

A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center

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ABSTRACT

This paper summarizes 2-1/2 decades of full-scale aircraft and rotorcraft crash testing performed at the Impact Dynamics Research Facility (IDRF) located at NASA Langley Research Center in Hampton, Virginia. The IDRF is a 240-ft.-high steel gantry that was built originally as a lunar landing simulator facility in the early 1960's. It was converted into a full-scale crash test facility for light aircraft and rotorcraft in the early 1970's. Since the first full-scale crash test was performed in February 1974, the IDRF has been used to conduct: 41 full-scale crash tests of General Aviation (GA) aircraft including landmark studies to establish baseline crash performance data for metallic and composite GA aircraft; 11 full-scale crash tests of helicopters including crash qualification tests of the Bell and Sikorsky Advanced Composite Airframe Program (ACAP) prototypes; 48 Wire Strike Protection System (WSPS) qualification tests of Army helicopters; 3 vertical drop tests of Boeing 707 transport aircraft fuselage sections; and, 60+ crash tests of the F-111 crew escape module. For some of these tests, nonlinear transient dynamic codes were utilized to simulate the impact response of the airframe. These simulations were performed to evaluate the capabilities of the analytical tools, as well as to validate the models through test-analysis correlation. In September 2003, NASA Langley closed the IDRF facility and plans are underway to demolish it in 2007. Consequently, it is important to document the contributions made to improve the crashworthiness of light aircraft and rotorcraft achieved through full-scale crash testing and simulation at the IDRF.

INTRODUCTION

The Impact Dynamics Research Facility was originally built as a Lunar Landing Research Facility (LLRF) that became operational in 1965. The steel A-frame gantry structure is 240-ft. high, 400-ft. long, and 265-ft. wide at the base. The LLRF was used to train Apollo astronauts to fly in a simulated lunar environment during the last 150-ft. of descent to the surface of the moon. The astronauts performed these tests in a Lunar Excursion Module Simulator (LEMS) that was tethered to the gantry. The gantry suspension system was designed to support 5/6th of the total weight of the LEMS, thus simulating the reduced (1/6th) gravitational field of the moon. The surface beneath the gantry was modified to resemble the lunar landscape and many of the tests were performed at night to mimic the actual lighting conditions during the moon landing. Photographs of the LEMS descending onto the simulated lunar surface at the LLRF are shown in Figure 1. In 1985, the facility was designated a National Historic Landmark based on its significant contributions to the Apollo Moon Landing Program. References 1 and 2 describe the operational features of the LLRF and the results of flight tests performed using the facility.

At the end of the Apollo program, the LLRF was converted into a full-scale crash test facility for investigating the crashworthiness of General Aviation (GA) aircraft and was designated the Impact Dynamics Research Facility (IDRF). The purpose and benefit of full-scale crash testing, as defined in Reference 3, is "to obtain definitive data on the structural response of aircraft and on the loads transmitted to the occupants during a crash impact. These data can be used for correlation with results of analytical predictive methods. Full-scale aircraft crash tests can also be used to evaluate crashworthy design concepts both for the aircraft structure and for seat and restraint systems." One of the important features of the IDRF is the ability to perform full-scale crash tests of light aircraft and rotorcraft under free-flight conditions; and, at the same time, to control the impact attitude and velocity of the test article upon impact. Also, full-scale crash tests can be performed for a wide range of combined forward and vertical velocity conditions. Most GA aircraft tests are performed with a higher forward velocity and a lower vertical velocity. For example, the 1994 crash test of the Lear Fan 2100 aircraft was performed at 82-fps forward and 31-fps vertical velocity. Conversely, helicopters are typically tested with a lower forward and higher vertical velocity. For example, the 1999 crash test of a Sikorsky prototype helicopter was performed at 31.5-fps forward and 38-fps vertical velocity. Currently, the IDRF is limited to test articles weighing 30,000 lb. or less.



(a) LEMS descending to the surface.



(b) LEMS tethered from the gantry.

Figure 1. Photographs of the LEMS descending to the simulated moon surface.

Since the first full-scale crash test was performed in February of 1974, the IDRF has been used to conduct: 41 full-scale crash tests of GA aircraft including landmark studies to establish baseline crash performance data for metal and composite aircraft, 11 full-scale crash tests of helicopters including crash qualification tests of the Bell and Sikorsky Advanced Composite Airframe Program (ACAP) helicopters, 48 Wire Strike Protection System (WSPS) qualification tests of Army helicopters, 3 vertical drop tests of Boeing 707 transport aircraft fuselage sections, and 60+ drop tests of the F-111 crew escape module. In September 2003, NASA closed the IDRF and plans to demolish the facility by 2007. Consequently, it is important to document the contributions made to improve the crashworthiness of aircraft and rotorcraft achieved through full-scale crash testing and simulation at the IDRF. Thus, the objectives of this paper are to describe the IDRF gantry facility; to highlight most of the major full-scale crash test programs that have been performed at the IDRF since 1974; and to document the application of analytical methods to simulate structural impacts.

DESCRIPTION OF THE IDRF

A photograph of the IDRF is shown in Figure 2(a). The gantry structure is oriented in an east-west direction and is composed of truss elements arranged in three sets of inclined legs to give vertical and lateral support. An additional set of inclined legs located at the east end of the gantry provides longitudinal support. The legs are inclined at an angle of 25-degrees from vertical and they are 265 ft. apart at the ground level. An enclosed elevator and a stairway provide access to the overhead work platforms. A movable bridge spans the gantry at the 217-ft. level and runs the length of the gantry. In 1981, a 70-ft. vertical drop tower, designated the Vertical Test Apparatus, was added beneath the northwest leg of the gantry, shown in Figure 2(b), for the purpose of conducting vertical drop tests of Boeing 707 fuselage sections. These tests were conducted in support of a full-scale crash test of a remotely-piloted Boeing 720 transport aircraft that was conducted at Edwards Air Force Base in 1984 (see Reference 4).



(a) IDR gantry.



(b) Vertical drop tower.

Figure 2. Photograph of the IDR located at NASA Langley Research Center.

