusion into occupied areas. It should be assumed that the forward fuselage roof is buried to a depth of 2.0 in. in soil for the inverted attitude and that the load is uniformly distributed over the forward 25 percent of the occupiable fuselage length. It should also be assumed that the forward fuselage side is buried to a depth of 2.0 in. in soil for the sideward attitude and that the load is uniformly distributed over the forward 25 percent of the occupiable fuselage length. The fuselage should be capable of sustaining a 4-G (i.e., 4.0 x aircraft BSDGW) load applied over the area(s) described for either the inverted or sideward attitudes shown in Figures 13 and 14 respectively, without permitting sufficient deformation to cause injury to seated, restrained occupants. For both cases (Figures 13 and 14), the 4-G distributed load should be analyzed for any angle of load application ranging from perpendicular to the fuselage skin (i.e., compressive loading) to parallel to the fuselage skin

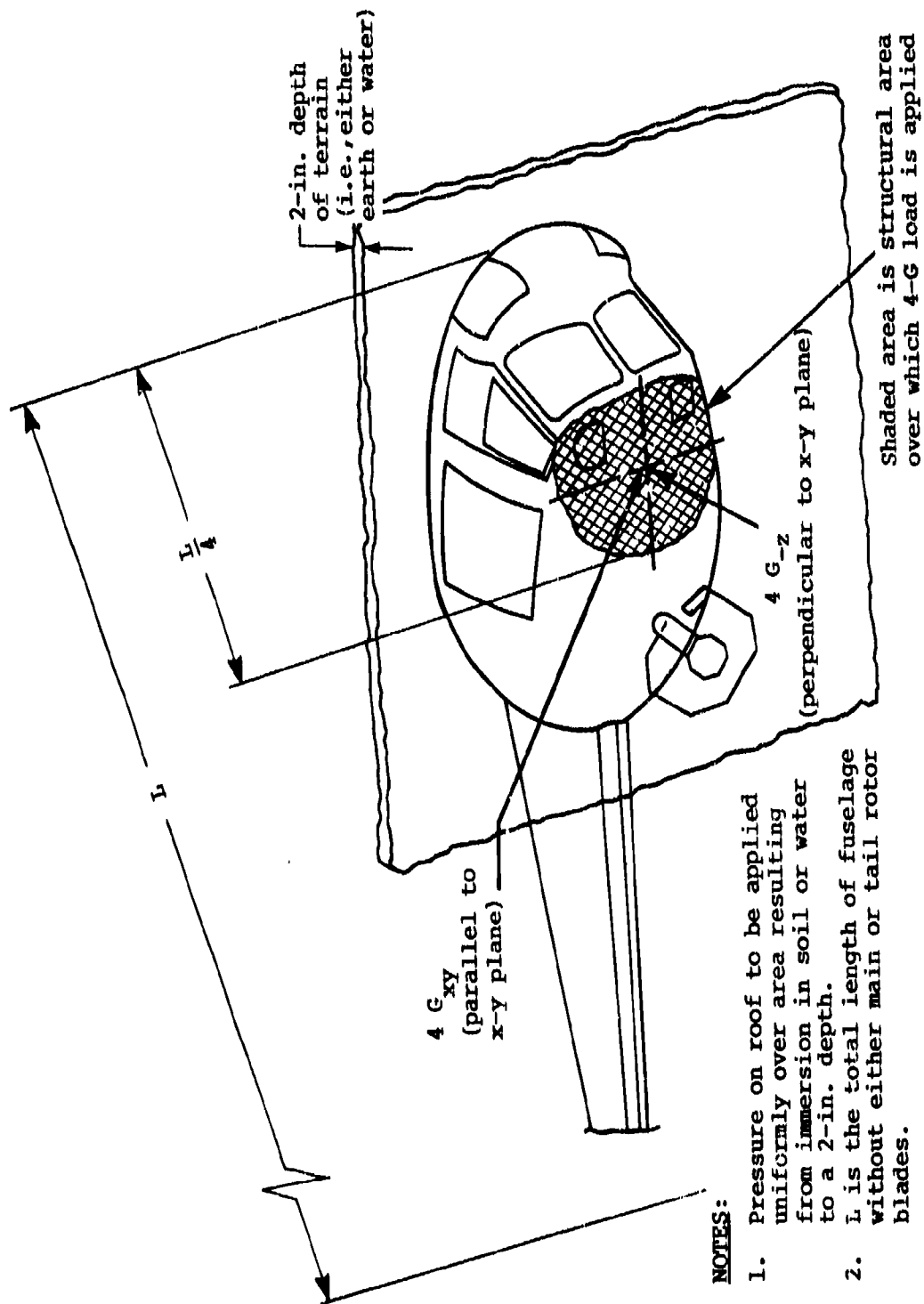


Figure 13. Rollover, roof impact design condition.

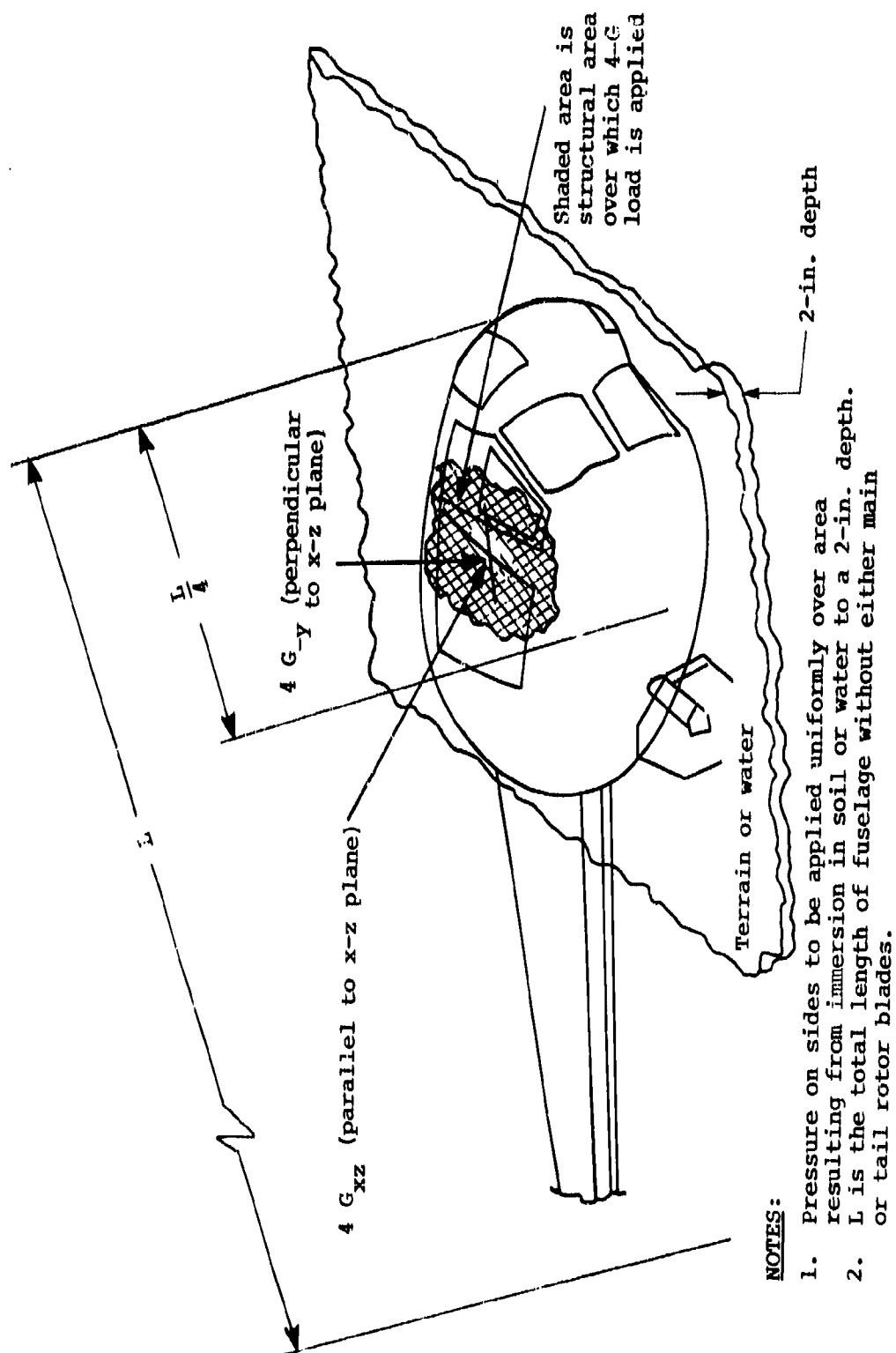


Figure 14. Rollover, side impact design condition.

(i.e., shear loading). When designing for this condition, it should be assumed that all doors, hatches, transparencies, canopies, and similar openings cannot carry any loading.

5.3.1.5 Wings and Empennage: Wing design should possess frangible characteristics to allow wings to break free from the fuselage under high longitudinal inertia loads for distributed impact loads caused by striking a barrier such as an earth mound. Empennage structure should be designed to collapse or break away during longitudinal crash impact.

5.3.1.6 Engine/Transmission Mounts: For light fixed-wing aircraft, engine mounts, both on the engine and on the supporting structure, should be designed to keep the engine attached to the basic structure supporting the mount under the crash conditions cited in Table 2, even though considerable distortion of the engine mount and support structure occurs. The basic structure supporting the engine should fail or separate before engine mount failure occurs. Engine mounts and supporting structures, including firewall bulkheads, should be designed to minimize earth scooping. Engine casing design should be compatible with these requirements.

Transmissions and rotor masts of helicopters should be designed to prevent potentially hazardous displacement or tilting under the crash conditions cited in Table 2. The transmission, rotor mast, rotor hub, and rotor blades should not displace in a manner hazardous to the occupants during the following impact conditions:

- Rollover about the vehicle's roll or pitch axis on sod.
- Advancing and retreating blade obstacle strikes that occur within the outer 10 percent of blade span assuming the obstacle to be an 8-in.-diameter rigid cylinder.

Unless otherwise specified, all engines, transmissions, rotor masts, armament systems, external stores, and rotor hubs should be designed to withstand the following ultimate load factors (G) and remain restrained:

- Applied Separately

Longitudinal	±20
Vertical	+20/-10
Lateral	±18

● Applied Simultaneously

	Design Conditions		
	1	2	3
Longitudinal	±20	±10	±10
Vertical	+10/-5	+20/-10	+10/-5
Lateral	±0	±9	±18

5.3.1.7 Shape of Fuselage Cross Section: The shape of the fuselage has an inherent influence on the inward load-deformation properties of the fuselage. Both crash test experience and accident analysis indicate that an ellipsoidal shape is optimum for the fuselage. A cylindrical cross section inherently provides a curved surface to resist inward crushing. In addition, an ellipsoidal fuselage will result in lower rollover loads than would a flat-sided fuselage under identical conditions. Even though operational considerations may prevent the use of an exact ellipsoid-shaped fuselage, an approach to this shape is a worthwhile design goal.

5.3.1.8 Landing Gear: The landing gear geometry should be such that no abnormal characteristics result from aircraft taxis, takeoffs, and landings at the basic structural design gross weight on terrain with slopes of up to 12 degrees, or from landing sideways on a 15-degree slope under zero wind. The sink speed need not exceed 6 ft/sec for the above slope conditions. A differential kneeling landing system should not be utilized to satisfy this requirement. There should be no restrictions imposed due to positioning the aircraft relative to the sloped site. The landing gear should be capable of ground taxi, towing, ground handling, takeoff and landing roll, and landings including autorotative landings at design sink speeds in accordance with AMCP 706-201 (Reference 18).

The gear system should be designed to minimize entanglement with wires, brush, landing mats, and other obstructions and should have provisions for attachment of flotation and ski devices to permit operation on snow, water, and marshy areas. The gear flotation capability should be such as to allow the aircraft, empty except for full fuel load and an additional 200 lb, to be towed across soil with a California Bearing Ratio of 2.5 by vehicles normally assigned to aviation units (i.e., 1/4-ton or 3/4-ton truck).

18. ENGINEERING DESIGN HANDBOOK, HELICOPTER ENGINEERING, PART ONE, PRELIMINARY DESIGN, AMC Pamphlet 706-201, U. S. Army Materiel Command, Alexandria, Virginia, August 1974.

5.3.1.8.1 Tail Bumper: Tail bumper wheels or skids should be provided as necessary. Skids should have a simple, hardened-surface, replaceable shoe to absorb the wear and damage of impact.

5.3.1.8.2 Ground Clearance: The ground clearance, with aircraft level, for the antitorque (tail) rotor (exclusive of tail bumper wheel or skid structure), fairings, control surfaces, and external stores should not be less than 16 in. It should be assumed that the aircraft is at rest at BSDGW and that the landing gear struts are in the normal position with normal tire pressure. Alternatively, with the aircraft in any of the following attitudes the clearance should not be less than 6 in.:

- Three-point and, where applicable, four-point attitude with all shock absorber struts fully compressed and all tires flat.
- Three-point attitude with main wheel shock absorber struts and tires under static deflection, nose-wheel shock absorber strut fully compressed, and nose-wheel tire flat.
- Tail down, rolled attitude with main wheel shock absorber strut fully compressed, main wheel tire flat, and nose gear at maximum extension. The longitudinal attitude of the rotary-wing aircraft should correspond to that obtained by contact of the aft fuselage structure or tail bumper with the ground or deck. The lateral attitude should correspond to that obtained by rotating the aircraft 5 degrees about its roll axis.

5.3.1.8.3 Landing Gear Location: The landing gear subsystem location should minimize the possibility that a part of the gear or support structure will be driven into an occupiable section of the aircraft, or into a region containing a flammable fluid tank or line, in any accident falling within the crash conditions of Table 2. If this cannot be accomplished by location, the gear should be designed to break away under longitudinal impact conditions, with points of failure located so that damage to critical areas is minimized.

Failure of the landing gear should not result in a failure of any personnel seat/restraint system or seat/restraint system tiedown. Failure of the landing gear should also not result in blockage of a door or other escape route, or prevent the opening of any door or other escape route.

5.3.1.8.4 General Strength Requirements: Unless otherwise specified, strength and rigidity requirements should be provided in accordance with MIL-S-8698. The limit sink speed at the BSDGW should be 10 ft/sec (level ground) and 6 ft/sec on a 12-degree slope in any direction. The forward velocity for level ground contact should be all speeds between 0 and 120 percent of the airspeed corresponding to minimum power required for level flight and landing gross weight. The reserve energy sink speed should be 12.25 ft/sec. The following paragraphs of MIL-A-008862 should apply for ground loads: 3.3 (except 3.3.7), 3.4, (except 3.4.3), 3.5, and 3.6. An analytical casting factor of 1.25 should be applied for the design of all castings which will not be static tested to failure, or which are not procured to MIL-C-21180. The yield factor of safety should be 1.0.

5.3.1.8.5 Vertical Crash Force Attenuation in the Landing Gear: Landing gear, including the skid-type, should provide maximum practical energy-absorption capabilities to reduce the vertical velocity of the fuselage as much as possible under the crash conditions defined in Table 2. Forward and aftward motion of the wheel in wheel-type landing gear of the trailing-arm type is allowable in meeting this requirement.

The landing gear should be of the load-limiting type, and should be capable of decelerating the aircraft at BSDGW from a vertical impact velocity of 20 ft/sec onto a level, rigid surface without allowing contact of the fuselage proper with the ground. Plastic deformation and damage of the gear and mounting system are acceptable in meeting this requirement; however, the remainder of the aircraft structure should be flightworthy after such an impact, with the exception of the main rotor blades. The aircraft should be capable of meeting this requirement in accidents with simultaneous fuselage angular alignment of ± 10 -degree roll and pitch.

5.3.2 Ancillary Equipment Retention

Ancillary equipment is a general term for all removable equipment carried inside the aircraft that could constitute a hazard to personnel if unrestrained during a crash. Ancillary equipment includes emergency and survival equipment, aircraft subcomponents, and miscellaneous equipment. Typical items in each of these categories are:

- Emergency Equipment

Oxygen bottles
Fire extinguishers
First aid kits
Portable searchlights
Crash axes

- Survival Equipment

Survival kits
Life rafts
Life jackets
Locator beacons
Special clothing
Food and water

- Subcomponents

Panel-type consoles containing control circuitry
Radio and electronic equipment
Auxiliary power units
Batteries
Special equipment

- Miscellaneous Equipment

Navigation kits
Briefcases
Log books
Flashlights
Luggage
Toolboxes

All ancillary equipment frequently carried aboard an aircraft should be provided with integrated restraint devices or anchors to the aircraft structure. Restraint devices or anchors should ensure retention of the equipment during any survivable crash of the severity cited in Table 2. Stowage space for nonrestrained items that are not regularly carried aboard an aircraft should be provided in all aircraft. This space should be located so that the items stored in it cannot become hazards to personnel in a survivable crash.

5.3.2.1 Strength: Restraint devices and supporting structure for ancillary equipment should be designed to restrain applicable items when exposed to static loads of 50 G downward, 10 G upward, 35 G forward, 15 G aftward, and 25 G sideward. Load-limiting devices are recommended for restraint of heavier equipment. Load-limiter stroking should not allow equipment to enter an occupant strike envelope.

5.3.2.2 Emergency and Survival Equipment Stowage Location:

Equipment should be: (1) located close to the primary crew chief station, if applicable; (2) stowed in easy view of crew and passengers; and (3) easily and reliably accessible in an emergency. Equipment should not be placed in areas where cargo shifting or fuselage distortion will prevent or impair access to it. Equipment stowage location should minimize the potential adverse effects of extreme temperatures, abrasion, and uncleanness.

5.3.2.3 Retention Devices Release for Emergency and Survival Equipment: Retention devices used to restrain emergency and survival equipment should be capable of quick release without the use of tools by one person using one hand. Release should be effected by a single motion actuating one device and should not require more than 5 sec from time of contact with the actuating device to the time when the equipment either falls free or is lifted free. If equipment is stowed in an enclosure, no more than 5 sec should be required for opening the enclosure and removing the equipment. Aircraft attitude should not adversely affect release device operation. It should be possible to see the latch position (open or closed) of the release device. The release device actuating handle should be of a color that contrasts with the surrounding area and be easily discernible in poor light or smoky conditions. No more than 30 sec should be required for release of life rafts and their deployment outside the vehicle. Time should be measured from the moment when the operator takes a stand adjacent to the release device or enclosure of the raft until the raft hits the water uninflated.

5.3.3 Occupant Retention

Seating and litter systems should ensure that occupants are retained in their precrash positions within the aircraft during crashes of the severity cited in Table 2. Seating and litter systems design should be coordinated and interfaced with the design of the other aircraft areas to achieve a completely integrated and efficient crashworthy aircraft system design. Seat and litter design should provide the greatest practical amount of support and contact area for the occupants in the directions of the most severe and likely impacts. Seats should provide an integral means of crash force attenuation. Occupant comfort should not be compromised to the extent that flight safety and/or crew efficiency is adversely affected. Volume IV contains a detailed discussion of occupant retention.

5.3.4 Cargo Retention

Cargo restraint should:

- Be as light in weight as possible.
- Require minimum storage space when not in use.
- Be easy to install and remove.
- Be easily and reliably adjustable for different sizes and shapes of cargo.
- Provide sufficient restraint of cargo in all directions to prevent injury to personnel in impacts of the severity described in Table 2.
- Not permit cargo to shift in flight during turbulent weather.

If the structure of the fuselage and floor is not strong enough to withstand the cargo crash loads, load limiters should be used to limit the loads transmitted to the structure. Cargo restraints should be capable of maintaining their integrity under longitudinal loads of 16 G peak with a longitudinal velocity change of 43 ft/sec. Lateral and forward strength-deformation characteristics are discussed in Section 6.6.5.11. Nets used to restrain small bulk cargo should be constructed of material with low-elongation characteristics in order to reduce dynamic overshoot to a minimum. Restraining lines without load limiters used for large cargo, as defined in Table 4, for longitudinal restraint should be so arranged that maximum load in all lines is reached simultaneously. Restraining lines having different elongation characteristics should not be used on the same piece of cargo. If load limiters are used, restraining lines should be metal cables with low-elongation characteristics to ensure the most efficient energy absorption.

5.4 TESTING

5.4.1 Aircraft System Testing

Instrumented, full-scale crash test(s) should be conducted: (1) to verify analyses performed and (2) to substantiate the capability of the aircraft system to prevent occupant fatalities and minimize the frequency and severity of occupant injuries during crashes of the severity cited in Table 2.

TABLE 4. AIRCRAFT CARGO CATEGORIES

Small bulk cargo (net restraint)	Large rigid cargo (line restraint)
This class includes all boxes or unpacked cargo of approximately 3 ft ³ or less in size.	This class includes all rigid cargo of 3 ft ³ or more in size.
<u>Examples:</u>	<u>Examples:</u>
1. Ammunition boxes	1. Wheeled or tracked vehicles
2. Foodstuffs	2. Aircraft engines
3. Medical supplies	3. Fuel barrels
4. Clerical supplies	4. Artillery pieces
5. Vehicle maintenance components	5. Special weapons (priority cargo)

5.4.2 Landing Gear Crash Testing

Instrumented drop tests should be conducted: (1) to verify landing gear crash force attenuation and crash loading strength characteristics analytically predicted and (2) to substantiate the capability of the aircraft landing gear to meet the criteria of Section 5.3.1.8. Drop testing of wheel and skid landing gear should be conducted in accordance with paragraph 9-2.3 of AMCP 706-203 (Reference 19) and should include demonstration of compliance with the reserve energy and crash impact requirements of Section 5.3.1.8. The 20-ft/sec sink speed drop test should be conducted with the landing gear oriented in a 10-degree nose down and 10-degree roll attitude and drop tested onto a level, rigid surface with a sink speed of 20 ft/sec at ground contact. Landing gear should also be drop tested in a 0-degree roll, pitch, and yaw attitude onto a level, rigid surface with a sink speed of 42 ft/sec at ground contact to demonstrate crash impact energy-absorption capability. Rotor lift for all drop tests should not exceed two-thirds of the BSDGW.

19. ENGINEERING DESIGN HANDBOOK, HELICOPTER ENGINEERING, PART THREE, QUALIFICATION ASSURANCE, AMC Pamphlet 706-203, U. S. Army Materiel Command, Alexandria, Virginia, April 1972.

5.4.3 Cargo Restraint

Design loads are specified in Section 6.6.5.11. Static tests to these loads are recommended. All deformation measurements are to be made at the floor level. Sufficient dynamic tests should be made to assure that design predictions can be based on static test results.

5.4.4 Seat and Restraint System

Testing requirements for seats and occupant retention systems are described in Volume IV.

5.4.5 Fuel System

Testing requirements for fuel systems are described in Volume V.

5.4.6 Ancillary Equipment Retention

Design loads are specified in Section 6.6.5.9. Static tests to these loads are recommended.

5.4.7 Static Structural Crash Load Testing

It is important that compatibility at the structural interfaces between the airframe and all attached components is ensured. The design of the fuselage structure, including the hard points and load distribution structure around the hard points, must be coordinated with the design of the attaching components. Structural properties for all loading conditions and design features, such as structural releases, must be coordinated to achieve the desired compatibility.

The importance of this aspect of system design requires that compatibility be demonstrated. Static tests of components attached to the fuselage structure by their normal attachment provisions should be performed to demonstrate compatibility. Components such as seats, cargo, engines, transmissions, landing gear, and attachments for any ancillary or heavy equipment located in an area which could create a hazard for the occupants if freed during crash loading should be tested. The ultimate design crash loads should be applied in all principal loading directions to demonstrate that the attachment points as well as the load-bearing sections of the fuselage are capable of maintaining structural integrity during a crash. The application of proof loads instead of ultimate crash design loads is an acceptable, although minimum, test condition.

6. AIRFRAME PRINCIPLES AND CONCEPTS

6.1 INTRODUCTION

In designing for airframe crashworthiness, there are certain criteria that are applicable whether the results are approximate or precise. First, and most important, the structure surrounding occupiable areas must remain reasonably intact, without significantly reducing occupant living space. If occupants are injured during a crash because the protective shell simply collapses around them, then efforts to improve survivability through such methods as improvement of occupant restraint or reduction of postcrash hazards are futile. An aircraft which does not provide the protective shell can never be crashworthy.

Ideally, for crashworthiness, the structure should be designed to minimize occupant accelerations to survivable levels in a severe crash environment, while maintaining the required survivable volume and retaining large mass items, interior equipment, seats, and cargo. In addition, consideration should be given to minimize the effects of rollover, earth plowing, and cabin penetration. Obviously, other considerations must also be addressed in defining the airframe structural configuration.

6.2 GENERAL DESIGN CONSIDERATIONS

Airframe structure should first be designed for normal airloads, ground handling loads, and fatigue life, while considering the details of the aircraft specification with respect to size, range, performance, space envelopes, etc. After the basic structural layout has been defined, the effects of crash loads must be considered to determine where structural modifications are needed to improve crashworthiness. Concurrent with this process, space allocations must be made and locations for critical systems, landing gear, equipment racks, seats, cargo tie-downs, emergency exits, etc., must be determined to ensure an integrated approach to the solution of the crashworthiness problem.

To improve crashworthiness, design changes allowing the structure to remain more nearly intact through improved compliance or improved progressive, yet predictable, deformation can sometimes be more effective than direct increases of strength. Every attempt should be made to accurately determine the magnitudes and distribution of crash loads throughout the structure, and the structure should be designed to these loads.

The use of safety factors of 1.0 with safety margins of 0.0 based upon the crash load factors presented elsewhere in this

volume will generally be considered satisfactory. Safety factors may be increased by known amounts as special conditions may warrant; however, caution is needed so that overdesigning of certain areas does not adversely affect the protection offered by the entire structural system. Safety factors and safety margins used in the design of joints and connections should be consistent with those discussed above.

In areas where large gross structural deformations are anticipated, joints should be analyzed and designed to reduce the probability of failure under large angular deflections as well as large linear displacements. The objective of these considerations is to keep structural sections intact and to ensure that when massive crushing or large deformation occurs, maximum energy absorption also occurs. Consideration also must be given to areas of structure where a predetermined failure sequence is deemed necessary to provide optimum occupant protection. Joint failure can be controlled so deformation occurs away from occupied space, thus eliminating the problem of occupied space penetration by the ends of failed structural members. Furthermore, if joints are designed to retain an effective pin connection after failure of the majority of fasteners, a certain level of structural continuity can be retained. This can result in a structure that retains the capacity to resist loading after the primary impact, thereby affording protection during rollover, pitchover, and intrusion of massive items.

Often, plastic yielding of materials will relieve stress concentrations before the ultimate strength of members are reached, making the consideration of stress concentrations, from a strength standpoint, less important. However, very often the presence of stress concentrations induces local fractures and eventual structure failure with low overall energy-absorbing capacity.

During a crash, rapidly increasing loads, not instantaneous loads, are applied. In most cases, a minimum of 10 msec is required for loads to reach maximum values. Under such conditions, inertia effects may be of importance, but strain rate effects in materials are probably insignificant.

6.2.1 Initial Layout

Structurally, the aircraft must be capable of performing its mission of carrying the required payload. Initial layouts must consider the volume required to carry the requisite crew, passengers, and cargo after allocation of space for aircraft systems. The structure needed to carry and/or house the systems and occupants must be laid out to adequately support all systems and to provide basic structural protection in a crash environment.

Figure 15 shows a structure designed to protect the occupants in crash conditions. Adequate space for allowing the structure to stroke and/or collapse to absorb energy in the support of large mass items must be provided. At the same time, seated occupants and cargo must be restrained and G levels restricted to provide a survivable environment. Crashworthy seats must be supported by an integral part of the primary structure. To preclude the seat bottoming on the floor of the aircraft, sufficient stroking distance must be allowed for impact conditions defined in Table 2.

6.2.2 Analysis and Simulation

Once the design is defined, the next step is to simulate the preliminary concept. Computer simulations, such as described in Chapter 7, are used to model primary structure, large mass items, systems, occupants, and cargo. Then, potential impact conditions are simulated to investigate the aircraft's dynamic response, structural collapse, and acceleration environment.

An iterative process is used to optimize energy-absorption concepts, structural distributions, failure modes, mass retention concepts, landing gear locations, etc. This process, conducted concurrently with inputs from design, stress, and performance, ensures design optimization. Further modifications are made to control weight and weight distribution, producibility, maintainability, safety, and cost.

6.2.3 Design Review and Final Aircraft Format Selection

Several cycles of iteration may be required before the optimum design, adequately satisfying the requirements of the basic helicopter specification, evolves. The result is a final product that satisfies the major specified requirements with a minimum of compromise.

From the beginning, emphasis must be placed on the need to implement crashworthiness features. This provides an integrated approach where all influencing constraints, particularly weight, cost, and space are considered and optimized. Crashworthiness cannot be added to a design without certain compromises, possibly even penalties, involving weight, cost, and structural complexity. However, crashworthiness, when integrated with the original design, can be achieved with a minimum and acceptable level of these penalties.

6.3 MATERIALS AND STRUCTURAL PROPERTIES

Current helicopters are constructed primarily of metallic materials. Some secondary and fairing components are made from

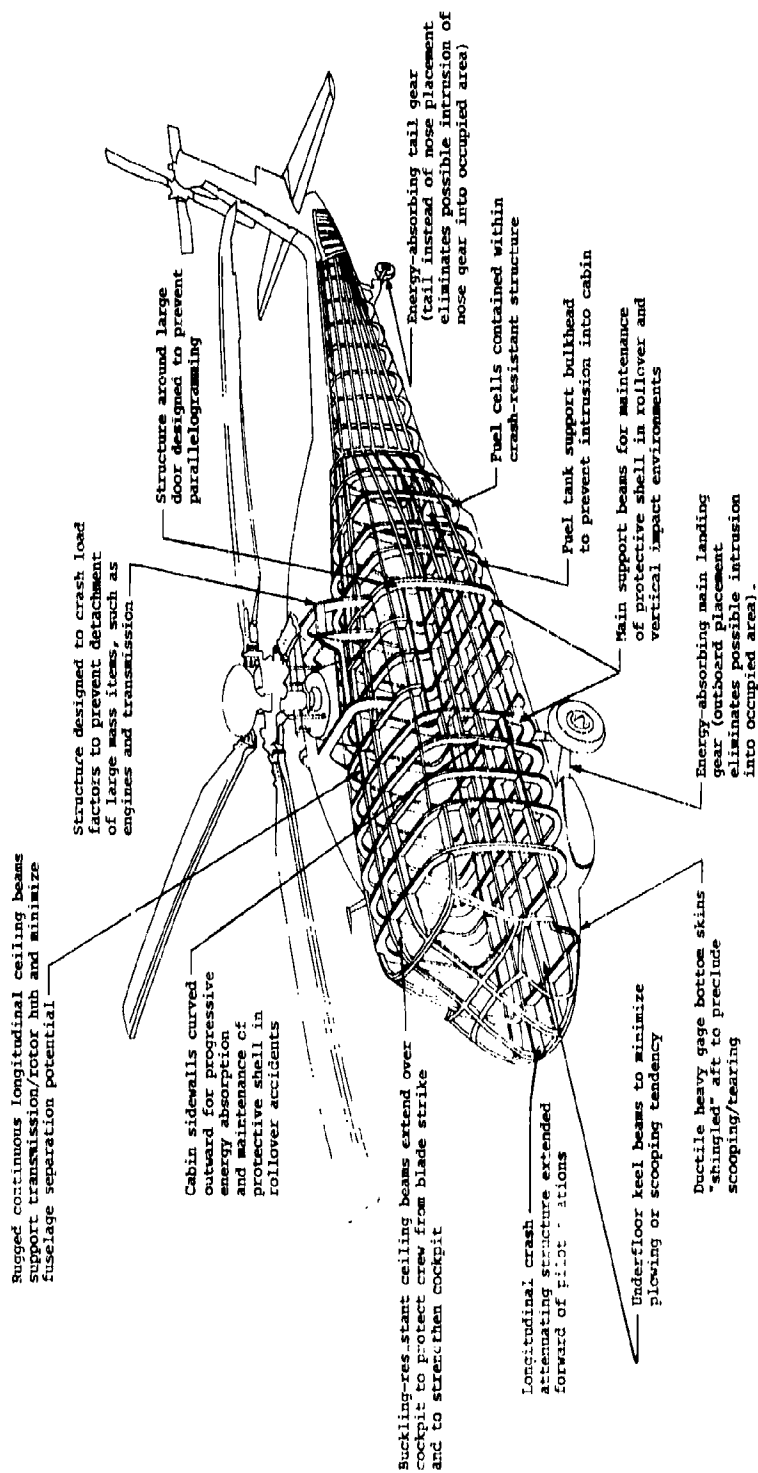


Figure 15. Structural layout for occupant protection in a crash environment.

nonmetallic materials or composites, i.e., combinations of metallics and nonmetallics.

For crashworthy structures, the basic requirements are to maximize energy absorption while maintaining adequate volumes and acceleration levels for occupant survival, and to minimize fire risk.

Other requirements for a safe interior environment include the following:

- Controlled collapse mechanisms.
- Material failure modes that do not produce projectiles.
- Joint designs and fastener selections that control failure mechanisms and minimize the formation of projectiles.

MIL-HDBK-17 (Reference 20) and MIL-HDBK-5 (Reference 21) contain basic design data for materials.

Subsequent sections discuss these requirements with reference to both metallic and composite structures.

6.3.1 General

The kinetic energy of an aircraft subjected to a crash is absorbed in a number of ways, including deformation of aircraft structure. Absorption of energy through structural deformation can work effectively as an occupant protective device if the structure surrounding the occupant protective shell is allowed to deform, thus attenuating the forces transmitted to the occupiable section. The protective shell must remain intact during this process. The use of surrounding structure as a buffer can be accomplished more efficiently if the impact causes crushing without complete rupture of structural members. Material properties can greatly affect the degree to which this is actually achieved.

20. Military Handbook, MIL-HDBK-17, PLASTICS FOR AEROSPACE VEHICLES, PART I, REINFORCED PLASTICS, Department of Defense, Washington, D. C., 1 January 1971.
21. Military Handbook, MIL-HDBK-5, METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES, Department of Defense, Washington, D. C., 15 September 1976.

Material ductility is required to ensure that crushing, twisting, and buckling can occur without rupture. The structural shell should be able to deform without fracture insofar as possible.

All exterior surfaces and all structures which could be exposed to contact with the impact surface should be constructed of nonsparking materials to reduce the postcrash fire hazard. The friction sparking problem and results of friction sparking ignition experiments using various typical aircraft materials are discussed further in Section 6.3.5 and in Volume V.

Fabrication techniques and structural configurations, especially for areas where severe damage is probable, should be selected after consideration of the overall effects of structural failure on occupant protection. Wherever possible, multiple structural members should be used instead of larger single structural members, so that localized impact damage will not result in complete loss of structural integrity. Multiple load paths also aid in maintaining uniform force transmission characteristics throughout structural collapse.

6.3.2 Material Strength and Elongation Characteristics

Material strength and elongation characteristics are described in applicable military handbooks. In using these properties, one should bear in mind that for some materials, such as steel, handbooks present only guaranteed minimum strength and elongation data; for other materials, such as aluminum, values are presented indicating both minimum guaranteed strength and the strength values which statistics show will be met or exceeded by 90 percent of the materials under consideration. The 90-percent probability values are normally somewhat higher than the guaranteed values. The particular application should be considered in deciding whether to use minimum guaranteed values or statistically based values. For design of structural members, such as members supporting heavy overhead masses, where failure could result in a severe loss of occupant protection, the use of minimum guaranteed values would be reasonable. For design of structures likely to be subjected to massive crushing, such as airplane nose structures, the use of statistical values would be justified. As in these two simplified examples, the choice of which strength value to use should be based upon the consequences of failure.

6.3.3 Failure Modes Controlling Material Selection

In a crash environment, structural failure modes should not create potentially injurious conditions for cabin or crew section occupants. When occupant protection is considered, the following failure modes should be avoided:

- Inward buckling structures, such as sidewalls, bulkheads, and floors.
- Failures of members such as frames that result in jagged, failed ends protruding into occupied space or fuel cells.
- Fastener failures that may produce structural discontinuities and projectiles.
- Brittle fractures that suddenly unload, causing impulse effects in adjacent structures with potential for progressive failures and generation of projectiles.
- Emergency exit surrounds that distort excessively and preclude the opening or removal of doors or windows after the crash sequence.
- Flammable fluid container penetrations with the potential for postcrash fire generation.
- Occupied area penetrations by failed structural elements or exterior agents.

Brittle structural failures can be avoided by choosing materials with good fracture toughness characteristics and a considerable degree of ductility before ultimate failure. The choice of structural geometry can alleviate potential ingress of failed structure into occupied space.

Also, predetermined failure points can be introduced into a design to help control structural response under dynamic loading conditions. These points may be structural plastic hinges that allow earlier plastic yielding and rotations in weaker sections. Alternatively, joints may be designed to fail progressively to allow rotation of structural elements with subsequent load redistribution. A final joint condition of effectively pin-ended members will quite often be more desirable than member break-away.

Typical examples of failure modes discussed in this section are shown in Figures 16 through 22, demonstrating, in particular, the requirements for failure away from occupied areas and prevention of potentially damaging projectiles and structural elements. These photographs were taken after a vertical impact of a test vehicle onto a concrete ground plane at a velocity equivalent to at least a 95th-percentile potentially survivable accident. The structural failures, in general, did not result in unacceptable intrusions into occupied space.

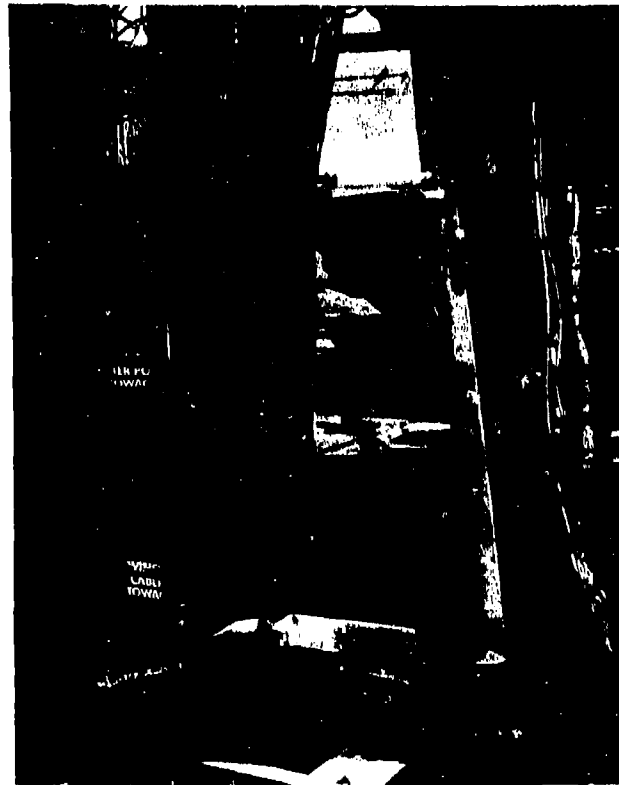


Figure 16. Compressive buckling at base of butline beam structure on a medium cargo helicopter following vertical impact.

The resulting sharp-edged elements could have been eliminated by using materials with better fracture toughness properties and/or increased dimensions.

It is interesting to note that, historically, aircraft fuselage sections have been shaped to preclude inward collapse mechanisms. Circular, elliptical, and contoured rectangular shapes have been used to accommodate the requirements for structural efficiency and optimization of useful volume. The major factors degrading older designs were the lack of requirements to withstand crash-induced loading and the lack of choices in materials. At the time, materials with the high strength, ductility, and fracture toughness properties now accepted as the norm did not exist.

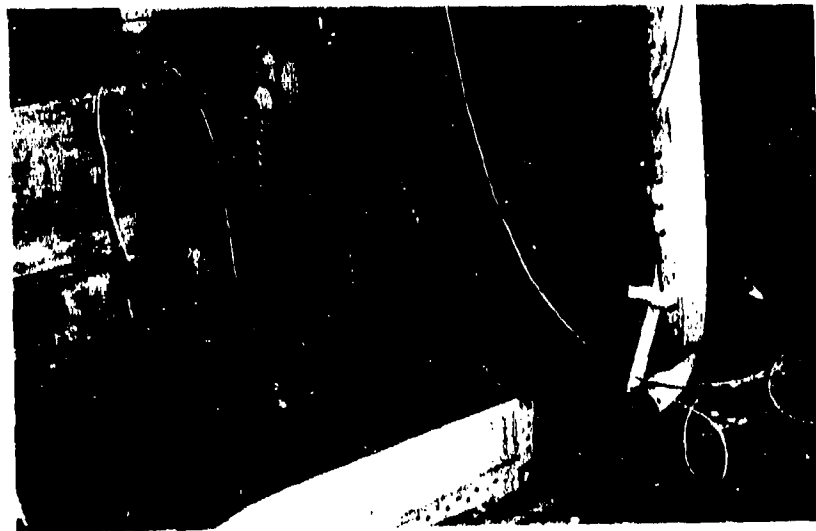


Figure 17. Typical buckling collapse of vertical bulkhead and buttline beam on a medium cargo helicopter following vertical impact.



Figure 18. Typical frame failure away from occupied space in the cockpit area of a medium cargo helicopter following vertical impact.

6.3.4 Composite Materials

Composite materials offer certain advantages over metallics in some areas of helicopter structure, primarily the advantage of reduced weight. However, their high stiffness and lack of ductility require that composites be investigated very carefully before being implemented in structural areas where high levels of energy absorption are required and large stroking distances are considered necessary. Figure 23 compares typical stress-strain curves for an aluminum alloy and a graphite/epoxy composite in tension. The shaded areas indicate the potential energy absorption capabilities; the difference between the two materials should be noted, i.e., the ratio $A_{7075}/A_{GE} = 12.3$.



Figure 19. Typical frame failure away from occupied space in the cabin area of a medium cargo helicopter following vertical impact.

Table 5 presents values for ultimate strengths and elastic moduli for several typical structural composites. These data allow comparisons among various nonmetallic materials.

Another available method of energy absorption that may achieve adequate performance is incorporation of filler materials, such as honeycombs and structural foams. For longitudinal and lateral impacts, it is feasible to incorporate energy-absorption features of this type; but for the support of large mass items with high energy content, other techniques are probably necessary. Of course, any limitations on the use of energy-absorption techniques will be dependent, to a degree, on the size and overall layout of the aircraft needed to satisfy mission requirements. For structural energy absorption adequate

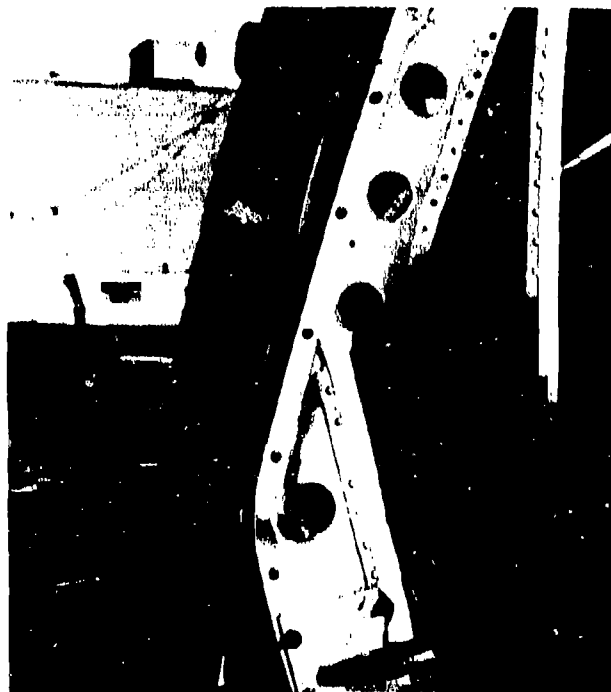


Figure 20. Failure modes resulting in jagged elements protruding into occupied space in the cabin area of a medium cargo helicopter following vertical impact.



Figure 21. Rotational joint failure with compression and bending in a medium cargo helicopter following vertical impact.



Figure 22. Failure of frame member and joint with fragmentation, compression, and bending in a medium cargo helicopter following vertical impact.

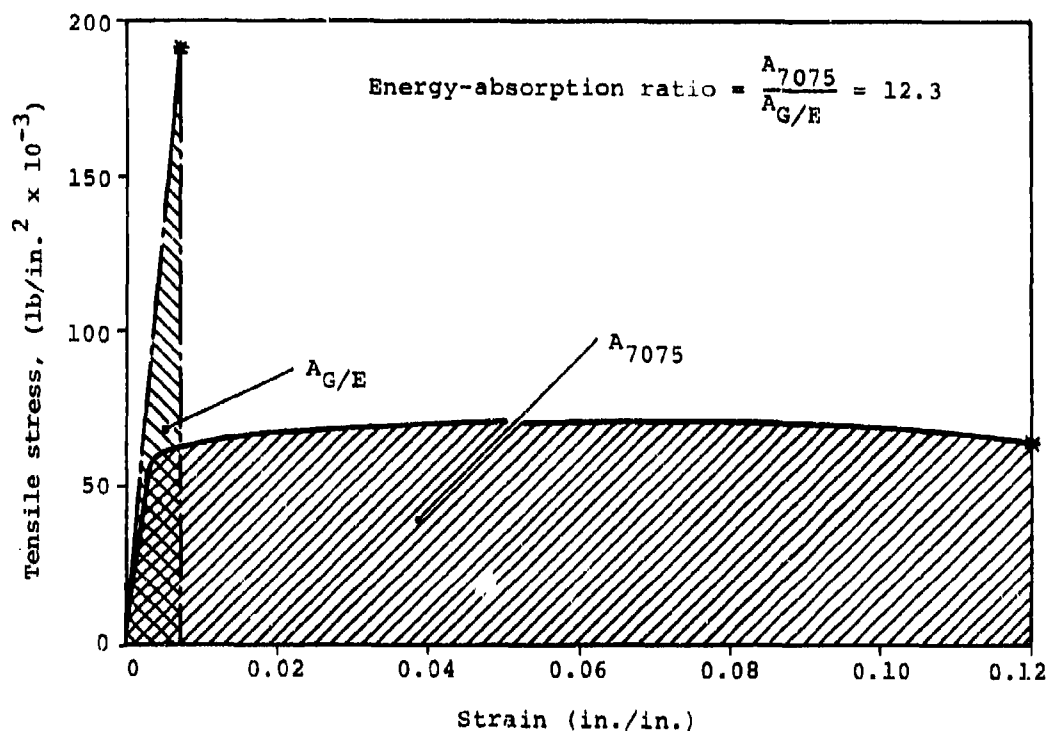


Figure 23. Stress-strain relationship for aluminum alloy (7075) and 0 degrees graphite/epoxy composite.

for occupant survival in the crash conditions of Table 2, optimization studies may indicate that some major primary structural elements need to be manufactured from metallic materials, whereas composites may find use in other areas.

The effect of thermal mismatch is a major potential problem area that must be fully investigated when using mixed construction techniques. The use of boron/epoxy or graphite/epoxy materials in close conjunction with other materials must be carefully examined in the conceptual design stage because of the generation of internal stresses induced by differences in thermal expansion coefficients.

Combinations of composites with steel or titanium alloys can be satisfactorily designed for most structural applications, but combinations with aluminum alloys can lead to severe problems. If thermal curing of the bonding agent is also needed, this can further aggravate the induced stress problem and may result in warpage of the finished product.

TABLE 5. ULTIMATE STRENGTH AND ELASTIC MODULI
FOR TYPICAL STRUCTURAL COMPOSITES

Composite	Ultimate tensile stress (lb/in. ²)	Modulus of elasticity	
		Longitudinal (lb/in. ²)	Transverse (lb/in. ²)
Boron/epoxy [0]	192,000	30 x 10 ⁶ -30 x 10 ⁶	2.7 x 10 ⁶ -2.7 x 10 ⁶
Graphite/epoxy [0] (high modulus graphite)	110,000	25 x 10 ⁶ -25 x 10 ⁶	1.7 x 10 ⁶ -1.7 x 10 ⁶
Graphite/epoxy [0] (high strength graphite)	180,000	21 x 10 ⁶ -21 x 10 ⁶	1.7 x 10 ⁶ -1.7 x 10 ⁶
Boron/aluminum	160,000	34 x 10 ⁶ -30 x 10 ⁶	20 x 10 ⁶ -19 x 10 ⁶
Borsic/aluminum	140,000	32 x 10 ⁶ -30 x 10 ⁶	22 x 10 ⁶ -19 x 10 ⁶

Thermal mismatch problems are less severe when the two materials are in the form of sandwich face sheets and core since the flexibility of the core can absorb limited thermal displacements, particularly those normal to the core ribbon direction.

Boron/aluminum composites, on the other hand, are compatible with aluminum alloys, but their use with steel and titanium alloys must be carefully considered.

Table 6 gives values of thermal expansion coefficients for composite and metallic materials. The table and other useful design information can be found in Reference 22.

If composites are considered for primary crashworthy structure, the designer must be aware of the pitfalls (such as possible weight and cost penalties) that can render them less effective

22. Air Force Systems Command, ADVANCED COMPOSITE DESIGN GUIDE, Advanced Development Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, January 1973.

TABLE 6. THERMAL COEFFICIENTS OF EXPANSION FOR
COMPOSITE AND METALLIC MATERIALS
(REFERENCE 22)

Material	Coefficient of thermal expansion (10^{-6} in./in./°F)	
	Longitudinal	Transverse
Boron filament	2.7	NA
Epoxy matrix resin	2.7	27
Graphite fiber	-0.05	NA
E-glass filament	2.8	NA
Boron/epoxy [0]	2.3	10.7
Boron/epoxy [0 ₂ /±45]	2.4	7.7
Graphite/epoxy [0]	0.3	14.4
Graphite/epoxy [0/±45/90]	1.9	1.9
E-glass/epoxy [0]	4.8	-
E-glass (181 style weave)/epoxy	5.5	6.7
PRD-49/epoxy [0]	-6.0	-
PRD-49 (181 style weave)/epoxy	0.0	-
Aluminum		13
Steel		6
Titanium		5.6

than initially anticipated. Alternatively, if a composite structure with an energy-absorption capability less than that of a metallic structure is used, a survivable deceleration environment must be created by the use of landing gear with greater energy-absorbing capacity, energy-absorbing seats, and possibly some forms of floor load attenuation other than through primary structural deformation. Once again, such up-graded devices can introduce additional weight and may require extra installation space to allow adequate stroking distances.

Reference 23 presents a survey of the crash impact characteristics of composite structures and suggests the possible design concepts discussed below.

6.3.4.1 Overall Fuselage Concepts: Figure 24 illustrates an approach to satisfy the crashworthy fuselage consideration where the primary function is to maintain a protective shell around the occupied area. This can be accomplished by providing rollover strength in the form of elliptical sandwich-stiffened ring frames on the top and sides of the fuselage and a structural floor. Note that in Figure 24 the side fillets are designed to provide better rigidity and corner continuity between the floor and the sidewalls, while they will also act to absorb energy and distribute loads from a side impact. The foam-filled Kevlar tubes would be multifunctional in that they would act as floor beams to satisfy the normal airworthiness criteria of strength and stiffness; they would also function as energy absorbers to react the vertical and lateral crash impact forces. The heavy sandwich construction with local strap reinforcement on the lower mold-line surface would act as a shear and axial load path to satisfy the normal airframe requirements, while functioning as a skid during a longitudinal impact to prevent plowing and gouging. A common post-crash hazard is entrapment of the occupants due to collapse of the emergency exits. The hatches could be reinforced with a filament-wound composite tube that would provide the strength and stiffness required to prevent the distortion of the hatch region. This local reinforcement could also serve as a framing member that would redistribute the airloads around the cutouts. Local details, such as seat attachment points in the floor or cabin roof, need to be in areas where the airframe distortion during crash impact would not adversely affect the operation of the seat stroking mechanism or the seat belts. Consequently, reinforcements in the form of a higher density core in the sandwich construction or a filament-wound lug are shown in a typical application.

