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NASA/FAA General Aviation Crash Dynamics Program—A Status Report

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The objective of the Langley Research Center general aviation crash dynamics program is to develop technology for improved crash safety and occupant survivability in general aviation aircraft. The program involves three basic areas of research: controlled full-scale crash testing, nonlinear structural analyses to predict large deflection elasto-plastic response, and load attenuating concepts for use in improved seat and subfloor structure. Both analytical and experimental methods are used to develop expertise in these areas. Analyses include simplified procedures for estimating energy dissipating capabilities and complex computerized procedures for predicting airframe response. These analyses are being developed to provide designers with methods for predicting accelerations, loads, and displacements of collapsing structure. Tests on typical full-scale aircraft and on full- and subscale structural components are being performed to verify the analyses and to demonstrate load attenuating concepts.

Introduction

IN 1972, NASA embarked on a cooperative effort with FAA and industry to develop technology for improved crashworthiness and occupant survivability in general aviation aircraft. The effort includes analytical and experimental work and structural concept development. The methods and concepts developed in this ongoing effort are expected to make possible future general aviation aircraft designs having enhanced survivability under specified crash conditions with little or no increase in weight and acceptable cost. The overall program is diagramed in Fig. 1. NASA's responsibility in this joint program is shown by shaded boxes, the FAA's role by unshaded boxes, and joint efforts by cross-hatched boxes.

Crashworthiness design technology is divided into three areas: environmental, airframe design, and component design. The environmental technology consist of acquiring and evaluating field crash data to support and validate parametric studies being conducted under controlled full-scale crash testing, the goal being to define a crash envelope within which the impact parameters allow human tolerable acceleration levels.

Airframe design has a twofold objective: to assess and apply current, on-the-shelf, analytical methods to predict structural collapse; and to develop and validate new and advanced analytical techniques. Full-scale tests are also used to verify analytical predictions, as well as to demonstrate improved load attenuating design concepts. Airframe design also includes the validation of novel load limiting concepts for use in aircraft subfloor designs.

Component design technology consists of exploring new and innovative load limiting concepts to improve the performance of the seat and occupant restraint systems by providing for controlled seat collapse while maintaining seat/occupant integrity. Component design also considers the design of nonlethal cabin interiors.

Langley's principal research areas in the joint FAA/NASA crash dynamics program are depicted in Fig. 2. These areas include full-scale crash testing; nonlinear finite element analysis; seat, occupant, and restraint simulation; and energy absorbing seat and structural design concepts. Subsequent sections deal with these topics.

Full-Scale Crash Testing

Full-scale crash testing is performed at the Langley Impact Dynamics Research Facility[1] shown in Fig. 3. This facility is the former Lunar Landing Research Facility modified for free-flight crash testing of full-scale aircraft structures and structural components under controlled test conditions. The basic gantry structure is 73 m (240 ft) high and 122 m (400 ft) long supported by three sets of inclined legs spread 81 m (267 ft) apart at the ground and 20 m (67 ft) apart at the 66 m (218 ft) level. A movable bridge with a pullback winch for raising the test specimen spans the top and transverses the length of the gantry.

Test Method

The aircraft is suspended from the top of the gantry by two swing cables and is drawn back above the impact surface by a pullback cable. An umbilical cable used for data acquisition is also suspended from the top of the gantry and connects to the top of the aircraft. The test sequence is initiated when the aircraft is released from the pullback cable, permitting the aircraft to swing pendulum style into the impact surface. The swing cables are separated from the aircraft by pyrotechnics just prior to impact, freeing the aircraft from restraint. The umbilical cable remains attached to the aircraft for data acquisition, but it also separates by pyrotechnics before it becomes taut during skid-out. The separation point is held relatively fixed near the impact surface, and the flight path angle is adjusted from 0 to 60 deg by changing the length of the swing cable. The height of the aircraft above the impact surface at release determines the impact velocity which can be varied 0 to 26.8 m/s (60 mph). The movable bridge allows the pullback point to be positioned along the gantry to insure that the pullback cables pass through the center of gravity and act at 90 deg to the swing cables.

To obtain flight path velocities in excess of 26.8 m/s (60 mph) a velocity augmentation method has been devised which uses wing-mounted rockets to accelerate the test specimen on its downward swing. Two Falcon rockets are mounted at each engine nacelle location and provide a total thrust of 77,850 N.

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Index categories: General Aviation; Structural Design; Structural Dynamics.

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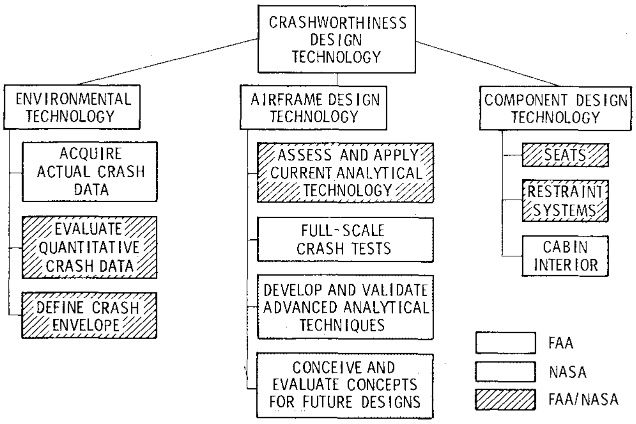


Fig. 1 Agency responsibilities in joint FAA/NASA general aviation crashworthiness program.

