# CRASH SURVIVABILITY ANALYSIS OF COMMUTER AIRCRAFT SEATS AND RESTRAINT SYSTEMS

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## Introduction

Although crashworthiness has been considered during design of several current military helicopters, the design of aircraft has traditionally been based on airworthiness, or performance in flight. Occupant protection provisions in civil aircraft have been generally limited to enhancement of post-impact survivability through emergency evacuation and flammability requirements, and seats and restraint systems have merely been designed to comply with specified static strength requirements. However, during the past five years the U.S. Federal Aviation Regulations (FARs) have been significantly upgraded with respect to seat/restraint system strength and attachment of seats to the aircraft structure. Human tolerance levels and aircraft structural characteristics have been considered in development of the new standards. First, in accordance with the recommendations of a joint industry/government/academic committee, FAR Part 23, which deals with small airplanes, was amended to require dynamic testing of seats and restraint systems for "normal and utility" (general aviation) aircraft with capacity for fewer than 10 passengers (1). Performance criteria are similar to those specified by the U.S. Department of Transportation for automobiles but also include a limit on "pelvic force," in order to prevent spinal injuries which may be caused by the vertical component of impact force. The amended regulations apply to all general aviation aircraft manufactured since 1986. Subsequently, FAR Part 25 for transport category aircraft was amended to require dynamic testing of seats and restraint systems, although to less severe acceleration levels in order to allow for the larger structures of those aircraft (2).

A third category of aircraft, one that has not been affected by the rule modifications, is the commuter type, which typically seats 10 to 20 passengers, is closer in size to general aviation aircraft than to large transports, and is also covered by FAR Part 23. The Federal Aviation Administration (FAA) is currently involved in development of a proposal to amend the regulations for commuter aircraft. In support of this effort, a research program that includes full-scale aircraft drop tests, sled tests of seats, and computer simulations is being conducted. The objective of this paper is to describe a set of test conditions and acceptance criteria presently under consideration and the concurrent research program for their evaluation.

## Commuter Aircraft Seat Dynamic Test Requirements

Although a formal proposal for amending the commuter aircraft regulations has not yet been issued, the FAA has chosen as a starting point two dynamic tests and a set of related acceptance criteria similar to those that have already been adopted for general aviation. For the first test, the seat is to be pitched upward 60 deg on the sled, so that the impact velocity of 9.5 m/s (31 ft/s) has forward and downward components with respect to the seat. The deceleration pulse is to have a peak value of at least 32 g, which is to occur not more than 0.03 s after impact. In the second test, the seat is positioned upright, but is to be yawed 10 deg with respect to the impact vector. The impact velocity is to be 12.8 m/s (42 ft/s), and the peak deceleration, 26 g, occurring not more than 0.05 s after impact. The two test conditions are illustrated in Fig. 1. In order to account for the effects of the floor deformation that may occur in an accident, the floor rail on one side of the seat must be rotated 10 deg about a lateral (pitch) axis; the other rail must be rotated 10 deg about a longitudinal (roll) axis, as illustrated in Fig. 2.

Both tests use a 50th percentile anthropomorphic dummy; the dummy must include provision for measurement of pelvic force, the force that is transmitted to the dummy pelvis through the spinal column. By means of extensive experimentation using modified dummies and comparison of those test results with injury data from military ejection seats, this

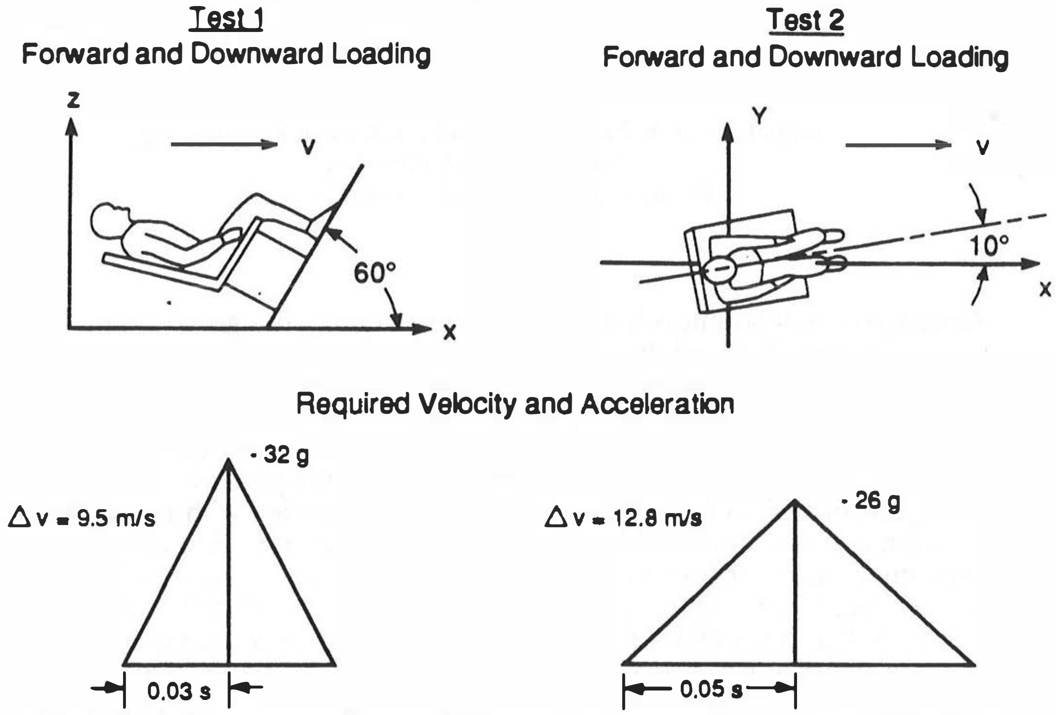


Fig.1 Dynamic tests under consideration for commuter-category aircraft seats.