6.3.4.2 Composite Material Concepts for Vertical Impact: In order to reduce the inertia forces experienced by the occupant in a crash, energy-absorbing material must be placed between the ground and the floor of the cabin. Normally, this location is occupied by controls, wires, and life-support systems; consequently, the overall design must take this into account.

23. Cronkhite, J. D., et al., INVESTIGATION OF THE CRASH-IMPACT CHARACTERISTICS OF ADVANCED AIRFRAME STRUCTURES, Bell Helicopter Textron; USARTL Technical Report 79-11, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1979, AD A075163.

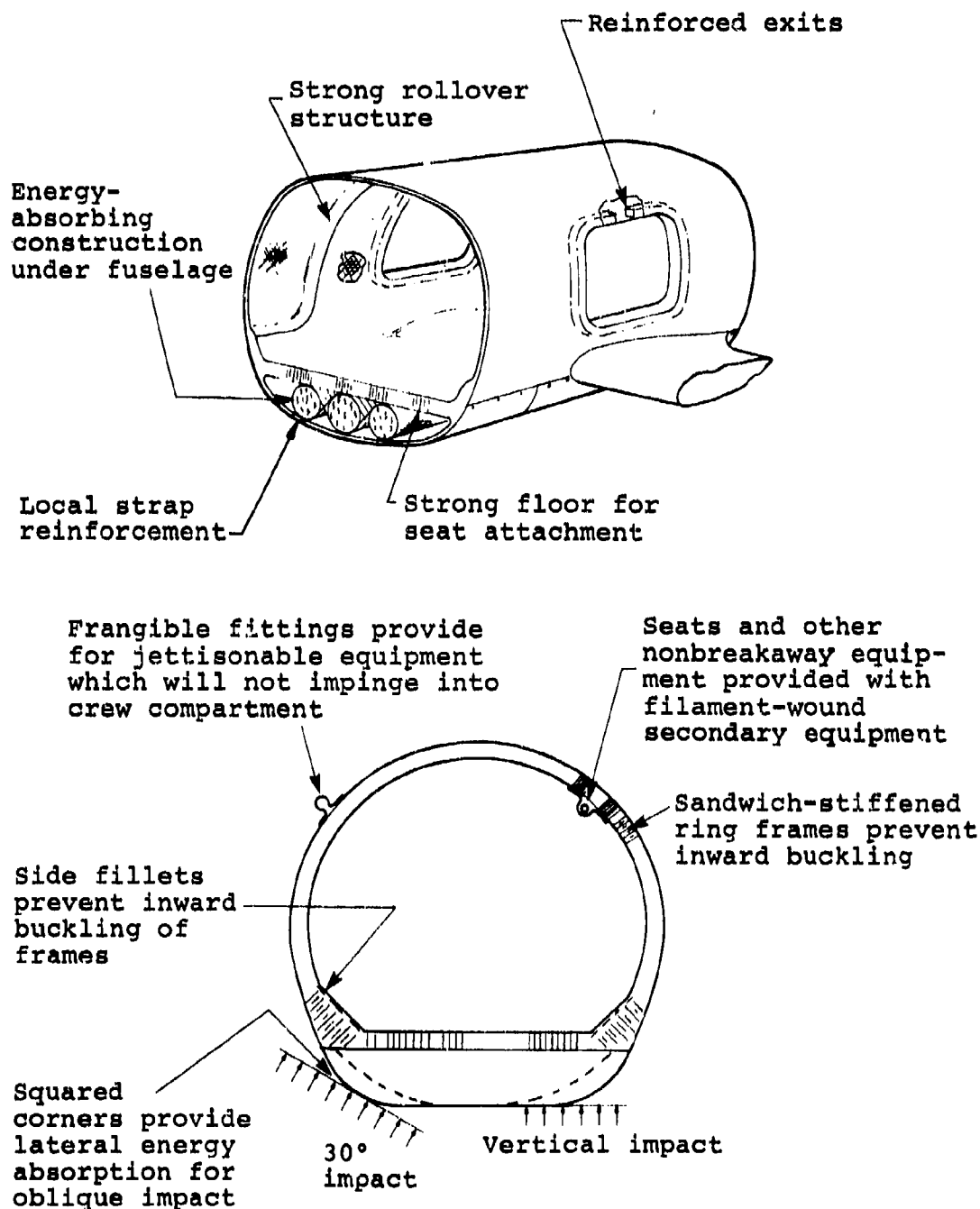


Figure 24. Overall fuselage concepts. (From Reference 23)

The beam and bulkhead concepts shown in Figure 25 are designed to react the vertical, longitudinal, and lateral impact loads; however, the most efficient direction for providing a progressive collapse is vertically. In each of the four concepts shown, it is assumed that the floor structure would also be designed to react the crash impact forces without failure. The concepts shown are directly applicable to many current fixed- and rotary-wing aircraft because their structural arrangement is similar. The first and second concepts would promote progressive crushing by stratifying the core and skins using the less-dense core and the less-stiff skin at the lower ends. The variation of skin stiffness would be accomplished by deleting plies. The stratification would have two effects: It would promote the crushing at the lower surface, and it would provide the increased strength of the core and skin adjacent to the floor where it is needed for local reinforcements or for seat or equipment attachments. Design support tests would be used to select the material, fiber orientations, etc.; however, a promising candidate for fulfilling both the airworthiness and crashworthiness criteria is graphite because of its high specific-energy absorption and its high strength and stiffness.

The third concept features a frangible corrugated core that is bonded to the face sheets at the nodes. This concept requires the normal airworthiness loads to be shared by the face sheet and corrugated core. During a crash impact, the face sheets would act as short columns with a length equivalent to the corrugation node spacing. When the face sheets fail as a column, the corrugated core would continue to crush and dissipate the energy. Kevlar was chosen as a material candidate for the face sheets based on a series of component tests. These tests demonstrated that, although Kevlar has a lower compression allowable than other composite materials, it also has a favorable failure mode for progressive folding that is required for this concept. The fourth concept uses the corrugated Kevlar face sheets to carry the shear loads during normal operations. These sheets would be continuously supported by the core in a manner that would cause the crash impact loads to be shared by the sheets and core. The design would have a peak crushing load which would be determined by the column stability of the face sheets, and an effective crush distance as governed by the energy-absorption qualities of the core.

Figure 26 shows three concepts using tubular shapes which address the combined lateral/vertical or oblique impacts. From a manufacturing viewpoint, the tubular concepts would offer the opportunity for filament winding and may also offer a cost advantage. Again, all of the concepts are predicated on the design of a structural floor system of sufficient strength and

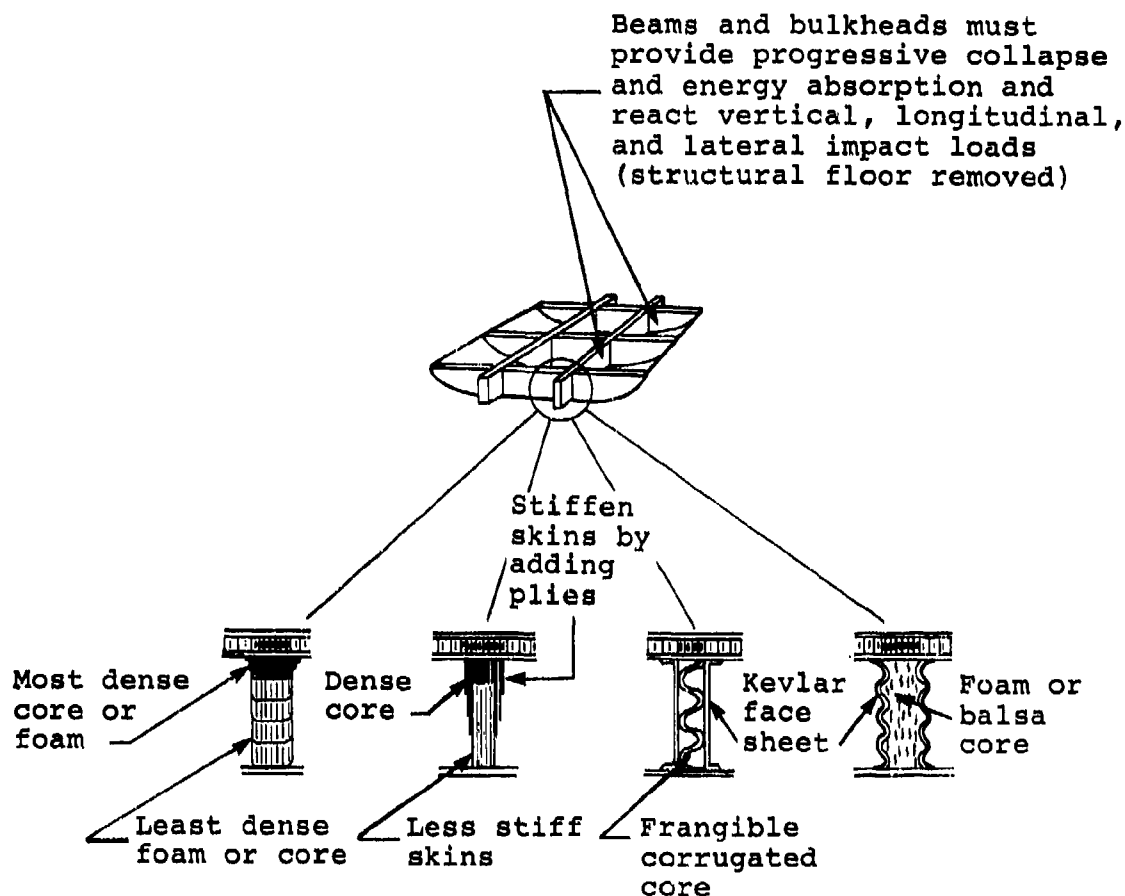
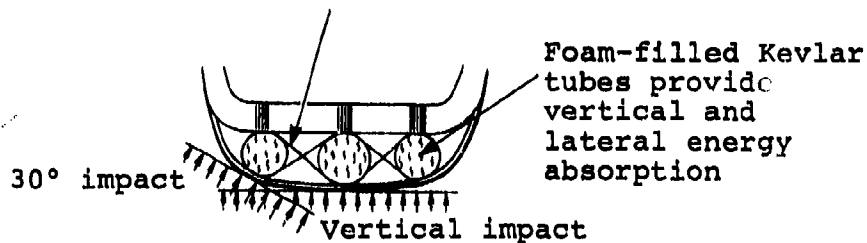


Figure 25. Energy-absorption concepts - beams and bulkheads (vertical impact). (From Reference 23)

stiffness to react the crash impact forces. The heavy hatched area in the floor represents local reinforcement for seat or cargo attachments that coincide with the tube reaction points.

In these concepts, the energy-absorbing agent is the foam or honeycomb structure. In the first concept, Figure 26(a), the vertical forces are dissipated by the foam and reacted directly by the floor structure. For an oblique impact, the Kevlar straps would resist the tendency of the outer tubes to roll by reacting the side forces with a truss action. The straps would also replace the normal subfloor bulkheads to react the normal flight loads. The truss is used instead of the bulkheads because it permits the tubes to expand freely in a lateral direction instead of being constrained by the bulkheads.

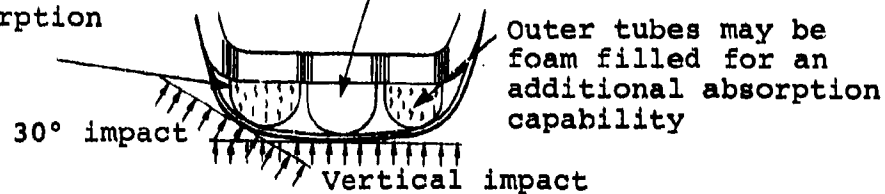
Kevlar straps maintain structural integrity and react side loads



(a)

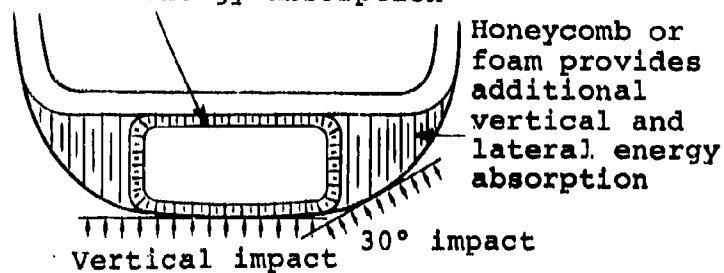
Corrugated Kevlar semi-tube provides vertical and lateral energy absorption

No foam in center section for controls routing



(b)

Filament-wound sandwich double-tube substructure around crushable core provides vertical and lateral energy absorption



(c)

Figure 26. Energy-absorption concepts - tubular construction (oblique vertical impact). (From Reference 23)

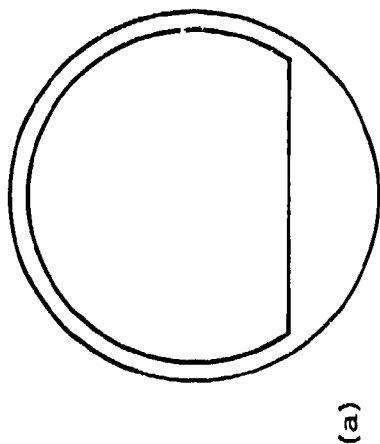
X
The second concept, shown in Figure 26(b), uses the center tube to route the controls, wires, and hydraulic lines. The tubes would be stiffened circumferentially by corrugations to increase their load capacity for both the normal airworthiness and crash impact design conditions. It is felt that the stiffened tubes would dissipate a portion of the crash impact energy working in conjunction with the foam, but tests would be required to determine the relative efficiencies of both filled and unfilled tubes.

The third concept, shown in Figure 26(c), uses the filament-wound sandwich tubes to form a housing for routing controls, etc., down the center of the aircraft. The vertical legs of the tubes are supported by a core of honeycomb or foam so they would progressively crush in a vertical impact and not fail catastrophically. The side impact forces would be reacted by the honeycomb or foam, which would distribute it to the floor.

6.3.4.3 Fuselage Sidewall Concepts: The fuselage sidewall concepts shown in Figure 27 are essentially designs which are intended to preserve the protective shell. The concepts illustrated in Figure 27(a) through (c) make use of the geometrical advantage of a circular cross section to reduce load concentrations while providing a strong sidewall to prevent failure. The sidewalls may contain multiple frames or use sandwich construction to react the crash impact forces. However, the sandwich construction would also provide some energy dissipation in addition to its structural integrity. The fourth concept, Figure 27(d), enhances this premise by applying energy-absorbing material to the sidewalls in a manner similar to the subfloor concepts.

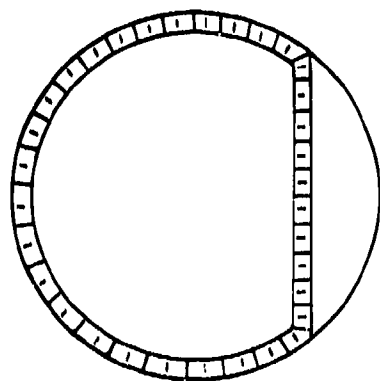
6.3.4.4 Longitudinal Impact Antiplowing Concepts: In a longitudinal impact, the main considerations are to ensure the integrity of the structural shell, to minimize earth scooping or plowing of the lower fuselage, and to provide some energy-absorbing material forward of the occupied area to dissipate the crash impact forces.

Figure 28 shows the strong floor structure required for the lateral and vertical impact conditions fairing into a sled-like nose that will act as a landing skid and as a backup structure to react the longitudinal impact forces. The current functions for the nose structure are to house electronic equipment, batteries, radar units, and ballast, and to act as a storage location for the nose gear. The design concept must be modified to satisfy these requirements while also integrating crushable energy-absorbing material to react the impact force. The belly skin would be fabricated in one section, similar to a large



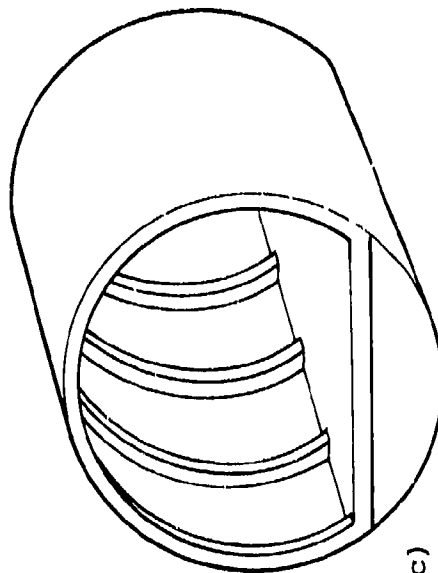
(a)

Circular cross section to
reduce rollover loads



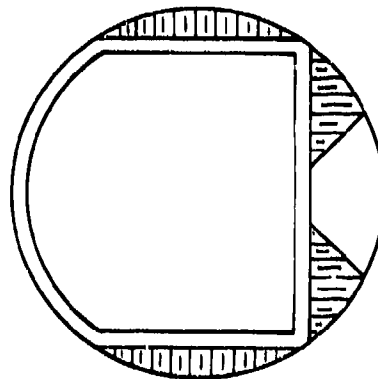
(b)

Strong sidewall to prevent
protective shell failure



(c)

Redundant sidewall frames
for rollover loads



(d)

Crushable material for load
control and distribution

Figure 27. Fuselage sidewall concepts - lateral impact. (From Reference 23)

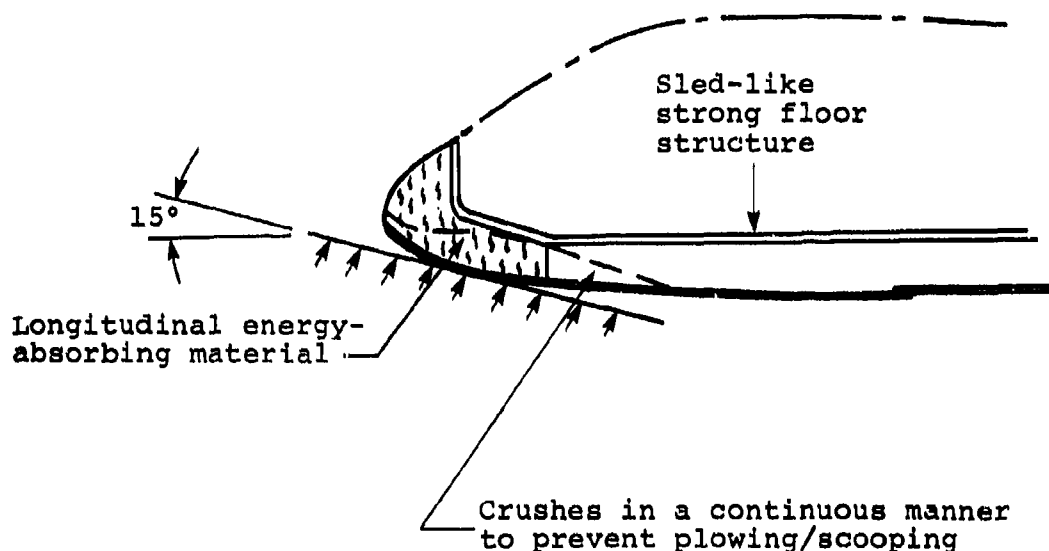


Figure 28. Antiplowing concepts - longitudinal impact. (From Reference 23)

bathtub, to minimize joints that could fail and present a protrusion gouging into the earth's surface. This method of construction eliminates parts and has been suggested as a means for reducing cost of composite components. A sandwich construction using Kevlar face sheets is a material choice that offers strength in shear and a resistance to tearing or puncture. All panels and hatches would be designed to have a leading edge that laps under the skin so that it would not act as a scoop during the large deformations that occur in a crash. The one-piece skins in conjunction with the energy absorbers, which could be foam-filled Kevlar tubes, would be encouraged to collapse in a continuous manner by including longitudinal straps under the absorbers to add bending strength and to act as a skid.

6.3.4.5 Joint Concepts: The joints and attachment fittings of a crashworthy airframe structure must be able to perform the following functions:

- Withstand large deflections without failure in those areas where large deformations are anticipated.
- Connect the large overhead mass items to the fuselage such that failure or separation of the major structural members supporting the items occurs before the joint fails.

Of the two considerations, the first imposes the greater constraint on a joint constructed of composite materials or, for that matter, on a metallic fitting manufactured from a casting or a forging since such configurations generally have a lower strain to failure than a sheet-metal-type joint. Composite joint concepts should have redundant or back-up load paths to satisfy the above considerations while relying on the airframe structure to absorb the energy and redistribute crash loads. Most of them contain some metal and therefore are considered hybrids.

In the concept shown in Figure 29(a), the primary load path is the bolted connection between the fitting and the bulkhead. The filaments around the bolts would be designed such that they would not begin to accept any load until the primary load path in the joint has yielded.

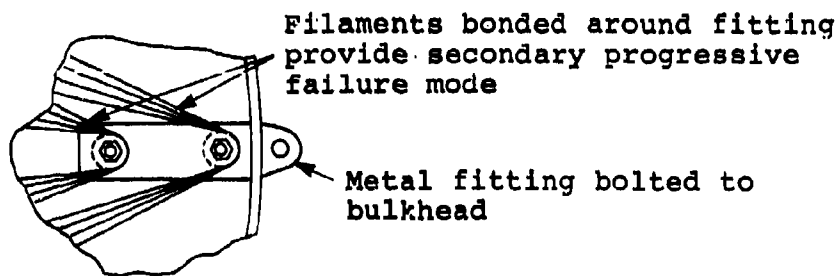
The joint concept shown in Figure 29(b) uses a primary load path through the attachment hole and the bondline between the fitting and the skin. A secondary load path exists between the filaments that are wound in a "racetrack" fashion around the fitting and the skin.

The concept shown in Figure 29(c) depends upon the bond joint between the fitting and the skin for its primary load transfer. The secondary load path uses the mechanical connection provided by the rivets to transfer the load from the fitting to the metallic back-up plate to the composite face sheets. The rivets also provide a tension capability to resist peeling forces which are present due to the eccentric load paths.

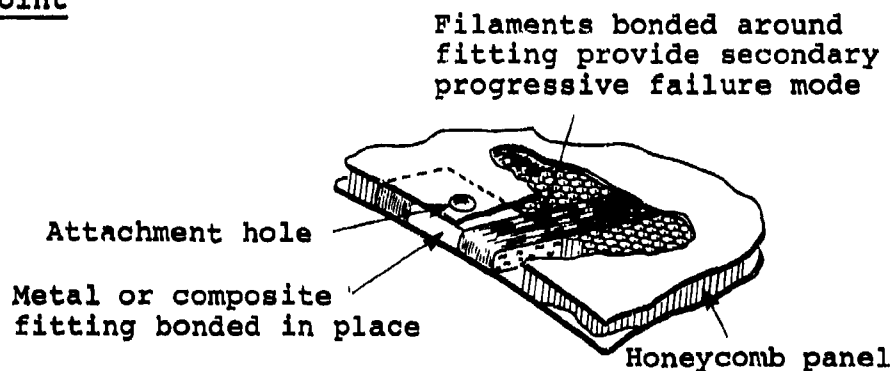
The flattened filament-wound cone concept shown in Figure 29(d) provides a progressive failure mode which causes the joint to contract circumferentially as it elongates longitudinally. After failure of the matrix, the joint would still retain some residual strength due to the fibers contracting around the metal insert.

6.3.5 Spark Generation

Two types of sparks should be considered potential ignition sources. The friction spark is a particle abraded from a parent material through contact with a moving surface. Initially, the particle is heated by friction. If the friction is great enough, the material's combustion temperature will be reached, causing the particle to ignite. Electrostatic sparks result from the discharge of an electrostatic charge accumulated on parts during normal operation. The discharge may be triggered when crash forces cause separation of the parts. This section is concerned only with material selection to minimize spark generation.

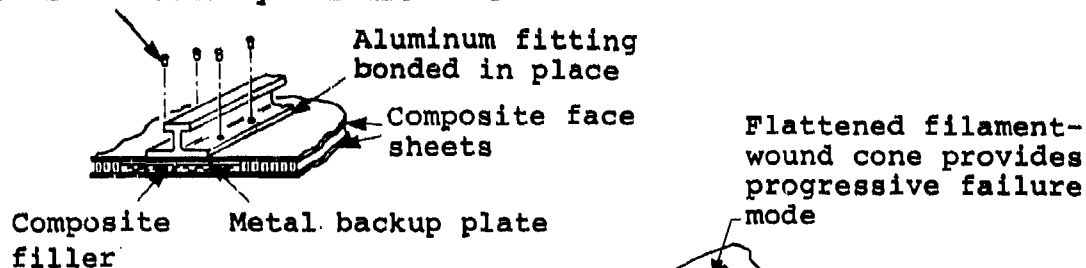


Hybrid joint
(a)



Hybrid or all composite joint
(b)

Rivets and metal backup plate provide secondary failure mode



Hybrid joint
(c)

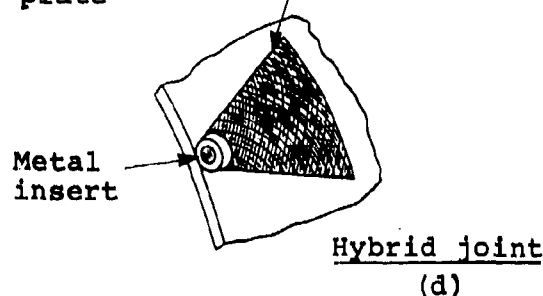


Figure 29. Crashworthy joint concepts. (From Reference 23)

Friction sparks become possible ignition sources when portions of aircraft structure scrape along the ground. While all common metals can be abraded, not all sparks are sufficient to ignite spilled fluids; rather, ignition is dependent on the thermal energy of the spark.

Thermal energy is a function of the following parameters:

- Bearing pressure of structure on ground.
- Sliding velocity of structure relative to ground.
- Metal hardness.
- Temperature at which metal particles burn.

Table 7 gives some results of research conducted by NASA to determine the minimum conditions under which friction sparks from metallic materials typically used in aircraft construction will ignite.

TABLE 7. MINIMUM CONDITIONS UNDER WHICH CERTAIN ABRADED METAL PARTICLES WILL IGNITE (REFERENCES 24 & 25)

Metal	Minimum bearing pressure (lb/in. ²)	Drag speed (mi/h)
Titanium	21-23	less than 5
Chrome-molybdenum steel	30	10
Magnesium	37	10-20
Stainless steel	50	20
Aluminum	1455*	40

*Ignition was not obtained with aluminum.

24. Pinkel, I. I., et al., MECHANISM OF START AND DEVELOPMENT OF AIRCRAFT CRASH FIRES, Lewis Flight Propulsion Laboratory; NACA Technical Note 2996, National Advisory Committee for Aeronautics, Cleveland, Ohio, 1953.
25. Campbell, J. A., APPRAISAL OF THE HAZARDS OF FRICTION-SPARK IGNITION OF AIRCRAFT CRASH FIRES, Lewis Flight Propulsion Laboratory; NACA Technical Note 4024, National Advisory Committee for Aeronautics, Cleveland, Ohio, May 1957.

Two approaches can be used to alleviate the hazards posed by friction spark ignition. One approach is to select materials that possess high ignition thresholds or will not ignite at all for those structures apt to strike the ground plane. The other approach is to prevent a loss of flammable fluids in a crash environment. Perhaps the most practical approach to the problem is to minimize the probability of ignition and fuel loss for a given design configuration.

Aluminum alloys are the least likely to cause ignition of spilled fuel; however, the abrasion rate for aluminum is high, which can result in rapid wear and subsequent tearing. This, in turn, exposes other structures that may be manufactured from materials prone to generate sparks. To minimize the probability of belly skin loss, relatively thick skins made of ductile materials are recommended.

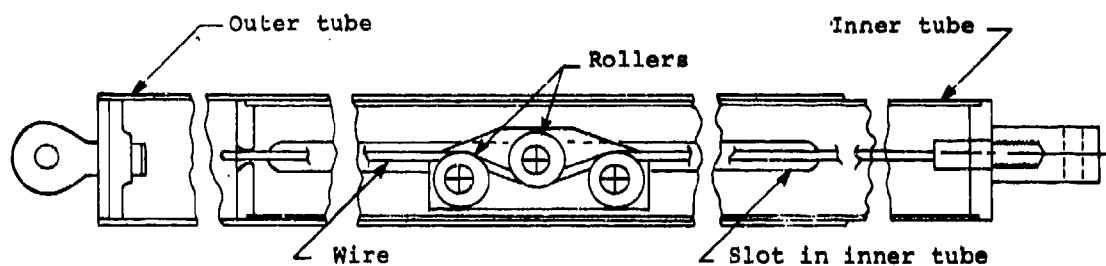
Particular attention should be given to attachment points for hoists, landing gears, boarding steps, and other components located in anticipated impact areas. Also, particular attention should be given to steel nuts, bolts, and washers that can contaminate otherwise spark-free areas.

Composites included in aircraft structures have not been considered as potential ignition sources. However, if the aircraft belly primary structure is constructed from composites, the high bearing pressures and sliding velocities may generate sufficient heat in the form of hot spots to ignite spilled flammable fluids. The relevant properties to ensure that ignition temperatures cannot be developed must be fully investigated for any composite located in such an area of pressure and velocity.

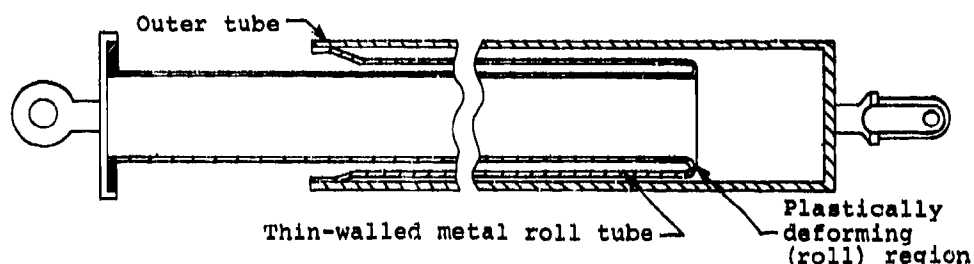
6.4 ENERGY-ABSORPTION DEVICES

Several methods of absorbing energy have been investigated in the past. Some may be included in the primary aircraft structure to help control the deformation sequence during a crash; however, none are applicable for use as major structural members, such as beams. Several possible concepts for accomplishing this aim are illustrated in Figure 25, and a major program to develop this type of structural member is now in progress.

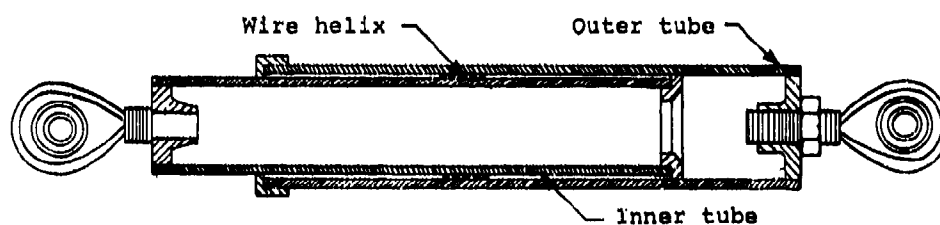
Energy-absorbing devices that operate under uniaxial tension or compression and utilize plastic deformation of metal are described in detail in Chapter 5 of Volume IV, particularly with respect to application in seats. Certain of these devices such as those in Figure 30, are also applicable in cargo restraint systems, to be discussed in Section 6.6.5.11. Since the amount of energy absorbed is a function of the area under



(a) Wire bending - absorbs energy by plastic bending of wire over rollers



(b) Inversion tube - absorbs energy by inverting a thin-walled tube



(c) Rolling torus - absorbs energy by rolling wire helix between concentric tubes

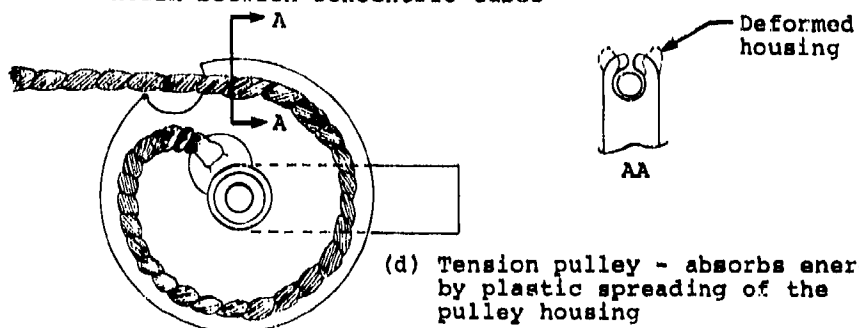


Figure 30. Examples of energy-absorbing devices.

the stress-strain curve traversed by the absorbing device, it is advantageous to strain the material well in excess of its yield point. Care in designing such features into primary structure must be taken since element failure, or a sequence of failures, could reduce a perfectly good protective structural envelope into a collapsible mechanism resulting in a dangerous loss of living space.

Shock struts used in crashworthy landing gear absorb energy by the flow of oil through an orifice, where the pressure drop is sensitive to the stroking velocity. Operation of such a gear is discussed further in Sections 6.5.1 and 7.3.1.

6.5 LANDING GEAR

The design of landing gear for improving crashworthiness presents two definite problems. First, the landing gear must protect the fuselage against contact with the impact surface to the greatest extent possible. Thus, the landing gear must possess certain strength characteristics and energy-absorbing capabilities. The second problem arises once the maximum strength and energy-absorbing capabilities of the landing gear are reached. The designer must attempt to ensure that the landing gear does not fail, and in the extreme case, if failure does occur, to ensure that occupant injury does not result from the failure.

The energy-absorbing capabilities of the landing gear are important primarily in the vertical impact, because maximum occupant protection can be obtained only if every inch of available stopping distance is used to provide a controlled deceleration of the fuselage section. Since both rotary- and fixed-wing aircraft may sometimes impact with relatively large vertical velocities, the landing gear should provide maximum energy absorption to reduce the velocity of the fuselage cabin as much as possible before it contacts the ground.

The relationship between energy-absorbing stroke, peak load factor in G, and velocity change can be obtained from the following energy balance:

$$\frac{1}{2} mv^2 = \int F ds = \eta F_{\max} S \quad (2)$$

where m = mass of aircraft being decelerated
 v = impact velocity
 $F_{\max}$ = maximum force exerted by the structure during the stroke
 S = stroke distance
 η = efficiency of landing gear system.

Substituting the relationship

$$a_{\max}/g = G_{\max} \quad (3)$$

where g = gravitational constant
 $G_{\max}$ = peak load factor
 $a_{\max}$ = maximum deceleration

produces the desired relationship:

$$S = v^2 / 2\eta g G_{\max} \quad (4)$$

As an example, an 18.25-G peak load-limited gear with a stroke of 18 in. and 100-percent efficiency would decelerate the aircraft completely from an impact velocity of 42 ft/sec, which is the total vertical velocity change of a 95th-percentile survivable rotary- or light fixed-wing aircraft.

This stroke can be achieved by single-stage struts. In practice, the ground clearance and underfloor structure are often determined by other design requirements, such as ease of ingress and systems installation, that result in a ground-to-aircraft belly clearance of less than 18 in.

MIL-STD-1290(AV) (Reference 1) requires prevention of fuselage ground contact for a 20-ft/sec vertical impact velocity through landing gear energy absorption and a capability to withstand a 42-ft/sec impact without failure of the gear or attachments. These conditions can be met with a two-stage strut.

The first stage provides protection up to 20 ft/sec. This requires a strut cylinder design that prohibits bursting when the internal pressure reaches the level consistent with the

42 ft/sec impact velocity. After initial stroking and ground impact occur, the second stage and crushing of the underfloor structure occur in parallel.

The benefits that can be gained from effective vertical energy-absorbing landing gear design extend even further. The fuselage is protected from impacts until much of the energy associated with vertical velocity is dissipated. With vertical energy absorption in seats remaining the same, the limits of survivability are extended. Also, less energy is available for deformation of fuselage structure. This means that floor structure remains more continuous, emergency exits are more likely to operate, and flammable fluids can be more easily contained in fuselage tanks. Thus, provision of effective energy-absorbing landing gear for high sink rates yields improvement of all survivability factors. These benefits apply equally to conventional fixed-wing aircraft and vertical take-off aircraft.

In view of the variation in efficiency of various energy-absorption devices, a landing gear stroke of at least 18 in. is recommended. Fuselage structure strength must be compatible with landing gear strength to assure maintenance of occupant living space during gear stroking if the gear is mounted adjacent to the cabin or cockpit areas.

The gear should provide the specified protection in accidents that involve an aircraft attitude as shown in Section 5.1, Table 3.

6.5.1 Wheel-Type Gear

Crashworthy landing gear consists of controlled motion devices that absorb the kinetic energy of the vertical velocity of the aircraft by stroking without rebound; this is, in effect, plastic deformation. The energy-absorbing performance of the total landing gear system is dependent on its load-stroke characteristics and its attachment to primary structural members.

In severe longitudinal impacts typical of fixed-wing aircraft, kinetic energy levels are so great that effective use of landing gear for energy absorption does not appear to be practical. In these crashes, sufficient stopping distance to keep accelerations at relatively low levels is usually available, and landing gear failure usually occurs if the gear strikes an abrupt obstacle, such as the lip of a runway. For longitudinal impact at velocities up to 160 mi/h, it has been found that less than

1 percent of the total kinetic energy at impact is absorbed by failure of the landing gear (Reference 26).

The problem in designing landing gear for longitudinal impact, then, is not to provide energy absorption capable of protecting the occupiable portion of the aircraft, but to design landing gear systems in which failure of the gear does not produce increased danger for occupants. The hazards involved include rupture of flammable fluid tanks and lines and local penetration of the fuselage shell, particularly in the occupiable areas.

Some hazards caused by failure of the structure supporting the landing gear may be prevented by locating the landing gear away from flammable fluid systems and occupiable areas. If this approach is impractical, landing gear components should be designed so the gear is carried away on impact, with the points of failure located where minimum damage to critical aircraft areas will occur. The particular problems associated with a given aircraft will dictate the method to be used.

Crash impacts may occur with combined longitudinal and vertical velocities. Provisions allowing the landing gear to be driven upward and rearward, either into supporting structure or by stroking the energy absorbers, must be made without increasing impact hazards. One method of accomplishing this is to leave an open bay behind and above landing gear locations to permit displacement. Another is to place landing gear elements at extreme outside corners of the structural enclosure where displacement will occur outside the fuselage profile.

One concept for crashworthy landing gear struts employs valves that bypass fluid and allow high impact velocities to be tolerated without causing hydraulic overpressure in the cylinders.

Figure 31 shows the load-stroke characteristics for different landing gear concepts. Curve A shows the response of a fixed-orifice strut that is not equipped with a pressure blow-off valve. As illustrated, the curve is steep, the strut failure point is reached without absorbing a great amount of energy, and the energy is proportional to the area under the curve.

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26. Reed, W. H., and Avery, J. P., PRINCIPLES FOR IMPROVING STRUCTURAL CRASHWORTHINESS FOR STOL AND CTOL AIRCRAFT, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc.; USAAVLABS Technical Report 66-39, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, June 1966, AD 637133.

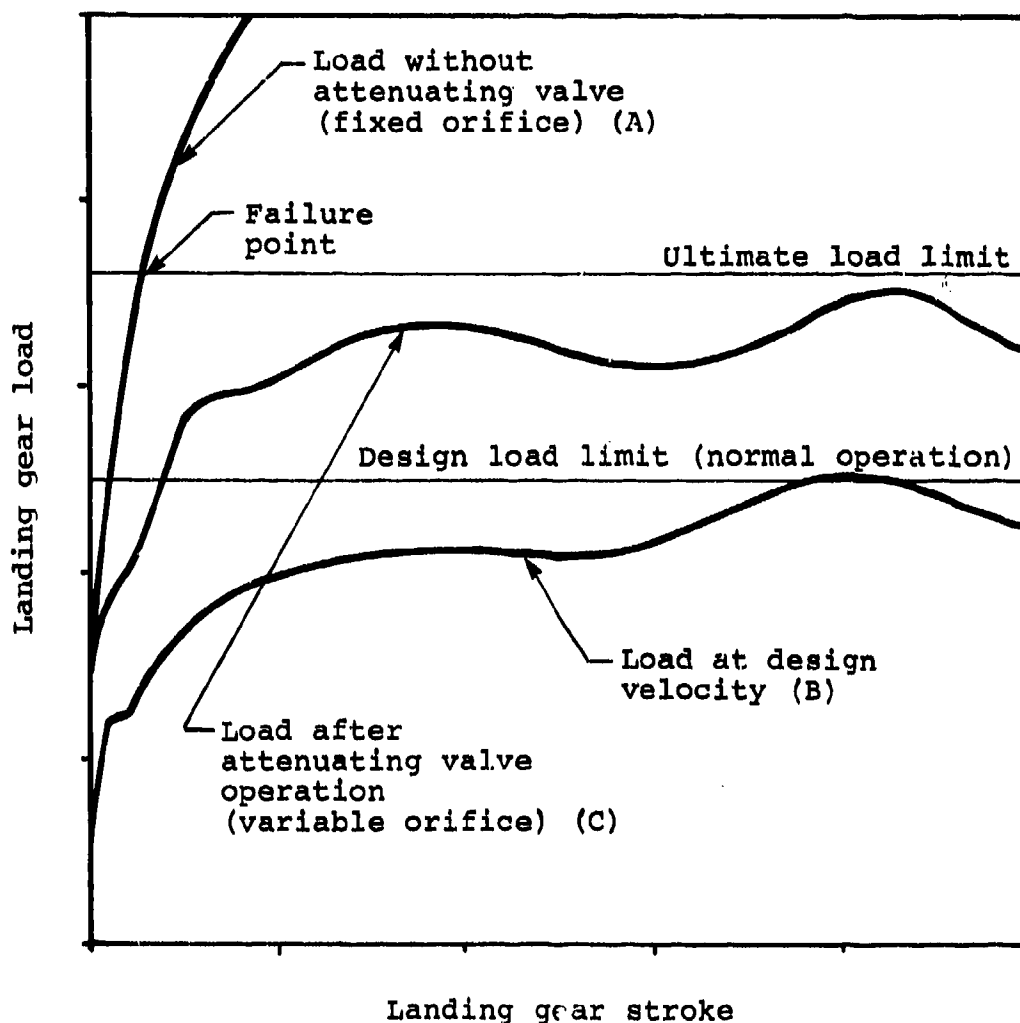


Figure 31. Landing gear characteristics.

The best concept in Figure 31 for an energy-absorbing strut is one having a variable-orifice valve. Such a design allows for maximum operational conditions, as shown in Curve B, and for high-velocity impact, as shown in Curve C. In both instances, loads approaching the maximum allowable within the design constraints for normal operation, or proof condition, and crash impact, or ultimate condition, are generated.

A major problem in designing such a strut is the variable-orifice valve. Such a valve system must be able to sense the high velocities associated with crash impacts and respond to

change the orifice size in the very short time span available. The response rate must be very rapid to preclude excessive cylinder pressure and possible rupture.

Variable-orifice valves are not available at present due to the major problem of producing a reliable device with a response rate compatible with the short-term transients associated with crash impacts. Current research into designing variable-orifice valves should soon yield a producible strut system that works to its energy-absorbing limit for both normal operational landings and crash impacts.

Figure 32 presents a helicopter landing gear configuration designed to meet the requirements of MIL-STD-1290(AV) (Reference 1). It incorporates two-stage struts using fixed-orifice valves and blow-off devices, as indicated, to provide the required level of energy absorption at stroking rates of up to 42 ft/sec. Operation of such a gear is discussed quantitatively in Section 7.3.1. For comparison with the desirable strut performance, using a variable orifice, Figure 33 shows the load-stroke characteristics for a state-of-the-art landing gear for a helicopter such as that shown in Figure 32. As illustrated, the cylinder pressure, or load, increases rapidly until the blow-off valves open. This results in a drop in load-carrying capability, which then remains approximately constant until the full stroke condition is reached. Then, as shown, strut motion stops, and the load builds up once again due to strain energy effects. The energies involved in the process are indicated, and it should be noted that after the 20 in. or so of travel, the aircraft velocity is 36.3 ft/sec when ground impact of the fuselage occurs.

A major problem to overcome when designing landing gear installations is the effect of side loads. Helicopter crashes often occur with some roll attitude (see Section 3.4 of Volume II) and when impact occurs with trees or overhead wires, a purely lateral impact can be initiated. When considering crash loads, it is important to assess the effects of side loading and design landing gear elements and structural attachments to withstand such loads. In the past, crash hazards have been compounded due to loss of landing gear integrity when side loads caused failure as initial ground impact occurred. When a crash occurs laterally or with a roll attitude, the aircraft will often rotate to a sensibly upright position after initial ground contact. After this, energy can be absorbed by vertical stroking of the gear struts only if complete gear integrity is maintained during the transition from lateral to vertical loading.

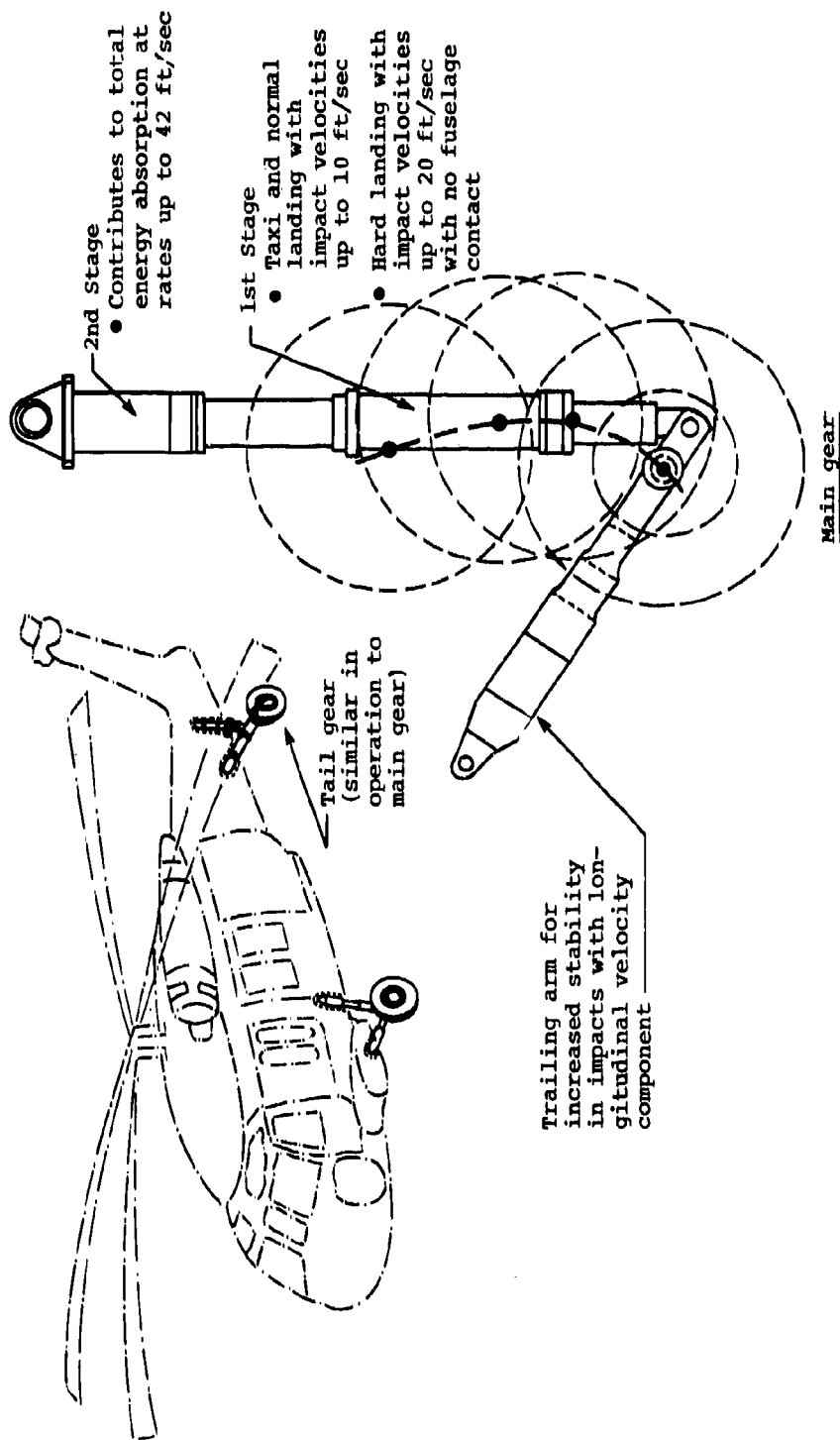


Figure 32. Landing gear configuration.

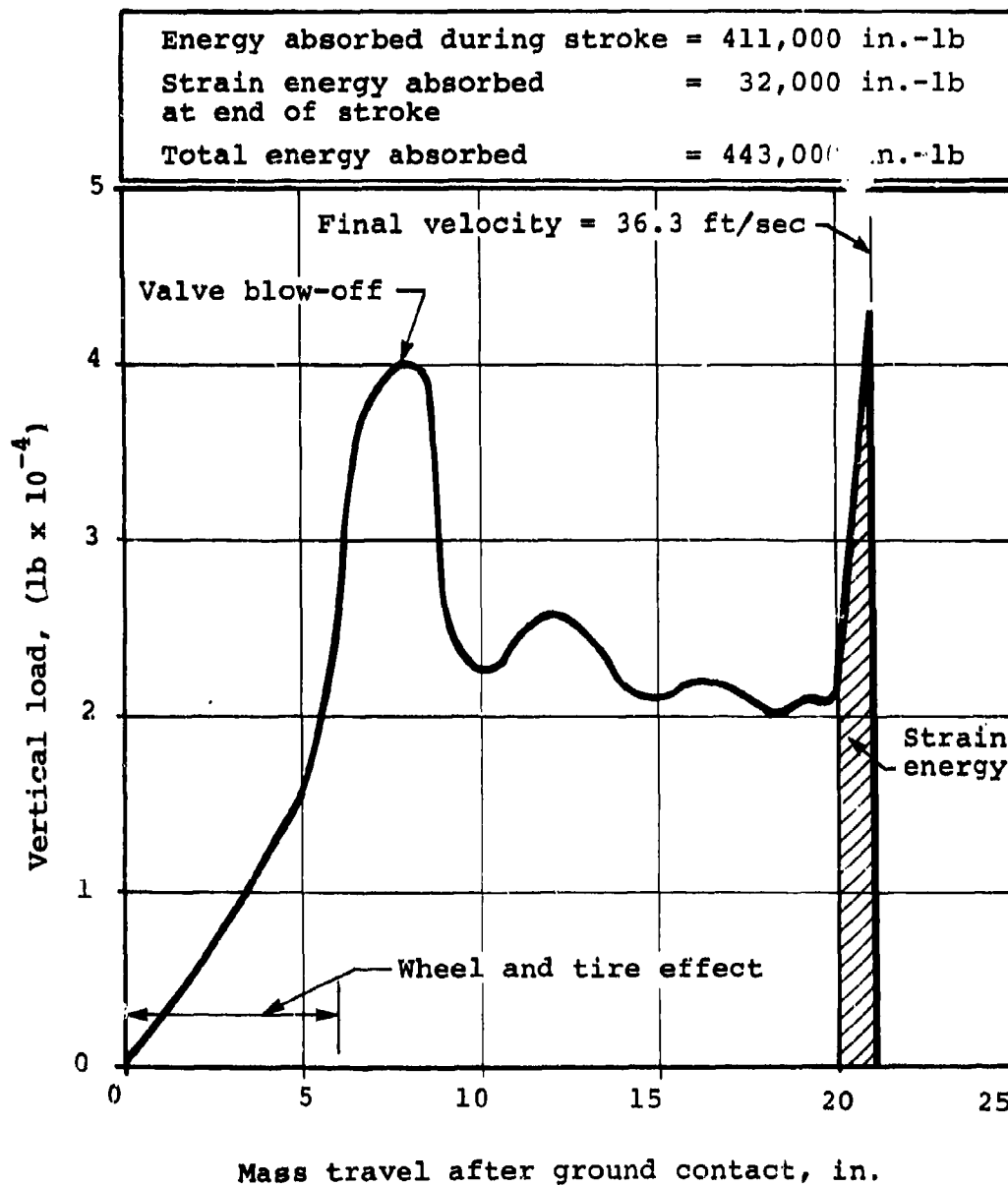


Figure 33. Nose landing gear crash energy absorption.

