Crashworthiness Analysis of Commuter Aircraft Seats

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16. Abstract

During the past several years, the Federal Aviation Regulations (FAR) have been significantly modified with respect to seat/restraint system strength, attachment of seats to the aircraft structure, and the means by which they are to be evaluated. Aircraft accident data, human tolerance levels, and aircraft structural characteristics have been considered in the development of these new standards. Dynamic testing is now required for seats to be installed in general aviation aircraft, transport category aircraft, and rotorcraft. Performance criteria are similar to those specified by the Federal Motor Vehicle Safety Standards 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. A category of aircraft that has not as yet been affected by the rule modifications is the commuter type aircraft, which seats 10 to 19 passengers. Since this airplane is closer in size to general aviation aircraft than to large transports, it is also covered by FAR Part 23. The Federal Aviation Administration is currently involved in the conduct of a test program addressing commuter aircraft occupant crash safety. In support of this effort, a research program the includes full-scale aircraft drop tests, sled tests of seats, and computer simulations is being conducted. This report describes the use of the SOM-LA (Seat/Occupant Model - Light Aircraft) program in modeling three commuter aircraft seats. The predicted response of the seats to a potential set of test conditions is described.

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EXECUTIVE SUMMARY

During the past several years, the Federal Aviation Regulations (FAR) have been significantly modified with respect to seat/restraint system strength, attachment of seats to the aircraft structure, and the means by which they are to be evaluated. Aircraft accident data, human tolerance levels, and aircraft structural characteristics have been considered in the development of these new standards. Dynamic testing is now required for seats to be installed in general aviation aircraft, transport category aircraft, and rotorcraft. Performance criteria are similar to those specified by the Federal Motor Vehicle Safety Standards 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. A category of aircraft that has not as yet been affected by the rule modifications is the commuter type aircraft, which seats 10 to 19 passengers. Since this airplane is closer in size to general aviation aircraft than to large transports, it is also covered by FAR Part 23. The Federal Aviation Administration is currently involved in the conduct of a test program addressing commuter aircraft occupant crash safety. 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. This report describes the use of the SOM-LA (Seat/Occupant Model - Light Aircraft) program in modeling three commuter aircraft seats. The predicted response of the seats to a potential set of test conditions is described.

INTRODUCTION

During the past several years, the Federal Aviation Regulations (FAR) have been significantly modified with respect to seat/restraint system strength, attachment of seats to the aircraft structure, and the means by which they are to be evaluated. Aircraft accident data, human tolerance levels, and aircraft structural characteristics have been considered in the development of these new standards [1]. Based on 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 [2, 3]. Performance criteria are similar to those specified by the Federal Motor Vehical Safety Standards 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 new general aviation aircraft manufactured since 1989. Also, FAR Part 25 (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 [4]. FAR parts 27 and 29, which apply to rotorcraft, have also been amended to include dynamic test criteria.

Another category of aircraft that has not as yet been affected by the rule modifications is the commuter type aircraft, which seats 10 to 19 passengers. Since this airplane is closer in size to general aviation aircraft than to large transports, it is also covered by FAR Part 23. The Federal Aviation Administration is currently involved in the conduct of a test program addressing commuter aircraft occupant crash safety. 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. This report describes a potential set of test conditions and acceptance criteria and the concurrent research program for their evaluation.

COMMUTER AIRCRAFT SEAT DYNAMIC TEST REQUIREMENTS

A possible starting point for developing dynamic test criteria for commuter airplanes is to establish a set of two dynamic tests and related acceptance criteria similar to those that have already been adopted for general aviation but with more severe deceleration levels. For the first test, the seat would be pitched upward 60 deg on the sled, so that the impact velocity of 31 ft/s has forward and downward components with respect to the seat. The deceleration pulse would have a peak value of at least 32 g, which should occur not more than 0.03 s after impact. In the second test, the seat is positioned upright, but would be yawed 10 deg with respect to the impact vector. The impact velocity would be 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 would be rotated 10 deg about a lateral (pitch) axis; the other rail would 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 compressive force has been related to the potential for injury to the lumbar spine due to an upward acceleration of the body [5].

