Overview of Usage of Crash Dynamic Analytical Methods in Civil Aircraft Research and Certification Programs

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Abstract

The Federal Aviation Administration (FAA) is actively involved in a number of research and certification activities where crash dynamic analytical methods and simulations are an integral part of those activities. Seat occupant models and simulations are being used to support the selection of the critical test cases in seat dynamic certification tests, to establish design guidelines for the design of structures that must comply with the Head Impact Criteria (HIC), and to guide research activities directed to the development of both a HIC component tester and side facing seat certification standards. Seat/occupant computer models and simulations are also being used in the design stage of various airbag systems to optimize those systems and also to obtain predictions of the results of full-scale development and qualification tests. Airframe computer models and simulations are being used in support of aircraft accident investigation, to predict and assess the results of full-scale fuselage impact tests, to evaluate the impact characteristics and occupant injury potential of unique airframe structures, and to evaluate the water impact characteristics of rotorcraft. Some examples of these activities are presented.

Past Activities

The FAA has long been active in the development and application of crash dynamic computer modeling methods. An early study was focused on the development and validation of an analytical method used to predict the acceleration environment, structural deformations and bending moments on a representative 4 foot diameter, 22 ½ long constant section fuselage model, shown in Figure 1, that was subjected to a crash impact load (Ref. 1).

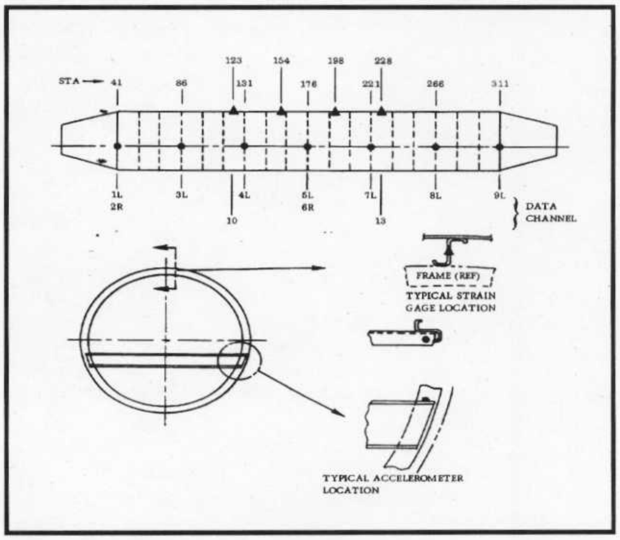


Figure 1 - Basic Test Model Configuration

The development of the hybrid computer program KRASH and the seat/occupant computer modeling programs SOMLA and SOMTA in the mid-seventies are other early examples where the FAA fostered the development and application of crash dynamic analytical methods.

The development of program KRASH was initially sponsored by the U.S. Army to evaluate the airframe response and strength characteristics of rotorcraft structures. The FAA sponsored further enhancement of program KRASH to extend its application to small fixed-wing general aviation civil airplanes as shown in Figure 2 and to transport category airplanes. Those enhancements culminated in the release of the public domain version of KRASH that was designated KRASH 85 (Ref. 2). Further FAA sponsored enhancements included the modeling of soft soil terrain impact conditions.

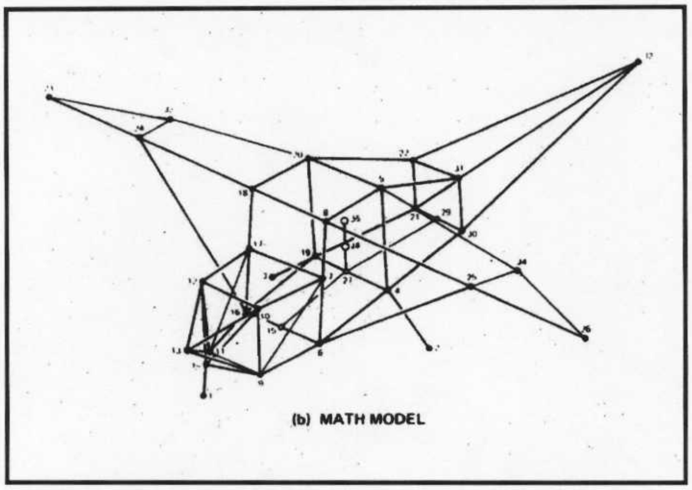


Figure 2 - An Early KRASH Small Airplane Model

Programs SOMLA (Seat Occupant Model Light Aircraft) and SOMTA (Seat Occupant Model Transport Aircraft) provide an analytical means to evaluate an occupant's response and injury potential when subjected to various impact conditions. These models combine a lump mass three-dimensional representation of a human body with a finite element model of the seat structure and restraint system. The FAA initially sponsored the development of above seat/ occupant simulation codes in 1975 (Ref. 3). These modeling codes were enhanced in 1991 (Ref. 4), and lastly enhanced in 1997 to include the capability to model discrete energy absorber elements (Ref. 5).

Research/Development Activities

<u>FAA Crash Dynamics Program Plan</u>

The FAA made early use of the developing KRASH and SOMTA analytical tools in their structuring of the FAA's Crash Dynamics Program Plan that lead to the definition of the seat dynamic performance standards found in 14 CFR Part 25, §25.562. The comprehensive Crash Dynamics Program Plan illustrated in Figure 3 was structured to identify survivable crash scenarios that would then be related in a concerted manner using analyses and tests to the airframe's and seat/occupants' impact response and the potential for occupant injury. The program elements highlighted in Figure 3 were key analytically based elements that were used to conduct the numerous parameter studies needed to supplement the sparse full-scale test data elements. An example of one of those parameter studies was the FAA sponsored use of program KRASH to predict the airframe impact response and structural performance of a transport category airplane subjected to a range of survivable impact conditions.

The Controlled Impact Demonstration (CID) was a joint FAA/NASA full-scale airplane air-to-ground impact test conducted in December 1984 using a Boeing Model 720 airplane. The objectives of the test were to measure the airframe impact response and evaluate the effectiveness of several crashworthiness features including the effectiveness of anti-misting fuel to suppress a post crash fire. A view of the CID airplane at the time of the ground impact of the fuselage is shown in Figure 4. The CID impact test provided a unique opportunity to analytically simulate a full-scale airplane impact test with the KRASH "stick model" model shown in Figure 5 and to validate the simulation model using the measured impact data.