6.5.2 Skid Gear

The simplest form of skid gear, which offers advantages of low cost and weight, is the bent tube attached to structural frame members. The skid gear can also provide improved support in landings on soft or marshy terrain. This type of gear provides a limited level of energy attenuation in heavy landings. The skid system is basically a nonlinear structure providing a constant spring rate for small deflections only. Such a design provides a low-cost means of creating small elastic deflections during normal landings while providing energy dissipation efficiencies comparable to those of an oleo strut. However, in a heavy landing or crash the skids deflect appreciably and the nonlinear plastic characteristics of such a system prevail.

During plastic bending the moment arm increases, lowering the loads as the deflection increases until the fuselage contacts the ground. A further problem manifests itself when lateral impact conditions occur due to sideslip velocity or roll attitude in a primarily vertical impact. Then, digging-in of the skid can cause rollover and/or collapse of the skid under the belly of the aircraft, conditions that are not desirable for energy attenuation or crash survival.

Improvements to the fixed-skid concept have been designed in an attempt to provide some level of energy absorption with rate damping. In addition, such a system can be tuned to minimize the effects of dynamic excitations that may produce ground resonance. Figure 34 shows the basic skid system used on one observation helicopter and an improved, pitch-interconnected concept (Reference 27). The improved design was initiated to reduce the nose-down pitching response of the aircraft and, hence, minimize the incidence of blade-tail boom strikes. Although tail boom clearances were improved, the new concept did not satisfy the MIL-STD-1290(AV) requirement for no ground contact by the fuselage for a 20-ft/sec vertical impact (Reference 1). Only 17.5 ft/sec was reached before fuselage contact.

27. Logan, A. H., ANALYTICAL INVESTIGATION OF AN IMPROVED HELICOPTER LANDING GEAR CONCEPT, Hughes Helicopters; USAAMRDL Technical Report 76-19, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1976, AD A029372.

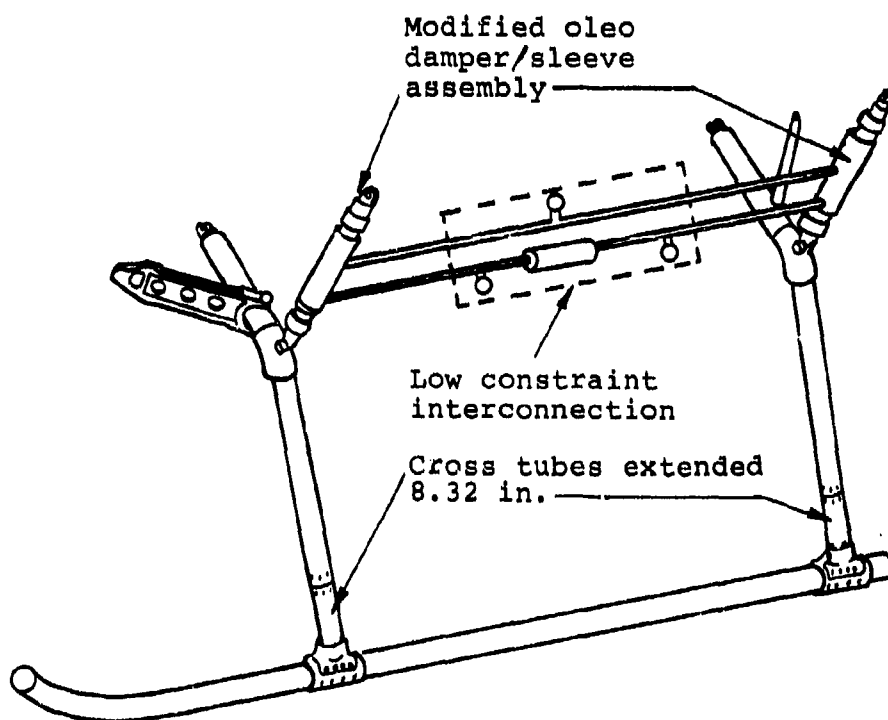
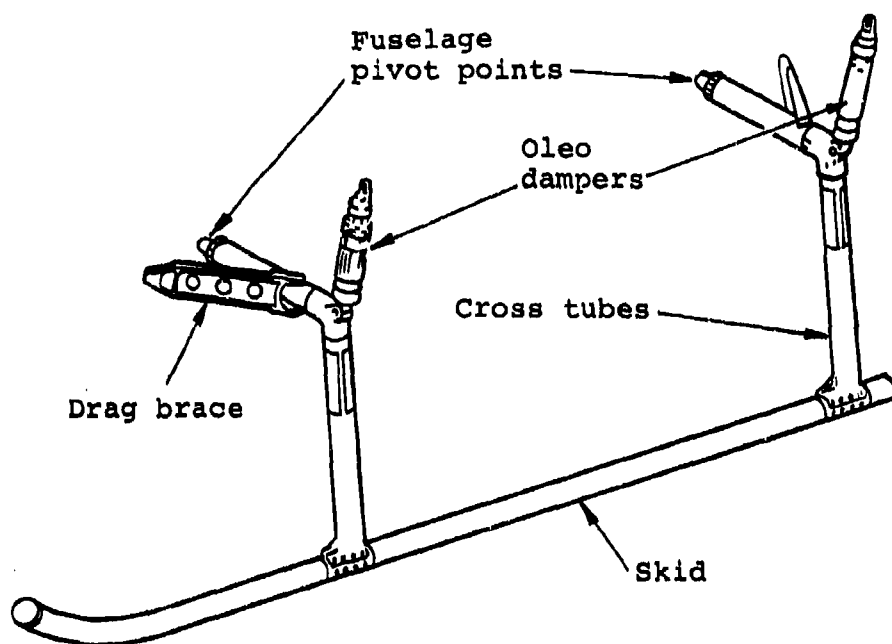


Figure 34. Helicopter skid gear and improved, pitch-interconnected concept.

6.6 FUSELAGE

6.6.1 General

Efforts to improve aircraft crashworthiness begin with improvements in fuselage design, since the fuselage provides the occupants' protective shell. In this section, principles for improving fuselage structure and methods for accomplishing these improvements are presented.

In order to conduct a meaningful program aimed at improving overall structural crashworthiness, a means of measuring crashworthiness is essential. Two indices of crashworthiness that have been proposed are:

- The degree of cabin collapse, under standard crash conditions, chosen through consideration of the respective aircraft operating characteristics.
- The level of acceleration experienced by occupants during the crash.

Whenever structural design, or changes in design, brings about a reduction in the degree of collapse that may be expected in a crash and/or in the level of accelerations experienced by occupants, the probability of occupant survival is increased.

Acceptance of these indices as structural crashworthiness criteria permits a crashworthiness comparison of various configurations subjected to similar crash conditions and leads to consideration of several methods which offer promise of increasing the probability of occupant survival in aircraft accidents. These include:

1. Increase in the energy-absorption capacity of the structure surrounding occupiable areas to provide added protection for these areas.
2. Alteration of the structure that makes initial contact with the ground to reduce gouging and scooping of soil, hence lowering accelerations and transmitted forces.
3. Modification of structures such as the antitorque rotor, empennage boom, support system for the external stores, and, in certain cases, the landing gear to ensure that if these parts fail, they fail safely. Component breakaway during a crash can be used to effect a reduction in the mass of the aircraft, hence reducing the strength requirement for the cabin structure.

4. Reinforcement of cockpit and cabin structure to enable the structure to withstand greater forces without collapse.
5. Modification of fuselage structure to allow increased deformation or collapse of structure in unoccupied regions, thus permitting additional structural energy absorption.

The shape of the fuselage has an inherent influence on all these methods except 3. Rectangular cross sections can be designed to provide the same crashworthy characteristics as spherically, cylindrically, or elliptically shaped fuselages; however, in practice they are not. The circular or elliptical cross sections normally are stronger structures. Also, the cavities between curved fuselage skin and flat floors or essentially flat inner walls provide volume for the inclusion of energy-absorbing material. The result has been that curved fuselage configurations are generally more crashworthy than rectangular ones. Figure 35 shows a light observation helicopter shape and component layout advantageous for providing crash impact protection (Reference 28).

To determine the potential contributions of all possible methods of improvement, it will be necessary to evaluate each aircraft on the basis of its own structural characteristics and the anticipated operating characteristics which indicate probable modes of impact.

An understanding of the potential influence upon crashworthiness of methods 1, 2, and 3 above will be helpful in selecting methods of structural improvement which will effectively and efficiently increase the probability of occupant survival.

6.6.2 Energy-Absorption Capacity of Forward Fuselage

From a consideration of conservation of energy, the initial kinetic energy of an impacting aircraft must be accounted for in energy dissipated during the deformation of both soil and structure. Therefore,

$$\frac{m_A (v_o^2 - v_f^2)}{2} = U_G + U_S \quad (5)$$

28. Smith, H. G., DESIGNING HELICOPTERS FOR IMPROVED CRASH SURVIVABILITY, paper presented at NATO/AGARD Aerospace Medical Panel Specialist Meeting, Oporto, Portugal, 23, 24, and 26 June 1971.

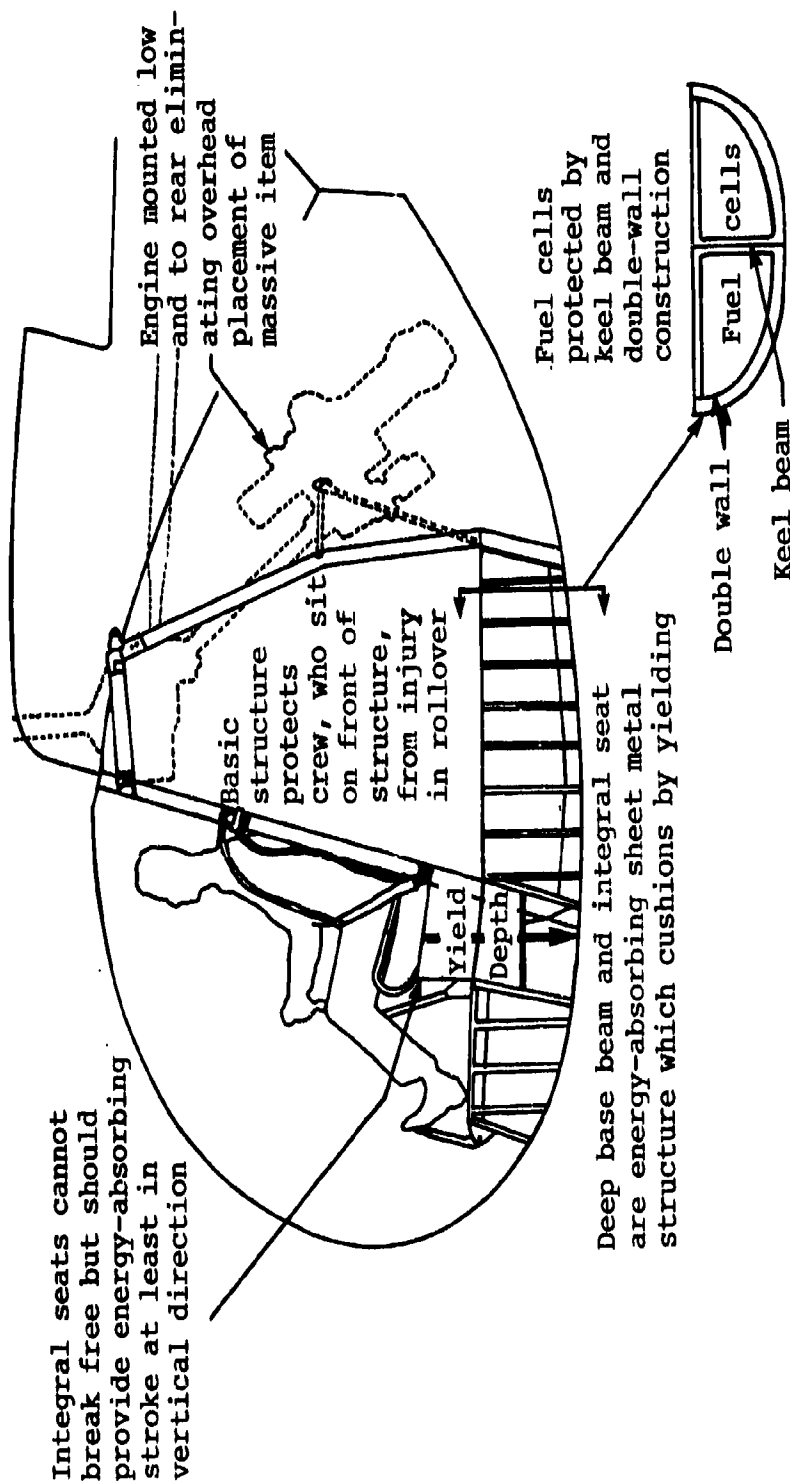


Figure 35. Observation helicopter - layout of crashworthy features. (From Reference 28)

where m_A = mass of aircraft
 v_o = initial impact velocity of aircraft
 v_f = velocity remaining after impact
 U_G = energy dissipated in soil deformation and ground friction
 U_S = energy dissipated in structural deformation.

This equation states that the reduction in aircraft kinetic energy must be equal to the energy absorbed by deformation of earth and structure and is simplified by the assumption that there is no change of aircraft mass during the impact.

As a simplified model, the structural energy absorption, U_S , may be expressed as

$$U_S = P_{av}S + U'_S + U_C \quad (6)$$

where P_{av} = average force developed in collapse of structure forward of the cabin

S = linear deformation (reduction in length) of structure forward of the cabin

U'_S = deformation energy in structure other than in the cabin or structure forward of the cabin

U_C = energy to be absorbed in cabin deformation.

The cabin deformation energy, U_C , represents the quantity of energy absorbed by deformation of cabin structure, and may be obtained from Equations (5) and (6):

$$U_C = \left[\frac{m_A (v_o^2 - v_f^2)}{2} - U_G \right] - (P_{av}S + U'_S) \quad (7)$$

This equation for cabin deformation energy is valid if conditions reach or exceed the point of onset of cabin deformation.

Assuming a fixed mass and velocity and ignoring control over energy dissipated outside the aircraft, the factors that are controllable in Equation (7) are P_{av} , S , and U'_S .

Consequently, U_c , the energy which must be absorbed in cabin collapse or collapse of the protective shell, may be reduced by:

- Increasing P_{av} , the average crushing force acting during collapse of structure forward of the cabin. P_{av} may be increased for a given maximum collapse force by providing forward structure which will maintain a force as nearly uniform as possible during collapse. In addition, P_{av} may be further increased by admitting an increase in the maximum force applied to the forward structure. This latter option is limited, however, by the existing strength of the cabin. If, for example, the maximum collapse force for forward structure were to exceed the cabin collapse strength, then the energy-absorption objective would be defeated, as the cabin deformation would commence prior to full collapse of forward structure and, therefore, prior to full energy dissipation in the forward structure.

Another point to be considered is the effect of forward structural modifications upon the second crash-worthiness index, occupant acceleration. If the maximum collapse force is increased, aircraft acceleration will increase, adversely affecting this second index. The trade-off between the energy-absorption benefits of increasing P_{av} by increasing the maximum force and the detrimental effects of increasing maximum aircraft acceleration must therefore be considered.

- Increasing the available deformation distance, S , which would also permit greater energy absorption in the forward structure. (This could be accomplished without increasing the maximum collapse force.) This factor should definitely be considered in original design. It could be accomplished by placing the cabin as far aft as practical, as on modern agricultural aircraft.
- Increasing the deformation energy absorbed in aircraft structure other than forward structure or cabin structure. This would further contribute to a lower cabin deformation energy requirement. Structural design which permits plastic deformation of structure at selected points away from occupiable areas could accomplish this.

Application of any of these principles to the airframe design, with a given cabin structural configuration, will make it possible for the aircraft to withstand impact at increased velocity without collapse of the protective shell, thus extending the limits of survivable conditions and improving survivability in crashes under less severe conditions.

6.6.3 Reduction of Earth Flowing

Under certain conditions of impact and structural deformation, the forward section of an impacting aircraft, particularly a helicopter with a blunt nose, deforms to become a scoop, picking up a mass of earth and "driving" it to the velocity of the aircraft. This process is accomplished in a very short time interval; therefore, the principle of conservation of momentum may be applied to the system, which includes the mass of soil that must be accelerated, referred to as the effective mass of earth, and the aircraft mass. Accordingly, conservation of momentum leads to the relationship

$$m_A v_0 = (m_A + m_E) v \quad (8)$$

where m_A = mass of aircraft

m_E = effective mass of accelerated earth

v_0 = initial impact velocity of aircraft

v = velocity of combined system immediately after impact.

Solving Equation (8) for v , we obtain

$$v = \left(\frac{m_A}{m_A + m_E} \right) v_0 \quad (9)$$

To find the interaction force involved in the momentum exchange, an impulse-momentum relationship may be applied to the earth mass as a free body.

$$\int_{t_1}^{t_2} F dt = m_E v \quad (10)$$

where F = interaction force

t_1 = time just prior to impact

t_2 = time directly following momentum interchange.

By definition of the average force,

$$\int_{t_1}^{t_2} F dt = F_{av} \Delta t \quad (11)$$

where

$$\Delta t = t_2 - t_1$$

Substituting Equations (9) and (11) into Equation (10) yields

$$F_{av} = \left(\frac{m_A m_E}{m_A + m_E} \right) \frac{v_o}{\Delta t} \quad (12)$$

Consequently, the average acceleration of the aircraft mass due to the acceleration of the earth mass is

$$a_A = \frac{F_{av}}{m_A} = \left(\frac{m_E}{m_A + m_E} \right) \frac{v_o}{\Delta t} \quad (13)$$

Also,

$$m_E = K A v_o \Delta t \quad (14)$$

where K is a constant and A is the cross-sectional area of the gouge in the earth.

Thus,

$$a_A = \frac{K A v_o^2}{m_A + K A v_o \Delta t} \quad (15)$$

which indicates that the deceleration of the aircraft varies with the square of the initial velocity (where the scoop effect is a dominant factor and Δt is small). Thus, at high impact velocities, the scoop phenomenon assumes a greater significance. Experimental evidence substantiates the fact that impact accelerations do increase with the increasing impact velocity; however, maximum aircraft acceleration due to impulsive acceleration of earth is limited by the strength of the aircraft structure. Experimental evidence also indicates that, under high rates of loading, the force transmission ability of structures increases due to the stabilizing effect of lateral inertia during buckling of the structural members.

As an example of the use of Equation (15), assume that the following conditions exist:

$$v_o = 140 \text{ ft/sec}$$

$$\Delta t = 0.02 \text{ sec}$$

$$m_E = 0.185m_A$$

Then

$$a_A = \left(\frac{m_E}{m_A + m_E} \right) \frac{v_o}{\Delta t}$$

$$a_A = \left(\frac{0.185}{1.185} \right) \left(\frac{140}{0.02} \right)$$

$$a_A = 1092 \text{ ft/sec}^2 = 34 \text{ G}$$

If the impact velocity, v_o , and the time interval, Δt , remain unchanged but the effective earth mass, m_E , is reduced to $0.10 m_A$, the average impulsive acceleration of the aircraft becomes

$$a_A = \left(\frac{0.1}{1.1} \right) \left(\frac{140}{0.02} \right) = 637 \text{ ft/sec}^2 = 19.8 \text{ G}$$

Increasing the impact velocity, v_o , to 160 ft/sec (under the aforementioned assumption that acceleration varies with velocity squared), when $m_E = 0.185m_A$, results in an aircraft acceleration

$$a_A = \left(\frac{160}{140} \right)^2 1092 = 1430 \text{ ft/sec}^2 = 44 \text{ G}$$

And if a mass of earth equal to $0.1m_A$ is accelerated under an impact velocity of 160 ft/sec, the average acceleration is computed to be 25.8 G.

Figure 36 shows a family of curves relating impulsive aircraft acceleration to the ratio of effective earth mass to aircraft mass for various impact velocities. The duration of the impulsive loading varies with impact velocity, although the curves are based on a single assumed value of 0.02 sec for the 140-ft/sec impact.

In addition to the force associated with momentum exchange, soil penetration by projecting structure gives rise to a drag force, sometimes called the "plowing effect." This force adds to other soil reactive forces. The plowing force should be distinguished from the impulsive force associated with momentum exchange, because it is a steady-state force depending upon velocity, soil strength and density characteristics, and projected area of interference. It should be noted, however, that a design which effectively reduces the scoop effect also helps to reduce the plowing effect contribution.

6.6.4 Reduction of Aircraft Mass

As suggested earlier, it is possible to reduce the aircraft mass through planned breakaway of portions of the aircraft during a crash. An analysis of the influence of the reduction of aircraft mass is presented here.

The expression for cabin deformation energy, U_C , which was obtained from the solution of Equations (5) and (6), is repeated below:

$$U_C = \left[\frac{m_A (v_o^2 - v_f^2)}{2} - U_G \right] - (P_{av}S + U_S^i) \quad (7)$$

Changes in effective aircraft mass during a crash would leave the energy absorbed in collapse of forward structure, $P_{av}S$, and the energy absorbed in plastic deformation of other aircraft structure, U_S^i , essentially unaffected. The energy dissipated outside the aircraft in soil deformation, U_G , would, on the other hand, be influenced by the aircraft mass. This soil deformation energy assumes several forms: principally, the energy associated with superficial friction and that involved in the plowing, scooping, and compression of soil.

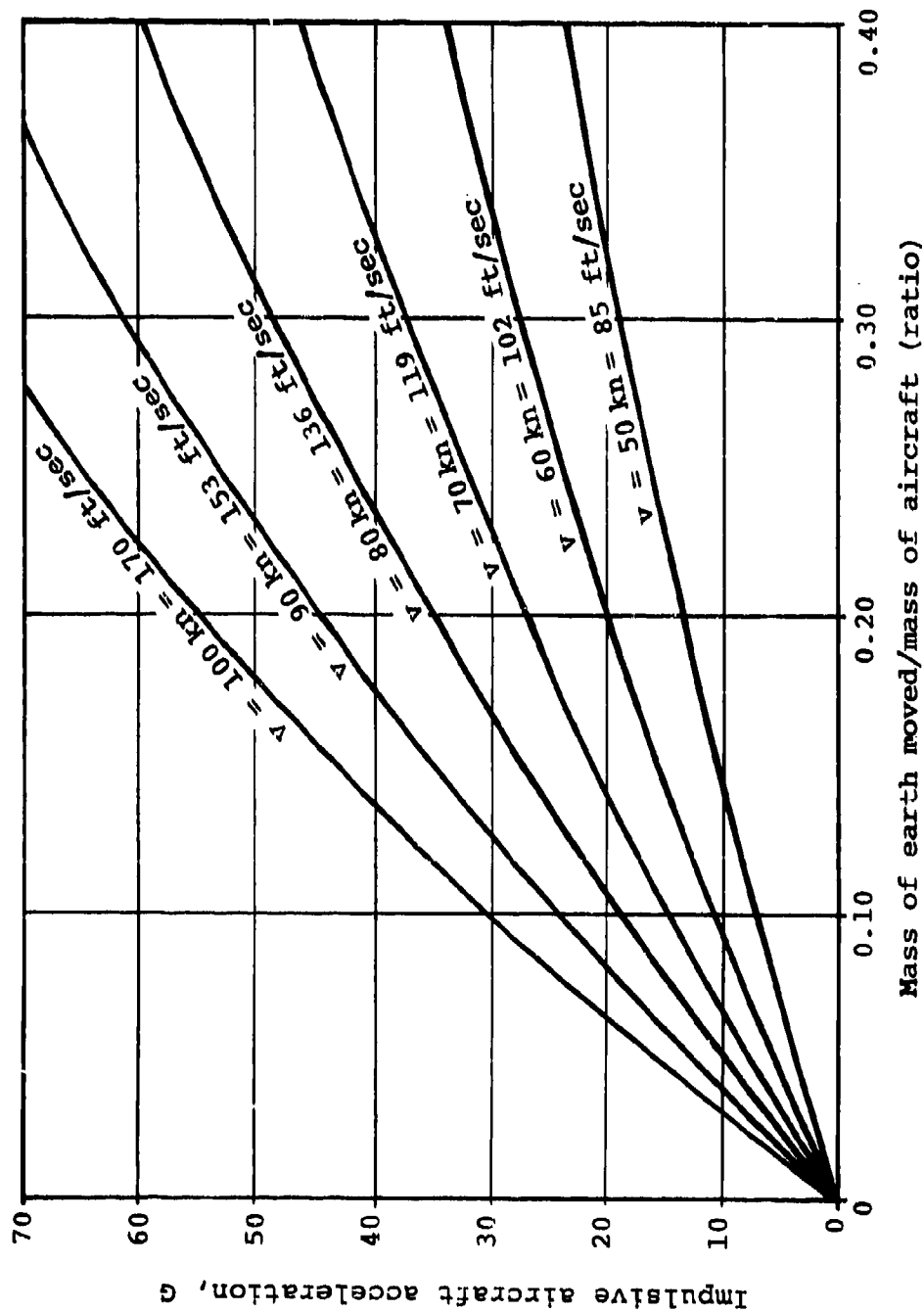


Figure 36. Impulsive aircraft acceleration as a function of velocity and ratio of accelerated mass of earth to aircraft mass (based upon assumed time, Δt , for acceleration of earth mass).

With a reduced aircraft mass, contact forces would tend to be less, and energy dissipated in friction would be reduced. Also, with reduced aircraft mass (assuming that the force transmitted through deforming structure is controlled by structural collapse strength and is therefore constant with respect to mass change), less time would be required to accomplish a given velocity change. This would allow less time to dissipate energy in soil deformation. Consequently, a reduction in mass of the aircraft would also serve to reduce the energy absorbed at or within the ground. As a plausible approximation, in the absence of a developed soil dynamics study, the magnitude of U_G was assumed to be proportional to the aircraft mass.

Denoting the effective aircraft mass after breakaway of portions of the aircraft by m_A' , an expression may be written for the cabin deformation energy with reduced mass:

$$U_C = \left[\frac{m_A'}{m_A} \right] \left[\frac{m_A (v_o^2 - v_f^2)}{2} - U_G \right] - (P_{av}S + U_S') \quad (16)$$

where U_G denotes the soil deformation energy obtainable without reduction in mass.

A numerical example will serve to illustrate the influence of mass reduction more clearly. In this case, it is assumed that the soil deformation energy for a given accident environment is equal to 70 percent of the initial kinetic energy, or

$$U_G = 0.7 \left[\frac{m_A (v_o^2 - v_f^2)}{2} \right] \quad (17)$$

Then the equation becomes

$$U_C = \frac{m_A'}{m_A} \left[0.15 m_A (v_o^2 - v_f^2) \right] - (P_{av}S + U_S') \quad (18)$$

and, for the following impact conditions,

Aircraft weight = 8000 lb

$m_A = 250$ slugs

$v_O = 140$ ft/sec

$v_f = 80$ ft/sec

$P_{av} S = 300 \times 10^3$ ft-lb

$U'_S = 50 \times 10^3$ ft-lb

The cabin deformation energy is

$$U_C = \frac{m_A'}{m_A} (495 \times 10^3) - (350 \times 10^3) \text{ ft-lb}$$

Consequently, if there is no reduction of the mass of the aircraft during the crash, the cabin deformation energy is

$$U_C = (145 \times 10^3) \text{ ft-lb}$$

For a mass reduction to 0.85 of the original mass, the requirement for cabin deformation energy is reduced to

$$(U_C)_{0.85m_A} = 0.85 (495 \times 10^3) - (350 \times 10^3) \text{ ft-lb}$$

$$(U_C)_{0.85m_A} = (71 \times 10^3) \text{ ft-lb}$$

This illustration shows the reduction of cabin deformation energy which is possible through a small reduction of aircraft mass.

6.6.5 Design Concepts for Improved Crashworthiness

6.6.5.1 General: In the foregoing discussion, it was noted that improvement of airframe crashworthiness is accomplished through improvement in either one or both of two survivability factors: the ability of the protective container to maintain living space for occupants during a crash, or the attenuation of accelerations experienced by the occupants during a crash.

When considering any design concept for improving structural crashworthiness, the survivability factor to be improved must be kept in mind and, additionally, the energy-dissipation characteristics of the crash must be understood.

There is a basic difference between the dissipation of kinetic energy in crashes which are primarily longitudinal (high velocity, low angle) and those that are primarily vertical.* In longitudinal impacts onto relatively flat surfaces, a high percentage of the initial kinetic energy of the aircraft is dissipated in compression and acceleration of masses of earth and in friction between the aircraft and the earth. Consequently, in this type of longitudinal crash, a relatively low percentage of the initial kinetic energy is absorbed by structural deformation. In primarily vertical impacts, longitudinal impacts into barriers, and lateral impacts, much more of the initial kinetic energy must be absorbed by the structure.

This leads to separate consideration of design concepts for improving crashworthiness under primarily longitudinal impact conditions and under other impact conditions.

6.6.5.2 Improvement of Crashworthiness in Longitudinal Impacts: Since, in primarily longitudinal crashes, the compression and scooping of earth contribute a major part of the floor accelerations experienced within the cabin, the first topic presented is a discussion of methods for reducing the scooping or plowing of earth.

When the forward sections of an aircraft deform so that a scoop is formed and earth is impulsively accelerated, two adverse effects may occur. First, high acceleration of the aircraft may occur. Second, the large forces required to accelerate the earth mass may be concentrated in a small area and cause local

*As used here, "longitudinal" refers to the orientation of the velocity vector with respect to the impact surface, i.e., parallel to the impact surface. "Vertical" impact refers primarily to the autorotation type impact for rotary-wing aircraft.

collapse of the cockpit protective shell. Reduction of earth scooping will thus lower fuselage floor acceleration levels and tend to prevent the buckling of the protective container.

Reduction of earth scooping can be accomplished by structural design which eliminates those surfaces that can gouge or dig into terrain. The structural design should provide a large, relatively flat surface so that the aircraft skids along on top of the terrain.

One design method involves the prevention of inward buckling of fuselage lower nose skin. This would be similar to preventing a thin spherical shell from buckling under excessive uniform loading. A method of accomplishing this is shown in Figure 37. The design method shown may not increase the longitudinal strength of the nose section, but it will reduce the tendency to buckle inward due to vertical loads distributed over the lower nose surface. If this design is to be effective, the lower skin should be a ductile, tough material with enough thickness to resist tearing. The skin should remain continuous to provide a skidding surface. It is recommended that the forward fuselage belly skins on aircraft weighing up to 3,000 lb be capable of sustaining loads of 1,500 lb/in.; over 3,000 lb but under 6,000 lb, 2,400 lb/in.; and over 6,000 lb, 3,000 lb/in. The above running loads are to be applied over the forward 20 percent of the basic fuselage length.

This method for reducing earth scooping increases the deformation strength of the underfloor structure, thus increasing the deceleration levels at the floor level due to vertical velocity components. Therefore, the reinforcement should not be continued back any further than necessary under occupied sections of the fuselage. Modifications to reinforcing structure under occupied regions are presented in Section 6.6.5.3.

Strong structural crossmembers can present abrupt contour changes during deformation, thus forming the lip on the scoop that tends to trap earth. Forward underfloor frame members may be canted aftwards at the bottom to provide an upward load component on the aircraft that tends to prevent, or limit, digging in of the structure. The longitudinal strength of the nose section can be increased by the use of strong continuous structural members running fore and aft in the underfloor section of the aircraft. These beams can be used to support the crossmembers and act as skids to further reduce scooping or digging-in tendencies. Figure 38 illustrates this type of construction.

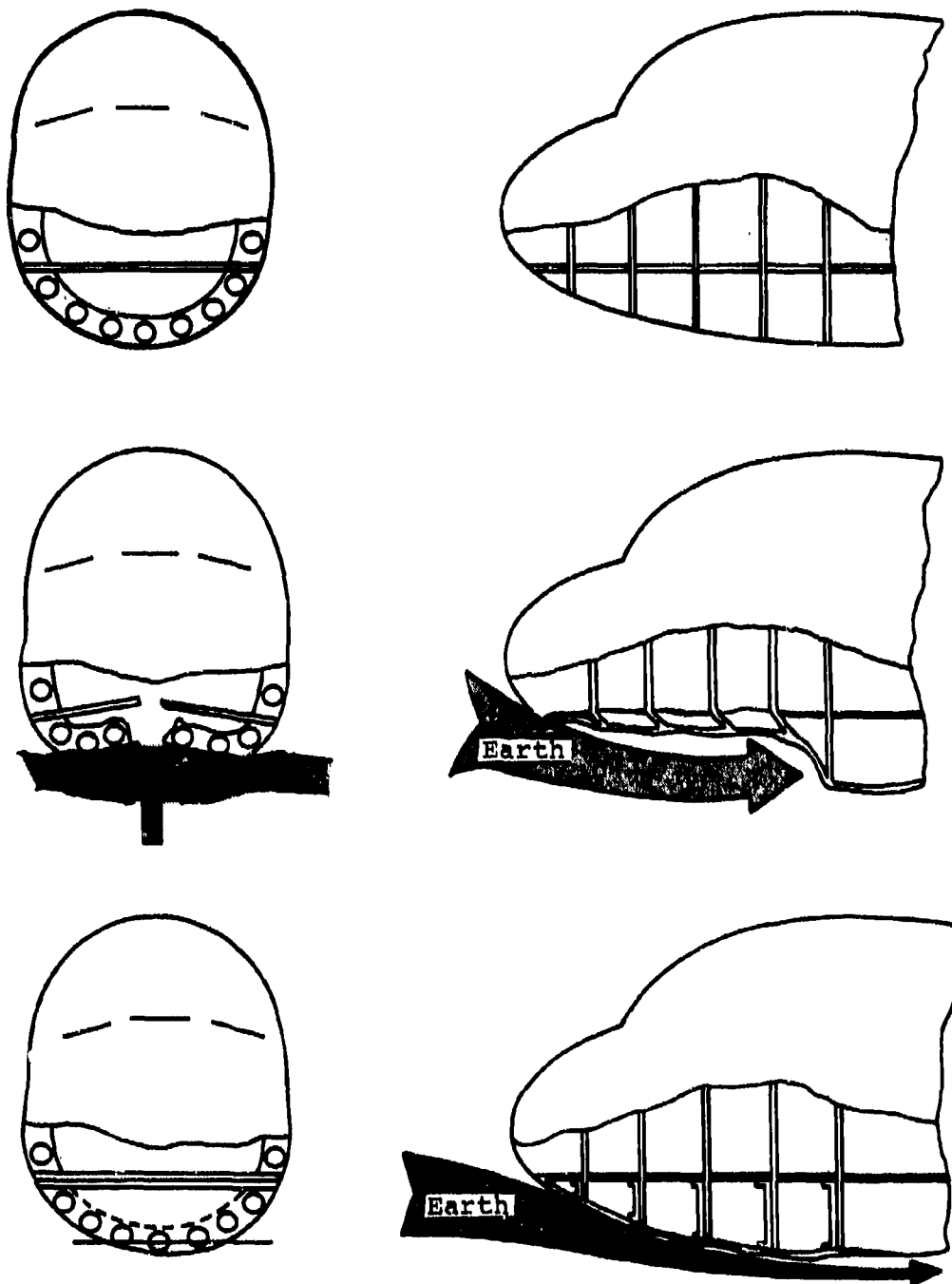


Figure 37. Method of reinforcing nose structure to provide increased resistance to vertical loads and to reduce earth scooping.

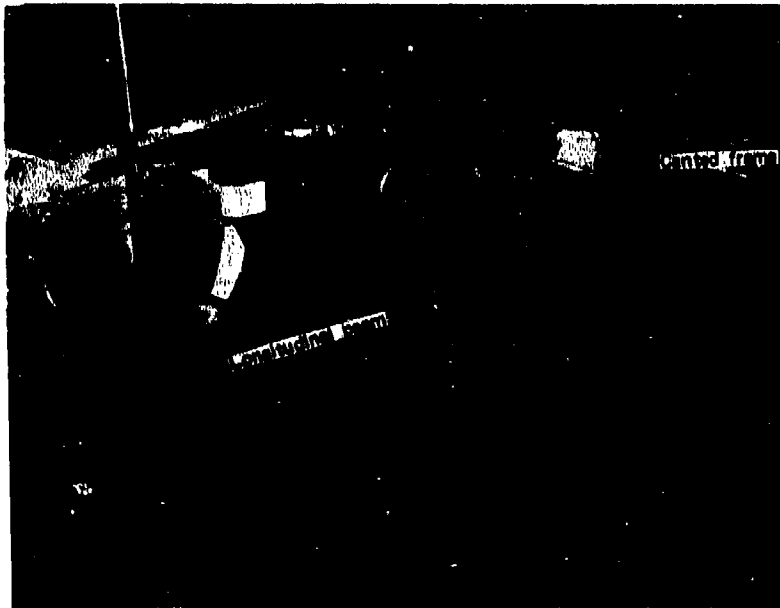


Figure 38. Typical underfloor canted frame and longitudinal beam member to minimize nose plowing.

Additionally, the underbelly skins, made from thick sheet material, are shingled in an aftward direction to preclude their picking up at the front edge. These features are illustrated in Figure 39.

These typical structural features of a passenger-carrying helicopter may be used also for other types of aircraft, at least in principle. Obviously, certain operational and structural features require special attention when crashworthy primary structure is designed.

Often, in aircraft with the engine mounted in the nose, or in the design of engine nacelles, structural bracing as discussed above is not practical because the structure beneath the engine is a very light secondary structure made up of removable doors and cowlings. The engine and engine mounts, however, may be strong enough to support a skidding surface if a filler is provided between the engine and the lower skin. The filler may be made of lightweight plastic foam or honeycomb material, contoured to fit the lower surface and to fill as much space as possible between the skin and the engine, as illustrated in the lower sketch of Figure 40. The attachments of removable

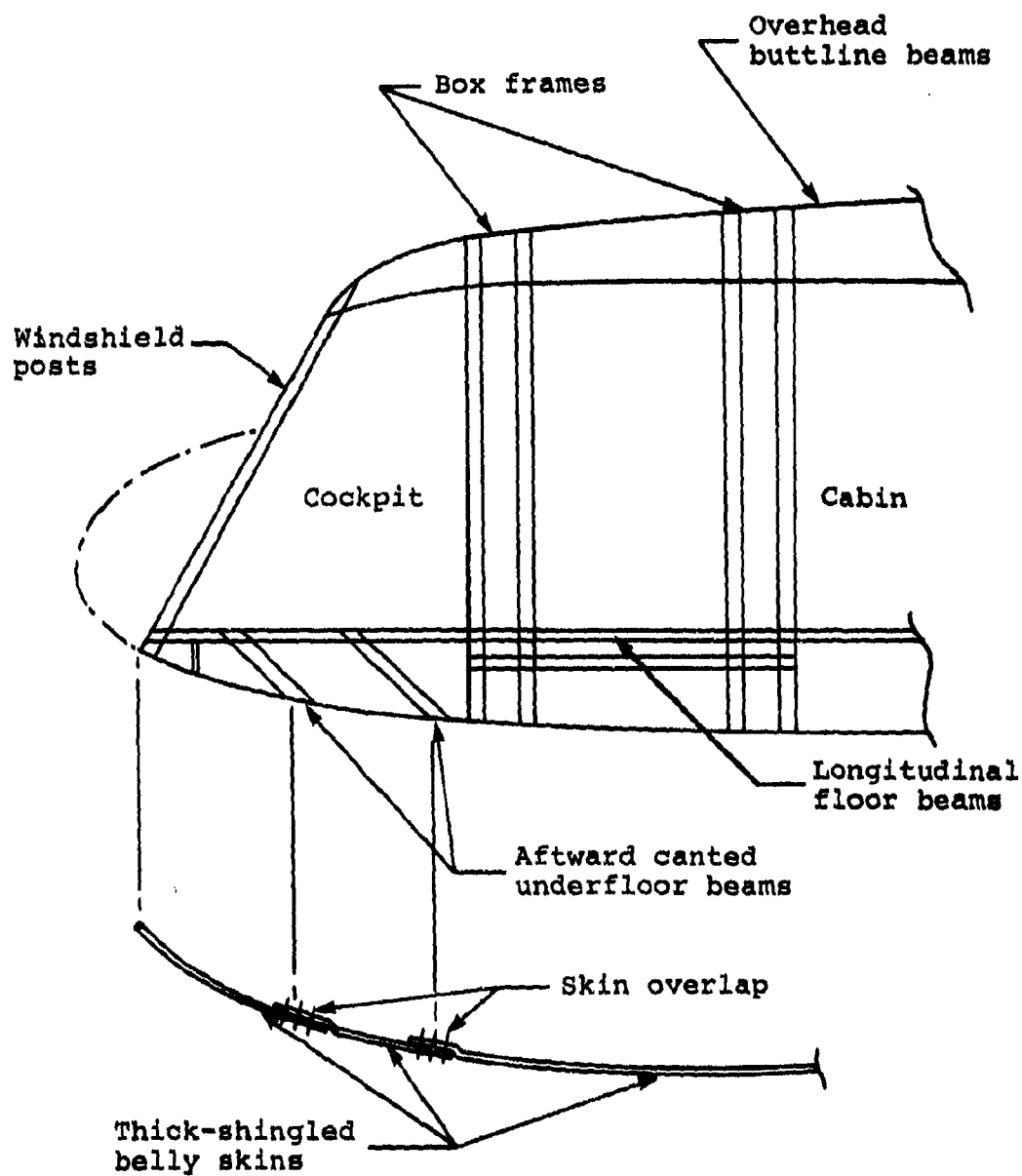


Figure 39. Features of helicopter nose section to prevent nose plowing.

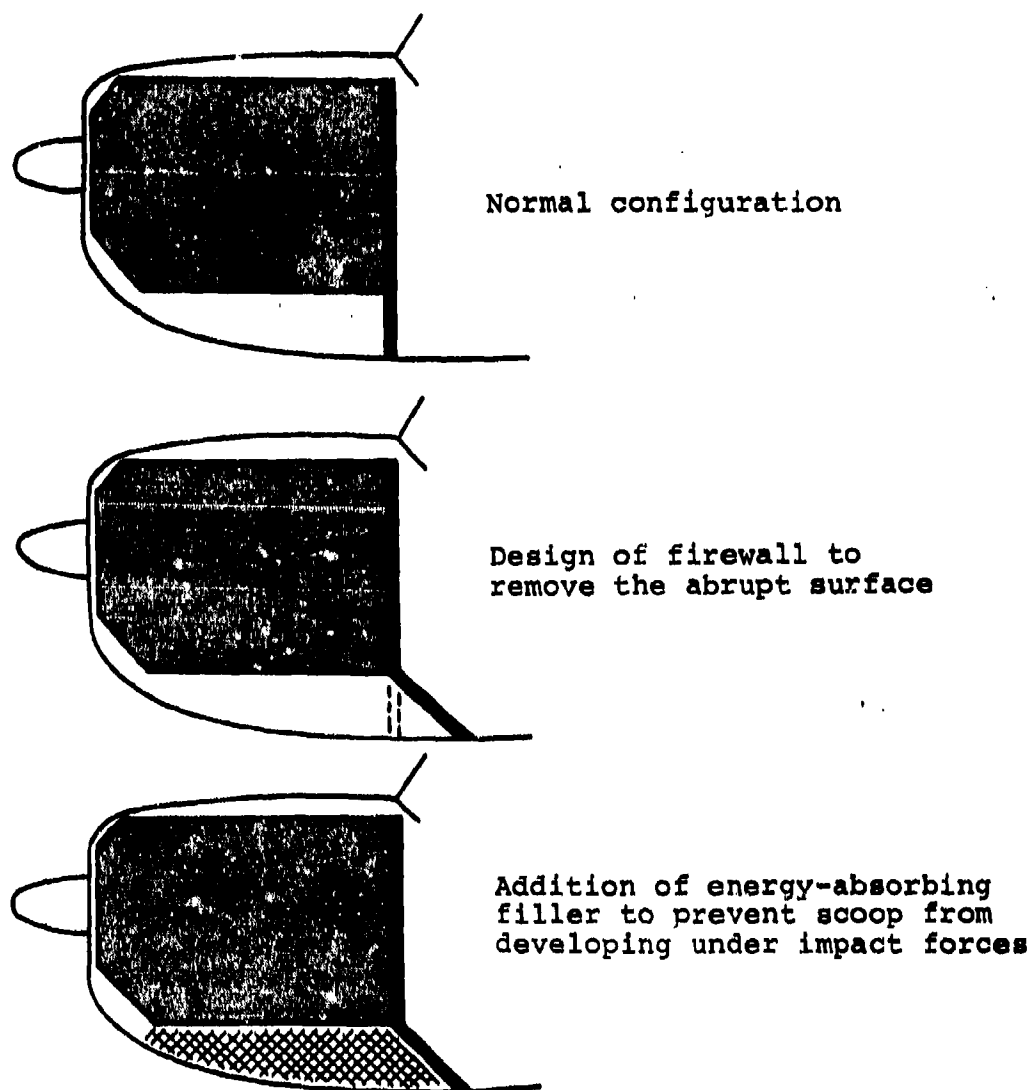


Figure 40. Two methods of reducing earth scooping in engine-mounting areas.

access doors and cowling should logically be strong enough to sustain the impact loads, even when considerably deformed.

In multiengine aircraft, the engine nacelles may present as much of an earth scoop as the nose of the fuselage; and, since the engines are often attached to the strong, rigid wing center section, the forces produced by engine earth scooping are transmitted to the fuselage cabin.

Use of the design concepts discussed above can be helpful in reducing the harmful contribution of engine and fuselage nose earth scooping. The results of full-scale experimental crash tests indicate that longitudinal aircraft accelerations produced by earth scooping can be significantly reduced by the application of these methods.

Most aircraft crashes occurring at impact angles up to 30 degrees involve a rapid change in pitch attitude to quickly align the aircraft fuselage with the impact surface. The resulting angular acceleration produces a fuselage bending moment which usually causes a compression of upper members of the forward fuselage. This compression is combined with compression of the fuselage due to the longitudinal forces of impact. The result is a compressive buckling failure of fuselage structure. When the failure occurs in personnel areas along the fuselage, the protective shell is compromised.

It is sometimes possible to provide sufficient strength to prevent fuselage bending failure. If this is not practical, it is desirable to determine the probable failure points and to position passengers away from those locations to minimize the risk of injury in a crash. Cargo tiedown attachments should be designed to prevent loss of cargo restraint, should fuselage bending failure occur.

The design of floor structure and the floor support structure also has a considerable effect upon the protection offered by the cabin structure as a protective shell. The floor structure should be strong enough to carry the loads which will be applied to it by passenger and cargo restraint systems (see Sections 6.6.5.10 and 6.6.5.11) without the need for supports which carry through to the lower fuselage skin and stiffeners. Such supports transfer crash loads applied at the outer fuselage surface directly into the floor. Buckling of the floor produced by such a load transfer can reduce the bending strength of the fuselage and also reduce the effectiveness of restraint systems which depend upon floor integrity. Evacuation of the aircraft can also be impeded by interruptions in the floor surface.

MIL-STD-1290(AV) requirements specify the following longitudinal impact protection: "At 15 to 20 ft/sec impact velocity, no hazard shall be posed to the pilot or copilot, and at 40 ft/sec, a 15-percent reduction in volume of the troop/passenger compartment must not be exceeded. Additionally, inward buckling of side walls shall not pose a hazard and postcrash egress must

not be impeded." The major structural elements of a helicopter designed to satisfy these crashworthiness requirements are emphasized in Figure 41 for the nose section, and in Figure 42 for the cabin/center section. The nose section structure is basically a propped cantilever with the underfloor structure being the cantilever and the props being the windshield posts that extend upward to the transmission-support buttline beams. Longitudinal loading is reacted primarily by underfloor beams that resist bending and secondly by windshield posts that transfer loads to the transmission buttline beams. Underfloor frame members and the outer skin assemblies provide lateral stability for the longitudinal members.

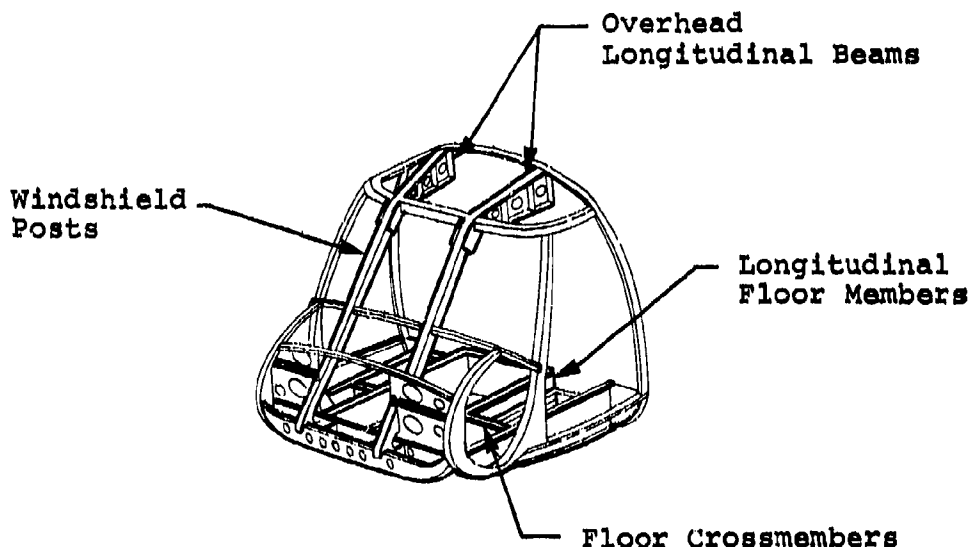
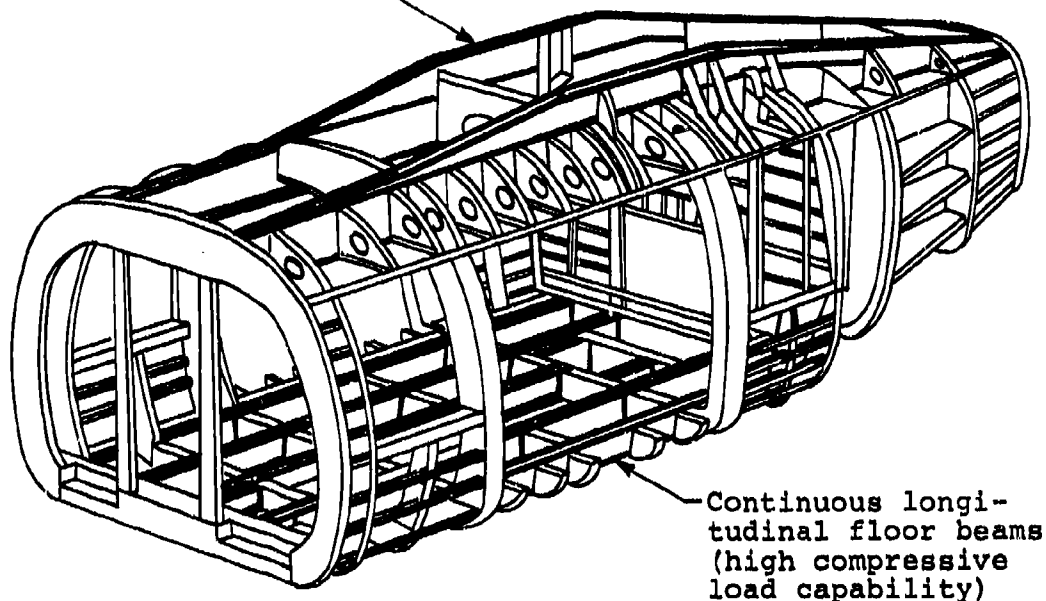


Figure 41. Longitudinal impact and blade strike protection: nose section. The figure delineates those members requiring careful design consideration.

