NEW TECHNOLOGIES TO ENHANCE ROTORCRAFT CRASH SAFETY

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Abstract

Crash safety of rotorcraft can be significantly enhanced using several new crashworthiness technologies under development. These technologies include actively controlled subsystems such as external airbags, crashworthy seats, landing gears, and crash load limiting elements for the transmission and rotor systems. These actively controlled subsystems can be integrated at the rotorcraft system level using an Active Crash Protection System (ACPS) that can sense an impending crash event and control the subsystems to enhance occupant crash safety. This paper presents the results of research and development efforts for various actively controlled crashworthy subsystems and their integration at the rotorcraft system level. The paper also addresses the potential benefits of these crash safety technologies using the Crashworthiness Index (CI) as a metric. CI scores calculated for deploying the new crashworthiness technologies individually and as an integrated system are also presented and compared to rotorcraft without these technologies.

1. INTRODUCTION

Most rotorcraft accidents are inherently survivable with appropriate levels of crash protection for the occupants. Introduction of passive crash protection systems such as crashworthy stroking seats, high-energy landing gears, and energy absorbing airframe structures have initially resulted in improvements in occupant crash survivability.

However, many of these passive crashworthy subsystems were developed for specific aircraft gross weights and crash impact conditions. Accident data indicates that the effectiveness of the passive crash protection systems decrease with heavier aircraft gross weight, higher sink rates, and non-rigid impact surfaces.

The effectiveness of the crash protection systems can be significantly enhanced by utilizing an ACPS that can sense an impending crash event and then actively control the response of the crashworthy subsystems to provide the optimum level of occupant crash protection for the crash impact conditions.

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The Boeing Company in collaboration with the U.S. Army Aviation Development Directorate (ADD) has developed a prototype ACPS and the associated active crashworthy subsystems to improve the crash safety of rotorcraft occupants.

The performance of the ACPS and integration of the active subsystems are being demonstrated by hardware-in-the-loop simulations, prototype hardware fabrication, and testing including a full-scale rotorcraft drop test.

2. CRASH SCENARIOS

The rotorcraft crash impact scenarios include combination of vertical and longitudinal impacts. The longitudinal crash impacts can be mitigated by designing anti-plowing forward fuselage structures to minimize longitudinal accelerations. Major mass item retention structures are used to retain the major mass items under the longitudinal accelerations. The human body tolerance to longitudinal accelerations is relatively high. Occupants can survive the typical longitudinal accelerations during a crash so long as they are properly restrained to avoid secondary impacts with the rotorcraft interior.

The vertical crash impacts at high sink rates are significantly more hazardous for the occupants since the human body tolerance to vertical accelerations are low. Occupants can suffer spinal injuries if the vertical accelerations exceed the spinal injury thresholds. It is also more challenging to maintain a livable volume for the occupants in vertical crashes. The major mass items such as engines, transmission, and rotor system subjected

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to high vertical accelerations are typically located above the livable volume and may result in collapse of the supporting structure.

3. CRASHWORTHY SUBSYSTEMS

The crashworthy subsystems and energy absorbing airframe structures are used to reduce the vertical accelerations experienced by the occupants and to maintain the livable volume are shown in Figure 1. They include crashworthy seats, landing gears, energy absorbing subfloor and major mass item retention structures, and external airbags.

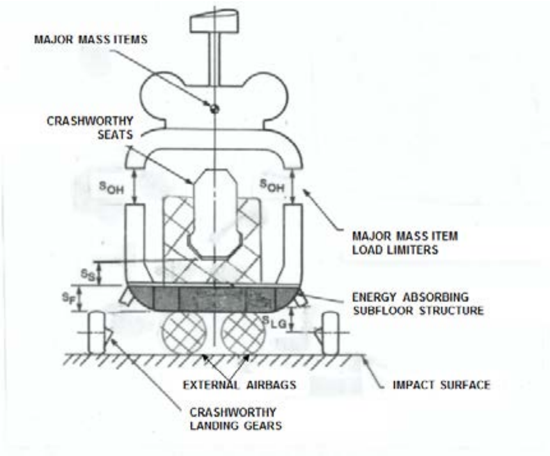

Figure 1. Crashworthy Subsystems and Energy Absorbing Airframe Structures

3.1. Smart Crashworthy Seat

The current generation rotorcraft crashworthy seats use Fixed Load Energy Absorbers (FLEA) that are optimized for the 50th percentile male occupants and specific crash impact conditions. Some of the current rotorcraft crew seats also utilize manually adjustable Variable Load Energy Absorbers (VLEA) to provide the same level of crash protection for different size occupants.