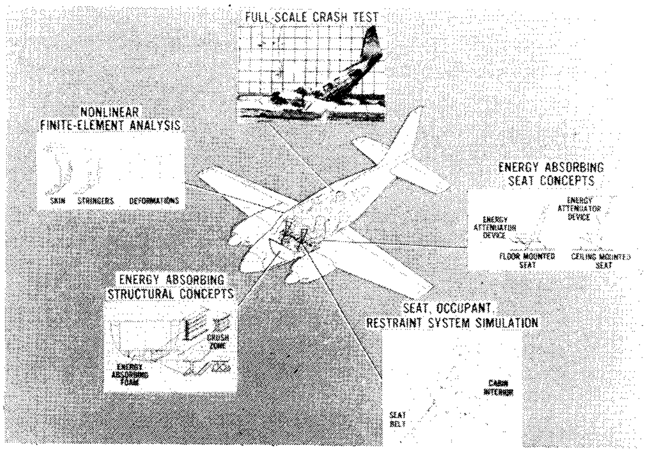


Fig. 2 Research areas in Langley general aviation crash dynamics program.

The aircraft is released after rocket ignition, and the rockets continue to burn during most of the downward acceleration trajectory but are dormant at impact. The velocity augmentation method provides flight path velocities of 26.8-44.7 m/s (60-100 mph) depending upon the number and burn time of the rockets used.

Instrumentation

Data acquisition from full-scale crash tests is accomplished with extensive photographic coverage, both interior and exterior to the aircraft using low-, medium-, and high-speed cameras and with onboard strain gages and accelerometers. The strain gage type accelerometers (range of 250 and 750 g at 0-2000 Hz) are the primary data generating instruments, and are positioned in the fuselage to measure accelerations both in the normal and longitudinal directions to the aircraft axis. Instrumented anthropomorphic dummies (National Highway Traffic Safety Administration Hybrid II) are on board all full-scale aircraft tests conducted at Langley. The location and framing rate of the cameras are discussed in Ref. 1. The restraint system arrangement and type of restraint used vary from test to test.

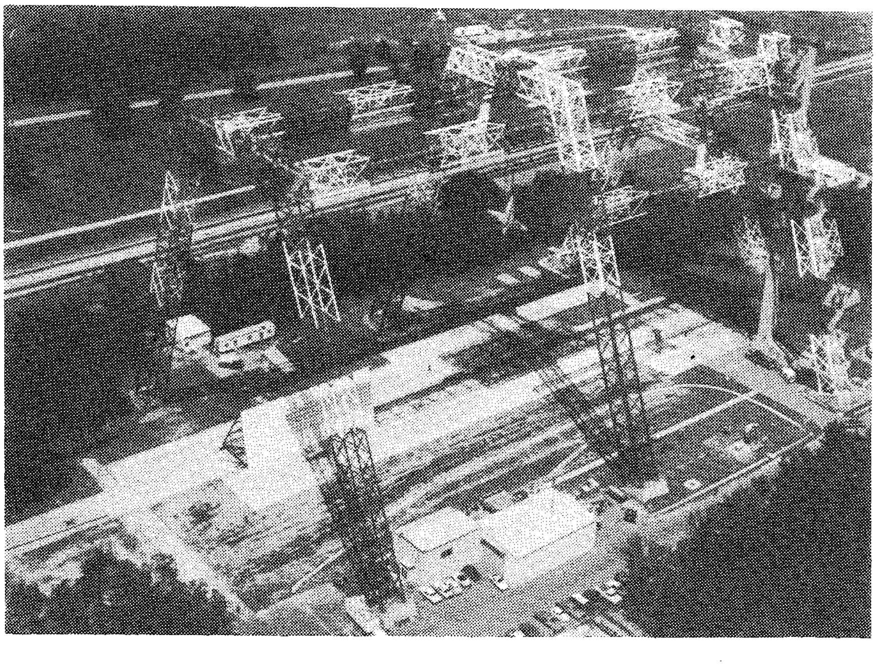
Tests Conducted

A chronological summary of the full-scale crash tests conducted at the Impact Dynamics Research Facility is represented in Fig. 4. The shaded symbols are crash tests that have been conducted, the open symbols are planned crash tests. Different symbols represent different types of aircraft under different impact conditions; for example, ○ represents a twin-engine specimen impacting at 26.8 m/s (60 mph) while △ represents the same twin-engine specimen, using the velocity augmentation method, impacting at 40.2 m/s (90 mph). Various types of aircraft have been successfully crash tested at Langley from 1974 through 1978 including CH-47 helicopters, high and low wing single-engine aircraft, and aircraft fuselage sections. Data from these tests are presented in Refs. 2-6. The aircraft fuselage section tests are vertical drop tests conducted to simulate full-scale aircraft cabin sink rates experienced by twin-engine aircraft tested earlier. The response of the aircraft section, two passenger seats, and two dummies are being simulated analytically (see section on Nonlinear Analysis). Some single-engine crash tests were conducted using a dirt impact surface but most were conducted on a concrete surface. The dirt embankment was 12.2 m (40 ft) wide, 24.4 m (80 ft) long, and 1.2 m (4 ft) in depth. The dirt was packed to the consistency of a ploughed field with a CBR of approximately 4. The variation of full-scale crash test parameters is not complete and does not consider such effects as aircraft overturning, and cartwheeling, fire, or tree and obstacle impact.