In the past, other proposed methods of absorbing energy have suggested the use of masses of crushable material. Honeycombs, expanded foams, or similar materials share the major disadvantage of using relatively large volumes of installation space. Such space usage can result in system installation compromises, enlarged profiles, and increased primary structure weight to accommodate such energy attenuation methods. They do, however, still provide a method warranting consideration and trade-off.

Longitudinal beams
(high compressive
load capability)



Continuous longitudinal floor beams
(high compressive
load capability)

Figure 42. Longitudinal impact protection in cabin section.

The cabin structure, by virtue of specific aircraft mission requirements for rapid troop ingress and egress, contains a large area of cutouts necessitating a longitudinal beam system for carrying major loads. In the upper vertical structure, two buttline beams continue into the cockpit section to provide continuous paths for crash loads in the longitudinal direction. Figures 43 and 44 show details of typical beams. Loading at and below the floor level is transferred from the cockpit through the cabin by longitudinal floor beams.

6.6.5.3 Improvement of Crashworthiness in Vertical Impacts: For a primarily vertical impact (or for the vertical component of any impact), structural energy-absorption requirements differ appreciably from those of a longitudinal impact. In a vertical impact, there exists no possibility of low-force-level (and hence low acceleration level) energy absorption external to the aircraft comparable to the frictional energy absorption in a longitudinal skid. The velocity change in the vertical

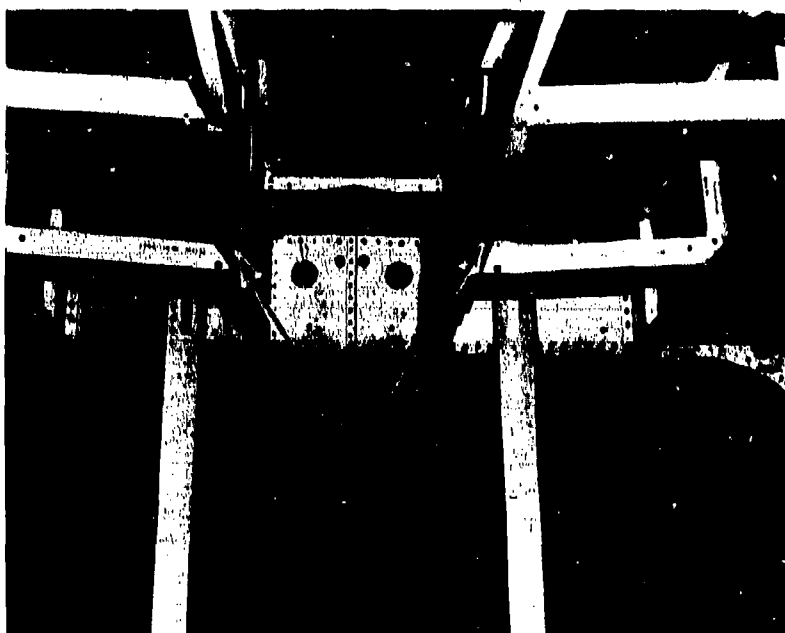


Figure 43. Typical longitudinal beams adjacent to cockpit for longitudinal continuity of overhead structure.

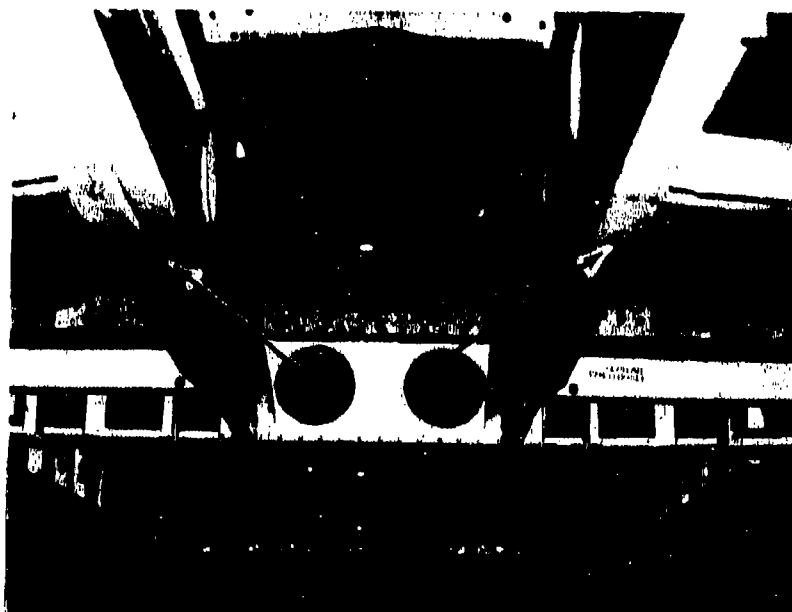


Figure 44. Typical full-depth longitudinal beams for overhead support of large mass items and longitudinal continuity of structure.

direction must be accomplished in a short time interval. Consequently, when the vertical velocity component is high, crashes are generally characterized by large structural deformation and high accelerations at aircraft floor level.

Several studies have treated methods of reducing the effects of the high floor accelerations upon occupants. These studies have resulted in recommendations for providing energy-absorbing passenger and crew seats to protect occupants in crashes at energy levels which are survivable from the standpoint of general cabin collapse (see Volume IV). It is also apparent that increasing the energy-absorbing stroke of the floor through vertical strength reduction can reduce floor acceleration levels.

In order to evaluate potential improvements in crashworthiness of cabin structure for vertical impacts, two idealized extreme configurations are presented that serve to point out problem areas. First, consider a fuselage section in which the aircraft mass is concentrated at the top of a fuselage section. This model is schematically illustrated in Figure 45.

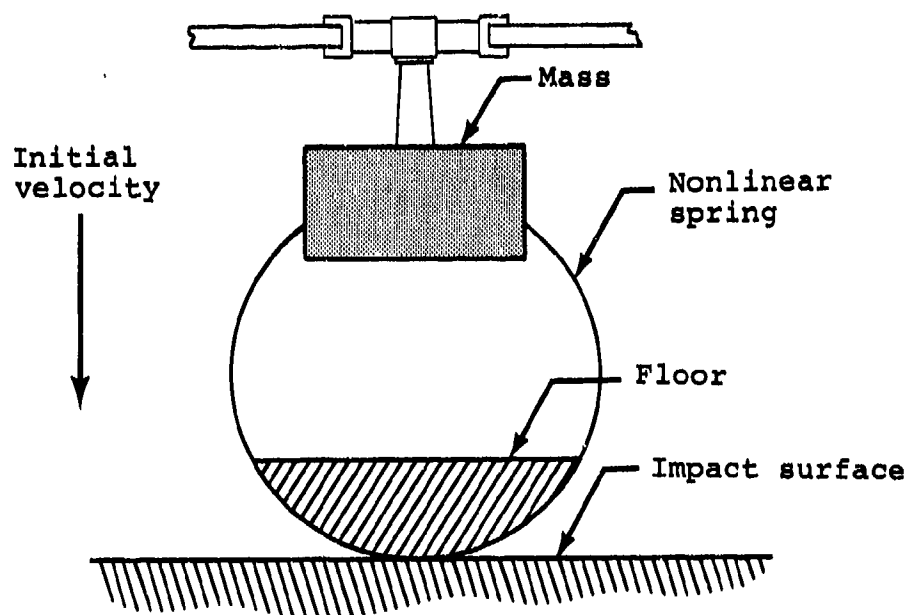


Figure 45. Fuselage structure with overhead large mass items (idealization).

The fuselage acts as a nonlinear spring which is initially elastic and remains so for a moderate deformation; thereafter, the spring force reaches a critical value that produces a plastic collapse of the support structure.

For such a model, a vertical impact requires that substantially all of the kinetic energy of the mass be converted to deformation energy of the structure. If this kinetic energy is large, complete collapse of the structural support, i.e., the cabin, can occur, depending, of course, upon its strength.

This model of the fuselage can reasonably be extended to include a crushable region below the cabin floor which would deform plastically for forces below the critical load for the upper fuselage sidewalls. This crushable region would then absorb energy, providing an increased buffer against general collapse.

The opposite extreme of this fuselage model consists of a structure of negligible weight with the aircraft mass concentrated at or near the bottom of the fuselage. Figure 46 illustrates this configuration schematically. Upon vertical impact with this second configuration, without a crushable subfloor structure, the kinetic energy of the mass would be largely dissipated in the soil with perhaps high acceleration levels occurring at the floor. The light upper structure in the cabin, however, would not collapse even for high-energy impacts.

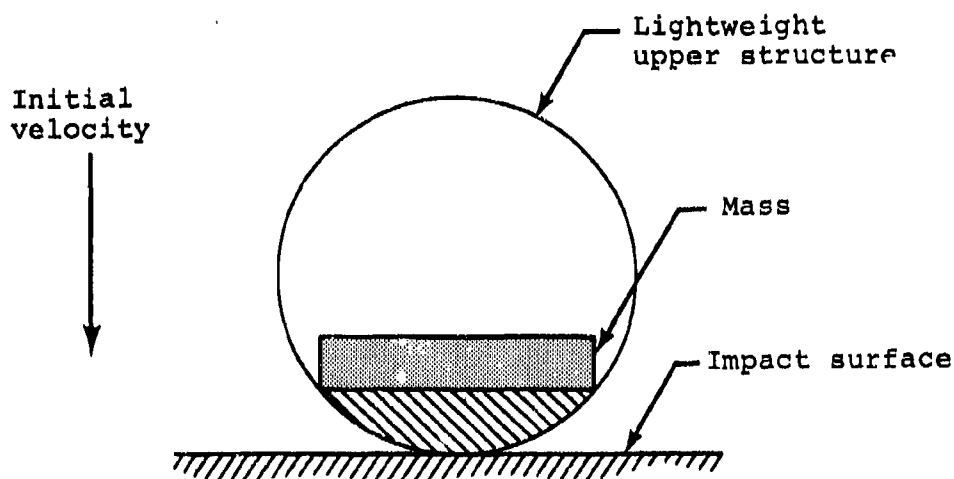


Figure 46. Fuselage structure without overhead mass items (idealization).

If crushable subfloor structure were included in the model, then a sizeable portion of the kinetic energy could be dissipated in subfloor deformation. The subfloor energy absorption could serve to attenuate the floor acceleration.

Actual conditions generally fall between the two idealized extremes presented above. To the extent that large masses are secured to the upper fuselage in typical helicopters or high fixed-wing aircraft, cockpit/cabin collapse presents a serious problem. To the extent that mass is concentrated at cockpit/cabin floor level, energy absorption in the subfloor structure, and the associated acceleration attenuation, may assume significant beneficial proportions in reduction of floor accelerations.

Considering again the two proposed crashworthiness indices - (1) extent of cockpit/cabin collapse and (2) cockpit/cabin (floor) acceleration level - an evaluation may be made of potential improvements in crashworthiness for vertical impacts for a given design.

The threat of general cockpit/cabin collapse under vertical impact may be reduced in any of several ways: First, to the extent that it is feasible, either in original design or by modification, or in cargo and equipment tiedown, a transferral of mass from the top of the fuselage to the floor would be beneficial. Second, a general strengthening of cabin structure may be effected so as to increase the structure's resistance to vertical collapse. Localized strengthening at locations of large concentrations of mass attached to upper structure will provide an increased resistance to general vertical collapse. Third, modifications in fuselage structure that increase elastic energy absorption or provide for plastic energy absorption at loads less than the general collapse load help to maintain the primary cockpit/cabin integrity. Fourth, any increase in energy absorption in the subfloor structure realizable at load levels below the fuselage collapse load further helps to protect the cockpit/cabin against collapse. The threat of high vertical acceleration at the floor may also be reduced by providing subfloor crushable structure. The crushing resistance of the subfloor structure may be optimized to meet the conditions of the anticipated vertical impact velocity and the mass associated with the cockpit/cabin floor. The conceptual cap-and-web beam design illustrated in Figure 47 (Reference 29) is

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29. Haley, J. L., Jr., HELICOPTER STRUCTURAL DESIGN FOR IMPACT SURVIVAL, paper presented at the Joint Symposium on Environmental Effects on VTOL Designs, Arlington, Texas, November 1970.

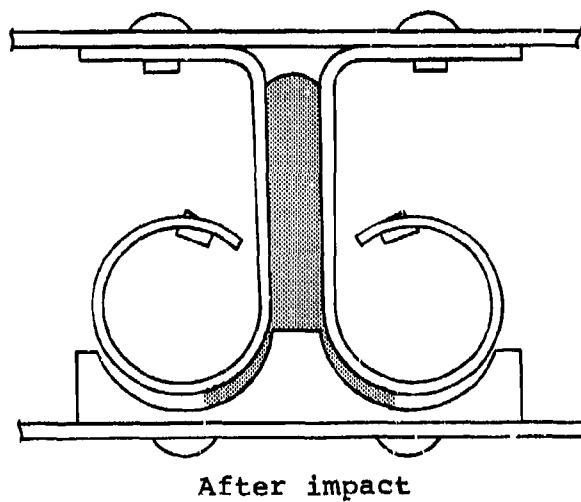
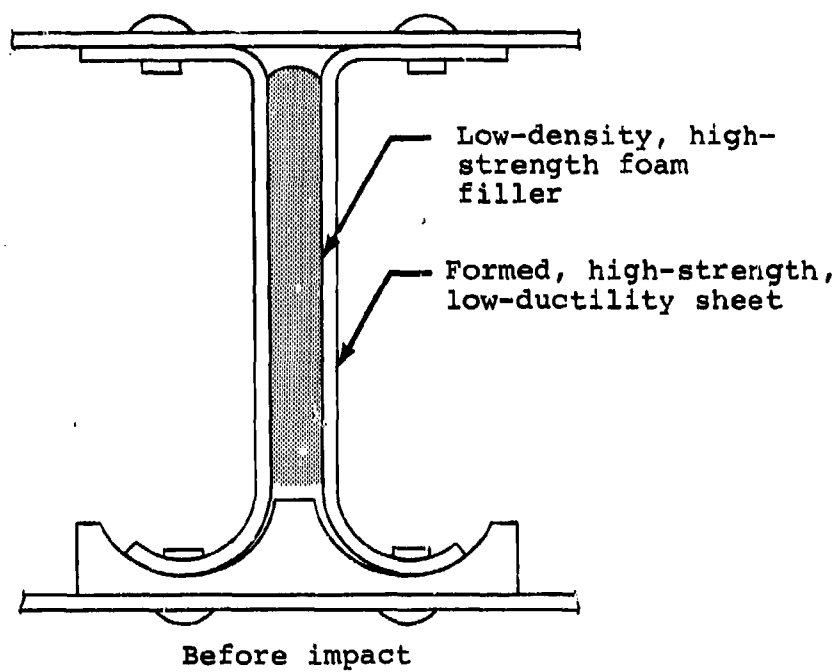


Figure 47. Cap-and-web combination beam design with potential energy-absorbing capability. (From Reference 29)

shown used under a strong floor structure reinforced by conventional beams in Figure 48. The configuration results in the desired combination of a nonscoop-forming keel design, a continuous strong floor, and an energy-absorbing understructure that provides the crashworthy design concept illustrated in Figure 49. The belly skin material should be tough and ductile to permit deformation without tearing. Energy-absorbing thickness is shown in the side walls for lateral impact protection. Also, forward underfloor frame members may be canted aftwards, as previously shown in Figure 38, Section 6.6.5.2, to provide an upward load component on the aircraft that tends to prevent, or limit, digging in of the structure.

A 42-ft/sec impact vertical velocity component, with varying degrees of pitch and roll, is specified in MIL-STD-1290(AV) (Reference 1). Allowable vertical deformation of the cockpit/cabin for this condition is limited to 15 percent. However, for overhead-mounted crashworthy seats, adequate stroking distance must be ensured after consideration of plastic and elastic deflections of the structural elements.

Figure 15, Section 6.2.1, shows a typical structural layout for a single-rotor, utility-type helicopter with large mass items mounted overhead and large door cutouts for rapid ingress and egress. To prevent excessive intrusion into the occupied cabin, the support of large mass items is of primary importance. This is achieved by using deep longitudinal buttline beams and built-up box-frame members. The box-frame structure is achieved by adding skin to the inboard and outboard profiles of two adjacent frame members, thus producing a closed-box structure. Such a section is stronger and more stable under compressive loading conditions than two individual frame sections acting together. Figure 50 shows typical sections through box frames of this type; section variation can be tailored to the anticipated loading conditions at any point in the structure. When using this type of construction, care should be taken to provide adequate inspection capability in enclosed areas where corrosion may occur and cause potentially hazardous structural strength degradation. Alternatively, adequate protective coating must be used and wet assembly techniques employed to provide protection against corrosion for time periods equivalent to major structural overhaul intervals.

Widely spaced frames that are skinned on the inside profile may be fitted with detachable skin panels to allow the location of equipment and system elements in the space between the frames. However, only nonhazardous equipment should be located in such areas; combustibles and potential ignition sources are not to be installed in such locations.

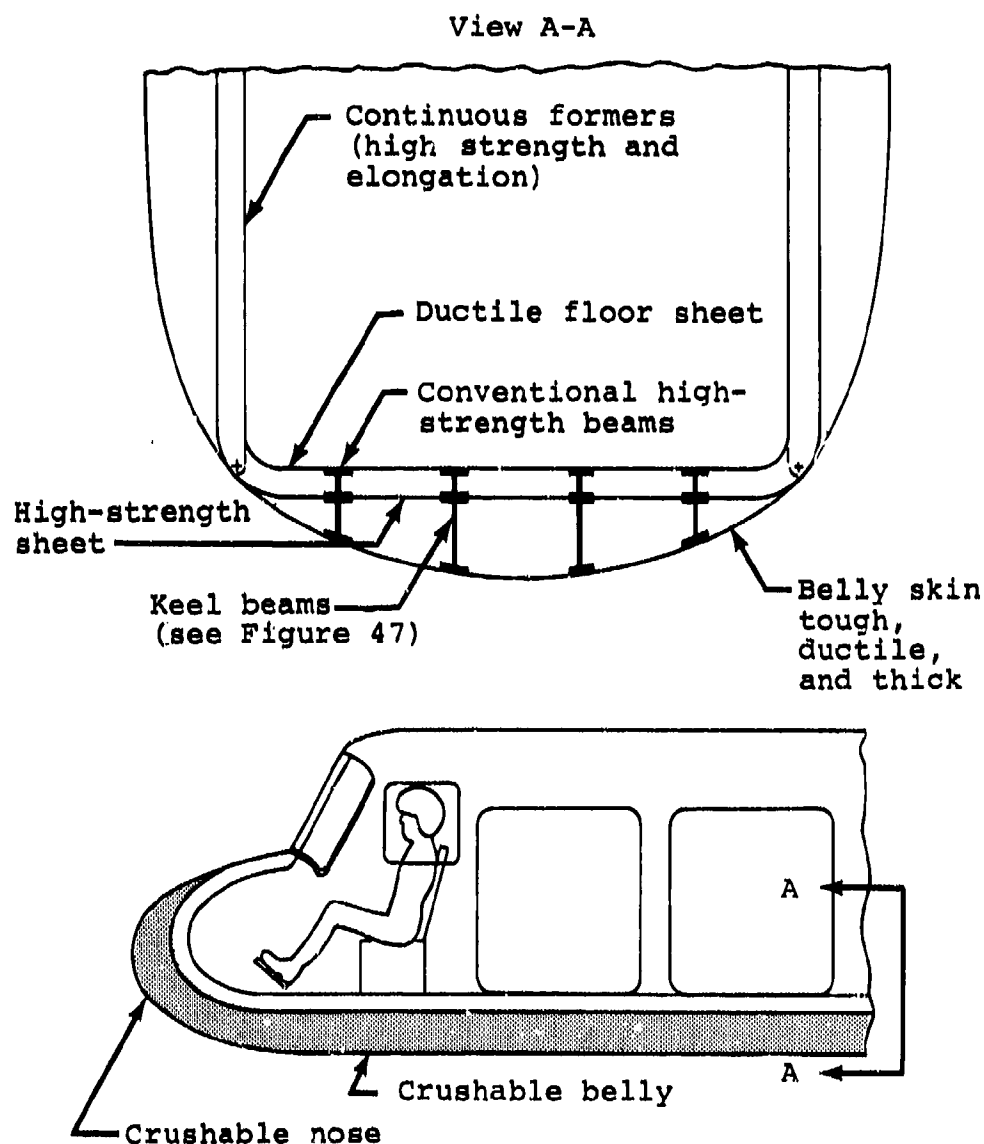


Figure 48. Conceptual structural configurations to absorb maximum energy for sideward, longitudinal, and vertical impact forces.

The underfloor structure, landing gear, and crashworthy seats are other structural elements providing a measure of occupant protection from the effects of a vehicle impact.

The optimum energy-absorption capability of underfloor structure is a direct function of the available stroking distance between the cockpit/cabin floor and underside of the aircraft. This distance varies for different aircraft types and results

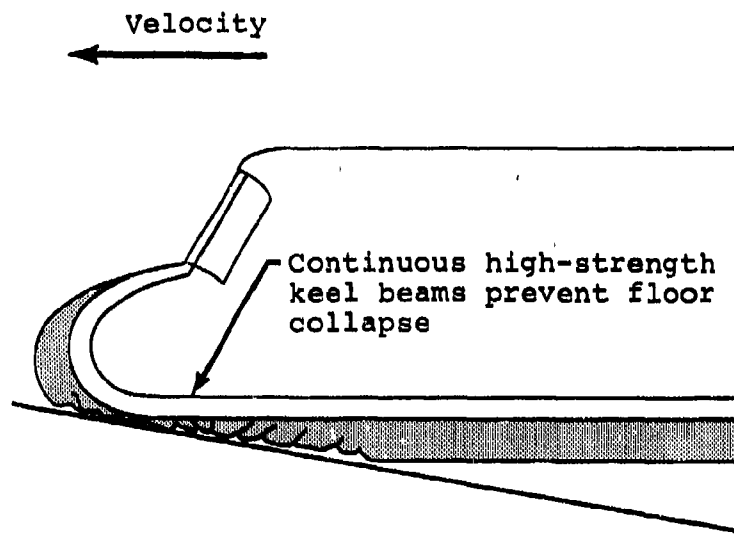


Figure 49. Crushable belly deforms inward without buckling floor or reducing living space.

in differing landing gear-to-structure-to-seat energy-absorption distributions. This emphasizes the need for a crashworthy seat designed as an integral part of a helicopter and suggests that a common seat design cannot be used efficiently for several types of aircraft.

With a possible exception for small single- or twin-seat helicopters, large mass items and their support should be designed to eliminate overhead threat. If transmissions do break loose and pivot forward, some overhead protection against the subsequent movement is necessary. Protection against blade impact and/or impact by large mass items that have pivoted forward or completely broken loose is required. Figure 51 shows details of the overhead protection provided by structural continuity of the windshield posts and longitudinal beams mating with the cabin section.

Finally, energy-absorbing landing gear can be used to reduce the severity of cabin accelerations for less severe impacts. To illustrate the reduction in floor acceleration that can be

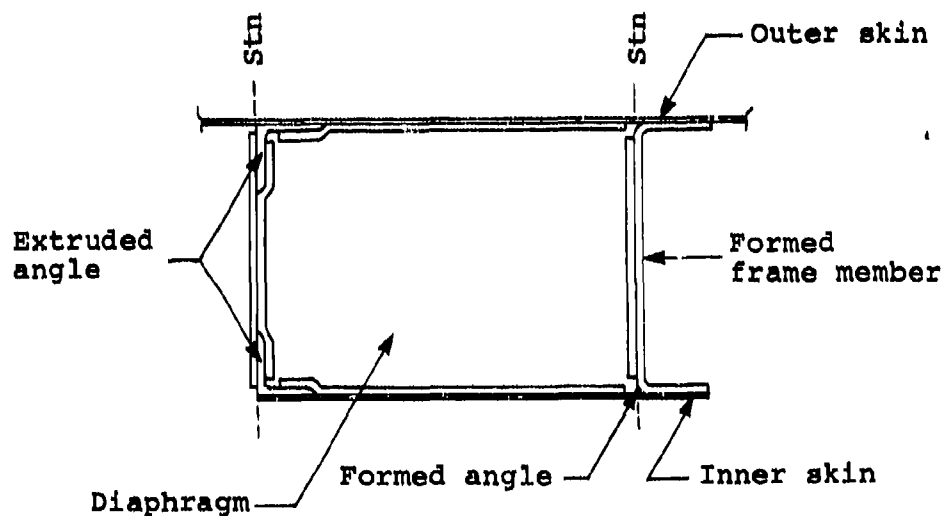
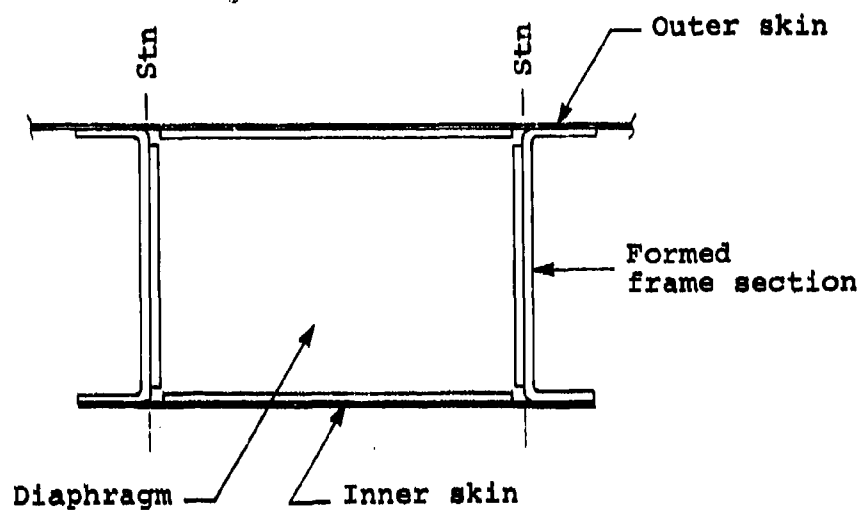


Figure 50. Examples of closed box-beam frame sections.



Figure 51. Typical cockpit overhead longitudinal beam member.

achieved through proper design, a trade-off was made of a specific helicopter using the analytical model described in Reference 30. Figure 52 shows graphically the reduction in peak floor accelerations achieved by the redesign of landing gear, fuselage belly, and both landing gear and fuselage belly. The gear redesign included an increase in strength from 4 to 8 G and an increase in stroking distance from 9 to 15 in. A fuselage belly strength of 19 G was assumed with the capability of a 15-in. stroke and 0-G/in. plastic slope as opposed to 22 G with a plastic slope of 20 G/in. for the standard design. Decelerative forces were calculated for the fully loaded configuration. Note that a 20-percent reduction was realized for the landing gear improvement and 45 percent for the fuselage. Both improvements provide a total reduction in floor G level of 65 percent for the helicopter involved in a 30-ft/sec vertical impact.

30. Gatlin, C. I., et al., ANALYSIS OF HELICOPTER STRUCTURAL CRASHWORTHINESS, Volumes I and II, Dynamic Science, Division of Marshall Industries; USAAVLABS Technical Reports 70-71A and 70-71B, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 880680 and AD 880678.

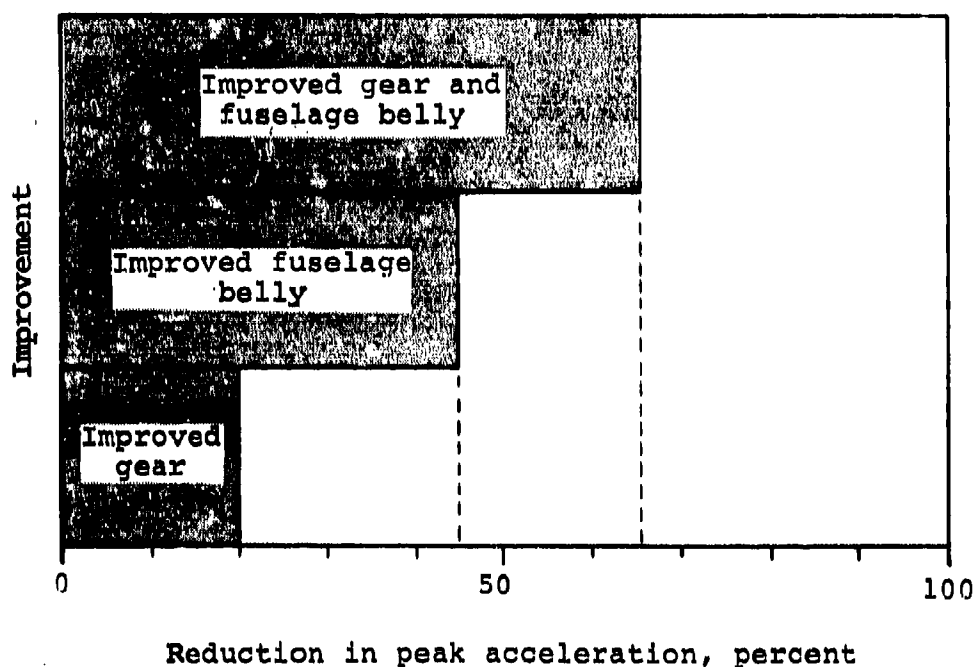


Figure 52. Floor acceleration comparisons (30-ft/sec vertical impact). (From Reference 30)

The principles discussed in this section for providing increased resistance to vertical collapse and reducing acceleration levels for vertical impacts are quite similar to the principles discussed earlier for longitudinal impacts. Therefore, no further discussion of the relative merits of the use of each method is necessary. However, it is important to realize that these principles for improving fuselage crashworthiness for longitudinal, vertical, and lateral impacts are applicable to the design of both conventional takeoff and vertical takeoff aircraft. Consideration of these aspects of crashworthiness becomes more important as the normal approach sink rates of conventional aircraft increase and as helicopters develop greater forward approach speeds.

6.6.5.4 Lateral Impact and Rollover Protection: The load-carrying members indicated for vertical and rollover protection in Figure 15, in general, provide protection against lateral impacts and must be designed for this function.

Rollover protection must be provided to withstand loading applied to the structure during the dynamic stage when rotation is occurring and after the aircraft has come to rest in any

attitude. In addition, sufficient emergency exits must be accessible and operable with the aircraft in any postcrash attitude. The required occupant protection for this type of impact is specified in Table 3, Section 5.1.

Figure 53 indicates one approach to providing the primary load-carrying structure needed to resist the effects of a post-impact rollover. The structural elements needed for similar protection in the cockpit area are emphasized in Figure 54.

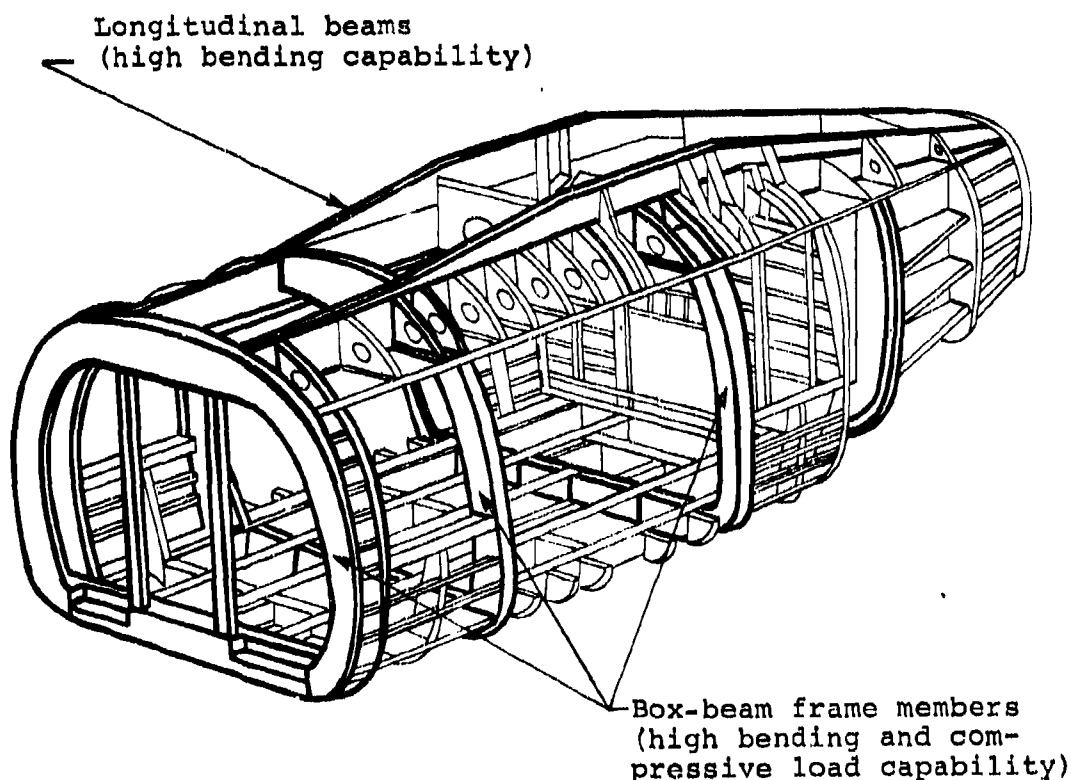


Figure 53. Overhead mass protection and rollover protection in cabin section.

Rollover protection in the cabin section is provided by the buttline beams, longitudinal floor beams, and main box frames. The cockpit of the helicopter shown in Figure 15 is protected by a mesh of structural elements, the majority of which are

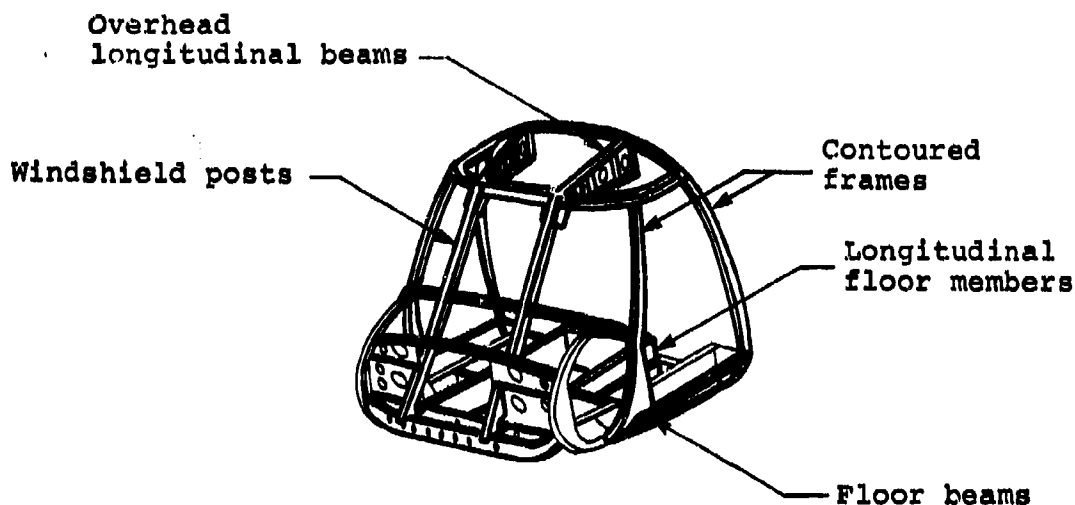


Figure 54. Rollover protection in nose section. The figure delineates those members requiring careful design consideration.

door and transparency support members. These are shown in Figure 54; details of the sections and materials used are shown in Figure 55. Reference 31 contains more detailed information on lateral rollover protection.

Prevention of main rotor blade entry into the cockpit is an extremely difficult task due to the conflicting requirement of good pilot visibility. Structural members that can deflect a main rotor blade will have to be large in size, thus restricting the pilot's visibility. A roll cage cockpit that could minimize blade intrusions would include large structural beams overhead and on the outboard sides. High-strength windshield posts and door posts that attach the overhead structure to the floor beams provide the remainder of the roll cage.

High-strength deflector beams might be installed forward of the windshield rather than as windshield posts, as shown in Figure 56. Moving the beams further away from the pilot will minimize the pilot's visibility restriction. Such external deflector beams could also deflect wires up over the cockpit.

31. Fox, R. G., LATERAL ROLLOVER PROTECTION CONCEPTS, Bell Helicopter Textron, USAVRADCOM Technical Report 80-D-1, Applied Technology Laboratory, US Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, January 1980, AD A081420.

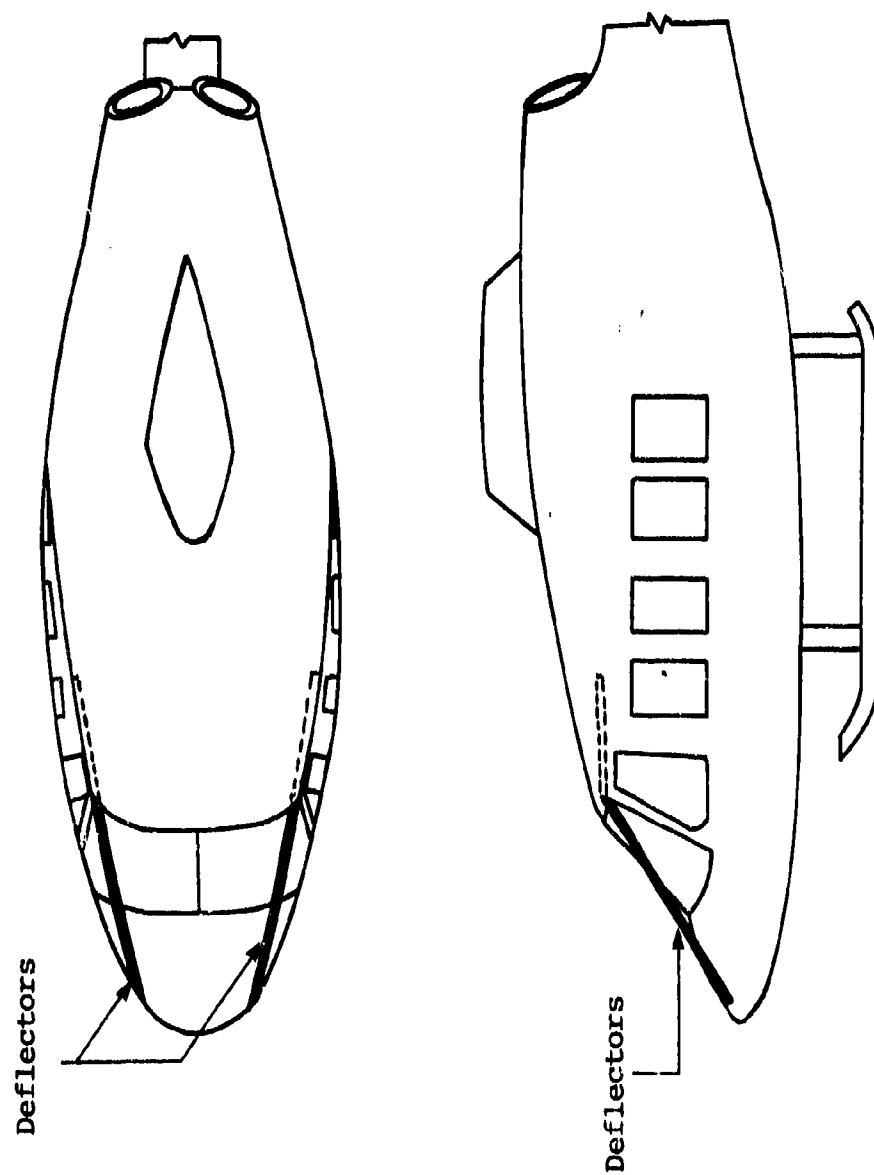


Figure 56. Externally mounted blade strike deflectors. (From Reference 31)

6.6.5.5 Rotor Blade, Wing, and Empennage Design: Plastic deformation of aircraft elements outside the occupied area is an additional method of absorbing aircraft energy. Elements such as rotor blades, wings, tail sections, and even external stores can be bent, battered, or destroyed in the process of bringing the occupied section to a successful halt. When trees, ground obstacles, or uneven terrain are involved, impacts with blades, wings, etc., often occur. Energy is expended in breaking the impacted object, or failing the aircraft element. Rotor blades on helicopters can significantly contribute to energy absorption if the aircraft impacts into trees. The rotating blades incrementally chop the trees until rotor motion stops, or until blade separation occurs. In either case, an appreciable quantity of energy can be absorbed, providing that the attachment strength to the basic fuselage is adequate to prevent the blades from being detached, or the rotor mast and transmission system being torn out of the aircraft.

Contrary to the case of the fuselage structure, where indiscriminate use of composites produces poor energy absorbers, composite helicopter rotor blades offer a desirable degree of energy absorption. For example, when a composite blade impacts and severs tree limbs, damage occurs to cause progressive delamination between the axial fibers due to adhesive failure. This process, called brooming, does not destroy the longitudinal load-carrying elements in the blade; these elements can continue to flail the tree and transfer energy from the aircraft to the tree.

An additional property of composites that can be used to advantage is the high modulus of elasticity achievable by using certain fibers such as boron. A stiffer blade that reduces deflections and reduces the probability of a blade strike on the fuselage crown can thereby be designed.

When rotor blades with metal spars are subjected to tree impacts, successful energy absorption takes place until a tree element too strong for the blade to sever is impacted. Then the blade will fail by plastic bending or by completely detaching from the rotor. During these failure sequences, fuselage impact may occur as a result of blade motions or impact by detached blade pieces. Such occurrences are unavoidable, and overhead fuselage structure must be designed to preclude penetration.

Blade tips can be made frangible to crush upon impact. Deformation of the tip should be as controlled as possible. For example, if a frangible tip with tip weight fractures and leaves the blade, the resultant main rotor centrifugal unbalance may

cause severe pylon damage. Therefore, blade tips should retain their weights during the blade strike. A replaceable frangible blade tip concept (from Reference 32) is shown in Figure 57.

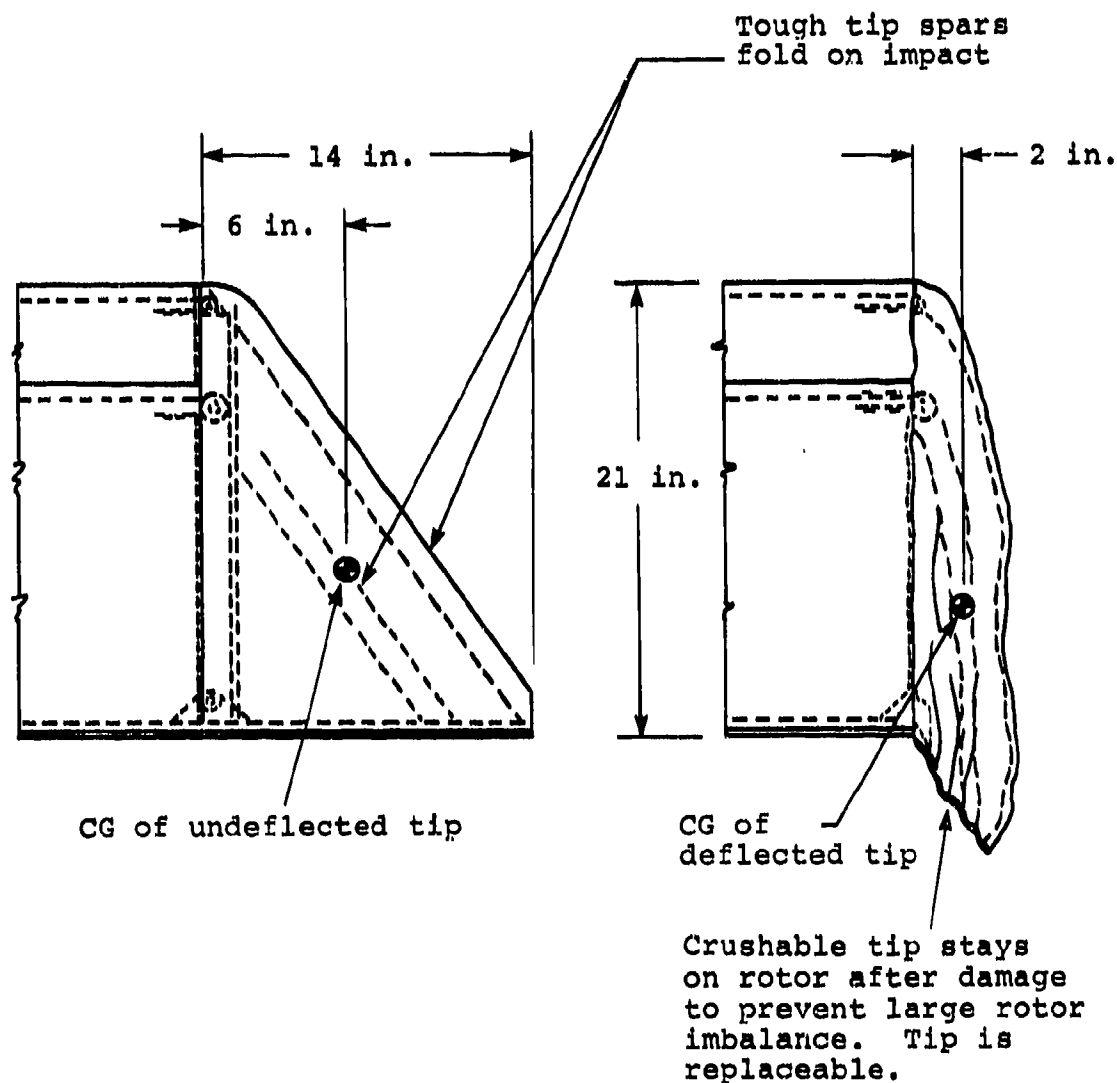


Figure 57. Frangible main rotor blade tip. (From Reference 32)

32. Gupta, B. P., HELICOPTER OBSTACLE STRIKE ANALYSIS, Bell Helicopter Textron; USARTL Technical Report 78-46, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1979, AD A069877.

For future main rotor blades, it may be possible to design a blade that can accept localized destruction during a blade strike such that harmful blade strike loads are not transmitted to the mast. The blade should progressively fail inward starting at the blade tip. Filament-reinforced composite materials could accept the failure of the resin material, yet retain some of the load-carrying capability of the fibers (Reference 31). Some means for blade balance weight retention should be included.

Analysis of strength and energy-absorption characteristics of typical wing structures for various modes of failure indicates that the energy absorbed by wing deformation and failure does not significantly reduce the total longitudinal kinetic energy. Wing failures typically account for only 5 percent, or less, of the total kinetic energy which may be present in a crash of moderate velocity (Reference 33). The use of the wing structure as an effective deformable energy absorber, then, does not appear to be promising. Increasing this energy-absorption capability to a significant level would involve adding material to structural members which can already adequately withstand normal loading. This approach would be doubly inefficient in that nonstructural weight would have to be added to improve energy absorption, and, in all likelihood, most of the added material would not be used effectively in any particular crash.

On the other hand, it is reasonable to design the wings so that the wing sections outboard of the fuselage break free from the fuselage structure under high longitudinal impact forces. This could account for a considerable reduction in mass, especially if the wings contain fuel. As discussed earlier in the fuselage design section, this reduction in mass can effectively reduce the requirements for cabin structure energy-absorption capability.

Wing impacts usually occur in one of two ways. Either a tree, pole, or similar object is hit, producing highly concentrated loading, or the wing strikes a barrier, such as an earthen mound or a dike, which produces loading that is more evenly distributed along the wing's leading edge. Crushing and shear strength, for typical wings, will allow trees or poles to cut into the wing as the aircraft moves forward, until the wing is cut off or until the pole breaks. The fore-and-aft loads under these conditions are low in terms of their effect on fuselage accelerations. In fact, even the more evenly distributed loads can produce fuselage accelerations of perhaps only 5 G.

33. Greer, D. L., CRASHWORTHY DESIGN PRINCIPLES, Convair, Division of General Dynamics Corporation, San Diego, California, September 1964.

Wing removal also can provide the possibility of removing flammable fluids to areas farther away from the fuselage and occupants. It is understood that other design considerations may make these goals difficult to attain; however, the possible benefits make design for wing loss in severe accidents definitely worthy of consideration.

Empennage structure or, for that matter, any structure aft of the occupiable cabin, provides no beneficial effects during a longitudinal crash. Instead, the mass tends to increase the compression loads which must be supported by cockpit/cabin structure. Therefore, if empennage structures can be designed to collapse during a longitudinal impact, the requirements for cockpit/cabin structural strength and energy-absorption capability will be reduced.

6.6.5.6 Design of Engine Mounts and Structural Support of Overhead Masses: Engine mounts should be designed to keep the engines attached to the basic structural members supporting the mounts (nose section, wing, aft fuselage section, etc.) throughout a survivable crash, even though considerable distortion of the engine mounts and/or support structure may occur. This will reduce the fire hazard and the localized damage to other structure which occurs when engines break free and are traversed by the aircraft.

The strength of engine mounts and fittings, including both those integral to the engine and the interfacing mounts on the supporting structure, should be such that failure or separation of the major structural members supporting the mounts occurs before engine mounts or fittings fail under any anticipated crash conditions. Structural support of massive components located overhead, such as the transmission and rotor mast on helicopters, should be designed to withstand the following loads: lateral, 18 G; longitudinal, 20 G; and vertical, 20 G. These strengths are necessary to assure that overhead components do not penetrate the occupants' protective shell.

Engine mounts and supporting structures, including firewall bulkheads, should be designed to minimize earth scooping, as discussed in Section 6.6.5.2.

6.6.5.7 Emergency Exit Structure: The structural framing around all emergency exits should be rigid enough to prevent deformation to such a degree that emergency exits are inoperable under crash conditions. In addition, the structure should be designed to withstand at least a 5-G load based on the maximum gross weight of the aircraft when it is inverted. The structure should also be able to withstand a transverse load of 5 G applied between the floor and ceiling of the aircraft.

Locations of emergency exits should be considered in the overall design of aircraft. These exits must be placed in locations which are favorable for rapid egress. If components near exit locations are likely to be damaged to the extent that the exit will be blocked, then this possibility must be considered and allowances must be made to compensate for it. An example of this situation is the location of an emergency exit near a landing gear attachment in a helicopter. Upon vertical impact, the landing gear could be driven upward into the floor structure, causing severe distortion of the floor structure, thus impeding escape.

6.6.5.8 Fuel Tank Installation: Fuel systems are designed to store and transmit flammable fluids to their respective energy generators. Hazardous conditions can occur if fuel is spilled and ignited. MIL-T-27422 (Reference 34) and Volume V define the requirements for the design and installation of crash-resistant aircraft fuel systems.

