Analysis of Aircraft Dynamic Behavior in a Crash Environment

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Differences in the crash environments and design aspects that influence occupant survivability in military and commercial aircraft are discussed. Available analytical techniques for assessing structural behavior during a crash are described. The application of a hybrid technique in assessing aircraft structural behavior and trends in crash environments is provided. Representative mathematical simulations of aircraft crash tests and correlation with light fixed-wing and rotary-wing aircraft test results are shown. The results of a recent FAA/NASA sponsored research program involving the review of transport accidents from 1964 to 1979 and the formulation of potential crash scenarios to be considered with future analysis and test verification are presented. Current and future analytical model studies to ascertain the crash dynamics of large transports are also discussed.

Introduction

IN the 1955-1965 era, a popular approach to a determination of aircraft structural crash design capability was to perform full-scale crash tests. Tests of this nature are extremely expensive, particularly as the test articles have increased in size, as the current wide-body jets have. In addition to cost, the test conditions are not repetitive; the results are highly dependent on the impact conditions and airplane configuration, as well as measurement selection. Consequently, essentially only one test parameter data set per test is available. Unfortunately, during this time period, there was limited correlation with analysis and extrapolation of the test data. However, the 1970s witnessed significant advances in computer modeling of nonlinear crash dynamic behavior, both at the substructure and airframe levels. In particular, hybrid (combining analytical and empirical data) and finite element techniques have had the opportunity to be correlated with test data generated for the purpose of verifying and improving the analytical methods. This paper describes differences in the crash environment associated with various categories of aircraft, discusses experimental verification of hybrid analysis with light fixed-wing and rotary-wing aircraft, and describes efforts to develop analytical techniques for transport aircraft.

Crash Environment

The definition of the crash environment is essential before any aircraft crash dynamics capability can be determined. Unfortunately, no single crash environment is applicable to all aircraft. Size, speed, configuration, and operational aspects associated with aircraft all influence the crash environment. Therefore no universal definition of a crash environment is possible. Descriptions of a survivable crash can include velocity envelopes, crash pulses, crash load factors, and crash scenarios. Comparison of the survivable crash environment and responses of the structures indicates significant differences between small and large aircraft. The survivable large transport accident usually occurs around airports at flight-path velocities below 150 knots and vertical descent rates at less than 20 ft/s. These conditions are normally associated with landing and takeoff operations such as short landings, overruns, and skidding off the runway. Smaller aircraft, such as helicopters and general aviation airplanes, have lower longitudinal velocities but higher vertical rates of descent during a crash condition; accidents can include stall/spin and emergency landings on unprepared terrain. The percentage of occupiable space in large transports greatly exceeds that of smaller aircraft. Furthermore, occupants of small aircraft are much closer to the airframe/terrain impact point, due to obvious airframe construction differences. The crash pulses experienced by transport occupants vary along the length of the fuselage more so than do the pulses for small aircraft.

The crash environment for military helicopters, as defined by 95th percentile survivable crash pulses in different directions, was established for U.S. Army helicopters on the basis of 373 accidents that occurred between July 1960 and June 1965.[1] In a recent update of the U.S. Army Crash Survival Design Guide,[2] the recommended design environment was presented as the design pulse. Although the crash environments are identical to the historical 95th percentile survivable crash pulse, the U.S. Army recognizes that improved crashworthiness increases the severity of the survivable crash, thereby producing a never-ending increase in the level of crashworthiness at the expense of aircraft performance. The U.S. Army defines a survival envelope[2] as "the range of impact conditions—including magnitude and direction of pulses and the duration of forces occurring in an aircraft accident—wherein the occupiable area of the aircraft remains substantially intact, both during and following the impact, and the forces transmitted to the occupants do not exceed the limits of human tolerance when current state of the art restraint systems are used." The U.S. Army design pulses are applicable to all aircraft in a given category, regardless of weight and operational requirements. Figure 1 (Ref. 2) shows a three-dimensional envelope of combined longitudinal, lateral, and vertical velocity (ft/s) changes for helicopters.

Light fixed-wing (general aviation) aircraft weighing ≤12,500 lb operate at speeds up to 280 knots, carry from 1 to 17 people, have one or two engines, and have a low- or high-wing configuration. Aircraft of this type can be involved in stalls, ground collisions, and collisions with obstacles. Accidents[3] have occurred on terrains that are flat (40%), rolling (22%), mountainous (11%), hilly (8%), or dense with trees (9%), and at airports (2%). The current emergency landing conditions for airplanes categorized as normal utility, and acrobatic, are described in FAR 23.561 (Ref. 4).

The emergency conditions for Transport Category Airplane, Normal Category Rotorcraft, and Transport Category Rotorcraft, are provided in FAR 25.561 (Ref. 5), FAR 27.561 (Ref. 6), and FAR 29.561 (Ref. 7), respectively. As is the situation for light aircraft, the structure must be designed to

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give each occupant every reasonable chance of escaping injury in a minor crash landing. Recent in-depth studies[8-10] of large transport accidents over the most recent 20-year period revealed that while no accidents are alike in every respect, there are broad similarities for groups of accidents. These similarities allow for a rational arrangement of hundreds of accidents into a few candidate crash scenarios, as is depicted in Table 1. Accidents that are initiated when the aircraft is on the ground, and where no unpredictable hazards are involved, are rarely fatal. Conversely, when impact occurs at high speed and with a large impact angle, as accidents away from airports often do, the accident has a high probability of fatality. In between the extremes, the outcome, in terms of occupant survivability, depends on the surrounding hazards. Figure 2 (Ref. 9) shows the distribution of the severity of accident vs accident type. There are distinct events that can occur during a transport airplane accident. The likelihood of occurrence of each event and the involvement of structural systems—i.e., fuel tank, seat and attachments, fuselage, and wing—is very much related to the particular crash scenario. For each potential crash scenario several failure modes could occur; one such event is illustrated in Fig. 3. Each structure-related initial failure can lead to additional structure involvement and subsequent failure. The consequences of these events and/or failures are many, including fuel tank/line rupture, mass item failure, floor/door deformation, loss of seat integrity, and excessive occupant loads. The associated hazards to the occupant are fire (including smoke and inhalation), trauma, and evacuation fatalities/injuries.

