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CRASHWORTHINESS - A MATURING DISCIPLINE

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Abstract

The growth of crashworthiness as a recognized engineering discipline in the USA is reviewed from its inception in the 1960's to its application to future helicopters. During the conflict in southeast Asia, the U.S. Army recognized the need for helicopters to be more crash survivable. Studies of accidents and the cause of injuries led to research programs for the development of the technology to reduce thermal and impact injuries in potentially survivable mishaps. Following the evolution of design guidelines and criteria, and the technology required to meet those criteria, the U.S. Army required its application and now has in-service helicopters that have demonstrated this increased crashworthiness.

The UH-60A BLACK HAWK utility helicopter was the first helicopter to go into production that was designed to be crashworthy from it inception. Several years of service experience have demonstrated the effectiveness of its design features.

The U.S. Navy has also taken advantage of improving crashworthiness technology, both for older in-service aircraft and some new models. The SH-60B SEAHAWK Naval version of the UH-60A includes most of the proven features of that aircraft but has increased emphasis on the problems of overwater operations. New crashworthy seats with variable load attenuation systems are being installed in H-3 SEA KING and H-53 SEA STALLION helicopters that have been in service for many years.

Crashworthy fuel systems including high strength flexible fuel cells and fuel lines equipped with self-sealing breakaway valves, are also in production for retrofit to the H-53 models. Very large capacity fuel cells in the composite sponsons of the mine-sweep version of the H-53 are also crashworthy, even with complete sponson separation from the fuselage.

Studies have shown that civil helicopter mishaps are less severe than those in military operations. However, the general application of crashworthiness technology to civil rotorcraft even to lower levels is dependent on certification rule changes only now being formulated in notices of proposed rule making.

U.S. Army Experience, Research and Development

In 1967, the U.S. Army was equipped with approximately 8,000 helicopters and had 10,000 pilots to fly them (Reference 1). At that time, it was noted that reduction in injuries could be achieved in most major helicopter accidents by the protection of the inhabited area, restraint of the occupants, structural and occupant (seat) energy absorption, and fuel containment; in other words, the application of crashworthiness. Much of the early research and development was performed under U.S. Army contract, as reported in Ref. 2, and resulted in the publication in 1967 of the first of a series of aircraft Crash Survival Design Guides, (Reference 3), the latest being the five volumes of USARTL-TR-79-22, (Reference 4). The prevention of post-crash fires and the resulting thermal injuries and fatalities was the U.S. Army's first priority. Most Army helicopters were re-equipped with crashworthy fuel cells, able to meet the stringent requirements of MIL-T-27422B (Reference 5), self-sealing breakaway valves, and high strength flexible hose fuel lines. As a result, fuel spillage has been controlled such that thermal injuries and fatalities in survivable accidents have been reduced from 41% in 1969 to essentially zero in 1982, as reported in Reference 6, and still continue that way.

The U.S. Army continued to develop crashworthiness technology, as described in Reference 7, including full-scale crash testing such as that of the Bell Helicopter-Textron YAH-63 prototype Advanced Attack Helicopter, human tolerance definition, improved energy attenuators, and seat restraint systems. In addition, the Army continued to support programs to develop the required crash impact characteristics of composite helicopter structures (Reference 8). Both Bell Helicopter and Sikorsky Aircraft have designed and successfully flown Advanced Composite Aircraft Program (ACAP) demonstrators under U.S. Army contract and both will be crash tested at the NASA-Langley test facility later this year.

U.S. Army Production Helicopters

Of greater significance is the U.S. Army's recognition that crashworthiness is not only able to save lives and reduce injuries, but is also cost effective in a few years of fleet service. This recognition led to the inclusion of crashworthiness design criteria in the procurement specifications of the Army's two new helicopters, the Sikorsky UH-60A BLACK HAWK utility helicopter and the McDonnell Douglas AH-64A Apache attack helicopter. The UH-60A went into service first. Its crashworthiness design features, shown in Figure 1, are described in some detail in Reference 9.