Smart crashworthy seats with Actively-Controlled Seat Energy Absorbers (ASEA) and their integration with ACPS offer several improvements over the FLEA and VLEA technologies. ASEA stroking load can be automatically set, thus eliminating any possible errors due to manual adjustment by the crew members. The ASEA stroke load setting can also be optimized to reduce the probability of occupant spinal injuries based on the occupant size, available seat stroke space, and the severity of the crash impact as predicted by the ACPS.

The prototype smart crashworthy seat ASEA developed by Boeing is shown in Figure 2. The key components include a VLEA, servo-motor, couplers, control board to control the ASEA, load cells, and an optical sensor to record the vertical adjustment position of the seat. The stroking load is controlled using a servo-motor attached to the load control cable. The rotary position of the servo-motor is monitored and controlled by a motor controller based on inputs from sensors and the communication interface to the ACPS. The sensors mounted on the seat include load cells mounted on the top of the ASEAs as well as a displacement sensor mounted on the seat back.

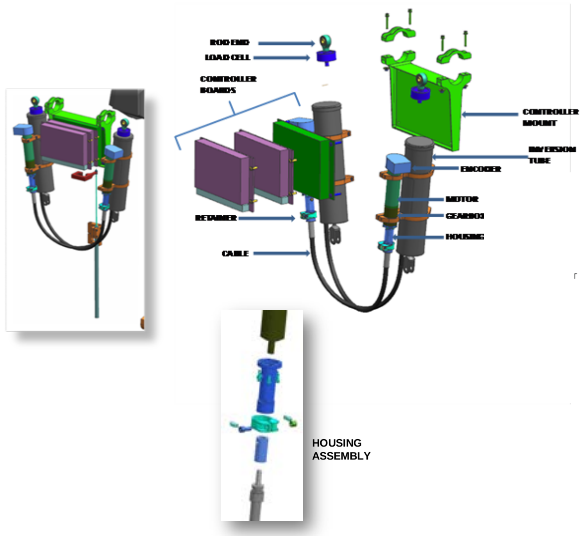

Figure 2. Smart Crashworthy Seat ASEA Assembly

Actual installation of the ASEA assembly on a rotorcraft crew seat is shown in Figure 3. The load cells have a low profile that is easily integrated with the ASEA. The displacement sensor is based on optical encoder technology where the optical sensor head senses the vertical adjustment of the seat using an encoded metal strip. The encoded metal strip is adhesively bonded to the moving part of the seat and the optical sensor is mounted on the fixed part of the seat assembly.

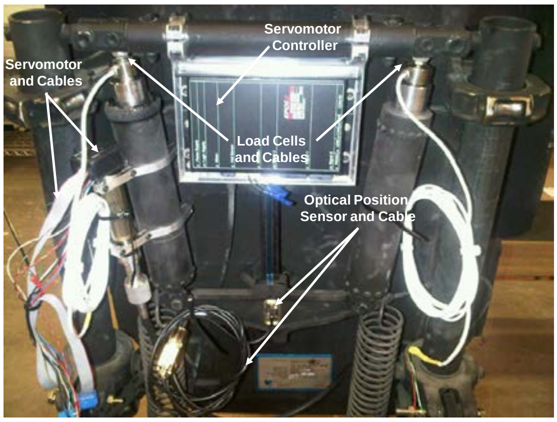

Figure 3. ASEA installation on a Rotorcraft Crew Seat

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3.2. Major Mass Item Load Limiters

Crashworthiness design requirements include retention of major mass items such as the rotor systems, transmissions, and engines during a crash impact. The retention structures typically include rigid space truss type of structures which are primarily loaded axially to transfer the crash loads from the major mass items to the airframe structure.

