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Basic Principles of Helicopter Crashworthiness

By

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Crashworthiness can be defined as the ability of an aircraft and its internal systems to protect occupants from injury in the event of a crash. In general, injury in aircraft crashes can be considered to arise from three distinct sources: (1) excessive acceleration forces; (2) direct trauma from contact with hard surfaces, and; (3) exposure to environmental factors such as fire, smoke, water, and chemicals resulting in burns, drowning or asphyxiation. Consequently, effective crashworthiness designs must consider all possible sources of injury and eliminate or mitigate as many as practical for a given design impact limit. This involves considerations of (1) strength of the container (cockpit and cabin), (2) adequacy of seats and restraint systems, (3) energy attenuation, (4) elimination of injurious objects in occupants local environment, and (5) post-crash factors, principally fire prevention and adequacy of escape routes.

The U.S. Army UH-60 Black Hawk and AH-64 Apache helicopters were the first helicopters built to modern crashworthiness specifications. This paper uses data gained from the

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investigation of crashes of these helicopters to illustrate basic crashworthiness principles and to demonstrate their effectiveness when systematically incorporated into helicopter designs.

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Introduction

The concept of providing occupant crash protection in aircraft is almost as old as powered flight itself. The first few crashes of powered aircraft suggested the need for helmets to provide head protection and leather jackets to prevent serious abrasions. Although seat belts were first developed to retain pilots during acrobatic flight, it did not take long for pilots and designers to recognize the value of occupant retention in a crash. Nevertheless, it was not until the 1940s that scientists and designers, notably Hugh DeHaven and his colleagues, began seriously to approach crash survivability from a total system concept (DeHaven, 1969).

Although most of the current concepts of crash survivability were established over 40 years ago, implementation of these concepts into operational aircraft has been remarkably slow. In fact, fully integrated crashworthy designs had been limited to a few agricultural aircraft until the U.S. Army committed itself to improving the crash survivability of its helicopters during the conflict in Southeast Asia. This work lead to the publication of the Aircraft crash survival design guide which is a compendium of crashworthy design criteria for light fixed-wing and rotary-wing aircraft (Department of the Army, 1989). This guide, now in its fifth edition, has become the primary source of information for crashworthy design criteria for helicopters. Indeed, the criteria specified in the Design Guide were used to establish the design specifications for the Army's UH-60 Black Hawk and AH-64 Apache helicopters and form the basis of the Army's current general crashworthiness design standard (Carnell, 1978; Department of Defense, 1984). The effectiveness of the crashworthiness concepts incorporated into the UH-60 and AH-64 has been proven in numerous crashes of these helicopters (Shanahan, 1991; Shanahan and Shanahan, 1989a and 1989b). Surprisingly, operators of civil helicopters and government regulators have been reluctant to incorporate similar design features into the civil helicopter fleet.

Crash injury

It is imperative to understand that injury and death are not inevitable consequences of an aircraft crash. In fact, most epidemiological studies of crashes have shown that up to 90 percent of crashes are potentially survivable for the occupants (Bezreh, 1963; Haley, 1971; Haley and Hicks, 1975; Hicks, Adams, and Shanahan, 1982; Mattox, 1968; Sand, 1978; Shanahan and Shanahan, 1989b). This assessment is based on the fact that the forces in most crashes are sufficiently low that use of currently available airframe and component technology could prevent occupant injury.

In order to prevent injury in crashes, it logically follows that one must understand how injuries occur. Injury in crashes may be classified as either traumatic or environmental (Table 1). Traumatic injury is due to an adverse transfer of mechanical energy to an individual and is the most common form of injury seen in helicopter crashes. Environmental injury is injury caused by environmental factors such as water leading to drowning, heat leading to burns, or fumes leading to asphyxiation. Environmental injury is usually the predominant form of injury for crashes occurring in water or when a major postcrash fire occurs.

Table 1.

Classification of helicopter crash injury mechanisms

A. Traumatic injury
   1. Acceleration
   2. Contact
B. Environmental injury

Traumatic injury can be described further as contact injury or acceleration injury. In a strict sense, both forms of injury arise from application of force to the body through an area of contact with an accelerating surface. In the case of acceleration injury, force application is more distributed so that the site of force application usually does not receive a significant injury. The site of injury is distant from the area of application and is due to the body's inertial response to the acceleration. An example of acceleration injury is rupture of the aorta in a high sink rate crash. Here the application of force occurs through the individual's thighs, buttocks, and back where he is in contact with the seat. The injury itself is due to shearing forces generated from the aorta's and heart's inertial response to the resulting upward acceleration of the body.

A contact injury, on the other hand, occurs when a localized portion of the body comes into contact with a surface in such a manner that injury occurs at the site of contact ("the secondary collision"). Relative motion between the body part and the contacting surface is required. An example of this type of injury is a depressed skull fracture resulting from the head striking a bulkhead or other rigid object. A mixed form of injury also may occur when acceleration generated by a localized contact produces injury at a site distant from the point of contact as well as at the point of contact. A localized head injury with contrecoup brain injury is the classic example of this mixed form of injury.