Those of the AH-64A are described in Reference 10. Both helicopters follow many of the recommendations of the Crash Survival Design Guide TR71-22, (Reference 11) and were designed to the crash impact conditions therein. With almost ten years of service, the UH-60A has sustained over twenty severe mishaps, as reported in Reference 12; some occupants, particularly pilots and co-pilots, survived extremely severe crashes with minor injuries. It was noted that, except for crashes in which the aircraft landed inverted, all occupants survived the crashes in or near the design envelope and that occupants survived some crashes whose severity significantly exceeded the design level.

To quote the U.S. Army, "many UH-60A personnel survive in non-survivable accidents". Having been designed to similar criteria, it can be expected that the AH-64A Attack Helicopter will exhibit similar crashworthiness performance.

It is likely that the U.S. Army will expect at least the UH-60A level of crashworthiness in the future LHX helicopters. This may be quite a challenge to the designers because of its small size, compact configuration, and its use of a retractable landing gear. In summary, the U.S. Army continues to be the leading advocate of aircraft crashworthiness in the development of criteria, advancing technology and its application to new helicopter programs.

U.S. Navy Research and Development

The U.S. Navy has also pursued the improvement of crash safety. The U.S. Navy approach to crashworthy seating systems from the 1960's to 1982 is described in Reference 13. During that time, the U.S. Navy supported a large number of

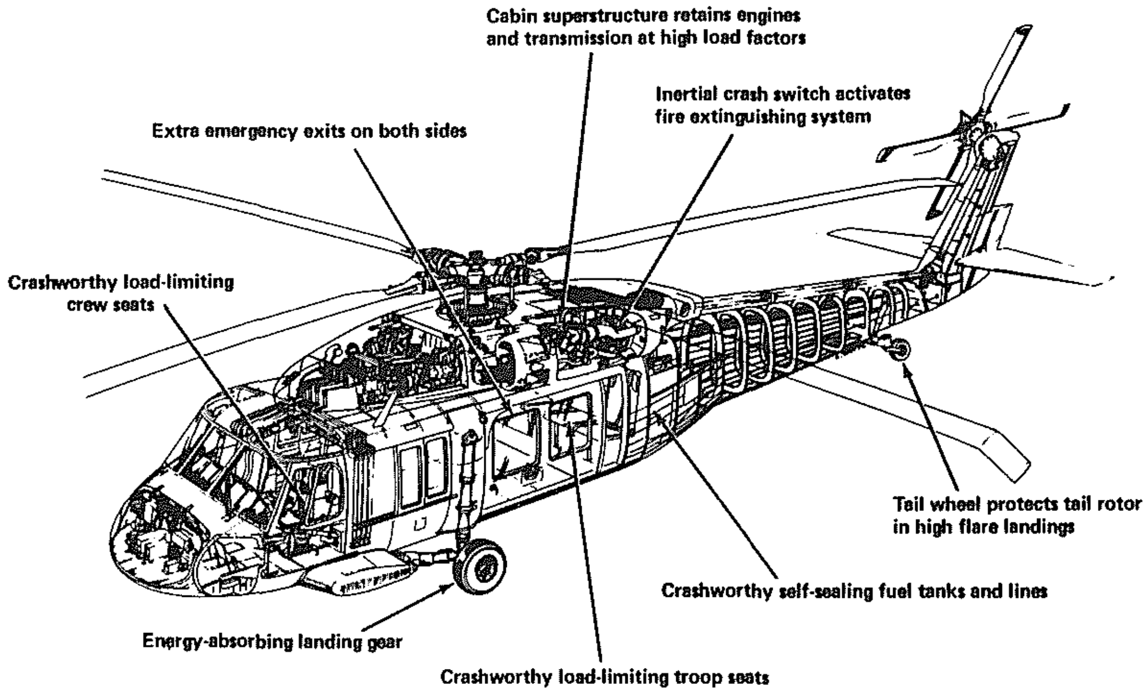

Figure 1. UH-60A BLACK HAWK Crashworthiness Features

research and development programs that resulted in a family of crashworthy seats, both armored and unarmored, for pilot/co-pilot, troop, passenger and gunner seats. The U.S. Navy also supported the development and testing of a variable load energy attenuation system. This system, with a dial setting of the occupants total equipped weight, was designed to stroke at a load factor of 14.5g throughout the range of weight from a lightly equipped 5th percentile pilot to a heavily equipped 95th percentile pilot.