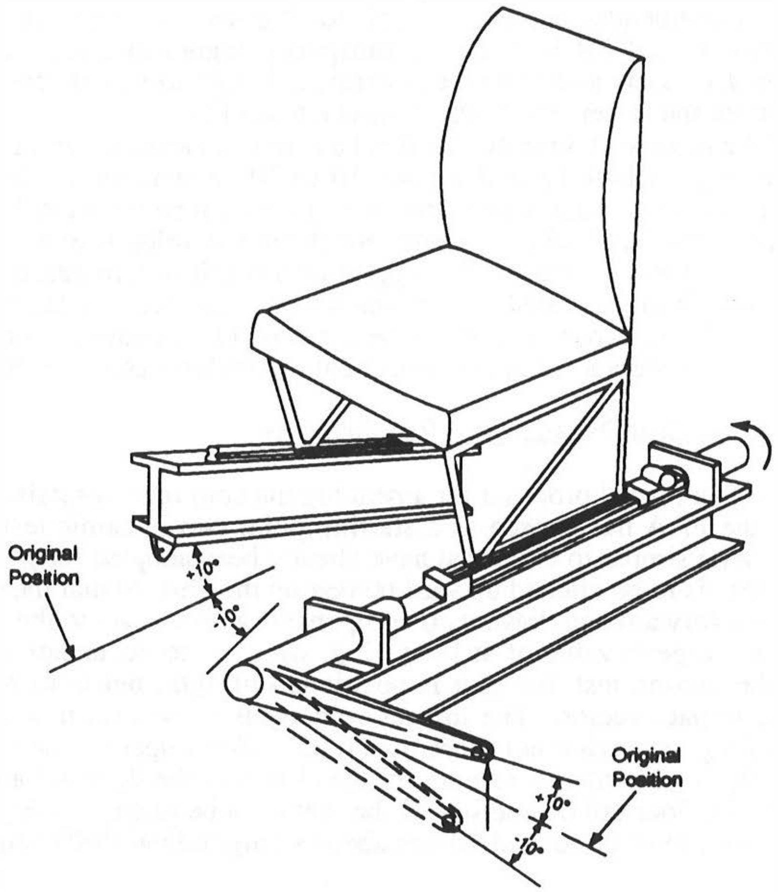


Fig. 2 Floor warping requirements under consideration for commuter aircraft seat tests.

compressive force has been related to the potential for injury to the lumbar spine due to an upward acceleration of the body (3).

Suggested pass/fail criteria include a requirement that, although deformation of the seat structure is permitted, attachments of the seat and restraint system must both remain intact. Specific injury-related limits are a HIC of 1000, a femur load of 10 kN (2250 lb), and a pelvic compressive load of 6.67 kN (1500 lb). Upper torso restraint is required only for the front (pilot) seats, where the load in a single shoulder belt should not exceed 7.78 kN (1750 lb), or the sum of the loads in dual straps, 8.90 kN (2000 lb).

## Full-Scale Aircraft Crash Testing

In order to investigate the applicability and practicality of proposed FAR amendments for commuter-type aircraft, the FAA Technical Center embarked on a program of testing and analysis. Because the vertical component of impact forces can be a significant part of the injurious environment in an airplane crash, testing of full-scale aircraft began with vertical drops to determine the nature of vertical accelerations at the floor. The first two tests used airplanes at the smaller end of the commuter category, an Aero Commander 680E and a Cessna 421. Fully instrumented dummies were placed in all seats. Accelerometers were installed on the floor at major frame locations. Each aircraft was dropped in a flat configuration onto a rigid platform from a height of 3.4 m, so as to achieve an impact velocity of 8.2 m/s, equal to the vertical component of the combined longitudinal/vertical test.

In the Aero Commander high-wing aircraft, the wing assembly crushed down into the cabin up to a maximum penetration of more than 50 cm at a time of 0.18 s after initial impact, as shown in the photograph of Fig. 3. After elastic recovery of the structure, the cabin interior height under the wing was found to have been reduced by more than 30 cm. The subfloor structure in the center of the aircraft crushed less than 1.5 cm so that the floor between the inboard seat tracks remained nearly flat, as shown in Fig. 4. Outboard sections of the floor were pushed downward by the fuselage sidewall. The outboard seat track on the right side of the aircraft, moving with the floor, was pushed down approximately 4.3 cm relative to the center floor section and rotated 16 deg about its own axis. On the left side of the aircraft, the outboard seat track was pushed downward approximately 3.8 cm and rotated about 6 deg. The seats (in the absence of longitudinal loading) remained in place on the tracks, although attachment fittings were bent and the seat back structure on two of them failed under the aftward component of force from the dummy. The acceleration measured on the aircraft floor varied from one location to another but, when filtered in accordance with SAE Recommended Practice J211 (4), exhibited peak values between 20 and 50 g, in the range of the proposed 32-g seat test requirement.

The low-wing Cessna aircraft did not experience any significant deformation of the cabin structure in the flat drop. In fact, the stiff wing structure limited crushing of the subfloor structure to less than 2.5 cm but caused accelerations that exceeded 70 g.