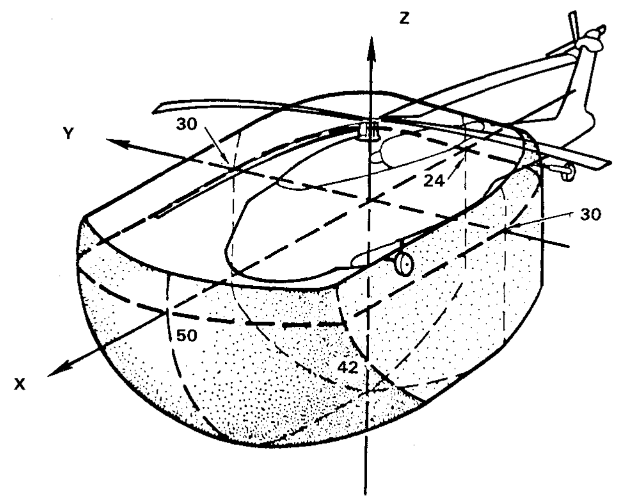

Fig. 1 Three-dimensional display of design velocity change envelope for helicopters.

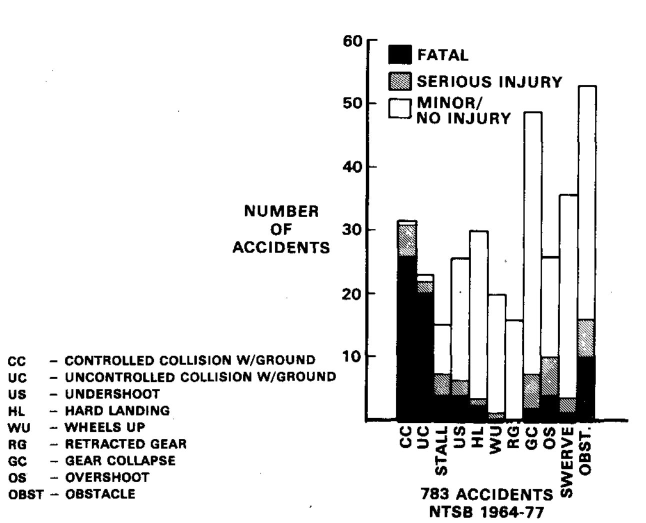

Fig. 2 NTSB accident data, injury severity as a function of accident type.

Airplane Crash Tests

In the 1950-1965 time period there were crash tests performed with transport category fixed-wing aircraft. These tests, which are noted in Table 2, cover a range of airplanes up to 159,000 lb gross takeoff weight and provide some insight into possible trends. One trend would appear to be for the floor response to decrease in peak magnitude and increase in pulse duration as aircraft mass (size) increases, as is noted in Table 3 (Ref. 16) and Fig. 4 (Ref. 17). However, this is a fairly general statement, since the response can be expected to vary along the length of the fuselage. Figure 5 (Ref. 17) illustrates this point, as well as the sensitivity of the response magnitude to impact angle. Unfortunately crash test data for transport airplanes are limited. The largest airplane crash tested weighed 159,000 lb, which is substantially lighter than many current transport airplanes, particularly the wide-bodied jets. It is unlikely that many larger aircraft will be full-scale crash tested in the near future. Consequently, it is anticipated that analytical methods will be a viable alternative to determine crash dynamics characteristics of transport airplanes.

KRASH Experimental Verification

The crash analysis of light fixed-wing[11] and rotary-wing[12] aircraft, using KRASH—a hybrid† digital computer program which solves Euler equations of motion for N interconnected masses, each with a maximum of six degrees of freedom—has met with general acceptance with general aviation and helicopter manufacturers, as is attested to by the current large number of KRASH users. Figure 6 (Ref. 12) shows the postimpact configuration for a combined vertical (23 ft/s) and lateral (18.5 ft/s) full-scale crash test of a utility-type helicopter. Figure 7 (Ref. 11) shows the postimpact configuration for four full-scale crash tests of a single-engine high-wing general aviation aircraft type. In both crash test programs, high-speed film, accelerometer recorded data, and deflection measurements were used to correlate test and analysis results. The test conditions for the fixed-wing aircraft are provided in Table 4. The aircraft configurations noted in Figs. 6 and 7 were used to help verify KRASH as an analytical tool for crash dynamics.

The helicopter math model is shown in Fig. 8. The comparison of analysis with the helicopter crash test results is shown in Fig. 9. The light fixed-wing airplane math model is shown in Fig. 10. Figure 11 shows a comparison of analytical and test data for the light airplane tests. It is interesting to note that for the light airplane, while the differences in test and analysis peak load magnitudes could vary substantially in some instances, the overall trend in the analysis for each of the four impact conditions is consistent with trends observed in the test data. The significance of this comparison is heightened when it is recognized that only one math model, Fig. 10, was used throughout all four light airplane tests. Figure 12 shows a comparison of the deformation experienced by the airframe for three of the four fixed-wing airplane tests. There was no significant damage to the airframe in the nose-up impact (Test 2); thus the results are omitted from the figure. The time history responses (not shown) for the verification test of both the helicopter and airplanes indicated that the significant response phenomena experienced during the test were simulated in the analysis.

