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Helicopter Crashworthiness — Part One

In this first of a two-part series, the author reviews efforts to study and improve crash survival and helicopter accident.

by

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Perceived occupant safety is an important part of the public acceptance of helicopter transportation. There are three levels of design effort involved in aviation safety: (1) preventing the occurrence of an emergency, (2) minimizing the effect of an emergency, and (3) minimizing injuries in a crash. This paper discusses the present status of civil helicopter crashworthiness activities in the United States for the third level — crash survival. It combines information from References 1, 2, and 3 with later unpublished information.

Why Improve Crash Survival?

Why should one consider improvements in crash survival? The answer is that some accidents will continue to occur regardless of aircraft design features. How do these accidents affect the occupants? In the United States, the National Transportation Safety Board (NTSB) and Federal Aviation Administration (FAA) collect data on accidents. These data for U.S.-registered helicopters from 1982 through 1986 were analyzed in an evaluation of configuration effects on occupant injuries.

Serious (major/fatal) injuries were categorized by the initiating accident cause factor for helicopters with single turbine engine and twin-turbine engines and it was found that between 25.8 and 34.4 percent of the known serious injuries in single and twin-turbine helicopters, respectively, occurred in accidents resulting from material failures.

Airframe and engine manufacturers will certainly continue to try to eliminate material failures completely as accident causes. Yet, even if they were to succeed, occupants would still be injured by accidents resulting from other causes; 74.2 and 65.5 percent of the occupants involved in crashes of single and twin-turbine helicopters, respectively, would still be seriously or fatally injured. Obviously, there is good reason for continuing to improve crash survival features of helicopters.

The Rotorcraft Airworthiness Requirement Committee (RARC) of the Aerospace Industries Association of America (AIAA) established a Crashworthiness Project Group (CPG) to develop and recommend realistic crashworthiness criteria for future civil helicopters. The members of the CPG represented Bell Helicopter Textron Inc., Boeing Helicopters (formerly Boeing-Vertol Helicopters), McDonnell Douglas Helicopters (formerly Hughes Helicopters), and Sikorsky Aircraft. The resulting recommendations (2) were for energy-attenuating seats with shoulder harnesses and crash-resistant fuel systems.

The CPG limited its consideration to future civil helicopters for which a type certificate application has not yet been made. This allows the designer to plan on larger engines and any other changes needed to accommodate the weight penalty of safety features. Thus, a balanced design is maintained if the safety improvements are included in the initial concept. A large weight increase on a current helicopter can degrade the safety it already has by reducing hover and climb performance.

Background

The historic regulatory approach has been to ensure that an aircraft is safe to fly by requiring a minimum static strength level. U.S. Code of Federal Aviation Regulations (FARs) 14, Parts 27 and 29 specify these for helicopters with gross weights under 6,000 pounds (2,722 kg) and over 6,000 pounds (2,722 kg), respectively. Helicopters are designed to meet or exceed these minimum static strength standards. The present FARs (27.561 and 29.561) have only one specific crash requirement: that the helicopter be able to endure a five-feet-per-second (1.5 m/s) drop impact without causing serious injury to occupants using safety equipment.

The present helicopter seat has a static strength requirement of 4G forward, 4G downward, 2G lateral, and 1.5G upward for a 170-pound (77 kg) occupant. The manufacturer must verify that a seat meets the static strength requirements by analysis and by performing a static pull test on a test seat for each of the specified directions.

Civil vs. Military

The U.S. Army and others have analyzed accidents involving Army helicopter and light fixed-wing aircraft to determine occupant crash survivability factors and what improvements should be investigated. The culmination of these research activities was the Crash Survival Design Guide, the latest revision of which is TR 79-22 (4). The first major use of this military research was the development, production, and installation of the crash-resistant fuel system (CRFS) to prevent massive post-crash fires in survivable army helicopter accidents.

The first CRFS was installed by Bell Helicopter Textron Inc. (BHTI) in the UH-1H in May 1970. Since CRFS introduction, there have been very few thermal fatalities in survivable Army helicopter accidents. This is an outstanding safety accomplishment. However, the U.S. Army accepted a large weight penalty to ensure the success of the CRFS. The situation is different for the commercial operator.