## Analysis of Aero Commander Seat Response to Vertical Drop

The response of existing commuter aircraft seat designs to a range of crash conditions has been examined using the SOM-LA computer program, which was developed under FAA sponsorship (5,6). This program combines an 11-mass, 29 degree-of-freedom model of the vehicle occupant with a finite element model of the seat structure. As a check on validity of the seat model, the conditions of the Aero Commander vertical drop test were first simulated, using the acceleration measured at the floor, and the predicted seat response was compared with test results.

The SOM-LA finite element model of the Aero Commander seat structure, which consists mainly of welded steel tubing, is shown in Fig. 5. Nodes 1 through 4 are attached to the floor. The lap belt is attached to the seat at nodes 17 and 18. During simulation of the 8.2-m/s drop, the yield strength of the steel frame was reached at approximately 0.030 s in the 1.9-cm-diameter tubular members that run along the left and right sides of the seat (at nodes 19 and 20). A maximum force of 8670 N exerted by the dummy downward on the seat was predicted at a time of 0.035 s. At that time, the side tubes were bowed downward approximately 1.3 cm at nodes 19 and 20, as shown in the side view presented as Fig. 6. All of the single-passenger

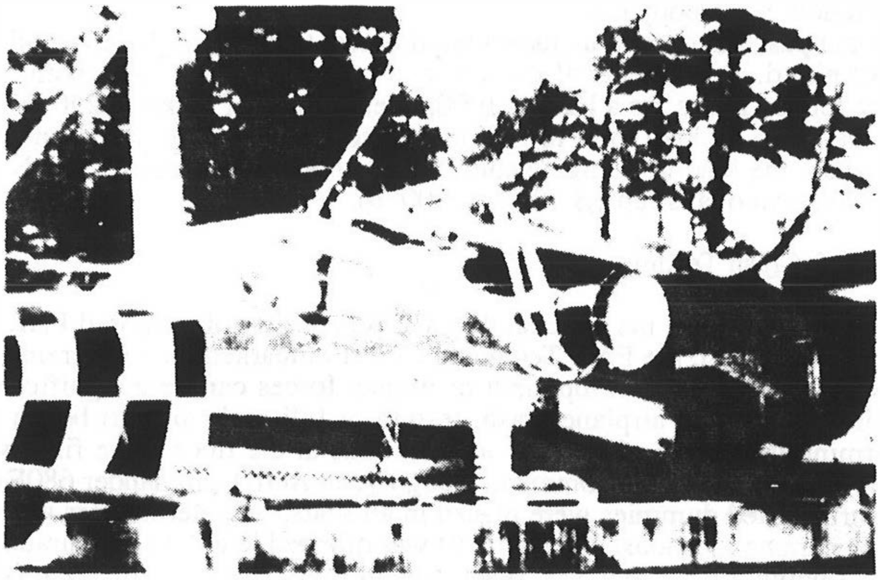

Fig. 3 Aero Commander 680E aircraft during 8.2-m/s drop.