Full-scale crash tests are performed at the IDR using a pendulum swing technique, as illustrated schematically in Figure 3. Two pivot-point platforms are located at the top of the west end of the gantry, one on the north and one on the south side. The platforms support two winches used for controlling the length of the swing cables. A pullback platform is located on the underside of the movable bridge that traverses the 400-ft. length of the gantry in an east-west direction. This platform also supports a winch for lifting the test aircraft using the pullback cable. The swing and pullback cables connect to the aircraft swing and pullback harnesses. The harnesses are designed specifically for the aircraft configuration being tested. The cable lengths of the aircraft swing and pullback harnesses can be adjusted to provide a wide range of roll, pitch, or yaw attitudes at impact. The harness cables are typically mounted to hard points on the airframe. Ideally these hard points are located such that a line connecting them passes through the center-of-gravity of the test article. During the test, the aircraft is raised through the pullback cable to the desired drop height. Following a countdown, the pullback cable is pyrotechnically cut, releasing the aircraft to swing towards the impact surface. Just prior to impact, the swing cables are pyrotechnically separated from the aircraft such that it is completely unrestrained

during the impact. More detailed descriptions of the IDRf full-scale crash test procedures are provided in References 3 and 5.

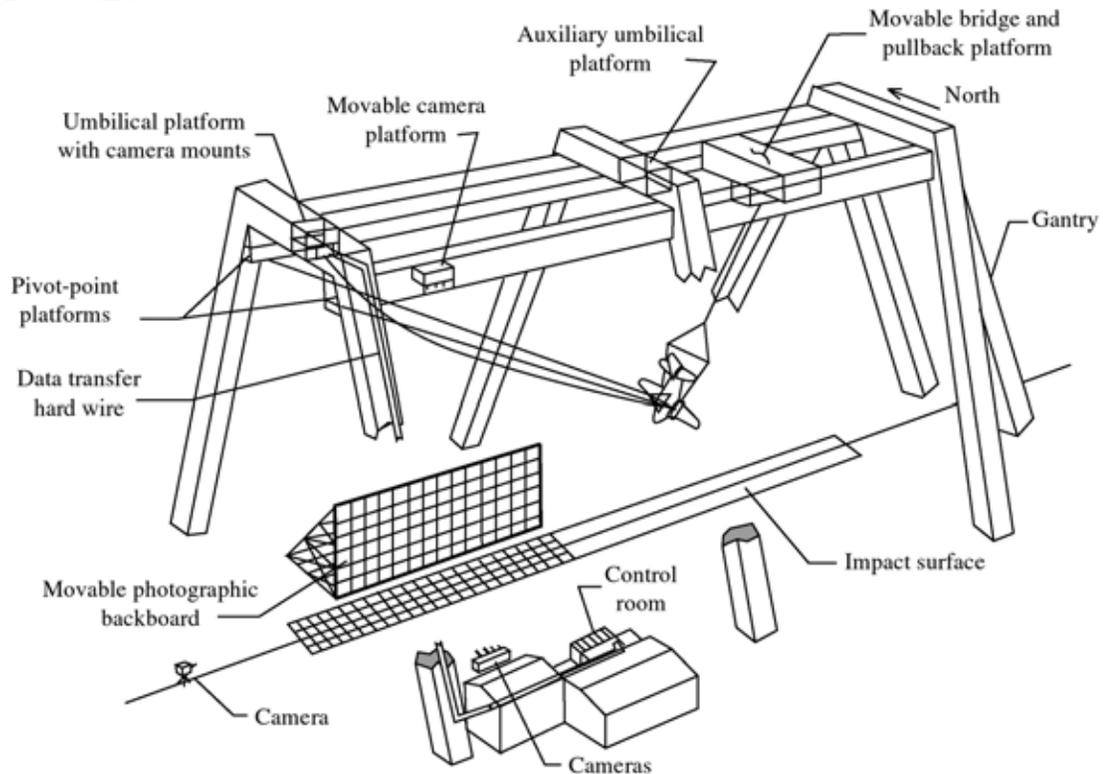


Figure 3. Schematic drawing of the IDRf illustrating full-scale crash test procedure.

GENERAL AVIATION AIRCRAFT CRASH TEST PROGRAM

In 1974, a cooperative research program was initiated between NASA, the FAA, and the GA aircraft industry to improve the crashworthiness of small aircraft [6-15]. The objectives of this program were to determine the dynamic responses of the aircraft structure, seats, and occupants during crash events; to determine the effect of flight parameters at impact (flight speed, flight-path angle, pitch angle, roll angle, etc.) on the magnitude and pattern of structural damage; to determine the failure modes of the seats and occupant restraint systems; and to determine the impact loads imposed upon the occupants. The program included extensive analytical work, test data evaluation, and structural concept development that were focused on enhancing the survivability of future GA aircraft with minimal increase in weight and cost.

Dynamic structural response data were obtained by conducting full-scale crash tests of GA aircraft under a variety of impact conditions. In all, 33 crash tests were performed during the 10-year period from 1974 through 1983. Most of the test articles (Piper Aztecs and Cherokees) were obtained for scrap aluminum value because the aircraft had been submerged during a flood at the Piper plant in Pennsylvania and they could not be certified, retrofitted or sold. Later crash tests were performed on Cessna 172 aircraft and larger pressurized Piper Navajos. Some of the test parameters included the impact velocity, the attitude of the airframe at impact, and the impact surface (hard surface and soft soil). Photographs of selected impact tests performed in support of the GA aircraft crash test program are shown in Figure 4.



Figure 4. Photographs of several GA aircraft full-scale crash tests performed at the IDRF.

Most of the full-scale crash tests of GA aircraft were performed using the pendulum-swing technique, described previously. This test method was sufficient to achieve impact velocities typical of the take-off and landing velocities of small GA aircraft (81- to 88-fps). However, these impact velocities were insufficient for crash tests of larger pressurized Piper Navajos that were conducted in the early 1980's. For these tests, a Velocity Augmentation System (VAS) was used in which rockets were attached to the wings of the aircraft. The rockets were fired while the aircraft was in the pullback position, allowing them to build thrust prior to release. Using this procedure, impact velocities of between 132- to 176-fps could be obtained. A photograph of one of the VAS tests of a Piper Navajo is shown in Figure 5.



Figure 5. Photograph of a full-scale crash test of a Piper Navajo aircraft with VAS.