The military gives the helicopter manufacturer specific requirements for a military helicopter application. The military must get exactly what it specified or it will not accept the helicopter. For commercial models, the manufacturer designs, tests, qualifies, and produces a helicopter that meets or exceeds the requirements in the FARs as interpreted by the FAA. Having done so, the manufacturer must then sell the helicopter in a competitive market to an operator who in most cases must make a profit in an even more competitive market. Thus, it is RARC's position that safety requirements for future civil helicopters should be improved to realistic and beneficial levels, not to a mandated, overly severe level based on specific military requirements.

The crash conditions for civilian helicopters differ from those for military helicopters, and therefore the criteria for crash safety features also differ. The vertical helicopter crash condition is the most important criterion that affects helicopter design. Figure 1 (4) shows the vertical velocity component of U.S. Army light fixed-wing and rotary-wing aircraft involved in survivable accidents. It indicates that 95 percent of those accidents occurred with a vertical velocity component of 42 feet per second (12.8 m/s) or less. A more recent study limited to U.S. Army helicopters (5) indicated that the helicopters involved in 95 percent of survivable accidents had a vertical velocity component of 30 feet per second (9.1 meters per second — m/s) or less (Figure 1). The recent FAA civil helicopter crash scenario study (3) indicates that 95 percent of survivable civil helicopters involved in accidents impact at 26 feet per second (7.9 m/s) or less, as shown in Figure 1. Thus a realistic civil helicopter criterion for vertical impact is 26 feet per second (7.9 m/s), and not the 42-foot-per-second (12.8 m/s) military requirement. It should be noted that at 26 feet per second (7.9 m/s) the kinetic energy that must be attenuated is 27 times that which must be attenuated at the present five-feet-per-second (1.5 m/s) impact standard of the FARs.

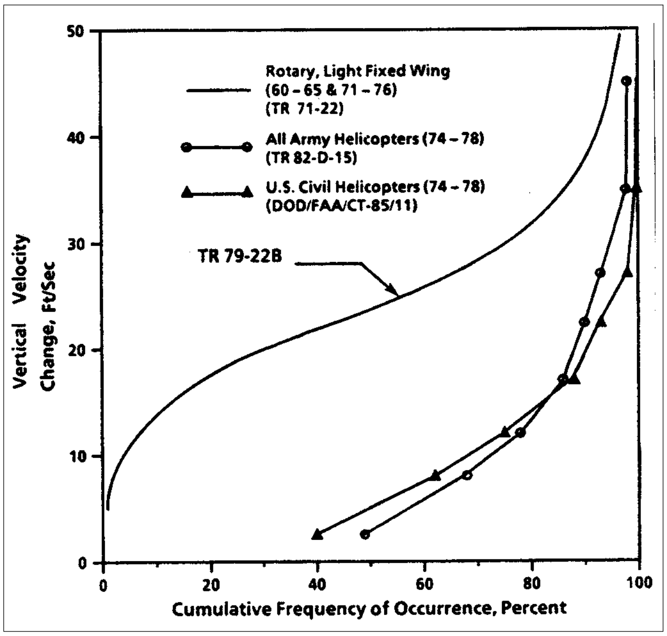

Figure 1

The crash scenarios of U.S.-registered civil helicopters were analyzed in Reference 3 to determine crash safety criteria. The frequency of injuries, their severity per the Abbreviated Injury Index, and the type of crash scenario were combined to rank the crash scenarios by their injury potential (Table 1). This study showed that the six most serious crash hazards were:

- Post-crash fires;
- Excessive deceleration loads;
- Unusual aircraft impact conditions due to wire strikes;
- Occupant restraint problems/clearances, allowing striking of structure;
- Lack of available shoulder harness, allowing striking of structure; and,
- Injuries that prevented escape in water and led to drowning.

With the exception of wire strikes, the remaining five hazards can be significantly reduced by an energy attenuating (absorbing) seat with shoulder harness for each occupant and a crash-resistant fuel system.

Crash Survival Requirements

Crash survival has four basic requirements:

- Maintain a livable volume;
- Restrain the occupant;
- Keep occupant crash loads within human noninjury tolerance; and,
- Provide means and time to escape.

Livable Volume

The first requirement is to maintain a livable volume around the occupants throughout the crash sequence. It is quite meaningless to invest in special seats and restraints only to have the roof structure crush down to the floor. Some fuselage deformation into the cabin is acceptable as long as it does not significantly interfere with the occupants' living space. The fuselage should be a rugged structure that will accept some localized deformation.

