Crash Certification by Analysis – Are We There Yet?

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Abstract

This paper addresses the issue of crash certification by analysis. This broad topic encompasses many ancillary issues including model validation procedures, uncertainty in test data and analysis models, probabilistic techniques for test-analysis correlation, verification of the mathematical formulation, and establishment of appropriate qualification requirements. This paper will focus on certification requirements for crashworthiness of military helicopters; capabilities of the current analysis codes used for crash modeling and simulation, including some examples of simulations from the literature to illustrate the current approach to model validation; and future directions needed to achieve "crash certification by analysis."

Introduction

The rationale for incorporating crashworthy design features into rotorcraft is to minimize the number of fatalities and serious injuries experienced by the crew and troops, and to reduce the amount of structural damage to the airframe and payload during a severe, but survivable, crash. Ideally, the initial cost and weight associated with incorporating crashworthy design features are offset by cost savings associated with the reduced number of injuries and lower levels of aircraft damage. Crashworthy design of rotorcraft requires a systems approach in which various subcomponents work together to absorb and dissipate the kinetic energy of impact. During a crash, the helicopter must limit the loads and decelerations that are transferred to the occupants to humanly tolerable levels, usually through crushable landing gear, energy absorbing subfloors, and load-limiting seats. Structural collapse of fuselage frames and other structural components used to support the overhead rotor and transmission mass must be prevented, thereby providing a livable volume for the occupant. The seats, restraint systems, seat track, and floor provide a secure tie down in the crashworthy helicopter, thus preventing the occupant from becoming a projectile inside the fuselage during a crash. In addition, head strike potential should be mitigated or eliminated through the use of pre-tensioned restraint systems and/or cockpit airbags. Occupant survivability also depends on eliminating post-crash fire hazards and providing for emergency egress. The crashworthy helicopter must be capable of all these things while experiencing high transitory, multi-directional decelerations associated with impact onto different terrains.

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Historically, MIL-STD-1290A (AV) [1] defined the certification requirements for crash performance of military helicopters by specifying a list of lateral, vertical, longitudinal, and combined velocity impact conditions that the airframe must withstand with minimal collapse and associated loss of volume (15% or less). The military standard encouraged the designer to demonstrate compliance with the requirements by using analytical methods. However, the standard also states that: "Instrumented full-scale crash test(s) are desirable to substantiate the capability of the aircraft system to prevent fatalities and minimize injuries during crashes of the severity cited herein. If the system testing is not conducted, then analysis shall be required to show that the individual components and subsystems function together effectively to achieve the specific overall level of crashworthiness." Thus, the military standard established both full-scale crash testing and analytical modeling as tools to achieve crash certification.

The purpose of this paper is to discuss certification or qualification of helicopter crashworthiness by analysis. The terms 'certification' and 'qualification' are used interchangeably in the paper and they are defined as "confirmation that a design requirement or military specification has been met or achieved." The paper begins with a brief review of crash safety requirements for military helicopters. Next, a summary of modeling and analysis procedures is provided. In order to assess the accuracy of crash simulations, examples are summarized in which the codes are used to simulate full-scale aircraft crash tests. Finally, future directions needed to achieve "crash certification by analysis," are discussed in two subsections: Design Requirements and Improved Analytical Methods.

Brief Review of Crash Safety Requirements

Military helicopter design requirements for crashworthiness were developed by close examination of U.S. Army accident data during two different studies. The first study reviewed all accident data for rotary- and light fixed-wing aircraft that occurred between July 1960 and June 1965. During a second study, attack and cargo helicopter accidents that occurred from January 1971 through December 1976 were studied. The data from these studies were examined to determine the velocity changes in the vertical and longitudinal directions at impact for survivable crashes. The results of the study showed that the 95th percentile of all survivable accidents occurred at less than 42 ft/s vertical and 50 ft/s longitudinal impact velocities. Analysis of the data also showed similarity between rotary- and light fixed-wing aircraft. Consequently, the same criteria were used to qualify both types of aircraft. In general, there were insufficient data to determine a lateral velocity distribution. Thus, a representative value of 30 ft/s lateral velocity was selected. Later, reductions were made in the longitudinal velocity change and in the attitude angles based on economic factors and operational constraints. However, the vertical and lateral velocity requirements were unchanged.

The findings from the two studies mentioned previously and many additional investigations into the safety and survivability of Army helicopters led to the development of the Crash Survival Design Guide in 1965, which was a compilation of a series of reports on accident analyses, full-scale crash test data, proposed design criteria, and prototype crashworthy systems. Since then, the Guide has been updated and expanded several times to encompass the increasing knowledge gained from continuing research in rotorcraft crashworthiness. Today, the latest edition of the Aircraft Crash Survival Design Guide [2], published in 1989, consists of five volumes.

Information contained in the Crash Survival Design Guide was used in the development of Military Standard MIL-STD-1290A (AV) for Light Fixed and Rotary-Wing Aircraft Crash Resistance [1], which establishes minimum crash resistance criteria for implementation in the initial stages of aircraft system design. The initial release of the standard was in January 1974, and it was subsequently revised in September 1988. In the late 1980's, an Aeronautical Design Standard ADS-36 for Rotary Wing Aircraft Crash Resistance [3] was developed specifically for qualifying the U.S. Army's new reconnaissance and attack helicopter, the RAH-66, which eventually became the Comanche helicopter. The ADS-36 contains similar information as the MIL-STD-1290A (AV); however, some of the criteria were modified so that the RAH-66 would be designed with crash resistance equivalent to the existing UH-60 Black Hawk. For the discussions in this paper, the crash requirements in the military standard will be described.

MIL-STD-1290A (AV) contains seven different specifications for aircraft crashworthiness, as listed in Table 1. The crash performance requirements for each of these impact conditions are summarized in Table 2. To meet the performance requirements, the designer is requested to demonstrate the capabilities of the aircraft to withstand various velocity change criteria using *analytical methods*. However, the MIL-STD-1290A (AV) does not specify which analytical methods or codes should be used to perform these analyses. Separate military specifications for landing gear, seats, fuel tanks, and other subsystems are also cited in MIL-STD-1290A (AV).

Appendix A in MIL-STD-1290A (AV) lists the testing requirements for various aircraft components and subsystems including the fuel system, crew and troop seats, litter supports, landing gear, and flammability tests. The General Requirements section of the military standard states that, "The component and subsystem tests described in Appendix A are mandatory. Instrumented full-scale crash test(s) are desirable to substantiate the capability of the aircraft system to prevent fatalities and minimize injuries during crashes of the severity cited herein. If the system testing is not conducted, then *analysis* shall be required to show that the individual components and subsystems function together effectively to achieve the specific overall level of crashworthiness."