The retention strength is specified in terms of static or dynamic load factors in forward, lateral, and downward directions. These load factors typically far exceed the flight and landing loads on the retention structure. Therefore, major mass item retention crashworthiness requirements can result in significant weight penalties for the airframe structure. In addition, in severe crashes where the strength of the retention structure is exceeded, the major mass items can also be a hazard to the occupants.

The disadvantages of the rigid major mass item retention structures can be overcome by using load limiting structural elements (LLSE). LLSEs can provide local energy absorption capability through large deformations to decelerate the major mass items and reduce the loads applied by the major mass items to the airframe structures. LLSEs can also be actively controlled to modulate the loads with the objective of enhancing occupant survivability and reducing airframe damage.

A prototype LLSE developed by the U.S. Army ADD and Boeing is shown in Figure 4. It includes shear tabs for load control and composite crush tubes for energy absorption.

Figure 4. Prototype LLSE to limit the Major Mass Item loads during a crash impact.

The shear tabs enable load variability of about 50 percent by using a servomotor and gearing controlled by ACPS based on the input from the sensors.

The energy absorption capability of the LLSEs can be scaled as needed by using several concentric crush tubes. The prototype LLSE also uses spherical bearings at the ends to eliminate bending moments while it strokes as part of a major mass item support assembly.

Drop tests of the LLSEs were conducted to evaluate their performance. The test configuration for a final drop test of a test article which represents the weight of a typical rotorcraft transmission and rotor system assembly is shown in Figure 5.

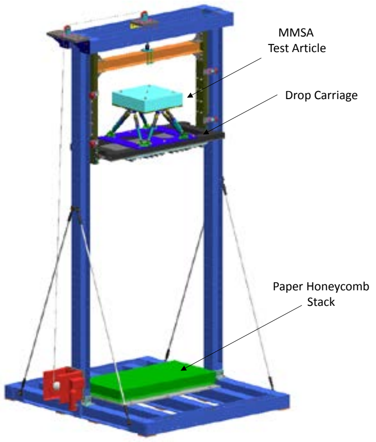

Figure 5. Major Mass Structural Assembly (MMSA) Drop Test Setup

The test results shown in Figure 6 indicated that the LLSEs were able to reduce major mass item loads (as measured by accelerations) by about 50 percent.

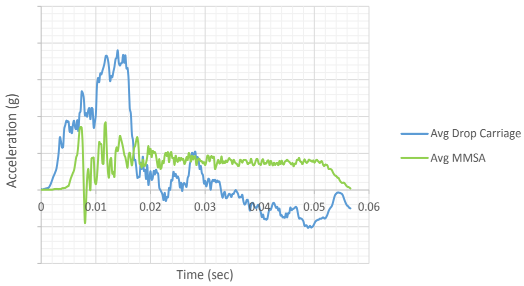

Figure 6. MMSA Drop Test Accelerations vs Time

3.3. Smart Crashworthy Landing Gears

The primary purpose of the landing gears is to support the rotorcraft on the ground during normal landings and to provide protection to the occupants during crash impacts by absorbing part of the system kinetic energy. The energy absorption capability of the landing gears is typically provided by shock struts. The shock struts employ single or multi-stage hydraulic fluid and nitrogen systems to provide damping to avoid ground resonance and to

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provide energy absorption capability during crash impacts.

One drawback of the current landing gear technology is that the shock strut loads are highly dependent on impact velocity and aircraft gross weight. The shock strut loads may exceed the design strength of the airframe attachment fittings at high sink rates and heavier aircraft gross weights which may result in occupant injuries and aircraft damage. The effectiveness of the current landing gears are also reduced during crash impacts on non-rigid (soft soil and water) surfaces.

Smart crashworthy landing gears utilize actively controlled shock struts to control the landing gear loads during crash impacts. The shock strut loads are set to optimum values based on the ACPS predicted impact conditions and aircraft gross weight. The active shock strut control can limit the landing gear loads applied to the airframe attachment fittings to eliminate structural failures that may result in occupant injuries during crash impacts. The shock strut loads may also be controlled to maximize the energy absorption capability of the landing gears on non-rigid impact surfaces based on ACPS inputs.

A prototype smart crashworthy landing gear with active load control features is shown in Figure 7. In addition to the active load control, the prototype landing gear also includes retraction capability to reduce drag and a composite primary structural component (trailing arm) to achieve weight savings.