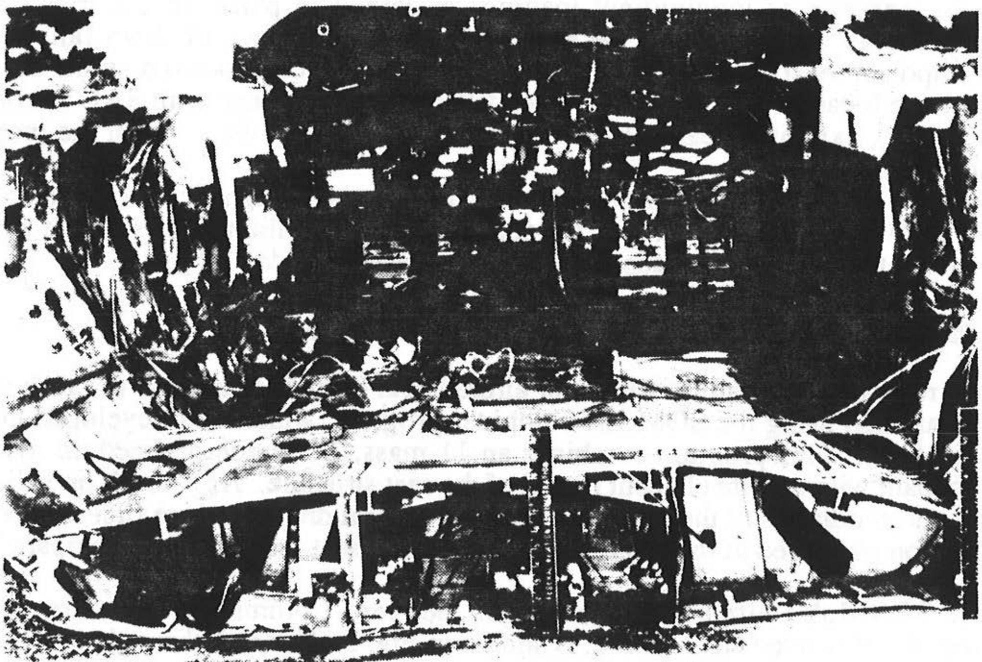

Fig. 4 Forward section of Aero Commander 680E aircraft following 8.2-m/s

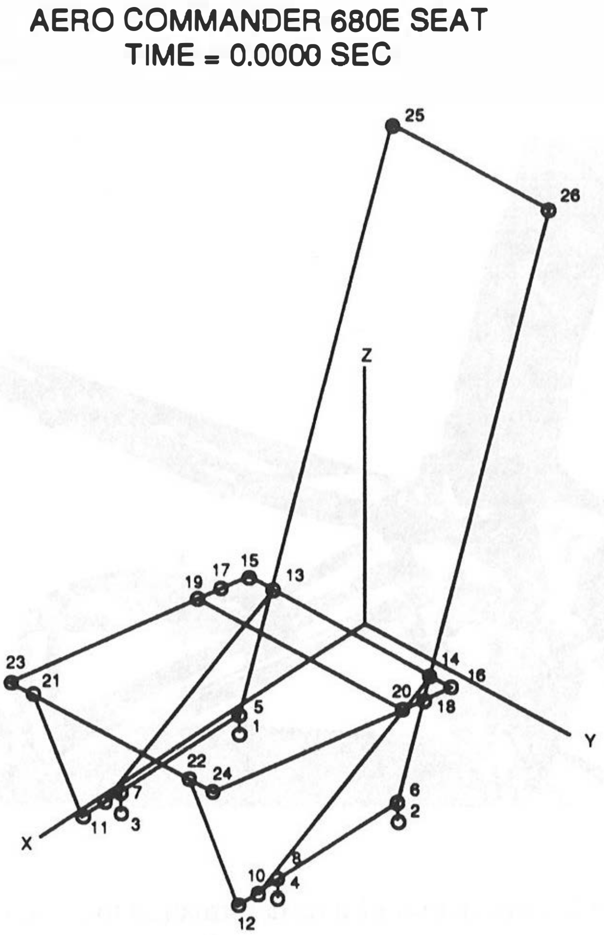


Fig. 5 Finite element model of Aero Commander seat structure.

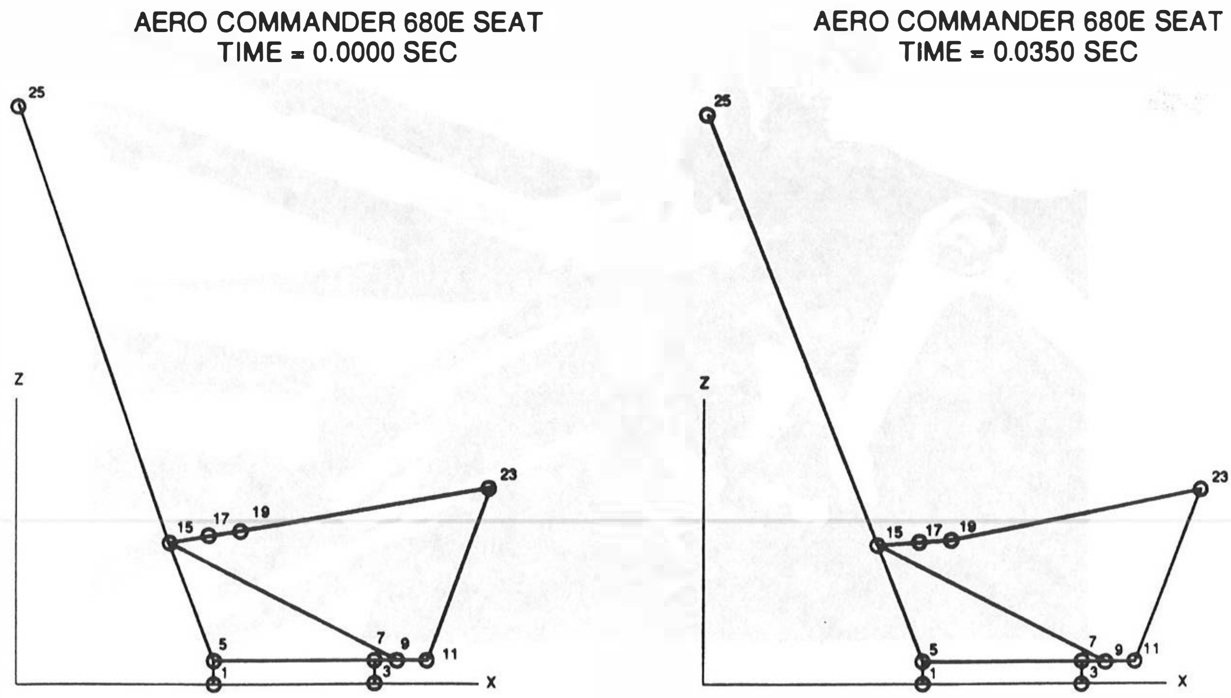


Fig. 6 Aero Commander seat structure deformation predicted for 8.2-m/s drop.

seats installed in the aircraft during the test experienced deformation in the same region of the frame as predicted. Typical deformation can be seen in Fig. 7. Two of the seat frames bent enough to crack in the vicinity of nodes 19 and 20 on the model, as shown in Fig. 8.