†A hybrid model allows the user the flexibility to utilize available information, experimental or analytical, in the development of the structure representation. KRASH is available through the Federal Aviation Administration.

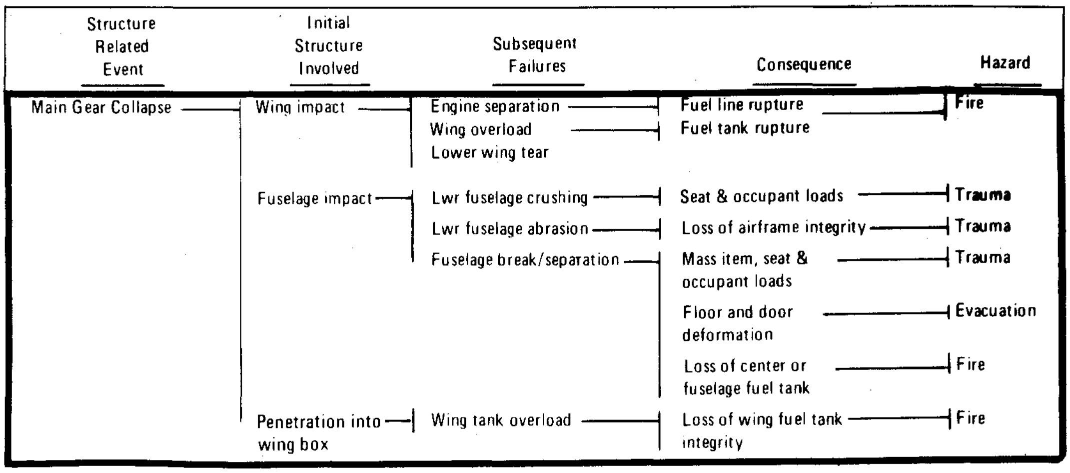

Fig. 3 Flow diagram, candidate crash scenario.

Table 1 Identification of candidate crash scenarios

Candidate crash scenario	Impact conditions	Accident type	Terrain	Hazard
Ground-to-ground, overrun	Low sink speed Low forward velocity Symmetrical airplane attitude Gears extended	Takeoff abort Landing overrun	Runway Hard ground	Ditch Mound Slope Slab Light stanchion
Air-to-ground, hard landing	High sink speed Landing velocity Symmetrical airplane attitude Gears extended	Hard landing Undershoot	Runway Hard ground	None
Air-to-ground, impact	High sink speed Landing velocity Unsymmetrical airplane attitude Gears extended/retracted	Uncontrolled/controlled Ground collision Stall Undershoot	Wooded Hilly	Trees Slopes Buildings

Table 2 Summary of transport airplane fixed-wing crash test conditions

	Approximate weight		Velocity,		
Airplane	kg	(lb)	m/s	(ft/s)	Slope, deg
C-82	19,026	(42,000)[a]	40.8	(133.8)	16
Lodestar	9,739	(21,500)[a]	39	(127.9)	12
			48.8	(160.2)	16
C-46	18,120	(40,000)	41.4	(136.7)	14
			43.5	(142.6)	27
L1649	72,027	(159,000)	52.4	(172.0)	6
			33.5	(110.0)	20
DC-7	55,266	(122,000)[a]	67.2	(220.5)	8
			49.3	(161.7)	20

[a]Maximum takeoff weights, test weight not stated.

Table 3 Comparison of peak decelerations and durations

Airplane	Longitudinal deceleration, g	Approximate duration, s
Fighter, FH-1	40	$\leq$0.02
Packet-type cargo, C-82	15	0.02
Unpressurized transport, Lodestar	16	0.05-0.08
Pressurized transport, C-46	9	0.200

Transport Airplane Crash Modeling

Unlike crash modeling for general aviation and helicopters, the modeling of transport aircraft for crash dynamics has not yet been verified with experimental data. Current studies[13] are being performed utilizing available accident and test data. The hybrid math models for the light aircraft and helicopters shown earlier contained 31-48 masses and 37-100 beam elements. Transport airplanes, because of their size and the number of occupants involved, could easily require an order-of-magnitude more for the number of masses and beams, if the same detail were needed. Finite-element structural models and occupant representations could easily result in transport airplane models requiring several thousand masses and elements. For example, modeling of light airplane substructure[14] utilized almost three times as many degrees of freedom (DOF) in the detail finite element model as compared with the more approximate hybrid lumped mass model. In addition, the computer time and cost using the finite element model was also shown to be two orders of magnitude greater than the hybrid method, yet with the conclusion that the hybrid analytical results were closer to the test results. Table 5 (Ref. 9) indicates various types of analyses and ranges of techniques that could be used for transport airplanes in the future. Part of the rationale for not necessarily having to develop an analytical model in extreme detail is as follows:

1) During many of the potential crash conditions (runway overrun, hard landing, gear collapse) the overall vehicle remains intact and, to a first approximation, behaves linearly.

2) Nonlinear behavior is restricted to localized areas mostly on the lower extremities of the airplane in direct contact with the ground.