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 Head Injury Criterion (HIC) of 1000, a femur load of 2250 lb, and a pelvic compressive load of 1500 lb. Upper torso restraint would be required only for the front (pilot) seats, where the load in a single shoulder belt should not exceed 1750 l. or the sum of the loads in dual straps, 2000 lb.

Test 1
Forward and Downward Loading

Test 2
Forward and Lateral Loading

Required Velocity and Acceleration

$\Delta v = 31$ ft/s — 32 g — 0.03 s

$\Delta v = 42$ ft/s — 26 g — 0.05 s
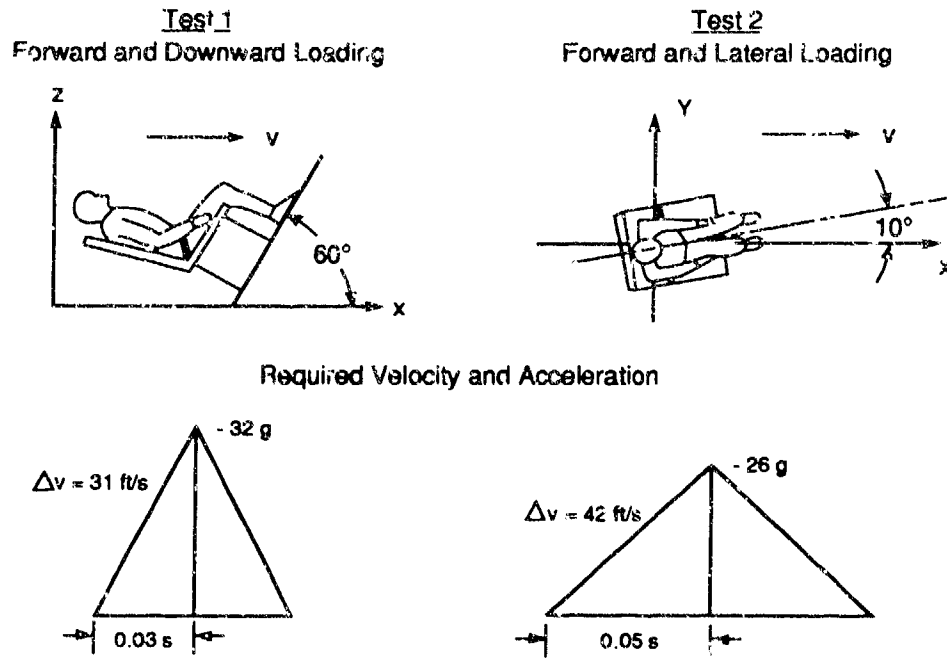
Fig.1 Dynamic tests under consideration for commuter-category aircraft seats.