Controlled Crash Test and Las Vegas Accident

On Aug. 30, 1978, a twin-engine Navajo Chieftain, carrying a pilot and nine passengers crash landed in the desert

Fig. 3 Langley Impact Dynamics Research Facility.



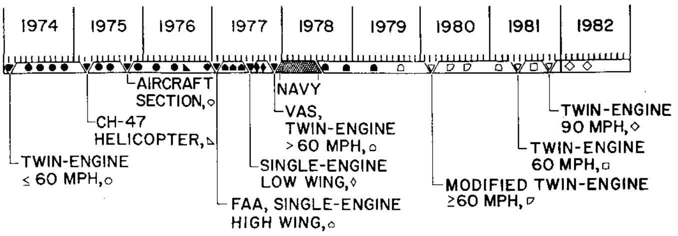


Fig. 4 General aviation crash test schedule.

Fig. 5a Controlled crash.

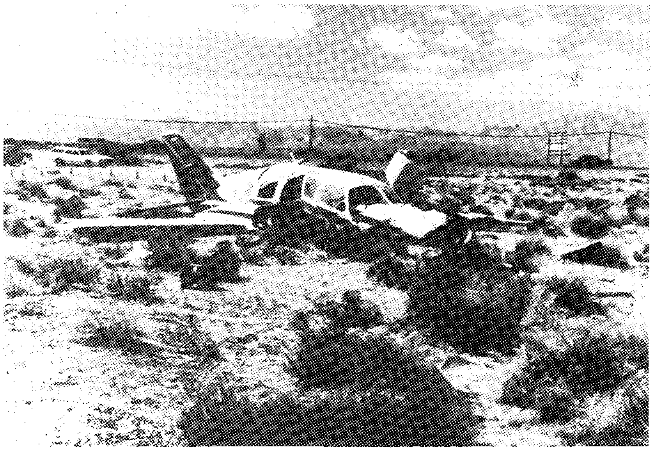


Fig. 5b Las Vegas accident.

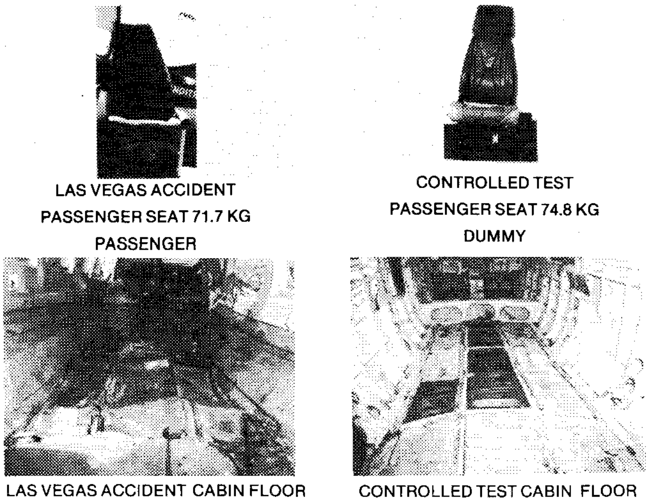


Fig. 6 Damage comparison between controlled test and Las Vegas accident.

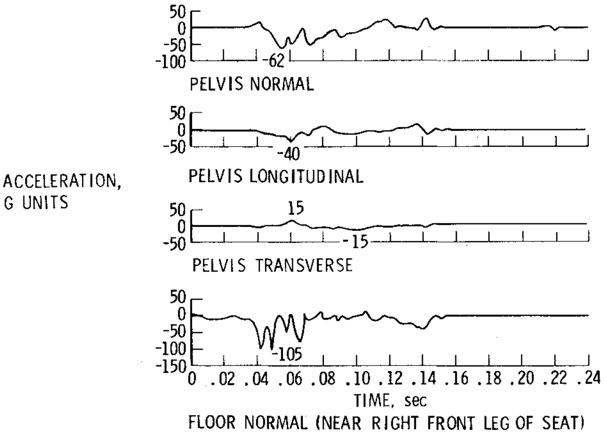


Fig. 7 Acceleration time histories from first passenger and floor of controlled crash test (−12deg pitch, 41.4 m/s flight path velocity with 5 deg left roll, 1 deg yaw).

shortly after taking off from the North Las Vegas Airport. All 10 persons on board were killed. A comparative study of this Navajo Chieftain crash and a similar NASA controlled crash test was made. The controlled crash test chosen employed the velocity augmentation method wherein the aircraft reachs a flight path velocity of 41.4 m/s (92.5 mph) at impact. The pitch angle was −12 deg, with a 5 deg left roll and 1 deg yaw. Figure 5 shows photographs of the two aircraft. The NASA specimen is a twin-engine pressurized Navajo, which carries six to eight passengers, and although the cabin is shorter in length it is similar in structural configuration to the Chieftain.