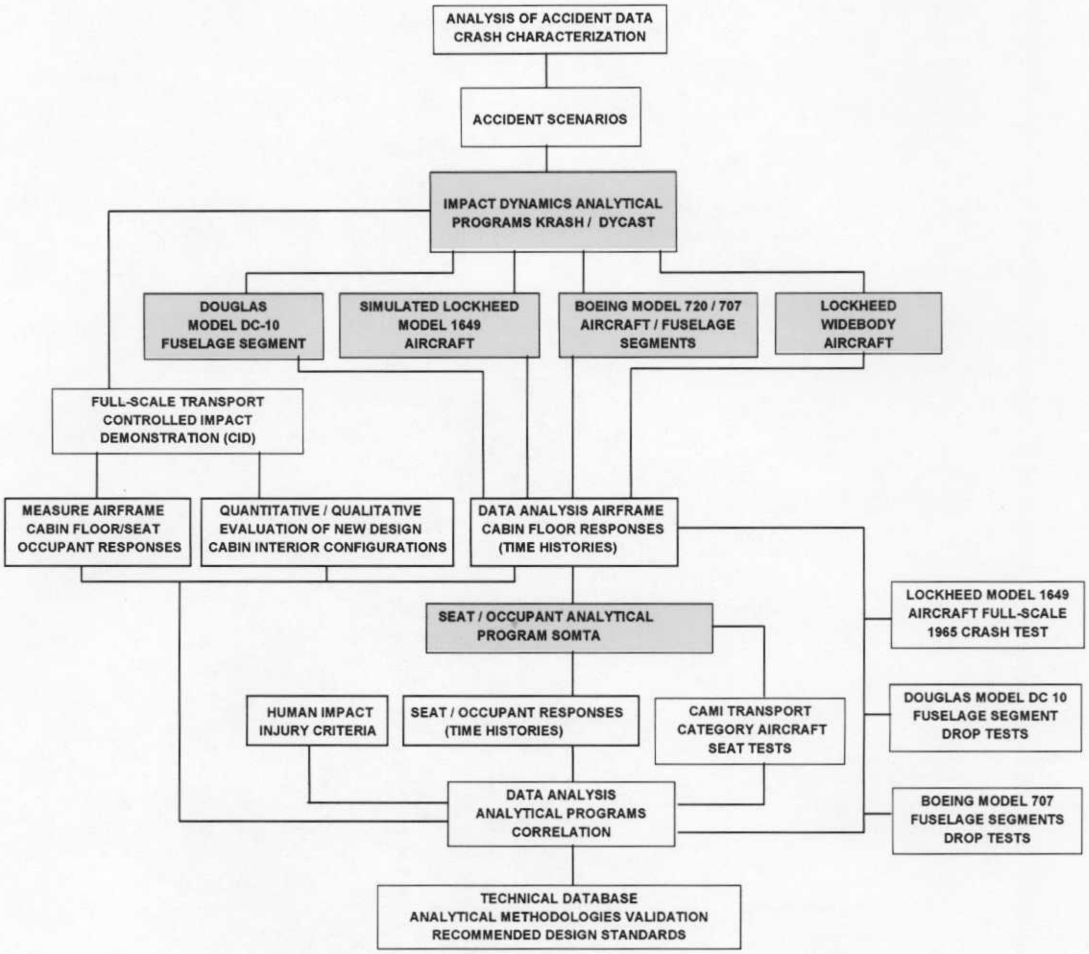


Figure 3 - FAA's Crash Dynamics Program Plan

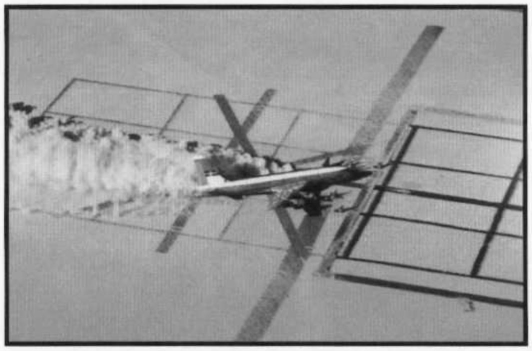


Figure 4 - CID Fuselage Ground Impact

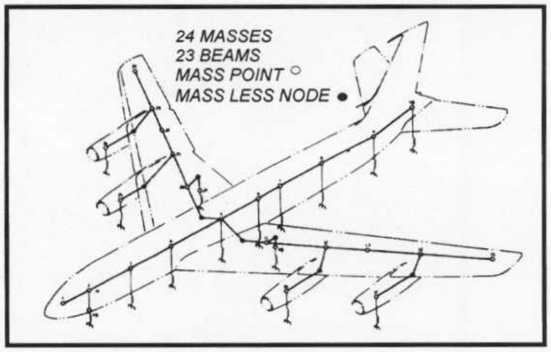


Figure 5 - KRASH CID Stick Model

A comparison of the results of the KRASH simulation of the CID test and the fuselage acceleration environment measured during the full-scale CID test at the time of the ground impact is shown in Figure 6. The validated KRASH "stick model" was used in a parameter study to define a proposed survivable impact velocity envelope for transport category airplanes that is shown in Figure 7. The limits of that survivability envelope were established considering both the effects of the acceleration environment and the loss of the protective fuselage shell. The survivability envelope shown in Figure 7 was used in concert with data developed by other elements of the FAA's Crash Dynamics Program Plan to define the seat dynamic performance standards found in 14 CFR Part 25, §25.562 for transport category airplanes. A more comprehensive review of this subject and other related crash dynamics program elements that were analytically based can be found in References 6, 7, and 8.

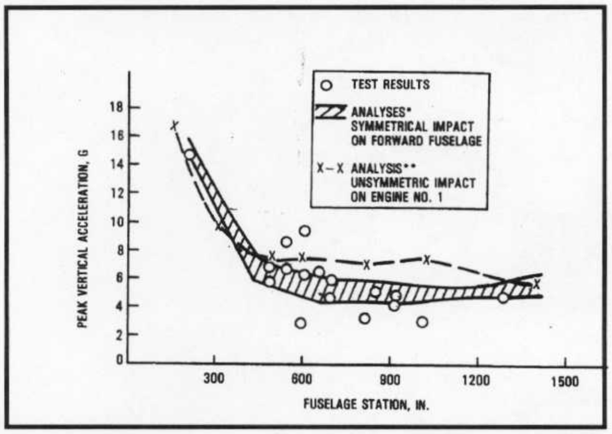


Figure 6 - Comparison of CID Test and KRASH Analysis

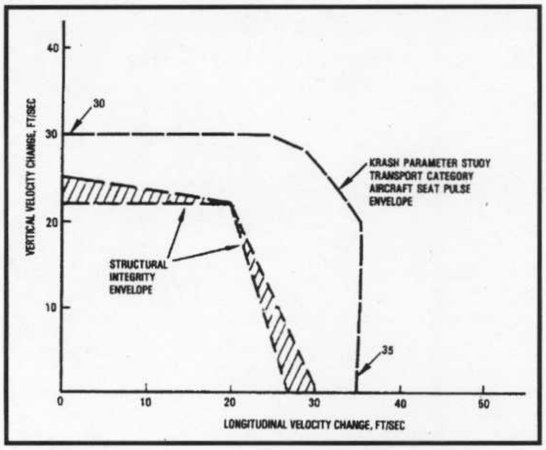


Figure 7 - Proposed Survivability Envelope

<u>Side Facing Seat Research Studies</u>

The Federal Aviation Administration (FAA) has defined dynamic performance standards for the certification of aircraft seats that can be found in 14 Code of Federal Regulations (CFR) Part 25. However, sideward facing aircraft seats were not emphasized in the development of the seat dynamic performance standards, and thus the human occupant impact injury criteria found in those standards are more applicable for forward or aft facing seats. To remedy this deficiency, the Federal Aviation Administration (FAA) is ardently working with a number of research organizations to develop human impact injury criteria that will be applicable for occupants of sideward facing aircraft seats. A comprehensive research program with TNO Automotive and the Medical College of Wisconsin is now in progress whose tasks include a review of existing neck injury tolerance levels, seat/occupant computer modeling studies, a dynamic seat test program with EuroSID-2 side impact dummies and Post Mortem Human Subjects, assessments of the resultant injury criteria and tolerance levels, and the proposal, evaluation, and validation of a standard sideward facing seat dynamic test and certification procedure. Past and current seat/occupant simulations related to this research subject are reviewed.

CAMI/GESAC DYNAMAN Study

An early study at the FAA's Civil Aerospace Medical Institute (CAMI) was initiated to investigate the potential for injury of sideward facing seat occupants (Ref. 9). That study interactively used full-scale seat/occupant impact tests and DYNAMAN simulations of those tests to evaluate a number of potential occupant injury parameters. The results of the study showed fair to good agreement between the tests and the simulations for a number of load and injury parameters. The only injury parameter that consistently exceeded published tolerance limits was the lateral neck moment. Even though this early study did not establish tolerance limits for neck lateral loading applicable for sideward facing seat occupants, it did provide a foundation for further research studies that were directed towards a more comprehensive evaluation of seat/occupant interaction and the potential for occupant injury.

CAMI/NIAR 1999 Study

A cooperative study between CAMI and the National Institute for Aviation Research (NIAR) at the Wichita State University, in conjunction with the Aircraft Design and Manufacturing Research Center (ADMRC), expanded on the initial CAMI/GESAC study (Ref. 10). Some of the objectives defined for the CAMI/NIAR study were:

- Investigate potential occupant injuries corresponding to single and multiple-occupant (divan-type) sideward facing seat configurations with injury criteria used in the automotive industry.
- Demonstrate an "equivalent level of safety" as compared to that on forward or aft-facing seats.
- Identify potential configuration(s) that provide the highest level of occupant protection.

The CAMI/NIAR study interactively used the results of seat/occupant computer models, full-scale seat dynamic tests with various side impact test dummies, and parameter studies to assess a number of seat/occupant configurations in an attempt to establish a set of pass/fail injury criteria along with design guidelines and testing procedures. Figure 8 depicts that schematic approach.

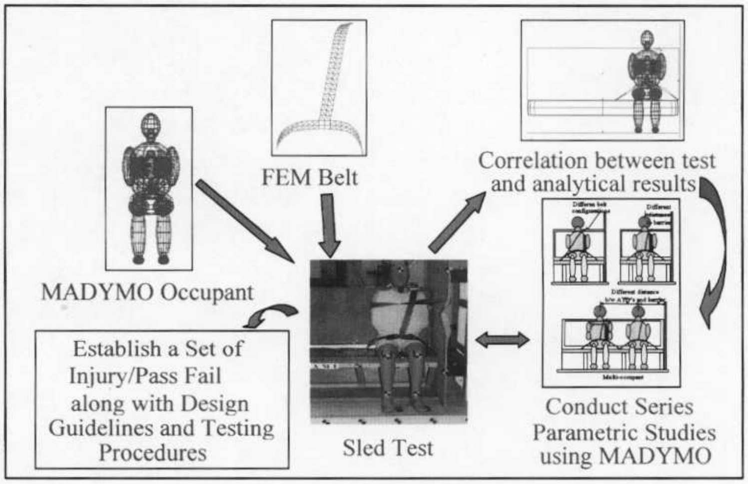


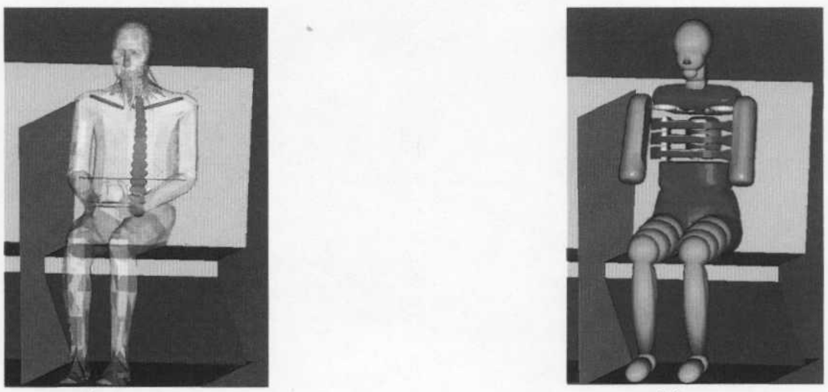
Figure 8 - CAMI/NIAR Methodology

While both the CAMI/GESAC and CAMI/NIAR studies provided much insight with respect to the performance of sideward facing seats and the definition of potential injury mechanisms for the occupants of those seats neither study established any proposed limits for lateral neck loading. A more complete description of the above tasks and the results of another FAA study that evaluated related automotive safety research, human subjects and cadaver impact tests can be found in Reference 11.