Occupant Restraints

Injury studies of U.S. Army helicopter occupants in (Reference 4) shows that life-threatening injuries occurred primarily to the head, neck, body torso, and spine (Figure 2). Tolerance to impact loads can be changed significantly by the method of restraint. The tolerances shown in Table 2 are for a young male aviator in good physical condition. They can vary with factors such as age, muscle tone, rate of onset, and duration. The tolerances for civilian occupants would be lower, but the relative improvement due to restraints should be comparable.

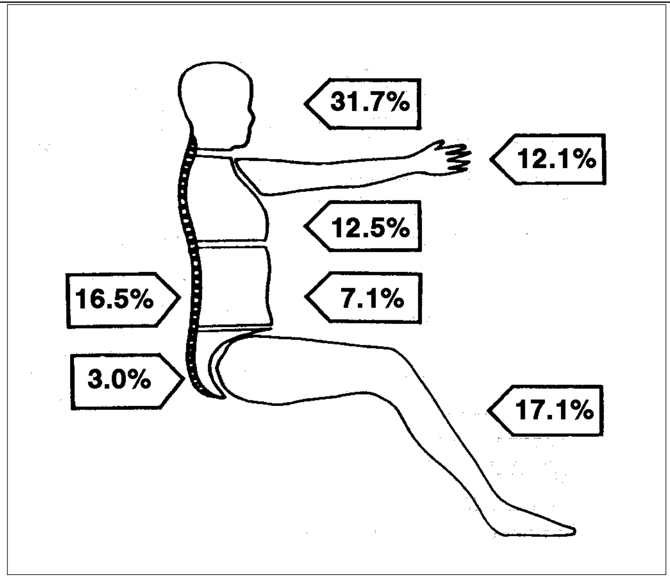

Figure 2

	Human Tolerance (Uninjured)	
	Lap Belt Only (Ref. 6)	Harness & Lap Belt (Ref. 4)
Longitudinal ($-G_x$)	15 G (0.002 Sec)	45 G (0.1 Sec) 25 G (0.2 Sec)
Vertical ($+G_z$)	4 G (Uninjured)	25 G (0.1 Sec)
Lateral ($\pm G_y$)	11 G (0.1 Sec)	20 G (0.1 Sec)

Table 1

In the forward direction, eyeballs out (as in a head-on nose impact), the human body is capable of withstanding about 15Gs with a lap belt only, assuming that the area in front is clear of obstructions. However, the addition of a shoulder harness to restrain the upper torso increases the uninjured tolerance in this direction to about 45Gs, a three-fold increase.

The most important impact direction for a helicopter occupant is vertical (or eyeballs downward). A shoulder harness increases human tolerance without injury for the vertical direction from 4Gs to 25Gs, an improvement factor of six. Laterally, the shoulder harness increases tolerance by a factor of two.

Not only does the shoulder harness prevent many disabling or fatal injuries during many impact sequences, but it also permits the occupant to remain conscious and coherent by preventing a severe head impact. This can be important if the time to escape is short, as in a water crash. The reason a shoulder harness is so effective in the vertical impact or vertical component is that it holds the upper torso upright, keeping the spine aligned properly and allowing it to carry much higher crash loads.

The position of the occupant at impact is important. The occupant must sit upright and against the seat back or a shoulder harness cannot function properly. Seat strength is important, but increasing the vertical seat strength without ensuring that a shoulder harness is used is a meaningless waste of time, money, and weight. The tolerance of the human, with lap belt only, to vertical impact is 4Gs, above which body flailing is expected. Thus, a 20G seat with only a lap belt would be a weight penalty that made no improvement in injury prevention.

Comparing major and fatal injuries in survivable accidents for civil and military helicopters. Note that the injury percentages are fairly similar for the different type aircraft, except for the spine injuries. This indicates that more than 30 percent of the major and fatal injuries in survivable civil helicopter accidents were related to the spine. This is nearly twice as high as for the military occupants. One of the differences is believed to be the difference in age of the occupants. Reference 3 indicates that the average age of the military pilots was 26 years, whereas the average age of general aviation pilots was 38.

The effect of age on the spinal injury tolerances indicated that the amount of load to cause spinal compression fracture (on cadavers) decreased dramatically as the person's age increased (7). Civil helicopter occupants, being older, have less tolerance to impact than military occupants.