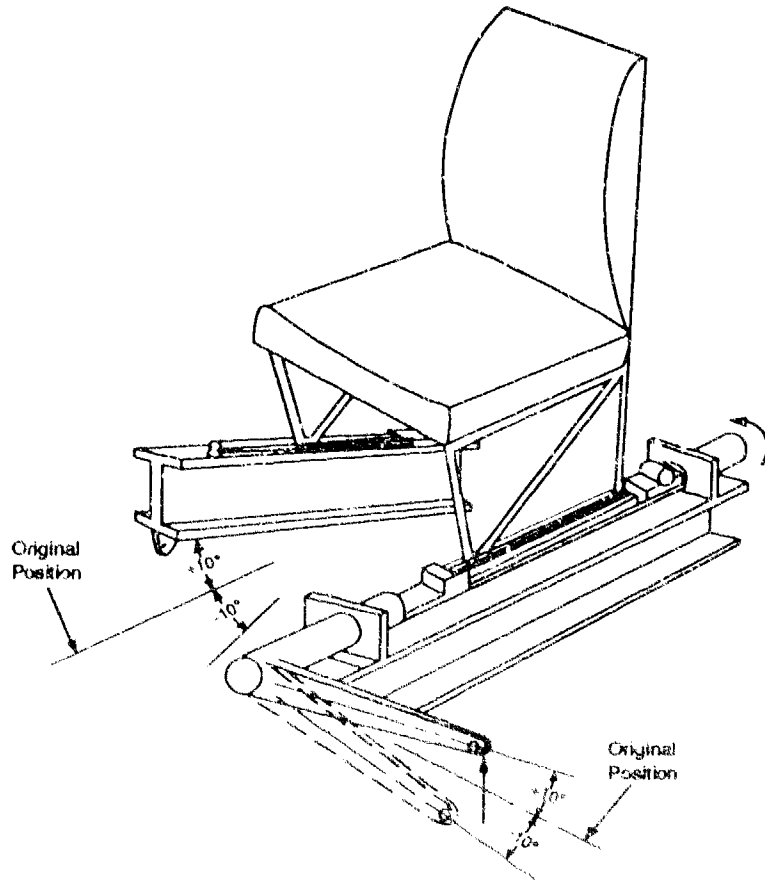Original Position

Original Position

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

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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 occupant 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 11.2 ft, so as to achieve an impact velocity of 26.8 ft/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 20 in. 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 12 in.. The subfloor structure in the center of the aircraft crushed less than 0.5 in. 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 1.7 in. 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 1.5 in. 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 [6], 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 1.0 in. but caused accelerations at the floor 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 