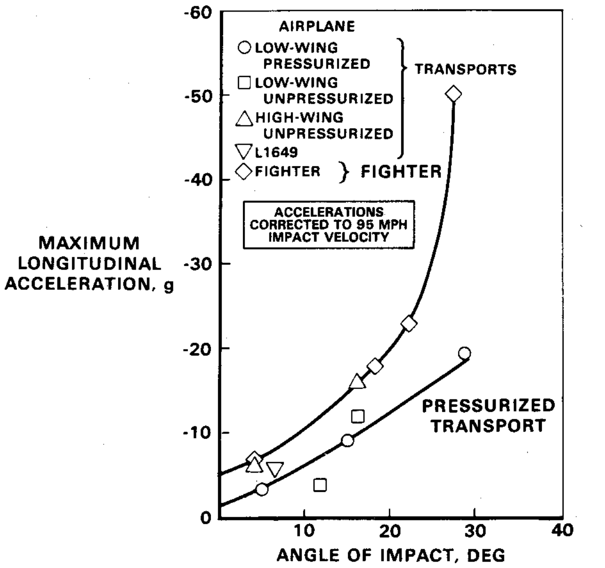

Fig. 4 Effect of airplane configuration and impact angle on maximum longitudinal acceleration.

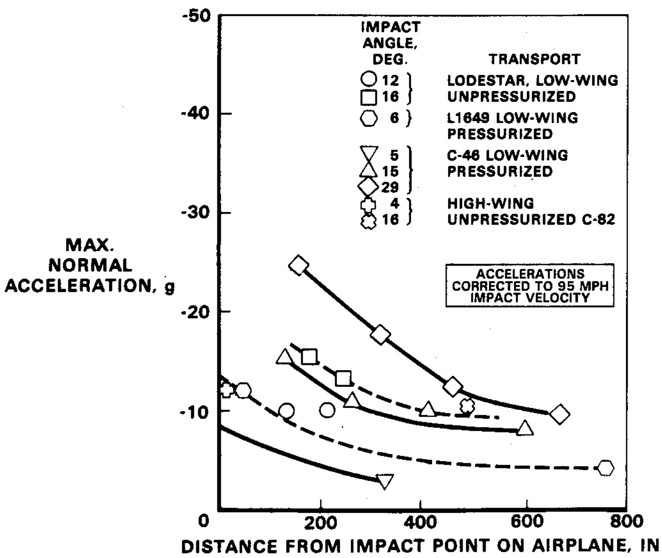

Fig. 5 Effect of position in airplane, airplane configuration, and impact angle on maximum normal acceleration.

3) Since local crushing and nonlinear behavior is not sufficiently widespread throughout the airplane to alter the basic linear behavior of the overall structure, lumped masses, driven at selected discrete locations representative of local crushing behavior, could be used to predict the dynamic response of the overall airplane structure.

For compliance with governing criteria, the impact loads, acting at the fuselage, landing gear, and wing engine atachments, must be within their respective structural strengths; otherwise additional analyses are required. These are key elements, and their load deformation characteristics have to be determined analytically or by means of test.

While, ideally, it would be desirable to model the airframe and occupants in detail, this is probably not practical or necessary for reasons discussed previously. An approach currently being investigated consists of using three analytical models in combination or in sequence: 1) fuselage/airframe, 2) floor, and 3) seat/occupant.

Figures 13-15 show some representative models of each. The model shown in Fig. 13 represents the airframe and to date has not exceeded 44 masses, including a simple

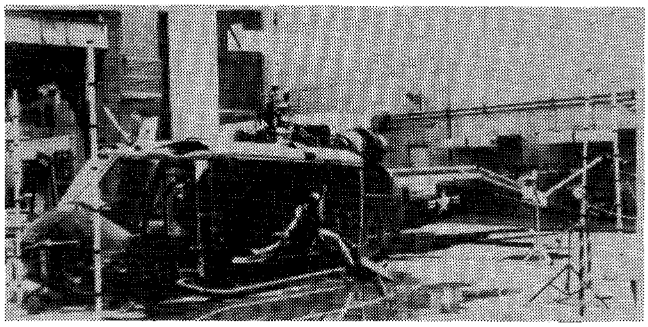

Fig. 6 Post-test damage, UH-1H helicopter crash test.

Table 4 Summary of single-engine high-wing airplane crash test impact conditions

Impact velocities, mph				
Along flight path	55.5	50.8	58.1	55.9
Longitudinal	47.4	48.6	47.6	48.4
Vertical	28.7	14.8	33.2	31.9
Angles, deg				
Flight path (γ)	−30.72	−17.0	−34.86	−32.0
Impact (θ)	−30.17	13.5	−39.4	−34.8
Attack (α)	0.57	+30.5	−4.54	−2.8
Roll (ϕ)	+4.13	+3.25	+18.75	1.0
Yaw (ψ)	−3.27	−11.5	−7.9	1.0
Rotational velocities, deg/s				
Pitch (θ)	46.4	6.9	14.3	18.2
Roll (ϕ)	Negligible	Negligible	Negligible	Negligible
Yaw (ψ)	Negligible	Negligible	Negligible	Negligible

γ is negative in dive
θ is positive nose up relative to ground
α is positive nose up relative to flight path
ϕ,ϕ are positive right wing down
ψ is positive tail left and $\theta = \gamma + \alpha$ ft/s = 1.467 × mph

floor/seat/occupant representation at several locations to account for interaction. The primary purpose of this model is to simulate a crash scenario, such as an overrun, which could require a simulation of from 0.5 to 1.5 s of crash sequence. The response at selected fuselage mass stations is utilized as input to a subsequent floor model. For a simulation involving wing impact, such as due to tree penetration, this model could be altered to provide more detail for the wing region.