U.S. Navy Production Helicopters

The first Navy helicopters equipped with crashworthy seats were the SH-60B SEAHAWK, shown in Figure 2. These helicopters are derivatives of the UH-60A but with some major changes to the airframe, landing gear and equipment.

To accommodate landing on the landing platforms of small ships, the tail landing gear is moved to the forward end of the tail section. The dual-oleo energy - absorbing main and tail landing gears of the UH-60A are replaced with long stroke single-oleo gears. The aircraft is also equipped with an emergency flotation system for use in ditching situations, together with an improved Helicopter Emergency Egress Lighting (HEEL) system that facilitates the crew's finding their way out in darkness and underwater.

A cable haul down and deck retention system is used to facilitate deck landing in high seas and adverse weather. Other equipment includes radar, a sonobuoy dispenser, and a magnetic anomaly detector (MAD), all for specialized submarine detection. Torpedoes and external fuel tanks can also be carried.

Figure 2. Sikorsky SH-60B SEAHAWK® Helicopter

The helicopter maintains many of the UH-60A crashworthiness design features, including the crashworthy fuel system. The fuel cells, with an increased capacity, are of similar construction but meet a drop test height of 40 ft. rather than the 65 ft. height of the UH-60A fuel cells.

The pilot and co-pilot seats, shown in Figure 3, are crashworthy; they use a 5 point high strength restraint system and have been qualified by dynamic testing. The seat has a welded aluminum bucket that strokes downward at a load factor of 14.5g. It is able to stroke a minimum distance of 11 inches, into an opening or well in the cockpit floor.

Two of these same seats are installed in the SH-60B cabin on raised seat rails for the sensor operators at their consoles. The helicopter also uses two passenger seats in the cabin that are production UH-60A troop seats equipped with cushions to improve comfort.

Figure 3. SH-60B Crashworthy Crewseat

U.S. Navy Retrofit Programs

Programs funded by the U.S. Navy for crashworthy crew seats for retrofit to the SH-3 and CH-53 A/D helicopters are described in References 14 and 15. The program for the SH-3D, G, and H crewseats, one of which is shown in Figures 4, is part of a comprehensive Service Life Extension Program (SLEP) to extend the use of the helicopters well into the 1990's. It resulted in the first production application of the Navy's variable load attenuation systems. Also a first, I believe, is the use of a seat bucket of graphite epoxy composite material, with some areas of Nomex® honeycomb core material.

The variable load energy attenuators (VLEA's) consist of an inverting aluminum tube that provides the minimum stroking load. Additional stroking load is provided by a number of balls that deform the tube into flutes when they are pulled down the inside of the inverting tube. The load variation is attained by varying the radial position of the balls and thus the depth of the flutes; the load increase when the balls are moved outward by a conical member that is positioned axially by a cable from an adjustment dial at the side of the seat.

Figure 4. SH-3 Crew Seat

Another goal of the program was to limit the loads on the seat support structure to prevent its failure and separation of the seat in accidents with high g forward loads. This was accomplished by the use of load-limiting rear support struts that extend, allowing the seat to move forward about 6 inches at the seat reference point. The seats were successfully qualified by their passing of four dynamic tests. The first three tests, with 5th, 50th and 95th percentile equipped aviators were with combined vertical, longitudinal, and lateral loads accomplished by testing the seats pitched 30° nose down and rolled 10°. The effectiveness of the VLEA's was demonstrated by the consistency of the stroke of the seat; 11.6 inches for the 5th percentile (165 pounds) occupant, 11.4 inches for the 50th percentile (202 pounds) occupant, and 11.2 inches for he 95th percentile (237 pounds) occupant. A vertical test seat is shown in Figure 5.