Table1. Crash Impact Design Conditions, with Landing Gear Extended

Condition No.	Impact Direction (Aircraft Axes)	Velocity Change (ft/s)	Object/ Surface Impacted
1	Longitudinal (cockpit)	20	Rigid vertical barrier
2	Longitudinal (cabin)	40	
3	Vertical*	42	Rigid horizontal surface
4	Lateral, Type I	25	
5	Lateral, Type II	30	
6	Combined high angle* <u>Vertical</u> Longitudinal	<u>42</u> 27	
7	Combined low angle <u>Vertical</u> Longitudinal	<u>14</u> 100	Plowed soil

*For the case of retracted landing gear, the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 26 ft/s.

Several additional comments should be made regarding crash criteria. More recent studies of military helicopter accidents [4-6] show clearly that the "one size fits all" approach to crash design criteria is not appropriate. A recommendation from Reference 4 is that "design standards should be tailored to class or type of aircraft in order to minimize cost and maximize the crash protection offered by each type of helicopter." A similar recommendation is stated in Reference 5, "cost/benefit trade studies should be conducted…to establish the optimum required design crash velocity." In addition, Reference 6 recommends a "variable crash resistance design criteria for military helicopters as a function of their size, main rotor blade disk loading, rotor blade inertia, autorotative rate of descent, and mission type." Data contained in References 4 through 7 indicate that more recent accident studies show that a significant change has occurred in the kinematics of military helicopter crashes. As new and improved crashworthy design features have been introduced over time, the data show that survivable helicopter accidents are occurring at higher impact velocities. Consequently, since crash design requirements are based on accident statistics, it is important to update the statistical data on a regular basis. Likewise, the design requirements should be re-evaluated periodically to ensure their validity and relevance.

It is important to note that there are no requirements for full-scale crash testing of civil rotorcraft, similar to MIL-STD-1290A (AV) or ADS-36. Instead, there are seat requirements described in the Federal Aviation Regulations, Parts 27 and 29, for normal and transport civil rotorcraft (see References 8 and 9). These criteria are summarized in Reference 10, and comparisons of military and civil requirements are presented in References 11 and 12. In general, the findings show that civil helicopters typically crash at consistently lower velocities than do military helicopters. Consequently, applying the military standard to civil helicopters is not appropriate.

Finally, MIL-STD-1290A (AV) was canceled by the US Department of Defense in the mid-1990's to give defense contractors more freedom to develop creative and innovative designs without the constraints provided by the military standards.

Table 2. Performance Requirements for Crash Design Conditions

Impact Direction	Performance Requirement
Longitudinal - Cockpit (ΔV_x)	The designer shall demonstrate *analytically* that the basic airframe is capable of impacting longitudinally into a rigid vertical barrier at a constant velocity of 20 ft/s without crushing the pilot or copilot stations to an extent that would either preclude evacuation of the aircraft or preclude a livable volume for the aircraft occupants. For this impact, the engines, transmission, and rotor system shall remain intact.
Longitudinal - Cabin (ΔV_x)	The basic airframe's capability to impact longitudinally into a rigid vertical barrier or wall at a constant velocity of 40 ft/s without reducing the length of the passenger/troop compartment by more than 15% shall be demonstrated *analytically*. Any consequent inward buckling of walls, floor, and/or roof shall not be hazardous to the occupants and/or restrict their evacuation.
Vertical (ΔV_z)	The designer shall *analytically* demonstrate the capability of the aircraft system, with rotor/wing lift equal to structural design gross weight (SDGW) and with landing gear extended, to withstand vertical impacts of 42 ft/s on a rigid horizontal surface without (1) reducing the height of the cockpit and troop compartment by no more than 15%, and (2) allowing the occupants to experience injurious accelerative loading. For the case of retracted landing gear, the designer shall *analytically* demonstrate the capability of the aircraft to withstand impacts of 26 ft/s on a rigid horizontal surface with the same requirements as for the gear extended case. The capabilities, with gear up or down, are required for all aircraft orientation (attitudes) upon impact in +15° to -5° pitch and ±10° roll.
Lateral (ΔV_y)	The designer shall *analytically* demonstrate the capability of the aircraft to withstand lateral impacts of 25 ft/s for Type I and 30 ft/s for Type II aircraft without reducing the width of the occupied areas by more that 15%. Precautions should be taken to minimize the chances that the occupants, including their extremities, could become trapped between the structure and any impacting surfaces following failure of doors, canopies, or hatches.
Combined	The designer shall *analytically* demonstrate the capability of the aircraft with 1 SDGW rotor/wing lift and with landing gear extended to withstand the following combined impacts without a reduction of the cockpit or cabin compartments that would seriously injure the occupants: (1) a combined impact onto a rigid horizontal surface with vertical and longitudinal velocity changes of 42 and 27 ft/s, and (2) a combined impact onto plowed soil with vertical and longitudinal velocity changes of 14 and 100 ft/s, respectively.

Modeling and Analysis Procedures

As noted earlier, the military standard for crash resistance, MIL-STD-1290A (AV), clearly states the intent for the designer to demonstrate compliance with the various velocity change requirements through analytical methods. There were likely two main reasons for encouraging the use of analytical methods. First, crash testing of full-scale aircraft, especially prototype aircraft, is relatively expensive. Also, due to the limited availability and high cost of test articles, it is generally not feasible to perform repeated tests or a large number of tests for different impact conditions. Secondly, the timeframe for the initial publication of the military standard in the mid 1970's corresponded with the initial release of KRASH, a kinematic lumped-spring-mass crash analysis code [13-14]. During this same time period, a new code, DYNA3D [15], was being developed at Lawrence Livermore National Labs under sponsorship by the Department of Energy. DYNA3D was an explicit transient dynamic finite element code capable of simulating high-speed impacts. Later, the public domain version of DYNA3D was obtained by commercial vendors who made modifications and now market commercial versions such as MSC.Dytran [16] and LS-DYNA [17], to name a couple of the many spin-offs. To assess the current state-of-the-art in computational methods for crash analysis, it is important to understand the capabilities of each of the commonly used codes. Thus, brief descriptions of KRASH, MSC.Dytran, and LS-DYNA are provided in the following subsections.

<u>KRASH</u>

The Lockheed-California Company developed KRASH [13-14] under initial sponsorship by the U.S. Army in 1974. The FAA later supported further development of the code. The most recent public domain version of the program to be released was KRASH85. The KRASH program predicts the response of vehicles to multidirectional crash environments. Structural models are developed from massless interconnecting beam elements, concentrated rigid body masses, and spring elements. The beams represent the stiffness characteristics of the structure between the masses. Plastic deformation is accounted for through stiffness reductions. The masses can translate and rotate under the influence of external forces including gravity, aerodynamic, and impact forces; as well as the constraint provided by internal element forces. Impact forces are introduced into the model through nonlinear external springs attached to the masses. Spring stiffness must be input as a force-deflection table that may be determined through component testing or independent finite element analysis prior to conducting the KRASH analysis.