Figure 14 depicts a symmetrical one-row floor model which contains seat/occupant mass and stiffness for interaction with the floor. Mass node designations 1,1 and 1,3 represent the floor-post attachment to the lower fuselage. The upper end of the floor posts attach to the floor beneath the outboard passengers. In the model shown in Fig. 14, masses 6 and 7 each represent a two-passenger seat. Since the model is symmetrical, an eight-occupant seating arrangement would be treated for a complete airplane. A model to treat unsymmetrical impact conditions increases size, and the cost of performing the analysis increases correspondingly. One can easily visualize that the floor and support structure could vary from aircraft to aircraft and from one section to another. The output desired from the model illustrated in Fig. 14 would be the floor pulse as an input to an occupant/seat configuration. Since different regions of the fuselage can exhibit their peak response at different times, the math model representing one portion of the crash sequence could realistically be run for 100-300 ms of simulated crash time.

Figure 15 illustrates a two-passenger seat/occupant arrangement. As in the case of the floor model, the excitation

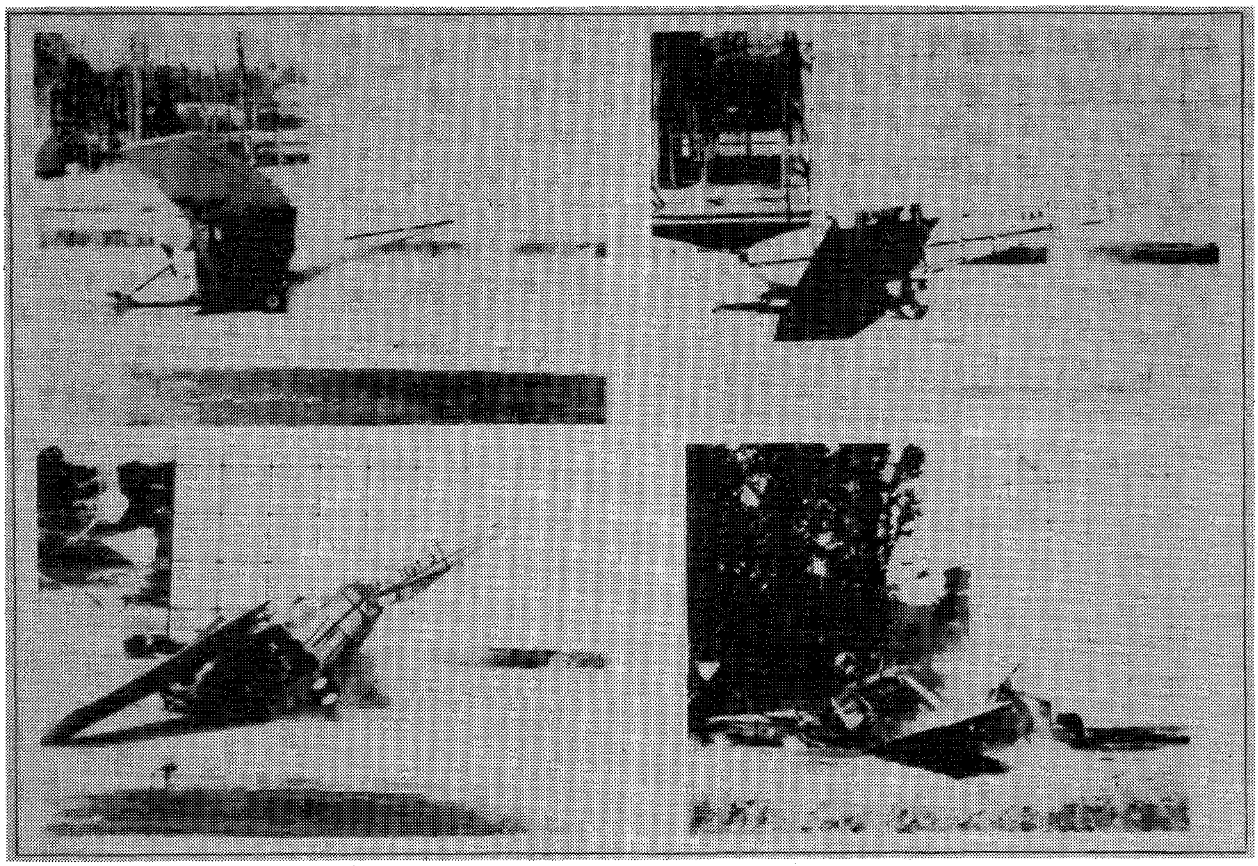

Fig. 7 Post-test damage, single-engine high-wing airplane crash tests.