FAA / TNO Automotive / and Medical College of Wisconsin Research

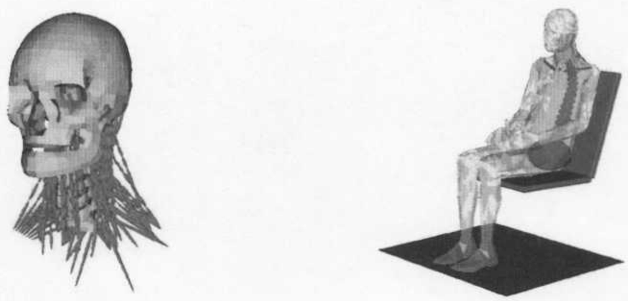
Post Mortem Human Subject (PMHS) and Dummy Simulations - Simulations are being performed with human models and a dummy model on a rigid sideward facing seat subjected to a lateral acceleration to evaluate and design the PMHS test program. The human model responses are not only compared with the dummy model responses to guide the PMHS test program but they will also be used to establish the transfer functions that may exist between humans and the test dummy. Figure 9 illustrates some examples of these simulation models.

Post Mortem Human Subjects Simulations - Simulations of the PMHS in lateral loading were performed using the MADYMO human model with a detailed neck shown in Figure 10. The human body model has been validated for frontal, rearward and lateral loading. In lateral impact, the human body model has been validated for 4 to 37 G. Analysis was firstly conducted using the horizontal crash pulse specified in FAR 25.562 (b)(2), triangular, peak 16-G, minimum duration 90 ms. A rigid wall was placed next to the subject's shoulder in order to create a worst case scenario for the neck in lateral loading. The effect of the load magnitude was then determined by repeating the simulations with a pulse of half the magnitude (peak 8-G). The human model simulations were then repeated with a 5-point belt. The human model 5-point belt simulations were also repeated with neck muscle activity equal to 50% of the maximum muscle forces. An example of some of the results of that analysis follows.



a) b)

Figure 9 - a) Human Model in Sideward Facing Seat b) Dummy Model in Sideward Facing Seat



a) b)

Figure 10 - a) Detailed Neck Model b) Combined 50th Percentile Male Human/Detailed Neck Model

Example Human Model Applications – The results of some of the applications of the above models are shown in Figures 11 and 12 where the human model responses at two impact severity levels, with and without a 5-point belt, and with 50% neck muscle activity are compared. The dashed horizontal lines in the figures show the AIS 1 injury level range. The continuous horizontal lines show the AIS 2 injury level range. Comparing the peak responses of the human model in the three different situations, it can be seen from the following figures that:

- At 16-G impact as well as at 8-G impact the 5-points belt increased the peak head lateral angle, but did not affect the peak head lateral angular acceleration significantly.
- At 16-G impact as well as at 8-G impact the simulated muscle activity decreased the peak head lateral angle and the peak head lateral angular acceleration significantly.
- The effect of the muscle activity was larger for the 8-G impact than for the 16-G impact.

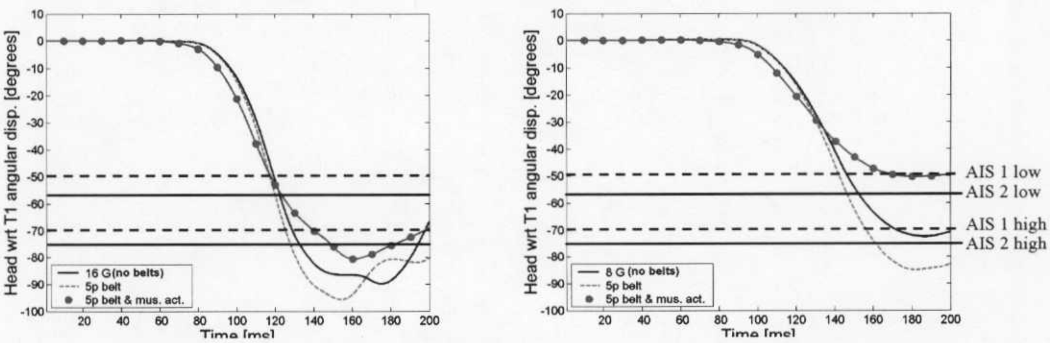


Figure 11 - Head w.r.t. T1 Lateral Angular Displacement.
Human Model Simulation Without Belts Compared With 5-Point Belt
and With 5-Point Plus 50% Neck Muscle Activity

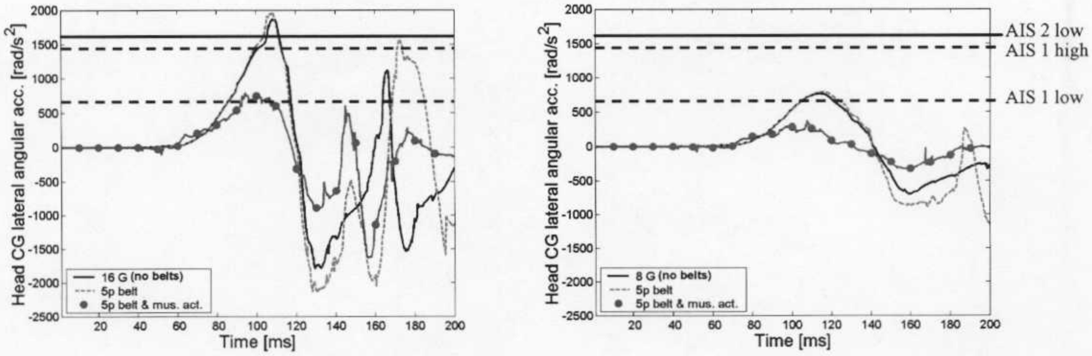


Figure 12- Head Lateral Angular Acceleration.
Human Model Simulation Without Belts Compared With 5-Point Belt and With 5-Point Plus 50% Neck Muscle Activity

Other Model Applications – The above example human model application is but one of many simulations that are being conducted as part of the joint FAA/TNO Automotive/Medical College of Wisconsin research effort. The PMHS tests and the simulations that are used to guide and maximize the understanding of the PMHS tests continue. Additionally a EuroSID-2 test will be performed just prior to each PMHS test to supplement the simulations and to gather the kinematics and injury parameter data that will be correlated to the injuries seen in each PMHS test. The EuroSID-2 test will also serve as a final checkout of the sled, camera and data acquisition systems to ensure good data would be acquired during the high value PMHS test. A more comprehensive review of this subject can be found in Reference 12.

Development of Head Impact Protection Design Guidelines and Subcomponent Head Impact Protection (HIC) Tester

Head Impact Protection Design Guidelines

The seat dynamic performance standards found in 14 CRF 25, §25.562 for transport category airplanes require an assessment of the potential of head impact injury by use of the Head Impact Criteria (HIC) (small airplane and rotorcraft certification standards contain like requirements). The large variety of head strike surfaces that can be found in aircraft as seen in Figure 13 makes HIC compliance a significant challenge for engineers designing cabin interior furnishings.

The FAA sponsored the National Institute for Aviation Research (NIAR) to develop an engineering design methodology and guidelines that might be used to simplify the design and certification of a cabin interior furnishing (Ref. 13). MADYMO seat/occupant computer models were used to simulate head

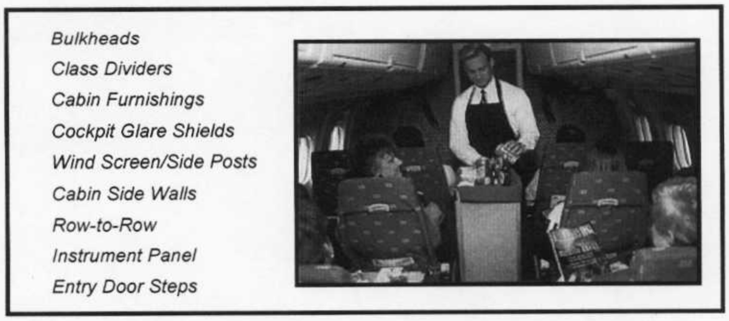


Figure 13 - Examples of Head Strike Surfaces

strikes to analyze and design an energy absorbing bulkhead and to develop a bulkhead design process based on some simple design curves.

Figure 14 below shows an example of a seat/occupant/bulkhead MADYMO model that was used by NIAR to establish bulkhead stiffness and strength design guidelines for head impact protection for front row seating (Ref. 14).

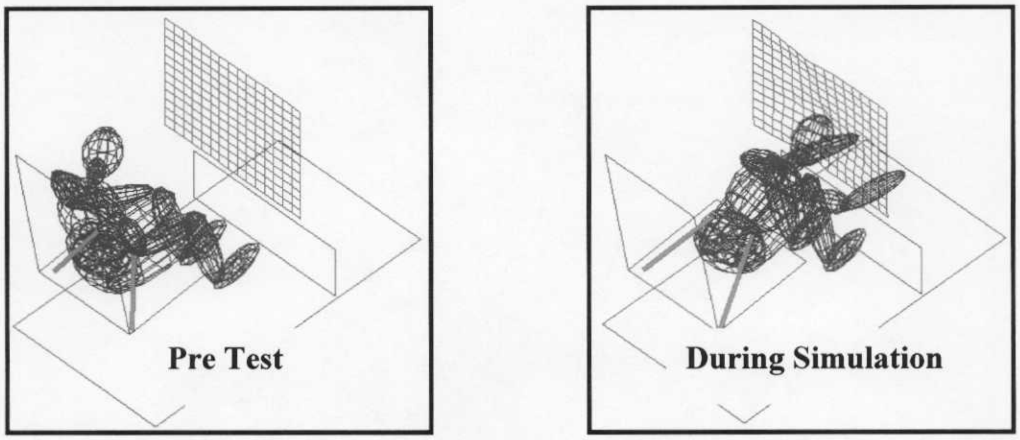


Figure 14 - Example NIAR Seat/Occupant/Bulkhead MADYMO Model

The results, both the kinematics and the HIC values, of the NIAR seat/occupant/bulkhead simulations for a variety of impact conditions and bulkhead impact surfaces were compared to full-scale seat dynamic tests to validate the NIAR MADYMO model and simulations. Figures 15 shows comparisons of the kinematics between the simulations and full-scale test for three different head strike setback distances.