A commercial version of KRASH is available from Dynamic Response Incorporated (DRI-KRASH). DRI-KRASH contains several upgrades to the KRASH85 version including (1) a water impact algorithm, (2) a landing gear module, and (3) a severity index for predicting head injury. In addition, the DRI-KRASH code contains an improved pre-processor for model generation and a post-processor for data reduction.

In general, KRASH models are relatively easy to put together, though considerable engineering judgment is required to define the beam stiffness properties. The models are relatively small, consisting of only a few beam elements, masses, and springs, and, consequently, they execute quickly on a personal computer. KRASH simulations rely heavily on experimental data as input to define spring stiffness properties. For example, spring elements might be used to represent the crushing response of the subfloor/tub section or the crushable stage in a landing gear. Component crush test data are used to define the load-deflection response of the springs.

<u>MSC.Dytran</u>

MSC.Dytran [16] is a three-dimensional, explicit finite element code capable of analyzing high-speed problems involving large deformation of structures and solids. The original DYNA3D command structure was modified such that the command structure of MSC.Dytran is similar to NASTRAN [18]. MSC.Dytran has the capability to model non-uniform gas dynamics and fluid-structure interactions. It does this by coupling a Lagrangian processor for structural modeling with an Eulerian processor for modeling the gas dynamics. In addition, MSC.Dytran offers contact elements to handle sliding and frictional contact of structural elements. The code has been commercially available since 1992 and has been applied to several problems related to high-speed impact such as airbag analysis, ballistics, blast vulnerability, blast containment, ship collision, bird strike, and helicopter crashworthiness.

<u>LS-DYNA</u>

LS-DYNA [17] is a general-purpose finite element code for analyzing the large deformation dynamic response of structures including structures coupled with fluids. The main solution methodology is based on explicit time integration. An implicit solver is also available. A wide variety of contact definitions are available including self-contact, surface-to-surface contact, and node-to-surface contact. Spatial discretization is achieved by the use of eight-node solid elements, two-node beam elements, three- and four-node shell elements, truss elements, membrane elements, discrete elements, and rigid bodies. LS-DYNA currently contains over one hundred constitutive models and ten equations-of-state to cover a wide range of material behavior. Fluid-structure interaction problems are simulated using Arbitrary Euler-Lagrange (ALE) coupling. Recently, a Smooth Particle Hydrodynamic (SPH) method was added to provide additional "hydrocode" capabilities. LS-DYNA is operational on a large number of mainframes, workstations, and PC's, and can be executed using shared memory processors (SMP), or with multiple parallel processors (MPP).

Illustrative Examples of Test and Analysis Correlation

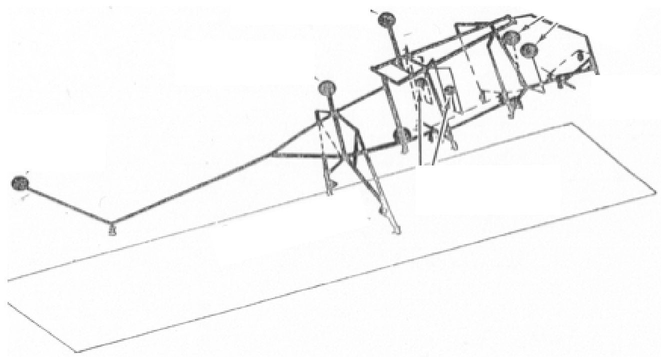
In order to assess the fidelity and accuracy of analytical codes, examples are summarized in which the codes described previously are used to simulate a full-scale crash test. In general, rigorous mathematical methods have not been used to correlate crash test data and analytical predictions, even though a great deal of research is being performed to develop these methods, both in the time and frequency domain. In general, analysts typically use global parameters to evaluate the level of correlation, such as overall deformation and timeline of events, comparison of acceleration and velocity results, and prediction of discrete structural failures. These illustrative examples highlight typical simulations performed by the authors and others. They are provided to demonstrate the application and complexity of the various approaches, as well as some of the limitations in the predictive capability.

KRASH Simulation of the Sikorsky ACAP Helicopter

Since KRASH was developed under sponsorship by the U.S. Army and was initially released at approximately the same time as the military standard for crash resistance, it is appropriate to assume that the U.S. Army would encourage the use of this code by defense contractors in developing new aircraft and would accept KRASH simulation results as proof of crash performance. An example will be illustrated. In the late 1970's, the U.S. Army initiated the Advanced Composite Airframe Program (ACAP) [19-23]. The purpose of the ACAP was to demonstrate the potential of advanced composite materials to save weight and cost in airframe structures while achieving systems compatibility and meeting Army requirements for vulnerability reduction, reliability, maintainability, and crash resistance. In 1981, the US Army awarded separate contracts to Bell Helicopter Textron and Sikorsky Aircraft Corporation 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. Crash tests of the Bell and Sikorsky ACAP static test articles were conducted in 1987 to demonstrate their impact performance and to verify compliance with crash requirements [21], [23].

The Sikorsky-developed KRASH model of their ACAP helicopter is shown in Figure 1(a), along with a photograph of the test article, shown in Figure 1(b). The model was developed to aid in the early design process [20]. It consisted of 53 discrete masses, 23 spring elements, 75 beam elements, and 44 nodes. The spring elements were used to represent the tires and landing gear stages. The impact test was performed at 38 ft/s vertical velocity, with an impact attitude of 10° pitch and 10° roll. The test conditions did not match the MIL-STD-1290A (AV) requirements; however, the vertical velocity selected for the test matched the vertical velocity requirement in ADS-36.

The correlation between drop test data and the pre-test KRASH simulation is presented in three categories in Reference [21]. First, a timeline comparison is discussed that shows the timing of key events, such as initial right landing gear contact, left gear contact, nose gear contact, initiation of honeycomb stroking in the gears, and fuselage contact. The correlation of the timing of these events is very good. Next, comparisons of force and displacement responses of the landing gear are shown. These correlations are also excellent. Finally, the acceleration responses of the rotorcraft transmission mass, engines, and occupants are presented. The test-analysis correlation of the vertical acceleration response of the main transmission mass is shown in Figure 2.



(a) KRASH model.

(b) Photograph of the 1987 drop test.

Figure 1. Sikorsky ACAP model and test article.