Distinction is made between these various mechanisms of injury since prevention necessarily involves different strategies. The prevention of acceleration injury requires the attenuation of loads in a crash so that excessive loads are not transmitted to an occupant. Typically this is achieved through the use of energy absorbing landing gear, crushable under floor structure and energy absorbing seats. Prevention of contact injury requires the implementation of strategies that will prevent body contact with potentially injurious objects. This may be achieved through body restraint systems, ruggedized airframe designs to prevent intrusion of structure or high mass components into occupied areas, and removal of or "delethalization" of objects within the potential strike zone of occupants. Prevention of environmental injury involves a host of strategies tailored to the particular environmental hazard of interest. Certainly, in this category, the most significant hazard is postcrash fire.

Basic principles of crashworthy design

Crashworthiness can be defined as the ability of an aircraft and its internal systems and components to protect occupants from injury in the event of a crash. The precise relationship between a particular helicopter design and crash injury is complex and engineering solutions may be quite intricate. However, the basic principles of crashworthiness design are quite straightforward, even intuitive. These principles may be summarized by the acronym "CREEP" as follows:

C - Container
R - Restraint
E - Energy absorption
E - Environment (local)
P - Postcrash factors

Container

The container is the occupiable portion of the helicopter -- the cockpit and cabin. It should possess sufficient strength to prevent intrusion of structure into occupied spaces during a survivable crash, thus maintaining a protective shell around all occupants. Since structural collapse causing severe contact injury is one of the most frequent injury hazards encountered in helicopter crashes, this point cannot be overemphasized (Figure 1). The container must also be designed to prevent penetration of external objects into occupied spaces. Another consideration

Figure 1. A crash where the roof completely collapsed, crushing the two rear cabin occupants. Surprisingly, one survived due to excellent restraint and a roof mounted, energy absorbing seat that collapsed with the roof.

related to the container is high mass item retention. Transmissions, rotor systems, and engines should have sufficient tie-down strength to ensure that they do not break away and enter occupied spaces in survivable crashes. Finally, the floor and the nose of the helicopter should possess sufficient structural strength and be shaped so as to prevent plowing or scooping of earth during crashes with significant longitudinal velocity since plowing decreases stopping distances and results in higher decelerative loads. In general, cockpit/cabin designs should allow for no more than 15 percent dynamic deformation when subjected to the design crash pulse.

Restraint

A frequent occurrence in aircraft crashes is that either the seat tears from its attachments or the restraint system fails (Figures 2 and 3). This results in ejection of the occupant or it allows him/her to strike injurious objects. Regardless of the

Figure 2. This seat became dislodged from its attachments with the pilot still strapped into it during a UH-1 crash. The pilot's fatal injuries were, in large part, attributed to the failure of his seat to retain him in place during the crash.

Figure 3. The most commonly identified failure point in most restraint systems is at the attachment hardware where the webbing is attached to the seat or floor.

strength of the container, if the occupant is not appropriately restrained throughout the crash sequence, his/her chances of survival are severely reduced. Seats, restraint systems, and their attachments should have sufficient strength to retain all occupants for the maximum survivable crash pulse. In addition, seat attachments should be designed to accommodate significant degrees of floor warpage without failure.

Since contact injury occurs at least five times more frequently than acceleration injury, careful consideration should be given to restraint system design (Shanahan and Shanahan, 1989b). In small aircraft with confined interiors (most helicopters), both lap belt and upper torso restraint are essential for crash survivability of crew and passengers. Not only does upper torso restraint reduce upper body flailing and contact with interior structures, but it also provides for greater distribution of acceleration loads across the body. A tie-down strap (crotch strap) incorporated into the restraint system helps reduce the potential for "submarining." Submarining is a situation where the lap belt rides up above the bony structure of the pelvis and compresses the soft organs of the abdomen. This frequently results in serious abdominal injury or spinal distraction fractures. Many so called "seat belt injuries" can be attributed to this mechanism.

As an adjunct to standard belt type restraint systems, the U.S. Army is currently developing multibag, airbag systems for use in some of its helicopters (Alem et al., 1991). As in the automobile, these systems have tremendous potential for reducing the incidence of flailing injuries and should be economically adaptable to civil applications (Figure 4).

Energy absorption

Unlike transport category, fixed-wing aircraft, helicopters and light fixed-wing aircraft provide little crushable structure to attenuate crash forces. This is particularly true for the vertical direction ($+G_z$). Consequently, additional means of absorbing crash forces in the vertical direction frequently must be provided to prevent acceleration injury in potentially survivable crashes of helicopters. Kinematic studies of helicopter crashes have shown that the primary crash force vector is vertical in most survivable crashes (Shanahan and Shanahan, 1989a). Furthermore, depending on the type helicopter, vertical velocities may be quite extreme (Shanahan and Shanahan, 1989a).