Location of a flammable fluid-carrying tank in an aircraft is an important factor in minimizing postcrash fire hazard. The location must be considered with respect to occupants, ignition sources, and probable impact areas. Greater distance between occupants and the fuel supply tends to increase potential escape time if there is a fire because it reduces the likelihood of fuel entering the occupied area. The tank also should be kept away from probable ignition sources. While this is not always feasible, tanks should not be installed in or over the engine compartment, the battery, or other primary ignition sources. An extremely important consideration is the location of tanks with respect to probable impact damage. The effects of penetration by aircraft hardware, such as landing gear, or ground obstacles require that the tank be located where there is minimal probability of penetration with the subsequent fire risk. Fuel containment is of primary importance, even if proximity of the tank to occupiable areas and ignition sources must be accepted as the only alternative.

The installation of fuel tanks within the primary structure matrix must be carefully determined in conjunction with the following design considerations:

34. Military Specification, MIL-T-27422, TANK, FUEL, CRASH RESISTANT, AIRCRAFT, Department of Defense, Washington, D. C., 13 April 1971.

- Fuel containment, with or without crashworthy fuel cells, for high G impacts.
- Minimization of structurally generated jagged edges, etc., which may cause fuel cell penetration.
- Maximization of distances from potential ignition sources.
- Sufficient distance from belly of aircraft to minimize potential for tank wall penetration by rocks, tree stumps, posts, etc., located on impacted surface.
- Sufficient distance from landing gear to preclude tank penetration due to gear failure.
- Large mass items located away from fuel tanks wherever possible to prevent excessive compression of tank volume and/or penetration.
- Occupied areas segregated from and located as far away as possible from tanks.
- Fuel cell supports and system hardware attachments designed to allow major structural deformation without tearing of cells and/or attachment points which result in fuel spillage.
- Fuel tanks regular in shape, cylindrical or rectangular, to minimize the effects of internal pressure due to structural compression and to reduce the propensity to snag on structural elements.
- Structural deformation not exceeding the compression capability of the fuel cell under survivable crash impact conditions.

In summary, the fuel tank installation should be, wherever possible, mounted well above the bottom of the aircraft and situated as far as possible from large mass items, landing gears, occupied areas, and potential ignition sources.

Adequate support of fuel cells is required to minimize the probability of penetration. Figure 58 shows a typical interior support structure for a fuel cell. Closely spaced frame members are interconnected by metallic strips to provide a uniform support matrix to minimize cell compression and distortion under severe impact conditions.



Figure 58. Typical interior support structure for fuel cell.

One method of improving the resistance to penetration by fractured metal is the use of a plastic foam as a tank cavity liner. A foam liner would accomplish two objectives: (1) it would assist in preventing fuel cell penetration or cutting by sheet metal components, and (2) it could fill a void space between internal rib stiffeners on some tank cavities, thus removing the possibility of fuel vapor collection in the voids.

Attention to these requirements, and use of the latest crash-worthy fuel system techniques, will result in a satisfactory installation.

6.6.5.9 Ancillary Equipment Retention: Objects that are unrestrained or dislodged from their attachment during a crash behave as missiles during the crash sequence. They can cause injuries by striking the occupants directly or, in the case of larger masses, by striking seats or other retention system components, causing failures of these items. Therefore, all ancillary equipment carried within the occupiable portion of the aircraft must be restrained so that it cannot become dislodged during a survivable crash.

All ancillary equipment frequently carried aboard the aircraft must be provided with integrated restraint devices or anchors to the aircraft structure. Stowage space for nonrestrained items that are not regularly carried aboard the aircraft should be provided in all aircraft. This space must be located where items stored in it cannot become hazards to personnel in a survivable crash.

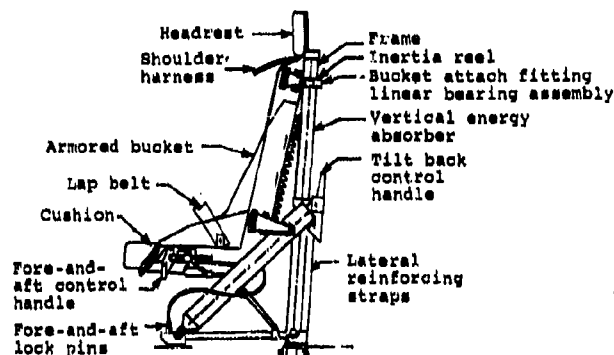
To provide adequate protection during severe but survivable crashes, ancillary equipment restraint must equal or exceed the load capability of the aircraft seats. As stated in Section 5.3.2.1, restraint devices and supporting structure for ancillary equipment must be designed to restrain the equipment during exposure to the following static loads:

Downward:	50 G
Upward:	10 G
Forward:	35 G
Aftward:	15 G
Sideward:	25 G

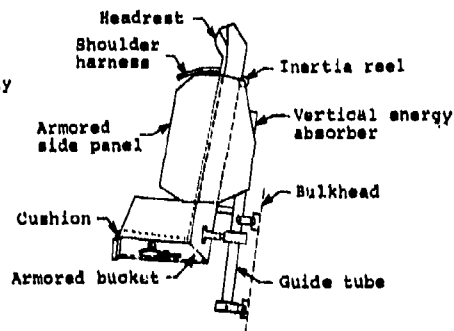
It is a relatively simple task to restrain small items of equipment to withstand the static loads specified above. For larger items, however, significant weight penalties may be incurred or the available supporting structure may not be capable of withstanding the anticipated loads. For these reasons, load-limiting devices are recommended for the restraint of heavier equipment. However, load-limiter stroking must not allow any equipment to enter an occupant strike envelope. (Occupant strike envelopes are discussed in Volume II.)

6.6.5.10 Seat Installations: Three major categories of seats are used on U. S. Army helicopters: crew (pilot/copilot), gunner, and troop seats. Crashworthiness specifications in MIL-STD-1290(AV) require that each seat occupant be provided with a survivable environment when the aircraft is subjected to a 95th-percentile potentially survivable impact (Reference 1). To meet this requirement, energy must be absorbed and living space maintained as the total aircraft system is decelerated. Ideally, each occupant must be brought to a state of rest without incurring debilitating injury that might preclude timely egress after a crash impact. Various energy-absorbing seat concepts are illustrated in Figure 59.

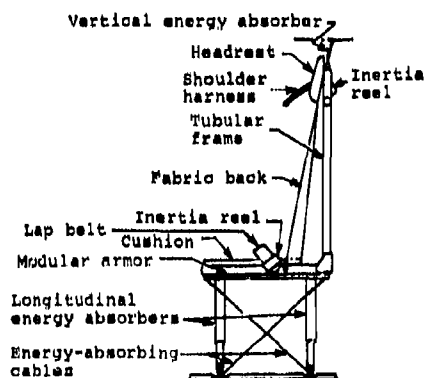
Seats are installed to act as part of the decelerating system and complement the landing gear and deforming fuselage structure. Whichever seat type is used, the total system must be considered when the seat-to-structure interface is evaluated.



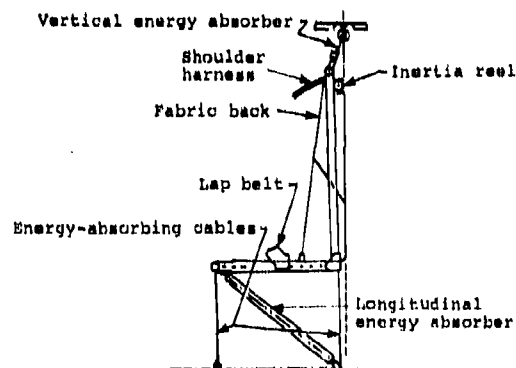
(a) Crewseat, armored bucket, floor-mounted



(b) Crewseat, armored bucket, bulkhead-mounted



(c) Gunner seat, side-facing frame construction



(d) Troop seat, forward-facing, frame construction

Figure 59. Typical crashworthy seat configurations.

As extreme examples, if the landing gear and structure could always decelerate the aircraft well within the survival envelope for the occupants, the seat-to-structure loading would be low and seat energy absorption unnecessary. Alternatively, if the landing gear and structure combination were extremely rigid and the seat had to provide the major portion of the protection to the occupant, a much longer stroking distance would be needed to absorb enough energy to fully decelerate the occupant within tolerable load limits.

When assessing the seat installation, it is necessary to know the design impact conditions, the total energy content, and the predicted energy-absorption capability of the landing gear and primary structure. Whether the crashworthy seats are floor mounted or suspended from the overhead structure can be incorporated into the computations regarding energy absorber load limitations, stroking distance, etc.

The question of occupant restraint must also be considered. Restraint systems are designed to allow each occupant a sufficient degree of movement to complete assigned tasks in relative comfort and to provide adequate restraint in a crash environment. Restraint system loads must be transmitted to the primary structure via the seat structure to ensure correct restraint if the seat strokes.

Where crashworthy stroking seats are used, an additional factor must be considered when defining the geometry of the structure. This factor is the increased strike envelope derived from the seat moving from its position for normal flight operations to its final postimpact location. Modification of the strike envelope is dependent upon whether the seat has the capability for uniaxial, biaxial, or triaxial stroking.

Because energy-absorbing stroke in the vertical direction is mandatory, items that surround the seat, such as consoles and collective controls, should be placed to allow for lateral and longitudinal deflection of the seat without blocking the vertical stroke. The required clearance will vary depending on the specific seat design and whether the lateral and longitudinal motion results from intentional energy-absorbing stroke or from elastic or plastic deformations of the structure. Three inches of dynamic lateral deflection is common even in an elastic structure designed for vertical stroke alone. Of course, this amount of deflection is not likely to be retained throughout the entire vertical stroke; however, as much clearance as possible should be provided.

A minimum of 12 in. of vertical seat stroke is recommended (from the lowest vertical adjustment position), as discussed in Section 8.3.1 of Volume IV. Because of the desired positioning of the seat in the aircraft, 12 in. may be difficult to provide between the seat bucket and the floor. In these cases a hole, or well, in the aircraft floor should be provided to allow additional stroking distance for the seat. At least 2 in. of clearance should be maintained between the outer edges of the bucket and the innermost hardware extension on the sides or front of the well including the tracks.

The underfloor or bulkhead structure, depending on where the seat mounts, and the aircraft attachment hardware should be designed to withstand the loads and moments generated by the seat. The loads and moments should be those applied by the specific seat for all design loading conditions and for all positions in the aircraft. In other words, the design of the aircraft structure and the seat should proceed concurrently, with reaction loads and moments calculated for the specific seat used in designing the aircraft structure.

6.6.5.11 Cargo Retention

6.6.5.11.1 General: Cargo carried within transport vehicles should be restrained to whatever degree is necessary to ensure survival of the crew and passengers in a potentially survivable crash. In order to determine the types of cargo restraining devices needed for U. S. Army Aircraft, it is important to consider the following related factors:

- Type of aircraft.
- Tiedown backup structure and likely crash modes.
- Type of cargo being carried.
- Crew and passenger locations relative to cargo.
- Aircraft and cargo tiedown provisions.
- Cargo/personnel clearance envelopes.
- Type of restraint devices available.

The type of aircraft and its predominant crash mode should dictate the selection of appropriate restraint criteria; e.g., forward, lateral, aft, and up. Helicopter and fixed-wing aircraft crash modes differ, and the simplest, most effective tiedown arrangement should be sought for the specific needs of each aircraft.

The types of cargo to be flown and the restraint criteria will determine the available tiedown clearance. An awareness of aircraft structural response to impact will help to identify realistic clearance envelopes for specific personnel locations. Consideration should also be given to restraint integrity in the event of local structural discontinuities and/or secondary or tertiary impacts.

Aircraft and cargo tiedowns and restraint devices in use have been designed to various criteria, some of which are obsolete.

As passive devices, they should not be subject to time-dependent or environmental deterioration. In many cases, the tiedowns will prevent maximizing restraint effectiveness or result in inadvertent failure. Restraint devices may possess the required structural strength but may be unsuitable if not optimized for crash pulse loading, i.e., if they are too soft or too stiff. The devices may not be equipped to maintain the cargo captive at all times during aircraft movement (e.g., rollover) occurring after the main impact has been survived.

New, broad-based military requirements call for multimodal bulk cargo handling. Palletized cargo will become more prevalent in use. A single cargo package moved in this manner between source and destination offers speed and economy.

Some U. S. Army aircraft will be dedicated to cargo handling, if only on a special mission basis, to extend retail delivery to the battle zones. For this reason, the restraints must be adaptable to and compatible with the USAF 463L System for protection of the aircraft crew.

Cargo netted to 463L pallets (References 35 and 36) are restrainable to USAF flight load criteria (Reference 37). The USAF cargo tiedown criterion requires 3 G forward to minimize the portion of mission effort devoted to cargo restraint.

The designer should be aware, however, of the basis for the differing USAF philosophies and practices. The USAF and commercial operators of large cargo aircraft have accumulated over 40.4 million hours of flight time between January 1960 and July 1976. Analyses of major and minor accidents over this time interval have shown that the risk of passenger fatality above the 3-G forward restraint criteria is statistically rare for USAF operations (Reference 38).

35. Military Specification, MIL-P-27443, PALLET, CARGO, AIRCRAFT, TYPE HCU-6/E, HCU-12/E, AND HCU-10/C, Department of Defense, Washington, D. C., 24 February 1967.
36. Military Specification, MIL-N-27444, NET, CARGO TIEDOWN, PALLETS, HCU-7/E, HCU-15C, HCU-11/C, AND HCU-16/C, Department of Defense, Washington, D. C., 8 May 1969.
37. Military Specification, MIL-A-8421, AIR TRANSPORTABILITY REQUIREMENTS, GENERAL SPECIFICATION FOR, Department of Defense, Washington, D. C., 25 October 1974.
38. CARGO AIRCRAFT AND SPACECRAFT FORWARD RESTRAINT CRITERIA, USAF Technical Report 76-30, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, December 1977.

Army warehouse pallets provide no restraint; cargo may be loose or only lightly secured to the pallet by banding (a 1-G restraint).

Both pallet systems must be given additional restraint to meet U. S. Army crashworthiness criteria, albeit minimizing restraint time is also a necessity (Reference 39).

6.6.5.11.2 Cargo Categories: In the selection of restraint devices and procedures, it is important to define the probable types of cargo that will be carried. U. S. Army cargo has traditionally been divided into two categories, based primarily on size, as listed in Table 4 (Section 5.4.1). Small cargo (up to approximately 3 ft³ in size) when routinely handled is banded to wooden Army pallets to expedite handling by fork lifts. These loads can best be restrained by nets attached to aircraft floor fittings. Nets specifically designed for this purpose do not exist. They should be of a lightweight, low-elongation material that can be conveniently sized and compactly stowed. Presently, netting of such loads means using heavy, cumbersome equipment normally used for handling external cargo. The exceptions to this are the adjustable size nets used with 463L pallets, which are sufficiently large to accommodate a large number of small packages stacked within a volume as large as 108-in. length x 88-in. width x 96-in. height. These nets are restrained to structural tiedown rings integral with the pallets. The deficiency of the present 463L net is its elasticity, which is incompatible with U. S. Army crash survival criteria.

Large or bulky cargo can best be restrained individually by cables, ropes, or chains that are attached to the floor or sidewalls of the aircraft.

It is assumed that both categories of cargo (including, for example, packs, rifles, rations, and wheeled or tracked vehicles) will sometimes be carried along with troops. If troops are to be transported along with both types of cargo, crash protection should be provided for troops as well as crewmembers. Where aircraft are dedicated to cargo shuttle missions, cargo crash restraints should be provided primarily for flight crew protection.

6.6.5.11.3 Strength: It is recommended in Volume IV that the design strength of troop seats be sufficient to retain personnel in 95 percent of survivable crashes. Should cargo carried

39. Shefrin, J., et al., INTEGRAL HELICOPTER CARGO RESTRAINT SYSTEM, The Boeing Vertol Company; USAAVLABS Technical Report 69-68, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, October 1969, AD 864899.

alongside, forward, or aft of troops also be restrained to the same level? Perhaps it should be; however, the weight of a restraint system capable of keeping a maximum cargo load in place at such load levels would be high. Several factors other than the expected floor pulses, indicated in Figure 60, affect the retention strength level required for cargo. In particular these include the type of cargo, where it is located, and how it is restrained in the aircraft.

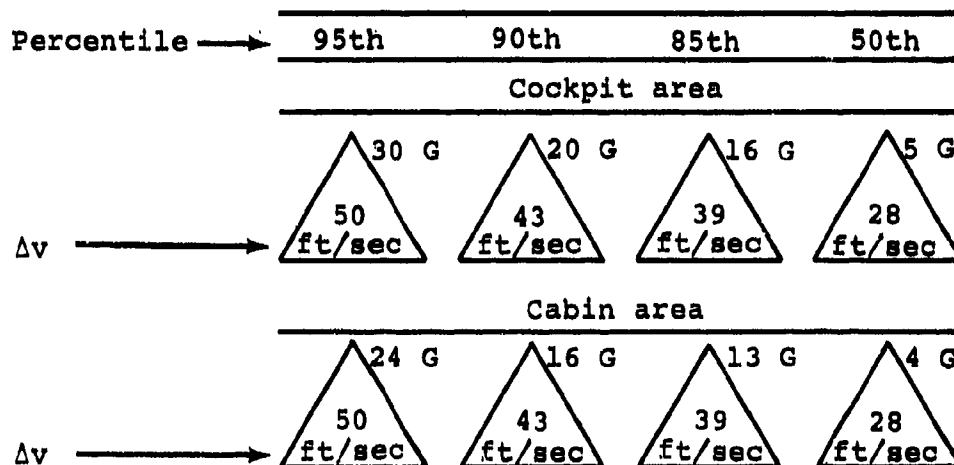


Figure 60. Aircraft floor longitudinal pulses for rotary- and light fixed-wing aircraft.

Most small cargo (see Table 4 of Section 5.4.1) probably will be restrained by a net stretched over several items. It is also probable that the same net will be used to secure any number of boxes. Therefore, statistically, a net designed for a given load will be loaded to a lower value in most accidents. Furthermore, failure of a cargo's net restraint is not likely to be as large a threat to human survival as the failure of an occupant's seat restraint would be. For example, failure of a single net midway in a row of nets would not become lethal until other nets also failed. Therefore, for practical reasons; i.e., the low actual probability of injuries caused by displaced cargo and the structural problems involved in restraining cargo to levels equal with personnel restraint, it is concluded that the cargo restraint level can reasonably be less than the 95th-percentile level.

Of course, in the case of large cargo carried behind troops, the above reasoning does not apply. However, a detailed cargo restraint study by the Boeing Vertol Company (Reference 39) indicates that most items of large cargo are carried outside the helicopter by sling.

On this basis, it is recommended that cargo nets and lines be designed to sustain slightly lower loads, e.g., the 90th-percentile crash pulse rather than the 95th-percentile standard required for human restraint systems. Floor longitudinal acceleration pulses are shown for the 50th-, 85th-, 90th-, and 95th-percentile cases in Figure 60. The crash severity is reduced significantly at the 90th-percentile value over that for the 95th percentile. Selection of the 90th-percentile value reduces the peak deceleration from 24 G to 16 G and the velocity change from 50 ft/sec to 43 ft/sec.

6.6.5.11.5 Energy Absorption: As in crewseat energy absorption, the use of load limiters for cargo restraint is recommended. In the cargo application, the load limiter controls the cargo restraint load level and physical movement into space not occupied by personnel. For the aircraft cabin pulse shown at the 90th-percentile level in Figure 60, calculations have been made as developed for seat and occupant displacement (Volume IV) to show the required restraint G level and the corresponding stroke for energy-absorbing or load-limiting restraint systems. The required G-level-versus-displacement relationship, shown in Figure 61, results from minimizing the restraint systems' structural strength (and hence, their weight) and establishing an acceptable load displacement. These results neglect any restraint system elasticity or longitudinal friction. NASA and AvSER crash data indicate that a vertical floor acceleration is always present to some degree simultaneously with the longitudinal acceleration. The presence of the vertical (normal) force allows the development of some (aiding) longitudinal friction force; however, the friction force may be offset by the dynamic overshoot due to elasticity in the system, or by cargo/floor interface rollers.

Recommended performance goals for such load-limiting restraints are shown in the forward longitudinal load-versus-displacement curve, Figure 61, and the lateral load-versus-displacement curve, Figure 62.

To meet the necessary energy-absorption requirements, restraint displacement must rise rapidly to the left of and above the lower base curve, terminating its displacement above the minimum acceptable load (ultimate strength) curve.

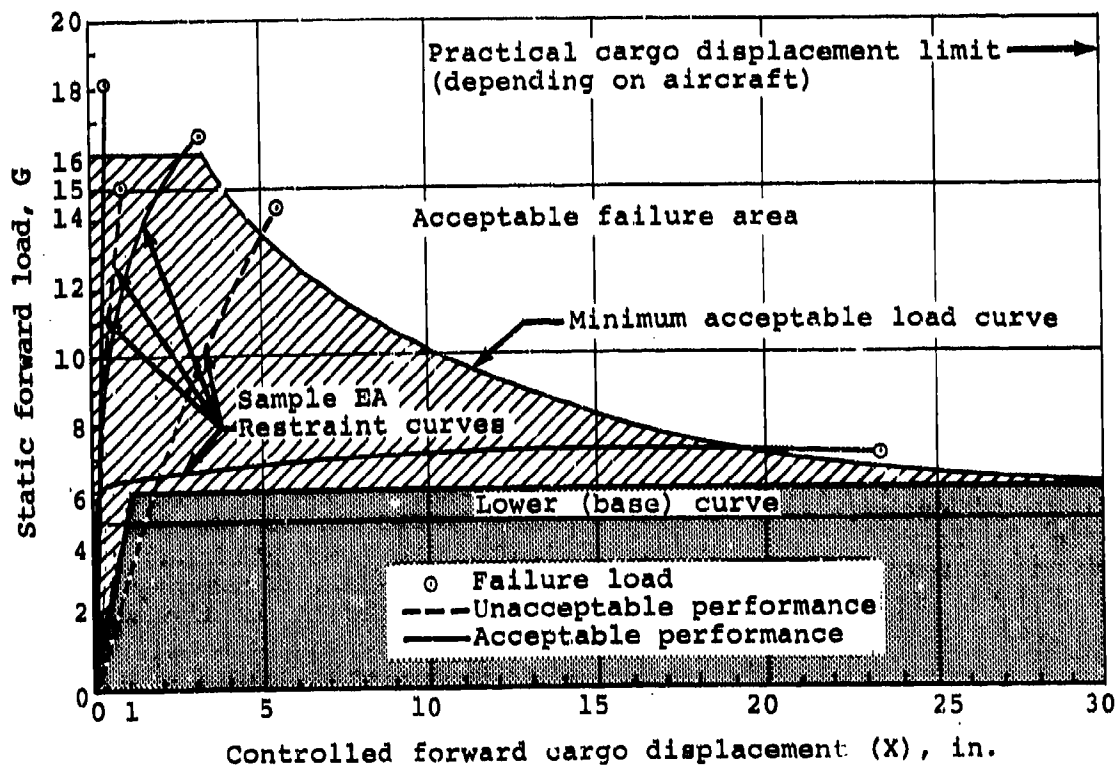
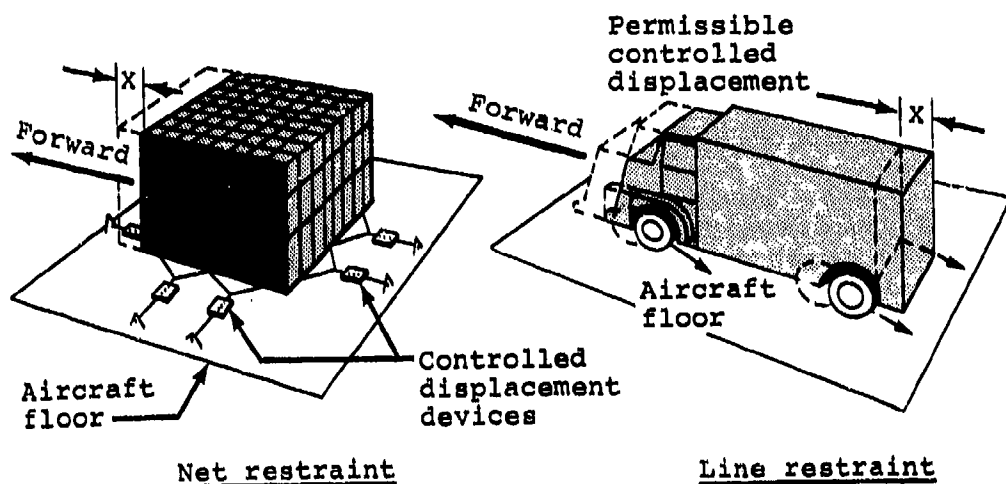


Figure 61. Load-displacement requirements for energy-absorbing cargo restraint systems (forward loading of rotary-wing and fixed-wing aircraft).

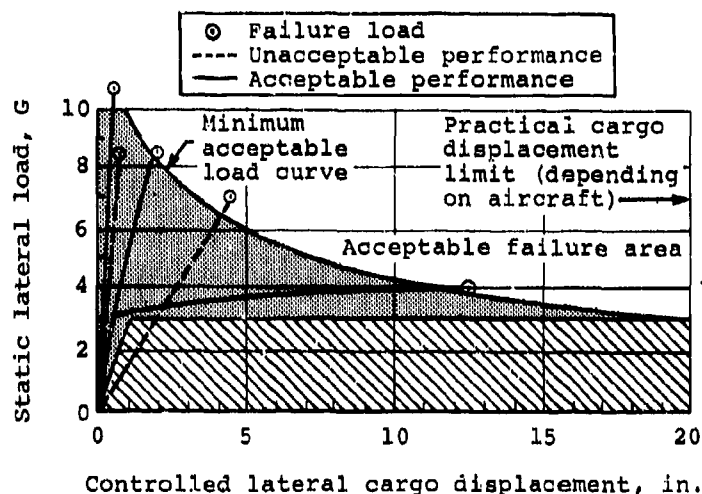


Figure 62. Cargo lateral load-displacement requirements.

Similar load-limiter calculations have been made for the lateral direction, and these values are shown in Figure 62. The lateral strength requirements are based on a 90th-percentile velocity change of 21 ft/sec and a 10-G triangular pulse.

While the troop/cargo mix situation has received the most attention in this portion of the design guide, special cargo missions exclusively involving the aircraft crew may possibly require other design solutions; i.e., emphasis on forward longitudinal restraint and crew isolation. An extreme case of this nature, involving both crew and passengers, is the Navy C2-A COD fixed-wing aircraft where extremely tight quarters, requirements for high utilization of the volume devoted to cargo, and a forward longitudinal restraint of 20 G prevail (Reference 40). These conditions have dictated the use of a structural locker for multidirectional restraint.

Recent research was conducted in energy management restraint (low elasticity/load limited) systems applied to the Navy aircraft. The test results, Figure 63 (Reference 41), provide an

40. Hate, R. L., NAVY CARGO RESTRAINT CRITICAL REVIEW, NADC Technical Report 74082-30, Naval Air Development Center, Warminster, Pennsylvania, May 1974.
41. Shefrin, J., DEMONSTRATION OF ADVANCED CARGO RESTRAINT HARDWARE FOR COD AIRCRAFT, The Boeing Vertol Company; NADC Technical Report 77154-60, Naval Air Development Center, Warminster, Pennsylvania, December 1978.

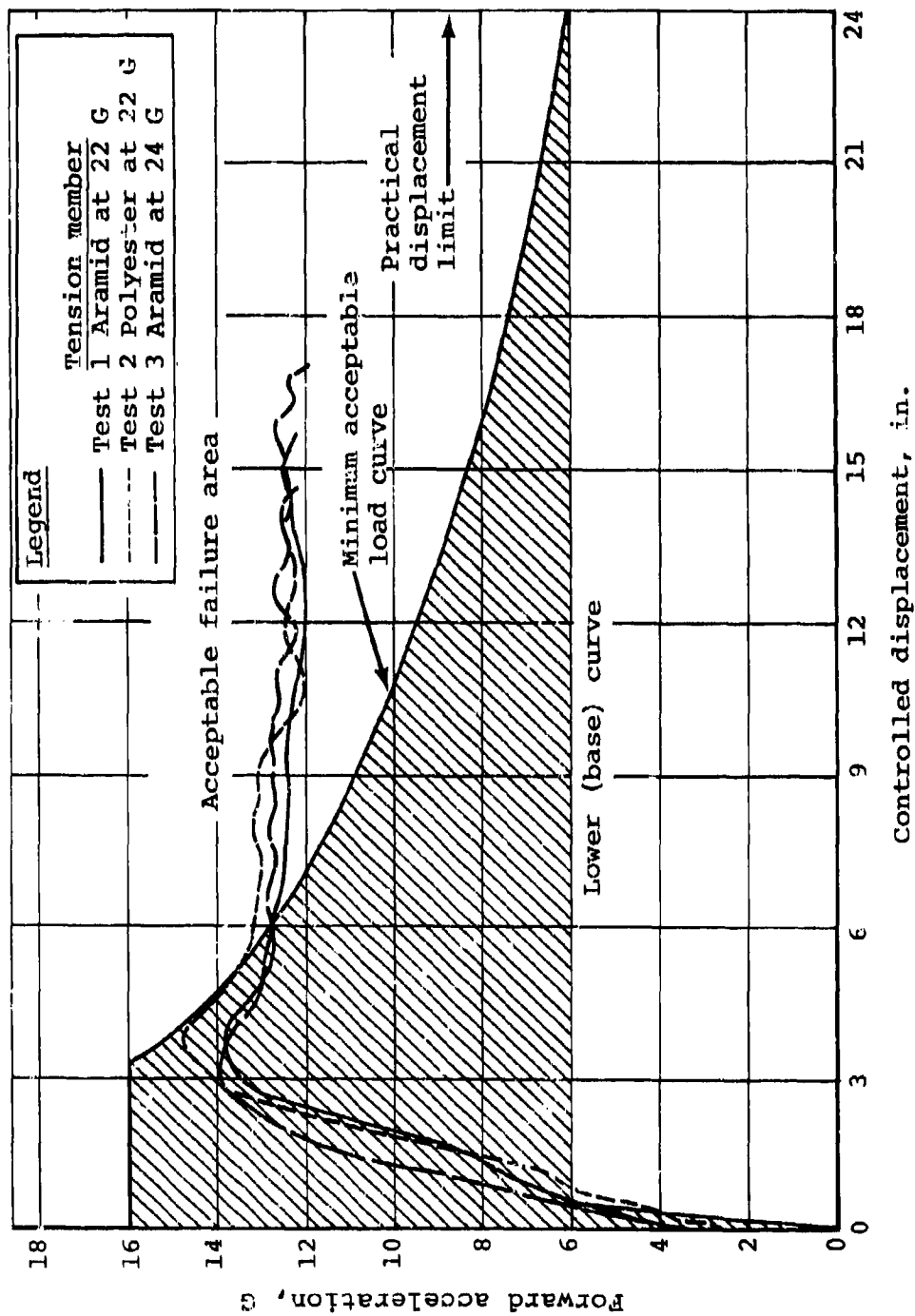


Figure 63. Results of integrated cargo restraint/crash simulation tests using energy absorbers and low-elongation tension members and forward longitudinal load-displacement requirements. (From Reference 41)

illustration of the performance of crashworthy cargo restraint systems.

Shown are the plotted results of tests at two levels of acceleration with two load-limited systems, each system having different elastic deformation characteristics.

These tests illustrate a comparative acceptability relative to the knee of the base curve, which is used as a target for limiting system deflection. The most efficient systems (Tests 1 and 3) were achieved with members possessing the highest stiffness. Thus, Systems 1 and 3 maximized the probability of protecting nearby personnel, and minimized the problems of stored energy (rebound) and dynamic overshoot.

In the tests, three identical metallic load limiters were used. The first and third tests employed an aramid, low-elongation restraint device (tension member), and the second test used a polyester restraint (approximately double the strength of the aramid capability to achieve equivalent strain). All configurations may be considered acceptable where ample displacement space is available. However, minimizing the elastic displacement in trade for plastic deformation of the load limiter provides more energy absorption for a given cargo displacement. The minimum cargo displacement could be achieved with the load limiter alone (without the tension member). The displacement curve for a load limiter alone would have fallen to the left of the Test 1 curve, due to a higher stiffness preceding stroking. If extra load-limiter stroke capability is available, the system will provide an increased measure of performance at percentile pulse levels above the 90th without pull-out or bottoming.

The selection of design load levels for load limiters is important to ensure stroking and to protect the aircraft floor tiedowns from ultimate load failure, as evidenced by the results of the U. S. Army/NASA cargo experiment crash test of a CH-47C helicopter (Reference 42, Test T-40, August 1976). Floor attachments failed as a result of two factors:

42. Burrows, L., Lane, R., and McElhenney, J., et al., CH-47 CRASH TEST (T-40) STRUCTURAL, CARGO RESTRAINT, AND AIR CREW INFLATABLE RESTRAINT EXPERIMENTS, USARTL Technical Report 78-22, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, April 1978, AD A055804.

- Limiter design load level was less than 2 percent below fitting ultimate strength.
- Inadequate consideration was given to the variability in both the limiter loads and the tiedown fitting strengths.

A load-limiter design that is too conservative, however, is counterproductive to minimizing cargo restraints. Longer stroke requirements are also a result of this approach. This may mean that higher fitting strengths should be considered for new aircraft designs and that old aircraft fittings should be upgraded. The payoff for this approach is optimization of the restraint problem and achievement of maximum productivity in restraining internal cargo.

The design strength values for cargo along all axes of loading are summarized in Table 8 on the basis of the 90th-percentile pulse. The aftward and upward loads in Table 8 are based on expected rebound loads of approximately 30 percent of the peak input values. Hardware designs should not allow disengagement of the restraint during a crash. Restraints usually slacken in the time period between initial impact loading and rebound, and a restraint hook without a keeper can become disengaged during this short interval.

TABLE 8. CARGO RESTRAINT LOADS AND DISPLACEMENT REQUIREMENTS

Item no.	Load direction (with respect to floor)	Restraint load	Controlled displacement
1	Forward	See Figure 61	See Figure 61
2	Aftward	5 G	No requirement
3	Lateral	See Figure 62	See Figure 62
4	Downward	16 G	No requirement
5	Upward	5 G	No requirement
6	Forward and Lateral	See Figure 61	See Figure 61
	Combined	4 G	No requirement

The 16-G downward loading of Table 8 is recommended to ensure that the cargo does not crush the floor, and perhaps destroy the longitudinal restraint for personnel or cargo, during the initially high vertical impact loading. This requirement should not be difficult to meet for the net-restrained bulk cargo because this cargo will probably be stacked on pallets that will assist in load distribution. Shoring, however, will probably be required to prevent floor penetration by wheeled vehicles. Combined forward and lateral loads are considered realistic; Item 6 in Table 8 is included to ensure that the system will not fail under this type of loading.

Displacement requirements are not suggested for the aftward, downward, and upward loads in Table 8 because these loading directions are not considered to be as potentially hazardous as the loads in the forward and lateral directions. Upward restraint is usually not a problem since all restraints used act in unison for this direction.

For personnel located aftward of the cargo, a buffer spacing to allow for restraint system elasticity under the 5-G loading should be considered. Restraints are snugged-up, but very little stretch is actually removed. Normal preload is in the range of 150 to 350 lb. Therefore, cargo movement in response to an aftward 5-G rebound load can be expected. The magnitude of the total cargo motion will depend upon the type and characteristics of the restraints used and the elasticity and/or deformation of the backup structure.

6.6.5.11.5 Net Design: Nets should be designed to restrain the small (bulk) cargo up to the specific loads in Table 8 with a minimum of elongation to reduce overshoot. New webbing fibers such as polyesters and aramids should be used. Their relative elongation and weight advantages over nylon are shown in Table 9 (Reference 41).

TABLE 9. CARGO NET MATERIALS - RELATIVE CHARACTERISTICS

<u>Webbing fibers</u>	<u>Elongation @ 5000 lb (percent)</u>	<u>Weight (lb)</u>	<u>Breaking strength (lb)</u>
Nylon	7.5	3.0	1.1
Polyester (Dacron)	2.0	5.9	1.8
Aramid (Kevlar)	1.0	1.0	1.0

Present disadvantages affecting the adoption of aramid fibers for tension member application are cost, low abrasion resistance, and fabrication technique development.

Nets should be designed for the most critical loading conditions, i.e., a high stack with small boxes. Such a loading would tend to cause a larger diaphragm action on the net as the individual boxes slide over each other. More concentrated loads may be encountered in restraining palletized loads on floor rollers.

6.6.5.11.6 Cable, Rope, Strap, or Chain: Large cargo of the type outlined in Table 4 (Section 5.4.1) can be secured most easily by cables, straps, ropes, or chains (lines). The simultaneous use of these devices must be carefully considered, however, because their differing elastic moduli can result in premature failure of the stiffer devices before the others are fully loaded (Reference 43).

In cases where the use of load-limiting devices is not possible, retaining lines for the longitudinal direction should be arranged to simultaneously attain the maximum load in all lines. A combination of fabric ropes and steel cables should not be used on the same piece of cargo because of the difference in their elastic stiffnesses. Also, symmetrical restraint configurations should be used to avoid overloading individual tiedowns and, eventually, failing the system.

With load-limiting devices, it is desirable that metal cables, or other low-elongation tension members stressed below the yield point, be used. A low elongation of the lines used with load-limiting devices is essential to ensure that the energy is absorbed in the most efficient manner. If stretchable metal cables are used as integral load-limiting devices, they will be stressed above the yield point, and the low-elongation line will not be applicable. Metal cables possess handling qualities that discourage their use. Nonmetallic fiber materials, which are lighter in weight as well as more flexible and stowable, should be used wherever possible.

43. Russo, A., Jr., CARGO RESTRAINT SYSTEM PHASE I REPORT, All American Engineering Company, Wilmington, Delaware, January 1964.

7. ANALYTICAL METHODS

7.1 INTRODUCTION

Crashworthiness technology can be extended beyond simple concepts by simulation of the crash phenomena. As shown in MIL-STD-1290(AV), there are several sets of crash conditions that must be investigated in support of the design process. Additional sets of impact conditions may appear critical for certain specific systems, and these require examination as well. These conditions may be simulated by analytical models, scale models, and full-scale tests.

The objective of simulation is to provide a rational basis for the sequence of events and the modes of failure of vital elements of structure during the crash. Complex interactions of crash, inertial, and structural forces which contribute to the structural distortion and the acceleration environment experienced in a crash can be observed. Dissipation of the potential and kinetic energy of the aircraft can be studied for conditions that exist in the crash sequence. Structural distortion with subsequent ruptures, volumetric reductions, and penetration of occupied spaces can be assessed, and estimates of the acceleration levels on critical components and occupants obtained.

In terms of fidelity, the dynamic testing of full-scale structures most closely approximates actual crash conditions, especially if velocity components and impacted surface conditions can be realistically represented. However, during the early design stages of a new aircraft, full-scale testing is untimely and costly. In fact, the testing of full-scale airframes has been confined to technology development, rather than design development and improvement.

In this chapter are presented discussions of kinematic and dynamic relationships as applied to the crash environment, analytical methods of crash simulation, and methods for obtaining the properties required for such simulation.

7.2 DYNAMICS OF THE CRASH ENVIRONMENT

7.2.1 Kinematic Relationships

Relationships among the kinematic quantities of position, velocity, and acceleration form the basis for the study of dynamic phenomena. Although these relationships are generally well known, use of their precise definitions facilitates an understanding of the crash event and its analysis. Therefore, a discussion of these relationships as applied to the crash environment is presented below.

Consider first an aircraft impacting a rigid vertical barrier as shown in Figure 64. The position of Point C fixed in the aircraft relative to a point fixed on the ground is referred to as X . A change in position is referred to as displacement S . In this case, assume that the displacement of C is measured from its position at the time when the aircraft just contacts the wall. If a change in displacement ΔS occurs in a time interval Δt , then the average velocity of the aircraft over that interval is

$$\bar{v} = \frac{\Delta S}{\Delta t} \quad (19)$$

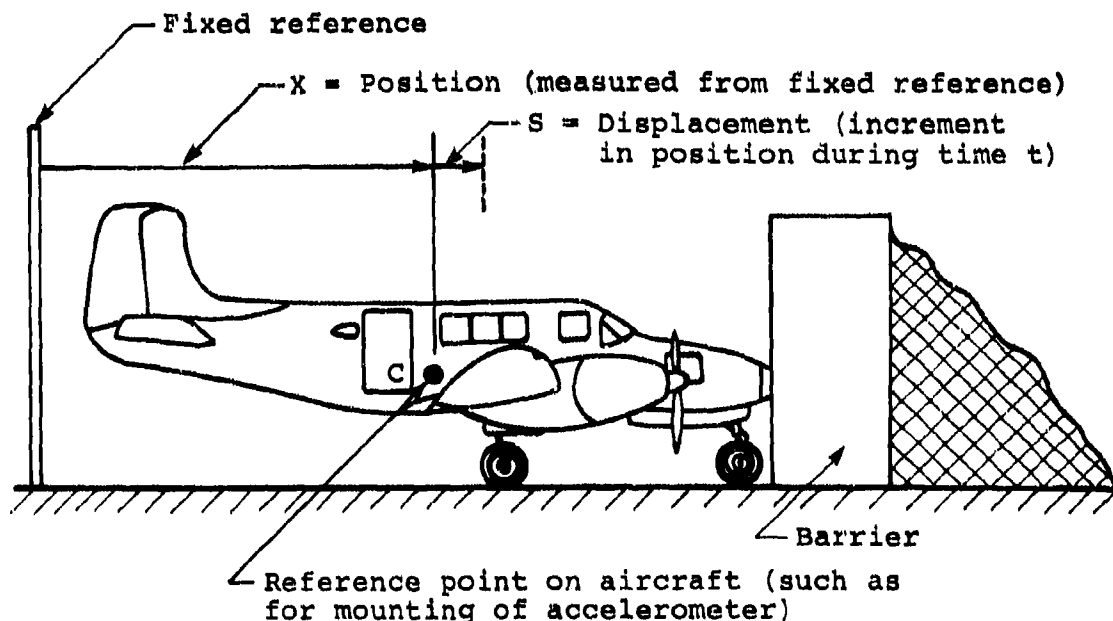


Figure 64. Definition of position and displacement for crashing aircraft.

As the time increment is taken to be very small, Equation (19) yields the instantaneous velocity

$$v = \lim_{\Delta t \rightarrow 0} \frac{\Delta S}{\Delta t} = \frac{dS}{dt} \quad (20)$$

Note that velocity has the units of length per unit time, i.e., feet per second.

If in the same time interval the aircraft undergoes a change in velocity Δv , the average acceleration over the interval is given by

$$\bar{a} = \frac{\Delta v}{\Delta t} \quad (21)$$

and the instantaneous acceleration by

$$a = \lim_{\Delta t \rightarrow 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt} \quad (22)$$

Note that acceleration has units of velocity per unit time, i.e., feet per second per second.

A graphical examination of the relationships among position, velocity, and acceleration will aid in understanding their application in the crash environment. Referring to Figure 65, assume that the aircraft of Figure 64 has a velocity v_0 just prior to contacting the barrier and that the velocity of Point C, fixed in the aircraft, varies with time as shown in Figure 65(b).

First note that in Equation (22) defining acceleration that "a" is the height of the a-t curve and $\Delta v/\Delta t$ (for small Δt) is the slope of the v-t curve in Figure 65. Thus Equation (22) indicates that the height of the a-t curve is equal in magnitude and sign to the slope of the v-t curve, that is

$$a = \frac{dv}{dt} \quad (23)$$

This is an invariant relationship and any data, whether experimentally or theoretically obtained, must meet this criterion to be valid.

In a similar way Equation (20) indicates that the height of the v-t curve is equal to the slope of the s-t curve.

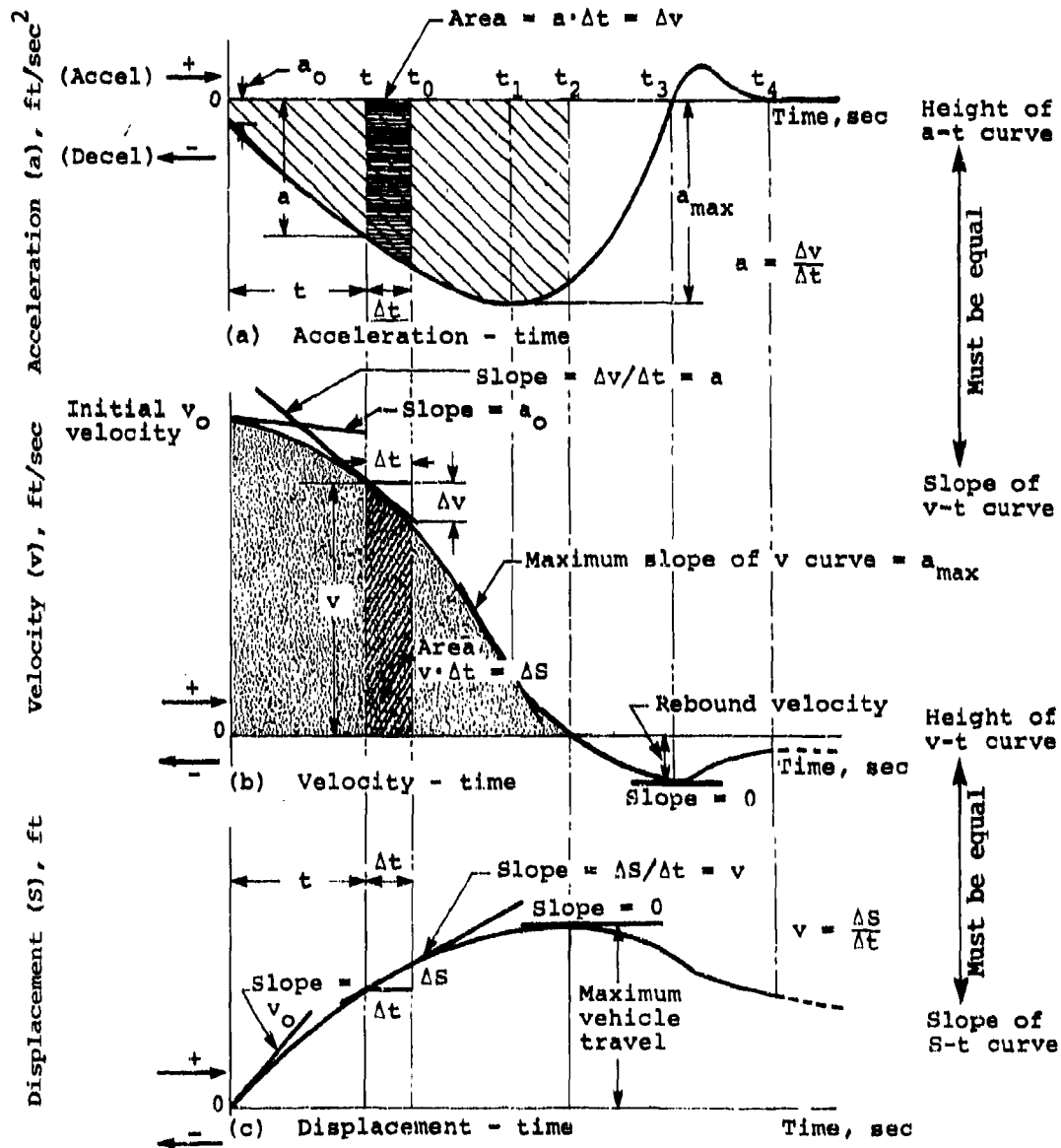


Figure 65. Assumed relationship for illustration of crash kinematics.

Rewriting Equation (23) and integrating, the change in velocity over any time interval between t_0 and t is

$$\Delta v = v - v_0 = \int_{t_0}^t a dt \quad (24)$$

Therefore, the total change in velocity during a given interval is equal to the area under the a - t curve in the interval. As an example, consider the total crosshatched area between $t = 0$ and $t = t_2$ in Figure 65(a). This area is equal to the initial velocity v_0 , that is, the change in velocity between $t = 0$ and $t = t_2$.

Note that the acceleration in Figure 65 is negative (deceleration), thus producing a negative velocity change or reduction in velocity from v_0 to 0. A positive acceleration, on the other hand, produces an increase in velocity.

The same condition exists between the velocity and displacement curves, that is,

$$\Delta s = \int_{t_0}^t v dt \quad (25)$$

or, in other words, the total distance travelled is equal to the area under the v - t curve. Thus the maximum vehicle travel, as in Figure 65(c), would be equal to the area shaded with dots under the v - t curve of Figure 65(b).

The following important points may be noted in Figure 65:

- The velocity is changing at its most rapid rate when the acceleration (or deceleration) is maximum, at time t_1 .
- The displacement reaches a maximum when the velocity becomes zero, time t_2 .

- The velocity need not necessarily be zero (time t_2) when the acceleration is maximum (time t_1).
- The area contained within the deceleration pulse (from t_0 to t_3) is equal to the initial velocity plus the rebound velocity.
- The area under the deceleration curve between t_2 and t_3 is equal to the rebound velocity.

7.2.2 Energy Absorption During Deceleration

According to Newton's second law of motion, the resultant force (F) acting on a mass (m) produces an acceleration (a) according to

$$F = ma = m \frac{dv}{dt} \quad (26)$$

Applying Equation (20),

$$F = m \frac{dv}{ds} \frac{ds}{dt} = mv \frac{dv}{ds} \quad (27)$$

Multiplying by the incremental displacement ds and integrating,

$$\int_{s_1}^{s_2} F ds = \int_{v_1}^{v_2} mv dv = \frac{1}{2} mv_2^2 - \frac{1}{2} mv_1^2 \quad (28)$$

which states that the work done on a mass m by resultant force moving through a change in displacement from s_1 to s_2 changes the kinetic energy of the mass, which is defined as

$$\text{Kinetic Energy, } T = \frac{1}{2} mv^2 \quad (29)$$

Work done by force F during the change in displacement is defined as

$$\text{Work} = \int_{S_1}^{S_2} F dS \quad (30)$$

which is equivalent to the area under the curve of force versus displacement between any two displacements, as illustrated in Figure 66.

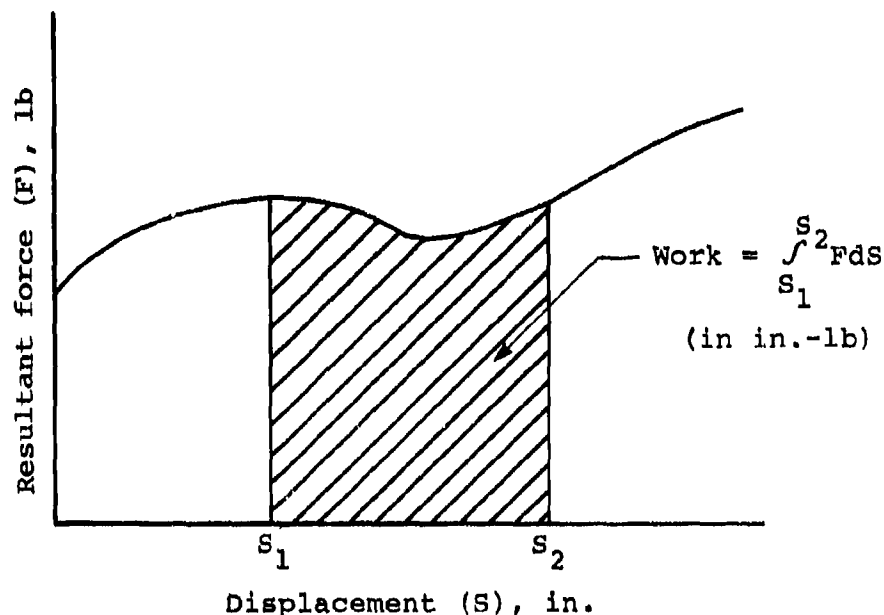


Figure 66. Definition of work.