Since it was not possible to evaluate all potential impact scenarios, most of the tests were performed for impact conditions that represented some of the more serious, but potentially survivable GA airplane crashes. The data obtained during the GA aircraft crash test program was used to define the levels of acceleration typically experienced by the airframe structure and by the occupants during crash events. The occupant data were compared with different human injury prediction criteria to determine injury risk levels during airplane crashes. The structural data from this landmark crash test program was used to establish impact criteria for aircraft seats that are still used as the FAA standard for seat certification testing today. Later, the data were used as the foundation for the Crash Survival Design Guide for GA aircraft [16].

Lear Fan 2100 Full-Scale Crash Test

In the early 1980's the focus of the GA crash research program at NASA Langley shifted from metal airframe structures to composite materials. As part of this effort, two prototype Lear Fan 2100 aircraft were obtained for crash testing when the Lear Fan Company went into bankruptcy. The Lear Fan aircraft was constructed primarily of graphite-epoxy composite fabric using a frame-stiffened skin design [17]. The subfloor of the aircraft consisted of stiff aluminum keel beams supported by composite stanchions. Since the airframe did not contain sufficient energy absorbing components, a decision was made to test one aircraft in the unmodified, or baseline, configuration and to retrofit the second aircraft with a composite energy absorbing subfloor. The development of the composite subfloor is described in References 18 and 19. Photographs of the crash test of the baseline Lear Fan aircraft are shown in Figure 6.



(a) Aircraft in the release position.



(b) Post-test photograph.

Figure 6. Lear Fan 2100 aircraft crash test.

The crash test of the baseline aircraft was performed in 1994 at 82-fps forward and 31-fps vertical velocity conditions onto a rigid impact surface. The aircraft was tested with three load-limiting and four standard non-crashworthy aircraft seats, all of which were forward facing. In addition, a plywood bulkhead wall was installed in front of the most rearward pair of seats to accommodate the installation of an airbag. An instrumented anthropomorphic test dummy was restrained in each seat. Results from this crash test showed, for the first time, that floor-level accelerations of this composite aircraft were much higher than those of comparable all-metallic aircraft. These findings indicated that this type of composite airframe design is not optimum for crashworthiness [20].

Beech Starship

As part of the Advanced General Aviation Transport Experiment (AGATE) research program, a full-scale crash test of the Beech Starship was performed in 1995. The Starship was the first composite aircraft to obtain FAA certification; however, it is no longer in production. The airframe is fabricated of a composite sandwich construction with Kevlar face sheets and a Nomex honeycomb core. The aircraft has built-in crashworthy design features, as described in Reference 21. The full-scale crash test was performed at 83-fps forward and 27-fps vertical velocity at the IDRF. During slide out following the

initial impact, a secondary impact occurred onto an earthen barrier. This impact was planned to generate longitudinal loading of the seats and occupants to evaluate an airbag protection system. Pre-release and post-test photographs of the Beech Starship are shown in Figure 7.



(a) Pre-release photograph.



(b) Post-test photograph.

Figure 7. Pre- and post test photographs of the Beech Starship.

Modified Cirrus SR-20

In 1995, NASA awarded a Small Business Innovative Research (SBIR) contract to Terry Engineering, Inc. to investigate design modifications for improved crashworthiness of light aircraft, including anti-plowing features. One objective of the research project was to evaluate aircraft modifications that would alleviate high longitudinal accelerations during soft soil impact. Ideally, the modifications to the aircraft should enable it to skid along the surface of the soil just as it would during an impact with concrete. As part of the SBIR, Terry Engineering worked with Cirrus Aircraft to develop the design modifications. Over a two-year period from 1996-1997, four full-scale crash tests were conducted, two onto concrete and two onto soft soil. Each test was performed for the same impact attitude and velocity conditions. A photograph of one of the four aircraft is shown in Figure 8 in the release position at the IDRf. The modifications were effective and demonstrated the potential of relatively minor design changes to improve overall crash performance of the airframe [22, 23].



Figure 8. Photograph of the modified Cirrus aircraft.

Modified Lear Fan 2100 Crash Test

A full-scale crash test of a second Lear Fan aircraft was performed at the IDRf in 1999. This aircraft was retrofitted with a composite energy absorbing subfloor and was tested under the same impact conditions as the baseline aircraft, 82-fps forward and 31-fps vertical velocity. The purpose of the test was to evaluate the effectiveness of the new subfloor design, to generate data for correlation with

analytical predictions, and to determine the dynamic response of side-facing seats. The aircraft was configured with side-facing seats and anthropomorphic test dummies. The crash test was performed in a similar manner as the 1994 test, with one exception. During slide out of the aircraft following the initial impact, the aircraft hit a plywood and earthen barrier, as shown in Figure 9. The purpose of this secondary impact was to introduce significant longitudinal loads into the airframe to test the ability of the side-facing seats to adequately restraint the occupants. The tests provided data to guide needed improvements in the design of side-facing seats.



Figure 9. Post-test photograph.

Modified Lancair Crash Test

As a final demonstration of the technology developments of the AGATE research program, a full-scale crash test of a modified Lancair aircraft was performed at the IDRf in 2001. The purpose of the test was to demonstrate the efficacy of employing a systems approach to crashworthiness for GA aircraft. Some of the crashworthy features of the aircraft included an energy absorbing subfloor, load-limiting seats, advanced restraint systems, and anti-plowing features. The crash test was performed at 96-fps resultant velocity. This impact condition is much more severe than the current FAA requirements for dynamically certified seats. A photograph of the aircraft just following initial impact is shown in Figure 10. The full-scale crash test of the modified Lancair was successful since the survivable cabin volume was retained during the impact and the occupant loads were within survivable limits.



Figure 10. Photograph of the modified Lancair aircraft immediately after impact.

TRANSPORT AIRCRAFT CRASH TEST PROGRAM

In the early 1980's, NASA partnered with the FAA to conduct the Controlled Impact Demonstration (CID) research program [24, 25]. The primary objective of the CID was to evaluate the performance of a fuel additive, anti-misting kerosene or AMK, to reduce the potential of a massive fire upon impact of transport jets. As a final demonstration of the AMK technology, a full-scale crash test of a remotely piloted B720 transport jet was conducted in December 1984 at Edwards Air Force Base. A

photograph of this test is shown in Figure 11. NASA's interest in the test was in obtaining structural response data during a full-scale crash test of a transport aircraft. IDRF personnel designed the instrumentation layout and developed a redundant data acquisition system to ensure data collection, even in the event of fire. Also, all onboard cameras were thermally protected.

