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EVOLVING CRASHWORTHINESS DESIGN CRITERIA

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SUMMARY

Although significant strides have been made in recent years toward improving aviation safety, mishaps involving all classes of helicopters presently are and will continue to be a major, expensive U.S. Army problem in terms of casualties, materiel loss, and reduction in mission effectiveness. Modernday training and tactical employment requirements for the U.S. Army helicopter dictate that a large percentage of operations occur in the low-speed, low altitude flight regime, which contributes to the problem by reducing critical margins of safety normally associated with higher airspeed and higher altitude operations with accompanying greater time for response in case of an emergency. This increased probability of accident occurrence, coupled with the lack of an in-flight egress capability, makes design for crashworthiness essential for Army helicopters.

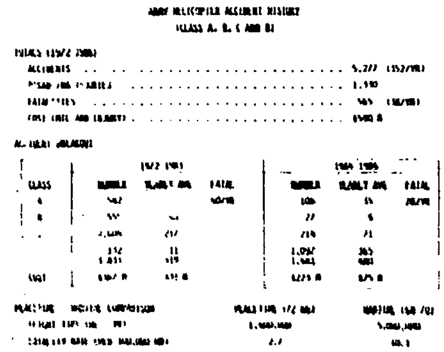
This paper discusses the evolution of crash survival design criteria for rotary-wing aircraft and its application to current and new generation Army helicopters. Emphasis is given to the need for a total systems' approach in design for crashworthiness and the necessity for considering crashworthiness early in the design phase of a new aviation weapon systems development effort. The actual application of crashworthiness to Army helicopters is presented with statistics that show dramatic reductions in fatalities and injuries with implementation of a crashworthy fuel system. The cost effective aspects of designing helicopters to be more crash survivable are also discussed.

INTRODUCTION

Research investigations directed toward improving occupant survival and reducing materiel losses in aircraft crashes have been conducted by the Army for more than 20 years. However, up until approximately 10 years ago the principal emphasis within Army aviation survivability was placed on accident prevention. Although this is indeed the ultimate objective deserving priority effort, past experience clearly shows that accident prevention alone simply is not sufficient. Mishaps of all natures involving Army aircraft have been, are, and will continue to be a major, expensive problem. Research has been accomplished on accidents worldwide involving Army aviation, and accident histories are routinely disseminated throughout the Army. Unfortunately, many lessons learned from these accident histories are not applied and hazardous design features remain and operational errors are repeated. Too many Army aircrewmen are still being fatally injured in potentially survivable accidents, and the percentage of major injuries and rate of materiel losses are still unacceptably high. There is no easy solution to the problem. Significant gains can be made, however, toward reducing these unacceptable accident losses, but to do so we must aggressively pursue a program that addresses key issues of both accident prevention and crashworthiness design. Since the helicopter's potential for accident is great due to its mission and the environment in which it must accomplish that mission, it is imperative that it be engineered to minimize damage and enhance occupant survival in crashes. In designing helicopters to be more crash survivable, two subissues then become paramount: establishing viable crashworthiness design criteria, and the more difficult task, applying these crashworthiness criteria to Army aircraft design.

To help establish the severity of the problem within U.S. Army aviation, Table 1 provides a summary of accident statistics for Army helicopters for the period of time from 1972 to 1986. During the period reviewed there were over 5,000 helicopter Class A, B, C, and D mishaps (an average of one a day) and over 550 occupant fatalities. The number of fatalities would, without question, have been much greater had not Army aircraft been retrofitted in the early to mid 70's with crashworthy fuel systems. The cost of these mishaps considering casualties and materiel were nearly 600 million dollars. These costs primarily reflect relatively low cost helicopter losses (i.e. OH-58, UH-1, AH-1) as compared to the higher cost modern helicopter (UH-60, AH-64). Also, they do not reflect the potentially greater costs that are associated with loss of mission capability. Further, these statistics are based on current peacetime experience which reflects a total cumulative flight time of approximately 1½ million hours per year for Army aviation with a fatality rate of approximately 2.5 per 100,000 hours of flying time. The severity of the problem increases severalfold during periods of combat, as demonstrated in Vietnam when, during the height of the conflict, total helicopter flight time was in excess of 5 million hours per year with the fatality rate of 10 per 100,000 hours.