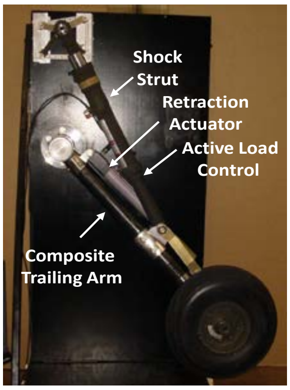

Figure 7. Prototype Smart Crashworthy Landing Gear

The load control system shown in Figure 8 uses interlocking shear tabs similar to the ones used for the prototype LLSE. The servomotor is controlled by ACPS based on crash impact conditions, aircraft gross weight, and impact terrain.

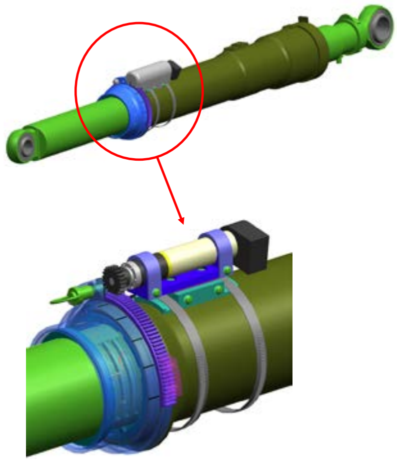

Figure 8. Shock Strut Active Load Control Implementation

The composite trailing arm was fabricated by automated fiber placement using IM7/8552 slit tape material system which results in about 15 percent weight savings relative to a metallic trailing arm.

3.4. External Airbags

This technology provides energy absorption capability that supplements the energy absorption provide by other crashworthy subsystems and the airframe. External airbags are also effective on soft soil and water where other crashworthy subsystems are not very effective.

The key to effectively utilizing external airbags is precise timing for airbag inflation before a crash impact. Active modulation of the vent area is also necessary to compensate for the severity of the crash as well as rotorcraft gross weight and attitude at impact. Finally, deploying external airbags in crash impacts with high longitudinal velocities may not be effective and can result in airbags being ripped off from the rotorcraft or in worst case cause the rotorcraft to pitch pole. Therefore, integration of external airbags with ACPS is necessary to sense the crash impact scenarios where the airbags can be safely and effectively deployed and actively controlled.

A prototype external airbag system developed by Boeing is shown in Figure 9. An MD-500 airframe was used as the test bed to develop and demonstrate the system. The prototype external airbag system configuration included four airbags. The airbags were fabricated using Polyurethane coated Kevlar fabric for durability and tear resistance.

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Figure 9. Prototype External Airbag System

The airbags were inflated using a hybrid gas generator technology which uses solid propellant and CO_2. The hybrid gas generator is capable of inflating the airbags in less than 150 msec. The advantages of a hybrid gas generator includes lower temperature of the gas generated as well as being able to maintain the gas pressure for longer periods in comparison to gas generators that only use solid propellant.

The airbags fabricated also included a burst disk as shown in Figure 10. The burst disk ruptures at a predetermined pressure and releases the gas stored inside the airbag.

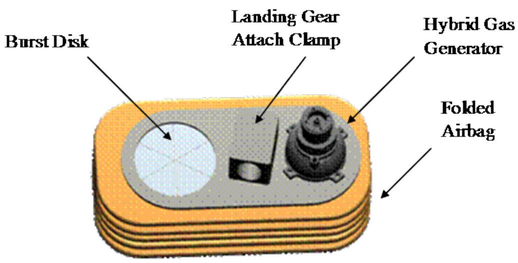

Figure 10. External Airbag Assembly including the Burst Disk and Hybrid Gas Generator

Several tests of the external airbags including a final test with a full-scale aircraft was conducted to validate the operation of the external airbags. The full-scale aircraft drop test shown in Figure 11 utilized a drop tower and a guide beam to provide impact conditions with combined vertical and longitudinal velocities.

Figure 11. Full-Scale Aircraft Drop Test Set-Up

The aircraft is attached to the guide beam through a set of rollers and is free to move along the beam. During the test, the aircraft is pulled back to the end of the beam away from the drop tower using a winch and a quick release hook. The end of the guide beam was then lifted to achieve the desired inclination angle.