In application of Equation (28) to the crash environment, an aircraft moving with initial velocity v_0 can be slowed to a reduced velocity v (which is zero when the aircraft comes to rest) by application of a force through a distance S

$$\int_0^S F dS = \frac{1}{2} m v_0^2 - \frac{1}{2} m v^2 \quad (31)$$

where the force acts in a direction opposing the velocity, as shown in Figure 67. Referring to Figure 67, it might be said that the kinetic energy of the aircraft is absorbed by crushing of its forward structure as its velocity is reduced.

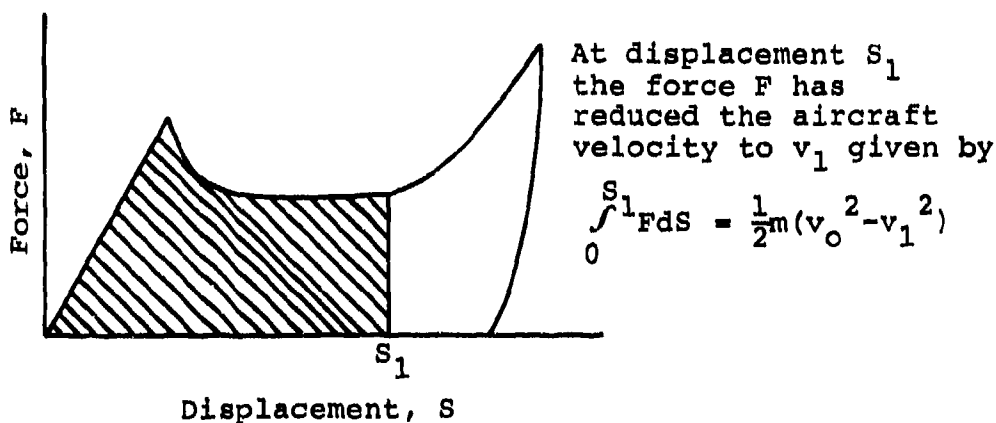
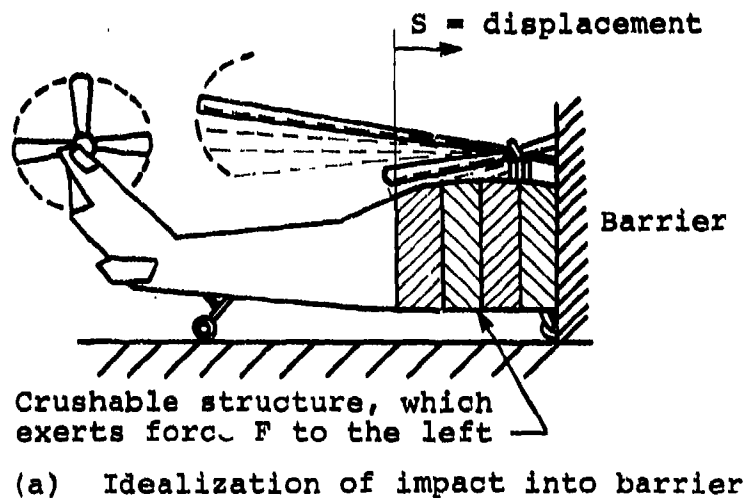
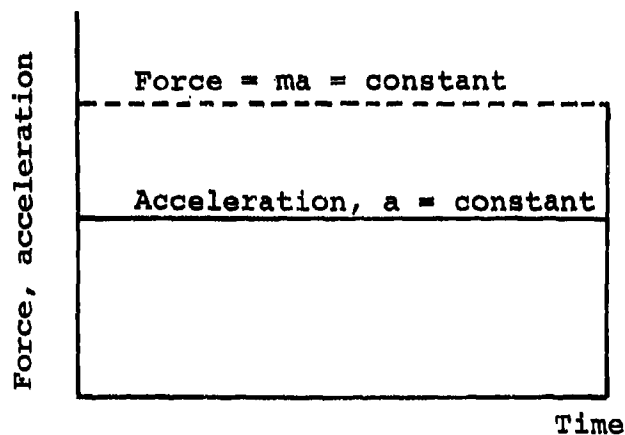
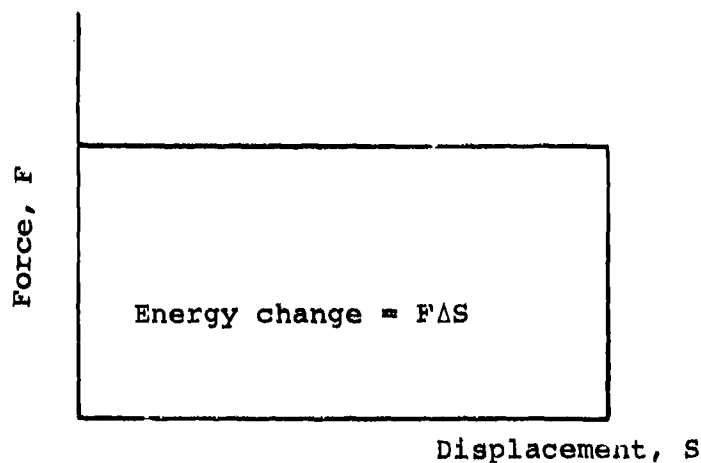


Figure 67. Illustration of impact reducing aircraft kinetic energy.

If a constant stopping force were applied, the velocity would be reduced at constant deceleration, as shown in Figure 68(a) and the force-displacement curve would be as shown in Figure 68(b).



(a) Constant acceleration versus time



(b) Constant force versus displacement

Figure 68. Illustration of deceleration by constant force.

Often, for protection of occupants, it is desirable to limit the decelerating force to some prescribed value. Given a maximum force, the most efficient energy-absorbing system would be the one requiring the smallest displacement, ΔS , which would be the constant-force system. Therefore, energy absorption by a constant force is often referred to as "ideal" energy absorption. The devices shown in Figure 30 exert a nearly constant force and thus act as nearly ideal energy absorbers. They are desirable for use where concentrated loads are applied and the transmitted force must be limited, such as in seats and landing gear.

Structural systems and certain materials, such as plastic foams and honeycomb materials, approach the ideal force-displacement curve to the extent shown in Figure 69.

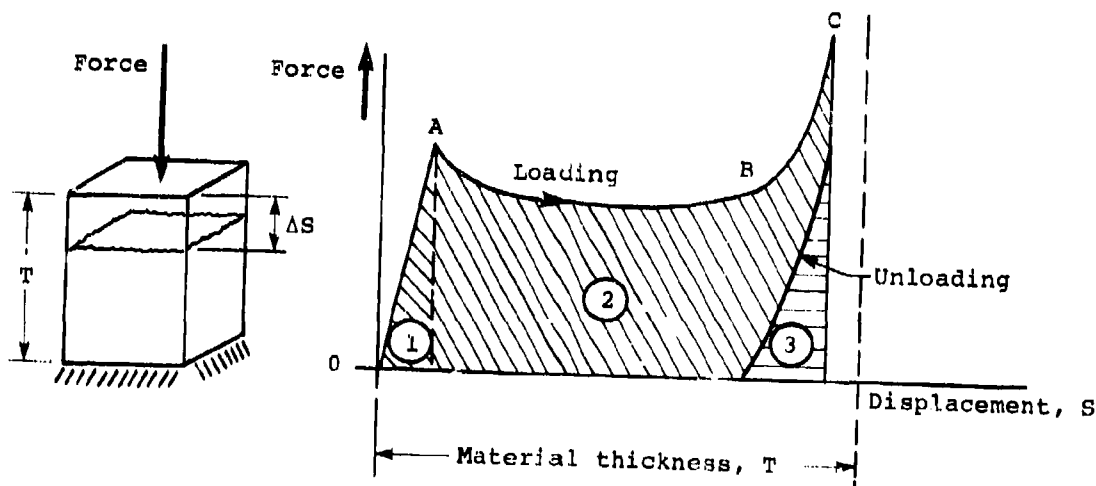


Figure 69. Force-displacement curve for honeycomb materials.

Again the area under this curve represents energy absorbed. The area can be divided into three important regions. If loading results only in reaching Point A in Figure 69, then unloading generally occurs along the elastic curve OA, and the energy indicated by Area "1" is restored to the system just as a spring releases its energy when it is unloaded. Area "2" represents inelastic, or plastic, energy absorption and if loading reached Point C the energy corresponding to Areas "1" plus "2" plus "3" is absorbed. However, as unloading occurs, the energy of Area "3" is restored in the form of rebound. Loading in the

region from B to C in the figure is often referred to as "bottoming," a condition in which the deforming structure or material has become compacted and the load increases rapidly with very little increased deformation.

The energy dissipated in locked-wheel skidding is of interest in calculating, for example, the initial velocity when the skidding distance is known. This is readily obtained from Equation (31) if it is assumed that during skidding the sliding forces are constant and are the only significant forces present. Thus, the work done by the sliding force is simply the force times the distance and from Equation (31), for $v_{\text{final}} = 0$,

$$FS = \frac{1}{2} mv_o^2 \quad (32)$$

or

$$v_o = \sqrt{\frac{2FS}{m}} \quad (33)$$

The sliding force F can be assumed to equal an average coefficient of friction times the normal force between the vehicle and the sliding surface, or the weight of the vehicle if the surface is horizontal, thus

$$F = \mu N = \mu W \quad (34)$$

and

$$v_o = \sqrt{\frac{2\mu WS}{W/g}} = \sqrt{2g\mu S} \quad (35)$$

where μ = coefficient of kinetic (sliding) friction

W = weight of vehicle

S = stopping distance

g = acceleration due to gravity = 32.2 ft/sec².

For the case $v_f \neq 0$ we can use the work-energy principle to obtain

Work = Δ Kinetic Energy

$$-\mu WS = \frac{1}{2} \frac{W}{g} [v_f^2 - v_o^2]$$

From which

$$v_f = \sqrt{v_o^2 - 2g\mu S} \quad (36)$$

and

$$v_o = \sqrt{v_f^2 + 2g\mu S} \quad (37)$$

For sliding on a slope of angle θ to the horizontal

$$v_o = \sqrt{v_f^2 + 2gS[\mu \cos \theta \pm \sin \theta]} \quad (38)$$

For sliding uphill the + sign applies; for sliding downhill, the - sign.

Example: The landing gear on an aircraft collapses and the aircraft slides 1200 ft, at which point it was estimated to have a residual speed of 50 kn. By dragging the wreckage with a tank retriever through a load-measuring device it is found that the required load to move the aircraft is 0.7 times the weight of the aircraft. To determine the speed when the gear collapsed

$$v_f = 50 \text{ kn} = 1.69 \times 50 = 83 \text{ ft/sec}$$

$$\mu = 0.7$$

$$v_o = \sqrt{(83)^2 + 2(32.2)(0.7)(1200)}$$

$$v_o = 246 \text{ ft/sec}$$

$$= 148 \text{ kn}$$

7.2.3 Stopping Distance

For a complete aircraft system, or a subsystem such as seat and occupant, average deceleration values ($\bar{G}$) can be determined for given velocity changes as demonstrated above, and from these data an average stopping distance can be computed.

$$v_o^2 - v_f^2 = 2g\bar{G}S \quad (39)$$

where v_o = impact velocity

v_f = final velocity (usually zero)

g = acceleration of gravity (32.2 ft/sec²)

$\bar{G}$ = deceleration in "G" units (average)

S = stopping distance.

Solving for S gives

$$S = \frac{v_o^2 - v_f^2}{2g\bar{G}} \quad (40)$$

This expression is useful for assessing the required stroking distance for a seat when impact velocity and acceleration limitations are known; however, it must be noted that this relation yields the total stroking distance, including deformations of the impacted surface and deflection of the gear, fuselage, and seat. Superposition of the seat, structure, and impacted surface characteristics can be used to assess the net average deceleration experienced by a seat occupant.

Figure 70 shows the variation of stopping distance as a function of $\bar{G}$ and velocity change (Δv) derived from the standard Newtonian equations for assumed constant acceleration.

These characteristics assume 100 percent efficiency, but real structure will react somewhat differently, requiring larger stopping distances for given velocity changes and/or deceleration levels. The elapsed time values can be used for assessing human tolerance potential when human injury criteria are known as functions of G level and exposure time.

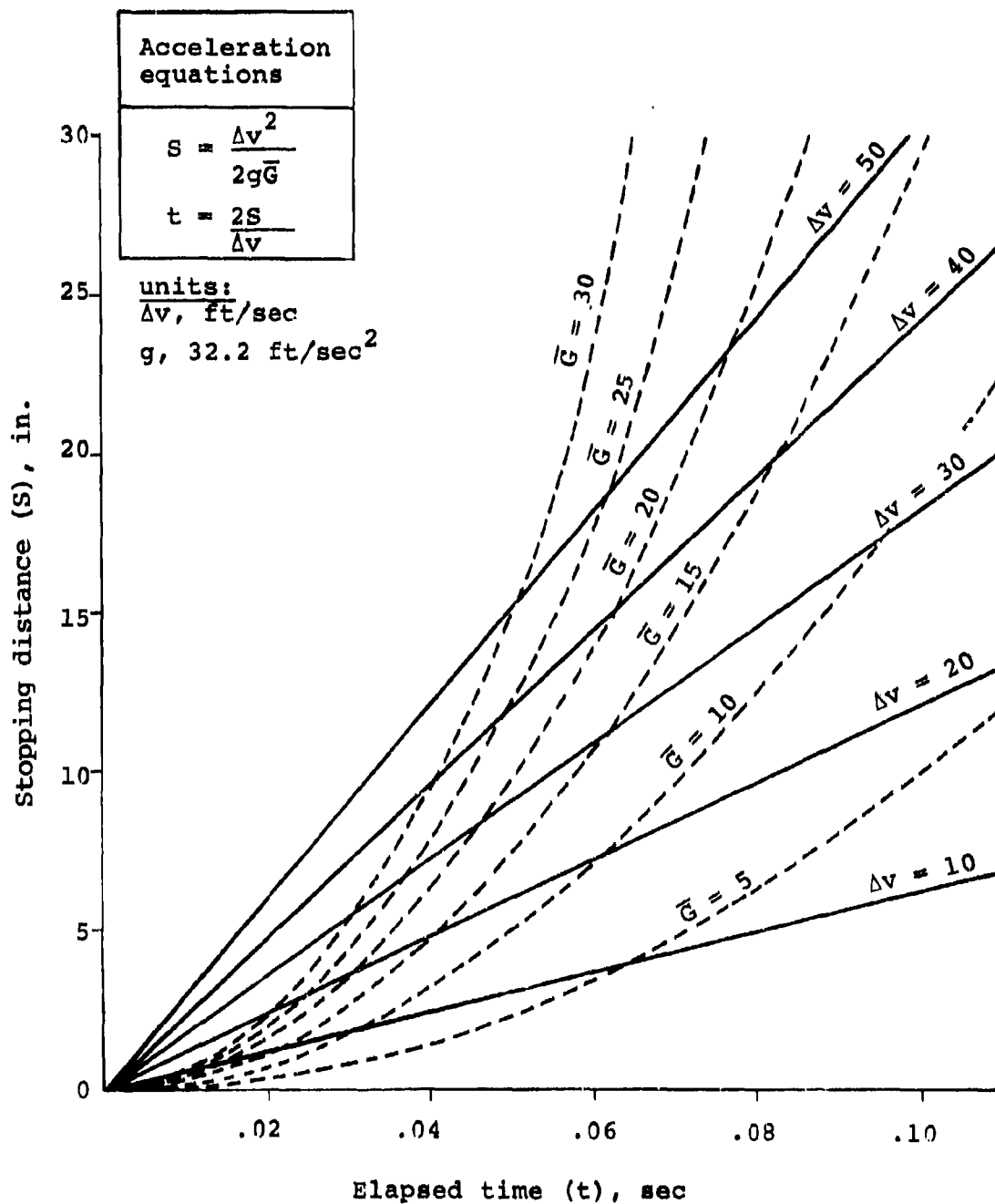
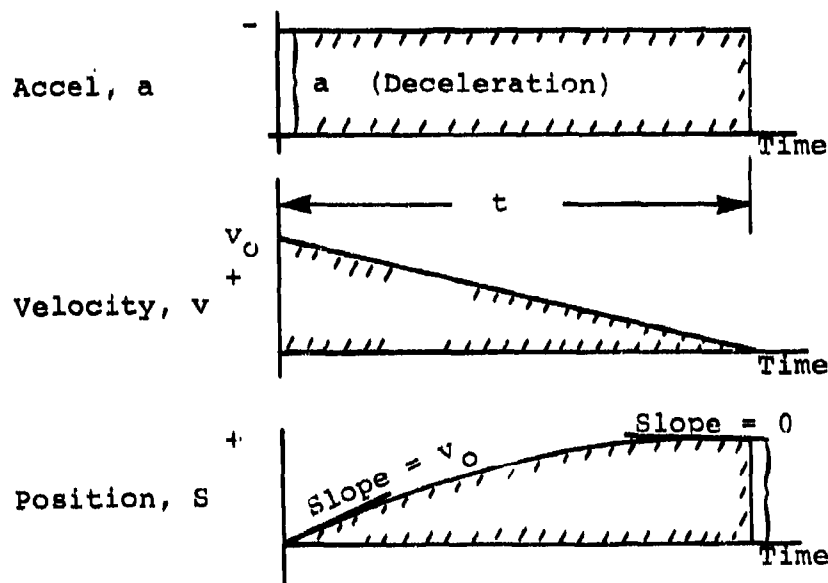


Figure 70. Theoretical stopping distance as a function of velocity change and average deceleration level.

Figure 70 is useful for the initial assessment of motion envelopes needed to provide occupants with a survivable decelerative environment and for the requirements of various structural energy-absorption elements.

It is interesting to compare several deceleration pulse shapes (negative acceleration) to show the effect pulse shape has on deceleration distance. Rectangular, triangular, and sinusoidal pulses are considered.

7.2.3.1 Rectangular Deceleration Pulse



From Equation (24) $v_0 = at$ (41)

Then $t = v_0/a$

From Equation (25) $S = \frac{1}{2} v_0 t$ (42)

So that $S = \frac{1}{2} v_0 \cdot \frac{v_0}{a}$

Or

$$v_o^2 = 2as \quad (43)$$

And

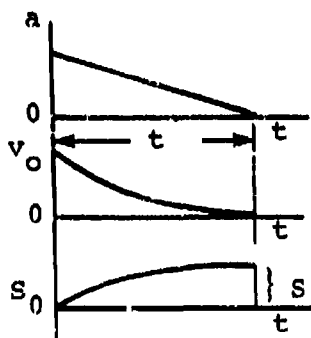
$$s = \frac{1}{2} \frac{v_o^2}{a} \quad (44)$$

The implications of Equations (43) and (44) are that for a large v_o , a very large stopping distance would be required. Or, for a small acceleration, a large stopping distance is required.

7.2.3.2 Triangular Deceleration Pulse

Comparing two triangular pulses here, one with zero rise (onset) time and another with zero offset time,

Zero rise time



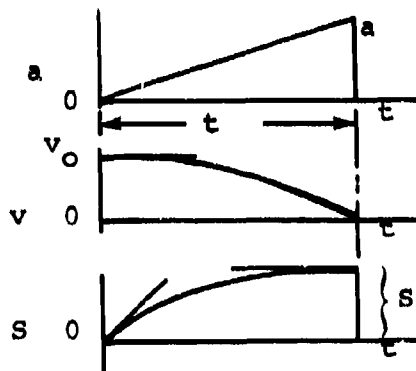
$$\frac{1}{2} at = v_o$$

$$t = \frac{2v_o}{a}$$

$$s = \frac{1}{3} v_o t$$

$$= \frac{1}{3} v_o \cdot \frac{2v_o}{a}$$

Zero offset time



$$\frac{1}{2} at = v_o$$

$$t = \frac{2v_o}{a}$$

$$s = \frac{2}{3} v_o t$$

$$= \frac{2}{3} v_o \cdot \frac{2v_o}{a}$$

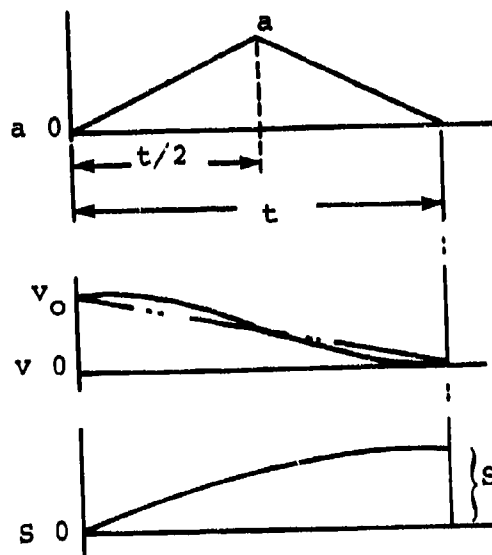
$$s = \frac{2}{3} \frac{v_o^2}{a}$$

$$s = \frac{4}{3} \frac{v_o^2}{a}$$

Note that the deceleration pulses are equal in time ($t = 2v_o/a$) but that the zero-rise-time case requires twice the deceleration distance of the zero offset time case.

7.2.3.3 Symmetrical Triangular Pulse

For a symmetrical (isoceler) triangular pulse,



$$\frac{1}{2}at = v_o$$

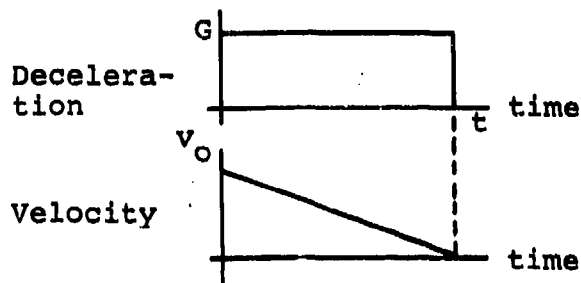
$$t = \frac{2v_o}{a}$$

$$s = \frac{1}{2} v_o t$$

$$= \frac{1}{2} v_o \left(\frac{2v_o}{a} \right) = \frac{v_o^2}{a}$$

7.2.3.4 Summary for the Case of Final Velocity, $v_f = 0$

Summaries for various shaped pulses are included below:



Rectangular Pulse

Pulse Duration:

$$t = \frac{v_o}{32.2G}$$

Deceleration Level:

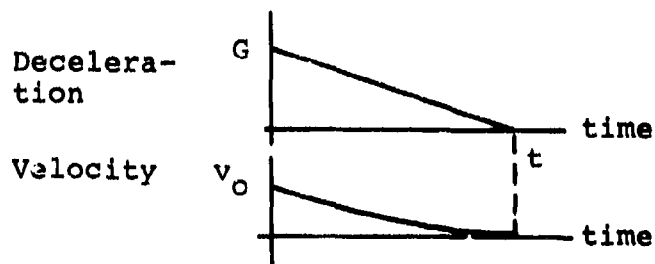
$$G = \frac{v_o^2}{64.4S}$$

Stopping Distance:

$$S = \frac{v_o^2}{64.4G}$$

Or:

$$S = \frac{32.2Gt^2}{2}$$



Triangular Pulse No. 1

Pulse Duration:

$$t = \frac{2v_o}{32.2G}$$

Deceleration Level:

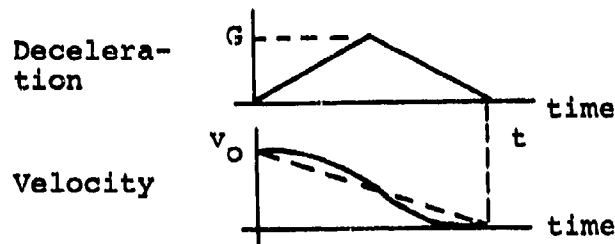
$$G = \frac{2v_o^2}{96.6s}$$

Stopping Distance:

$$s = \frac{2v_o^2}{96.6G}$$

Or:

$$s = \frac{32.2Gt^2}{6}$$



Triangular Pulse No. 2

Pulse Duration:

$$t = \frac{2v_o}{32.2G}$$

Deceleration Level:

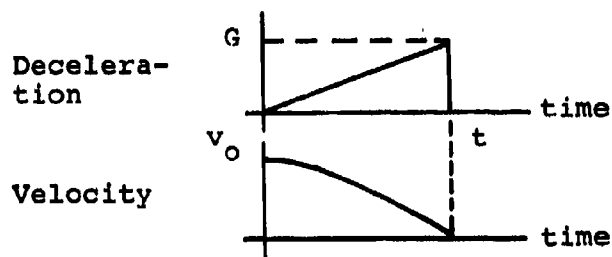
$$G = \frac{v_o^2}{32.2s}$$

Stopping Distance:

$$s = \frac{v_o^2}{32.2G}$$

Or:

$$s = \frac{32.2Gt^2}{4}$$



Triangular Pulse No. 3

Pulse Duration:

$$t = \frac{2v_o}{32.2G}$$

Deceleration Level:

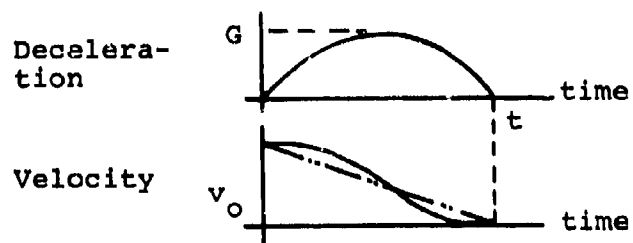
$$G = \frac{4v_o^2}{96.6S}$$

Stopping Distance:

$$S = \frac{4v_o^2}{96.6G}$$

Or:

$$S = \frac{32.2Gt^2}{3}$$



Half-Sine Pulse

Pulse Duration:

$$t = \frac{1.57v_o}{32.2G}$$

Deceleration Level:

$$G = \frac{0.7854v_o^2}{32.2S}$$

Stopping Distance:

$$S = \frac{0.7854v_o^2}{32.2G}$$

Or:

$$S = \frac{32.2Gt^2}{3.14}$$

A plot of these equations is given in Figure 71. Relative times and stopping distances are shown in Figure 72 for convenient visual comparison.

Note that the time to stop is equal for all three triangular deceleration-time pulses, but that the stopping distances are not. Minimum stopping distance is achieved with the rectangular pulse and hence it is the most desired pulse shape from a consideration of deceleration from maximum velocity at a given deceleration level in the shortest possible distance.

7.2.4 Energy Content of Aircraft at Impact

In a crash situation, immediately prior to impact, the complete aircraft system possesses a total energy which must be dissipated before the crash sequence is complete.

Sources of energy prior to impact include the following:

- Translational kinetic energy, (K.E.)_T
- Rotational kinetic energy, (K.E.)_R
- Potential energy, P.E.
- Strain energy, S.E.

The total energy input during the crash sequence, T.E., is

$$T.E. = (K.E.)_T + (K.E.)_R + P.E. + S.E. \quad (45)$$

7.2.4.1 Translational Kinetic Energy, (K.E.)_T: This energy component is a direct function of the aircraft mass and the velocity of the mass center at impact.

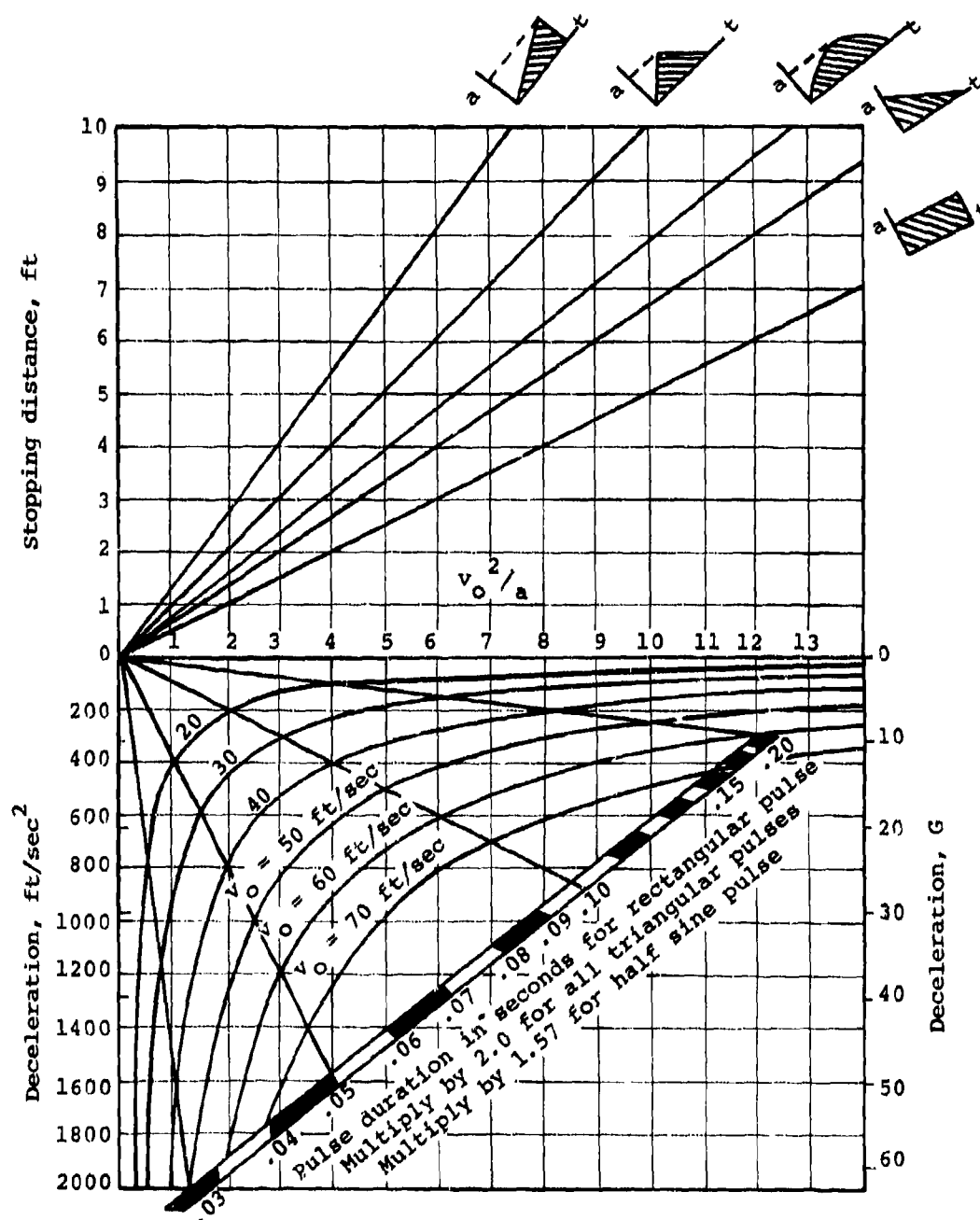


Figure 71. Deceleration, velocity, and distance as functions of time for five pulse shapes.

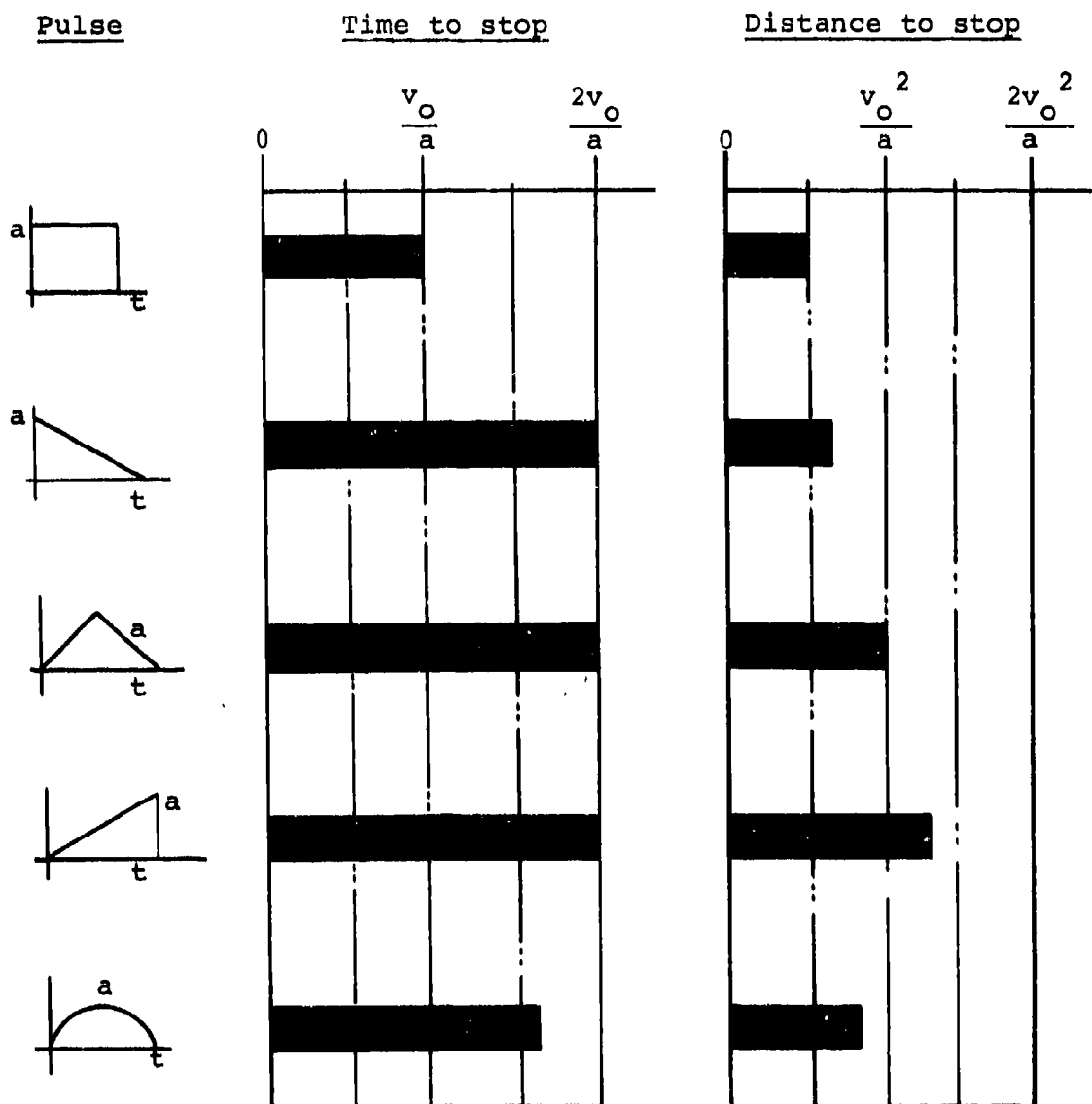


Figure 72. Comparison of stopping distances for various deceleration pulse shapes.

- if v_G = resultant velocity of mass center
 $\dot{x}_G$ = longitudinal component of velocity
 $\dot{y}_G$ = lateral component of velocity
 $\dot{z}_G$ = vertical component of velocity

$$\begin{aligned}
 (K.E.)_T &= \frac{1}{2} m v_G^2 \\
 &= \frac{m}{2} (\dot{x}_G^2 + \dot{y}_G^2 + \dot{z}_G^2)
 \end{aligned}
 \tag{46}$$

The total K.E. of the aircraft is the summation for all mass elements of the aircraft.

7.2.4.2 Rotational Kinetic Energy, $(K.E.)_R$: Rotational kinetic energy can take the form of total aircraft rotary motions about the three basic axes of rotation of aircraft elements such as engines or rotor systems. In a helicopter, two major sources of rotational energy may exist: the rotor head system, including the blades and rotating swashplates, and the rotating machinery elements, such as engines and transmissions. During a crash, the element with the energy content may impact external agents and/or the helicopter structure, thus imparting loading to the structural system. However, if, for example, gas turbine engines are not unduly disturbed from their attitude at impact, it is likely that there will be no appreciable change in the angular velocity of the rotational elements during the time span of the crash impact and no subsequent structural deformation.

Selective assessment of rotational kinetic energy contributions to the crash energy balance must be made.

$$\begin{aligned}
 \text{Basically, } (K.E.)_R &= \sum \frac{1}{2} I \Omega^2 \\
 &= \frac{1}{2} I_\theta \dot{\theta}^2 + \frac{1}{2} I_\phi \dot{\phi}^2 + \frac{1}{2} I_\psi \dot{\psi}^2
 \end{aligned}
 \tag{47}$$

where $\dot{\theta}$ = angular velocity component in x-z plane (pitch)

$\dot{\phi}$ = angular velocity component in y-z plane (roll)

$\dot{\psi}$ = angular velocity component in x-y plane (yaw).

and I_θ , I_ϕ , I_ψ , are the mass moments of inertia of the vehicle with respect to pitch, roll, and yaw axes, respectively, at its mass center.

7.2.4.3 Potential Energy, $(P.E.)$: For each crash sequence, the total potential energy input into the system equals the vertical displacement contribution of each mass from the time of impact until the time of completion.

$$P.E. = \sum (mg \Delta Z) \tag{48}$$

The effects of large mass items, such as transmissions and engines, are major contributors to the energy balance.

7.2.4.4 Strain Energy, (S.E.): Structural strain energy may exist as a result of structural deflections to accommodate in-flight loading. In addition, pressurized systems may represent a level of stored energy. However, such influences are expected to be minimal during a crash sequence.

7.2.5 Postimpact Energy Dissipation

After the aircraft's initial contact with the impacted surface, there are several ways of absorbing energy that bring the vehicle to a stop, while also providing a survivable environment for the occupants.

Possible major contributors in the energy-absorption process are the following:

1. Structural Deformation - Structural deformation provides the major means of energy absorption in a severe crash environment. Compression, tension, bending, torsion, and shear from low levels up to ultimate conditions all contribute to energy absorption.

Vertical inertia effects are reacted by crushing of the belly structure, while combined bending and compression of frame and bulkhead members provide support to the large mass items. Longitudinal resistance is provided by ground friction and nose plowing for impacts on planar surfaces and by compression for impacts into abutments.

2. Energy-Absorbing Landing Gear - The landing gear, an integral part of the structure, provides some level of energy absorption, depending on design criteria for the particular aircraft involved.
3. Breakaway of Large Mass Items - The breakaway technique for shedding energy has the effect of an instantaneous mass change resulting in a corresponding reduction in kinetic and potential energies of the remaining items of concern. A major problem involved is designing the vehicle to ensure clean breakaway characteristics with adequate clearance between each free mass item and the occupied area. If potential hazards from impacting occupied areas or generating fires can be identified, it is better to retain the large mass items and provide adequate structures to support them.

4. Ground Friction and Nose Plowing - Longitudinal deceleration is provided by ground friction and/or nose plowing, depending on the type of impacted surface. Structural design must preclude the digging in of structure that increases the deceleration and also may cause quantities of earth to be scooped inside the aircraft, or cause the aircraft to pitch over. Additionally, where hard surfaces are involved, materials that minimize the generation of sparks and hot spots should be chosen to reduce the potential for ignition if flammable fluids are spilled.

The ability to push a mass of earth by wedging action effectively increases the mass of the system. Energy is absorbed in accelerating the plowed material to the same velocity as the decelerating aircraft, and, as the earth mass incrementally increases, effective braking action due to momentum exchange ensues. Section 6.6.3 presents a more detailed discussion of plowing.

Impact with ground obstacles such as rocks, trees, and poles, can be included in this category of energy absorption. However, the relative sizes of the aircraft and obstacle are significant in establishing the quantity of energy absorbed. Usually these types of obstacles absorb small amounts of energy.

5. Energy-Absorbing Seats

The seat is the final link between an aircraft occupant and the ground. The seat and its attachments to the airframe structure must possess sufficient strength to keep the occupant within the aircraft's protective shell. Combined with the restraint system, the seat must prevent injurious contact between its occupant and the aircraft interior. Because the human body can tolerate relatively low deceleration levels in the direction parallel to the spine, it is imperative that some mechanism for energy absorption in the vertical direction be included in the seat design.

Although crashworthy seat design is covered in detail in Volume IV, the energy-absorbing stroke of the seat must be considered in design of surrounding structure to prevent interference with seat operation. In fact, probable longitudinal and lateral deflections must be added to the strike envelope of the seat in laying

out surrounding structure to assure that the critical vertical energy-absorbing stroke of the seat is not blocked.

7.3 LANDING GEAR ANALYSIS

Methods of analyzing performance of both wheel- and skid-type landing gear were surveyed and described in Reference 44. Applicable techniques are summarized below.

7.3.1 Wheel Landing Gear

The methodology for designing a strut-wheel landing gear delineated below is that contained in Reference 27 with some modification.

The typical oleo-strut-wheel landing gear is essentially an air-oil hydraulic cylinder as shown in Figure 73, which schematically represents one stage of the landing gear illustrated in Figure 32. The cylinder is pressurized with an air pressure that acts to balance the static loads of the vehicle and the dynamic loads during taxi. The air trapped within the cylinder follows the laws governing compressibility of a gas in a closed container that are simply described by

$$P_1 V_1^n = P_2 V_2^n \quad (49)$$

where P = pressure of the gas (lb/in.²)

V = specific volume (in.³/lb_m)

The subscripts 1 and 2 define the initial and final states of the gas, respectively, and the exponent n defines the nature of the process between states 1 and 2.

During taxi, the vehicle rides on an air cushion. Since the temperature of the air within the cylinder remains essentially constant during taxi, the process can be considered isothermal and n is approximately 1. However, during impact conditions the small time available for heat transfer from the rapidly compressed air ensures a nearly adiabatic process, for which $n \approx 1.4$.

44. Phillips, N. S., Carr, R. W., and Scranton, R. S., CRASH-WORTHY LANDING GEAR STUDY, Beta Industries, Inc.; USAAMRDL Technical Report 72-61, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1973, AD 765489.

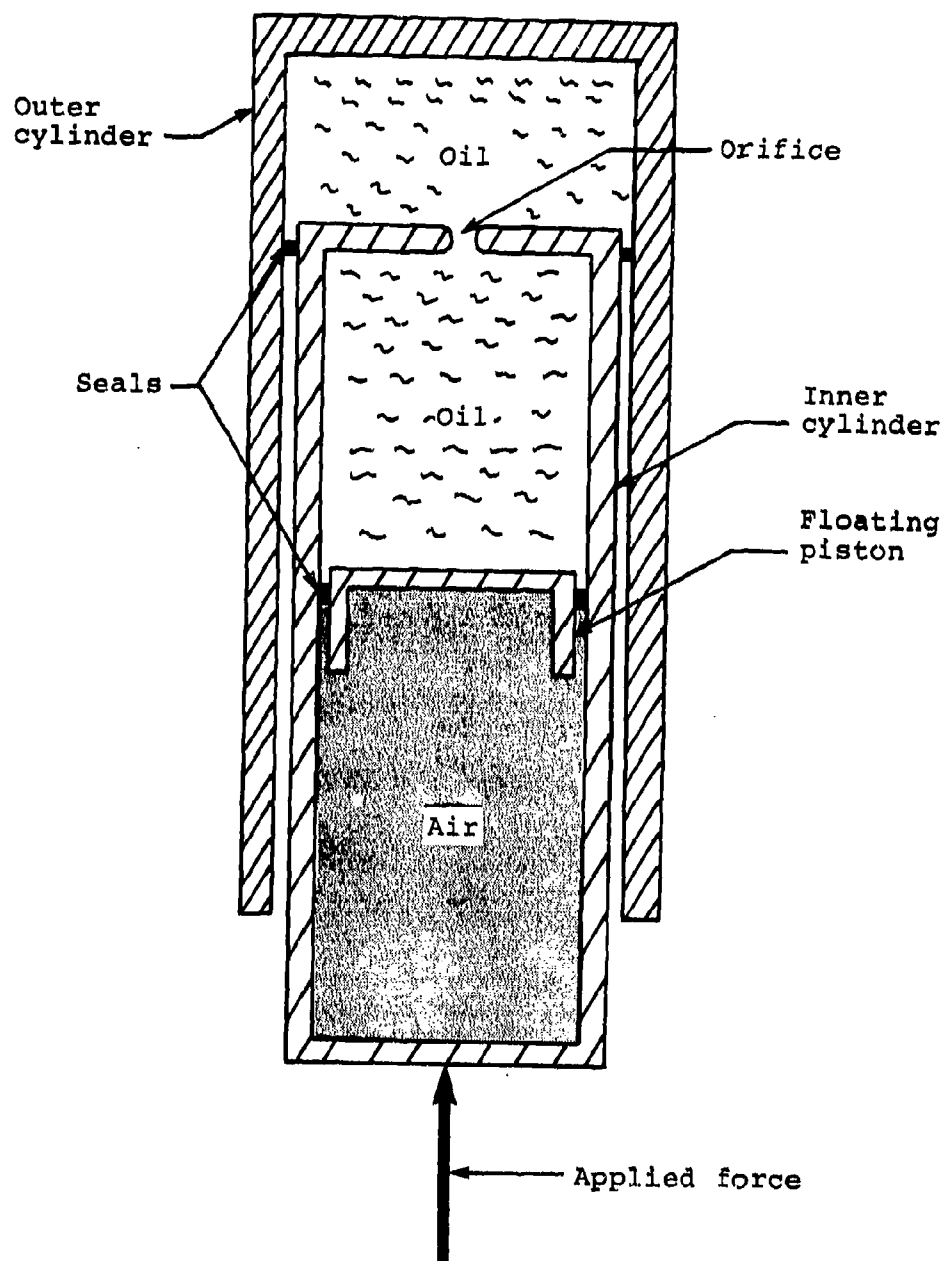


Figure 73. Shock strut schematic.

The hydraulic portion of the cylinder functions to limit loads during impact conditions. The high stroking rate of the gear is limited by the pressure generated in the oil as it is forced through the orifice, rather than by air pressure. As the fluid is forced through the orifice, the pressure in the cylinder is defined by Bernoulli's principle for an ideal fluid. The hydraulic force becomes

$$F_h = \frac{\rho A_h^3 (\dot{s})^2}{2(G_d A_n)^2} \quad (50)$$

where ρ = density (lb_m/in.³)

A_h = hydraulic area of the piston (in.²)

$\dot{s}$ = stroke velocity (in./sec)

G_d = orifice coefficient

A_n = orifice area (in.²)

This basic equation indicates why landing gear units have failed in the initial instants of impact without absorbing significant energy. If the vehicle impacts with a high velocity, the relative velocity across the strut is very large, and the force is proportional to the square of the relative velocity. The strut quickly becomes a rigid link between the ground and the fuselage, and the extreme forces separate the landing gear from its attachment points.

This applies to a single-stage strut without any blow-off capability. If a blow-off valve is incorporated, as discussed in Section 6.5, by sizing the orifice, the strut can be designed to stroke at high velocity levels and high load values. The incorporation of a variable orifice offers even more control over the load-stroke relationship and allows more energy to be absorbed, as illustrated in Section 6.5. The landing gear cylinder also resists motion through bearing frictional forces that act upon the piston.

The cylinder is supported to resist lateral loads associated with both operational and crash conditions.

All of the landing gear systems reviewed have the design features mentioned. Many variations are possible. The orifice usually is combined with a metering pin to adjust the orifice area with stroke length. Orifice and relief valve combinations

are used to introduce orifice variation as a function of force. Some liquid springs have been used where the function of the air pressure is replaced by compression of a fluid. These are a few of the possible variations that produce desirable refinements of the response but do not alter the basic characteristics of the landing gear.

The approach to the design of the particular landing gear is discussed here to demonstrate the various steps leading to a finished piece of hardware. The major airframe manufacturer generates a set of criteria for the landing gear design subcontractor. These are the appropriate military specifications, preliminary weight estimates, moments of inertia, center-of-gravity locations, landing gear stroke requirements, and vehicle attitudes.

If the energy relation is used, the sink rate, gross weight, and strut efficiency are needed to calculate a load factor. This is calculated for forward and aft centers of gravity, as well as for selected attitudes such as level two-point, level three-point, and tail down. The attitude is important because it modifies the stroke of the strut. It is assumed that the vehicle falls vertically, but the strut compresses along its axis. The output from the energy equation is the load factor.

The load factor is multiplied by the gross weight, and a summation of forces and moments is calculated for each landing condition. For the level three-point condition with maximum vertical reaction, it is assumed that each landing gear will have its dynamic vertical force apportioned according to the static distribution. The drag forces are one-quarter of the vertical forces, and the side forces are zero.

Therefore, referring to the diagram of Figure 74,

$$\Sigma F_V = V_A + V_M + \frac{2}{3}W - N_Z W = 0 \quad (51)$$

$$\Sigma M_O = V_A(a + b) - N_Z W(b) - Tc + \frac{2}{3}Wb + M_S = 0 \quad (52)$$

$$\Sigma D = D_A + D_M - T = 0 \quad (53)$$

where M_S = moment contribution due to landing gear drag

$$L = \frac{2}{3}W$$

$$D = \frac{1}{4} V_A$$

T = residual thrust

The strut load factors N_x , N_y , and N_z are then used to calculate the forces that each landing gear must carry. These forces are tabulated and analyzed to determine critical conditions.

The airframe manufacturer then supplies the landing gear manufacturer with the critical design conditions along with gross weight, maximum load factor, static load, stroke, piston diameter, attachment point locations, overall length, and tire type. The landing gear manufacturer examines each condition and calculates the reaction loads due to each.

The design is significantly influenced by pressure considerations. The air pressure within the cylinder must support the vehicle in a static configuration. The design specification indicates that the piston is of a given diameter to carry the maximum forces and strokes from full extension to full compression. Additional guidance is provided in MIL-L-8552 (Reference 45). From the various design conditions, the maximum axial force is selected for static conditions. A reasonably low static pressure (200 to 500 lb/in.²) is desired, although the specifications permit 2500 lb/in.². The difficulty is that decreased pressures dictate very great stresses during full compression and necessitate increased material thicknesses.

The cylinder must be designed to stroke a full stroke plus an amount sufficient to alleviate bottoming. Assuming the additional stroke is sufficient to create a compression ratio of four, and the static-to-full-stroke dimension is known, an additional stroke is calculated by

$$\frac{(\text{Full stroke} - \text{Static stroke}) + \text{Additional stroke}}{\text{Additional stroke}} = 4.0$$

The relation $P_1 V_1^{1.4} = P_2 V_2^{1.4}$ is then used to calculate the full extended pressure, which must be sufficient to ensure full extension, and to determine the fully compressed pressure, which is approximately a limit of 2500 lb/in.².

The hydraulic operation of the strut is a function of orifice size and metering pin design. There have been analytical investigations to define the orifice area-stroke relation based upon a desired constant force response; however, it appears at present that the design is more a function of previous experience.

45. Military Specification, MIL-L-8552, LANDING GEAR, AIRCRAFT, SHOCK ABSORBER, AIR-OIL TYPE, Department of Defense, Washington, D. C., 10 December 1968.

Landing gear manufacturers have orifice and metering pin data available with orifice coefficients that will enable them to design a preliminary configuration. Because the configuration is selected based upon a worst condition, it remains for test results to indicate how the strut responds to various inputs. That is, the design is known from empirical data to generate the proper efficiency for a given payload and drop height. Apparently, other conditions are not evaluated analytically but only through test. By examining the measured data, the metering pin is modified to reduce undesirable peak forces and improve the efficiency.

At this point in the system development, the preliminary data are compiled and the structural design is initiated. Overall lengths are known, externally applied forces are available, and internal pressure can be specified. These characteristics collectively dictate the necessary wall thicknesses and pivot point lug sizes. The remainder of the design becomes a stress analysis problem to be solved using classical techniques.