Table 1. Army Helicopter Accident History 1972-1986



Data from these accident and crash injury investigations (reference 1) have revealed deficiencies in the crashworthiness of the older, existing Army helicopters. Key deficiencies include:

- Structural collapse (roof downward and floor upward) causing loss of occupiable volume.
- Inward buckling of frames, longerons, etc., causing penetration wounds to personnel.
- Lethal internal structure causing head, chest and extremity injuries from occupant flailing.
- Floor breakup permitting seats to tear out and occupants to become flying missiles.
- Landing gear penetration into occupied areas and fuel systems causing contact injuries and fires.
- Landing gears not designed for sufficiently high sink rates and insufficient deformable airframe structure permitting excessive acceleration (G) forces to be transmitted to the occupants and causing excessive materiel damage.
- Intrusion of the occupied area by the main rotor gearbox and other high mass items causing crushing and contact injuries to the occupants.
- Insufficient structural stiffness permitting inward crushing and entrapment of occupants in rollover accidents.

CRASHWORTHINESS DESIGN CRITERIA

General

In-depth assessment of available crash data was first accomplished in the mid-60's by a joint Government/industry review team. The product of that team was the world's first crash survival design guide (CSDG) for light fixed- and rotary-wing aircraft, published in 1967. Revisions to this guide were made in 1969, 1971, 1980 (reference 2) and a current effort is scheduled for completion in 1989. Figures 1a and 1b depict the many facets of crashworthiness research and development that have directly helped to support the evolution of crashworthiness design criteria. Continual component development programs, full scale crash testing, and structural analyses efforts are being conducted which increase the knowledge base and provide new technology applicable to crashworthiness design, thus dictating the need for periodic revisions of the CSDG. In 1974, the CSDG was converted into a military standard (MIL-STD-1290)(reference 3). Although a draft revision to this MIL-STD exists (1290A), this revision will not be finalized until the completion of the current CSDG update effort. In addition, an Aeronautical Design Standard, ADS 36, entitled "Rotary Wing Aircraft Crash Resistance" (reference 4) was formulated to be specifically applied to the U.S. Army's Light Helicopter (LHX) development program. This will be discussed in more detail later in the paper.

Figure 1a

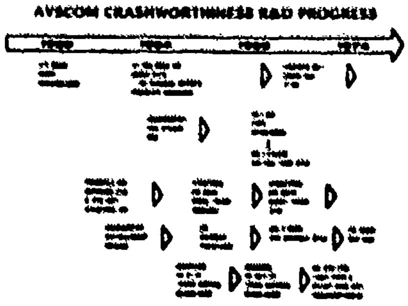
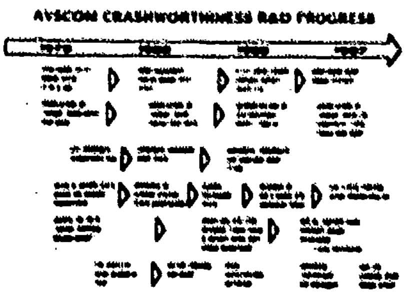


Figure 1b



MIL-STD-1290 addresses five key areas that must be considered in designing a helicopter to conserve materiel and provide occupant protection in a crash:

- Crashworthiness of the structure--assuring that the structure has proper strength and stiffness to maintain a livable volume for the occupants and prevent the seat attachments from breaking free.
- Retention strength--assuring that the high mass items such as the transmission and engine do not break free from their mounts and penetrate occupied areas.
- Occupant acceleration environment--providing the necessary crash load absorption by using crushable structures, load limiting landing gears, energy-absorbing seats, etc., to keep the loads on the occupants within human tolerance levels.
- Occupants environment hazards--providing the necessary restraint systems, padding, etc., to prevent injury caused by occupant flailing.
- Postcrash hazards--after the crash sequence has ended, providing protection against flammable fluid systems and permitting egress under all conditions.

Typical Army Crash Impacts

In the Army, typical crash impact conditions are depicted in Figure 2. Roll, pitch, and forward velocity is usually present along with vertical and forward velocity components. Some level of yaw attitude is also frequently present. This dictates the need for impact design criteria involving longitudinal, vertical and lateral velocity components.