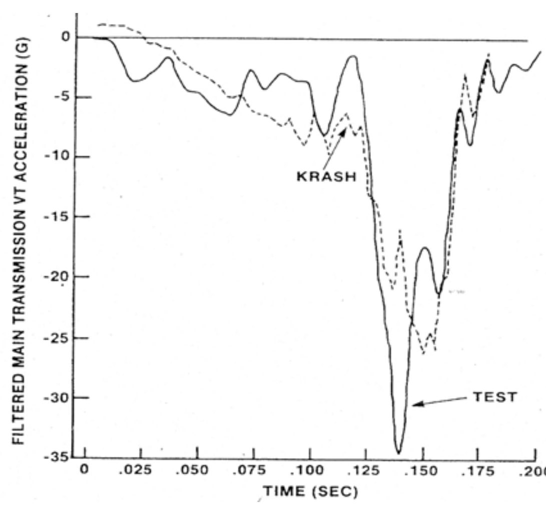


Figure 2. Comparison of the vertical acceleration response of the rotor transmission mass.

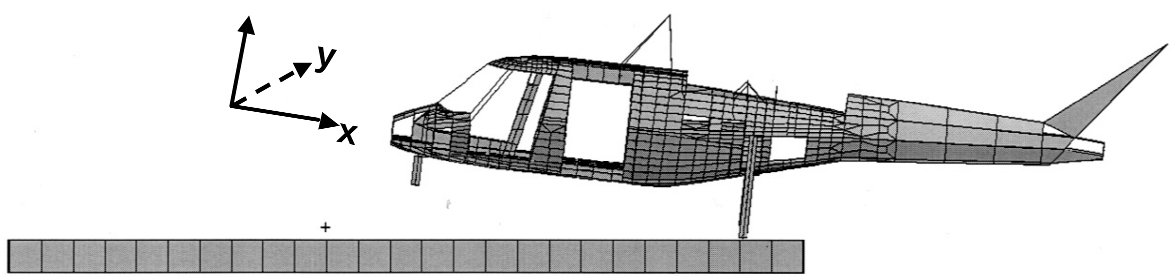
This example is just one of many that could be illustrated in which KRASH predictions showed excellent correlation with test data, especially in predicting the responses of landing gear, engines, and rotor transmission masses. Part of the explanation for the high level of agreement is the fact that experimental data are used in defining the properties of spring elements that make up the model. In the case of the Sikorsky ACAP, the landing gear properties had been determined from a prior drop test of the landing gear alone [22]. Also, the model was developed such that the inertial properties of the test article, i.e. total weight and center-of-gravity location, were matched exactly. Given these factors, one would expect that the response of the high mass items such as the engines and rotor transmission mass would be well predicted. Once a model, such as the Sikorsky ACAP helicopter model, is validated, it can be used to predict the response of the airframe to a variety of other impact conditions. The FAA and Cranfield Impact Centre have been cataloging existing KRASH models of different aircraft for use in the Aircraft Accident Investigation Tool (AAIT) [24]. Crash investigators use AAIT to simulate and reconstruct aircraft crashes as part of the accident investigation. The AAIT software package integrates the KRASH structural analysis code with the SOMTA [25] occupant simulation code into a single environment. AAIT output includes prediction of overall aircraft motion, sequence of breakup, contact marks, forces on occupants, etc.

MSC.Dytran Model of the Sikorsky ACAP Helicopter

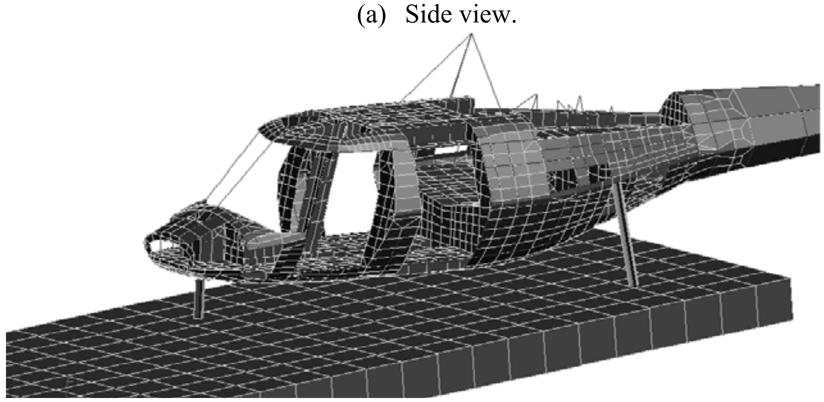
Next, an MSC.Dytran simulation of a full-scale crash test of a composite prototype helicopter, the Sikorsky ACAP, is highlighted [26-32]. In 1997, a full-scale crash test of the Sikorsky ACAP residual flight test article was conducted specifically to generate experimental data for correlation with the MSC.Dytran simulation. An existing modal-vibration model of the Sikorsky ACAP helicopter was obtained and converted into a model suitable for the impact simulations. An external user-defined subroutine was developed to represent the complex landing gear response. Analytical predictions of the sequence of events, structural damage, subfloor crushing, and the acceleration responses of the airframe and large mass items such as the engines and rotor transmission were correlated with the experimental data to validate the crash simulation.

Side and three-quarter views of the helicopter model and impact surface are shown in Figure 3. The final helicopter model consisted of 4,000 nodes and 7,000 elements, including 3,000 beam and rod elements, 3,000 quadrilateral shell elements, and 1,000 triangular shell elements. The impact surface was represented using 250 solid elements. Thirty-four different material property cards were used to represent a variety of composite laminates. A master-surface to slave-node contact was defined between the structural model and the impact surface.

To perform the simulation, a two-stage modeling approach was employed in which a rigid structural model of the helicopter was executed during deformation of the landing gear. At 0.045 seconds before fuselage contact, the x-, y-, and z-locations of all grid points and the corresponding nodal velocities in the rigid model were output to a file. These initial conditions were then input as the starting point of the flexible model simulation. This rigid-to-flexible approach was used to significantly decrease the CPU time required to complete the simulation, and because the rigid model made the introduction of the pitch angular velocity easier. The modeling approach is described more fully in Reference 28.



(a) Side view.



(b) Three-quarter view.

Figure 3. MSC.Dytran model of the Sikorsky ACAP helicopter.

A full-scale crash test of the Sikorsky ACAP flight test article was conducted in June 1999 [27]. For the crash test, the aircraft was outfitted with two crew and two troop seats and four instrumented anthropomorphic dummies. The measured test conditions were 38-ft/s vertical and 32.5-ft/s horizontal velocity onto a rigid impact surface with 6.25° nose-up pitch and 3.5° left-down roll attitude. A pitching angular velocity of 9.6°/s (increasing nose-up) at impact was measured from film analysis. Approximately 120 channels of data from the airframe, seats, and dummy occupants were collected at 10,000 samples per second. Pre- and post-test photographs are shown in Figure 4.