The RARC Crashworthiness Project Group recommended to the FAA that a shoulder harness be required for all occupants for future helicopter designs. They also recommended that the torso restraint system specification SAE AS-8043, developed by the Society of Automotive Engineers (SAE), be used in either the dual or diagonal shoulder belt configuration. SAE AS-8043 was compatible with dynamic seat testing recommended by the General Aviation Safety Panel for helicopters and for light fixed-wing aircraft. The SAE AS-8043 would double the lap belt loop strength from 3,000 pounds (13,345 newtons — N) to 6,000 pounds (26,689 N) and provide a 2,500-pound (11,121 N) shoulder belt. The FAA later created a new Technical Standard Order, TSO C114, Torso Restraint System, which included SAE AS-8043. The comment, "A passenger would not wear a shoulder harness if he had one," is typically voiced by people opposed to shoulder harness installations. The effectiveness and use of shoulder harnesses were determined from accident data of Reference 3. Table 3 shows the use of restraints by occupants of front and rear seats in civil helicopter accidents.

Restraint System Component	Front Seats (Percent)	Rear Seats (Percent)	Total (Percent)
Lap Belt			
Availability rate	97.8	100.0	98.2
Usage rate*	100.0	98.0	99.7
Shoulder Harness			
Availability rate	42.5	11.1	36.6
Usage rate	83.6	100.0	84.6

Table 2

Severity of Injury	With Upper Torso Restraint (%)	Without Upper Torso Restraint (%)
Moderate AIS = 1 or 2	84.6	60.0
Severe AIS = 3 or 4	9.6	34.3
Life Threatening AIS = 5 or 6	5.8	5.7

Table 3

The severity of injuries sustained by occupants of civil helicopter accidents given in Reference 3 data shows the effectiveness of the shoulder harness. Table 4 shows the percentage of occupant injury grouped by moderate, severe, and life-threatening injury severity by Abbreviated Injury Index (AIS) codes.

This shows that only 9.6 percent of those wearing a shoulder harness had severe injuries, compared with 34.3 percent of those using lap belt only.

Although each accident is unique and shoulder harness effectiveness may vary for a particular impact condition, the shoulder harness can significantly reduce injuries for the helicopter fleet. It should be noted that even with a shoulder harness, some injuries still occur. Thus another design feature is still needed for the attenuation of energy. *[See also "Shoulder Harness Restraints Considered" by Allen K. Mears in the July 1989 issue of Flight Safety Foundation's* Accident Prevention. *— Ed.]*

Energy Attenuation of Crash Loads

Impact dissipates the kinetic energy of a moving mass to bring it to a stop. Designs for aircraft crash protection aim to manage this energy dissipation and thereby limit the load transmitted to the occupant to a tolerable noninjurious level. This is typically called "energy attenuation". (Some people refer to it as "energy absorption".) Energy attenuation is analogous to a hydraulic pressure regulator that takes an input of various high pressures from a pump but allows only an output of a constant lower pressure. If the "constant lower pressure" is equivalent to a load that the spine can tolerate without serious injury, the system is referred to as an energy attenuating system. Thus an energy attenuating seat will accept the kinetic energy of the occupant and seat in a crash, but limits the vertical crash loads transmitted to the occupant. It spreads the load over a long period by slowing down the occupant over a distance (the seat stroke). The effect of stroking is shown by the formula for the average load during deceleration, assuming a triangular pulse:

$$\frac{G_{avg}\ (\text{Velocity})^2}{2_{gs}}$$

Where:
G_{avg} = average load applied as a multiple of the object weight.
Velocity = initial impact velocity expressed in feet per second (final velocity is zero)
g = 32.2 feet per second2 squared (gravitational constant)
s = stopping distance in feet.
Note: Peak load would be twice the average G.

For example, if an object impacts at 20 feet per second (6.1 m/s), and stops in 0.25 inch (0.64 cm), it has an average G load of 298G. If it strikes at the same velocity but stops in four inches (10.2 cm) of uniform stroking, its average G load is 18.6G. The latter G load is within human tolerance of non-injury loading, whereas the former is not. In the same way, an energy attenuating seat allows the occupant and seat pan to decelerate over a stroking distance while limiting the vertical loads transmitted to the occupant. Average G loading is often used as a limiting criterion in the design of energy attenuating seats. The goal is to use the shortest stroking distance that limits the load on the occupant to a noninjurious level.

One must be careful when using average G loads in relation to an aircraft crash. The G loading experienced at each point in the aircraft is unique and determined by its stopping distance. For instance, in the case of an aircraft that collides head-on with an obstacle, the seats are subjected to progressively lower G forces the farther aft they are located due to the energy absorbing effect as the fuselage crushes. Average G load, a meaningless and misleading concept for an accident, should be used only to describe the unique loading conditions at a specific point.