The guide beam inclination angle was selected such that when the aircraft is released by the release hook, it travels along the guide beam and achieves the desired longitudinal velocity as it comes off the guide beam. The height of the aircraft from the impact surface as it comes off the guide beam provides additional velocity such that the desired combination of vertical and longitudinal impact velocities are achieved at the point of impact.

The airbags were triggered by the ACPS based on data from a radar altimeter when the height falls below a threshold value. The installation of the ACPS hardware and radar altimeter is shown in Figure 12.

Figure 12. ACPS Hardware and Radar Altimeter installation for the Drop Test Aircraft

The aircraft vertical accelerations measured during the test are shown in Figure 13. The peak vertical acceleration measured was about 40 percent lower than a similar drop test conducted without external airbags.

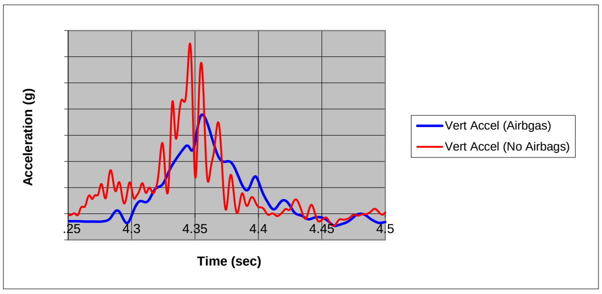

Figure 13. Full-Scale Aircraft Drop Test Vertical Accelerations

4. INTEGRATED CRASHWORTHY SUBSYSTEMS (ACPS)

The effectiveness of the crash protection systems can be significantly increased by utilizing an integrated ACPS that can sense an impending crash event and then actively control the crash response of the crash protection subsystems to

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provide the optimum level of crash protection for the crash impact conditions.

The overall ACPS architecture in a hardware-in-the-loop simulation configuration is shown in Figure 14. A key feature of the system is the Subsystem Control Unit (SSCU) that monitors the sensor data, predicts an impending crash event, and actively controls the crash protection subsystems.

The aircraft state data (altitude, velocity, acceleration, aircraft attitude, engine rpm, torques, etc.) from various sensors connected to the MIL-STD-1553 data bus is processed by the SSCU. Based on the time to impact and the impact conditions, active crashworthy subsystems are set to their optimum values and are activated prior to the crash impact. Each of the active crashworthy subsystems can have local sensors and feedback control loops to further optimize their performance during the crash impact event. ACPS architecture also has provisions for providing diagnostics and warnings on multi-purpose displays in the crew station.

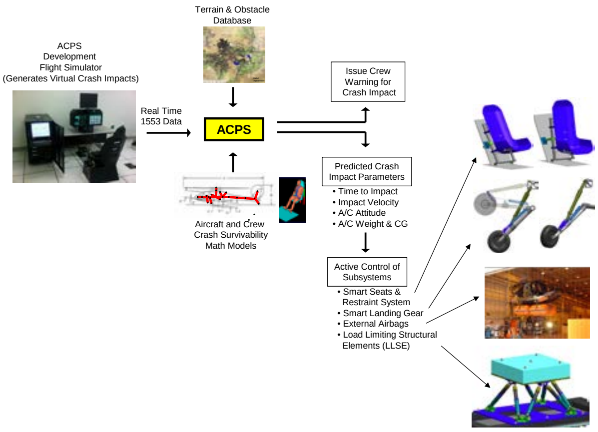

Figure 14. ACPS Architecture shown in a Hardware-in-the-Loop Simulation Configuration.

5. BENEFITS OF THE NEW CRASH SAFETY TECHNOLOGIES

The potential benefits of the new crash safety technologies were evaluated using the CI. CI was conceived as a new metric to quantify the crashworthiness capability of the rotorcraft designs (Reference [1]). Scores are assigned to key crashworthy design features of the aircraft including basic airframe crashworthiness (BAC), crew and troop seating systems, post-crash fire protection, emergency egress, and injurious environment are shown in Figure 15. The highlighted BAC scores are normally calculated based on analytical models. Crashworthy attributes of other design features are evaluated using ADS-11 guidelines (Reference [2]).