The B720 transport aircraft impacted the dry lakebed surface in a rolled (left-wing down) and yawed attitude at 17-fps vertical and 248-fps forward velocity. Tank traps, that were positioned to shear the wings, actually cut through an engine, providing a powerful ignition source for post-crash fire. However, in spite of the fire, data were retrieved from 97% of the 350 transducers on the aircraft. This data provided the first quantitative measurements of transport jet structural response during an actual free-flight crash. In addition to planning and coordinating the structural response data for the crash test, IDRF personnel were also heavily involved in performing crash simulations of the CID test, as described in the Crash Modeling and Simulation section of the paper.

In preparation for the CID crash test, vertical drop tests of three B707 transport fuselage sections were performed using the 70-ft. drop tower at the IDRF [26-28]. The objectives of the tests were to evaluate the integrity of the data acquisition systems that would be used on the CID and to generate data for model validation. The three sections were from the forward, center (wing box), and aft compartments of the aircraft. The drop tests were performed at 20-fps vertical velocity, which was slightly higher than the planned vertical impact condition for the CID. A post-test photograph of the B707 forward fuselage section is shown in Figure 12.



Figure 11. Photograph of the CID full-scale crash test of a B720 transport aircraft.



Figure 12. Photograph of the B707 forward fuselage section post-test.

DOD-SPONSORED CRASH TEST PROGRAMS

Numerous crash test programs have been conducted at the IDRF in support of the DOD during the period from 1975 through 1999. Most of these test programs will be described briefly in the following section of the paper. Additional information on DOD-sponsored test programs performed at the IDRF can be found in Reference 29.

Crash Testing of the CH-47 Chinook Helicopter

In 1975 and 1976, two full-scale crash tests of the CH-47 "Chinook" helicopter were performed in support of the U.S. Army Aviation Applied Technology Directorate (AATD) located at Ft. Eustis, VA. The CH-47 helicopter is a heavy lift, troop, and equipment transport helicopter. The objectives of the crash tests were to evaluate the load-limiting performance of the seats, the structural response of the airframe, and the integrity of the cargo restraint systems [30, 31]. A series of photographs showing the sequence of events during the crash test of the CH-47 helicopter is shown in Figure 13. Data acquired from these initial helicopter crash tests were used to correlate with kinematic computer models. Also, results from the tests highlighted several potential structural and post-crash fire hazards.

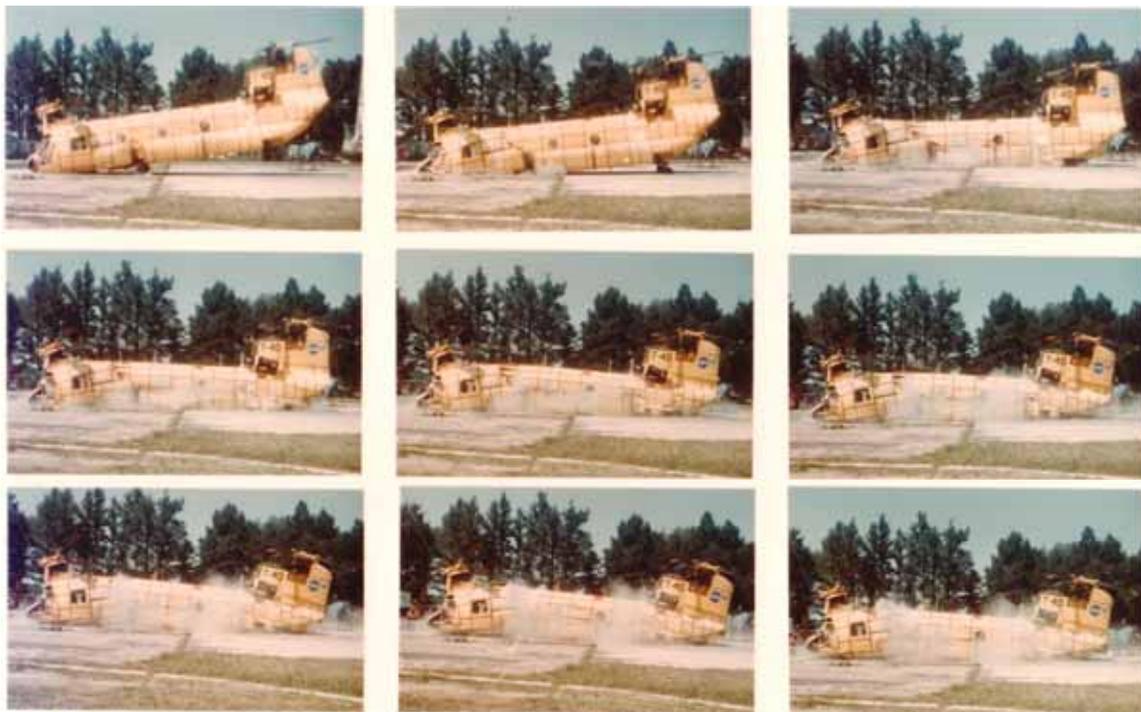


Figure 13. Series of photographs showing the deformation of the CH-47 helicopter during crash testing.

Tethered-Hover Test of the XFV-12A

In early 1978, a team of NASA, Navy, and North American Rockwell personnel performed tethered-hover tests of the full-scale XFV-12A at the IDRF [32]. A photograph of the XFV-12A during a tethered hover test is shown in Figure 14. Some fairly extensive modifications were made to the IDRF to allow tethered-hover tests for powered vertical take-off and landing aircraft. During six months of testing of the XFV-12A, major deficiencies were apparent in hovering flight, including marginal thrust augmentation and relatively poor handling qualities. The findings from this test program helped influence the Navy's decision to cancel the XFV-12A program [33].



Figure 14. Tethered-hover test of the XFV-12A in 1978.