Structural damage to the seats and cabin of the Navajo Chieftain and to the seats and cabin of the NASA test specimen are shown for illustrative purposes in Fig. 6. Much more corroborating structural damage is contained in Ref. 7. It is conjectured that the Chieftain contacted the nearly level desert terrain at a location along the lower fuselage on the right side opposite the rear door. An instant later, the rest of the fuselage and the level right wing impacted. The Chieftain's attitude just prior to impact is assumed, therefore, to have the following impact attitude: pitched up slightly, rolled slightly to the right, and yawed to the left. The two aircraft differ in roll attitude at impact but are comparable. The structural damage to the cabin of the Chieftain was much greater than that exhibited by the NASA controlled crash test under correspondingly similar impact attitudes. The damage pattern to the standard passenger and crew seats of the Chieftain was similar to that in the NASA tests, but generally exhibited more severe distortion. The damage patterns suggest similar basic failure modes and, in the case of the seat distortion, a flight path impact velocity in excess of 41.4 m/s (92.5 mph) for the Chieftain. Acceleration time histories from the first passenger seat and floor of the controlled NASA crash test are shown in Fig. 7 where the first passenger corresponds to the damaged seat shown in Fig. 6.

Because of the similarity in the damage patterns exhibited by seats 6 and 8 of the Chieftain and the first passenger seat of the NASA controlled test, generalized conclusions can be drawn relative to certain seat accelerations experienced by those passengers in the Chieftain. The peak pelvic accelerations of passengers 6 and 8 in the Chieftain accident were probably in excess of 60 *g* normal (to aircraft axis), 40 *g* longitudinal, and 10 *g* transverse.

Nonlinear Crash Impact Analysis

The objective of the analytical efforts in the crash dynamics program is to develop the capability of predicting nonlinear geometric and material behavior of sheet-stringer aircraft structures subjected to large deformations and to demonstrate this capability by determining the plastic buckling and collapse response of such structures under implusive loadings. Two specific computer programs are being developed, one focused on modeling concepts applicable to large plastic deformations of realistic aircraft structural components, and the other a versatile seat/occupant program to simulate occupant response. These two programs are discussed in the following sections.

Plastic and Large Deflection Analysis of Nonlinear Structures (PLANS)

Description

For several years Langley has been developing a sophisticated structural analysis computer program which includes geometric and material nonlinearities.[8,9] PLANS is a finite element program for the static and dynamic nonlinear analysis of aircraft structures. The PLANS computer program is capable of treating problems which contain bending and membrane stresses, thick and thin axisymmetric bodies, and general three-dimensional bodies. PLANS, rather than being a single comprehensive computer program, represents a collection of special-purpose computer programs or modules, each associated with a distinct physical problem. Using this concept, each module is an independent finite element computer program with its associated element library. All the programs in PLANS employ the "initial strain" concept within an incremental procedure to account for the effect of plasticity and include the capability for cyclic plastic analysis. The solution procedure for treating material nonlinearities (plasticity) alone reduces the nonlinear material analysis to the incremental analysis of an elastic body of identical shape and boundary conditions, but with an additional set of applied "pseudo loads." The advantage of this solution technique is that it does not require modification of the element stiffness matrix at each incremental load step. Combined material and geometric nonlinearities are included in several of the modules and are treated by using the "updated" or convected coordinate approach. The convected coordinate approach, however, requires the reformation of the stiffness matrix during the incremental solution process. After an increment of load has been applied, increments of displacement are calculated and the geometry is updated. In addition to calculating the element stresses, strains, etc., the element stiffness matrices and mechanical load vector are updated because of the geometry changes and the presence of initial stresses. A further essential ingredient of PLANS is the treatment of dynamic nonlinear behavior using the DYCAST module. DYCAST incorporates various time integration procedures, both explicit and implicit, as well as the inertia effects of the structure.

Comparison with Experiment

PLANS is currently being evaluated by comparison with experimental results on simplified structures. In the order of increasing complexity these structures are: an axial compression of a circular cylinder; a tubular structure composed of 12 elements with symmetric cross sections joined at common rigid joints; an angular frame composed of asymmetric angles and bulkheads with nodal eccentricities at the rigid joints; and the same angular frame covered with sheet material. Static and dynamic analyses of these structures loaded into the large deflection plastic collapse regime have been conducted with PLANS and compared with experimental data in Ref. 10 and reported on in Ref. 11. Presently an analytical simulation of a vertical drop test of an aircraft section is being compared with experimental full-scale crash data. Preliminary computer deformation patterns are shown in Fig. 8 using an implicit Newmark-Beta integration algorithm. The use of implicit time integration methods, for this particular nonlinear problem, resulted in more practical time steps than was previously obtained using an explicit Adams Predictor-Corrector algorithm. The results of this study are reported in Ref. 12.