In general, there are three locations where vertical energy absorbing capability may be integrated into a helicopter design--the landing gear, floor structure, and the seats. The Black Hawk and Apache rely heavily on the fixed landing gear and seats to provide the required attenuation of loads for the 12.8 m/s (42 ft/s) design pulse. The gear alone were designed to handle over

Figure 4. A U.S. Army experimental airbag system being tested in an attack helicopter cockpit mockup. The airbag is mounted on the lower portion of the gunsight.

half of the total occupant energy in a crash with the floor and the seats absorbing the rest. This system has been proven extremely effective since fatalities are rare for vertical impacts up to approximately 15.2 m/s (50 ft/s) in these helicopters. The main disadvantage of this energy management system is that it is heavily dependent on having extended landing gear. Retractable gear helicopters should rely less on the gear and place more capability in the structure, although automatic emergency gear extension systems may prove to be effective. In mounting energy absorbing landing gear, it is important to do so in such a manner that the gear do not disrupt important structure or protrude into occupied areas after their energy absorbing capability has been expended.

Energy absorbing seats have been extremely effective in preventing acceleration injury in crashes with predominately vertical force vectors (Figure 5). Numerous designs now are available through a number of manufacturers. Experience with these seats in crashes has produced several lessons. First, it is essential that seats have adequate tie-down strength so that they are not dislodged by crash forces. Second, designs that provide multi-axis stroking have not been as effective as those providing pure vertical stoking (Melvin and Alem, 1985). The increased head and torso strike zone tends to be far more disadvantageous than the minimal reduction in lateral and longitudinal accelerations

Figure 5. This seat stroked approximately 35.6 cm (14 inches) at 14.5 G in a UH-60 crash with an estimated vertical impact velocity of 15.2 m/s (50 ft/s). The pilot received no spinal injury.

provided by multiaxis designs. Third, the average load level for vertically stroking seats should not exceed 14-15G for military helicopters or 11-12G for civil helicopters (Coltman, Van Ingen, and Smith, 1986; Shanahan, 1991; Singley, 1981). The difference is based on differences in age and general health, and, therefore tolerance to impact, between the military and civilian populations. Finally, it is imperative that adequate stroke distance be provided to preclude "bottoming out" of the seat on structure since this situation results in extremely high acceleration spikes. As a point of interest, at least one manufacturer provides seats which have a variable-load energy absorber so that the seat may be adjusted to accommodate different weight occupants. This feature has considerable potential advantage where the weights of occupants vary significantly.

Local environment

In designing an aircraft interior, it is extremely important to consider the local environment of the occupants at all potential seating locations (Figure 6). A person's local environment refers to the space that any portion of his body may occupy during dynamic crash conditions. Any object within that space

Figure 6. The proximity of the cyclic and collective controls to the pilot is accentuated in stroking (energy absorbing) seats as shown in this demonstration of a UH-60 pilot seat after a severe crash.

may be considered an injury hazard (Figures 7 and 8). As an example, the cyclic and collective controls can pose a significant injury hazard to pilots during a crash, particularly when the visor on the flight helmet is not worn in the down position. The volume of that space will vary depending on the type restraint system anticipated and, to a lesser extent, on the anthropometry of the expected occupants. The maximum head strike distance is reduced by about 50 percent when upper torso restraint is utilized. Clearly, the primary concern must be for hazards within the strike zone of the head and upper torso, but objects within the strike zone of the extremities also should be considered.

It is important to evaluate the local environment of occupants during the design phase of an aircraft since many potentially hazardous objects may be placed outside of the strike zone if they are early recognized as hazards. In many cases placing hazardous objects outside of the strike zone is no more expensive

Figure 7a. Note the shapes and location of the abrasions and lacerations on the left side of the face of the pilot.