Table 5 Applicable analytical techniques for related crash scenario events

APPLICABLE EVENT RESPONSE	ANALYSIS	PROGRAM/PROCEDURE	PURPOSE	ADVANTAGE	DISADVANTAGE
• MAIN GEAR COLLAPSE • NOSE GEAR COLLAPSE • WING IMPACT (INITIAL)	LANDING GEAR DETAIL, RIGID AIRPLANE, CONTOURED TERRAIN; I.E., SLOPE	• MODAL • HYBRID	• OBTAIN FAILURE MODE OF GEAR(S) • ESTABLISH IMPACT CONDITIONS FOR AIRFRAME AND/OR WING STRUCTURE	• ECONOMICAL TO RUN • MODEL DETAIL WHERE REQUIRED FOR INITIAL EVENT	• INCOMPLETE ANALYSIS INSOFAR AS POST-FAILURE BEHAVIOR AND OCCUPANT RESPONSES
• WING GROUND IMPACT • FUSELAGE GROUND IMPACT • OBSTACLE PENETRATION INTO WING • LANDING GEAR PENETRATION INTO WING BOX • NOSE GEAR PENETRATION INTO FUSELAGE	AIRFRAME AND WING REPRESENTATION AND COMPLETE TIME HISTORY OF EVENTS SUBSEQUENT TO GEAR COLLAPSE	• HYBRID	OBTAIN • FAILURES • POST FAILURE BEHAVIOR • AIRFRAME RESPONSES • OCCUPANT RESPONSES	• PERFORM CONTINUOUS ANALYSIS FOR AIR FRAME AND OCCUPANT BEHAVIOR	• COULD LACK DETAIL REPRESENTATION IN SOME AREAS • RELATIVELY COSTLY TO RUN FOR SLIDEOUT CONDITIONS
• ENGINE SEPARATION • SLIDEOUT • OCCUPANT/SEAT • OVERHEAD RACK • FUEL TANK	SIMPLE ANALYSIS TO DETERMINE MASS RESPONSES, LOSS OF STRUCTURE AND POTENTIAL DOORSILL HEIGHTS AFTER SLIDEOUT	• DYNAMIC RESPONSE CURVE • HYBRID • EMPIRICAL RELATIONSHIP	DETERMINE • DYNAMIC RESPONSE OF MASS ITEMS • DYNAMIC STATIC RELATIONSHIPS • CONSEQUENCE OF LOSS OF STRUCTURE • DOORSILL HEIGHTS FOR EVACUATION	• SIMPLE TO APPLY • REPRESENTS THE BASIC PHENOMENA • CAN BE TRANSLATED INTO TEST REQUIREMENTS	• NOT DETAILED FOR STRESS PURPOSES
• SEAT/RESTRAINT/OCCUPANT	OCCUPANT, SEAT, RESTRAINT MODEL	• OCCUPANT MODEL	• OBTAIN DETAILS FOR SEAT, RESTRAINT SYSTEM, AND DELETHALIZATION DESIGN	• UTILIZE PROGRAM SPECIALIZING IN RESTRAINT SYSTEM AND OCCUPANT BEHAVIOR	• NOT REQUIRED IF ONLY BASIC OCCUPANT RESPONSE IS TO BE EVALUATED
• AIRFRAME LOADS • DOOR DISTORTION • FLOOR DISTORTION	AIRFRAME, FUSELAGE SHELL, DOOR DEFORMATION, WING SECTION DETAILS	• FINITE ELEMENT	• PERFORM DETAIL ANALYSIS OF A REGION, SECTION	• DETERMINE DETAIL BEHAVIOR WITH STRESS STRAIN RELATIONSHIPS	• COST IS RELATED TO DEGREE OF DETAIL DESIRED

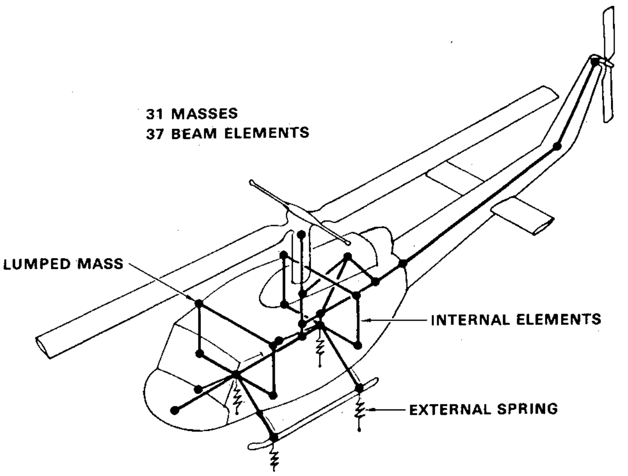

Fig. 8 Helicopter analytical model.

would be an acceleration pulse at the base, such as one would anticipate in a seat dynamic test. In the event a static test were to be simulated, a force time history would be applied to a test body block. A model of this type for dynamic pulse considerations need not be run for more than 200 ms crash simulation time. Individual, double, and triple passenger seat models could easily be established to assess the response occupant loading variations to a particular floor pulse. There are detailed occupant models[15] which can also be used to assess occupant response to a crash environment. In both the floor and seat/occupant models, care must be taken to ensure that the boundary conditions between models are matched.

The airframe model is used to obtain fuselage responses which are subsequently input to a floor model to obtain floor pulses. A comparison is made with reported data from a previous crash test of a narrow-body aircraft.[18] The range associated with the results is shown in Fig. 16. The trend in the analysis appears consistent with the test data. However, there