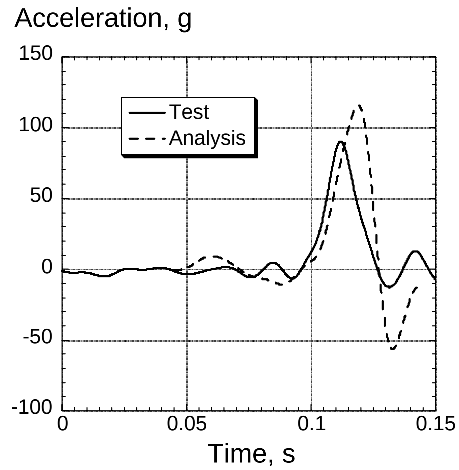
(a) Pre-test photograph.

(b) Post-test photograph.

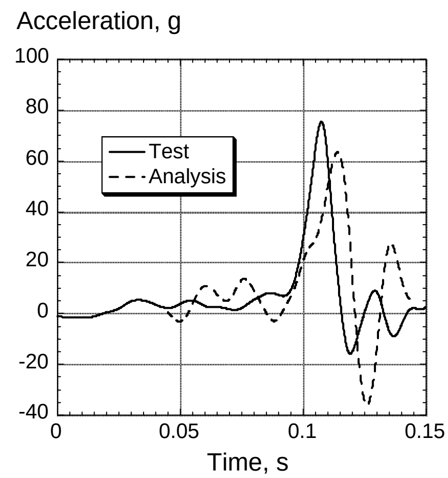
Figure 4. Pre- and post-test photographs of the Sikorsky ACAP residual flight-test hardware.

The test-analysis correlation of the full-scale crash test of the Sikorsky ACAP helicopter consisted of a comparison of a timeline of major events, a comparison of predicted and observed structural damage, and acceleration and velocity time history comparisons at nine different locations on the airframe. In general, reasonably good agreement was obtained. The simulation predicted the location and amount of maximum crushing in the subfloor and failure of one of the beams used to support the rotor transmission overhead mass. The simulation predicted the timing of major events within ±0.007 seconds. However, because a two-stage modeling approach was used in which the structural model was simulated using rigid material properties for the first 0.045 s, the failure of the tail, seen in Figure 4(b), was not well predicted. Comparisons of selected test and analysis filtered acceleration responses are plotted in Figure 5. These results show reasonable correlation, though the magnitude and/or timing of the peak accelerations may not agree exactly.

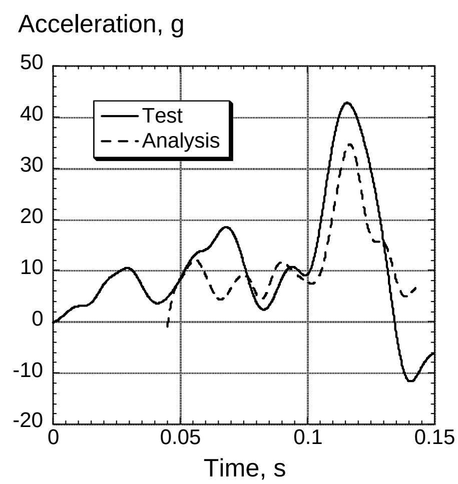
The modeling of the Sikorsky ACAP full-scale crash test illustrated several important issues regarding the successful application of nonlinear, explicit finite element codes. The first issue involved modeling of the landing gear. Considerable time was spent attempting to couple a mechanistic model of the landing gear to the finite element model of the airframe. Problems arose in trying to align the gears and to mitigate the large spike in force that was input into the finite element model at impact.



(a) Pilot floor.



(b) Right troop floor.



(c) Right engine.

Figure 5. Comparisons of selected vertical acceleration responses for the ACAP crash test.

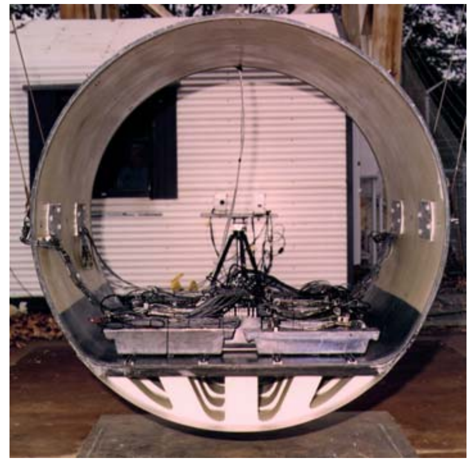
A two-stage modeling approach was implemented for this simulation that worked well. However, improved methods are needed to allow coupling of a mechanistic model of a landing gear with a full FEM of an aircraft or helicopter. Another issue involved modeling of composite material failure. Fairly simplistic failure models, such as maximum stress and/or maximum strain were used. Recently, the capabilities for modeling composite material failure using explicit transient dynamic codes have greatly improved. Finally, the transition from a modal-vibration NASTRAN model to an explicit nonlinear transient dynamic model was not easily accomplished and required several months' effort. Many of the material property definitions did not translate. In the modal-vibration model, all inertial properties were simulated using concentrated masses. Consequently, new material cards had to be defined for the MSC.Dytran simulation including material density. Since the mesh of the original modal-vibration model was too detailed in some regions and too coarse in other regions, considerable rediscretization was required. In general, the process of converting one type of model, e.g. a structural loads or modal-vibration model, into a crash simulation model is not an easy or straightforward task.

LS-DYNA Fluid-Structure Interaction Simulation

In this section, an LS-DYNA simulation of a vertical drop test of a composite fuselage section performed onto water is highlighted. Understanding multi-terrain impacts and how to model them is important because helicopters rarely crash onto hard prepared surfaces.

The U.S. Navy is concerned with the crash safety of its helicopter fleet due to the large number of crashes that occur on water. As a result, the Navy has sponsored research programs to improve the crash safety of rotorcraft during water impacts. In general, the structural response and load transfer mechanisms for water and soft soil impacts are much different than those on hard surfaces. Also, very little research exists on the crashworthy response of helicopters impacting into water as opposed to hard surfaces. The MIL-STD-1290A (AV) does not contain any specifications for water impact. However, the Navy does have water-ditching requirements. References 33 through 38 describe a few recent research studies involving simulations of water and soft soil impact. An example of one of these studies, documented in Reference 35, is summarized below.

A 25-ft/s vertical drop test of a 5-ft. diameter, 5-ft. long composite fuselage section [40] was conducted into a 3.5-ft. deep, 15-ft. diameter pool of water. The empty fuselage section weighed 208 pounds. The fuselage section, outfitted with instrumentation, seat rails, and ten 100-lb. lead masses attached to the floor, weighed approximately 1,200 pounds. A photograph of the composite fuselage section is shown in Figure 6(a). A frame from a video taken during the water impact test is shown in Figure 6(b).