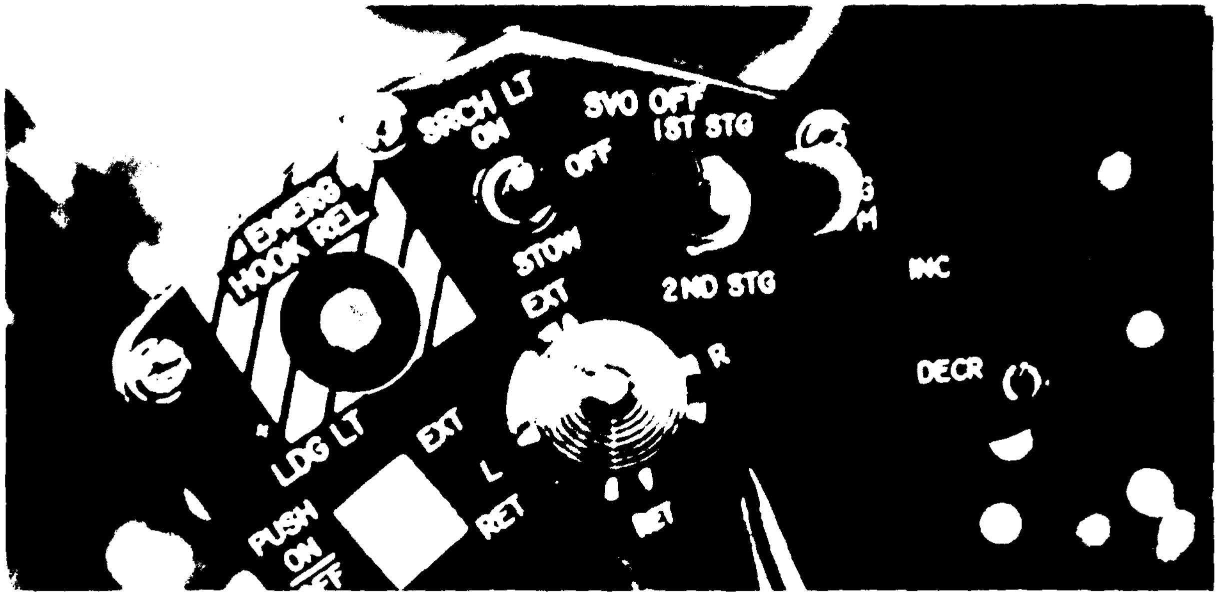

Figure 7b. A comparison of the pilot's injuries with the collective control demonstrates a concordance between his injuries and the metal guard around the "SVO OFF" switch and the "Chinaman's hat" switch. Minute particles of human tissue also were recovered from the switch guard.

Figure 8. Cyclic control recovered from a UH-60 crash shows longitudinal gouges made by the pilot's teeth. The pilot lost several anterior teeth in the crash, but received no other serious injury.

or difficult than placing them within the strike zone. It is simply a matter of recognizing the hazard. Potentially injurious objects that cannot be relocated can be designed to be less hazardous, padded, or made frangible.

Postcrash factors

Numerous aircraft accident victims survive the crash only to succumb to a postcrash hazard. These hazards include fire, fumes, fuel, oil, and water. Both civil and military crash experience has sadly shown that the most serious hazard to survival in helicopter crashes is fire. The design challenge is to provide for the escape of occupants after the crash under a host of adverse conditions. The approach may be either to control or eliminate the hazard at the source, to provide for more rapid egress, or a combination of both.

In the case of postcrash fire, controlling the hazard at the source has proven to be an extremely effective strategy for helicopters (Figure 9). Since the U.S. Army introduced crash resistant fuel systems (CRFS) into its helicopter fleet in the 1970s, there has only been one fire related death in a survivable crash (Shanahan and Shanahan, 1989b; Singley, 1981). Prior to the introduction of CRFS, up to 42 percent of deaths in survivable crashes of U.S. Army helicopters were attributed to fire (Haley, 1971; Singley, 1981). Considering the magnitude of the problem of postcrash fire in non-CRFS equipped helicopters and the incredible effectiveness of CRFS, it is most regrettable that helicopters continue to be produced without crash resistant fuel systems. This situation continues more because of the persistent failure of regulatory agencies to require CRFS use than that of the manufacturers to provide them. Indeed, many manufacturers have offered CRFS as an option, but few operators have opted to

Figure 9. **Fuel cell torn loose from Apache helicopter during a nonsurvivable crash. Fuel was completely contained; there was no postcrash fire.**

pay the additional cost, trusting instead that their helicopter will not be involved in a crash. Fortunately, significant progress now is being made in the regulatory arena. The U.S. Federal Aviation Administration (FAA) issued a notice of proposed rulemaking (NPRM) in 1990 to require CRFS in all newly certified helicopters, and at least one airframe manufacturer has incorporated CRFS into all airframes constructed since about 1982.

Other strategies employed to prevent the consequences of fire and fumes are to use fire retardant and low toxicity materials in the construction of aircraft and to provide physical separation of flammable materials from ignition sources and occupied areas.

For over water operations, the most important postcrash hazard is water. Because of their high center-of-mass, most helicopters rapidly invert and sink upon water entry whether the entry is controlled or uncontrolled. A high proportion of victims involved in water landings or crashes drown because they are unable to egress. Solutions to this problem have included use of helicopter flotation devices, improvements in interior emergency lighting, increased numbers of emergency exits, personal underwater breathing devices, and, most importantly, intensive underwater egress training programs.

Implementing crashworthiness

From the above discussion, it is apparent certain crashworthy features are more important than others in preventing injury in crashes. Although an integrated crashworthy design addressing the five basic factors is the most effective approach to reducing crash injury, significant improvements in crash survivability can be achieved through a more modest approach. This is particularly true for existing helicopters where it is usually not economically feasible to make extensive structural modifications. Frequently, relatively minor modifications such as replacing restraint systems or moving hazardous objects in the strike zone can prove highly effective. How does one rationally choose which features are more important than others? Accident statistics are useful for identifying the greatest hazards both in terms of frequency of occurrence and in terms of the seriousness of injuries caused by the hazard.