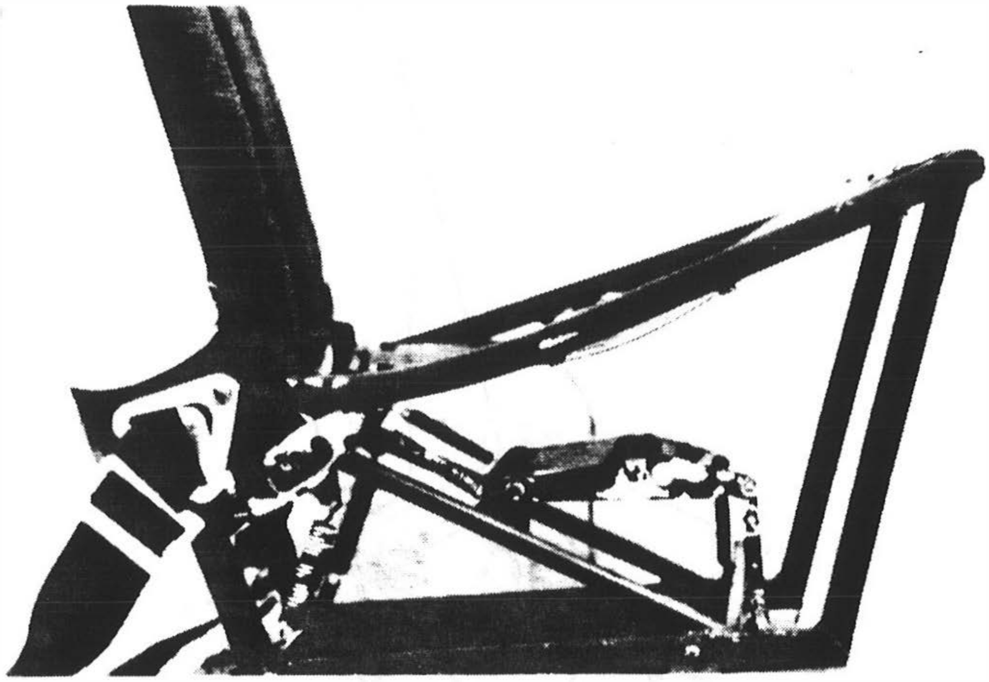

Fig. 7 Aero Commander seat frame deformation following 8.2-m/s drop.

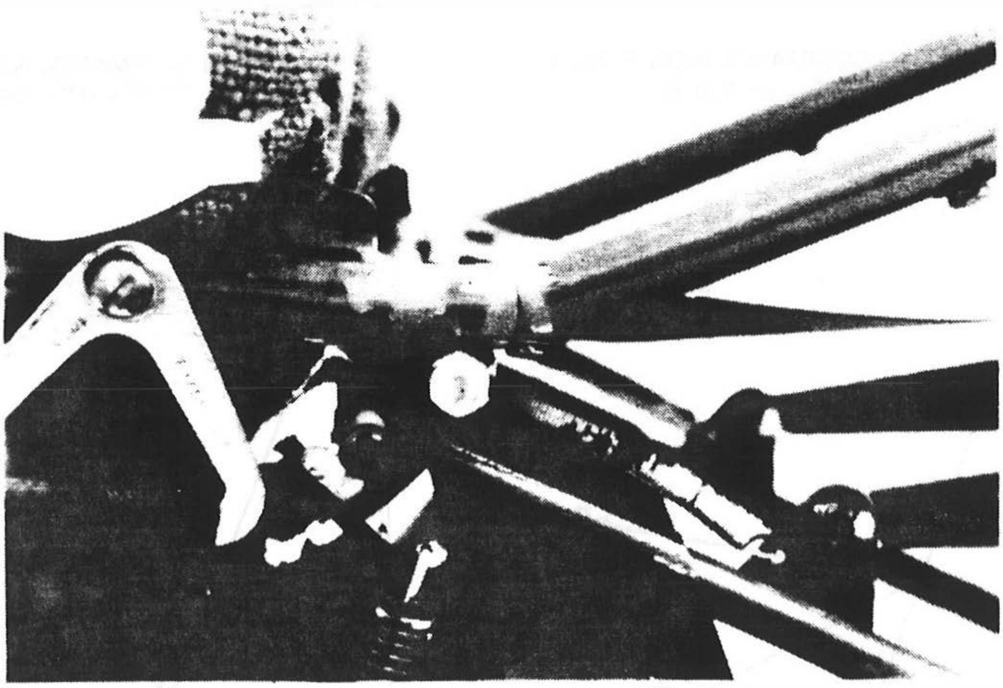

Fig. 8 Cracking in region of seat frame deformation, Aero Commander seat.

Analysis of Proposed Test Conditions

Following successful simulation of the Aero Commander seats that had been installed in the drop test, the SOM-LA program was used to analyze the response of three existing commuter aircraft seat designs to the proposed dynamic test conditions. The first was the Aero Commander seat described in the preceding paragraphs; the others were the passenger seats used in two of the most widely used commuter aircraft, the Beechcraft 1900 and the Fairchild Metro III. The finite element models of the Beech and Metro seats are illustrated in Figs. 9 and 10. The Beech seat is attached to the aircraft at nodes 1, 2, 22, and 27; the Metro seat, at nodes 1, 2, 3, and 4. Results predicted for the dummy in both dynamic tests are summarized in Tables 1 and 2. No floor deformations were applied in the simulations, for attempts to apply the proposed floor warping requirements in the program caused failure of all three seat models in the vicinity of the attachment points. Furthermore, the SOM-LA program has the capability to bypass the finite element model and simulate a rigid seat, which maintains the plane surfaces that support the cushions in fixed positions in the aircraft. In order to demonstrate the rigidity of the seats and the need for energy absorption in their structures, this option was exercised using the Metro configuration, and its results are also included in Tables 1 and 2 for comparison. As noted in Table 1, the Aero Commander seat structure failed during simulation of test condition 1, prior to application of the full test pulse. Therefore, program execution was terminated before the dummy response reached peak values of accelerations and forces.