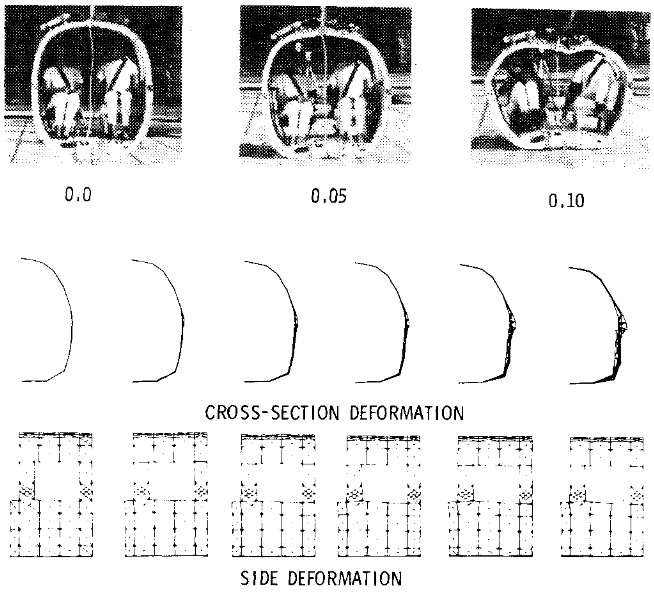


Fig. 8 Computer deformation patterns of an aircraft section impacting rigid surface with vertical velocity of 9.1 m/s (30 ft/s).

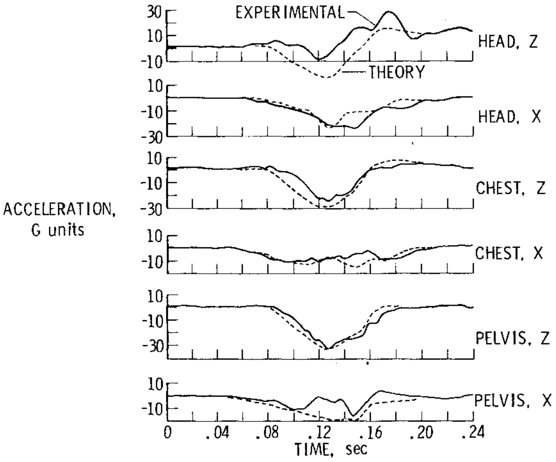


Fig. 9 Experimental and computer dummy accelerations for the −30 deg, 27 m/s full-scale crash test.

Modified Seat Occupant Model for Light Aircraft (MSOMLA)

Description

Considerable effort is being expended in developing a good mathematical simulation of occupant, seat, and restraint system behavior in a crash situation. MSOMLA was developed from a computer program SOMLA funded by the FAA as a tool for use in seat design.[13] SOMLA is a three-dimensional seat, occupant, and restraint program with a finite element seat and an occupant modeled with 12 rigid segments joined together by rotational springs and dampers at the joints. The response of the occupant is described by Lagrange's equations of motion with 29 independent generalized coordinates. The seat model consists of beam and membrane finite elements.

SOMLA was used previously to model a standard seat and dummy occupant in a NASA light aircraft section vertical drop test. During this simulation, problems were experienced with the seat model whenever the yield stress of an element was exceeded. Several attempts to correlate various finite element solutions of the standard seat with OPLANE-MG, DYCAST, and SOMLA, using only beam and membrane elements, to experimental data from static vertical seat loading tests were only partially successful. Consequently, to expedite the analysis of the seat/occupant, the finite element seat in SOMLA was removed and replaced with a springdamper system. Additional modifications to SOMLA added nonrigid occupant contact surfaces (nonlinear springs) and incorporated a three-dimensional computer graphics display. This modified SOMLA is called MSOMLA. A more complete discussion of MSOMLA, its computer input requirements, and additional experimental analytical comparisons can be found in Ref. 14.

Comparison with Experiment

A comparison of full-scale crash test data from the −30 deg, 26.8 m/s (60 mph) crash test and occupant simulation using MSOMLA is presented in Fig. 9. The comparisons between measured and computed acceleration pulses are excellent considering the seat and occupant were subjected to forward, normal, and rotational acclerations. This comparison, using full-scale crash data, demonstrates the versatility of the program's simulation capability.

Crashworthy Seat and Subfloor Structure Concepts

The development of structural concepts to limit the load transmitted to the occupant is another research area in Langley's crashworthiness program. The objective of this research is to attenuate the load transmitted by a structure either by modifying its structural assembly, changing the geometry of its elements, or adding specific load limiting devices to help dissipate the kinetic energy. Recent efforts in this area at Langley have concentrated on the development of crashworthy aircraft seat and subfloor systems.