Most analysts agree that the greatest threat to life in helicopter crashes is postcrash fire (Bezreh, 1963; Department of Transportation, 1990; Haley and Hicks, 1975). The frequency of fire in otherwise survivable crashes and the overwhelming effectiveness of crash resistant fuel systems clearly dictates CRFS be considered the single most important crashworthy feature in a helicopter. It should be stressed that a fully crash resistant fuel system includes not only a crash resistant fuel cell but also breakaway, self-sealing fittings at critical locations in the fuel lines, automatic backflow shutoff valves in fuel vent lines, judicious placement of ignition sources and fuel lines, isolation of fuel sources from occupied spaces, and appropriately designed fuel diverters.

What standards to apply in designing such a fuel system presents somewhat of a dilemma. The standards specified in MIL-T-27422B have been proven extremely effective in preventing fire in all survivable crashes of U.S. Army helicopters (Department of Defense, 1971; Shanahan and Shanahan, 1989b; Singley, 1981). However, exclusive of the ballistic requirements, these standards are considered by many to be excessive for civil helicopter operations. This perception lead to the development of the reduced standards specified in the FAA notice of proposed rulemaking for CRFS (Department of Transportation, 1990). Numerous civil helicopters have been equipped with fuel systems designed essentially to these standards, and preliminary results from crashes indicate that these systems may be equally effective as the military specification systems, at least for light helicopters with high inertia rotor systems. These standards may prove less adequate for transport category helicopters and smaller helicopters with low inertia rotor systems due to their tendency to crash at higher sink rates (Shanahan and Shanahan, 1989a). Time and additional crash experience most certainly will clarify this issue.

The second most serious injury hazard in helicopter crashes is contact injury. Since these injuries are due to a variety of mechanisms, the solution to the problem is considerably less straightforward than in the previous example. Probably the most important factor to consider in modifying existing helicopters is occupant restraint (Figure 10). Seats and restraint systems should, as an absolute minimum, meet the retention standards specified in the current Federal Aviation Regulations Part 27 (Department of Transportation, 1992). In most helicopters, it would be advisable to increase these standards by a factor of 1.5-2.0. Cockpit seats should be equipped with five-point restraint harnesses and all passenger seats should have four- or five-point harnesses. Lap belt only restraint should be considered inadequate. Potentially hazardous internal items such as a fire extinguisher and first-aid kits also should be adequately restrained and moved from potential strike zones or padded. There is no rational justification for using lesser standards for internal object retention than those applied to occupant retention.

Of almost equal importance in preventing contact injury in helicopter crashes is strength of the container. Contact injury is due to relative motion between the occupant and potentially injurious structure. Occupant motion can be controlled with well designed restraint systems, but if structure collapses onto occupants, the effectiveness of occupant restraint becomes relatively unimportant. Fortunately, structural collapse is not a consideration in all crashes, whereas occupant restraint always

Figure 10. Both pilots survived a very severe UH-60 crash with serious injuries. Survival was due to pilots being restrained in their energy absorbing seats.

is. Also, it is difficult, and frequently prohibitively expensive, to increase structural strength through a retrofit program. For this reason, occupant restraint is emphasized over structural integrity issues when considering modification of existing airframes. Nevertheless, one should remember that the properly restrained human is capable of withstanding accelerations of up to 40G without sustaining injury, and a container designed to a lesser standard will, under extreme survivable crash conditions, compromise occupant survival. Consequently, in newly designed helicopters, structural strength and occupant restraint should receive equal consideration. Design compromises in this area should be made with a clear understanding of the expected crash environment for the helicopter under design as well as with an understanding of crash injury mechanisms and human tolerance to impact.

A final consideration in preventing contact injury is high mass item retention. Current FAA standards for high mass item retention such as transmissions and engines are extremely low (Department of Transportation, 1992). Although a relatively infrequent hazard, intrusion of these components into occupied spaces frequently has tragic consequences. The results are particularly vivid when rotor systems penetrate the cockpit (Figures 11a and 11b). When appropriate consideration is given to the placement of these items with respect to occupied spaces and to their tie-down strength to the airframe, intrusion of these items can be practically eliminated as a hazard in survivable crashes (Shanahan and Shanahan, 1989b; Singley, 1981). Current FAA retention standards should be increased by a factor of at least 2.0.