Table 1. Analysis Results for Test Condition 1

| Seat | Acceleration Pelvis (g) | Acceleration Chest (g) | Acceleration Head (g) | HIC | Pelvic Force (kN) | Neck Moment[1] (N-m) |
|---|---|---|---|---|---|---|
| Aero Cmdr[2] | 27.4 | 24.6 | 26.6 | 5. | -10.9 | -0/+62 |
| Beech 1900 | 39.3 | 54.7 | 55.4 | 284. | -15.5 | -72/+114 |
| Metro III | 48.1 | 56.6 | 57.4 | 269. | -16.8 | -43/+151 |
| Rigid | 47.6 | 57.9 | 58.2 | 268. | -16.9 | -43/+153 |

Notes: 1. Sign convention for bending moments: + = flexion; - = extension.
2. Aero Commander seat structure failed at 0.039 s, halting program execution.

Table 2. Analysis Results for Test Condition 2

| Seat | Acceleration Pelvis (g) | Acceleration Chest (g) | Acceleration Head (g) | HIC | Pelvic Force (kN) | Neck Moment[1] (N-m) |
|---|---|---|---|---|---|---|
| Aero Cmdr | 28.0 | 41.3 | 74.9 | 855. | 12.1 | -74/+130 |
| Beech 1900 | 36.5 | 54.2 | 64.5 | 853. | 13.6 | -122/+100 |
| Metro III | 31.6 | 37.9 | 63.3 | 895. | 11.3 | -93/+152 |
| Rigid | 45.4 | 53.2 | 82.7 | 949. | 15.0 | -125/+115 |

Note: 1. Sign convention for bending moments: + = flexion; - = extension.

Referring to the simulation results for test condition 1, the maximum pelvic force presented in Table 1, for every seat, exceeds the proposed acceptance limit for compressive force (6.67 kN). In fact, except for the Aero Commander case, in which the seat structure failed prematurely, the compressive load predicted is more than twice the limit. The fact that the pelvic compressive load for the Beech and Metro seats is close to that predicted for the rigid

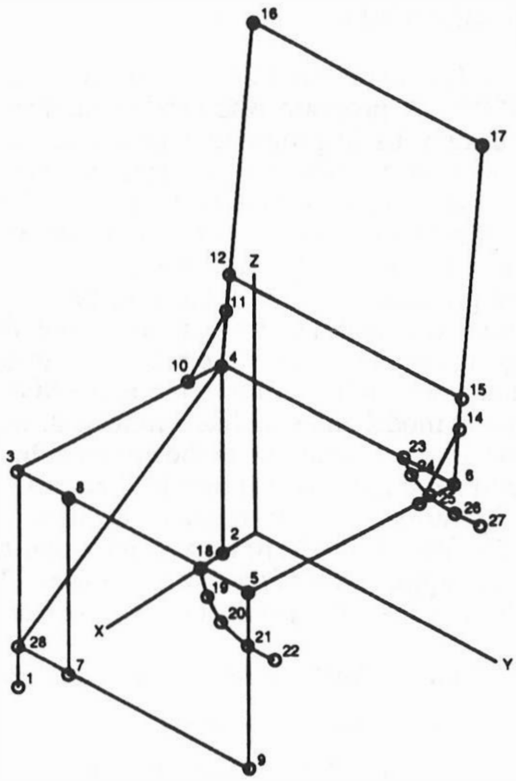

Fig. 9 Beechcraft 1900 seat model.

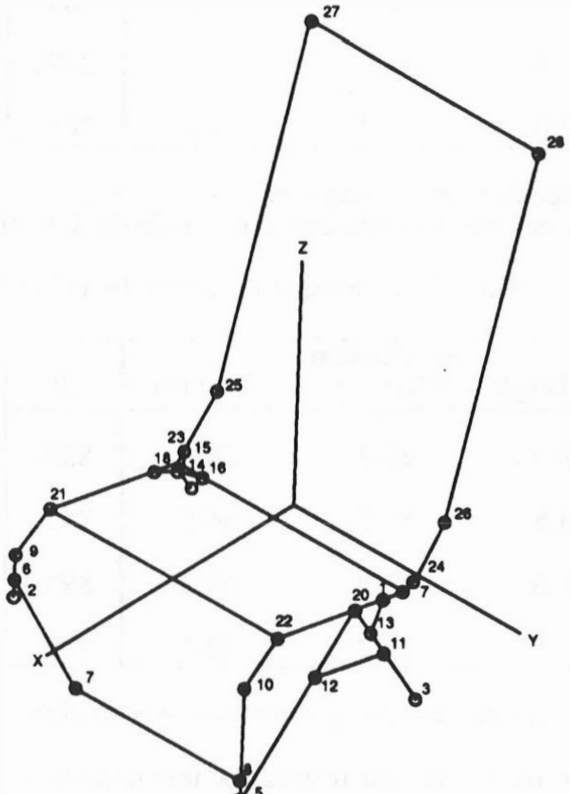

Fig. 10 Fairchild Metro III seat model.

seat indicates that some kind of vertical force-attenuating mechanism must be included in order that a seat be capable of meeting the pelvic force criterion.

The tabulated results predicted for test condition 2 are inconclusive with respect to the proposed pass/fail criteria. The maximum pelvic force in those cases is positive, implying tension, to which the injury criterion does not apply. The HIC values are acceptable, but no requirement has been included for simulation of the passenger environment for head strikes, such as on the seat back in front of the passengers. Bending moment in the neck, also presented in Tables 1 and 2 as computed by SOM-LA, is not listed among the proposed criteria. However, the moments predicted in simulation of test condition 2, in every case, exceed the neck tolerance limits proposed by Mertz and Patrick (7). Simply stated, these limits are 88 N-m for flexion and 48 N-m for extension.