has been developed under FAA sponsorship [7, 8]. This program combines an 11-mass, 29 degree-of-freedom model of the aircraft 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 26.8-ft/s drop, the yield strength of the steel frame was reached at approximately 0.030 s in the 0.75-in. diameter tubular members that run along the left and right sides of the seat (at nodes 19 and 20). A maximum force of 1950 lb 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 0.52 in. at nodes 19 and 20, as shown in the side view presented as Fig. 6. All of the single-passenger 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.

3

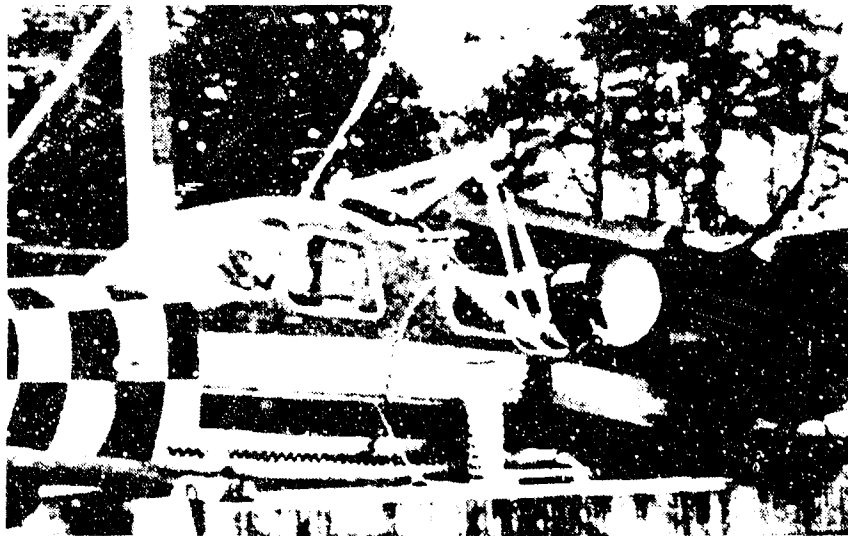Fig. 3 Aero Commander 680E aircraft during 26.8-ft/s drop.
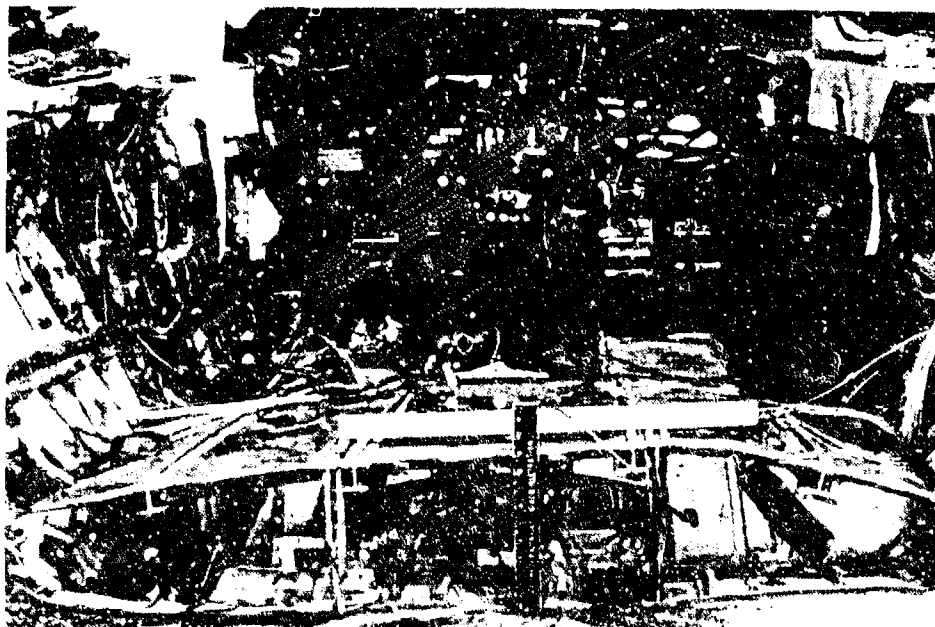
Fig. 4 Forward section of Aero Commander 680E aircraft following 26.8-ft/s drop.