(a) Pre-test photo.

(b) Photograph taken just after impact.

Figure 6. Photographs of the composite fuselage section and drop test.

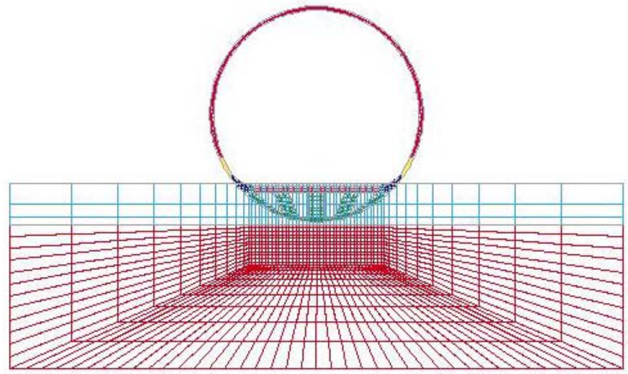
Post-test examination of the subfloor region revealed extensive damage to the outer skin. The center portion of all five foam blocks that were designed for energy absorption for a rigid surface impact showed no sign of crushing, and there was also very little debonding of the face sheets from the foam. A post-test view of the bottom of the section taken from the front is shown in Figure 7, in which the five foam blocks in the subfloor can be distinguished. The unsupported areas of the outer skin between the foam blocks showed the most damage. No damage was observed to the floor and upper fuselage cabin region.

A number of different LS-DYNA models were created to represent the air and water fluid regions. Both rectangular and cylindrical Euler meshes were created, and the size of the mesh was varied from constant 3 and 6-inch cubic meshes to a refined 1-in. mesh with a gradient. Also, a smooth particle hydrodynamic (SPH) model of the water was developed in LS-DYNA. Although the SPH model gave good results, it was somewhat slow in execution. A description of the various water models and their resultant predictions can be found in Reference 35. The LS-DYNA coupled fluid structural algorithm (ALE/Euler) has the capability to allow the bottom skin of the fuselage, which is the coupling surface, to fail. Models with and without failure of the bottom fuselage skin were created and compared.

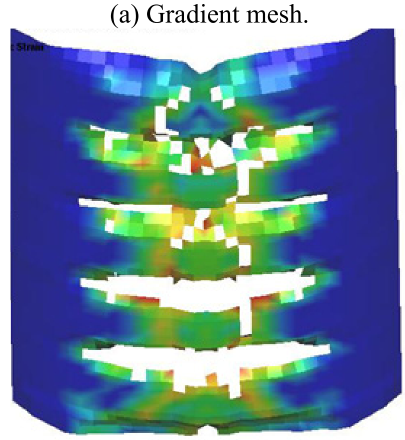
Figure 7. Post-test photograph of the bottom of the fuselage showing damage. The four dark regions are areas between the foam blocks.

In order to study the failure of the bottom skin, an LS-DYNA model was created with a refined 1-in fluid mesh directly under the section, which became coarser further from the section, as shown in Figure 8(a). The failure strain was set on the material card for the bottom fiberglass skin to allow the elements to fail after a given strain is reached. As failed elements were deleted, holes formed in the bottom surface that allowed the water to flow through the failed skin. The failure of the bottom skin is shown in Figure 8(b) for 0.01 seconds after impact. The figure shows the bottom skin of the fuselage viewed from an angle from above. In this case, the failure strain was set to 2 percent, which is a practical value for an angle-ply fiberglass laminate. The results show that the outer skin between the foam blocks fails catastrophically allowing the water to flow through as shown in the right side of the figure. Although the failure is dramatic, the initial peak accelerations were only reduced by a small amount from the original model without failure as shown in Figure 9. Note that both the analysis and test data were filtered with a low-pass filter. Since the run times for these models are long, the model with failure was only executed long enough to capture the fundamental pulse; i.e., 0.04 seconds. The amount of damage predicted by this simulation was more severe than observed.

Acceleration responses are shown in Figure 9 at two locations for LS-DYNA simulations with and without failure of the bottom skin. The acceleration pulses with failure of the bottom skin drop off too quickly after the initial peak due to the excessive failure. Since the actual strain-to-failure data for the angle-ply laminate was not available, the objective of specifying a failure strain was to determine the effect of failure on the simulation. Also, note that when the failure strain criterion was met, the elements were deleted. Other failure options available in LS-DYNA such as "constrained tied nodes failure" were not evaluated, but may reduce the severity of the damage. A finer mesh would be another option; however, a mesh-density study of the bottom skin was not performed. When failure strains were applied to this model, water did flow through the areas formed by the deleted failed elements. However, partially due to the coarse elements in the bottom skin, the failure was more severe in the model than observed in the test.



(a) Gradient mesh.



(b) Lower skin failures.

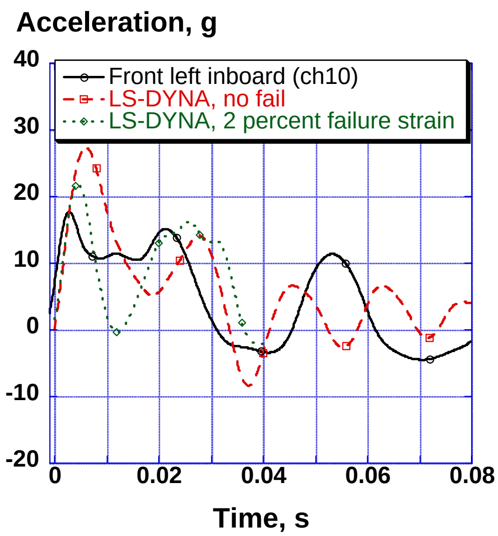
Figure 8. Front view of a slice of the gradient-mesh.

Future Directions

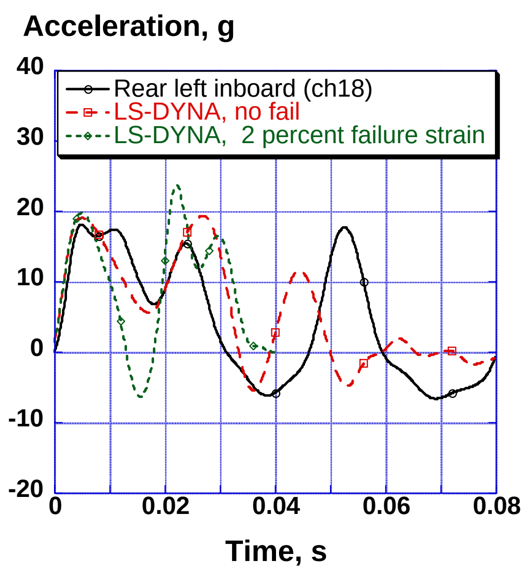
The future directions needed to achieve crash certification by analysis are discussed in this section and they are divided into two subsections: 1. Crash Qualification Requirements and 2. Improved Analytical Methods.