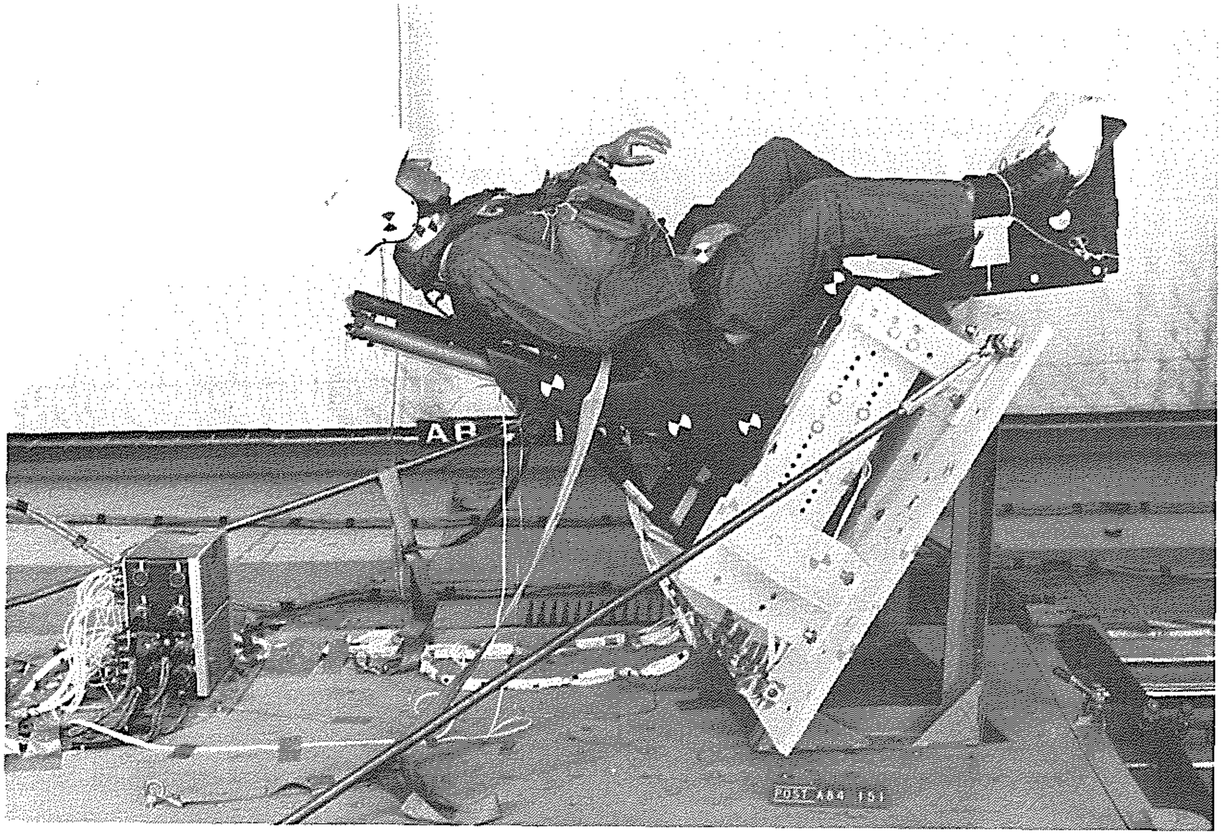

Figure 5. Combined Vertical Load Dynamic Test

All three tests were conducted from the full up seat position with a 45 fps velocity change and 48g peak deceleration pulse only because the available stroke was limited to twelve inches by a projecting portion of the test fixture. The fourth test, longitudinal forward with the seat yawed 15°, again used the 95th percentile dummy, and had a 30g peak loading with a 50 fps velocity change. As shown in Figure 6, the seat stroked forward 6.1 inches at the seat reference point and restrained the dummy in place in the seat.

As with the SH-60B, a large percentage of the SH-3 mishaps are expected to occur on water and these helicopters too are being equipped with the Helicopter Emergency Egress Lighting (HEEL) system. Crash safety is increased, since the seats minimize crew incapacitation while the lighting system minimizes disorientation even underwater, for better emergency escape.