AERO COMMANDER 680E SEAT
TIME = 0.0000 SEC

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

AERO COMMANDER 680E SEAT
TIME = 0.0000 SEC

AERO COMMANDER 680E SEAT
TIME = 0.0350 SEC

Fig. 6 Aero Commander seat structure deformation predicted for 26.8 ft/s drop.

Fig. 7 Aero Commander seat frame deformation following 26.8-ft/s drop.

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

ANALYSIS OF PROPOSED TEST CONDITIONS

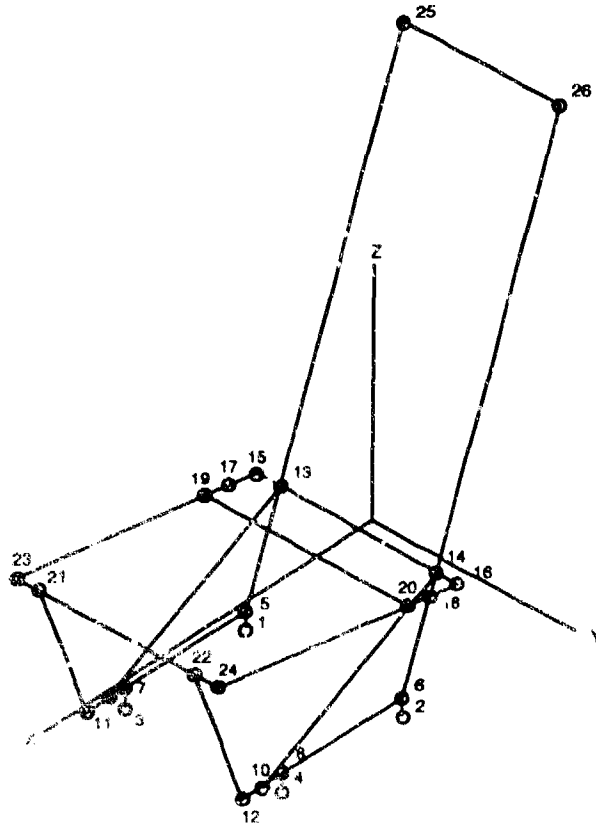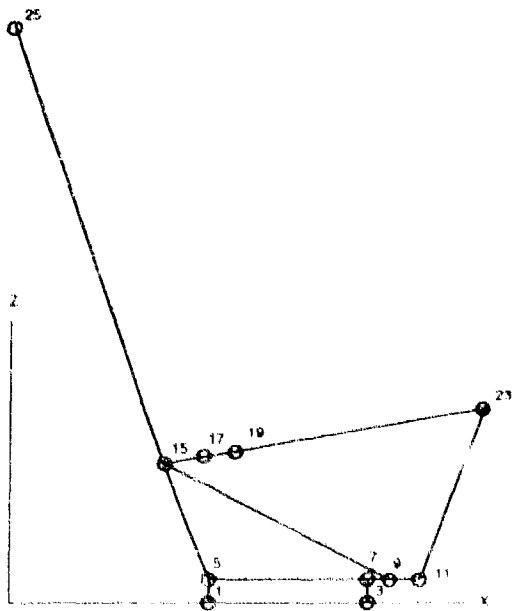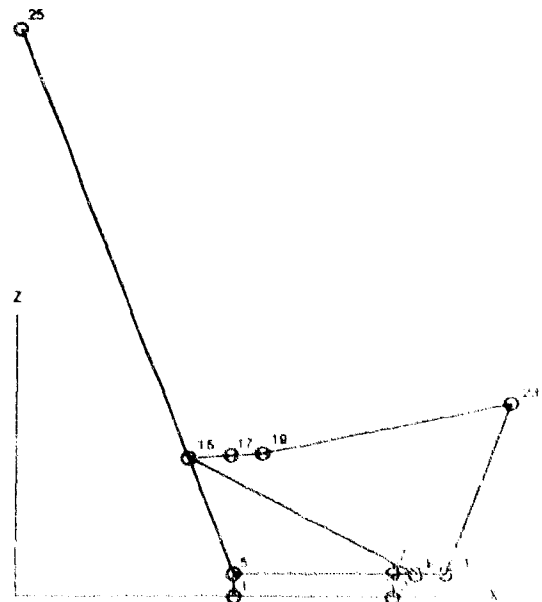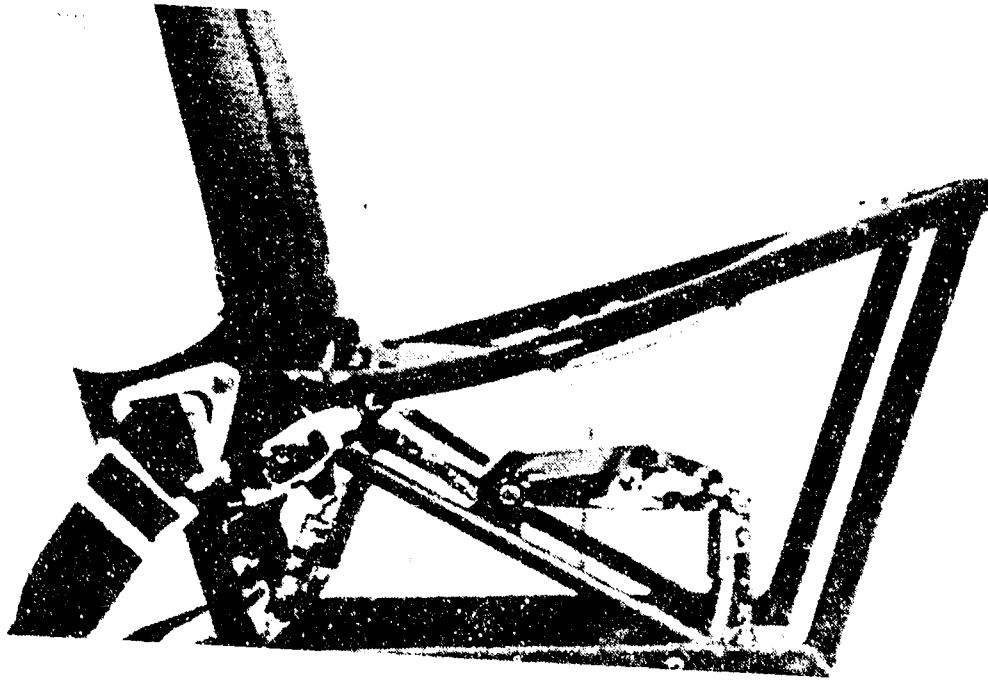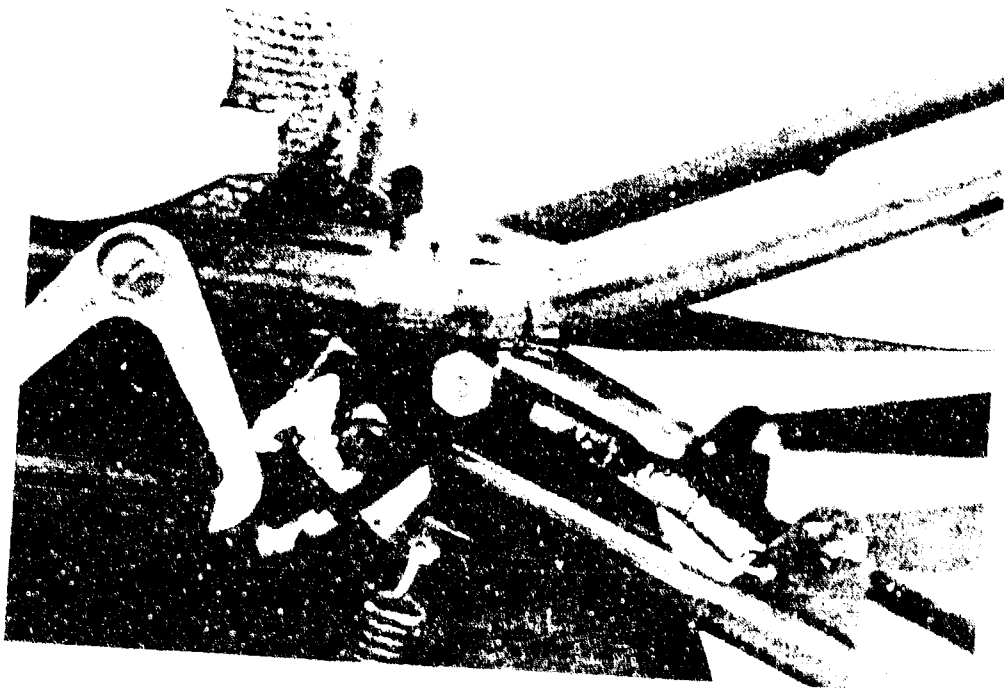Following successful simulation of the Aero Commander seats that had been installed in the test airplane, the SOM-LA program was used to analyze the response of three existing commuter aircraft seat designs to the proposed dynamic test conditions. The first was the Aero Commander seat described in the 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 Table 1. 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 supports 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 Table 1 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.