About 95% of Army helicopter mishap crash impacts have been in the potentially survivable range. Accordingly, helicopter crash resistance requirements given in Figure 3 were adopted by the Army in the early 1970's. Specifically, the aircraft structure shall provide a protective shell for occupants in crash velocity changes of the severity cited in Figure 3. Moreover, the structure and equipment shall allow deformation in a controlled, predictable manner so that forces imposed upon the occupants will be tolerable while still maintaining the protective shell. The forces imposed on occupants is governed by the stopping distance and pulse duration. Figure 4 illustrates this relationship and indicates the importance of controlled energy absorption in a crash.

Systems Approach

For maximum effectiveness, design for crashworthiness dictates that a total systems approach be used and that the designer consider such survivability issues with at least equal priority as other key design considerations such as weight, load factor, and fatigue life during the initial design phase of the helicopter. Figure 5 depicts the system's approach required relative to management of the crash energy for occupant

ATTITUDE. RELATIVELY LEVEL (± 10° ROLL; +15°/-5° PITCH)

VELOCITY. FORWARD SPEED ~ 10 FPS (7 MPH)
VERTICAL SINK SPEED ~ 15 FPS (10 MPH)

SURVIVABILITY: > 90%

Figure 2. Typical Crash Impact Condition U.S. Army Helicopters (Existing Fleet)

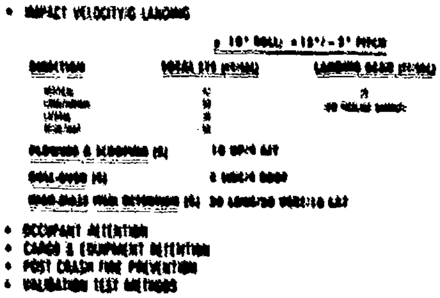


Figure 3. Key Crash-Resistant Design Requirements for Army Helicopters

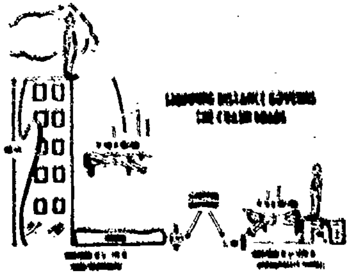


Figure 4. Impact Accelerations

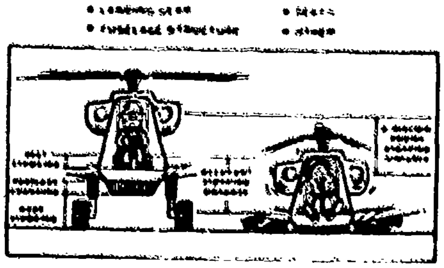


Figure 5. Systems Approach to Crashworthiness

survival for the vertical velocity crash design condition. The crash G loads must be brought to within human tolerance limits in a controlled manner to prevent injury to the occupants. This can be accomplished by using the landing gear, floor structure, and seat to progressively absorb crash energy during the crash sequence. That is, the occupant is slowed down in a controlled manner by stroking/failing the landing gear, crushing the floor structure, and stroking the seat at a predetermined load before being subjected to the crash pulse which by then has been reduced to within human tolerance limits. In addition, the large mass items such as the overhead gearbox are slowed down by stroking/failing of the landing gear or fuselage structure, and in some cases, by stroking of the gearbox within its mounts. With the advent of airframes constructed from composite materials (fiberglass, Kevlar, graphite) the need for a systems approach to crashworthiness, coupled with innovative design, becomes more urgent due to the characteristically nonductile behavior of these materials.

Crash Impact Design Conditions

A survivable crash is generally defined as one wherein the impact conditions inclusive of pulse rate onset, magnitude, direction and duration of the acceleration forces that are transmitted to the occupant do not exceed the limits of human tolerance for survival, and in which the surrounding structure remains sufficiently intact during and after impact to permit occupant survival. Inasmuch as the crew must stay with the helicopter in an impending crash, a high level of what constitutes a survivable or non-injurious crash impact velocity change is desirable and is a key objective of design for crashworthiness. The Army's crash impact velocity change design conditions for longitudinal impacts against a rigid barrier are 6.1 m/s (20 ft/s) for the cockpit and 12.2 m/s (40 ft/s) for the cabin. There has been little disagreement with this design requirement. The vertical velocity change crash impact design condition however, has continually been the subject of controversy. It is becoming evident that one set of crashworthiness design criteria is not necessarily practical for all rotary-wing aircraft, military and commercial, large and small. Factors such as the following must also be considered in future development of crashworthiness design criteria.