The Sikorsky SH-3 and CH-53 helicopters entered service in 1962 and 1967, respectively. Even then, the U.S. Navy recognized the need for crash safety improvements and specified that the crew seats and other major high mass item components such as rotors, transmissions and engines be retained at crash load factors of 20g downward, 20g forward and 10g sideward, acting separately.

Figure 6. Horizontal Load Dynamic Test

Main rotor and transmission and engine retention has proven effective; that of the crew seats less so. Thus, as with the SH-3 crashworthy seats, those recently developed for retrofit to the CH-53A/D helicopters, shown in Figure 7, are designed to limit the loads on the seat and its occupant so as not to exceed the floor strength of the existing aircraft.

Because of its operational environment in wartime, the seat is armored, providing protection for the occupant's torso from below, behind, and by an outboard hinged wing panel, from the outboard side against 7.62mm armor-piercing projectiles. The armor used is an inner Kevlar® laminate that provides the basic shape of the seat bucket with aluminum oxide ceramic armor tiles bonded to it and covered with a nylon fabric spall shield. The wing panel is supported by the fixed frame of the seat rather than the seat bucket. This prevents it's impacting the cockpit side console during seat stroke that would increase the vertical loads on the occupant. The seats also use the variable load energy absorber (VLEA) system, which is particularly helpful in the H-H3 application where the vertical seat stroke is more limited by the height of the seat above the cockpit floor (8-13 inches depending on the vertical adjustment position selected by the occupant). The equipped occupant weight range was increased; 164 pounds to 254 pounds to allow for the wearing of a protective armor insert and carrier on the occupant's chest.

Figure 7. CH-53A/D Crashworthy Crew Seat

The new high strength, low-elongation restraint system has adjusters in all five belts to accommodate the required range of occupant size, clothing and equipment.

The seat cushions are designed to limit occupant dynamic overshoot but still contribute to much improved comfort by their shape and internal air passages that allow air to blow through them. These seats too have demonstrated their capabilities during a thorough series of qualification tests and are now being installed in the CH-53A/D transport and RH-53D mine-sweeping helicopters.

The success of the Army's crashworthy fuel systems (CWFS) in improving crash safety did not go unnoticed by the Navy. A review of SH-3 Helicopter accidents showed that two out of three mishaps are on water; on land, the emergency energy absorption strut installed between the sponson and the fuselage and the rugged fuselage underside (designed for water landings), combine to minimize fuel spillage and post-crash fires. Thus, the SH-3 anti-submarine helicopter has not demonstrated the need for installation of a crashworthy fuel system.

On the other hand, 75% of the CH-53A/D mishaps occurred on land with post crash fire occurring in more than a quarter of the mishaps. Thus, the CH-53E three-engine derivative version of the CH-53A/D was the first to be equipped with a crashworthy fuel system.

The mishap experience of the CH-53A/D was used to establish the design criteria for a CWFS for the CH-53E SUPER STALLION. The four fuel cells, two in the sponson on each side of the fuselage, were of the typical high strength layered nylon fabric with high strength fittings designed to break-away from the containment structure. Both fuel cells were successfully tested to MIL-T-27422B, including the 65 ft. drop test, filled with water. Fuel spillage from the vent lines in rollover accidents was the cause of several CH-53A/D post-crash fires. The CH-53E vent lines were designed to prevent syphoning of the fuel and equipped with closure valves to prevent such spillage.

A CWFS for the CH-53A/D helicopters that uses the same design as one of the H-53E fuel cells is planned for retrofit by the U.S. Navy. The retrofit kit has been validated and needs only verification by Navy personnel to be ready for installation in the helicopters.

Another Navy derivative helicopter is the Sikorsky MH-53E SEA DRAGON, shown in Figure 8, designed and equipped for very long endurance airborne mine countermeasures (AMCM) missions. Mechanical, acoustic and magnetic minesweep missions can be accomplished. Its new features include a very large capacity crashworthy fuel system with provision for fueling the AMCM equipment, a composite tow boom and aperture guard, a short stub ramp that can be lowered 90° downward, and improved emergency egress provisions.