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 (1500 lb). 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 seat indicates that neither seat provides any inherent energy absorption capability in its structure. Therefore, some kind of vertical force-attenuating mechanism should be included in order that the seats be capable of meeting the pelvic force criterion.

Table 1. Analysis Results for Lap Belt Restraint

Seat	Acceleration Pelvis (g)	Chest (g)	Head (g)	HIC	Pelvic Force (lb)	Neck Moment[1] (lb-in.)
Test 1						
Aero Cmdr[2]	27.4	24.6	26.6	5.	-2450.	-0.0/+45.7
Beech 1900	46.5/161.[3]	51.3/159.[3]	55.0/261.[3]	4840.	-3480.	-53.1/+84.1
Metro III	48.1	56.6	57.4	269.	-3780.	-31.7/+111.
Rigid	47.5	57.9	58.8	277.	-3820.	-31.9/+114.
Test 2						
Aero Cmdr[4]	28.0	41.3	74.9	855.	+2720.	-54.6/+95.9
Beech 1900	29.7/179.[3]	50.8/184.[3]	64.0/388.[3]	10400.	+2940.	-86.4/+152.
Metro III[5]	31.6	37.9	63.3	895.	+2540.	-68.6/+112.
Rigid	32.6/215.[3]	58.7/142.[3]	71.0/679.[3]	25900.	+3430.	-76.6/+84.8

Notes: 1 Sign convention for bending moments: + = flexion; - = extension.
2 Aero Commander seat structure failed at 0.039 s, halting program execution.
3 Maximum acceleration magnitudes are before/after impact of chest & head on legs.
4 Aero Commander seat structure failed at 0.073 s, halting program execution.
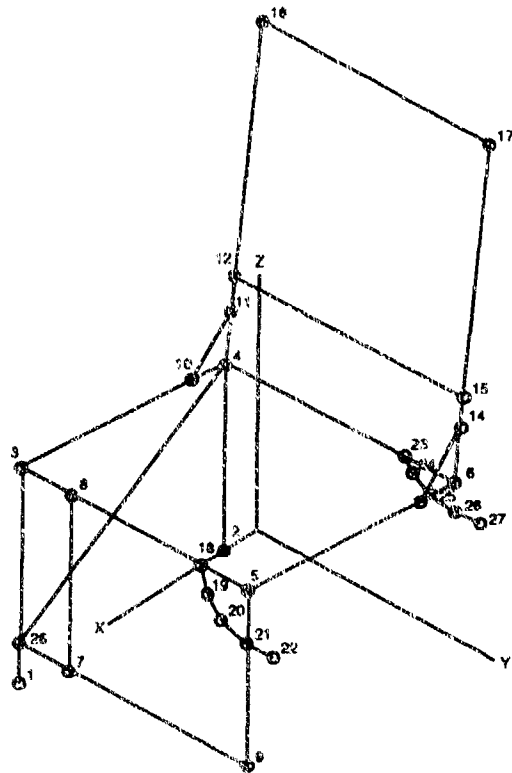5 Metro seat structure failed at 0.075 s, halting program execution.
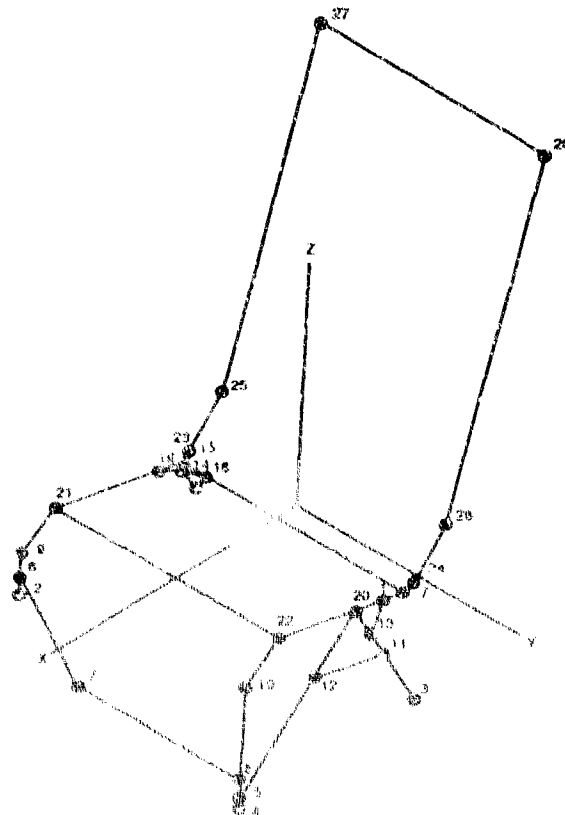
Fig. 9 Beechcraft 1900 seat model.