- Helicopter size and transportability requirements (space available for energy absorbing seats and crushable subfloor structure).
- Performance of the aircraft (e.g. disk loading, autorotational sink rate, flight velocity capability).
- Basic aircraft configuration.
- How the aircraft is to be employed.

Obviously, the smaller the aircraft the larger percent of weight empty that is devoted to crashworthiness for a given set of design impact conditions. This could lead to an impractical design. Also, commercial helicopter operations are generally less perilous than military operations indicating that commercial helicopter crash impact design requirements could be less stringent than for military systems. Ballistic tolerance is not a consideration in designing a crashworthy fuel system for commercial helicopters.

The following is a summary of vertical velocity crash impact vs. pitch and roll design criteria that have evolved over the past few years. It should be noted that this is for impact on a rigid surface without (1) reducing the height of the cockpit and passenger/troop compartments by more than 15% or (2) allowing the occupants to experience injurious accelerative loading.

Table 2. Vertical Velocity Crash Impact Design Criteria

	Velocity Change V (m/s)	Roll	Pitch
MIL-STD-1290 (Ref 3)	12.8 (42 ft/sec)	± 30°	± 15°
CSDG (Ref 2)	12.8 (42 ft/sec)	± 20°	+ 25° to - 15°
ADS-36 (Ref 4)	11.6 (38 ft/sec)	± 10°	+ 15° to - 5°
MIL-STD-1290A Draft	12.8 (42 ft/sec)	± 10°	+ 15° to - 5°

The original MIL-STD-1290 contained an impractical requirement for roll since a 30 degree attitude would result in only half the landing gear absorbing energy in a crash before fuselage contact, assuming it would stroke at all with such severe side loadings. The current published CSDG (reference 2) also specifies a too severe roll and negative pitch impact attitude requirement. This criteria is not substantiated by accident history data of roll and pitch values and designing to meet it has an adverse effect on aircraft system design and weight.

ADS-36 (reference 4) is based upon that level of crashworthiness that has been demonstrated by the UH-60 helicopter. Since Army aviation leaders have been pleased, for the most part, with the UH-60 crashworthiness, they have dictated their desire that the LHX have at least this level. ADS-36 and the draft MIL-STD-1290A are essentially the same except for the vertical velocity change requirement. The roll and pitch attitude values selected are derived from analysis of accident historical data presented in Figures 6 and 7. The attitude envelop specified in ADS-36 is presented in Figure 8 and it illustrates how the airframer can be relieved from having to design for the extreme corners of the combined roll and pitch conditions which rarely occur.

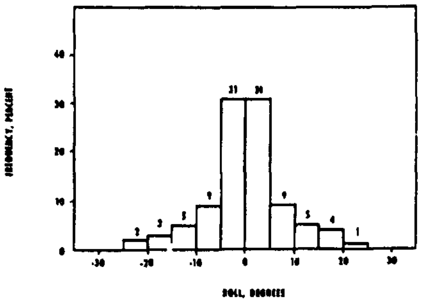


Figure 6. Aircraft Roll Angle at Impact for Survivable and Partially Survivable Army Helicopter Mishaps, 1972-1982

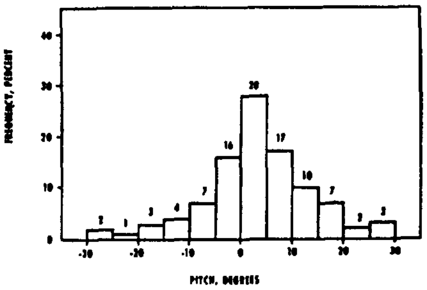


Figure 7. Aircraft Pitch Angle at Impact for Survivable and Partially Survivable Army Helicopter Mishaps, 1972-1982