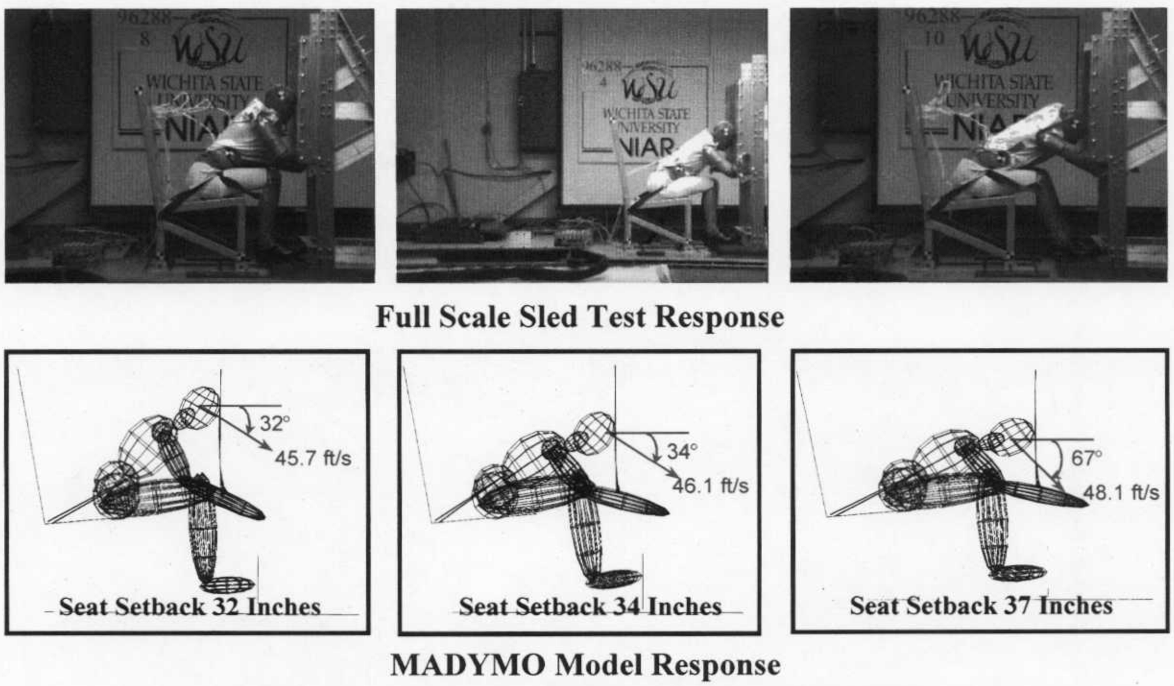


Figure 15 - Comparisons of Sled Tests and Analyses Results

Subsequent to validation of the MADYMO model a number of simulations were conducted with a variety of seat setbacks, impact angles, impact velocities, and impact surfaces to establish design guidelines for impact surfaces that might be located within the head strike envelope of front row seated passengers. Figure 16 illustrates two of the design guideline curves, one based on stiffness and the second based on the crush strength of the impact surface, that were developed in this program.

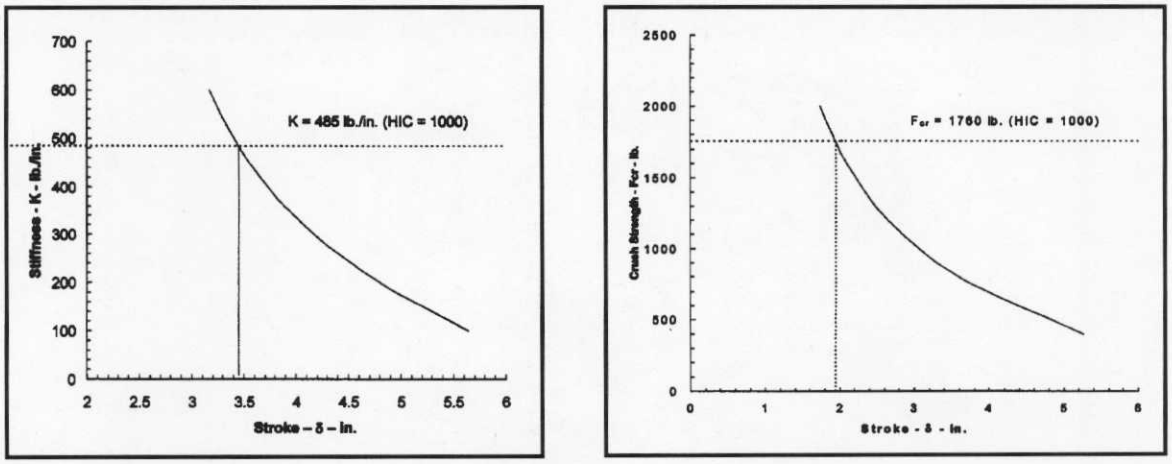


Figure 16 - Design Guidelines for Head Strike Surfaces

Development of a Head Impact Subcomponent Tester

As seen in Figure 13 front row bulkheads are not the only cabin interior furnishings that are located within the head strike envelopes of aircraft occupants. A HIC assessment is required for each interior cabin furnishing installation where a head strike may occur if the airplane's certification basis contains the seat dynamic performance standards. Currently the only available means to evaluate the HIC is by conduct of a full-scale sled impact test. If one considers the numerous interior cabin furnishings and the various installations that can exist on airliners and business jets it is readily recognized that a more efficient means, in both time and cost, needs to be available for HIC assessments other than full-scale sled impact tests.

In an effort to streamline the certification process with respect to HIC compliance the FAA sponsored a research and development program with the National Institute for Aviation Research to develop a Head Impact Criteria (HIC) Component Test Device (HCTD) that could be used in lieu of conduct of full-scale sled impact tests (Ref. 15, 16). Figure 17 illustrates the interactive test and analyses process that was used to develop the HCTD that makes use of full-scale sled test data, MADYMO simulations of various seat/occupant installations, MADYMO simulations of head strikes with the HCTD, and HCTD development and validation tests.

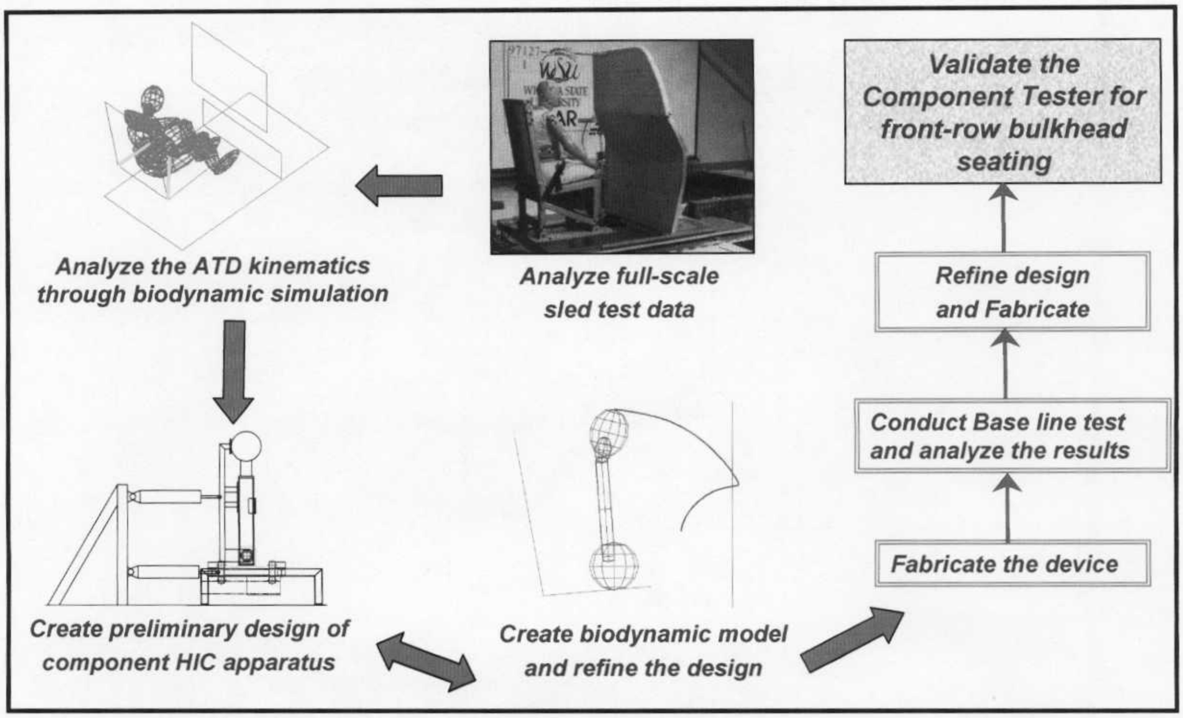


Figure 17 - HCTD Development and Validation Process

A HCTD shown in Figure 18 has been developed by NIAR and correlation with full-scale tests for some impact surfaces has been demonstrated. The HCTD is now undergoing further investigation and validation at the FAA's Civil Aerospace Institute (CAMI) for a variety of head strike conditions. The HCTD should be made available for public use subsequent to completion of CAMI's validation program.