Assessment Areas	Optimum Score
Crew Retention System Rating Summary	85
Troop Retention Rating Summary	85
Postcrash Fire Potential Summary - Spillage	128
Postcrash Fire Potential Summary - Ignition	127
Basic Airframe Crashworthiness Rating	295
Evacuation Rating Summary	60
Injurious Environment Rating Summary	30
TOTAL	810

	Assessment Areas	Optimum Score
	Basic Airframe Crashworthiness Rating Summary	
1	**Crushing of Occupied Areas**	
1a	Crushing of Cockpit	15
1b	Crushing of Cabin	15
2	Absence of Plowing Tendency	10
3	Resistance to Longitudinal Impact Loads	10
4	**Resistance to Vertical Loads**	
4a	Vertical Impact, Gear Extended	80
4b	High Mass Retention	20
5	**Resistance to Lateral and Rollover Impact Loads**	
5a	Lateral Impact	15
5b	Static Rollover	15
6	**Landing Gear Vertical Force Attenuation**	
6a	Vertical Impact, Gear Retracted	40
6b	High Angle Vertical Impact	20
6c	Low Angle Vertical Impact	20
6d	Tail Boom Protection	5
7	Landing Gear Location	5
8	Effects of Bird Strike	20
9	Effect of Fuselage Separation	5
	TOTAL	**295**

Figure 15. CI and BAC Score Categories

Evaluation of the benefits of the new crash safety technologies was conducted using the BAC score. The analysis conducted was focused primarily on the Vertical Impact scores. These are normally the most critical crashworthiness design conditions. It was assumed that the other design attributes can be incorporated into the aircraft configuration to achieve 90 percent of their full BAC scores.

BAC scores for the new crash safety technologies are shown in Figure 16. The results indicate that up to 30% increase in BAC scores relative to the baseline configuration can be achieved by integrating the new crash safety technologies into crashworthy design configurations. The results also indicate that the benefits of deploying these new technologies in an integrated ACPS system would be higher than deploying them individually in a federated manner.

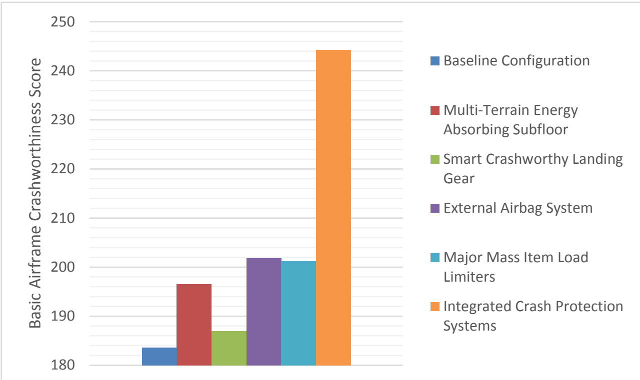

Figure 16. BAC Scores for New Crash Safety Technologies

Multi-Terrain Energy Absorbing Subfloor technology that can provide energy absorption capability non-rigid surfaces (soft soil and water) was also included in the evaluation. It should be noted that some of the crashworthiness and other benefits of these technologies, particularly for the smart crashworthy seats, are not fully captured by the BAC score. The benefits of the smart crashworthy seats may be captured in the CI scores for the Crew and Troop Seat CI category shown in Figure 15.

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6. CONCLUSIONS

There are several new crash safety technologies that can significantly improve the crash safety of rotorcraft. Prototypes of subsystems deploying these new crash safety technologies have been successfully developed and demonstrated.

An evaluation of the benefits of the new crash safety technologies indicate that benefits of deploying these technologies as an integrated ACPS system would be higher than deploying them individually in a federated manner.

Addition work needs to be done to further mature these technologies to Technical Readiness Levels (TRL) required for deploying them in new rotorcraft designs as well as for spiral technology insertions into existing rotorcraft platforms.

7. REFERENCES

[1] Full Spectrum Crashworthiness Criteria for Rotorcraft, RDECOM TR-12-D-12, U.S. Army Aviation Applied Technology Directorate, Ft. Eustis, VA, December 2011.

[2] Aeronautical Design Standard, Survivability Program Rotary Wing, ADS-11B, U.S. Army Aviation Systems Command, St. Louis, MO, May 1987.