The concepts of available stroke are paramount in determining the load attenuating capabilities of different design concepts. Shown in Fig. 10 are the three load-attenuating areas which exist between an occupant and the impact surface during vertical descent: the landing gear, the cabin subfloor, and the aircraft seat. Attenuation provided by the landing gear will not be included in this discussion since it is more applicable to helicopter crash attenuators. Using the upward human acceleration tolerance of 25 *g* as established in Ref. 15, a relationship between stroke and vertical descent velocity can be established for a constant stroking device which fully strokes in less than the maximum time allowable (0.10 s) for human tolerance. This relationshop is illustrated in Fig. 10. Under the condition of a constant 25 *g* deceleration stroke the maximum velocity decrease for the stroking available is 12.2 m/s (40 ft/s) for the seats and 8.2 m/s (27 ft/s) for the subfloor (assuming 30 and 15 cm [12 and 6 in.] in general for a twin-engine light aircraft). For a combination of stroking seat and stroking subfloor, the maximum velocity decrease becomes 15.2 m/s (50 ft/s). These vertical sink rates are comparable to the Army Design Guide recommendations[15] for crashworthy seat design.

Seat

A ceiling-mounted load limiting seat, shown in Fig. 11a, is similar in design to a troop seat designed for Army helicopters[16] and weighs 9 kg (20 lbm). This seat is equipped with two wire bending load limiters which are located inside the seat back and are attached to the cabin ceiling to limit both vertical and forward loads. Two additional load limiters are attached diagonally between the seatpan at the front and the floor at the rear to limit forward loads only. The seatpan in the design remains parallel to the floor while stroking. The length of the stroke is approximately 30 cm (12 in.) in the vertical direction and 18 cm (7 in.) in the forward. The wire bending load limiter is simply a wire element, mounted to pass over a three-wheeled trolley, housed in a tubular casing. In operation, the wire bending trolley, which is attached to the top housing sleeve, translates a wire loop along the axis of the wire during seat stroking at a constant force. This type of load limiter provides a near constant force during stroking, thus making it possible to absorb maximum loads at human tolerance levels over a given stroking distance.

The floor-mounted load limiting seat weighs 10 kg (23 lbm) and employs two wire bending load limiters which are attached diagonally between the seatpan at the top of the rear strut and the bottom of the front legs. While stroking, the rear struts pivot on the floor thus forcing the load limiter housing to slide up inside the seatback (Fig. 11b). The third load limiting concept tested uses a rocker swing stroke to change the attitude of the occupant from an upright seated position to a semi-supine position.

In dynamic tests conducted at CAMI (FAA Civil AeroMedical Institute), the sled or carriage is linearly accelerated along rails to the required velocity and brought to rest by wires stretched across the track in a sequence designed to provide the desired impact loading to the sled. A hybrid II,

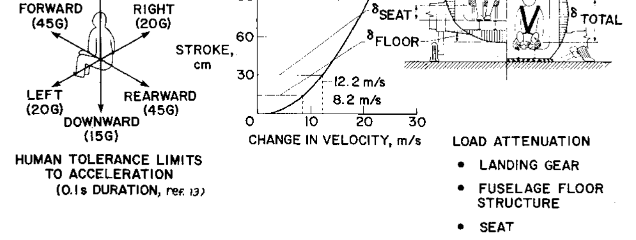


Fig. 10 Available stroke for energy dissipation in typical twin engine general aviation aircraft.