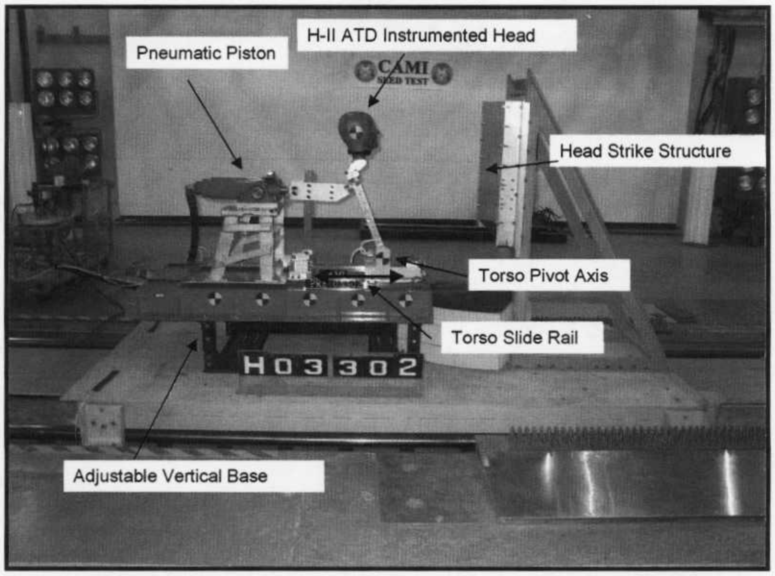


Figure 18 - National Institute for Aviation Research HIC Component Test Device

Development of Rotorcraft Civil Water Ditching / Impact Standards

The FAA has established a partnership with the U.S. Navy to develop analytical methods that could be used to evaluate current ditching standards and other water impact conditions and proposed new standards where deemed appropriate. Program KRASH was used to create models of four configurations of the Bell Helicopters Model 205 helicopter (summarized in Figure 21) that were used in the KRASH analysis of ditching and severe, but survivable, water impacts. The Bell Helicopters Model 205 helicopter KRASH models were based on a KRASH model of a Bell Helicopters Model UH-1H helicopter. That UH-1H KRASH model was previously validated by comparisons of the results of two full-scale fully instrumented water impact tests of the UH-1H helicopter and KRASH simulations of those tests (Ref. 17). Figure 19 shows one of the UH-1H helicopter tests at impact conditions of 28 ft/sec vertical velocity, 39 ft/sec longitudinal velocity, and four degrees nose-up pitch at the time of water impact. Figure 20 is an example of the corresponding KRASH model that was used in the model validation analysis and subsequent ditching and water impact simulations.

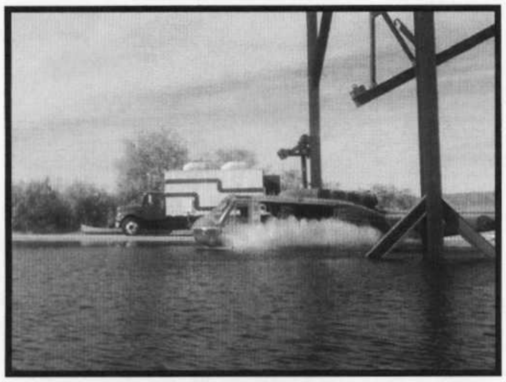


Figure 19 - Model UH-1H Helicopter Ditching Test

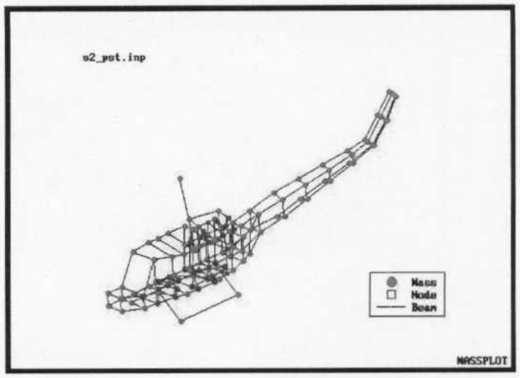


Figure 20 - Example Model UH-1H KRASH Model

Configuration No:	1	2	3	4
Description	max fuel all occ	min fuel all occ	floats max fuel 8 occ	aux fuel 10 occ
total gallons of fuel (220 or 400 max)	220	6.2	220	358.923
Empty Weight	5260	5260	5260	5260
total fuel weight	1435	40.4	1435	2370
baggage weight (400 max)	255	149.6	233.3	170
total occupants weight	2550	2550	1360	1700
FS of fuel CG	153.1919	143.6	153.1919	149.03
FS of baggage CG	268.5	257.96	266.33	260.00
FS of total occupants	107.8	107.8	84.5	91.00
overall Wt	9500.0	8000.0	8500.0	9500.0
overall FS (aft limit = 143.1)	142.55	138.79	142.78	141.38

Figure 21 - Summary of Configurations of KRASH Models Used in Parameter Study

The Bell Helicopters 205 helicopter KRASH model was used to perform parametric analyses for various sets of survivable water impact conditions (Ref. 18). Variations in aircraft impact velocity, attitude, aircraft weight, landing gear position, underside panel strength, mass item design load factors, flotation system performance, and water surface sea state conditions were considered in the analyses. Water impact design limit envelopes were established based on structural failure loads, occupant lumbar load, head injury, underside panel failures, major mass item retention, internal structure impingement loads, and seat stroke requirements. Figure 22 illustrates one of the design limit envelopes where the defined limits are compared to the current 14 CFR Parts 27 and 29 ditching standard. Figure 23 illustrates another water impact design limit envelope based on occupant seat load and stroke, the acceleration level of mass items, and internal bulkhead pressures limitations.

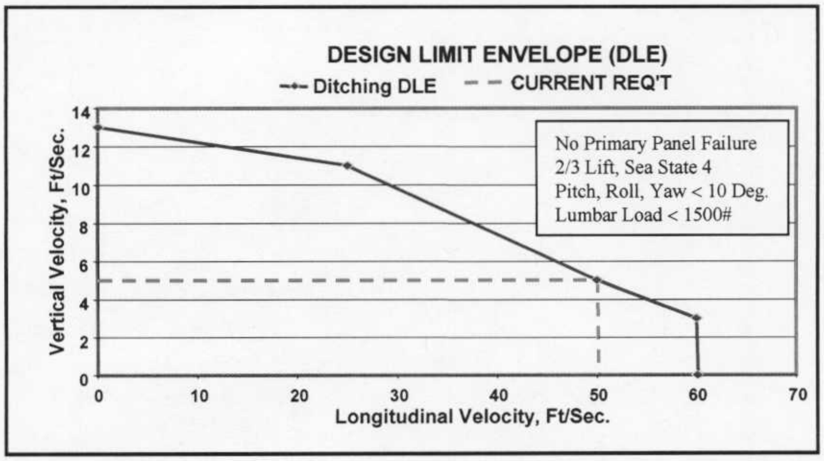


Figure 22 - Example Rotorcraft Design Limit Envelope

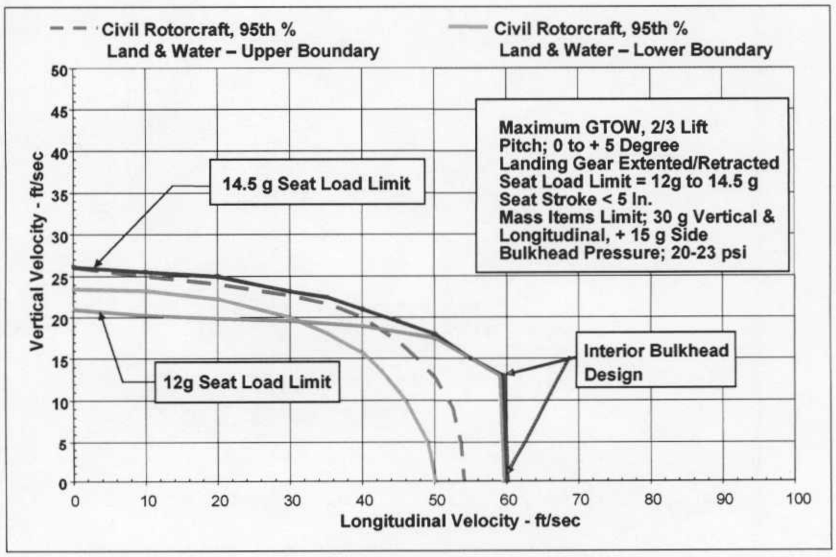


Figure 23 - Example Rotorcraft Water Impact Design Envelope

As a result of this effort a better understanding of viable design requirements for severe water impacts has been achieved. The KRASH water impact analytical methods can augment previous ditching compliance procedures such as scale model tests. There is also an increased confidence level in the ability of the analysis to simulate water impact scenarios as well as evaluate design changes. The results of this study can potentially become the basis of future regulatory or non-regulatory standards or other guidance materials that can be used for defining design requirements and compliance procedures related to water impact.

Usage and Applications of Analytical Methods

Aircraft Accident Investigation Tool (AAIT)

AAIT is a proprietary software package developed and supported by the Cranfield Impact Centre Ltd.. AAIT is a KRASH/Windows based computer program that includes a library of aircraft models that form the basis of the analysis, a pre and post processing graphical user interface, and an interface with the FAA developed SOMTA seat occupant computer model. The AAIT program's prime application is in the investigation of airplane accidents but it can also be used as a design aid and to conduct parameter studies to compare or optimize the crashworthiness features of aircraft.

The United Kingdom's Air Accidents Investigation Branch (AAIB) initiated the AAIT concept during their investigation of a Boeing Model 737-400 airplane accident that occurred near Kegworth, England, on January 8, 1989 (Ref. 19). The accident sequence of the Kegworth Boeing Model 737-400 airplane accident is illustrated in Figure 24.