7.3.2 Skid Landing Gear

As indicated in Figure 6, the skid-type landing gear has been used for many years on lightweight helicopters. It is a low-cost means of creating small elastic deflections during normal landings, while providing energy dissipation efficiencies comparable to those of the oleo strut at limit sink speeds of reserve energy impact velocities. The design problem associated with skids is that they are nonlinear structural elements. The skid has linearly related applied force and resulting deformation over the small amount of stroke that results in normal landing impact velocities. Beyond that point it is necessary to consider the plastic deformation of the skid.

The simplest design technique assumes the vehicle is supported by tubular members that cross horizontally at the bottom of the fuselage. The vehicle impact is in a horizontal attitude and dissipates all energy by the strain energy required for bending of the tubes.

The skid stiffness is idealized as a bilinear curve with slope decreasing to a small value after yielding to duplicate the load-deflection curve. This is derived from an idealized stress-versus-strain curve for the particular material used.

Since the load-deflection curve is piecewise linear, it is easily integrated to determine the potential energy as a function of skid deflection. The energy absorbed in the elastic region of the gear is

$$E_1 = \int_0^{\delta_y} P(\delta) d\delta = C\delta_y^2/2 \quad (55)$$

where $P(\delta)$ = applied load (lb)

δ = deformation of skid (ft)

δ_y = deformation at elastic limit (ft)

C = slope of the elastic range of the load-deflection curve (lb/ft)

E_1 = energy absorbed (ft-lb).

For the plastic portion of the curve the energy absorbed is

$$\begin{aligned} E_2 &= \int_{\delta_y}^{\delta} P(\delta) d\delta \\ &= \int_{\delta_y}^{\delta} [C\delta_y + C_1(\delta - \delta_y)] d\delta \\ &= C\delta_y (\delta - \delta_y) + \frac{C_1}{2} (\delta - \delta_y)^2 \end{aligned} \quad (56)$$

where C_1 = slope of plastic range (lb/ft).

By equating kinetic and potential energies, equations are developed to relate applied loads, elastic limits, vehicle masses, weights applied per skid, and impact velocities.

For a perfectly plastic material,

$$\delta = \frac{\frac{\delta_y}{2} + \left[\frac{RW}{(C - C_1)\delta_y} \right] \left(\frac{6v^2}{Rg} \right)}{1 + \frac{RW}{(C - C_1)\delta_y}} \quad (57)$$

where $R = 1 - \frac{\text{rotor lift}}{\text{weight}}$
 W = effective weight (lb)
 g = gravitational constant (ft/sec²)
 v = impact velocity (ft/sec).

Therefore, for varying impact velocities, rotor lift values, and desired effective weights on the skids, the deformation can be calculated. The load factor applied is then the ratio of applied force to effective weight:

$$n = \frac{F}{W} \quad (58)$$

The procedure requires approximating the stress-strain curve of a material, then approximating the resulting load-deflection curve for the integration process in the energy equations. The results of this type of approach have produced reasonable results when compared with test data.

The procedure shown has several distinct steps:

- Establish the stress-strain characteristics of the tube material.
- Calculate the force-displacement characteristics of the tube.
- Incorporate the force-displacement characteristics into an energy relation or set of dynamic response equations.
- Calculate the vehicle response.

7.4 SEMIEMPIRICAL ANALYSES OF AIRFRAME STRUCTURAL CRASHWORTHINESS

Several computer programs have been developed recently to analyze crash conditions. However, the accuracy obtained depends greatly on the ability to represent the proper crushing characteristics of the structure. The use of analytical tools to aid designers would be most beneficial during the preliminary stages of design when meaningful tradeoffs can be made among

weight, cost, space, and crashworthiness capability. It is at this time in the design process that potential changes can be achieved with the least cost penalty to a project. At this stage in the design, only a limited amount of data exists; probably little more than basic weights, stiffnesses, strengths, configurations, and sizing are available for analysis. To maximize the effectiveness of preliminary design analytical tools, the crushing characteristics of the typical vehicle structure must be obtainable with reasonable accuracy using relatively simple techniques.

Reference 46 describes a procedure for prediction of crushing characteristics of primary energy-absorbing structure, as summarized below.

7.4.1 Analysis Procedure

The general procedure for determining the total load-deflection characteristics, including failure and postfailure behavior for a given substructure, is discussed below. The procedure was demonstrated for a test specimen built to represent a section of a utility helicopter lower fuselage. The location of the segment in the lower fuselage and the four-edge support representative of the manner in which loads are transmitted from the fuselage to the transmission housing are shown in Figure 76. Included in the procedure is a step-by-step process with the following sequence:

1. Prediction of failure loads for stiffened panels.
2. Postfailure analysis of stiffened panels.
3. Main beam and bottom skin analysis.
4. Total substructure load-deflection curve.

46. Wittlin, G., and Park, K. C., DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF PROCEDURES TO DETERMINE NONLINEAR LOAD DEFLECTION CHARACTERISTICS OF HELICOPTER SUBSTRUCTURES SUBJECTED TO CRASH FORCES, Volumes I and II, Lockheed-California Company; USAAMRDL Technical Reports 74-12A, 74-12B, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, 1974, AD 784191 and AD 784192.

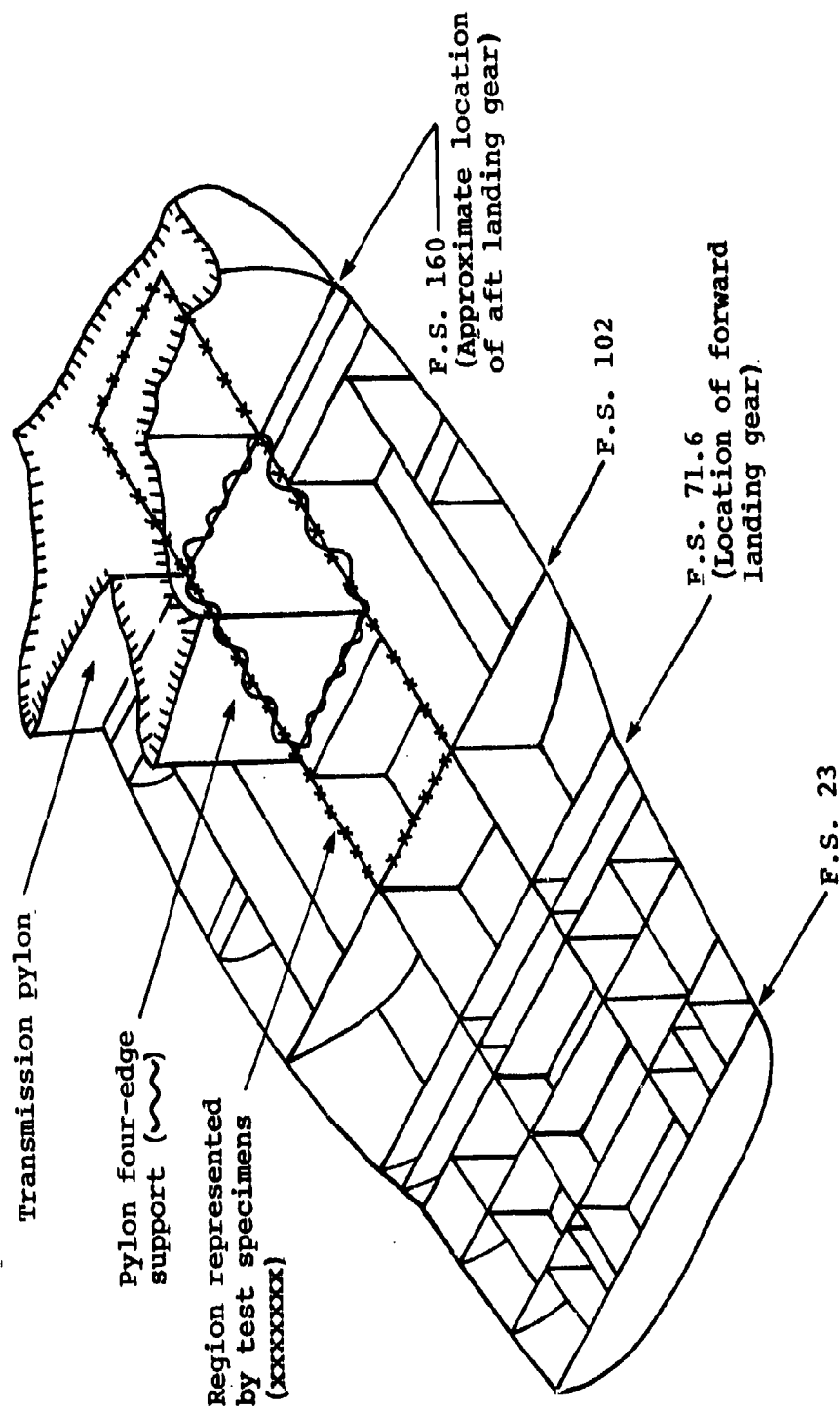


Figure 76. Lower fuselage bulkhead and stiffener arrangement. (From Reference 46)

In predicting the failure load of the model substructure, extensive use of the work of Needham (Reference 47) and Gerard (Reference 48) was made. For the postfailure analysis, the concept of D'Amato (Reference 49) was used as a base; however, a somewhat different failure mechanism was employed. Subelement crushing characteristics were superimposed in a piecewise sense to yield the total load-deflection curve. Depending upon the rivet pitch, spacing, and strength, a given structure may fail in one of several ways. Therefore, the procedure described herein takes into account monolithic, wrinkling, and interrivet failure modes. The basic equations were developed for a nondimensional slenderness ratio of $L/\rho = 20$. However, column effects were included for L/ρ ratios greater than 20. Although developed for angle-type stiffened panels, the procedure is reported to be applicable to a variety of panel types, including T-type stiffeners, formed angle stiffeners, extruded angle stiffeners, formed multicorner sections, hat-formed stiffened panels, and extruded-Y stiffened panels.

The failure loads were estimated using the semiempirical/analytical methods described in References 47, 50, and 51 for stiffened short panel elements. The analysis, as outlined, is based on two assumptions: (1) at the threshold of the failure load, full plastic hinges are developed at the constrained supports and the midsection of the panels, and (2) the free warping energy of the flange of the stiffening angles can be neglected.

As is discussed in Section 7.4.3 and in detail in Reference 46, these assumptions are considered on the average reasonable. The analysis neglects the effect of strain hardening, the influence of the axial force on the plastic hinge mechanisms of

47. Needham, R. S., THE ULTIMATE STRENGTH OF ALUMINUM ALLOY FORMED STRUCTURAL SHAPES IN COMPRESSION, Journal of Aerospace Science, Vol. 21, No. 4, 1954, pp. 217-229.
48. Gerard, G., HANDBOOK OF STRUCTURAL STABILITY, NACA Technical Note 3781-3785, National Advisory Committee for Aeronautics, Cleveland, Ohio, 1957.
49. D'Amato, R., STATIC POSTFAILURE STRUCTURE CHARACTERISTICS, WADC Technical Report 59-112, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1959.
50. Chitner, A. H., THIN WALLED STRUCTURES, John Wiley, New York, 1967.
51. Sechler, E. E., and Dunn, L. G., AIRPLANE STRUCTURAL ANALYSIS AND DESIGN, Dover, New York, 1963.

the stiffened panel, the changes in local failure pattern during the postfailure stage, and the effect of geometrical imperfections caused by manufacturing and/or damage. In light of the test results and correlation with analysis, these effects are probably not significant for this type of substructure.

7.4.2 Substructure Test Results

To verify the analytical results, experimental data were obtained during the same study by testing twelve specimens, representative of typical helicopter lower fuselage structure, under the following conditions: static load, dynamic impact (≤ 30 ft/sec), four-edge support, two-edge support, skin web thickness from 0.025 in. to 0.064 in., number of angle stiffeners from 12 to 40, and specimen depth of 6.125 in. and 12.125 in. The test specimens were 46 in. long, included five bays, and were 18 in. wide with a side panel at each side. Each specimen was supported in its normal manner. All comparative static and dynamic tests on similar specimens were performed at equal energy input levels. Instrumentation consisted of several strain gages to measure compression and bending, a linear variable differential transducer to measure deflection, accelerometers mounted on the impact head and load cells installed between the test specimen support and the ground for the dynamic tests.

The test program results yielded valuable information for future consideration. For example, for these types of structural elements, static testing to determine load-deflection characteristics should yield sufficiently accurate results when compared to dynamic test results, but in a more economical manner. A static test can provide the desired information with regard to shape of the load-deflection curve, peak failure load (in the program described herein the dynamically obtained failure loads are between 9 and 24 percent higher than the loads measured in static testing and the loads from predicted static calculations, respectively), deflection at which failure load occurs, and energy-absorption capability of the structure.

The test results show that during a dynamic test the amount of springback from the maximum deflected value is immediately evident. After a static test the structure will relax slowly (up to several days) to its permanently deformed position. The springback in the dynamic test was as high as 40 percent of the maximum deflected value for a test performed with an impact velocity of 30 ft/sec. This observation could be of consequence in areas such as doors, where distortion of structure affects occupant egress after a crash.

7.4.3 Correlation of Test and Analysis Results

Comparison of test and analytical data showed reasonable agreement with respect to peak failure load and energy-absorption capability, particularly for the dynamic tests in which load cells are installed. Figure 77 shows a comparison of the analytically predicted load-deflection curves with test data and illustrates good correlation with regard to shape of the curve as well as peak load and energy absorption. As can be noted in Figure 77, the typical response of the type of structure tested in this study is a relatively sharp load buildup in the elastic region up to the peak failure load (at approximately 0.35 in. or less of deflection). After failure, the load decreases at a rate less rapid than the initial buildup until the deflection reaches approximately 0.75 to 1.0 in. Thereafter, the load decreases gradually until the structure being crushed is confined and once again stiffens. This region, wherein confined crushing takes place, is very significant because the stiffness at this point can greatly influence the response of the upper masses (the transmission and engine of the test vehicle). The initial peak failure load, while of a substantial level, is of short duration and as such may not greatly influence the upper mass response.

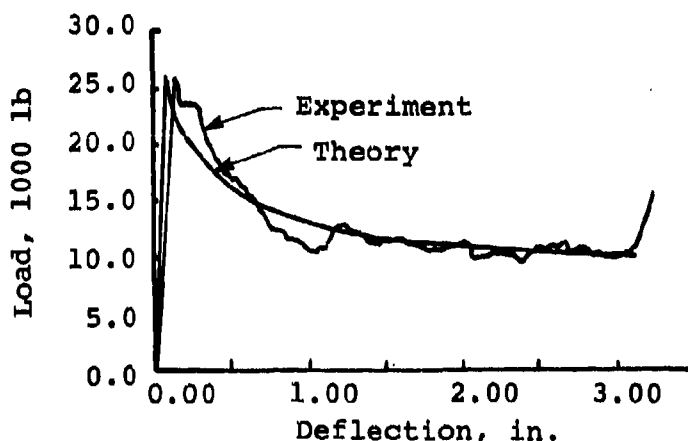


Figure 77. Predicted-versus-test load-deflection curves for a representative specimen. (From Reference 46)

Figure 78 shows a comparison of test and analytical results for three groups of specimens. A detailed discussion of the correlation between analysis and test is presented in Reference 46. The energy absorption was predicted within 8 percent of the test results for three of the five specimens that were

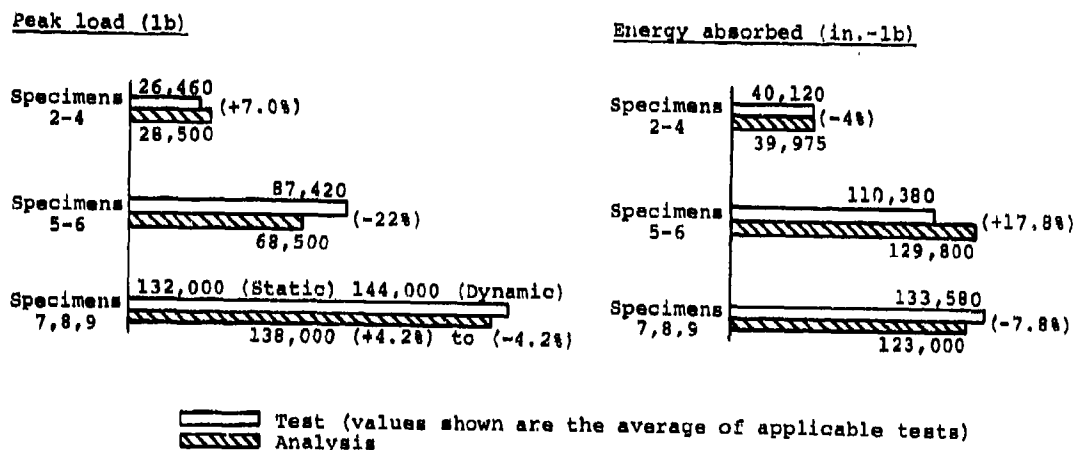


Figure 78. Comparison of test and analysis results for "like" specimens.

tested dynamically with load cells installed. Correspondingly, the load was predicted within 7 percent. For the other two specimens, the data are based on accelerometer time histories rather than load cells. These traces contain considerable noise, which makes it difficult to interpret the test data.

The results of the correlation studies indicate that it is practical to use relatively simple techniques to determine load-deflection characteristics of multiweb, angle-stiffened panels, typical of the lower fuselage of an existing utility model helicopter. The overall crushing behavior of the substructure can be predicted within reasonable accuracy although the failure mode of each individual stiffener cannot consistently be accounted for. The analytical procedure described herein is capable of determining satisfactorily the two most significant parameters for crushable structure, i.e., peak failure load and energy-absorption capability. The approach, as developed in this study, has limitations with regard to accurately predicting the deflection at which failure occurs and the deflections at which postfailure stiffening is encountered. Although the predicted failure deflection is a consistently lower value than that obtained from tests, it represents an extremely small percentage of the total crushing energy, to the extent that it is not significant as long as the peak failure load and load-deflection characteristics are properly defined. The analytical assumptions regarding the mode of failure in the postfailure region and the hinge formation at failure are considered valid in view of the test results. For example, although test results indicate that failures can occur in both

the asymmetrical and symmetrical modes, the predicted energy-absorption capability of the structure, which considers only the symmetrical mode, is still very close to test results. Thus, the assumption of a symmetrical failure is, on the average, reasonable.

7.4.4 Example of Analysis for Vertical Impact

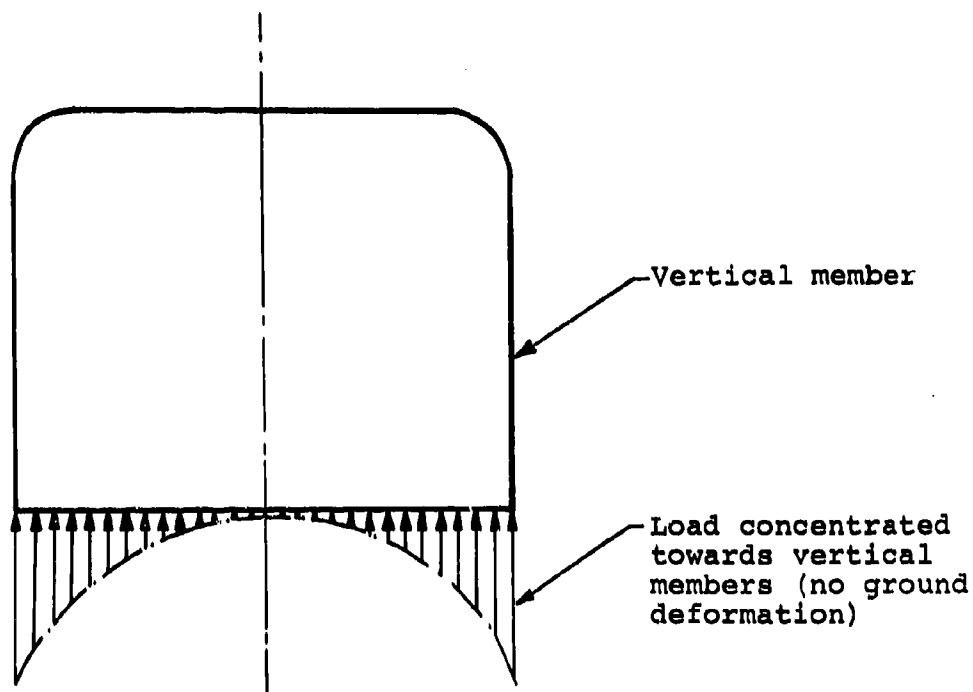
The example given here is an analysis to predict major structural collapse for the crash of a medium cargo helicopter at a velocity representative of a 95th-percentile potentially survivable accident. This analysis was performed for the full-scale crash test of a cargo helicopter conducted on 6 March 1975 at the NASA Langley Research Center's Impact Dynamics Research Facility, Hampton, Virginia (Reference 52). The impact velocity components selected for the test were 40 and 30 ft/sec for vertical and longitudinal velocities, respectively, producing a 50-ft/sec resultant velocity.

The structural response and failure modes in a crash environment are not easy to predict using static analytical techniques. Initially, the underfloor structure absorbs energy by crushing, but the amount of energy absorbed is dependent upon the type of ground impacted. Soft ground can displace and provide a reasonably uniform loading on the base of the structure, but a rigid ground plane results in more direct loading of the frame members. This difference is illustrated in Figure 79, where possible types of load distribution are shown for soft and hard ground impact planes.

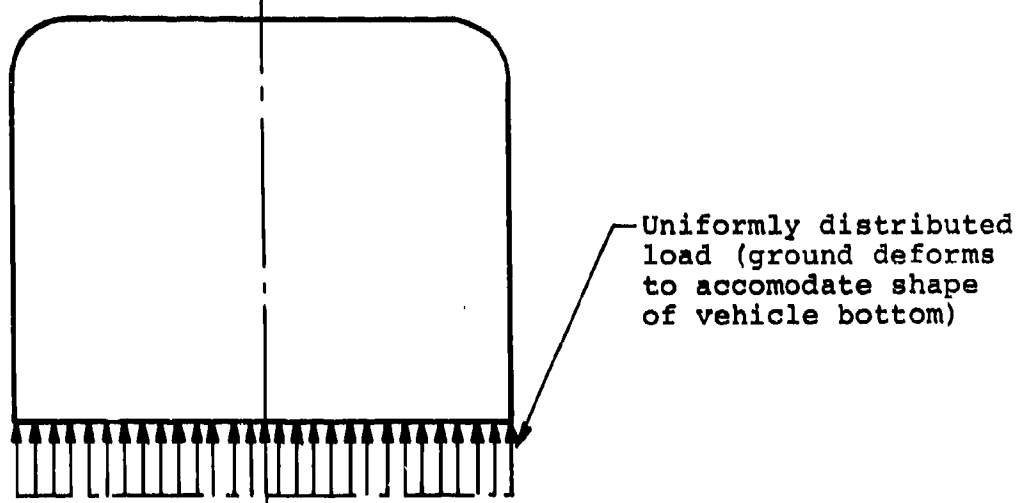
The helicopter occupants, assuming an otherwise survivable environment, must be protected from injury due to the collapse of basic structure or the penetration of occupied areas by large mass items. The following calculations demonstrate a semiempirical method of predicting overall reduction in the height of occupied areas.

Data obtained from past major accidents, either actual values or estimated impact conditions, have been used in conjunction with deformation information to obtain a simplified relationship between the static and dynamic load-carrying capabilities for structural elements. The case considered here involved the absorption of 135,000 ft-lb of energy with a 42.2-in. structural collapse.

52. 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.



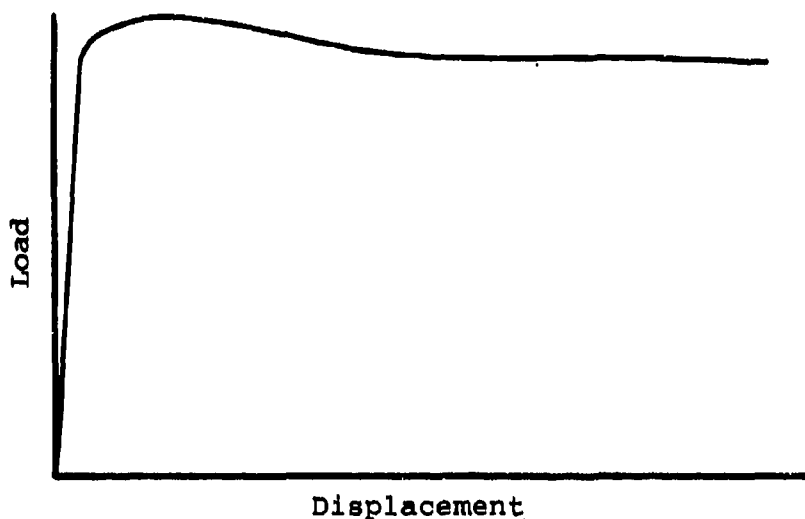
Load distribution for impact on hard ground, concrete



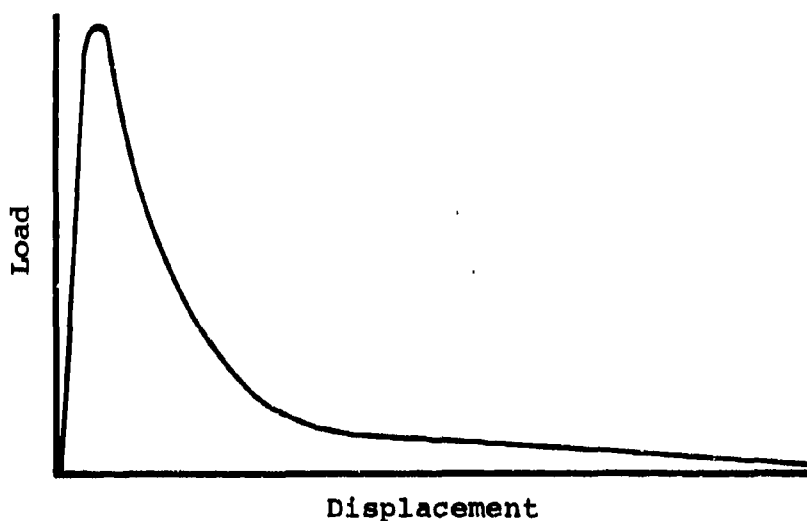
Load distribution for impact on soft ground, wet sod

Figure 79. Types of load distribution acting on helicopter structure for impact with soft and hard surfaces.

The general nature of the energy-absorbing characteristics of an element of airframe structure can be of the form shown in Figure 80. When stability is not the limiting criterion, the curve in Figure 80(a) is applicable; Figure 80(b) represents the response for stability-limited load capability.



(a) Load capability not limited by stability



(b) Load capability limited by stability

Figure 80. Typical load-displacement characteristics for airframe structure.

In severe impact conditions, stability is the limiting criterion for many structural elements of interest. Figure 81 shows simplified load-deflection characteristics for static load application to a stringer-skin combination subjected to compressive loading (Reference 53).

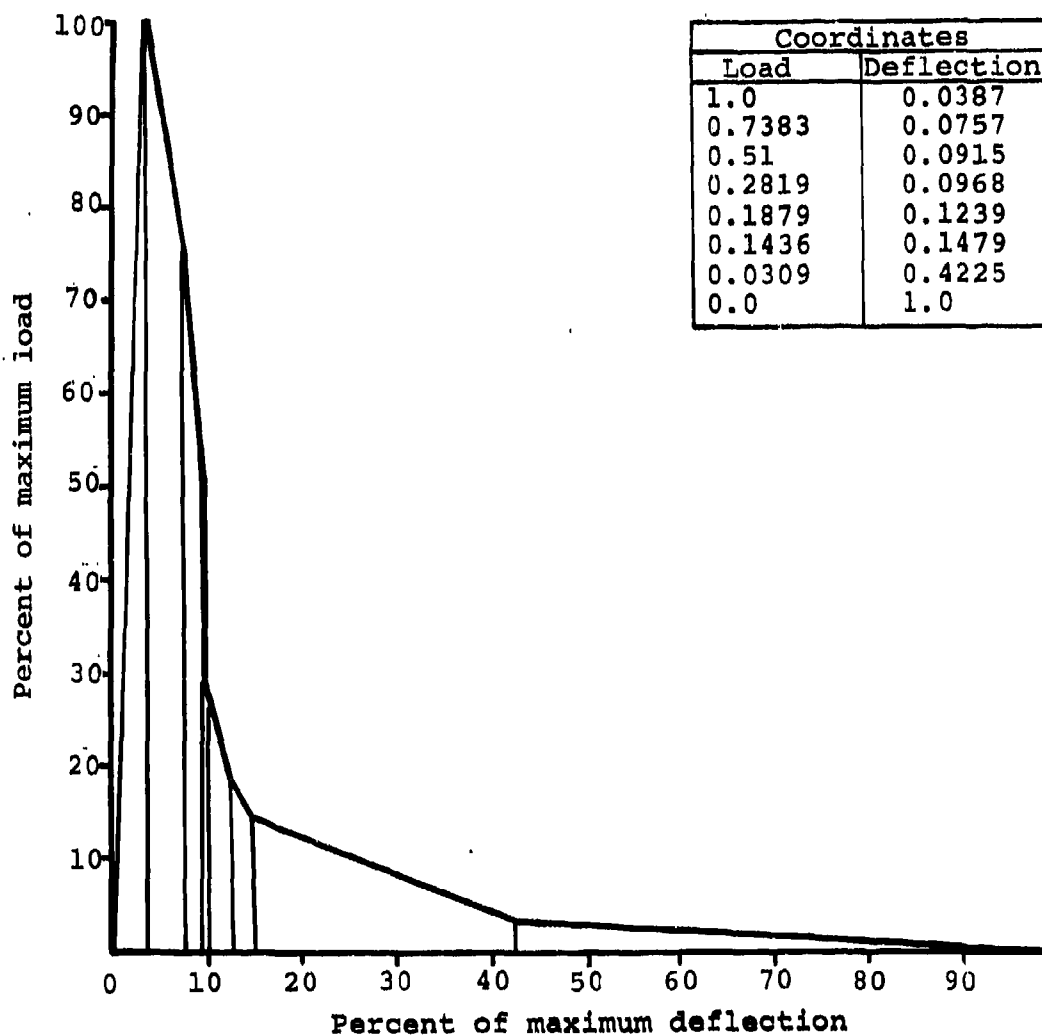


Figure 81. Simplified load-deflection characteristics for a statically loaded stringer skin combination. (From Reference 53)

53. Greer, D. L., Held, T. L., and Weber, J. D., DESIGN STUDY AND MODEL STRUCTURES TEST PROGRAM TO IMPROVE FUSELAGE CRASHWORTHINESS, Convair, Division of General Dynamics Corporation; FAA DS-67-20, Federal Aviation Administration, Washington, D. C., October 1967, AD 666816.

The area under a load-deflection curve determines the energy-absorption capability for the structure under consideration.

The basic section of a typical side frame member is shown in Figure 82. The crippling stress is computed as follows:

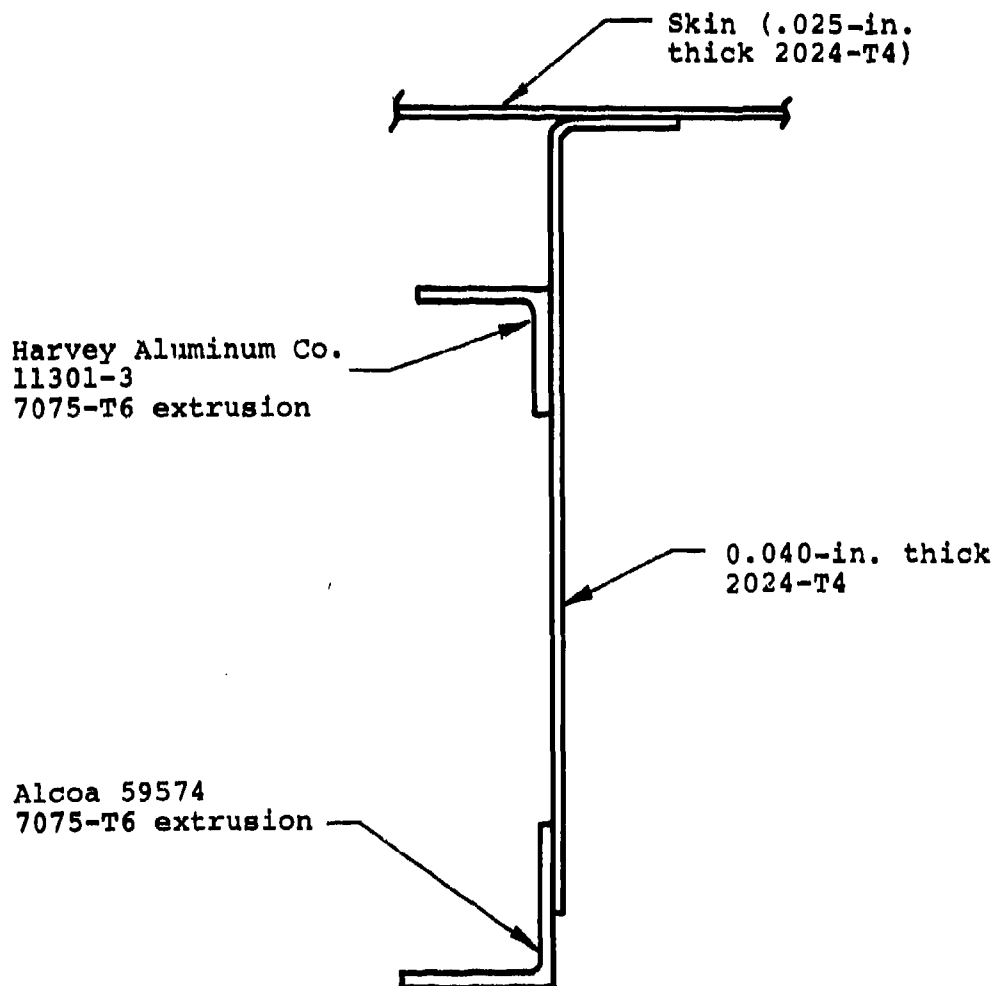


Figure 82. Typical frame section of side element of a medium cargo helicopter center fuselage.

For Harvey Aluminum Company extrusion 11301-3,

$$\frac{A}{\Sigma t^2} = \frac{0.210}{0.094^2 + 0.125^2} = 8.59$$

$$F_{CC} = 62,000 \text{ lb/in.}^2 \quad (\text{From Figure 83})$$

For Alcoa 59574,

$$\frac{A}{\Sigma t^2} = \frac{0.289}{0.188^2 + 0.125^2} = 5.67$$

$$F_{CC} = 70,000 \text{ lb/in.}^2$$

For the flanged web,

$$\frac{A}{gt^2} = \frac{(1.5)(0.040)}{(2)(0.040^2)} = 18.8$$

$$F_{CC} = 19,000 \text{ lb/in.}^2 \quad (\text{From Figure 84})$$

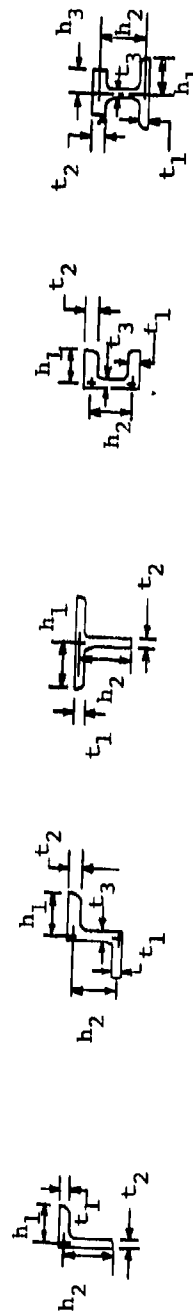
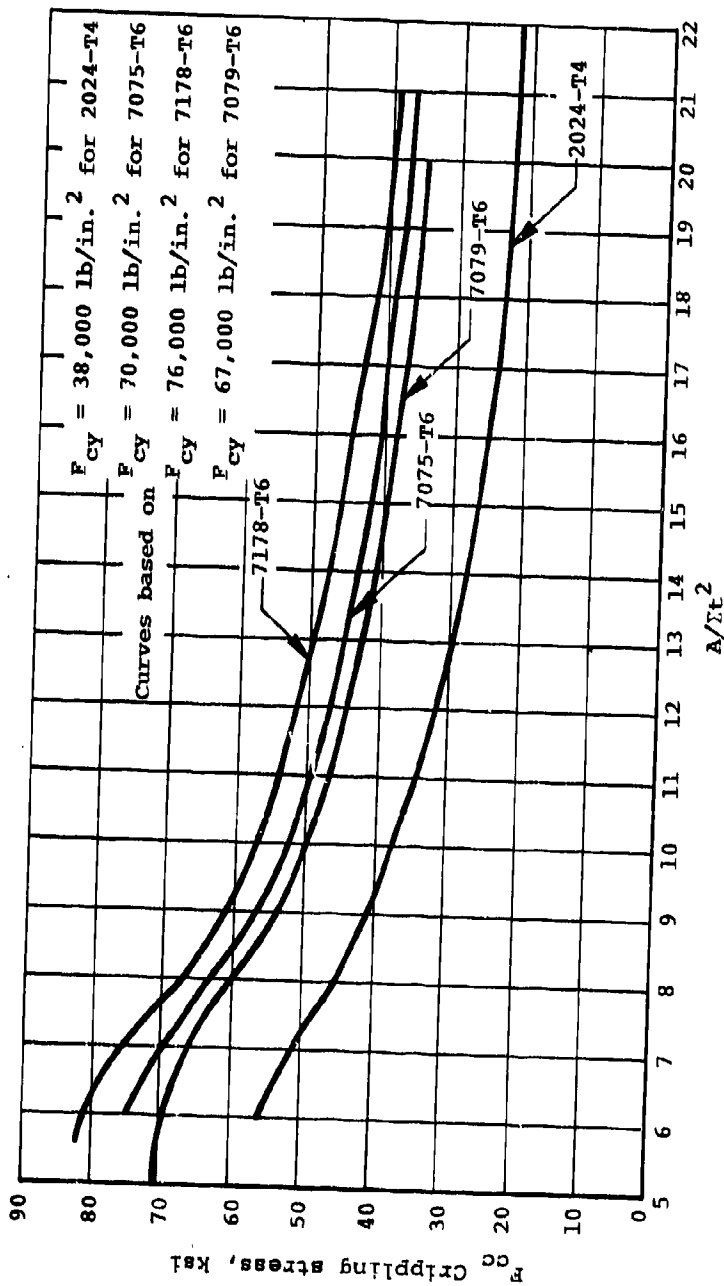
The total compressive capability of the frame element is computed as follows:

$$\text{Capability of stringer elements} = (62,000)(0.210)$$

$$+ (70,000)(0.289)$$

$$+ (19,000)(1.5)(0.04)$$

$$= 34,390 \text{ lb} \quad (\text{From Figure 85})$$



$A_1 = h_1 t_1$, etc.

For section: $F_{cc} = \frac{\sum (F_{cc}) \cdot A_i}{\sum A}$

Figure 83. Crippling allowables for typical aluminum alloy extrusions.

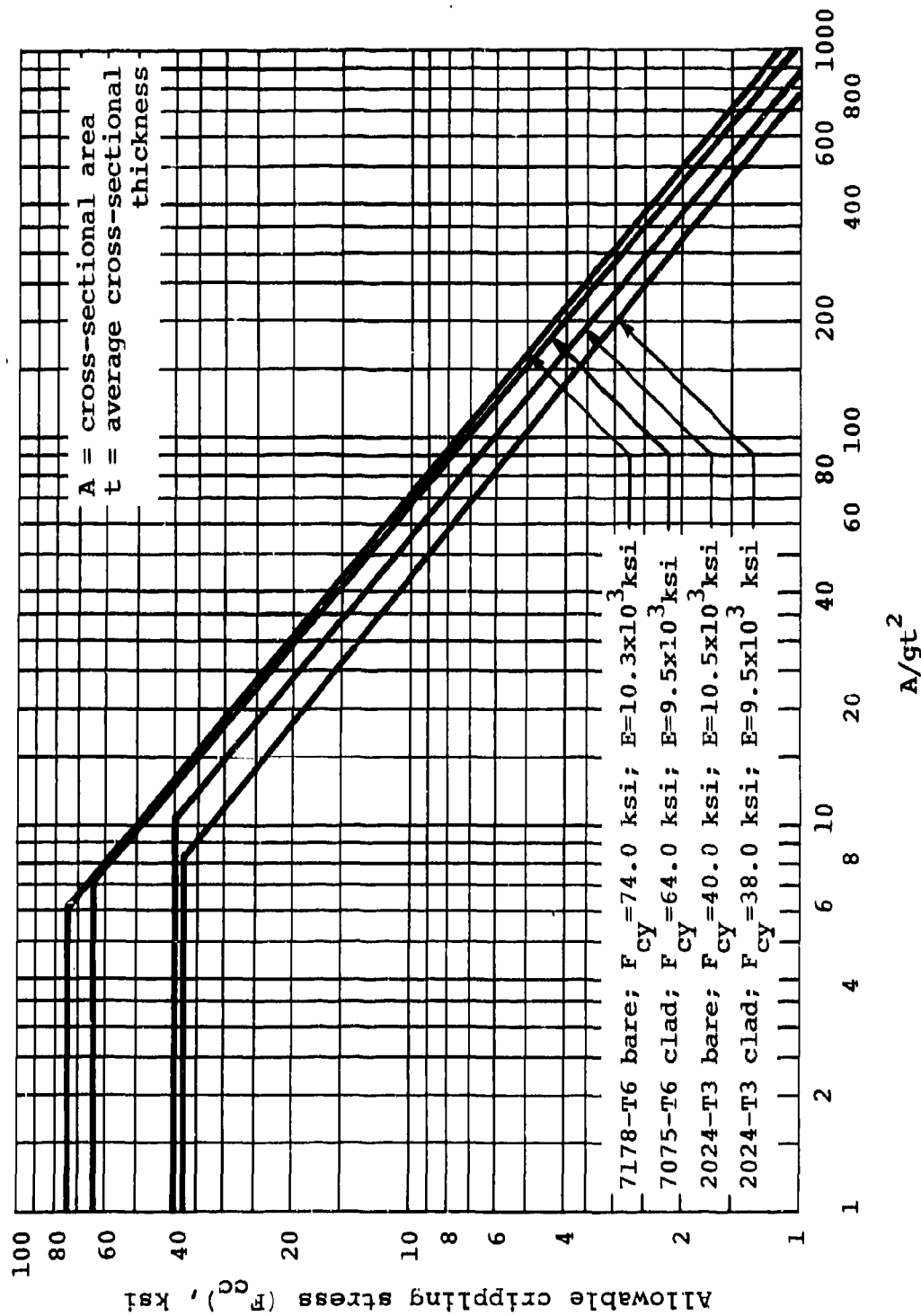


Figure 84. Crippling allowables for aluminum alloy formed sections other than simple zees and channels.

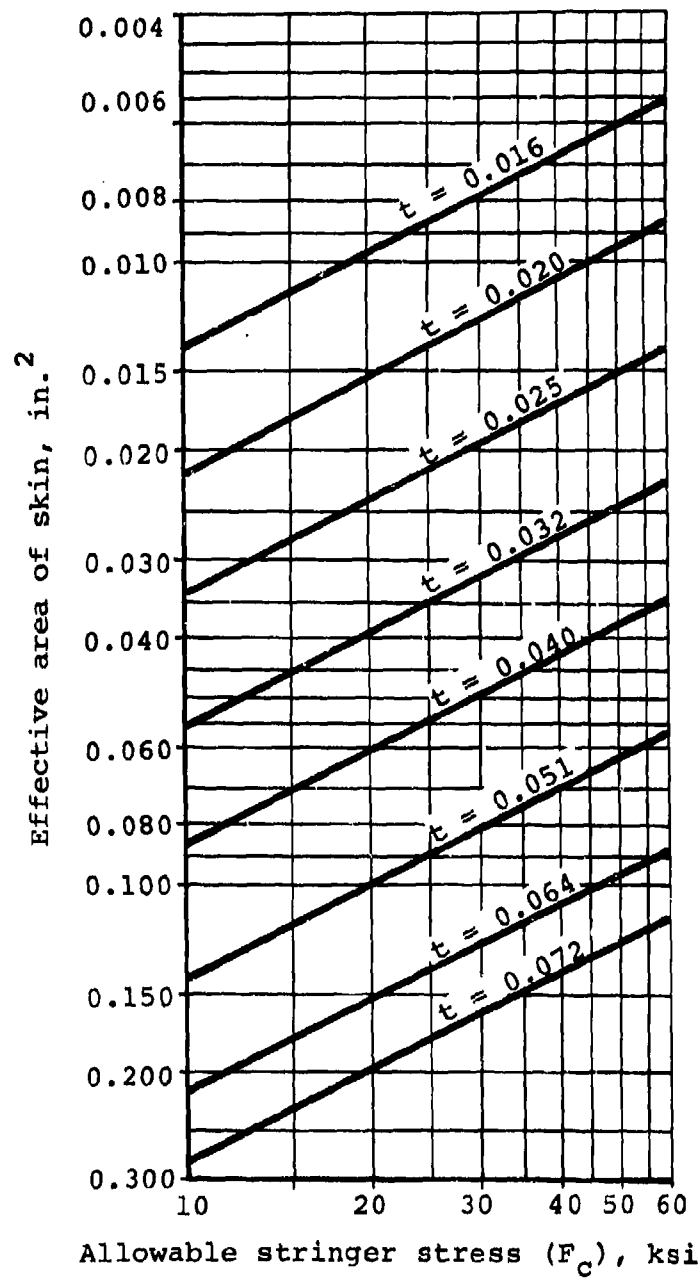


Figure 85. Effective area of skin for aluminum alloy stringer-skin combinations.

$$\begin{aligned}
\text{Capability of adjacent skin} &= (37,000)(0.034) \\
&+ (37,000)(0.032) \\
&+ (19,000)(0.024) \\
&= 2,898 \text{ lb}
\end{aligned}$$

Total compressive capability = 37,288 lb

This value is for one section through a typical frame member. for a symmetrical fuselage section, the total compressive capability is twice this value, or 74,576 lb.

From the photographs of helicopter crashes under known impact conditions, the average crushing of the typical frame section was 42.2 in. for the impact velocity considered.

Using this load value and total displacement in conjunction with the typical stringer-skin compression static characteristic shown in Figure 81, an estimation can be made for the correction required for dynamic energy-absorption capability. Using Figure 81 data, the energy absorbed is given by:

$$\begin{aligned}
E_A &= P y \Sigma A \\
&= (74576) \left(\frac{42}{12} \right) \Sigma A \quad (59)
\end{aligned}$$

where A = incremental area under curve in Figure 81

$$\begin{aligned}
&= (74576)(3.5) \left[(1.0) \left(\frac{0.0387}{2} \right) + \left(\frac{1.0 + 0.7383}{2} \right) 0.037 \right. \\
&\quad + \left(\frac{0.7383 + 0.5100}{2} \right) 0.0158 + \left(\frac{0.51 + 0.2819}{2} \right) 0.0053 \\
&\quad + \left(\frac{0.2819 + 0.1879}{2} \right) 0.0271 + \left(\frac{0.1879 + 0.1436}{2} \right) 0.0240 \\
&\quad \left. + \left(\frac{0.1436 + 0.0309}{2} \right) 0.2746 + (0.0309) \left(\frac{0.5775}{2} \right) \right]
\end{aligned}$$

$$\begin{aligned}
&= 261,016 (0.01935 + 0.03216 + 0.00986 + 0.00210 \\
&\quad + 0.00637 + 0.00398 + 0.02396 + 0.00892) \\
&= \underline{27,850 \text{ ft-lb (STATIC)}}
\end{aligned}$$

This result shows that the static collapse energy computation does not agree with the empirical value of 135,000 ft-lb.

Assuming rectangular characteristics would produce an overly optimistic energy-absorption value of 261,016 ft-lb. An assumption of triangular characteristics yields an energy-absorption capability of 130,508 ft-lb, and a comparison of this value with the actual kinetic energy of 135,000 ft-lb yields an error of only 3.34 percent, which is well within an acceptable range for such an analysis. Figure 86 shows the differences between the static and dynamic energy-absorption capabilities of a typical structural element; the result is based on actual test and accident data.

7.4.5 Example of Analysis for Longitudinal Impact

In the previous example, structural resistance to loading was assumed to be in the vertical plane of the helicopter. Additional structural crashworthiness requirements for the primarily longitudinal-lateral impacts are specified in MIL-STD-1290(AV) (Reference 1) and Section 5.3.1 of this document.

A similar method of analysis can be employed after defining the primary structural members assigned to resist the applied loading and after computing load-carrying limitations and potential stroking distances.

As a further example, the nose section of a developmental utility helicopter will be used. In the initial design definition phase, the requirements of MIL-STD-1290(AV) were specified for both the 20- and 40-ft/sec longitudinal impact conditions (see Table 3, Section 5.1). These requirements delineated the maximum acceptable intrusions into occupied space for the given impact velocities for longitudinal impacts into a vertical abutment. The basic design philosophy is that the kinetic energy involved in a 20-ft/sec crash impact velocity is absorbed into the 25 in. of structure forward of the rudder pedals. For a 40-ft/sec crash, energy is absorbed by the structure forward of Station 78; the area aft of Station 78 constitutes the cabin area.

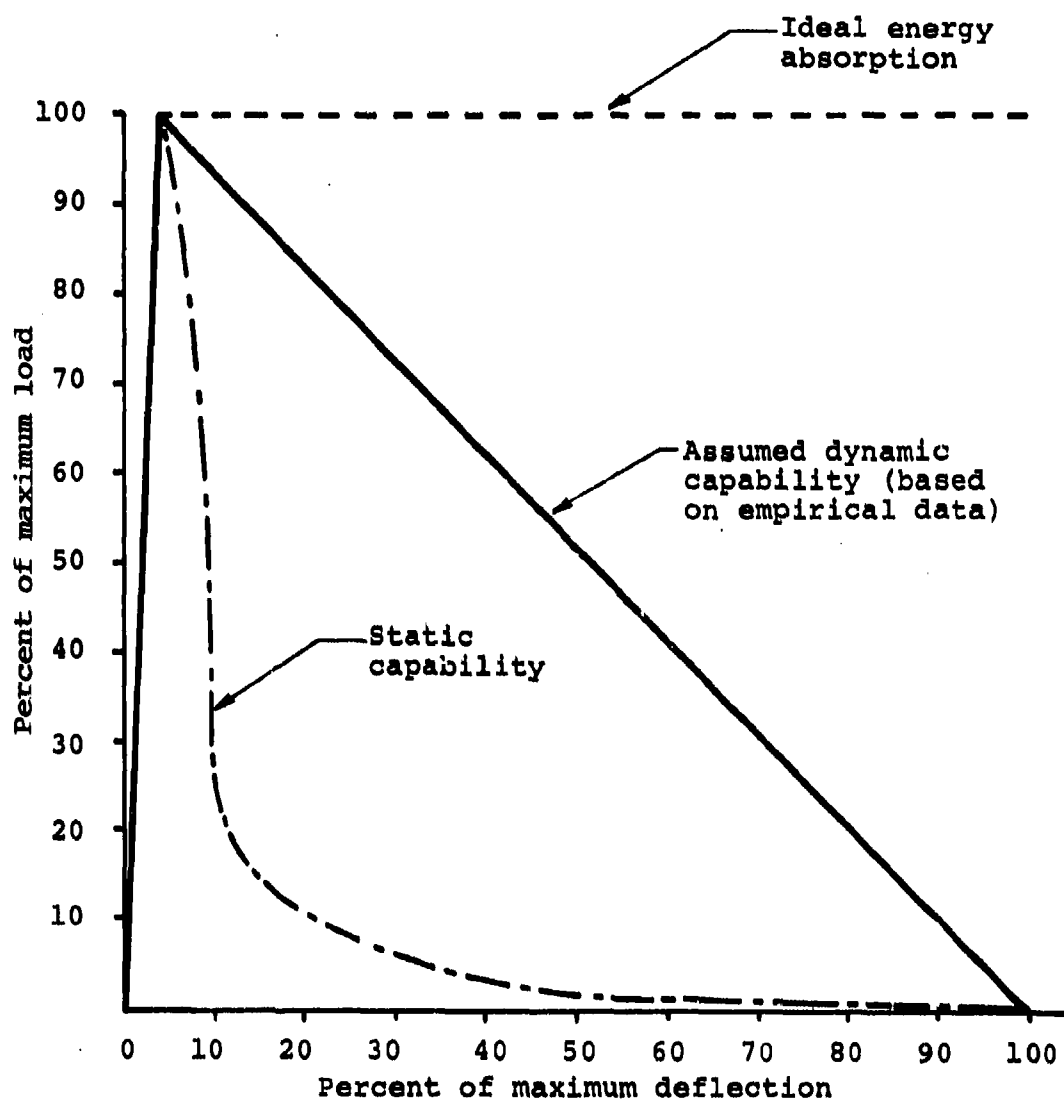


Figure 86. Estimated dynamic energy-absorption capability of typical fuselage structure.