<u>Crash Qualification Requirements</u>

It is highly recommended that the U.S. military establish a new military standard for crash resistance of rotary wing aircraft. This standard should focus on a systems approach to crashworthiness [6], [41] in which subcomponents are utilized to lower the acceleration levels transmitted to the occupants to a humanly tolerable level during a helicopter crash. These subcomponents include the landing gear, the subfloor, and the seats. In addition, the cabin structure must be designed with the proper stiffness and strength to maintain a livable volume for the occupants, to prevent failure of the seat attachments, and to retain the high mass items such as the rotor transmission and engine. Interior hazards such as the flight control stick and instrument panel should be minimized by providing adequate restraint systems and/or using cockpit airbags. Finally, post-crash hazards should be mitigated, allowing efficient occupant egress. These items were included in MIL-STD-1290A (AV) and should be included in any new proposed standards. However, upon reviewing MIL-STD-1290A (AV), it is apparent that the performance requirements are written to specify limits on reduction in cabin volume. There are no specifications for human tolerance to impact loading. If a new qualification standard is written, it should include performance requirements that ensure occupant survivability, such as limits on Head Injury Criteria (less than 1000), lumbar loading (less than 1,500 lbs.), and Dynamic Response Index of 20 or less based upon seat pan vertical acceleration responses, and comparison of occupant acceleration responses with the whole body acceleration tolerance curves developed by Eiband. A complete assessment of these occupant injury criteria is described in Reference 32.



(a) Front left inboard.



(b) Rear left inboard.

Figure 9. Filtered experimental acceleration responses compared with LS-DYNA predicted inboard accelerations with and without failure of the bottom fiberglass skin.

In addition, crash qualification criteria should be written requiring multi-terrain impact testing and simulation. The accident data indicate that 80% of all helicopter crashes occur on multi-terrain including soil and water [33]. Consequently, the importance of multi-terrain cannot be ignored, especially when research studies have shown that helicopters, designed for crash resistance onto hard surfaces, do not perform well during multi-terrain impacts [34-35, 37-39]. Also, landing gear are completely ineffective as energy absorbers during water impact. The requirement for multi-terrain crash resistance would increase the need for novel energy absorbing structural design concepts. In addition, external devices such as air bag systems could be used to augment the crash performance of helicopters during water or soft soil impacts.

To be effective and minimize cost and weight, a variable design requirement must be written based on helicopter type, mission, weight, and autorotative rate of descent [6]. The military standard defines one set of design criteria for all military helicopters. However, accident data show that it is easier for medium- to large-size helicopters to meet the requirement than it is for small-size helicopters. There is also the issue of weight penalty associated with crash design features. The "one-size-fits-all" approach penalizes the small-size helicopter because a larger percentage of its gross weight is dedicated for crash resistance. Consequently, a variable design approach is required that takes into account a helicopter's type, size, mission, and autorotative rate of descent.

Finally, the issue of testing versus analysis must be addressed. It is the opinion of the authors that analytical methods are not entirely sufficient to qualify or certify rotorcraft for crash resistance at this time. Therefore, it is recommended that at least one full-scale crash test be performed for qualification purposes. The test should be conducted with combined vertical and forward velocity components and should be performed onto an impact surface that would be most representative of the type of crash the helicopter would likely experience in the field, based on its mission. The crash test would serve to qualify the helicopter and would provide test data for validation of a three-dimensional finite element simulation. Consequently, the test article should be outfitted with seats, dummies, and restraint systems, and any other system that is intended for occupant protection. The helicopter should be instrumented to accomplish both tasks, i.e. certification for crashworthiness and test-analysis correlation. Once the model is validated for the test condition, a probabilistic analysis should be executed to determine other possible impact conditions or surfaces where the aircraft might be vulnerable, i.e., the validated model should be utilized to perform a complete vulnerability/risk assessment of the design.

Improved Analytical Methods

Attendees of the Workshop on Computational Methods for Crashworthiness [42], held September 2-3, 1992, at

NASA Langley Research Center, Hampton, Virginia, were asked to identify key technology needs for improved crash modeling and simulation. Their list is grouped under five main headings including (1) understanding the physical phenomena associated with crash events, (2) high-fidelity modeling of the vehicle and the occupant during crash, (3) efficient computational strategies, (4) test methods, measurement techniques, and scaling laws, and (5) validation of numerical simulations. Since many of the key technology needs identified during the workshop are still valid today, the list is reprinted from Reference [42].

<u>(1) Understanding the Physical Phenomena Associated with Crash</u>

This includes understanding (a) the mechanics of large dynamic deformations of structures including the effects of frictional contact; (b) the effects of inertial forces and of material strain rate sensitivity on the dynamic response; and (c) damage initiation and progression during crash. For the occupant, the factors that can be correlated with the level of injury or death (e.g., dynamic response index, head injury criteria, force in lumbar spinal region) need to be identified. The modeling details required to capture the different phenomena associated with the structural response during crash need to be identified.

<u>(2) High-Fidelity Modeling of Vehicle and Occupant</u>

The reliability of the predictions of the response of the structure and occupant during crash is critically dependent on: (a) the accurate characterization and modeling of material behavior; (b) high-fidelity modeling of the critical details of the vehicle and occupant (e.g. seat, fasteners, and the human anatomy); (c) modeling of the frictional contact between the vehicle and the impact surface, and between the different parts of the vehicle, including the need for accurate material constitutive models and properties for foam, padding, and textiles, especially the strain rate sensitivities, for modeling of the seat/occupant interaction.

<u>(3) Efficient Computational Strategies</u>

The effective use of numerical simulations for predicting the vehicle response during crash requires strategies for treating phenomena occurring at disparate spatial and time scales, using reasonable computer resources. The strategies are to be based on using hierarchical (multiple) mathematical models in different regions on the vehicle to take advantage of the efficiencies gained by matching the model to the expected response in each region. To achieve the full potential of hierarchical modeling there should be minimum reliance on a priori assumptions about the response. This is accomplished by adding adaptivity to the strategy.

<u>(4) Test Methods, Measuring Techniques, and Scaling Laws</u>

The effective coupling of numerical simulations with experiments requires a high degree of interaction between the computation analysts and the experimentalists. This is done at three different levels, namely: (1) laboratory test on small specimens to obtain material data; (2) component test to verify computational models and to determine empirical structural properties which can be used in hybrid experiment/numerical models; and (3) full-scale (or scale model) tests to validate the computational model and assess the need for model improvements.