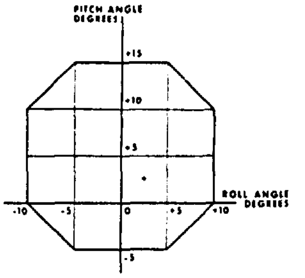


Figure 8. Roll and Pitch Attitude Envelope

Landing Gear

As a minimum, the landing gear shall be capable of decelerating the aircraft at normal gross weight from an impact velocity of 6.1 m/s (20 ft/sec) onto a level rigid surface within an attitude envelope of ±10 degrees roll and +15 degrees to -5 degrees pitch without allowing the fuselage to contact the ground and without gear penetration into an occupied area. Plastic deformation of the landing gear and its mounting system is acceptable in meeting this requirement; however, with the possible exception of the rotor blades, the remainder of the aircraft structure shall be flightworthy after impact. Prior to the 1970's, helicopter landing gear (usually skids) had relatively little energy absorbing capability and very limited capability to withstand lateral loads without failing. Skid gears were designed, typically to withstand an 8 ft/sec vertical impact speed without collapse at basic structural design gross weight (BSDGW). Too often in the past, a certain accident scenario has repeated itself in the Army's skid gear equipped aircraft. The helicopter will touch down with some roll attitude angle (out of an autorotation, perhaps) at a vertical sink speed slightly exceeding the skid capability. One skid fails, causing the helicopter to roll right or left, bringing the main rotor into contact with the ground. The reactive torque loads then exceed the capability of the transmission mounts and the rotor system/transmission departs the aircraft during the post impact gyration. Accidents such as described usually result in complete loss of the aircraft, serious injuries to the occupants and often fatalities. It is possible to totally avoid this type of accident for impacts involving sink speeds of 6.1 m/s (20 ft/sec, or 1200 ft/min) (or even greater), through use of a landing gear designed to absorb this amount of energy.

A high performance landing gear is the key component in the system approach to crashworthiness as well as in mishap prevention. Future helicopter systems will include very expensive mission equipment to the point that the airframe part of the system will be less than half the system cost. The 6.1 m/s (20 ft/sec) landing gear (or better) will help protect the airframe and expensive subsystems from damage, resulting in the major factor in substantiating the cost effectiveness of design for crashworthiness.

CRASHWORTHY FUEL SYSTEM (CWFS)

The crashworthy fuel tank specification, MIL-T-27422, was originally a joint services specification that was modified to require a crashworthy, ballistically tolerant (self-sealing) tank material that was developed during the mid and late 1960's. The modification, MIL-T-27422B (reference 5), was published in 1971. In addition to the 19.8 m/s (65 ft/sec) full-scale tank drop onto concrete requirement, the specification includes important puncture, cut and tear resistance tests that the tank wall material must pass.

If fuel is allowed to spill during survivable crashes, a postcrash fire is often the result due to the multitude of ignition sources available. Prior to the advent of crashworthy fuel systems, the Army studied 2382 survivable rotary-wing accidents occurring between 1967-69. Postcrash fires were present on 10.5 percent of the accidents and contributed to 39.3 percent of the fatalities. Through an intensive effort, the Army developed a CWFS consisting of self-sealing breakaway valves/couplings; frangible attachments; self-sealing fuel lines; cut, tear and rupture resistant bladders; and a means of preventing fuel spillage at all postcrash attitudes. The military specification, MIL-T-27422B, was developed with specific test requirements and pass/fail criteria for the CWFS. Though brute strength has some importance, the cut and tear resistance of the fuel tank material are key issues for successful fuel containment in deforming aircraft structure. The Army specification fuel tank material is also designed to be self-sealing for small caliber ballistic hits.

All Army helicopters now have a CWFS and postcrash fire statistics have been altered dramatically. During the period April 1970 to June 1976, a time when retrofit of the CWFS was in progress, for helicopter not CWFS equipped there were 65 thermal fatalities. This compares with only one fatality for helicopters equipped with the CWFS. Since 1976, there have been no thermal fatalities in potentially survivable accidents of Army helicopters.

Field evidence has shown that aircraft with the CWFS have experienced fuel system failures and resulting fires in severe accidents slightly above the human survival limit. This has verified the validity of current design criteria. No reduction in drop height, or of cut- and tear-resistance values should be considered, especially in light of the more severe crash impacts being experienced with higher performance helicopters such as the UH-60A.

RELATIONSHIP TO CIVIL AVIATION

In the civil aviation community, prevention of accidents has always been a high priority. However, even with technological advancements, increased mechanical reliability, improved pilot training, and intensive studies of accident causal factors, accidents do occur. Statistics indicate that for one decade (1967-1976) the number of general aviation aircraft involved in accidents was equivalent to at least 38 percent of the total U.S. aircraft production during that period. Estimates that an aircraft will be involved in an accident over a 20-year life range are as high as 60-70 percent.