7.4.5.1 20-ft/sec Impact: Figure 87 shows the basic structural elements to be considered; a summary of the analyses is as follows:

Longitudinal impact velocity changes = 20 ft/sec

Basic structural weight = 15,587 lb

$$\begin{aligned} \text{Kinetic energy to be absorbed} &= \frac{1}{2} m \dot{x}^2 \\ &= \left(\frac{1}{2}\right) \left(\frac{15587}{32.2}\right) (20^2) \\ &= \underline{96,813 \text{ ft-lb}} \end{aligned}$$

Figure 87 shows the basic structural sections that resist longitudinal loading. It should be noted in Figure 87 that these members are stabilized by formers located at approximately a 6-in. pitch.

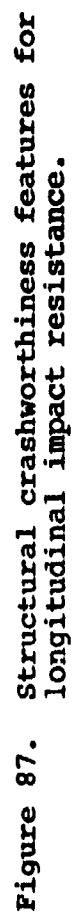
Using standard methodology for computing the crushing strength of each section yields:

Crushing strength of upper cap, BL 14.5 (left and right sides) = 25,569 lb

Crushing strength of lower cap, BL 14.5 (left and right sides) = 17,919 lb

NOTE: When these values are computed, the amount of effective skin actively participating is dependent on whether interrivet buckling occurs. If interrivet buckling is considered likely, the effective width of skin must be reduced as follows:

$$W_{\text{corrected}} = W_{\text{eff}} \cdot \frac{F_{1r}}{F_{cs}}$$



Where F_{ir} = interrivet buckling stress

F_{cs} = crippling stress of stringer.

Summation of the strength capabilities of the four longitudinal sections yields:

Total crushing strength, Station 13 to 38

$$= 2 (25568 + 17919)$$

$$= \underline{86,976 \text{ lb}}$$

Energy-absorbing capability

$$= 0.5 \times \frac{25}{12} \times 86796$$

$$= \underline{90,600 \text{ ft-lb}}$$

Equivalent Impact Velocity = 19.4 ft/sec

This value, within 3 percent of the desired 20-ft/sec capability, is acceptable when considering the assumptions made and the use of an empirical dynamic factor of 0.5.

7.4.5.2 40-ft/sec Impact: Similar computations are used for this analysis, but additional structure is involved. After the section from Station 13 to 38 has collapsed, members from Station 38 to 78 pick up the loads. The members involved are indicated in Figure 87, but the computations are not given since the process is the same as for the 20-ft/sec case.

7.4.6 Lateral Impact

Once again, resisting structure is identified and energy-absorption capability computed for the frame member sections in the crown and floor that resist volume reduction due to loading in the lateral direction. Summation of the buckling strengths, as demonstrated in Section 7.4.4, is used to determine volume reduction for the specified impact velocity to conform with the MIL-STD-1290(AV) requirements (Reference 1) summarized in Section 5.3.1.3.

7.4.7 Rollover

Postimpact rollover design requirements for load applications and for structural areas that must withstand that loading are specified in MIL-STD-1290(AV) and summarized in Section 5.3.1.4. Basically, a 4W requirement is defined; this can be satisfied by normal static structural analysis techniques.

Since a rollover maneuver is a secondary effect occurring after initial impact, an energy-absorbing analysis is unnecessary. The 4W, postimpact static analysis is adequate for substantiating the rollover performance of the helicopter because normally the primary impact will absorb most of the energy.

7.5 STRUCTURAL CRASHWORTHINESS SIMULATION COMPUTER PROGRAMS

Crashworthiness analysis as a scientific discipline is in a transitional stage between pure research and support of design functions. A number of digital computer programs for analysis of vehicle structures in a crash environment have been developed by the research community, and several of these, generally the simpler, have begun to find use in preliminary design. The more significant programs have been critically reviewed recently by several authors, including K. J. Saczalski (Reference 54), Hayduk, et al. (Reference 55), I. K. McIvor (Reference 56), and M. P. Kamat (Reference 57). The programs vary widely in their modeling characterization and mathematical

54. Saczalski, K. J., STRUCTURAL PROBLEMS ASSOCIATED WITH THE PREDICTION OF VEHICLE CRASHWORTHINESS, in Surveys of Research in Transportation Technology, AMD-Vol. 5, presented at ASME Winter Annual Meeting, American Society of Mechanical Engineers, 11-15 November 1973.
55. Hayduk, R. J., et al., NONLINEAR STRUCTURAL CRASH DYNAMICS ANALYSES, SAE Paper No. 790588, presented at Business Aircraft Meeting, Society of Automotive Engineers, Inc., Wichita, Kansas, 1979.
56. McIvor, I. K., MODELING, SIMULATION, AND VERIFICATION OF IMPACT DYNAMICS, Volume I, EXECUTIVE REPORT, Highway Safety Research Institute and Department of Applied Mechanics, University of Michigan, Ann Arbor, Michigan, October 1973.
57. Kamat, M. P., SURVEY OF COMPUTER PROGRAMS FOR PREDICTION OF CRASH RESPONSE AND OF ITS EXPERIMENTAL VALIDATION, in Measurement and Prediction of Structural and Biodynamic Crash-Impact Response, Winter Meeting, ASME, American Society of Mechanical Engineers, New York, 5-10 December 1976, pp. 33-48.

treatment of the model equations. They are easily grouped, however, into five main classes, namely:

1. Simplified spring-mass models.
2. Generalized spring-mass models.
3. Hybrid models.
4. Frame-type models.
5. Finite element models.

Simplified spring-mass models represent the vehicle by one to four lumped masses and up to eight nonlinear spring elements. Generalized spring-mass models are similar to the above except that they generally treat a larger number of masses and spring elements, which are typically more generally defined, thus lending some flexibility to the modeling process. Cited examples of spring-mass models are those of Sato (Reference 58), Emori (Reference 59), Tani and Emori (Reference 60), Miura and Kawamuro (Reference 61), all in the simplified category, and

58. Sato, T. B., et al., DYNAMICAL CONSIDERATIONS ON AUTOMOBILE COLLISION, Journal of the Society of Automobile Engineers of Japan, Vol. 20, No. 5 (1966) and Vol. 21, No. 9 (1967).
59. Emori, R. I., ANALYTICAL APPROACH TO AUTOMOBILE COLLISIONS, SAE Paper No. 680016, presented at Automotive Engineering Congress, Society of Automotive Engineers, Inc., Detroit, Michigan, January 1968.
60. Tani, M., and Emori, R. I., A STUDY IN AUTOMOBILE CRASH-WORTHINESS, SAE Paper No. 700175, presented at Automotive Engineering Congress, Society of Automotive Engineers, Inc., Detroit, Michigan, January 1970.
61. Miura, N. and Kawamura, K., AN ANALYSIS OF DEFORMATION MECHANISM IN HEAD-ON COLLISION, SAE Paper No. 680484, presented at Society of Automotive Engineers Mid-Year Meeting, Society of Automotive Engineers, Inc., Detroit, Michigan, May 1968.

those of Gatlin, et al. (Reference 62) and the Battelle Columbus Laboratories (Reference 63) in the generalized class.

Hybrid models are those requiring experimentally determined component behavior data as program inputs. A program developed by M. M. Kamal at the General Motors Research Laboratory is considered typical of this class (Reference 64). It uses three lumped masses and eight nonlinear spring elements to simulate unidirectional, frontal, or barrier impacts of automobile vehicles.

Frame-type models employ beam elements, instead of spring elements, and lumped or rigid body masses at the intersections (nodes) of the beam elements in either two-dimensional or three-dimensional configurations. Typical of this class are the crash simulation programs developed by researchers at Lockheed-California (Reference 65), Calspan (Reference 66),

62. Gatlin, C. I., Goebel, D. E., and Larsen, S. E., ANALYSIS OF HELICOPTER STRUCTURAL CRASHWORTHINESS, Volume I. MATHEMATICAL SIMULATION AND EXPERIMENTAL VERIFICATION OF HELICOPTER CRASHWORTHINESS, Dynamic Science, Division of Marshall Industries; USAAVLABS Technical Report 70-71A, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1971, AD 880680.
63. Herridge, J. T., and Mitchell, R. K., DEVELOPMENT OF A COMPUTER SIMULATION PROGRAM FOR COLLINEAR CAR/CAR AND CAR/BARRIER COLLISIONS, Battelle Columbus Laboratories; Report No. DOT-HS-800-64S, U. S. Department of Transportation, Washington, D. C., January 1972.
64. Kamal, M. M., ANALYSIS AND SIMULATION OF VEHICLE TO BARRIER IMPACT, SAE Paper No. 700414, presented at the International Automobile Safety Conference, Society of Automotive Engineers, Inc., Detroit, Michigan, May 1970.
65. Wittlin, G., and Gamon, M. A., EXPERIMENTAL PROGRAM FOR THE DEVELOPMENT OF IMPROVED HELICOPTER STRUCTURAL CRASHWORTHINESS ANALYTICAL AND DESIGN TECHNIQUES, Volumes I and II, Lockheed-California Company; USAAMRDL Technical Reports 72-72A and 72-72B, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1973, AD 764985 and AD 764986.
66. Shieh, R. C., BASIC RESEARCH IN CRASHWORTHINESS II - LARGE DEFLECTION DYNAMIC ANALYSIS OF PLANE ELASTOPLASTIC FRAME STRUCTURES, Calspan Corporation; Report No. DOT-HS-800-781, U. S. Department of Transportation, Washington, D. C., December 1972.

Philco-Ford (Reference 67), and Chrysler Corporation (Reference 68). Major differences among these lie primarily in the conceptual representations of the highly nonlinear behavior of the beam elements, and in the numerical methods used in the time-history solutions. The Calspan program limits application to two-dimensional structures, whereas the other three are capable of predicting three-dimensional response.

The finite element approach represents an attempt to make up for the limitations inherent in the lumped-parameter analyses, by employing more formal approximation techniques in the discretization of the structure and a greater reliance on more fundamental structural representations and properties. The limitations of this approach are found in the inherent tendency toward more complicated and expensive computations and the difficulties found in modeling the extensively complex phenomena associated with the crash environment. Such phenomena include large deflections and rotations in the deformed structure, regions of intense curvature (wrinkling), material strain rate effects, and interference and contact among structural components during the response. These procedures are not totally free of a reliance on testing and analytical judgment and, in fact, can be viewed as a somewhat more formal lumped-parameter system and used in connection with the more empirical procedure in hybrid, combination models.

A variety of finite element analyses directed toward the dynamic analysis of vehicle (primarily automotive) structures have been reported previously. However, most have been limited to beam-type elements and have, therefore, lacked the advantages of the general-purpose elastic analysis programs widely used in industry today. These models have been grouped with the frame-type models above. The response of vehicle structures under crash loadings is a complex process primarily involving:

67. Young, J. W., "CRASH": A COMPUTER SIMULATION OF NONLINEAR TRANSIENT RESPONSE OF STRUCTURES, Philco-Ford, Subsidiary of the Ford Motor Company; Report No. DOT-HS-09-1-125B, U. S. Department of Transportation, Washington, D. C., March 1972.
68. Thompson, J. E., VEHICLE CRUSH PREDICTION USING FINITE-ELEMENT TECHNIQUES, Chrysler Corporation; SAE Paper No. 780157, Society of Automotive Engineers, New York, January 1973.

- Transient, dynamic behavior.
- Complicated framework and shell assemblages.
- Large deflections and rotations.
- Extensive plastic deformations.

Most attempts at a complete, formal analysis of this process have been only partly successful due to a variety of limitations which, in particular instances, have included inadequacies in element formulations, material representations, or solution procedures. The field of nonlinear finite element analysis is currently an extremely active area of research with an extensive, related literature and a variety of methods and approaches. Consequently, a complete review of the field as background for this document is not attempted. Instead, major features of two finite element programs that have been specifically tailored to the class of problems inherent in vehicle crash response and employ or extend current avenues in finite element analysis that seem best suited to such problems are discussed. These are Grumman's DYCAST (Reference 69) and IITRI's WRECKER (Reference 70).

Reference 55 presents the results of three nonlinear computer programs, KRASH, ACTION (Reference 71), and DYCAST, used to analyze the dynamic response of a twin-engine, low-wing airplane section subjected to a 27.5-ft/sec vertical impact velocity crash condition. The three distinct analysis techniques for nonlinear dynamic response of aircraft structures are

69. Winter, R., Pifko, A. B., and Armen, H., Jr., CRASH SIMULATION OF SKIN-FRAME STRUCTURES USING A FINITE ELEMENT CODE, SAE Paper No. 770484, presented at Business Aircraft Meeting, Society of Automotive Engineers, Inc., New York, March 29 - April 1, 1977.
70. Yeung, K. S. and Welch, R. E., REFINEMENT OF FINITE ELEMENT ANALYSIS OF AUTOMOBILE STRUCTURES UNDER CRASH LOADING, Volume II, IIT Research Institute; Report No. DOT-HS-803-466, U. S. Department of Transportation, Washington, D. C., October 1977, PB 287589.
71. Winter, R., Pifko, A. B., and Cronkhite, J. D., CRASH SIMULATION OF COMPOSITE AND ALUMINUM HELICOPTER FUSELAGES USING A FINITE ELEMENT PROGRAM, AIAA Paper 79-0781, presented at AIAA/ASME/ASCE/AHS 20th Structures, Structural Dynamics, and Materials Conference, St. Louis, Missouri, 4-6 April 1979.

briefly examined and compared versus each other and the experimental data. The report contains brief descriptions of the three computer programs, the respective aircraft section mathematical models, pertinent data from the test performed at NASA Langley, and a comparison of the analysis versus test results. Cost and accuracy comparisons among the three analyses are made to illustrate the possible uses of the different nonlinear programs and their future potential.

The remainder of this chapter presents the structural models of greatest potential use in aircraft structural crashworthiness.

7.5.1 Program KRASH

The computer program KRASH was originally developed by Lockheed-California Company under U. S. Army auspices to analyze the dynamic response of helicopters subjected to a multidirectional crash environment (Reference 65). Subsequent development of KRASH was sponsored by the Federal Aviation Administration (FAA). The FAA's goal was to acquire an analytical tool with minimal additional development that could assist in the performance of structural crash dynamic analyses of general aviation fixed-wing airplanes. The general aviation version of KRASH has been exercised on four full-scale single-engine, high-wing, aircraft crash tests performed at NASA Langley's Impact Dynamics Research Facility.

Program KRASH is a digital computer program which predicts the structural response of vehicles to multidirectional crash environments. The program computes the time histories of N interconnected masses, each allowed six degrees of freedom, defined by inertial coordinates X_i , Y_i , Z_i and Eulerian angles ϕ_i , θ_i , ψ_i , where $i = 1, 2, \dots, N$. Euler's equations of motion are written for each mass. The equations of motion are integrated numerically to obtain velocities, displacements, and rotations. Gravitational forces, internal forces and moments, and external forces are computed. For small deflections, a linear analysis is obtained, and for large deflections, general plastic deformation is allowed. The program provides for unloading and subsequent reloading along a linear elastic slope.

Program KRASH describes the interaction between a series of massless interconnecting structural elements and concentrated rigid body masses to which the structural elements are attached at their ends with the appropriate end fixity (pinned, fixed). The structural elements can be connected between node points which are offset from, and rigidly attached to, selected mass points. The interconnecting elements represent the stiffness characteristics of the structure between the masses. The

masses can translate and rotate in all directions under the influence of the external forces (i.e., gravity, aerodynamic, impact), as well as the constraining internal element forces. The movement of the masses results in changes in the relative distortion of the structural elements and, in turn, results in a new set of element forces acting throughout the system.

Computer Program KRASH has the capability to:

- Define the response of six degrees of freedom at each representative location, including three translations and three rotations.
- Determine mass accelerations, velocities, displacements, and internal member loads and deformations at each time interval.
- Provide for general nonlinear stiffness properties in the plastic regime, including different types of load-limiting devices, and determine the amount of permanent deformation.
- Define how and when rupture of an element takes place and redistribute the loading over the structural elements involved.
- Define mass penetration into an occupiable volume.
- Define the volume change due to structural deformations of an occupiable volume.
- Provide for ground contact by external structure including sliding friction and a nonrigid ground surface.
- Include internal structural damping.
- Include a measure of injury potential to the occupants, e.g., the probability of spinal injury indicated by the Dynamic Response Index (DRI).
- Determine the distribution of kinetic and potential energy by mass item, the distribution of strain and damping energy by beam element, and the crushing and sliding friction energy associated with each external spring.
- Determine the vehicle response to an initial condition that includes linear and angular velocity about three axes and any arbitrary vehicle attitude and position.

- Provide a measure of the airplane CG velocity by means of translational momentum relationships.
- Analyze an impact into a horizontal ground and/or an inclined slope.
- Provide a measure of the internal stress state of internal beam elements.
- Analyze a mathematical model containing up to 80 masses and 150 internal beam elements.
- Treat up to 180 nonlinear element degrees of freedom.

A comprehensive discussion of the theoretical development of program KRASH is presented in Reference 72. A discussion of program KRASH input-output format as well as modeling techniques and applications are included in Reference 73. Reference 74 provides a discussion of design guidelines which can be used in conjunction with program KRASH in the structural crashworthiness analysis of general aviation airplanes. Information related to the program's system requirements and functional organization to facilitate bringing the program to an operational status on an individual user's computer system is contained in Reference 75.

72. Gamon, M. A., GENERAL AVIATION AIRPLANE STRUCTURAL CRASH-WORTHINESS USER'S MANUAL, Volume I, PROGRAM "KRASH" THEORY, Lockheed-California Company; FAA-RD-77-189-I, Federal Aviation Administration, Washington, D. C., February 1978.
73. Gamon, M. A., Wittlin, G., and LaBarge, W. L., GENERAL AVIATION AIRPLANE STRUCTURAL CRASHWORTHINESS USER'S MANUAL, Volume II, INPUT-OUTPUT, TECHNIQUES AND APPLICATIONS (Revised), Lockheed-California Company; FAA-RD-77-189-II, Federal Aviation Administration, Washington, D. C., September 1979.
74. Wittlin, G., GENERAL AVIATION AIRPLANE STRUCTURAL CRASH-WORTHINESS USER'S MANUAL, Volume III, RELATED DESIGN INFORMATION, Lockheed-California Company; FAA-RD-77-189-III, Federal Aviation Administration, Washington, D. C., February 1978.
75. LaBarge, W. L., GENERAL AVIATION AIRPLANE STRUCTURAL CRASHWORTHINESS PROGRAMMER'S MANUAL, Lockheed-California Company; FAA-RD-78-120 (Revised), Systems Research and Development Service, Federal Aviation Administration, Washington, D. C., June 1979.

The experimental validation of KRASH is summarized in Table 10. Examples of helicopter structures modeled by KRASH are the existing utility model shown in Figure 88 and a medium cargo model shown in Figure 89 (Reference 76). Also, demonstrating the use of KRASH to model a structure in greater detail, Figure 90(a) illustrates a half-model of the cargo helicopter nose section, where symmetry is utilized in modeling the structure to the left of the aircraft mid-plane. Reference 77 describes the drop test of a nose section from the cargo helicopter at an impact velocity 33.3 ft/sec, as shown in Figure 90(b), and correlation of test data with KRASH predictions.

7.5.2 Program DYCAST

The computer program DYCAST (Dynamic Crash Analysis of Structures) is one module of the PLANS (Plastic and Large deflection ANALYSIS of Structures) system of nonlinear finite element structural analysis computer codes. These programs have been developed under contract to NASA Langley Research Center as part of a joint NASA/FAA program in general aviation crashworthiness. The modules for static analysis of structures are described in Reference 78.

As usual in finite element modeling, the structure is idealized into natural structural components: stringers, frames, beams, skin sheets, and bulkhead sheets, using the element library of DYCAST. Some portions could be modeled crudely if in the judgment of the analyst detailed modeling was not necessary. The element library consists of:

76. Badrinath, Y. V., SIMULATION, CORRELATION, AND ANALYSIS OF THE STRUCTURAL RESPONSE OF A CH-47A TO CRASH IMPACT, The Boeing Vertol Company; USARTL Technical Report 78-24, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories, Fort Eustis, Virginia, August 1978, AD A062643.
77. Tanner, A. E., Widmayer, E., STRUCTURAL CRASHWORTHINESS, SIMULATION AND ANALYSIS, FINAL REPORT, The Boeing Vertol Company; USARTL Technical Report 78-21, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, unpublished.
78. Pifko, A. B., Levine, H. S., and Armen, H., Jr., PLANS - A FINITE ELEMENT PROGRAM FOR NONLINEAR ANALYSIS OF STRUCTURES, VOLUME I, THEORETICAL MANUAL, NASA CR-2568, National Aeronautics and Space Administration, Washington, D. C., November 1975.

TABLE 10. PROGRAM KRASH EXPERIMENTAL VERIFICATION

Aircraft	Gross Weight (lb)	Impact velocities (ft/sec)		
		Vertical	Longitudinal	Lateral
1. Rotary-wing, utility-type	8660	23	-	18.5
2. Single-engine high-wing	2400	46	70	-
3. Single-engine high-wing	2400	22	71.3	-
4. Single-engine high-wing	2400	49	70	-
5. Single-engine high-wing	2400	43	69.5	-
6. Twin-engine low-wing substructure	545	27.5	-	-

*Test performed on soil; all other tests on rigid surface.

- Stringers - Two types of axial force members are available, constant or linearly varying between nodes.
- Beams - Ten different cross sections are currently available for the 12-degree-of-freedom beam element. Axial force, shear forces, and torque are uniform along the length, with a linear variation of bending moments.
- Membranes - Triangular membrane elements are available with either constant strain or linear strain. Hybrid elements permit mixed strain conditions, i.e., constant strain along an edge with linear strain along the other two sides.
- Springs - An axial force stringer with the spring constants specified in tabular form has recently been added to the element library. It can be used to simulate structural sections with known axial

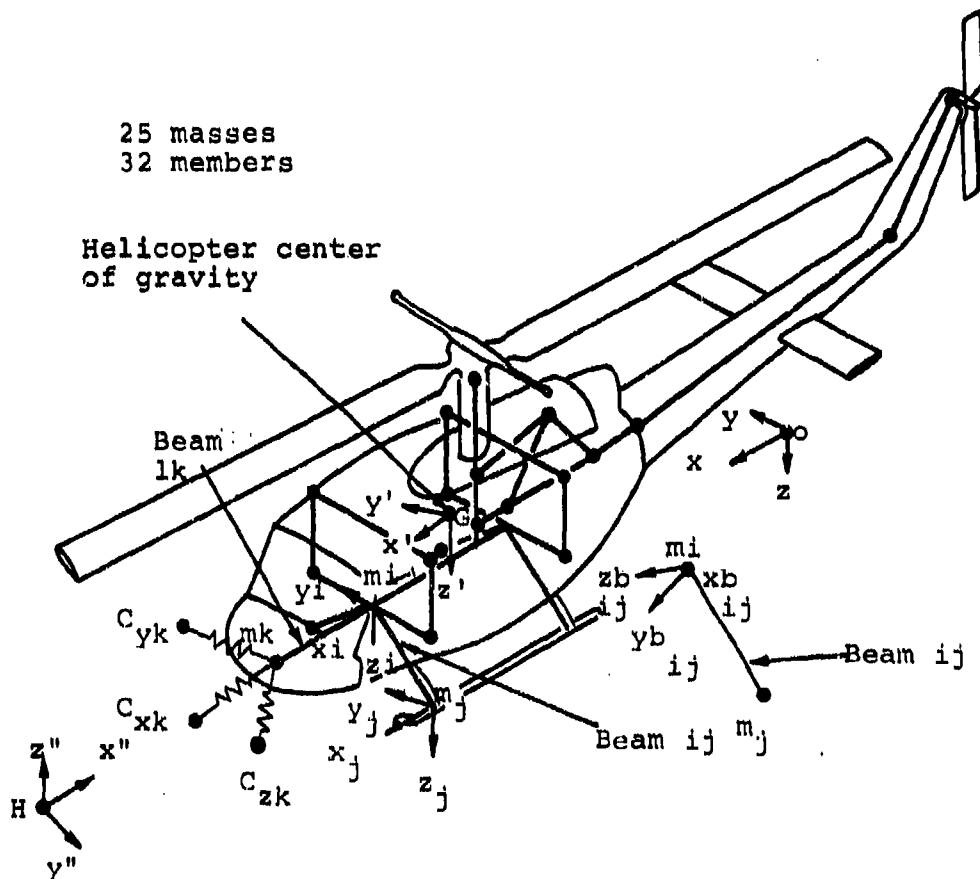


Figure 88. Model of existing utility helicopter.
(From Reference 65)

load-versus-deflection behavior; to represent an energy-absorbing device; or, as a gap element with zero stiffness over a certain range of deflection and nonzero thereafter.

DYCAST accounts for two types of nonlinearities which occur in dynamically loaded structures: material and geometric. The nonlinear material behavior, exhibited by metals yielding plastically, enters the simulation process through the stress-strain curves input by the analyst. Three types of stress-strain curves are permitted: elastic-perfectly plastic, elastic-linearly hardening, and elastic-nonlinearly hardening. The current element stiffnesses during a multi-step analysis

Shell and pylon
 Masses : 36
 Beams : 62
 Axial elements
 Tension only : 20
 Aft L.G. oleo : 2
 Landing gears
 External springs: 4
 Underfloor structure
 (Crush area)
 External springs: 12

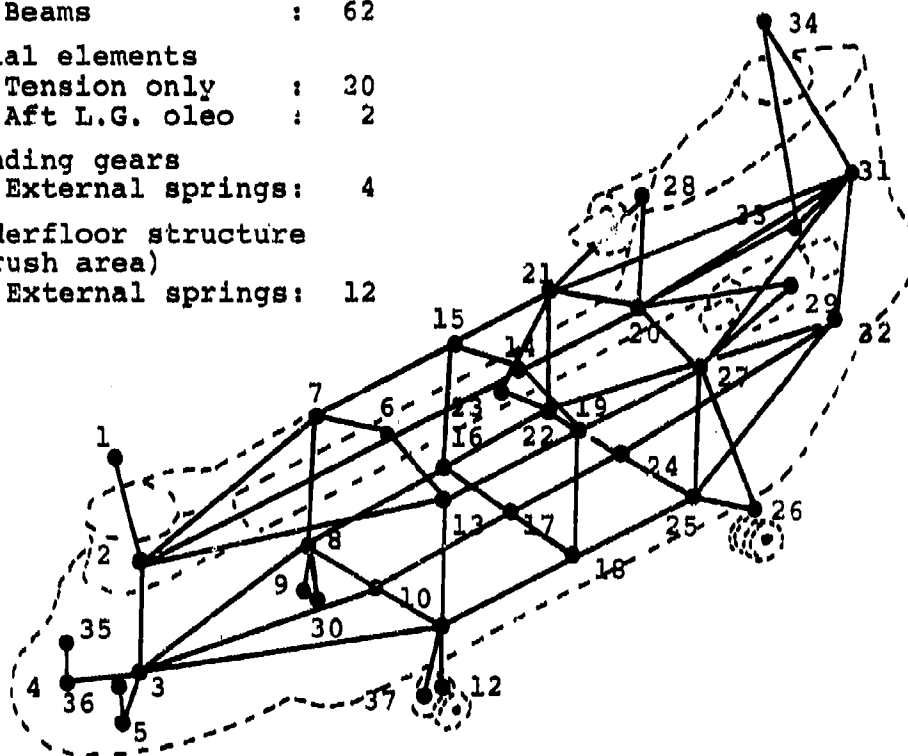


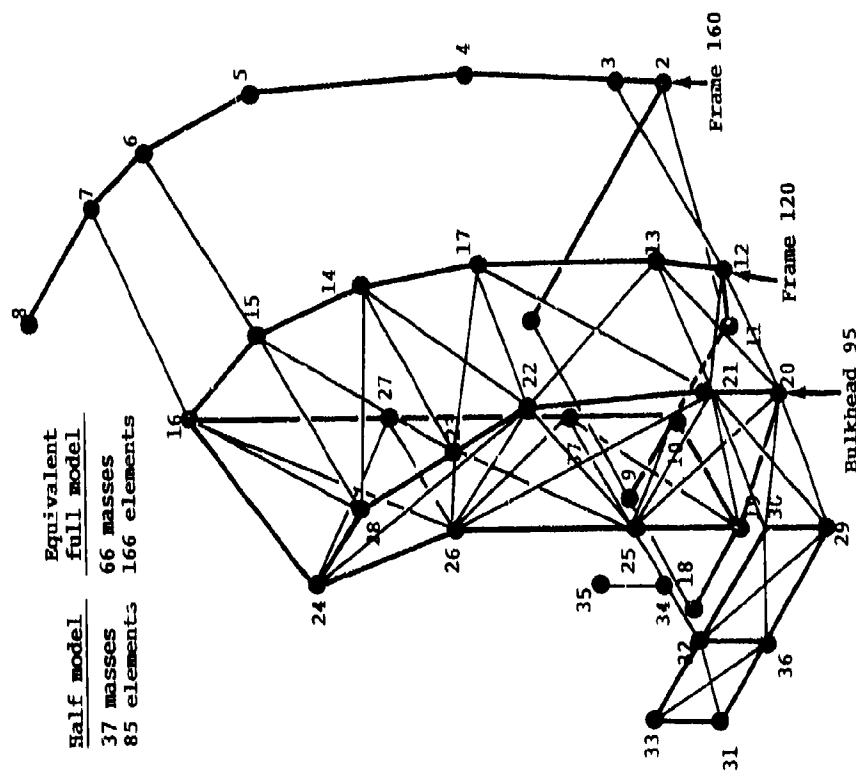
Figure 89. Model of existing medium cargo helicopter.
 (From Reference 76)

are determined using the tangent moduli corresponding to the current stress and strain, generalized for multiaxial states at various points in the element.

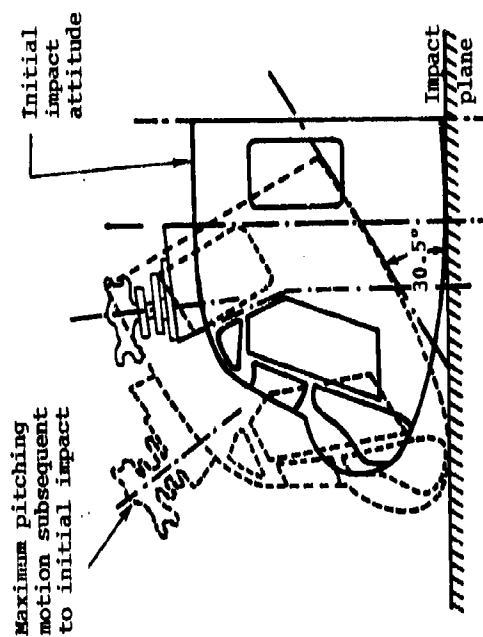
Geometric nonlinearities, due to large deformations of the structure, change the effective stiffness of the structure and are treated in DYCAST by an incremental convected coordinate approach. After each time increment the structure is reformed with straight elements between the displaced nodes; the previous values of accumulated strain, stress, and internal loads are carried forward as initial states in the reformed elements.

The incremental equations of motion for the system written in matrix form for an increment of time are:

$$[m] \{\Delta \ddot{u}\} + [K] \{\Delta u\} = \{\Delta P\} + \{R\}$$



(a) Half model of existing medium cargo helicopter nose section



(b) Initial impact attitude and subsequent nose-down pitching motion in medium cargo helicopter nose section drop test

Figure 90. Simulation of CH-47 nose section drop test. (From Reference 77)

where $[m]$ is the consistent mass matrix, $[K]$ the stiffness matrix, $\{\Delta u\}$ and $\{\Delta \ddot{u}\}$ the displacement and acceleration increments, $\{\Delta P\}$ the incremental external load vector, and $\{R\}$ the vector of equilibrium corrections. Both material and geometric nonlinear effects enter the system of incremental equations through the stiffness matrix $[K]$. This system of equations is integrated numerically to obtain the response of the structural model.

Currently, both explicit and implicit algorithms are implemented in DYCAST. Central differences and modified Adams predictor-corrector methods are the explicit algorithms; and, Newmark- β and Wilson- θ methods are the implicit algorithms. All methods but central differences permit a variable time step throughout the analysis.

DYCAST analysis results are printed histories of:

- Nodal displacements, velocities, and accelerations.
- Nodal forces and moments.
- Element strains and stresses through the cross-sections.

Postprocessing of saved data permits plotting of:

- Time histories of displacements, velocities, and accelerations.
- Views of the deformed structure at any time and from any viewing angle.

Further details of DYCAST can be found in References 69 and 78; and, as mentioned above, Reference 55 presents a comparison of DYCAST and KRASH modeling of the same section of fuselage structure.

7.5.3 Program WRECKER

Under the sponsorship of the National Highway Traffic Safety Administration, a finite element program called WRECKER has been developed by the IIT Research Institute for use in dynamic analysis of vehicle structures, including sheet metal, in a crash environment. The program consists of the following features:

- Large displacement, nonlinear static and dynamic, and elastic and plastic including strain-rate effects.
- Plate, spring, rigid link, and three-dimensional beam elements with a variety of beam end conditions.
- Options of using either the explicit or implicit time integration procedures.
- Options of specifying stress, mass and center of gravity, and energy output.

7.5.3.1 Solution Procedure: Two analysis procedures are used: the explicit or implicit, timewise numerical integration of the equations of motion for the node points (three translations and three rotations per node). The relative merits of implicit and explicit procedures and the importance of the mass formulation has been studied by Krieg and Key (Reference 79). The original version of WRECKER, documented in Reference 80, utilized only an explicit solution procedure, but WRECKER II, described in Reference 70, has both schemes.

An explicit procedure is exploited throughout the analysis by using lumped nodal masses and by calculating the internal forces at the nodes from direct integration of the element stress fields without reference to element or assembled stiffness matrices for the structure. The choice of an explicit integration procedure and a direct calculation of nodal forces results in a program with minimum (but still substantial) computer storage requirements. This, in turn, is equivalent to a capability of processing reasonably detailed and extensive structural models with relative ease. An early capability for handling relatively large problems is considered essential in developing realistic simulations of actual crash events because of the complex geometry and construction found in real vehicles.

The principal shortcomings of this integration procedure are the fairly extensive run times and the difficulty of obtaining results for static or quasi-static situations in which the

79. Krieg, R. D., and Key, S. W., TRANSIENT SHELL RESPONSE BY NUMERICAL TIME INTEGRATION, International Journal for Numerical Methods in Engineering, Volume 17, 1973.

80. Welch, R. E., Bruce, R. W., and Belytschko, T., FINITE ELEMENT ANALYSIS OF AUTOMOTIVE STRUCTURES UNDER CRASH LOADINGS, IIT Research Institute; Report No. DOT-HS-801-847, U. S. Department of Transportation, Washington, D. C., March 1976.

loading and response vary slowly with time. With regard to the latter observation, it was noted that, although the vehicle crash event is typically a high-speed phenomenon, low-speed or quasi-static crush testing provides valuable data regarding the performance of vehicle components and is an integral part of crashworthiness studies.

The implicit integration procedure requires the formation of the tangent stiffness matrix and the matrix inversion for the solution of incremental displacements at each time step. The choice of this procedure results in a program requiring considerably greater computer storage. However, this procedure is capable of carrying out dynamic analyses at substantially greater time steps than are admitted in the explicit version and permits simulation of quasi-static crush phenomena that involve slowly varying loadings and structural response.

7.5.3.2 Element Formulation: The treatment of large displacements and rotations employs a decomposition of the element displacement field into a rigid body rotation and translation associated with the local coordinate system attached to and moving with the element, and a remaining displacement field which describes the deformation of the element relative to the current position of the element axes. This transformation, in effect, removes the average rigid body rotation of the element and allows the use of small or moderate deflection element formulations in the calculation of element forces. In this manner, extremely large rotations and deflections can be accommodated by the analysis with accuracy depending primarily on the size of the elements relative to the curvature of the structure. Although a formal convergence theorem is lacking, the decomposition does hold for infinitesimal regions, and numerical studies show excellent agreement with classical solutions. The computer program at present includes low-order triangular plate elements, three-dimensional beam elements, and spring elements. A triangular membrane-hinge line element is also available but is not presently compatible with the beam formulation. Hinges and sliding joints, or a combination of both, are available in beam elements.

7.5.3.3 Material Properties: The computer program currently uses simple elastic-plastic stress-strain laws; a uniaxial relation for beam and spring elements, and a biaxial strain hardening Von Mises model for plates. Element forces and bending moment for given strain fields are calculated by piecewise linear numerical integration of the stresses at selected points in the cross section. Options of an explicit moment-curvature relationship and the strain rate effect are also provided. The program is designed to accommodate other constitutive relations.

In fact, linear relationships are provided at this level which result in more efficient computations for this class of problems.

7.5.3.4 Program Validation: The explicit version of WRECKER II was validated through a series of test problems involving beams, plates, and shells subjected to various types of loading. Also, as described in Reference 80, the front end of an automobile was modeled in simulation of 30- and 44-mi/h barrier crash tests. Reference 70 describes validation of the implicit procedure by comparison with previously obtained explicit solutions or, in the case of static loading, with classical linear and nonlinear solutions.

7.5.3.5 Computer Program Description: The program contains spring, beam, and triangular-plate finite elements and treats the large deflection phenomena by decomposing the element deformations into rigid body and deformation components before computing element forces. The numerical integration technique employed is a Newmark- β method.

The program consists of approximately 4500 cards and normally executes in 76 K words of core storage on the UNIVAC 1108 computer under the EXEC-8, version 27 operating system. A version of the program has been prepared and executed in 300 K bytes on an IBM 370/168 system under the H compiler with no optimization. The capacity of the program is approximately 150 nodes, 150 elements, 100 displacement boundary conditions, 5 different sets of material properties, and 10 distinct beam cross sections. The solution procedure is completely in core and makes use of a peripheral device for temporary storage during execution. A restart capability and output data storage are provided via optional external files.

7.6 POTENTIAL SOURCES OF BASIC STRUCTURAL DATA FOR CRASHWORTHINESS ANALYSIS

A major obstacle to analyzing structural crashworthiness is the difficulty of obtaining adequate data concerning the dynamic failure mechanisms of structural assemblies and elements. Such data are necessary for the analysis techniques described earlier, with the possible exception of the finite element methods. Data useful for structural analysis can be obtained from the several sources discussed within the following paragraphs.

7.6.1 Estimates

An estimate of the dynamic capability of a structural element or system can be obtained by using standard static failure criteria and multiplying the result by a dynamic correction factor. This method has limited usage since the factor usually specified for the overall failure sequence is representative of the energy-absorption variation between static and dynamic failure modes.

Consequently, a time history of element failure is not usually considered, but the net effect, in terms of energy absorption, is used to determine the gross capability of the structure considered. Such analyses are useful in defining the gross crash-worthiness contributions of structural layout prior to the use of more complex analysis techniques.

Care must be exercised when using such a technique since structural elements exhibit differing failure modes, and these modes may vary depending on the rate of load application. Additionally, the total load-carrying capability of a member also will be dependent on the rate of load application.

7.6.2 Aircraft Accident Data

Aircraft accidents can provide useful data concerning structural response if the wreckage can be examined in detail before it is disturbed from its postimpact location. Examination of the wreckage can yield data concerning the failure modes and sequences; the effectiveness of energy-absorbing features, if any; and the occupant environment experienced in terms of space, extremity flailing, acceleration levels, and injury causes.

Such a relatively subjective review also requires other data to enable the investigator to determine a complete crash scenario. Some of these data can be determined from the crash site itself, particularly terrain hardness, ground obstacles, impact attitude, mass item breakaway, flammable fluid containment, egress potential, etc. However, more important parameters that are harder to obtain include the impact velocity components and the acceleration environment in the occupied areas. In fact, these data probably will not be available in a recorded format unless the crashed aircraft happened to be a test vehicle with on-board instrumentation. As a result, the velocity components at impact are often estimated using the gross deformations of the structure and the motion of the aircraft relative to the ground. Simple energy and momentum techniques are

used to do this; and although the resultant velocity and acceleration estimates are the best available, such an analysis cannot apportion the energy absorption through the aircraft, i.e., in the landing gear, structure, seats, etc.

Reference 65 describes an examination of 3,657 U. S. Army rotary-wing aircraft accidents that occurred between 1967 and 1971 and a detailed review of 32 of these. References 81 and 82 describe investigation of general aviation accidents and the information that can be obtained.

A major contribution to the quest for better aircraft crash-worthiness made by crash analyses is the delineation of the good and bad features of a particular design. By compiling accident data, qualitative assessment of the desirable and undesirable features exhibited by various aircraft types can be made. Once a reasonable data base is compiled, the desirable features can be pinpointed and included in future designs or redesigns. Undesirable features can be suitably advertised to ensure their use is not continued.

7.6.3 Controlled Crash Testing

Controlled testing has been done in the past on a variety of aircraft to demonstrate the capabilities of structure, landing gears, fuel systems, etc. in typical crash environments.

81. Snyder, R. G., CRASHWORTHINESS INVESTIGATION OF GENERAL AVIATION ACCIDENTS, SAE Paper No. 750537, presented at Business Aircraft Meeting, Society of Automotive Engineers, Inc., Wichita, Kansas, 8-11 April 1975.
82. Snyder, R. G., GENERAL AVIATION CRASH SURVIVABILITY, University of Michigan, SAE Paper No. 780017, presented at Congress and Exposition, Society of Automotive Engineers, Inc., Detroit, Michigan, 27 February - 3 March 1978.

(See, for example, References 42, 52, and 83 through 85). Initially, such tests were often performed using powered aircraft that were remotely controlled or prealigned for impacts into selected terrain conditions. Useful data were obtained from many of these tests, although some resulted in postimpact fires and information loss.

A more recent approach for vertical impacts has been to drop test specimens from a fixed site or a moving carrier. Structural assemblies, small aircraft, and helicopters have been tested in this manner. Representative impact conditions and velocities can be achieved by adjusting the vertical drop height and/or the longitudinal velocity of the carrier as well as roll and yaw attitudes.

The largest facility used for full-scale crash testing of light aircraft and helicopters is the Impact Dynamics Research Facility at NASA Langley Research Center (Reference 86). Here aircraft are allowed to swing on cables that are preset to determine the overall impact attitude. Velocity components are controlled by varying the drop height, cable length, and cable anchor locations. Immediately prior to impact, the aircraft is released by pyrotechnic means. The ground impact and subsequent motions are then completely unrestrained.

83. Alfaro-Bou, E., and Vaughan, V. L., Jr., LIGHT AIRPLANE CRASH TESTS AT IMPACT VELOCITIES OF 13 AND 27 M/SEC, NASA Technical Paper 1042, NASA Langley Research Center, National Aeronautics and Space Administration, Washington, D. C., November 1977.
84. Castle, C. B., and Alfaro-Bou, E., LIGHT AIRPLANE CRASH TESTS AT THREE ROLL ANGLES, NASA Technical Paper 1477, National Aeronautics and Space Administration, Washington, D. C., October 1979.
85. Haley, J. C., Turnbow, J. W., and Walhout, G. J., FLOOR ACCELERATIONS AND PASSENGER INJURIES IN TRANSPORT AIRCRAFT ACCIDENTS, Aviation Safety Engineering and Research (AvSER), Division of Flight Safety Foundation, Inc., USAAVLABS Technical Report 67-16, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, May 1967, AD 815877L.
86. Vaughan, V. L., and Alfaro-Bou, E., IMPACT DYNAMICS RESEARCH FACILITY FOR FULL-SCALE AIRCRAFT CRASH TESTING, NASA Technical Note D-8179, National Aeronautics and Space Administration, Washington, D. C., April 1976.

The primary advantage of testing full-scale aircraft is that there is no need to interpret the data or attempt to extrapolate the results to other structural formats. All data such as velocities, attitudes, accelerations, and structural strains are measured directly as functions of time from impact. In addition, high-speed cameras can record displacements from various locations inside and outside the aircraft in order to provide visual time histories of structural and occupant response during the crash sequence. Postcrash review of damage also provides a direct indication of the aircraft's performance with respect to occupied volume penetration, seat and landing gear performance, large mass item retention, and flammable fluid containment.

Instrumented anthropomorphic dummies positioned and restrained in seats with typical restraint systems are used to investigate the potential for occupant survival. Seat occupant motions are photographed using high-speed cameras, and the occupant's potential for impacting the aircraft interior is assessed.

The above description of full-scale testing may imply that this is the only technique worth using to attain realistic conditions. However, it must be emphasized that such tests are expensive to run, and aircraft, especially new design prototypes, are difficult to obtain. In addition, such tests require careful planning with a redundancy of recording equipment because of the probability that some instrumentation channels may fail to function.

7.6.4 Scale Model Testing

Scale model testing has been used extensively when investigating the aerodynamic characteristics of aircraft, bridges, buildings, etc. Scale model testing for structural strength and deflection verification also has been used where material sizes allow. For evaluating crashworthiness, however, scale model testing becomes a more difficult problem, especially when severe plastic deformation and element rupture occur.

Scale modeling of major structural members may provide data that can be used for crashworthiness studies; however, when semimonocoque construction is considered, stringers and skin are often made from relatively thin sheet material, measuring from approximately 0.015 to 0.06 in. Depending on the structure being modeled, certain nondimensional parameters must be satisfied for both the model and the aircraft. Examples of these are:

$$\frac{X_1}{L}, \epsilon, \frac{\sigma}{E}, \dot{\epsilon} t, \frac{vt}{L}$$

where X_i = spatial coordinate
 L = characteristic length
 ϵ = strain
 σ = stress
 E = Young's Modulus
 $\dot{\epsilon}$ = strain rate
 t = time
 v = velocity

Some of these parameters involve the thickness of the material, and, for example, scaling 0.015 for a one-tenth scale poses major problems in the manufacture, handling, and tolerance effects when using 0.0015-in. shim material.

Reference 87 presents a discussion of scale modeling techniques applied to structural crashworthiness. Practical considerations in geometric scaling are discussed and illustrated using barrier tests of two different automobile front-end structures and an impulsively loaded section of semimonocoque cylinder similar to an aircraft fuselage.

A conclusion of that study was that for prototype structures in the 1,000-to-10,000-lb weight range, and for scale factors of from 3 to 8, a model test can be performed at less than half the cost of a corresponding full-scale test, depending on the scale factor, as demonstrated by Figure 91. It was concluded that scale model tests can meet the same objectives and could therefore replace many full-scale tests in a crashworthiness research and development program. Model tests are particularly useful for screening new concepts, for performing parametric experimental studies, and for the initial optimization of a given concept. Full-scale tests are still required for proving the concept and for making detailed measurements such as measurements of occupant response.

87. Holmes, B. S., and Colton, J. D., APPLICATION OF SCALE MODELING TECHNIQUES TO CRASHWORTHINESS RESEARCH, in Aircraft Crashworthiness, K. Saczalski, et al., eds., University Press of Virginia, Charlottesville, Virginia, 1975, pp. 561-582.

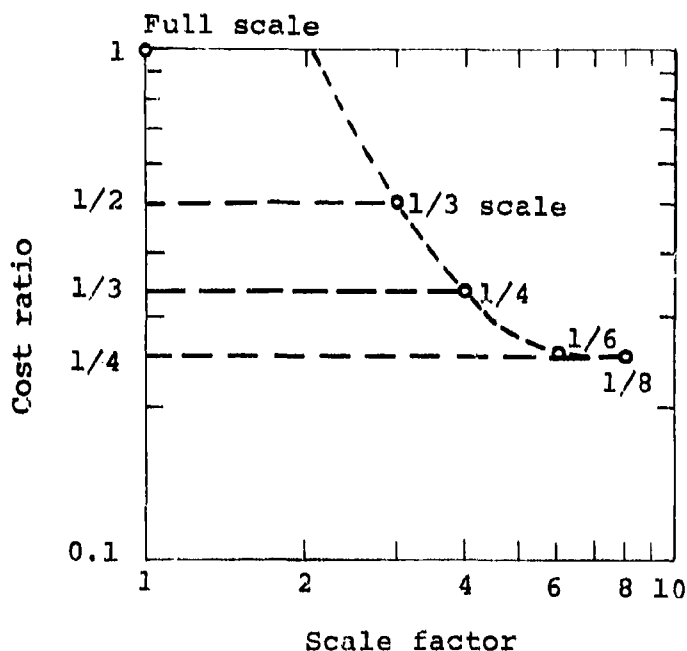


Figure 91. Cost ratio (scale model test cost/full-scale test cost) versus scale factor for structures weighing less than 10,000 lb. (From Reference 88)

Also, in another recent study 1/3-scale models of various configurations of stiffened sheet panels, like that shown in Figure 92 (Reference 88), were tested in order to determine the influence of the following parameters:

- Variation of the stiffener pitch (d) with respect to the height (h).
- Variation of the stiffener section (S) with respect to the panel sheet section.
- Variation of the lightening hole diameters (ϕ) with respect to the stiffener pitch.

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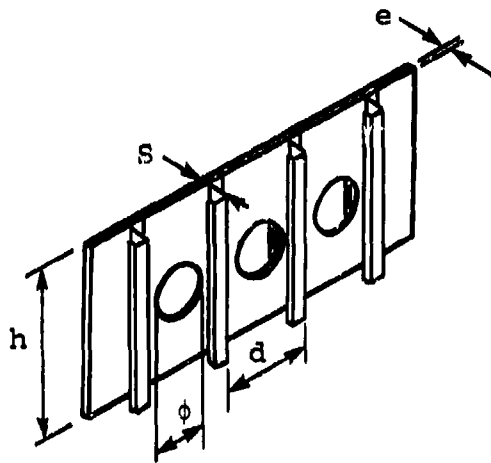


Figure 92. Stiffened panel specimen. (From Reference 88)

- Type of stiffener (Z sections, angles, stiffening beads).
- Load influence (distributed load, load concentrated at the ends).
- Bottom shape influence (flat bottom, curved bottom).

Comparison of model test results with those of full-scale tests showed that the models exhibited the same failure modes and predictable failure loads.

The techniques of dynamic testing become more involved as the required quantity of data increases. For instance, if the final deformation shape is the only result needed, the instrumentation and data handling requirements can be minimized. Since a test is of short duration, even for full-scale specimens, specialized equipment is required if data requirements are expanded to include time histories of structural response, acceleration, stress, etc. This equipment must have rapid response characteristics and maintain high fidelity measuring capability when subjected to high G levels.

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READER'S SERVICE LETTER
(For use in submitting comments, recommendations, corrections, and
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