The proposed amendment would require upper torso restraint for the pilot seats. Therefore, the two test conditions were simulated a second time for the three seat designs, this time including a three-point automotive-type restraint system. Results are presented in Tables 3 and 4. Dummy segment accelerations predicted for test condition 2 were reduced below those of Table 2 due to the prevention of head/chest impact on the legs, and all the predicted HIC values were acceptable. Therefore, these numbers were not included in Tables 3 and 4, but were replaced by maximum shoulder belt load. Just as predicted in the lap belt-only cases, the maximum pelvic force exceeds the 6.67-kN acceptance limit. As noted in Tables 3 and 4, both the Aero Commander and Metro seats failed early, before the dummy reached peak response. Strengthening the seats to prevent these structural failures would undoubtedly permit the tabulated forces to become higher.

Table 3. Analysis Results for Test Condition 1 with Upper Torso Restraint

| Seat | Pelvic Force (kN) | Neck Moment[1] (N-m) | Belt Load (kN) |
|---|---|---|---|
| Aero Cmdr[2] | -9.67 | -0.3/+60.9 | 2.04 |
| Beech 1900 | -15.2 | -58.3/+120. | 3.92 |
| Metro III[3] | -14.3 | -0.4/+47.5 | 1.26 |
| Rigid | -17.0 | -49.0/+164. | 1.46 |

Notes: 1. Sign convention for bending moments: + = flexion; - = extension.
2. Aero Commander seat structure failed at 0.048 s.
3. Metro seat structure failed at 0.043 s.

Table 4. Analysis Results for Test Condition 2 with Upper Torso Restraint

| Seat | Pelvic Force (kN) | Neck Moment[1] (N-m) | Belt Load (kN) |
|---|---|---|---|
| Aero Cmdr[2] | -2.48 | -0/+29.8 | 9.72 |
| Beech 1900 | -8.83 | -5.1/+171. | 12.5 |
| Metro III[3] | -6.10 | -0.6/+44.4 | 9.60 |
| Rigid | -8.44 | -8.1/+276. | 13.2 |

Notes: 1. Sign convention for bending moments: + = flexion; - = extension.
2. Aero Commander seat structure failed at 0.071 s.
3. Metro seat structure failed at 0.073 s.

Seat Retention

A major concern in designing for occupant survivability is the inertial loading of the seat on the fittings by which it is attached to the aircraft. Because of the large downward component of force it produces on the floor, test condition 1 tends to keep the seat in place. Test condition 2, however, with its significant forward loading component, exerts an upward pull on the rear legs of the seat and represents the critical conditionfor seat strength. The 10-deg yaw in the proposed requirements serves to create an unsymmetric loading that increases the severity of loading on one of the rear attachments. The SOM-LA program determines the loading at the seat attachment points between the seat structure and the aircraft, results that can be useful in design of the attachment hardware. Furthermore, success of the design would be ultimately demonstrated by testing.

In the preceding section, it was mentioned that none of the three seats being analyzed could survive the application of the proposed floor warping condition. Of particular concern with respect to seat retention are those aircraft in which one side of each seat is attached to the side of the fuselage, while the other side is supported on the floor. This configuration, which is schematically illustrated in Fig. 11, appears in some of the most frequently used commuter aircraft, including the Beechcraft 1900 and the Fairchild Metro. Fuselage deformation during a crash can cause significant movement of outboard seat attachment points relative to the inboard legs, which may exceed the floor warpage conditions specified by the proposed amendment. The investigation of a November 1987 accident involving a Beech 1900 showed that, although the fuselage remained intact, "every seat was found to have been separated from its floor mounts." The crash was fatal to both pilots and to 16 of the 19 passengers, and "the majority of the injuries sustained by the passengers were as a result of the secondary impact after the seats separated from their tracks." (8) Similar seat retention failures have also been reported in accidents involving the Metro aircraft (9).

Conclusions and Recommendations

Based on analyses of the proposed test conditions, several conclusions can be drawn. First, the close spacing of passenger seat rows in commuter aircraft makes head impact against the seat back likely in an accident with a significant longitudinal acceleration, as represented by test condition 2. Although the proposed amendment specifies a HIC limit, it needs to also include a method for evaluating the actual passenger environment, such as by the use of two seat rows in a dynamic test. For such cases, the possibility of neck injury should also be considered. Reference 10 describes a study of the effect of seat design parameters, including seat row spacing and seat back stiffness, on the potential for passenger injury in transport aircraft. Analyses reported there used data from sled tests that were conducted using two seat rows, as shown in Fig. 12 (11). Impact velocities were approximately 13.4 m/s, and deceleration levels, 9 to 16 g. Head impacts produced HIC values significantly above 1000 and neck moments in extensional bending considerably above the limits recommended by Mertz and Patrick. For commuter seat test condition 2 under consideration, the 26-g deceleration level appears to mandate the use of upper torso restraint for all seats, although required by the proposed amendment only in the front seats.

The high pelvic loads predicted by the SOM-LA program for test condition 1 indicate that energy absorption in the vertical direction would be necessary for meeting the requirements. A number of such seats have been developed, and those that have actually been installed in aircraft have demonstrated beneficial results (12-14).

Seat retention has been a problem in accidents involving commuter aircraft. The floor deformations produced by the Aero Commander drop test indicate that the proposed 10-deg-pitch/10-deg roll floor warp conditions are no more severe than deformations produced in actual floor structures; some aircraft may force even greater displacements on their seats. It appears from the SOM-LA simulations that none of the three seats modeled would survive these warping displacements, so that introducing new seats or modifying current seat designs to accommodate these displacements would certainly represent an improvement. The FAA Technical Center is planning a drop test of a Metro III aircraft in 1991. It would appear desirable to install on that aircraft some seats that have been designed, or at least modified, to meet the proposed floor warp conditions.