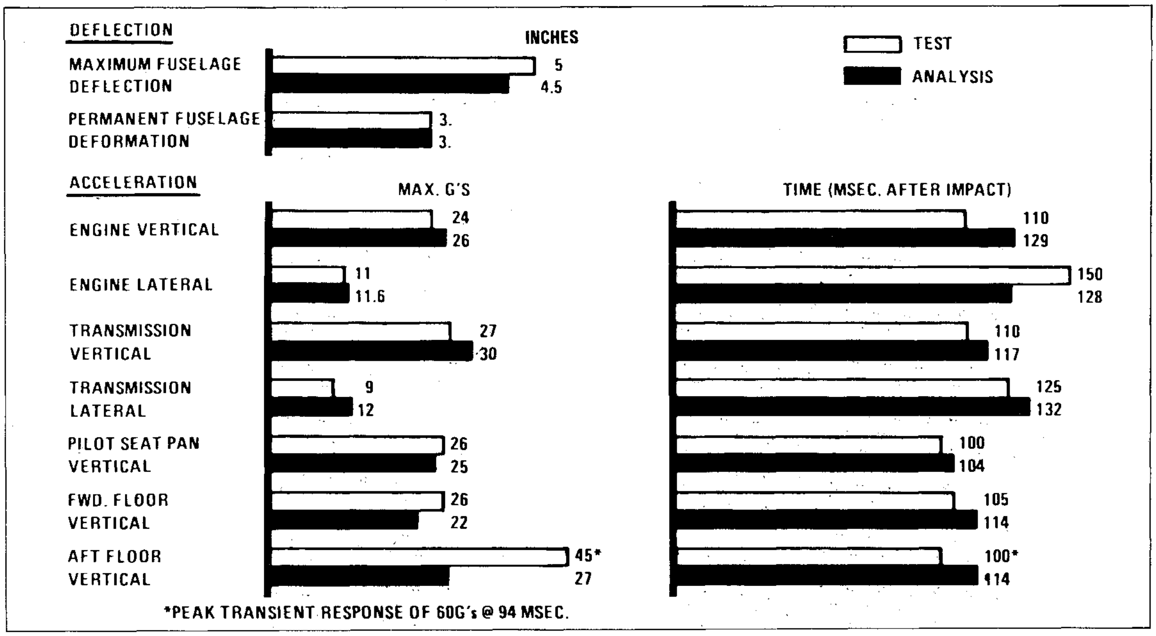

Fig. 9 Comparison of helicopter crash test and analysis results.

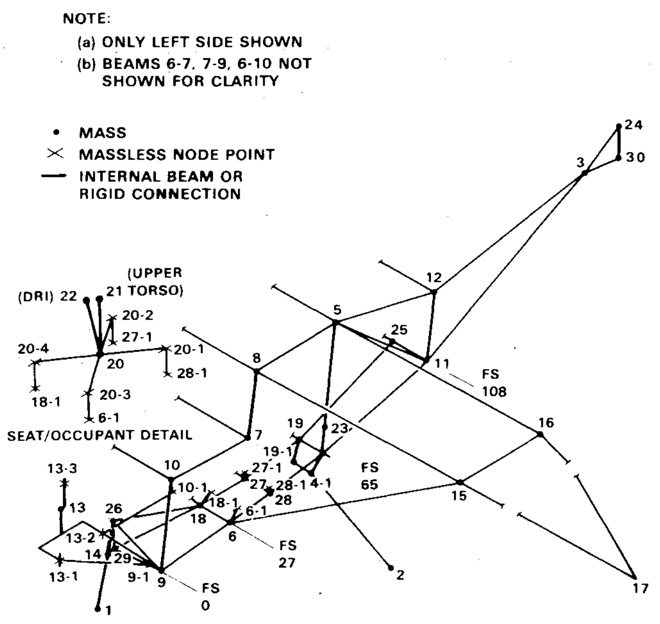

Fig. 10 Single-engine high-wing airplane analytical model.

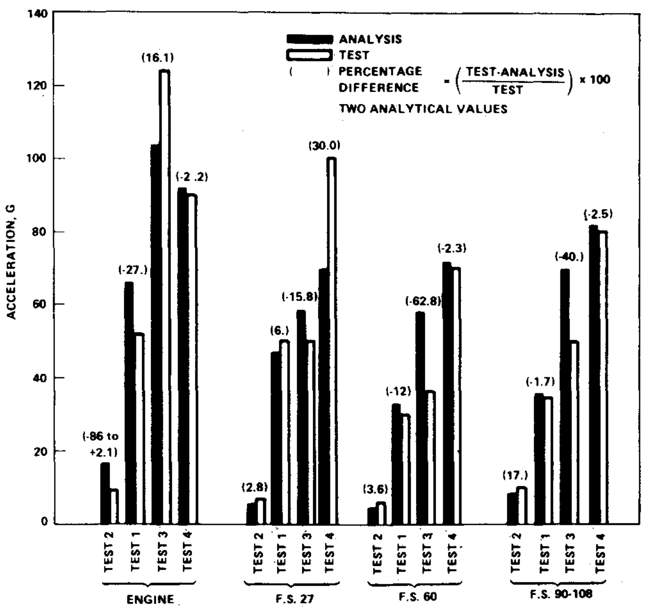

Fig. 11 Single-engine high-wing airplane analysis and test vertical responses.

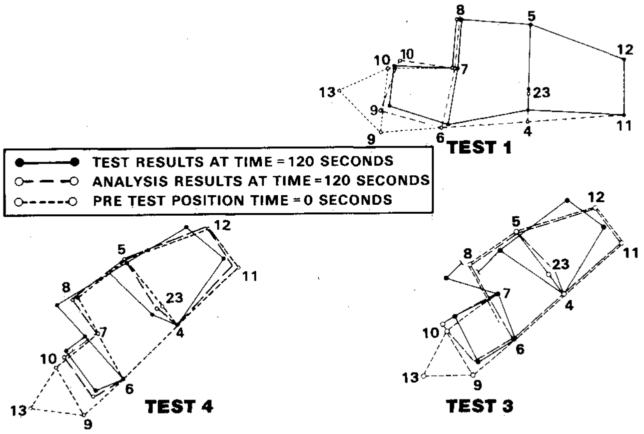

Fig. 12 Single-engine high-wing airplane analysis and test deformations.

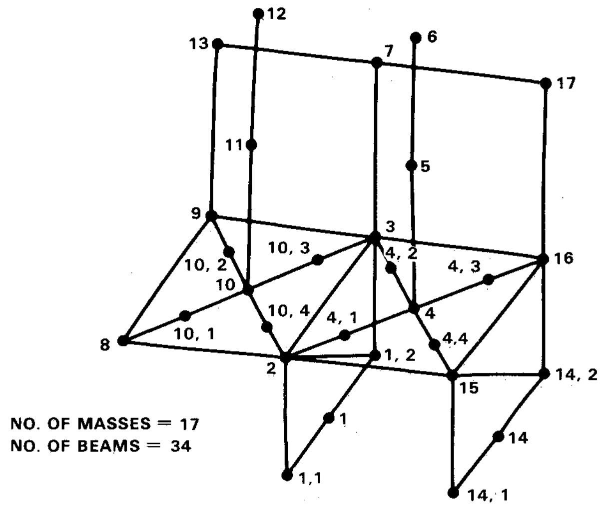

Fig. 15 Two-passenger seat/occupant model.