The last type of injury to consider is acceleration injury. Pure acceleration injuries are relatively uncommon in helicopters with well designed conventional seating systems, except at the extremes of the crash survivability envelope. The most common acceleration injury seen in helicopter crashes is spinal compression fracture which may occur at 25-30G_z in young to middle aged adults. Only a small portion of potentially survivable crashes exceed 30G at the floor, and a properly designed seat should prevent the occupant from experiencing loads significantly in excess of this value. However, poorly designed seats can produce spinal fracture in impacts as low as 8-10G_z. Typically, spinal fractures in low to moderate velocity crashes are caused by mounting seats above rigid panels or other nonfrangible objects such as

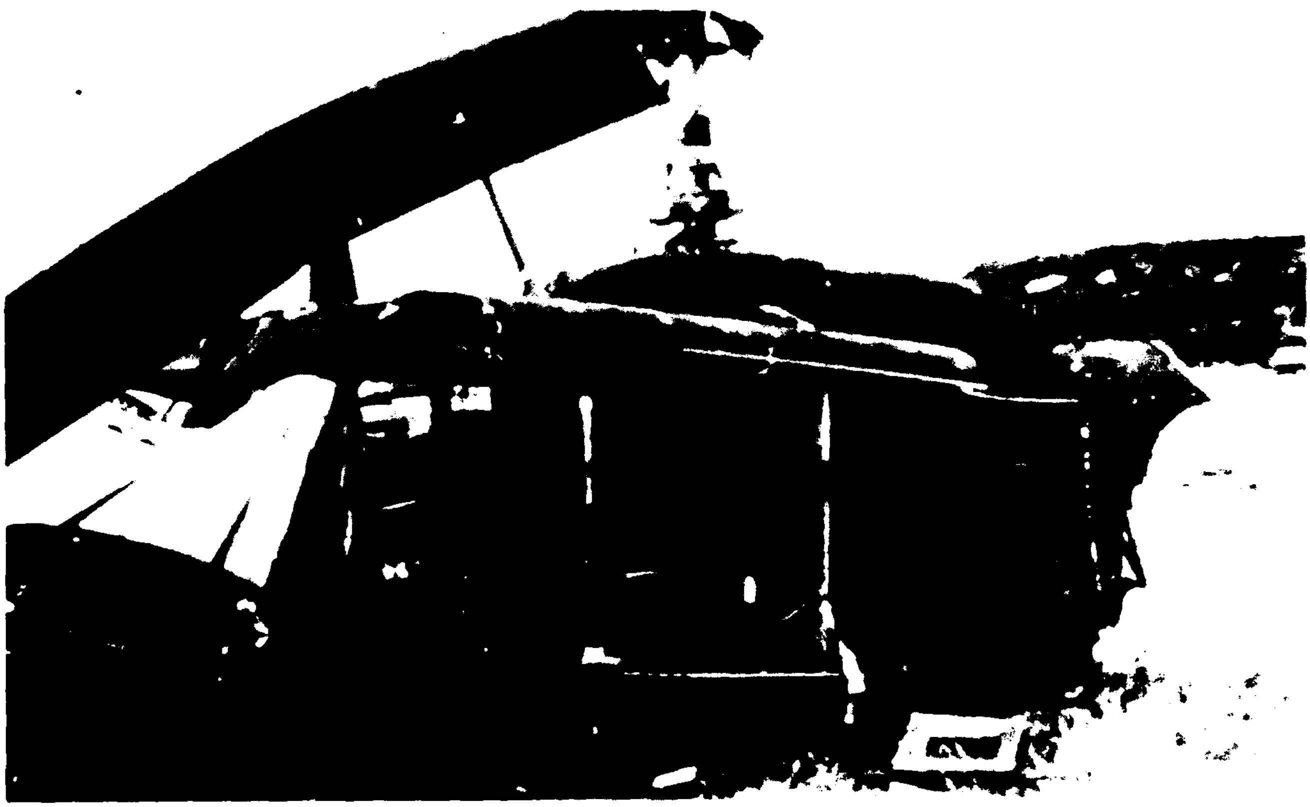

Figure 11a. Rotor intrusion into occupied spaces in survivable crashes is a serious hazard in many helicopters.