New test methods and measurement techniques are needed to study progressive failure, as well as soil and water impact. The influence of specimen size or scale factor on structural response is not well understood. Thus, testing of geometrically similar sub-scale models is not possible, until the scaling laws governing the phenomenon are understood. In particular, scaling laws are needed which account for the material behavior including elastic properties, failure initiation and ultimate strength, structural and topological details, as well as the loading characteristics.

<u>(5) Validation of Numerical Simulations</u>

In addition to validating the numerical simulations by component and full-scale tests, a number of carefully selected benchmark tests are needed for assessing new computational strategies and numerical algorithms, similar to the MacNeal Harder problems [43] for evaluating the robustness and accuracy of finite elements. These benchmark tests would provide a measure of confidence in new codes, or added functional capabilities to existing codes. They could also serve as a basis of code comparisons for efficiency and accuracy for modeling of impact problems involving large structural deformations in short time duration.

Some additional tasks need to be addressed if crash simulations are to have a significant impact during the design and certification phases of new aircraft. These include development of software for automated model and mesh generation, pre- and post-processing software for efficient input and reduction of data, advanced visualization techniques, and application of knowledge-based/expert systems and neural networks to crash simulation. LS-DYNA currently has the ability to perform adaptive meshing; however, this capability needs to be more fully augmented, especially for crash simulations.

A method needs to be developed for coupling mechanistic models with nonlinear finite element models, e.g. modeling of landing gear on aircraft and rotorcraft. This capability is needed since the loads generated at the landing gear/airframe interface are important and must be analyzed correctly. A study was performed to develop a method of accurately modeling landing gear in nonlinear finite element codes, as documented in Reference 44. A conclusion from the study states, "results of this MSC/DYTRAN landing gear modeling effort were very good. However, several concerns still remain. The performance of the landing gear remains very sensitive to small adjustments in the contact algorithm and integration time step. This new method of landing gear modeling has not yet been applied to models where either the landing gear, the fuselage, or both are modeled with flexibility."

Improved material modeling is a continuous, ongoing need, especially as new materials are developed and applied. It is also important that the existing and updated material models are well documented. For example, LS-DYNA has over one hundred material models available, which LSTC implements into the code when requested by customers. However, very little documentation exists to guide a new user in choosing the correct material model for his application. One shortfall common to all the codes is the lack of a delamination failure capability for composite materials. In general, it is difficult to implement delamination criteria in nonlinear, explicit transient dynamic finite element codes due to the small mesh size required. A small mesh is needed for accurate prediction; however, such a mesh may result in a reduction in the time step causing computation time to increase substantially. Also, the dynamic property data needed to predict delamination growth under impact conditions are not easily obtained. A review of several methods to incorporate delamination failure criteria for composites in MSC.Dytran is documented in Reference 45.

Finally, a new approach for quantifying test/analysis correlation needs to be developed and utilized. In the examples presented in this paper, test-analysis correlation is presented as a comparison of structural deformation and plots of filtered acceleration time histories. For the case of the MSC.Dytran simulation of the Sikorsky ACAP helicopter, the simulation predicted the maximum amount of subfloor crushing that was measured post-test. This example represents "good" correlation. For filtered acceleration time histories, the level of agreement is determined by comparing the magnitude and timing of the peak acceleration, and the pulse duration. Rarely will the analyst see "good" correlation between test and analysis in the sense of an absolute match for these three parameters. In general, the level of correlation is deemed "good or reasonable" if these parameters are "in the ball park." Thus, the need to re-evaluate the current crash data analysis and correlation methodologies for use with detailed finite element model simulations has been identified [46]. Recently, a project was initiated at NASA Langley to better quantify the accuracy of crash simulation results. The motivation for the project, as stated in Reference 46 was "to document modeling improvements, to evaluate design configurations analytically, and to enable certification or qualification by analysis."

Several important findings are repeated from Reference 46, as follows. "It is necessary to quantify and understand experimental variations, channel-to-channel, for symmetric locations, as well as test-analysis variations. Future crash finite element model development could be expedited by correlation with experimental modal analysis results, especially since the modal correlation will depend on the accuracy of the global stiffness and mass distribution of the finite element model. Also, this approach provides a second set of data for correlation, which is important given that most test articles are destroyed during crash testing." Continued work is needed to automate rigorous test-analysis correlation methodologies to improve and redefine the level of accuracy.

Reference 47 provides an excellent summary of a panel discussion on issues and directions of research in the areas of model updating, predictive quality of computer simulations, model validation and uncertainty quantification. This paper raises some pertinent questions, such as what model is appropriate for what purpose, and what does it take to be predictive? The authors of Reference 47 question the validity of calling a model predictive, when it has been validated through comparison with a single set of test data. Such a model does not guarantee accuracy of predictions for scenarios not represented by the test data. The authors of Reference 47 state, "It is our opinion that the focus of the research in model validation should be shifted from validating deterministic models to validating statistically accurate models." Such an approach would account for variability in the operational and testing environment and uncertainties related to manufacturing and fabrication tolerances. Thus, model validation should be strongly coupled with uncertainty quantification. Finally the authors of Reference 47 propose five topic areas that are "critical to the success of model updating, uncertainty quantification, and model validation for linear and nonlinear dynamics." These five topic areas are: uncertainty quantification, sampling and fast probability integration, generation of fast running meta-models, feature extraction, and statistical hypothesis testing.

Concluding Remarks

This paper has addressed some of the issues associated with crash certification by analysis. In particular, the certification standard for military helicopters, MIL-STD-1290A (AV), was discussed. This standard was cancelled by the US Department of Defense in the mid-1990's and one recommendation of this paper is that a similar, though more comprehensive standard be established in its place. The new standard should include: variable velocity requirements based on helicopter type, mission, weight, and autorotative rate of descent; performance requirements for occupant injury assessment; requirements for at least one full-scale crash test to be performed on the surface (rigid, water, or soft soil) that would be most typical, given the mission of the helicopter; and development of a finite element model of the test article to be used in nonlinear, explicit transient dynamic simulations. The purpose of the crash test would be twofold: to certify the helicopter for crashworthiness and to provide experimental data for test-analysis correlation. Once the model is validated for the test condition, it should be utilized to perform a complete vulnerability/risk assessment of the design.

The capabilities of existing crash modeling and simulation codes were summarized, and some examples from the literature illustrating the current test-analysis correlation procedures were shown. The authors of the paper believe that simulation capabilities are not sufficient at this time to achieve crash certification by analysis. Several suggestions for future directions in improved analytical methods are included in the paper.

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