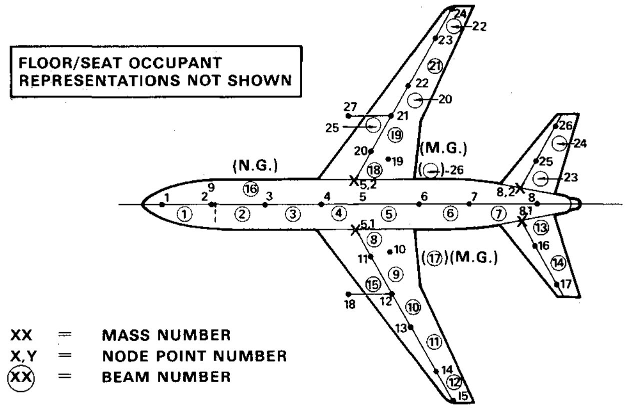

Fig. 13 Transport category airplane airframe analytical model.

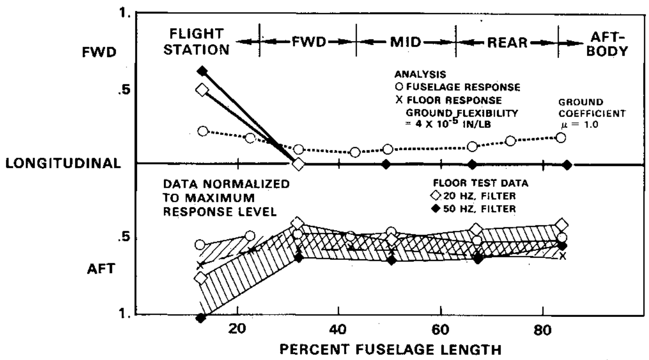

Fig. 16 Longitudinal acceleration vs fuselage location, slope impact.

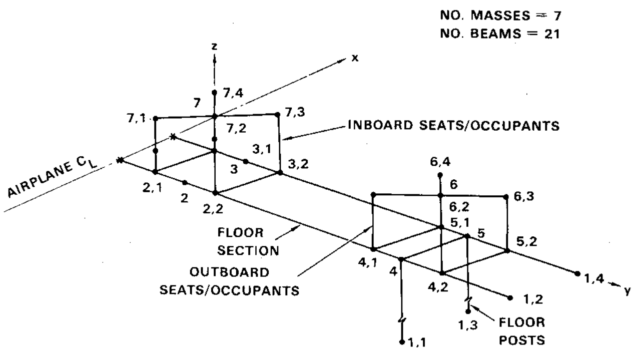

Fig. 14 Single-row transport floor, analytical model.

are differences, and their magnitude is dependent on the model's ability to represent the significant phenomena associated with the structure and the ground. The flexibility of the ground for the test was not documented. Additional tests, using the latest techniques, instrumentation, and appropriate documentation, with the goal of enhancing analytical prediction capability, would be desirable.

The concept of model modules to analyze transport accident scenarios offers some advantages. If a detailed floor system were included in the airframe model the cost would increase substantially for two reasons:

1) The detailed model would have to be run for 1 s even though a fraction of the time is required for a critical floor pulse.

2) The size of the model increases and the total model, including airframe representation, would have to be run at a finer integration interval as necessitated by the floor model requirements.

In addition, since the hybrid KRASH program has proved valuable in assessing trends, a change in one parameter, i.e., occupant weight, would require a total rerun at the maximum time and at a finer integration interval if the airframe, floor, and seat/occupant models were combined. In the modular approach outlined above, only the last model (seat/occupant) need be revised.

The transport aircraft seating configuration and the range of passenger size and weight vary considerably. For example, there are two and three seat configurations which may or may not be fully occupied. Even if occupied, the weight of the individuals could vary from fifth percentile females to 95th percentile males. The response and loading of each occupant seating configuration could vary for the same floor pulse excitation.

Conclusion

Aircraft can differ substantially in size, design, usage, and number of occupants involved, and, thus, no one crash environment is applicable to all aircraft. Due to these differences, analytical methods which may be appropriate for one class of aircraft may have to be modified for other aircraft categories. Program KRASH, which is currently being used by helicopter manufacturers to show compliance with U.S. Army crash design requirements, has been correlated with several full-scale light-wing and rotary-wing aircraft crash tests. Despite favorable crash analysis of small aircraft, there is a need to develop improved methods, or approaches, in the assessment of large transport crash dynamics. The large size of the structure, along with the range and numbers of occupants involved and the diverse potential crash scenarios indicate the need for additional refinement in the application of available analytical techniques. Fortunately, methodology is being refined under current FAA/NASA sponsorship. A full-scale crash test of a fully instrumented transport-type aircraft[19] is planned which will help to corroborate analytical predictive methods.

Acknowledgments

The results presented herein were achieved with the help of many individuals and organizations. In particular, the author gratefully acknowledges the contributions of my colleague, M.A. Gamon, for his continuous effort in the development of program KRASH, the support of the Lockheed-California Company management and personnel, the NASA-Langley Impact Dynamics Research Facility for their light fixed-wing crash test support, the U.S. Army, Fort Eustis Directorate for their early sponsorship, the FAA for recognizing the need to continue the development of analytical methods, and the Cessna Aircraft Company for their invaluable expertise during the light fixed-wing aircraft crash tests.

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