Recognizing this accident probability, it makes sense to apply a worthwhile degree of crashworthiness to contemporary design philosophy. Because of differences in mission profiles, civil aircraft are normally flown somewhat differently than Army helicopters. The civil helicopter crash environments may not be sufficiently severe to justify using all of the MIL-STD-1290 crashworthiness design techniques that have been addressed in this paper. From a cost viewpoint the easiest to justify might be the use of state-of-the-art restraint and energy absorbing seat systems, although the crashworthy fuel system should perhaps be at the top of the priority listing of needed crashworthy features. As composite airframe structures become more attractive from a cost/weight standpoint, their demonstrated potential to act as good energy absorbers should not be overlooked. Usually, however, design innovations to benefit crashworthiness will equate to a design in excess of the Federal Air Regulations (FAR's), which are intended as minimum requirements only rather than design goals. FAA Order DA 2100.1 clearly states, "Such standards do not constitute the optimum to which the regulated should strive."

Finally, not to be overlooked in the civil area is the very real economic savings that can be gained (in concert with crashworthiness) from the inclusion of an energy absorbing (EA) landing gear. The potential Army savings were addressed earlier and would certainly, to a degree, apply in the civil market. Avoided materiel damage from hard landings alone should go a long way toward justifying an EA gear.

Some design practices such as excellent protective structure around the occupant along with adequate restraint in agricultural aerial application airplanes are now standard procedure. In time, it is hoped that a variety of meaningful crashworthiness improvements will be providing increasingly higher levels of occupant protection and damage avoidance.

NEW REQUIREMENTS OF MIL-STD-1290A AND ADS-36

Hundreds of changes have been made to MIL-STD-1290 since its initial publication, the vast majority of which were to correct typographical errors and to enhance clarification. Nevertheless, a number of significant new requirements did evolve and some of the more important ones, not already mentioned are as follows:

- Type II aircraft have been expanded to include tilt prop/rotor aircraft.
- If system testing is not conducted, then analysis shall be required to show the individual crashworthy components and subsystems function together effectively to achieve the desired overall level of crashworthiness.
- For vertical impacts calculations should include a 1 W rotor lift factor. This is also true for the retracted gear condition.
- For the case of retracted landing gear the seat/airframe/landing gear pod combination shall have a vertical crash impact design velocity change capability of at least 7 m/s (23 ft/sec) at an impact attitude within ± 10° roll and + 15 to - 5° pitch.
- Figure 8 applies for all impact conditions which include an attitude envelope of ± 10° roll and + 15° to - 5°, pitch.
- Neither seats nor litters should be suspended from the overhead structure unless the ceiling is capable of sustaining, with minimum deformation, the downward inertial loads from occupied seats or litters under crash conditions.
- It is desired that in a 15.25 m/s (50 ft/sec) vertical impact that the height of occupiable areas not be reduced by more than 50% and that the surrounding structure not fracture.
- For head impact protection, frangible items, such as optical relay tubes, shall break away at a total force not exceeding 300 pounds.
- It is desired that the landing gear continue to absorb energy even after fuselage contact has been made to maximize the protection afforded by the gear.
- Type II aircraft wings used to support external stores prevent roll over in many accidents and should not be frangible, but should allow the stores to separate under G loads while maintaining the structural integrity of the wing. However, the wing should break off before the fuselage itself collapses in order to maintain fuselage structural integrity.

CONCLUSIONS

- Many helicopter occupants are still being fatally injured in potentially survivable accidents, and the percentage of major injuries and rate of materiel losses are still high, even though the technology and design criteria presently exist to significantly reduce these losses.
- Army aviation mission effectiveness can be significantly enhanced through the application of crashworthiness design to Army helicopters.
- Life-cycle costs can be significantly reduced through the application of crashworthiness design to Army helicopters early in their life cycle.
- MIL-STD-1290A/ADS-36 is a practical, viable, and cost effective requirements document.
- Although higher levels of crashworthiness can be achieved in a complete new helicopter system design, significant improvements can be made in the crashworthiness of existing helicopters through retrofit programs.
- The need exists to continually improve/update helicopter crashworthiness design criteria and standards.
- Military crashworthiness features and technology have direct application to the civil/commercial fleet.

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