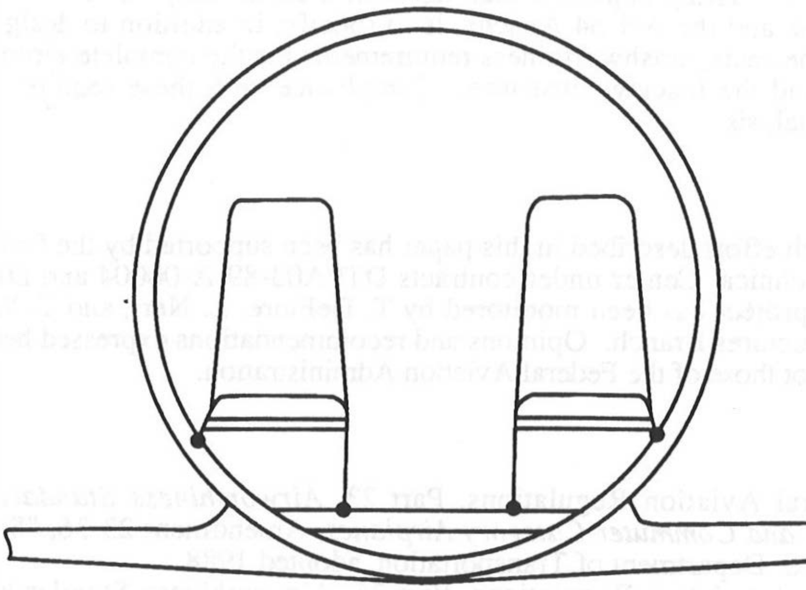

Fig. 11 Sidewall/floor-mounted seat configuration.

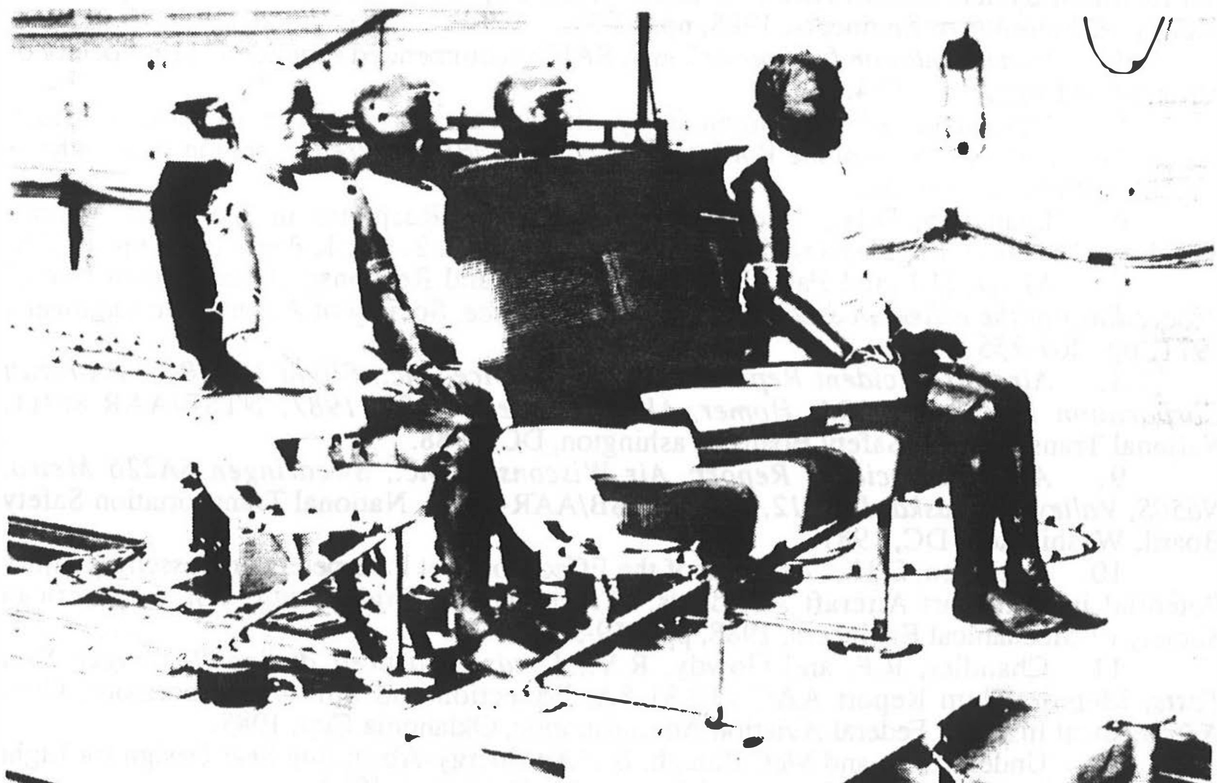

Fig. 12 Two transport aircraft seats and dummies prior to sled test.

The acceleration environment inside the aircraft can vary considerably from one aircraft model to another, as demonstrated by the drop tests of the Aero Commander and Cessna aircraft. A seat that might stay in place under the proposed floor warp conditions could break loose due to high inertial loads in an aircraft that has a stiff underfloor structure, such as the Cessna 421. The U.S. Army approach that has been used in design of two helicopters, the UH-60 Black Hawk and the AH-64 Apache, is to specify, in addition to design and testing requirements for the seats, crashworthiness requirements for the complete aircraft, including the landing gear and the fuselage structure. Compliance with these requirements may be demonstrated by analysis.

Acknowledgments

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