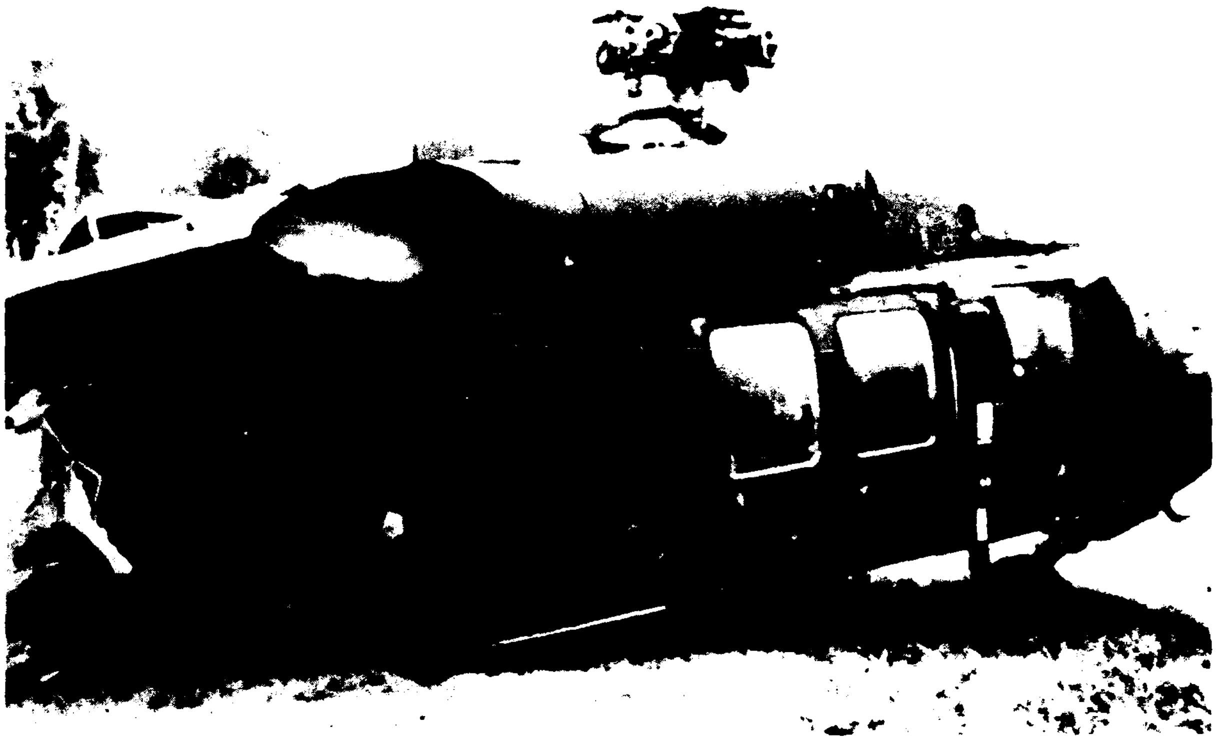

Figure 11b. Crashworthy design of UH-60 prevented dislodgement of the transmission during a crash. The blades broke away rather than flexing into occupied spaces.

batteries and from mounting relatively rigid seats directly on bulkheads or beams. In the first case, seats collapse onto unyielding objects causing the occupants to experience excessive vertical accelerations. In the later case, rigid bulkheads or structural members transmit excessive forces from the ground directly to the seat occupants.

To prevent acceleration injuries over the range of survivable impacts, all helicopters should be equipped with energy absorbing seats. Federal Aviation Regulations Parts 27 and 29 specify dynamic testing requirements for seats in newly certified helicopters (Department of Transportation, 1992). These requirements are adequate for light helicopters, particularly those with relatively high inertia rotor systems. However, for larger helicopters with low inertia rotor systems, one should consider using the more rigorous requirements specified in MIL-S-58095A (Department of Defense, 1988). Experience with the UH-60 and AH-64 suggests that large helicopters with low inertia rotor systems will crash at much higher vertical velocities than previously anticipated. These high sink rate crashes require significantly better load attenuation in the seats than specified in the FAA require-

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ments to provide protection against spinal injury. A less crash-worthy seat in either of these helicopters would have resulted in an unacceptable injury rate in potentially survivable crashes (Shanahan, 1991; Shanahan and Shanahan, 1989b).

In summary, the seating system in an aircraft must be viewed as part of the overall energy management system in a crash. The degree of capability built into the seat should be based upon an assessment of the projected or known crash environment and the load attenuation capability of the underfloor structure and landing gear. Above all else, designs that permit bottoming out on nonfrangible structure in a potentially survivable crash should be avoided.

Conclusions

Crashworthiness is not inherent in most aircraft designs since features that enhance crash performance do not usually improve operational performance or efficiency. There is usually a cost associated with crashworthy enhancements to an airframe. This cost may be expressed in increased base price, decreased performance, or increased weight. The latter two factors translate into increased operating cost. Counterbalancing these factors are the two major benefits provided by a crashworthy aircraft. First, crashworthiness results in reduced injury in crashes and, second, enhanced airframe crashworthiness frequently reduces repair costs or renders what would otherwise have been a destroyed airframe repairable after low velocity impacts. For example, the Black Hawk and Apache have demonstrated their ability to absorb hard landing impacts of up to 6.1 m/s (20 ft/s) with minimal or no damage to the aircraft and no injury to their occupants. For most other helicopters, similar impacts would have resulted in a destroyed airframe and the potential for serious injury to the occupants.

Considering these factors, the degree of crashworthiness incorporated into any helicopter design will always involve trade-offs between the perceived risk of a crash and increased cost. Unfortunately, in this assessment, the risk of a crash tends to be grossly overoptimistic, particularly when made by individuals responsible for managing development costs. This is equally true for the civil and military communities. As with most advancements in safety, significant advancements in crashworthiness are not likely to be made unless required by regulation. The challenge for regulators is to establish realistic crashworthiness standards that will be effective yet not cost prohibitive. For instance, it would be unreasonable to impose the complete U.S. Army crashworthy standards on civil helicopters of less than 10,000 pounds gross weight (Shanahan and Shanahan, 1989a and 1989b). Nevertheless, certain portions of the Army standards would be beneficial for all helicopters. The challenge to design engineers is to implement the standards through designs that minimize costs while maximizing effectiveness.