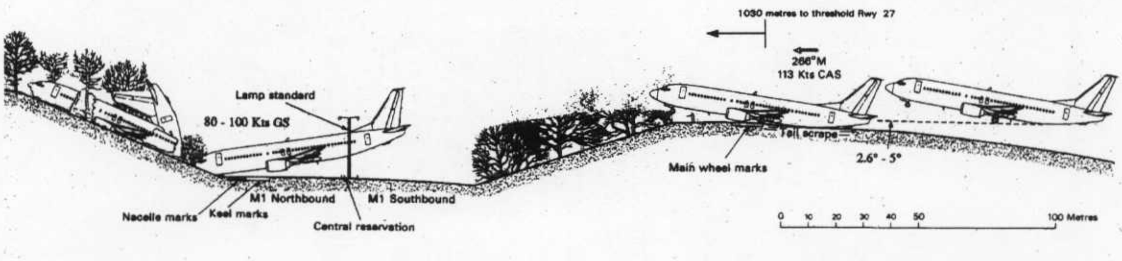


Figure 24 - Kegworth Airplane Accident Sequence

The AAIB sought to achieve a better understanding of the deceleration environment in the airplane's cabin throughout the crash event to enable them in turn to better understand a number of crashworthiness and survivability issues in that airplane accident. The AAIB approached the Cranfield Impact Center (CIC) to conduct a study of the accident case using a computer based dynamic analysis. CIC used a KRASH based analysis to simulate the crash event. That analysis proved to be very useful in the investigation of the Kegworth Boeing Model 737-400 airplane accident for it provided much insight with respect to the dynamics of the crash event. For example the time history of the vertical deceleration seen in the center cabin section of the airplane as calculated using the AAIT is shown in

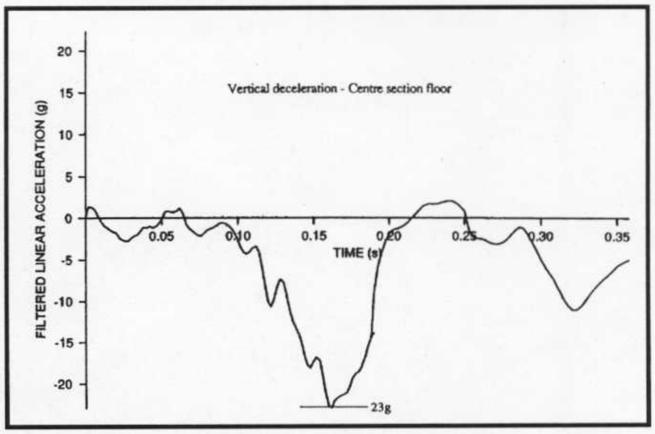
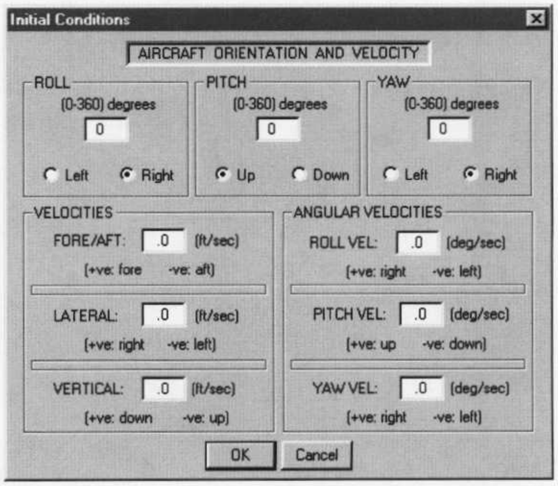


Figure 25 - Example Kegworth Deceleration Time History

Figure 25. A more complete review of the AAIT Kegworth airplane accident analyses that employed program KRASH can be found in the AAIB's accident report (Ref. 19).

Upon completion of the Kegworth airplane accident analysis the AAIB thought that the timeliness of the analysis could have been improved if there existed a library of some more typical aircraft computer models that could be simply and quickly modified by the accident investigator to reflect the crash event under investigation. The AAIB and the United Kingdom's Ministry of Defence (MOD) decided to commission the CIC to develop a KRASH based menu driven software code that became known as the AAIT. The FAA being a participant in the Kegworth Boeing Model 737-400 airplane accident investigation also saw the potential benefits of the AAIT program and they provided additional funding and technical advice regarding the AAIT program's content and features.



Initial Conditions Can Be Varied to Best Match Accident Case

Figure 26 - Example AAIT Menu

An example of one of the menu options found in the AAIT that defines the initial aircraft impact conditions is shown in Figure 26. Other menus also exist that can be used to modify the aircraft's structural properties, geometric configuration, and loading. A summary of the available AAIT library models is found in Table 1.

Table 1 - Summary AAIT Model Library

AAIT LIBRARY MODELS (END 2002)	
■ Westland Lynx Mk 8	■ MD-81
■ Westland SeaKing	■ SAAB 340
■ Westland EH101 Merlin	■ Shorts 330
■ Boeing Chinook	■ Piper Cherokee
■ ATR-42	■ Cessna 150/172
■ Embraer ER-145	■ Cessna 440
	■ Beechcraft 1900

The AAIT program has subsequently been successfully used in the accident investigation of the McDonnell Douglas Model MD-81 airplane accident that occurred outside of Stockholm, Sweden on December 27, 1991 (Ref. 20) and the Cessna Model 404 airplane accident at Glasgow, Scotland on September 3, 1999.

FAA's Full-Scale Airplane Drop Test Programs

Commuter Airplane Drop Tests Program

The FAA has conducted a number of full-scale airplane drop tests in support of the rulemaking action that proposed seat dynamic performance standards for Part 23 commuter category airplanes. Those drop tests were structured to measure the impact response characteristics of mid-size airplanes that might be used in commuter airline passenger service. Previous full-scale impact test programs were conducted with either small airplanes or transport category airplanes and fuselage sections. No full-scale impact response data existed for mid-size airplanes and the commuter airplane drop test program would be used to fill that data gap. Figure 27 summarizes the airplane models drop tested in this program and shows a typical acceleration time history plot acquired during the Alenia Model ATR-42 drop test.

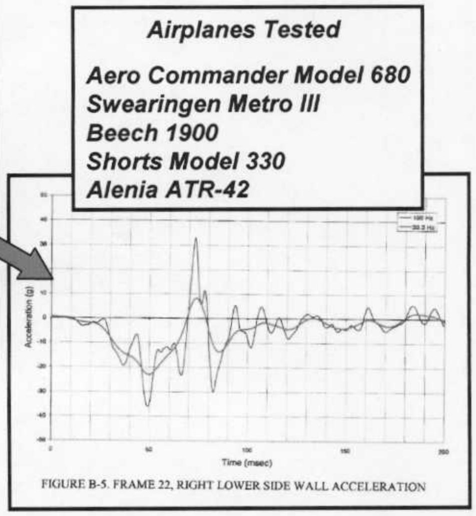


Figure 27 - Example Drop Test Summary and Typical Result

Two of the early drop tested airplanes, namely the Swearingen Metro III and the Beech 1900, were modeled with program KRASH and simulations were conducted to predict the impact test results and to demonstrate program KRASH's application to commuter category size airplanes. The KRASH models could also be used to analyze impact conditions that differ from the drop tests to further investigate the impact response characteristics of commuter category airplanes. The Swearingen Metro III drop test specimen and one comparison of the test and KRASH results is shown in Figure 28.

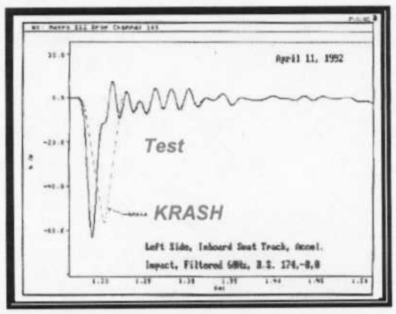


Figure 28 - Example of Swearingen Metro III Drop Test Specimen and Typical Result

ATR-42 Airplane Drop Test Simulation

The US Army Research Laboratory, Vehicle Technology Directorate at the NASA Langley Research Center through a continuation of a 1998 FAA Inter-Agency Agreement developed a finite element model of the ATR-42 commuter airplane. The ATR-42 airplane was drop tested at an impact velocity of 30 feet/second and the drop test was simulated using the LS-DYNA code. A three-quarter view of the ATR-42 airplane finite element model is shown in Figure 29.

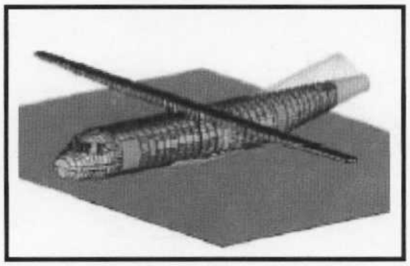


Figure 29 - ATR-42 Finite Element Model

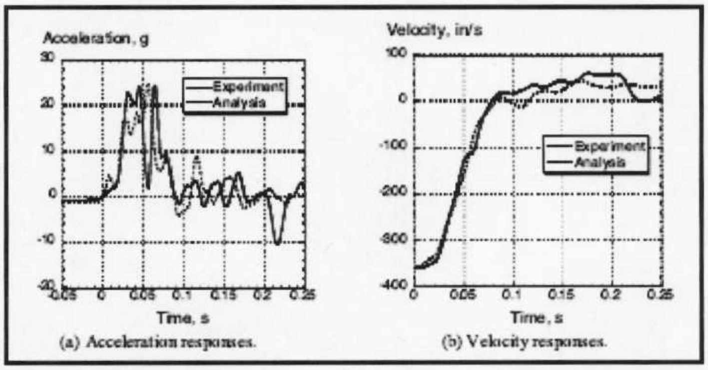


Figure 30 - Example of Test/Analysis Correlation at Right Outer Seat Track at FS 18

A comparison of the results between the drop test and the LS-DYNA analysis showed a high level of agreement between the acceleration and velocity time histories. An example of the level of correlation between the test and analytical data can be seen in Figure 30.