Wire Strike Protection System (WSPS) Testing

The U.S. Army AATD sponsored a series of Wire Strike Protection System (WSPS) qualification tests on different Army helicopters [34-36]. Based on helicopter accident data, it was found that many crashes occurred during nap-of-the-earth flight when pilots accidentally flew the helicopters into utility cables. A passive system was designed to minimize this problem. Two blade-type devices, fabricated of hardened steel, are attached to the top and bottom of the helicopter fuselage. During a wire strike, the cables are intended to slide either up or down the front of the helicopter and get caught in the blade-type device. The cable is then notched and severed. Qualification tests were performed at the IDRf to verify the passive WSPS design for all Army helicopters. The tests were performed by attaching a 3/8-in.-diameter steel cable to telephone poles located on opposite sides of the gantry. The helicopter was suspended from the gantry, pulled back into the release position, and then released to swing into the cable. The vertical elevation of the helicopter was adjusted to test different cutter locations, such as the roof or belly cutters. A photograph showing a WSPS test of an AH-1 Cobra helicopter is depicted in Figure 15. The passive WSPS concept, as validated during tests at the IDRf, has been highly effective in protecting helicopters against mishaps caused by wire strikes. Fewer accidents, injuries, and fatalities have resulted in Army helicopters that are equipped with WSPS. Currently the passive WSPS systems are installed fleet-wide on all military helicopters and are optional equipment on many commercial helicopters.



Figure 15. Photograph of a WSPS test performed on an AH-1 Cobra helicopter.

Full-Scale Crash Test of the Bell YAH-63 Helicopter

In 1981, a full-scale crash test of the YAH-63 prototype helicopter was conducted at the IDRFB [37]. This helicopter was designed and manufactured by Bell Helicopter Textron as its bid in the competition for the Army's Advanced Attack Helicopter (AAH) program. The crash test was performed to evaluate the energy-absorbing and load-limiting features of the airframe, landing gear, and seats. A pre-test photograph of the YAH-63 helicopter in the impact position is shown in Figure 16(a). A photograph of the YAH-63 during the crash test is shown in Figure 16(b). The Bell airframe did not win the award, which went to the Hughes Helicopter (now Boeing) AH-64 Apache.



(a) Pre-test photograph.



(b) Photograph during impact.

Figure 16. Pre- and post-test photographs of the Bell YAH-63 helicopter.

Full-Scale Crash Tests of the ACAP Helicopters

Full-scale crash qualification tests were performed of the Bell and Sikorsky Advanced Composite Airframe Program (ACAP) helicopters in 1987 [38-40]. The purpose of the Army-sponsored ACAP was to demonstrate the potential of advanced composite materials to save weight and cost in airframe structures while achieving systems compatibility and meeting military requirements for vulnerability reduction, reliability, maintainability, and survivability. In 1981, the U.S. Army awarded separate contracts to Bell Helicopter Textron and Sikorsky Aircraft Company to develop, manufacture, and test helicopters constructed primarily of advanced composite materials. Each company manufactured three airframes that were tested under a variety of static and dynamic conditions to demonstrate compliance with the program objectives. In addition, one helicopter airframe from each company was equipped to become a flying prototype. Crash tests of the Bell and Sikorsky ACAP static test articles were conducted in 1987 at the IDRFB in support of the U.S. Army AATD to demonstrate their impact performance and to verify compliance with crash requirements. Pre- and post-test photographs of the full-scale crash tests are shown in Figure 17. The Bell ACAP helicopter impacted with a combined 42-fps vertical and 27-fps forward velocity, while the Sikorsky ACAP helicopter impacted at 39-fps vertical velocity. These tests demonstrated the successful application of composite materials to save weight and maintenance costs in rotorcraft design, while also achieving improved crash performance.

Full-Scale Crash Testing of a AH-1S Cobra Helicopter with CABS and IBAHRS

In the early 1990's, the U.S. Army was actively supporting the development of crew restraint technologies based on studies showing that a high percentage of crash injuries resulted from occupants striking interior cockpit structures. In 1993, two full-scale crash tests of an AH-1S Cobra helicopter were conducted at the IDRFB to demonstrate the performance of active crew restraint systems under realistic crash conditions. In particular, the tests, sponsored by the U.S. Army AATD, were performed to evaluate the Inflatable Body and Head Restraint System (IBAHRS) and the Cockpit Air Bag System (CABS) [41]. IBAHRS is an active restraint system that consists of two sealed airbags integrated into a standard five-point restraint harness, with gas generators, a crash sensor, and airframe specific modifications. The IBAHRS airbags are attached to the underside of the shoulder straps to restrain the

torso of the occupant. CABS is an airframe-mounted system similar to that used by the automotive industry. The multiple bag design is cockpit specific and the sensor is tuned to the airframe crash characteristics. The combined forward and vertical velocity conditions that were selected for both tests are considered moderately severe and represent a high percentage of survivable crashes. The impact tests were conducted on both soft soil and concrete. A photograph is shown in Figure 18 of one of the full-scale crash tests of the AH-1S helicopter with IBAHRS and CABS deployed. In both tests the IBAHRS and CABS were fully deployed at the proper time to provide their maximum protection capabilities. This program demonstrated that these systems have the potential to reduce the number of injuries and fatalities resulting from occupant contact with interior cockpit structures in a crash. Currently, the U.S. Army has ordered retrofit of UH-60 Black Hawk and OH-58 Kiowa Warrior helicopters to be outfitted with CABS based in part on the results of this successful test program.



(a) Pre-test photograph of the ACAP helicopters. (b) Bell ACAP helicopter during full-scale crash test.



(c) Photograph of the Sikorsky ACAP helicopter during full-scale crash test.

Figure 17. Photographs of the Bell and Sikorsky ACAP helicopters, before and during full-scale crash tests performed at the IDRF.



Figure 18. Photograph of a crash test of the AH-1S helicopter with crew restraint systems.