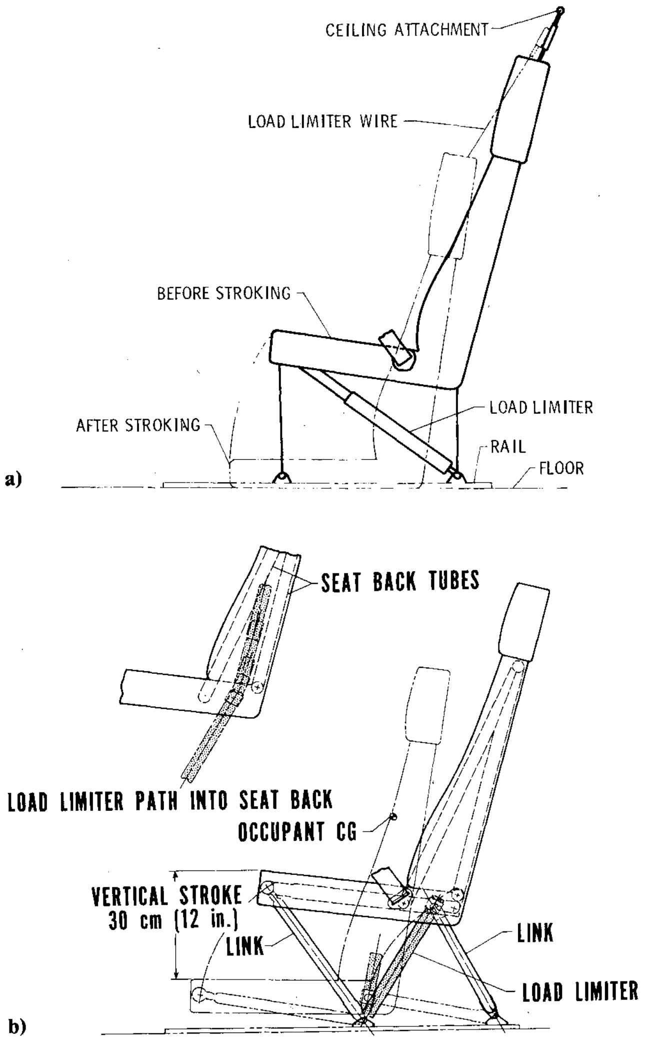
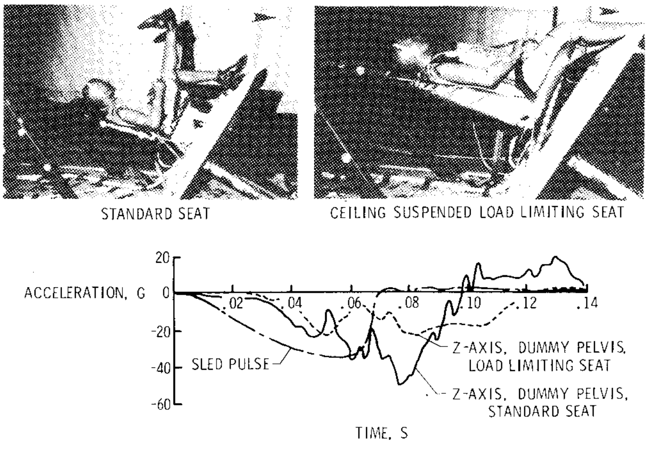
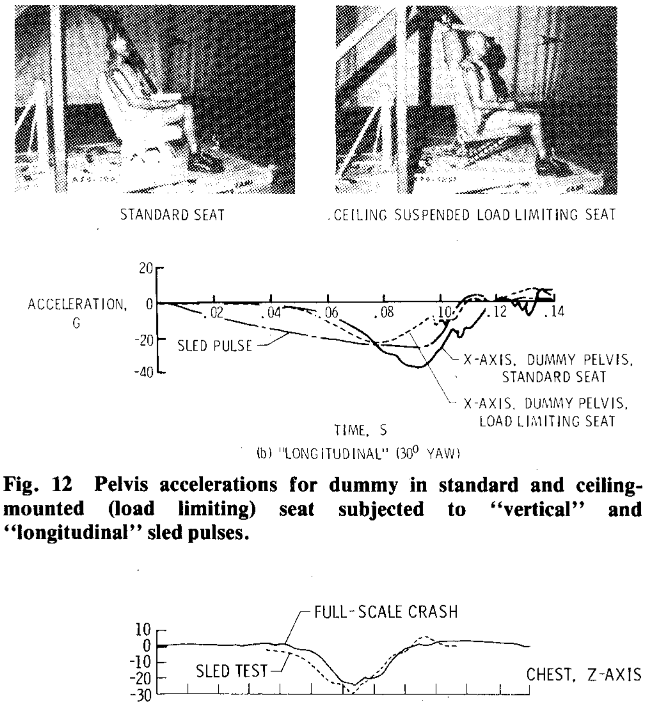


Fig. 11 Passenger seats with wire bending load limiters. a) Ceiling-supported passenger seat; b) Floor-supported passenger seat.



(a) "VERTICAL" (-30° PITCH, 10° ROLL)



(b) "LONGITUDINAL" (30° YAW)

Fig. 12 Pelvis accelerations for dummy in standard and ceiling-mounted (load limiting) seat subjected to "vertical" and "longitudinal" sled pulses.

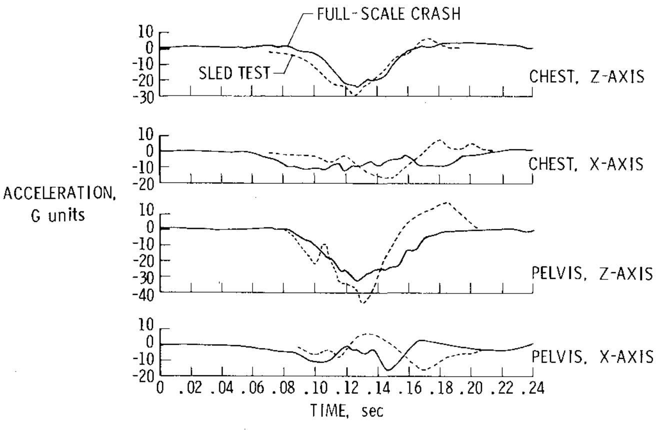


Fig. 13 Dummy accelerations from sled test and from a full-scale crash test under similar impact conditions.

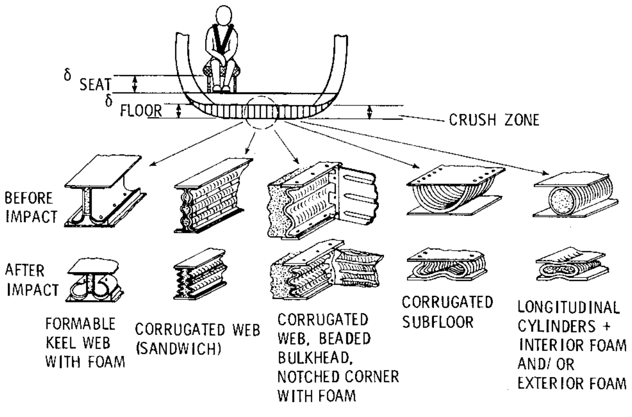


Fig. 14 Load limiting subfloor concepts.