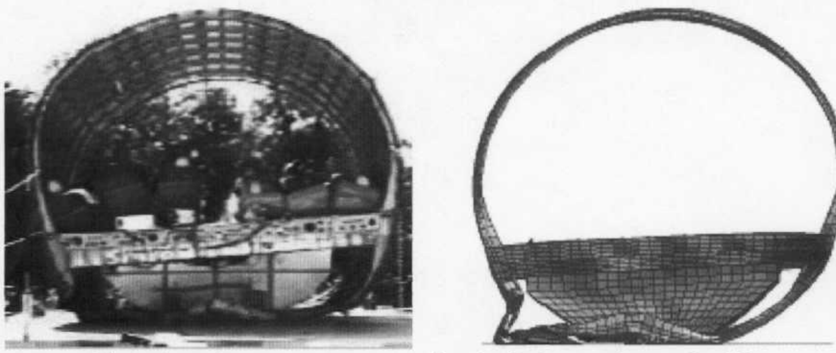
Figure 31 - Post Test View of Wing Penetration Into the Passenger Cabin

The simulation also importantly predicted the major airframe failure mode that being the fracture of the wing support frame structures and the resultant displacement of the wing into the passenger cabin of the airplane as shown in Figure 31. A comprehensive discussion of the results of this simulation task can be found in Reference 21.

FAA and NASA Program to Develop Fuselage Section Drop Test Analytical Models

In 1998 the FAA and the US Army Research Laboratory, Vehicle Technology Directorate at the NASA Langley Research Center initiated an Inter-Agency Agreement to conduct simulations of fuselage section drop tests being conducted at the FAA's Technical Center using the nonlinear transient dynamic analysis MSC.DYTRAN code (Ref. 22 and 23). Like with the aforementioned KRASH and LS-DYNA simulations of the commuter airplane drop tests the NASA MSC.DYTRAN simulations were conducted to evaluate MSC.DYTRAN's capability to simulate the drop tests and to predict the impact test results. A basic MSC.DYTRAN fuselage section model was created and modified to create other versions that were consistent with the FAA drop test specimens. For example one model version included under floor luggage with the overhead luggage bins and another version included an auxiliary fuel tank without the overhead luggage bins. Figure 32 shows a post test view of a transport category airplane fuselage section with an auxiliary fuel tank that was drop tested at a 30 feet/second impact velocity. A view of the structural deformation obtained from the simulated impact of the corresponding MSC.DYTRAN finite element fuselage section model is also shown in Figure 32.

Both the pretest and post test simulations of the various drop test configurations showed good correlation between the test and analytical results with respect to airframe and overhead luggage bin (where included) velocity change and acceleration levels, structural deformation, and failure modes. A comprehensive discussion and review of the results of this modeling task can be found in Reference 24.



a. Rear view picture post–test. b. Analysis rear view at time 70 ms.

Figure 32 – Example of MSC.DYTRAN Models Used to Simulate FAA Drop Tests

Drexel University Grant 99-G-046

FAA Grant 99-G-046 was provided to Drexel University to conduct a nonlinear transient dynamic analysis of a transport airplane fuselage section drop tested with under floor luggage and overhead luggage bins onboard. The Drexel University task was similar to the aforementioned NASA drop test modeling task but the Drexel University simulations were performed with LS-DYNA. The Drexel University fuselage section finite element models and the simulation results are similar to those seen in the NASA study and thus they are not further discussed herein. A comprehensive review of the results of the Drexel University grant can be found in Reference 25.

Certification Activities

LearFan Model 2100 Certification Program

The late 1970's certification program for the LearFan Model 2100 composite material airplane shown in Figure 33 is an early example of the application of KRASH in an aircraft certification program. The empennage of the LearFan airplane had a strengthened lower vertical fin that was intended to prevent potential propeller ground strikes during adverse takeoff or landing attitudes. A KRASH model of the LearFan airplane was developed to assess the "slapdown effects" from ground contact of the lower vertical fin, the energy absorption characteristics of the composite material airframe, and the potential for occupant injury from slapdown.

Figure 33 - LearFan Model 2100

Figure 34 – Post NASA Impact Test

The KRASH analysis of the LearFan Model 2100 was under review when the airplane's certification program was cancelled and the crash impact characteristics of the composite material airframe were not yet fully determined. However in 1980's NASA began focusing their crashworthiness studies on composite material structures and in 1994 NASA Langley's Impact Dynamics Research Facility crash impact tested a prototype version of the LearFan airplane shown in Figure 34. That crash impact test did show that the LearFan composite material airframe structure was not an optimum design with respect to energy absorption and crashworthiness. The acceleration environment measured during the impact test was found to be greater than that measured during impact tests of comparable airplanes with metallic airframe structures (Ref. 26).

Impact Characteristics of Unique Structures/Configurations

KRASH analysis has been used to analyze the impact response characteristics of a unique lower lobe seating configuration proposed for a wide body airplane. The proposed configuration is depicted in Figure 35. Questions arose regarding the potential differences in the crash impact survivability levels and the impact load environments between the main passenger deck and the lower passenger deck of the airplane.

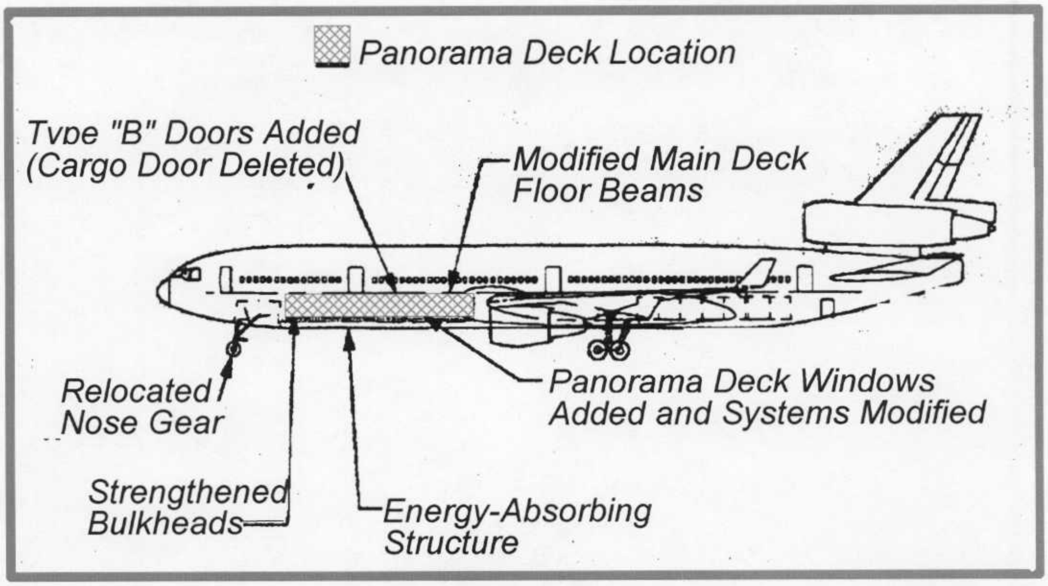


Figure 35 - Proposed Lower Lobe Seating Configuration

A KRASH fuselage section model (shown in Figure 36) representative of the structural characteristics of a wide body airplane was developed to investigate the protective capability of the fuselage shell, the impact acceleration environment, and the potential for occupant impact injury for a range of potentially survivable impact conditions. DRI and spinal load modules were included in the KRASH model to assess the potential for occupant spinal injury.

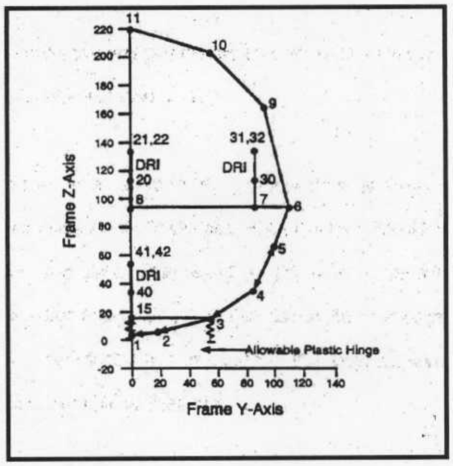


Figure 36 – KRASH Lower Lobe Model

A parameter study varying the impact velocity and weight of the wide body airplane fuselage section was conducted. Table 2 summarizes the parameter variations used in that study.

Figures 37 and 38 illustrate the acceleration environment in terms of peak G's that the passengers might be exposed to for the range of impact velocities and fuselage section weights used in the parameter study. As might be expected the passengers seated in the lower passenger deck could be subjected to a more severe impact environment and thus

Parameter Designation	Parameter Value
V1 V2 V3 V4	15 ft/s 20 ft/s 25 ft/s 30 ft/s
W1	440 lbs = 2 occupants (360 lbs @ masses 40,41/42) 4 seats (80 lbs @ mass 15)
W2	620 lbs = 3 occupants (540 lbs @ masses 40,41/42) 4 seats (80 lbs @ mass 15)
W3	800 lbs = 4 occupants (720 lbs @ masses 40,41/42) 4 seats (80 lbs @ mass 15)
W4	1100 lbs = 4 occupants (720 lbs @ masses 40,41/42) 4 seats (80 lbs @ mass 15) ballast (200 lbs @ mass 15)

Table 2- Summary of Parameter Variations Used in the KRASH Study

have more potential for spinal injury than those seated on the main passenger deck. This may not be surprising since the lower deck passengers are located closer to the point of impact and have less energy absorbing structure between them and the point of impact as compared to those seated on the main passenger deck. Both the DRI and the spinal load modules incorporated into the KRASH model confirmed the potential difference in occupant spinal injury for passengers seated on the lower passenger deck as compared to those seated on the main passenger deck (Ref. 27).