Figure 8. Sikorsky MH-53E Helicopter

The four crashworthy fuel cells with a total capacity of approximately 3200 U.S. gallons are supported in the two large co-cured graphite epoxy sponsons by blocks of rigid ballistic foam cut to the shape of the bottom of the cells. In flight, refueling can be accomplished from the cabin hover in-flight refueling (HIFR) connection or from the extendable refueling probe in the nose of the helicopter.

Once difference in design philosophy exists between the CH-53A/D & E and the MH-53E crashworthy fuel systems. The CH-53 A/D models had not suffered separation of the sponsons containing the fuel cells, therefore breakaway valves were positioned to accommodate only fuel cell displacement within the sponson structure.

The lower surface of the much larger MH-53E sponsons is level with the underside of the fuselage. In any severe mishap with a rolled attitude, the sponson will contact even flat ground first and is likely to separate from the fuselage. Thus, all the fuel lines passing from the sponson to the fuselage, engines, etc. are equipped with breakaway self-sealing valves at the expected separation point. Additionally, all attachments of the fuel cells to the sponson are designed to breakaway at the frangible fittings, allowing the cells to undergo considerable deformation within the sponson. In the fuel lines, ball type self-sealing breakaway valves are used to minimize pressure loss in the suction feed fuel system. In normal operation, fuel flows through the openings in the rotating balls retained in place by opposing springs and a small trigger ball. Upon separation of the valve halves by the crash impact, the trigger ball drops away allowing the valve balls to rotate 90° against stops at the fully closed position, closing both ends of the separated line. To avoid fuel spillage from the vent lines in rolled impact or when the aircraft rolls over, float-type vent values are used to close these lines. As in the CH-53A/D and CH-53E helicopters, the tanks are equipped with crushable fuel quantity probes with shoes on the end to prevent penetration of the fuel cell fabric.

The large sponsons are expected to increase available escape time in mishaps on water by providing additional buoyancy and stability. Exits of sufficient size and number are provided, three emergency escape hatches, one emergency escape window on each side of the cabin, and a large emergency escape window in the overhead rear ramp door. Emergency lighting, operable underwater, is also provided. At the present time, a change to the crashworthy H-53A/D crew seats is under consideration for future CH/MH-53E production helicopters.

In summary, the U.S. Navy has made significant progress in the application of crashworthiness technology to helicopters, particularly in the areas of crew seats and crashworthy fuel systems, and with additional emphasis on the water impact and ditching situations resulting from over water operations. One missing ingredient in the Navy's requirements is the inclusion in the aircraft design specifications of impact criteria in terms of velocity and impact attitude. Crash inertial load factors are not, in themselves, enough to ensure crashworthiness.

Recognizing that the Navy crash impact environment, as summarized in Reference 13, is similar to that included in the Army's Aircraft Crash Survival Design Guide, (Reference 4) it is expected that similar technology will be required and that similar benefits will result from its application.

Civil Helicopters

In 1978, Dr. Richard G. Snyder published a paper on "Occupant Injury Mechanisms in Civil Helicopter Accidents" (Reference 16), that stated that the 1977 U.S. civil helicopter fleet numbered some 7160 corporate, commercial and governmental helicopters in use and, (as of 1975), 27872 active helicopter pilots. The helicopters ranged in weight from a 450 pound (204 kg) empty weight single seat model to a demonstrator model of a 32000 pound (14500 kg) weight empty commercial intercity transport. In the period from 1964-1977, there was a total of 3575 accidents involving 7064 individuals, 82.7% of which received minor or no injury at all. There were 612 severe injuries and 613 fatalities. In the same time period, 339 occupants in helicopter accidents were exposed to post crash fire with 28 thermal fatalities reported. Dr. Snyder concluded that civil helicopters required improved occupant impact protection and that a serious effort should be made to obtain an record injury information in future accidents to provide a basis for further evaluation.