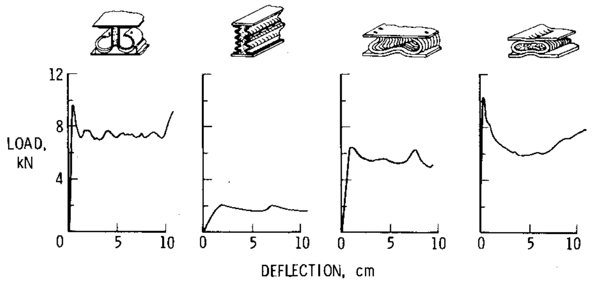


Fig. 15 Load deflection curves for load limiting subfloor concepts.

50th percentile dummy instrumented with accelerometers loaded the seats and restraint system on impact. The restraint system for these seats consisted of continuous, one-piece, lap belt and double shoulder harness arrangement.

Time histories of dummy pelvis accelerations recorded during two different impact loadings are presented in Fig. 12 with the dummy installed in a standard seat and in a ceiling-mounted, load limiting seat. The vertical impulse of Fig. 12a positioned the seats (and dummy) to impact at a pitch angle (angle between dummy spine and direction of sled travel) of −30 deg and a roll angle of 10 deg. In the "longitudinal" pulse (Fig. 12b) the seats were yawed 30 deg to the direction of sled travel. The sled pulses are also included in the figure and represent the axial impulse imparted to the inclined dummies. The x- and z-axis of the dummy are local axes perpendicular and parallel to its spine, respectively. The figure shows that for both impact conditions the load limiting seat in general provided a sizable reduction in pelvis acceleration over those recorded during similar impacts using the standard seat.

The impact condition associated with a dummy passenger in one of the full-scale NASA crash tests were quite similar to those defined by the sled test of Fig. 12a, particularly in terms of velocity change, thereby permitting a gross comparison of their relative accelerations. Figure 13 shows that comparison. Although the dummy acceleration traced from the two tests are similar in both magnitude and shape, some phase shift is evident. This agreement suggests that sled testing provides a good approximation of dummy/seat response in full-scale aircraft crashes.

Subfloor Structure

The subfloor structure of most medium size general aviation aircraft offers about 15-20 cm (6-8 in.) of available stroking distance, which suggests the capability to introduce a velocity change of approximately 8.2 m/s (27 ft/s) (see Fig. 10). Aside from that necessary for routing hydraulic and electrical conducts some volume is available within the subfloor for energy dissipation through controlled collapse. A number of energy absorbing subfloor concepts have been advanced and Fig. 14 presents sketches of five prominent candidates. The first three concepts, moving from left to right, would replace existing subfloor structure and allow for: 1) the metal working of floor beam webs filled with energy dissipating foam; 2) the collapsing of precorrugated floor beam webs filled with foam; or 3) the collapsing of precorrugated foam-filled webs interlaced with a notched lateral bulkhead. The remaining two concepts eliminate the floor beam entirely and replace it with a precorrugated canoe (the corrugations running circumferentially around the cross-section) with energy dissipating foam exterior to the canoe; and foam-filled Kevlar cylinders supporting the floor loads.

These five promising concepts are being tested both statically and dynamically to determine their load deflection characteristics. Some examples of the static load deflection behavior obtained from four of the five concepts are shown in Fig. 15.

After repeated testing and sizing (geometric optimizing) of these load limiting devices, the three most promising will be chosen for integration into complete subfloor units to be used as the subfloors in aircraft sections. Drop tests of these aircraft sections will then be conducted at velocities up to 15.2 m/s (50 ft/s) to evaluate their performance as compared to unmodified subfloor structure. A static crush test will also be performed on one of each of the subfloor units.

Conclusion

Langley Research Center has initiated a crash safety program that will lead to the development of technology to define and demonstrate new structural concepts for improved crash safety and occupant survivability in general aviation aircraft. This technology will make possible the integration of crashworthy structural design concepts into general aviation design methods and will include airframe, seat, and restraint system concepts that will dissipate energy and properly restrain the occupants within the cabin interior. Current efforts are focused on developing load limiting aircraft components needed for crash load attenuation, in addition to considerations of modified seat and restraint systems as well as structural airframe reconfigurations. The dynamic nonlinear behavior of these components is being analytically evaluated to determine their dynamic response and to verify design modifications and structural crushing efficiency. Seats and restraint systems with incorporated deceleration devices are being studied that will limit the load transmitted to the occupant, remain firmly attached to the cabin floor, and adequately restrain the occupant from impact with the cabin interior. Full-scale mockups of structural components incorporating load limiting devices are being used to evaluate their performance and provide corroboration to the analytical predictive techniques.

In the development of aircraft crash scenarios, a set of crash test parameters are to be determined from both FAA field data and Langley controlled crash test data. The controlled crash test data will included crashes at velocities comparable with the stall velocity of most general aviation aircraft. Close cooperation with other governmental agencies is being maintained to provide inputs for human tolerance criteria concerning the magnitude and duration of deceleration levels and for realistic crash data on survivability. The analytical predictive methods developed herein for crash analyses are to be documented and released through COSMIC.

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