Qualification Tests of an External Fuel System for the UH-1 Huey Helicopter

In 1994, three UH-1 Huey helicopters were crash tested at the IDRf to qualify an External Fuel System (EFS) proposed for National Guard helicopters. Pre-test photographs of one of the UH-1 helicopters outfitted with external fuel tanks are shown in Figure 19. The external fuel system included left and right conformal tanks each with a capacity of approximately 75 gallons. One right and two left external tanks were available for the qualification program. An additional right tank that was used previously in ballistic test evaluation was repaired and used in the crashworthiness qualification. These external tanks attach to hard points on the fuselage subfloor sides. All tests were conducted with a nominal 9,000-lb. gross weight for the helicopters including the EFS, simulated fuel, attached swing fixture, and instrumentation. The tests were conducted by swinging the aircraft pendulum-style into the ground with combined impact velocities from 32- to 51-fps and with a 51.3-degree flight path, a 10-degree nose-up pitch, and 0-degree yaw. The helicopters were rolled 15-degrees to the left for the first two tests and 26-degrees to the right for the third test. The pass/fail criteria for these tests were based on the nature and amount of leakage from the tanks. Water was used as a fuel substitute. Because of the higher specific gravity of water compared to aviation fuel, the main and external fuel tanks were filled to 80% of their capacity to represent the weight of the aviation fuel. Red and green water-soluble dyes were used in the EFS tanks to identify the source of any leakage that might occur and to distinguish leakage in the EFS from leakage in the main fuel system where clear water was used. As a result of the successful qualification tests performed at the IDRf, the EFS was approved for use on National Guard helicopters as a means of extending their range and/or increasing payload.



(a) Side view showing EFS.



(b) Rear view showing rolled impact attitude.

Figure 19. Pre-test photographs of a UH-1 Huey helicopter with external fuel tank.

Crash Testing of the F-111 Crew Escape Module

Beginning in the 1980's and continuing through the mid-1990's, impact tests of the F-111 crew escape module were performed at the IDRf in support of the U.S. Air Force. In the event of an emergency, the F-111 crew escape module is separated from the aircraft and the module descends to Earth with the aid of a parachute. However, even with the parachute, the Air Force reported that the impact of the crew module with the ground resulted in a high percentage of injuries and some fatalities. Consequently, an external airbag energy attenuation system was designed for the crew escape module. The airbag was located on the flat underside of the module and contained blowout plugs that were designed to tailor the amount of energy absorbed. During the 15-year period, over 60 impact tests were performed of the F-111 crew module with different airbag designs. The objectives of the tests were to: (1) determine the impact loads generated by the airbag system and subsequently transmitted to the occupants during impact; (2) to characterize the stability of the module under various impact attitudes; and, (3) to assess design changes to the airbag attenuation system. A photograph of an F-111 crew module with airbag inflated prior to an impact test at the IDRf is shown in Figure 20. Note the complex

cable system used to obtain the appropriate impact attitude for the test. Many of the tests were conducted onto a soft soil surface under a variety of roll, pitch, and yaw angles to represent the range of impact attitudes possible with a parachute landing. A series of photographs taken during one of these tests is shown in Figure 21. As stated in Reference 33, “As a result of the data provided to the Air Force, load attenuating crew seats were included in the F-111 and airbag and blowout plug design changes were made to the original airbags. Various changes to the module led to the design of a new airbag system, which was tested for qualification on the F-111 in the final series of tests prior to retirement of the F-111 fleet.”



Figure 20. Pre-test photograph of the F-111 crew escape module with airbag attenuation system.

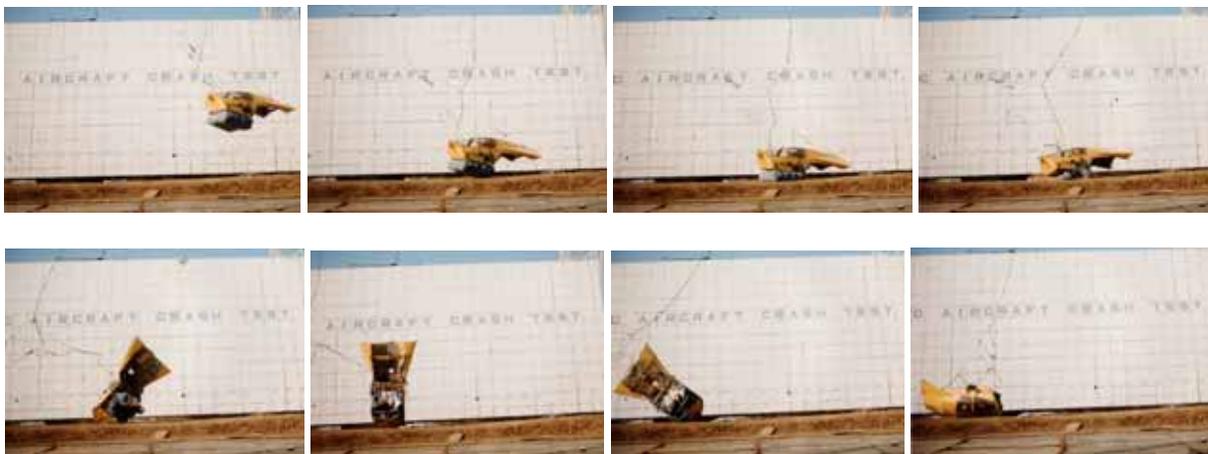


Figure 21. Series of photographs of an F-111 crew module impact test.

Full-Scale Crash Test of the Sikorsky ACAP Helicopter (Flight Test Article)

A full-scale crash test of the Sikorsky ACAP helicopter was performed at the IDRf in 1999. The main purpose of the test was to obtain experimental data for validation of a finite element crash simulation. The helicopter was the flight test article built by Sikorsky Aircraft under sponsorship by the U.S. Army during the ACAP. The helicopter was constructed primarily of advanced composite materials and was designed to meet the Army's stringent MIL-STD-1290A [42] crashworthiness criteria. For the crash test, the aircraft was outfitted with two crew and two troop seats and four instrumented anthropomorphic dummies. The test was performed at 38-fps vertical and 32.5-fps horizontal velocity

onto a rigid impact surface [43]. Approximately 120 channels of dynamic data were collected. Photographs of the helicopter taken just prior to and after impact are shown in Figure 22.

In addition to obtaining structural crash data for validating a nonlinear transient dynamic computer simulation, several ancillary experiments were included. A programmable electronic crash sensor unit (ECSU) was mounted on the cabin floor near the troop seats. The sensor was typical of the kind that might be used to inflate an airbag. During the test, the ECSU operated successfully and was very helpful in obtaining time synchronization between the exterior and interior cameras. In addition, the left and right fuel tanks were instrumented with two transducers each to measure the hydrodynamic pressure pulse during impact. The pilot and copilot dummies were seated in two military-qualified load-limiting seats from two different vendors. The troop dummies were seated in ceiling-suspended troop seats, each with two wire-bender energy absorbers that were mounted in the rear cabin area of the helicopter. The detailed seat and occupant response data obtained from the crash test were evaluated and the occupant data were correlated with injury prediction models [44].