The Federal Aviation Administration (FAA) recognized the importance of civil helicopter crashworthiness and the need for a better definition of the severity of civil helicopter accidents. The FAA Technical Center in Atlantic City, New Jersey funded a study of U.S. civil helicopter accidents occurring between 1974 and 1978 to determine typical impact conditions for use in formulating design criteria for future civil rotorcraft. The results of the study are summarized in Reference 17. It was found that the 95th percentile significant survivable vertical, longitudinal, and lateral velocity components were 26 fps, 50 fps, and 10 fps, respectively. The pitch, roll, and yaw angles were small. Little difference in these parameters was noted for three of the four weight classes studied; insufficient information was available for helicopters exceeding 12500 pounds maximum gross weight. The 95th percentile survivable vertical impact velocity of 26 fps is considerably less than that for U.S. Army helicopters (42 fps) and U.S. Navy helicopters (38 fps), presumably due to the type of missions flown and, to some degree, the basic crashworthiness of the airframe. Thus, considerably lower weight and cost penalties will be required to provide the desired crash safety in a substantial percentage of accidents to civil helicopters.

The Rotorcraft Airworthiness Requirements Committee (RARC) of the Aerospace Industries Association of America (AIA) established a Crashworthiness Project Group to develop and recommend realistic crashworthiness criteria for future civil helicopters. The results of the Group's efforts in energy absorbing seats, restraints, and crash resistant fuel systems are described in Reference 18. It was noted that present Federal Aviation Resulations, Part 27 and Part 29, require that helicopters meet or exceed minimum strength levels; the only specific crash requirement is to be able to accept a 5 fps impact without causing serious occupant injury. Seats are required to demonstrate static strengths of 4g forward, 4g downward, 2g lateral, and 1.5g upward for a 170 pound occupant.

The realistic crash criterion of 26 fps for vertical impact, seen in Reference 17, results in 27 times the kinetic energy of the present 5 fps impact requirement. Thus, the Group recommended the installation of energy attenuating seats equipped with shoulder harness (upper torso) restraint systems in accordance with a newly developed Society of Automotive Engineers (SAE) aeronautical standard, AS-8043, Aircraft torso restraint system, suitable for both fixed wing and rotary wing aircraft. Two dynamic seat qualification tests are recommended. The first is a forward impact test with a 10° yaw with an 18.4g peak triangular pulse and a 42 fps velocity change. The second is a vertical impact test with the seat pitched 30° nose down with a 30g peak triangular pulse and a 30 fps velocity change to provide the 26 fps velocity component perpendicular to the aircraft floor.

To reduce the severity of post-crash fires, the Group recommends the installation of crash resistant fuel systems with fuel cells designed to the criiteria of MIL-T-27422B (Reference 5), suitably reduced for civil helicopters.

For example, the fuel cell should be drop tested from a height of 50 feet with 80% of its normal capacity filled with water. In addition, stretchable hoses, extra length hoses, self-sealing breakaway valves, and frangible fuel cell attachments may also be needed to contain the fuel when structural deformation occurs.

In June ,1987, the FAA issued a Notice of Proposed Rulemaking (NPRM) on "Occupant Restraint in Normal and Transport Category Rotorcraft", Notice No. 87-4 for comments, suggestions, or arguments. The proposed changes are in general accord with those recommended by the Crashworthiness Project Group. In addition, it asks that any item of mass that could injure an occupant be restrained to ultimate inertia load factors of 4g upward, 16g forward, 8g sideward, 20g downward, including rotors, transmissions and engines. It is expected that the seats would require to stroke at 12g in order to keep the pelvic load measured in the anthropomorphic dummy, (ATD), below the limit of 1500 pounds.

A similar NPRM is expected in the near future on civil helicopter crash resistant fuel systems. Of course, any changes resulting form these proposals will apply only to new helicopters certified after their promulgation. Thus, it is likely to be many years before aircraft are in service with these improved features and capabilities.

Conclusion:

From its beginnings in the 1960's, crashworthiness has developed from a need based on accident experience into a new engineering discipline. Support of research and development by the U.S. Military Services and by the Federal Aviation Administration has resulted in the development of crashworthiness technology and its application to both old and new military helicopters. The need for civil helicopter crashworthiness is also recognized and will achieve its potential when mandated by the certificating agencies. Crashworthiness is indeed, a maturing discipline.

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