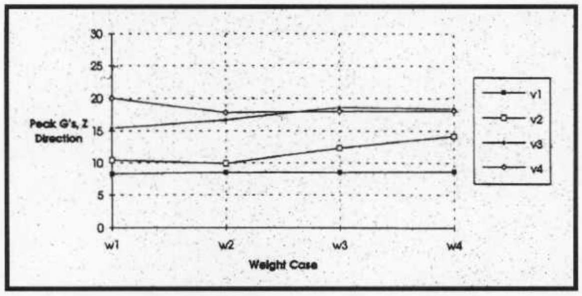


Figure 37 - Peak Vertical G's

Upper Center Floor Mass #8

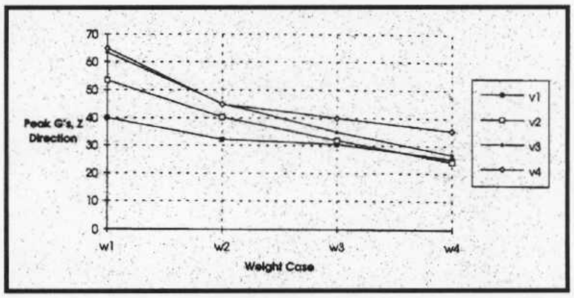


Figure 38 - Peak Vertical G's

Lower Center Floor Mass #15

Certification/Qualification of Aircraft Airbag Systems

The FAA has participated in the development and qualification of aircraft airbag systems for use in U.S. Army helicopters. MADYMO and MSC.DYTRAN computer simulations were used to evaluate the airbag deployment sequence and impact protection characteristics of those aircraft airbag systems. The computer simulations were also used to determine critical configurations and load cases to minimize the number of full-scale development and qualification tests. The computer simulations also allowed evaluation of several other non-test conditions such as out of position occupants. Figure 39 illustrates a comparison of one of the full-scale airbag impact tests and a computer simulation of that test.

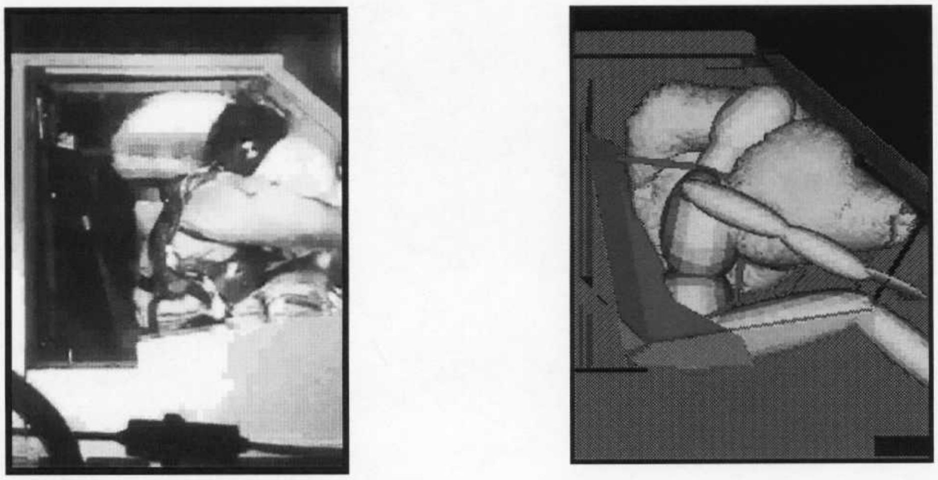


Figure 39 - Comparison of Full-Scale Test and

The FAA has received a variety of applications for installation of airbag systems in civil aircraft. Those applications include among others cockpit mounted airbags, bulkhead mounted airbags, and lap belt airbag systems. Like with the U.S. Army aircraft airbag installation program computer simulations were also used in the civil aircraft airbag certification programs to determine critical configurations and load cases to minimize the number of full-scale certification tests. An example of a civil aircraft lap belt airbag system in shown in Figure 40.

Figure 40 - Example of Civil Aircraft Lap Belt Airbag

Airbus Model A380-800

The European Joint Airworthiness Authorities (JAA) and the FAA both issued Special Conditions to address the unique design features of the Airbus Model A380-800 airplane. The particular design features that lead to the issuance of the Special Conditions are the A380-800 airplane's extensive double deck and its structure of greater scale than current large transport airplanes as shown in Figure 41. The objective of the Special Conditions summarized below is to ensure that the Model A380 airplane provides an equivalent level of crash survivability to that demonstrated by conventional large transport category airplanes.

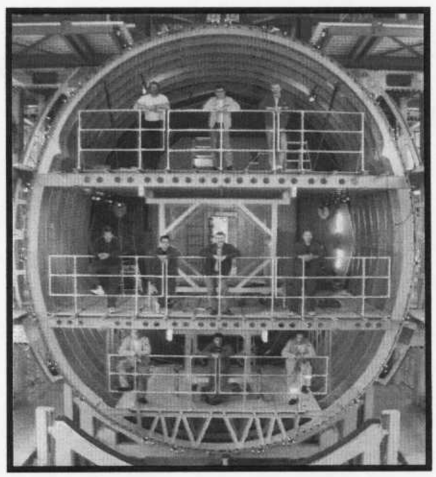


Figure 41 - Airbus Model A380 Fuselage Cross Section

1. Structural deformation will not result in infringement of the occupants normal living space.

2. It must be shown that the occupants will be protected from injury as a result of release of seats, overhead bins and other items of mass due to structural deformation of the supporting structure. The attachment of these items need not be designed for static emergency landing loads in excess of those determined in FAR §25.561.

3. The Dynamic Response Index (DRI) experienced by the occupants will not be more severe than that experienced on conventional large transport category airplanes.

A nonlinear transient dynamic finite element analysis of a typical Airbus A380 two bay fuselage section shown in Figure 42 was used to show compliance with the specific requirements of the special conditions. The finite element analysis simulated a ground impact condition at a vertical descent rate representing the limit of reasonable survivability for conventional large transport category airplanes.

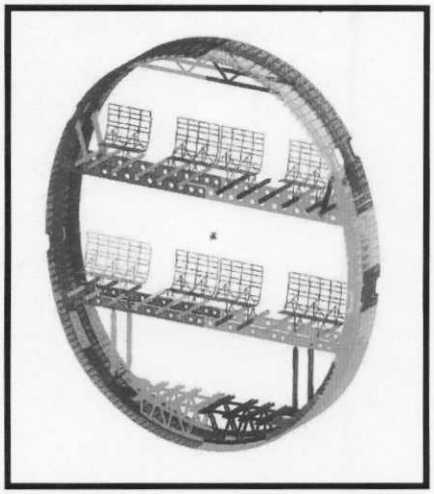


Figure 42 - Two Bay Finite Element Model

(Courtesy of Airbus)

The Airbus Model A380 two bay fuselage section finite element computer model and a similar Airbus Model A340 finite element computer model were used to show by both specific and comparative analyses that the above requirements of the Special Conditions were satisfied and an equivalent level of crash survivability to that demonstrated by conventional large transport category airplanes was achieved.

Concluding Remarks

The FAA has sponsored and participated in a number of research, development, and application programs that have had as a common objective the development of computer based analytical methods that could be used to simulate a crash event. Those included seat/occupant, hybrid lumped mass, and nonlinear transient dynamic finite element computer codes. The developed analytical tools have become valuable assets that are being used by designers and researchers to enhance the crashworthiness features of aircraft and to advance the state-of-the-art in aircraft crashworthiness.

Nonlinear crash dynamic analytical tools may be used in the aircraft seat certification process to select critical test cases and make changes in previously certificated seats. The new generation of very large and composite material transport category airplanes has also drawn on these analytical tools to demonstrate that their new airplane designs have an equal or better level of crash survivability as compared to their predecessors.

The FAA continues to support and encourage the research, development, and application of nonlinear crash dynamic analytical tools. Recently the FAA issued an FAA Advisory Circular that defines the acceptable applications, limitations, validation processes, and minimum documentation requirements involved when substantiation by computer modeling is used to support a seat certification program (Ref. 28). The FAA is currently investigating other means that can facilitate the use of analytical tools in the aircraft certification process.

The FAA's participation in other recent research programs such as the Advanced General Aviation Transport Experiments (AGATE) crashworthiness analytical and full-scale airplane test program and the European CAST (Crashworthiness of Helicopter on Water: Design of Structures using Advanced Simulation Tools) water impact research project has also enabled the FAA to share and gain further knowledge in new developments and applications of nonlinear crash dynamic analytical methods. The development and application of these analytical tools have progressed beyond their infancy stage and they are entering an unprecedented growth period as new enthusiastic and knowledgeable analysts enter this technological field.

Acknowledgement

This paper is a compilation of the works of the many dedicated individuals cited herein who have and continue to make numerous and significant contributions in developing the technology and analytical tools that form the basis for the enhancements in the level of crash survivability found in new civil and military aircraft designs.

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