(a) Photograph of the ACAP helicopter at impact.



(b) Post-test photograph.

Figure 22. Photographs of the Sikorsky ACAP helicopter.

Qualification Tests of an External Fuel Tank for the UH-60 Black Hawk Helicopter

The U.S. Army has retrofitted its entire helicopter fleet with crashworthy internal fuel systems to greatly reduce post-crash fire hazards. It also has a large inventory of 230-gallon external fuel tanks that were originally designed for ferry missions only and which could be jettisoned. These external fuel tanks were not designed to the same crash resistance standard as the internal fuel tanks. Because of the increased use of these tanks in low-level flying missions where the tanks cannot be safely jettisoned during a mishap, the external tanks need to be as crash resistant as the on-board tanks. In December of 1999, the U.S. Army AATD sponsored a full-scale crash test of a UH-60 Black Hawk helicopter at the IDRf to verify the performance of two modified 230-gallon external fuel tanks [45, 46]. The Black Hawk airframe used in this test was already crash damaged and did not have a tail cone. The external tanks can be mounted on the External Stores Support System (ESSS) utilized on the UH-60 Black Hawk, the AH-64 Apache, and the RAH-66 Comanche helicopters. The external fuel tanks were attached to the left and right outboard positions of the ESSS wings mounted on the helicopter. The tanks were filled approximately 80% full of water to simulate the full-tank weight of JP-8 fuel. The helicopter was impacted with vertical and forward velocities of 42- and 50-fps, respectively onto concrete. The attitude of the helicopter at impact was 6-degrees nose-up pitch, 17-degrees left roll, and 17-degrees right yaw. These impact conditions are much more severe than those specified in MIL-STD-1290A [42] for occupant survivability. Photographs depicting the full-scale crash test of the UH-60 Black Hawk helicopter are shown in Figure 23. The results of the test indicate that both external fuel tanks survived the severe impact condition with only minor leakage, even though they experienced a large transient pulse during the impact test. These findings validated the crash resistance of the modified fuel tank design allowing the Army to more fully utilize these ESSS-mounted tanks to provide extended range for helicopter missions.



(a) Test article in the release position.



(b) Photograph during impact.

Figure 23. Photographs of the UH-60 Black Hawk helicopter full-scale crash test.

CRASH MODELING AND SIMULATION

An important aspect of crashworthiness research is the demonstration and validation of analytical/computational tools for accurate simulation of airframe structural response to crash loads. The “validation of numerical simulations” was identified as one of five key technology shortfalls during the Workshop on Computational Methods for Crashworthiness that was held at NASA Langley Research Center in 1992 [47]. Analytical codes have the potential to greatly speed up the crashworthy design process, to help certify seats and aircraft to dynamic crash loads, to predict seat and occupant response to impact with the probability of injury, and to evaluate numerous crash scenarios not economically feasible with full-scale crash testing.

In the late 1970’s, NASA and the FAA jointly funded Grumman Aerospace Corporation to develop a nonlinear, structural dynamic finite element computer code called Dynamic Crash Analysis of Structures (DYCAST) [48]. The DYCAST element library included (1) stringers and rods having axial stiffness only; (2) beam elements; (3) triangular membrane elements; (4) triangular plate elements; and, (5) nonlinear translational or rotational spring elements that provide stiffness with user-specified force-displacement or moment-rotation tables in a piecewise linear manner. DYCAST was capable of accounting for both material and geometric nonlinearities. Also, both implicit- and explicit-time integration schemes were included to permit quasi-static and dynamic simulations. Some of the initial DYCAST simulations were performed to support the CID crash test program, including the development of B707 fuselage section models to simulate the vertical drop tests performed at the IDRF, as well as full-scale models of the B720 transport aircraft. Boeing and NASA-IDRF personnel jointly developed these models, shown in Figure 24, for test-analysis correlation. The models, which typically contained less than 100 elements, were primarily constructed using compound beam elements, concentrated masses, and nonlinear spring elements. The analytical and experimental correlations performed for these drop tests and the CID represented the first validated crash simulations of transport aircraft structures. Additional information on the DYCAST models of the B707 fuselage section and the B720 transport airplane can be found in References 49 and 50.

Currently, a new generation of crash analysis codes have been developed that can accurately simulate the nonlinear, transient dynamic response of airframe structures. These finite element codes, such as LS-DYNA [51], MSC.Dytran [52], and PAM-CRASH [53], use an explicit time integration method that eliminates the need to repetitively decompose large global stiffness matrices as is required for implicit codes. Explicit codes require an extremely small time step, typically less than a

microsecond, whose duration is controlled by the smallest element in the model. Thus, impact simulations having a pulse duration on the order of 30-40 milliseconds can require several CPU hours to solve on an engineering workstation. Consequently, efficient beam, shell, and solid elements are needed to achieve quick run times for very large models. The new codes are capable of modeling nonlinear geometric behavior including large structural deformations and rotations. In addition, numerous material properties can be selected to represent a wide variety of complex material and failure responses, including plasticity in metals; progressive failure in layered composite materials; and exotic foam and soil models.