Figure 5 shows a simplified version of the crash loads history that occurs in a severe, flat impact with a high vertical deceleration component for a typical helicopter. The skid gear absorbs crash energy until the fuselage hits the ground. If the helicopter has typical oleo wheel gear, this may not absorb much energy before it fails, because oleo motion is rate sensitive. (Specially designed oleos can be made to function at the higher crash impact speeds.) Likewise, if the gear is retracted at impact or the impact terrain (such as water) precludes landing gear functioning, the landing gear will absorb no energy.

Since the fuselage is fairly rigid, the G loading on the floor would peak out at a very high load. The standard aircraft seat will fail a few Gs higher than its design criteria, thus allowing the occupant to free-fall until he strikes the cabin floor. At this point, the occupant's body will try, unsuccessfully, to deform the cabin floor. This will result in extremely high and intolerable (probably fatal) loads. A rigid seat of high strength would only prolong the time before the seat fails and the occupant is once again in free-fall to the cabin floor. If an energy attenuating seat is used in this same impact, the landing gear and fuselage would see the same loading but the seat will allow the occupant to be slowed to a stop while applying a controlled tolerable load. As long as the seat pan loads do not exceed 23G for more than 5 milliseconds, the occupant with a shoulder harness restraint should not be seriously injured (8). Since, in this case, the energy attenuating seat was stroking at a constant 14.5G load, the occupant loading did not go into the hazardous zone. The FAA has recently established a limit of 1,500 pounds (680 kg) or less measured in a lumbar load cell of a Part 572 instrumented dummy (9). It should be noted that an energy attenuating seat cannot function unless a shoulder harness is used and the occupant is against the seat back.

Energy attenuating seats were first required by the U.S. Army in the Utility Tactical Transport Aircraft System (UTTAS), which was to become the Sikorsky UH-60A. The UH-60A energy attenuating crew seat has a maximum of 16 inches (40.6 cm) stroking distance. This required a hole in the floor to allow seat pan motion if the full stroke was needed. The seat, which uses an inverted-tube energy attenuator, entered service in 1978.

Boeing Helicopters, under NASA contract NAS1-14637, developed prototype energy attenuating passenger seats. The floor-mounted seat had a wire/roller energy attenuator mounted in the center leg braces. A ceiling-mounted seat design had a wire/roller energy attenuator mounted to the top of the seat back corners. As the seat stroked down, it pulled the wires through the seat-mounted rollers, thereby absorbing energy by bending wire. Boeing Helicopters developed this latter seat design under U.S. Army contract, and it was subsequently used as the UH-60A troop seat.

The first civil aircraft to go into production with an energy attenuating seat for each occupant was BHTI's Model 222, first delivered in 1980. In a crash with high vertical forces, the crew seat slides down vertical guide rails. This drives down a center tube, which crushes a carbon epoxy tube that is an energy attenuator. The passenger seats use a crushable rigid foam block beneath the seat pan to crush at the same 14.5G level for a 170-pound (77 kg) occupant as does the crew seat.

BHTI's Models 214ST and 412 share a common energy attenuating crew seat design. Like the 222 crew seat, it uses a carbon epoxy energy attenuator, but it has more stroking distance available. The original Model 412 passenger seat was an energy attenuating seat that used the wire/roller concept. It was similar to the ceiling-mounted seat, except for being mounted to a frame and having an antirebound feature. Like those of the 222, the energy attenuators are designed for 14.5G for a 170-pound (77 kg) occupant. These seats have the greatest vertical energy attenuation available in a civil aircraft crew and passenger seat.

Part Two of this series will be presented in the next issue. It will discuss crashworthiness tests and proposals to improve crash safety features for future rotorcraft designs. ♦

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About The Author

Roy G. Fox directs the System Safety Engineering Group as Chief Safety Engineer for Bell Helicopter, Textron. He joined Bell in 1966 immediately after graduation with a Bachelor of Science Degree in Mechanical Engineering from New Mexico State University. In addition to his work in safety engineering, Fox has been deeply involved in crash survival of military and civil helicopters. In this field, he has directed the Crashworthiness Project Group for the helicopter industry.

Fox is a member of the General Aviation Safety Panel for seat restraints and post-crash fire protection, and participates in the SAE committees on seat and restraint requirements. He is a lecturer on crash survival and human performance at the Bell Pilot Training School and the U.S. Federal Aviation Administration Helicopter Safety and Accident Investigation course.

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