Appropriate standards can only be established and revised through a program of detailed accident investigation where injury causation is investigated and documented as thoroughly as accident causation. This is a glaring deficiency of most agencies charged with the investigation of aircraft crashes today, and it explains why few accident data bases contain sufficient information upon which to develop realistic crashworthy standards. This is a problem that needs to be addressed by users, manufacturers, industry organizations, investigation agencies, and regulators alike.

The bottom line is that crashworthiness works. Figure 12 is derived from a recent publication comparing injury rates in a conventionally designed helicopter (UH-1) with a crashworthy helicopter (UH-60) (Shanahan, 1992). This graph plots mortality rate against vertical velocity at impact for both helicopter

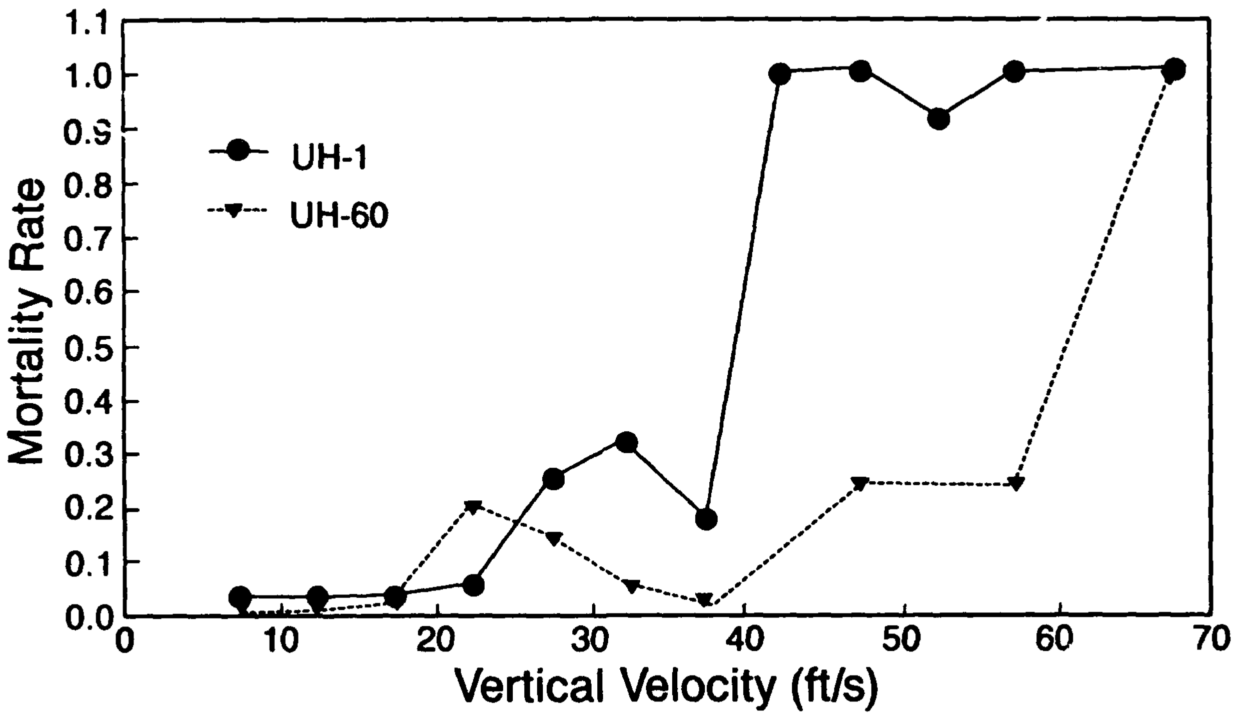

Figure 12. Cumulative frequency plot depicts the increasing probability of sustaining a fatal injury as vertical impact velocity inreases for the UH-60 and UH-1.

types. The mortality rate was calculated at 5 ft/s intervals of vertical impact velocity for each helicopter type and plotted on the graph. Mortality rate was calculated by determining the number of fatalities occurring within each increment of vertical velocity and dividing by the total number of occupants exposed to impacts with vertical velocities within the increment. Notice that both curves demonstrate a threshold velocity above which mortality essentially becomes one hundred percent. This threshold occurs in the UH-1 at a vertical velocity of approximately 12.2m/s (40 ft/s) and in the UH-60 at about 18.3 m/s (60 ft/s). Clearly, the UH-60 is able to provide protection to its occupants in considerably more severe crashes than the conventionally designed UH-1.

The technology is currently available to vastly increase the crashworthiness of the civil and military helicopter fleet worldwide. What is lacking is commitment and the allocation of necessary resources. If the true cost to society of injury incurred in helicopter crashes were assessed it would clearly show that a long term commitment to crash survivability would, in fact, be cost effective.

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