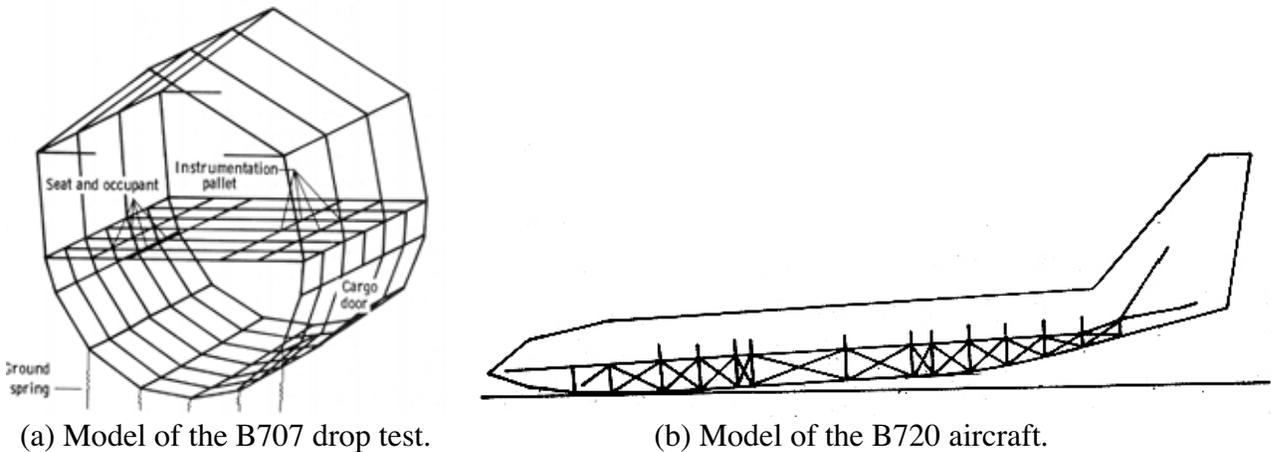


Figure 24. DYCAST models developed to support the CID.

In 1998, a research project was initiated to demonstrate the capabilities of state-of-the-art commercial crash simulation codes in predicting the dynamic structural response of a prototype composite helicopter, the Sikorsky ACAP helicopter, during a full-scale crash test. A crash simulation of the full-scale crash test was developed using the commercial nonlinear, explicit transient dynamic code, MSC.Dytran [52]. The objective of the crash simulation was to evaluate the capabilities of the code in predicting the response of a composite airframe subjected to impact loading. An existing NASTRAN [54] modal-vibration model of the Sikorsky ACAP helicopter was modified and converted into a model suitable for crash simulation. The MSC.Dytran model is shown in Figure 25. A two-stage modeling approach was implemented for the crash simulation and an external user-defined subroutine was developed to represent the complex landing gear response. Analytical predictions of structural deformation and failure, the time sequence of events, and the dynamic response of the airframe structure were generated. The numerical results were correlated with the experimental data to validate the simulation [55-58]. The level of agreement obtained between the experimental and analytical data builds further confidence in the use of nonlinear, explicit transient dynamic finite element codes as a crashworthy design and certification tool for aircraft.

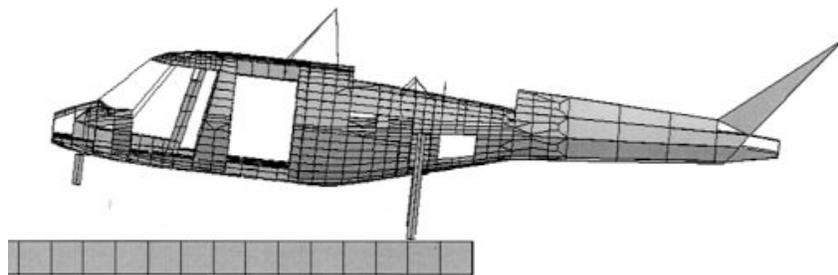
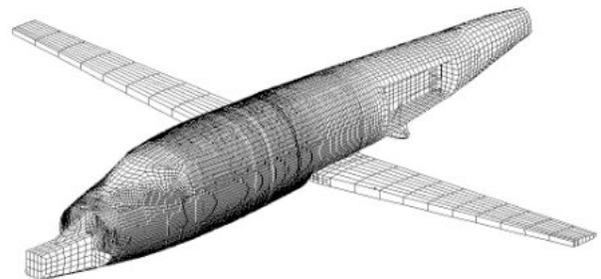


Figure 25. MSC.Dytran model of the Sikorsky ACAP helicopter.

A detailed finite element model of the Lear Fan aircraft was developed to simulate the 1999 impact test conducted at the IDRF. This test was the second full-scale crash test of a Lear Fan aircraft. Prior to the test, the aircraft had been retrofitted with an energy absorbing composite subfloor [18, 19]. Since no technical drawings were available to assist in the model development, a computerized photogrammetric survey was performed to provide geometric coordinates defining the geometry of the airframe. The final model of the Lear Fan aircraft is shown in Figure 26. Impact simulations were performed using the explicit nonlinear, transient dynamic code, MSC.Dytran [52]. The simulation accurately predicted key structural responses such as fuselage cracking at the forward wing attachment and failure of the fuselage frames along the centerline. The level of agreement achieved for this simulation was remarkable given the complexity of the geometry and the lack of detailed information on the composite material system used to construct the aircraft [59].



(a) Photograph of the 1999 crash test.



(b) Finite element model of the Lear Fan aircraft.

Figure 26. MSC.Dytran simulation of the full-scale crash test of the modified Lear Fan aircraft.

STATUS OF THE IDRF

The final full-scale crash test performed at the IDRF was a pendulum-swing test of a modified Lancair GA aircraft in 2001. However, vertical drop tests continued to be performed at the facility through 2003, including a vertical drop test of a fuselage section of an F-28 commuter-category aircraft. A large portion of this research was performed under sponsorship of the Accident Mitigation Element of the NASA Aviation Safety Program [60]. The Accident Mitigation Element was comprised of two parts: aircraft crash safety and crash-resistant fuel systems. On October 31, 2002, the funding for the crash safety portion (only) of the Accident Mitigation Element was cancelled. Subsequently, the IDRF gantry was officially closed by NASA Langley on September 30, 2003, and plans are underway to demolish the facility in 2007.

CONCLUDING REMARKS

The Impact Dynamics Research Facility (IDRF) is a 240-ft.-high gantry structure located at NASA Langley Research Center in Hampton, Virginia. The gantry facility was originally built as a lunar landing simulator during the Apollo Program and was used by the Apollo astronauts to practice lunar landings under realistic conditions. In 1972, the facility was converted to a full-scale crash test facility for light aircraft and rotorcraft. Since that time, the IDRF has been used to perform a wide variety of impact tests on full-scale aircraft and structural components in support of the General Aviation (GA) aircraft industry, the US Department of Defense, the rotorcraft industry, and NASA in-house aeronautics and space research programs. Most of the major full-scale crash test programs that were performed at the IDRF since 1974 are described in the paper including highlights of the civil GA aircraft test program, transport aircraft test program, military test programs, and crash modeling and simulation.

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