Fig. 10 Fairchild Metro III seat model.

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 Table 1 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 [9]. Simply stated, these limits are 65 lb-in. for flexion and 35 lb-in. for extension.

The baseline conditions being investigated 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 Table 2. Dummy segment accelerations predicted for test condition 2 were reduced below those of Table 1 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 Table 2, but were replaced by the maximum shoulder belt load, which exceeds the 1750-lb acceptance limit for test condition 2 applied to every seat. Also just as predicted in the lap belt-only cases of Table 1, the maximum pelvic force exceeds the 1500-lb limit. As noted in Table 2, 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.

Because of the high pelvic loads predicted for test condition 1 with its 32-g peak deceleration, another set of simulations was performed in which the seat models were subjected to the less severe dynamic test conditions that are required by FAR Part 23 for general aviation passenger seats. Although impact velocities and impact vector orientations remain the same, the peak decelerations are reduced to 15 g and 21 g for tests 1 and 2, respectively. Results for lap belt-only restraint are presented in Table 3, and results for three-point restraint (as required for all general aviation seats), in Table 4.

Table 2. Analysis Results for Three-Point Restraint

Seat	Pelvic Force (lb)	Neck Moment[1] (lb-in.)	Belt Load (lb)
Test 1			
Aero Cmdr[2]	-2170.	-0.23/+44.9	458.
Beech 1900	-3420.	-43.0/+88.3	880.
Metro III[3]	-3200.	-0.29/+35.0	284.
Rigid	-3830.	-36.1/+121.	329.
Test 2			
Aero Cmdr[4]	-556.	-0.0/+22.0	2190.
Beech 1900	-1980.	-3.8/+126.	2800.
Metro III[5]	-1370.	-0.44/+32.7	2160.
Rigid	-1900.	-6.0/+204.	2970.

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.
       4. Aero Commander seat structure failed at 0.071 s.
       5. Metro seat structure failed at 0.073 s.

Table 3. Analysis Results for General Aviation Passenger Seat Tests, Lap Belt Restraint

Seat	Acceleration Pelvis (g)	Chest (g)	Head (g)	HIC	Pelvic Force (lb)	Neck Moment[1] (lb-in.)
Test 1						
Aero Cmdr[2]	22.7	20.8	17.7	23.1	-1530.	-0.17/+49.5
Beech 1900	24.1	23.8	22.2	35.0	-1530.	-25.2/+41.0
Metro III	25.3	27.2	25.3	61.0	-1830.	-12.9/+62.5
Rigid	25.2	27.4	25.6	61.3	-1840.	-12.7/+62.9
Test 2						
Aero Cmdr[3]	14.6	3.9	6.0	0.9	+27.4	-22.6/+0.54
Beech 1900	30.5/284.[4]	73.3/192.[4]	62.8/294.[4]	5790.	+2630.	-82.9/+129.
Metro III[5]	24.7	49.7	67.7	477.	+3060.	-52.4/+0.92
Rigid	50.0/222.[4]	50.8/176.[4]	64.0/377.[4]	10300.	+3020.	-73.6/+67.5

Notes: 1. Sign convention for bending moments: + = flexion; - = extension.
2. Aero Commander seat structure failed at 0.093 s, halting program execution.
3. Aero Commander seat structure failed at 0.065 s, halting program execution.
4. Maximum acceleration magnitudes are before/after impact of chest & head on legs.
5. Metro seat structure failed at 0.122 s, halting program execution.

Table 4. Analysis Results for General Aviation Passenger Seat Tests, Three-Point Restraint

Seat	Pelvic Force (lb)	Neck Moment[1] (lb-in.)	Belt Load (lb)
Test 1			
Aero Cmdr[2]	-1420.	-0.17/+55.4	453.
Beech 1900	-1630.	-0.26/+51.6	715.
Metro III	-1880.	-9.30/+68.3	240.
Rigid	-1880.	-8.88/+68.8	233.
Test 2			
Aero Cmdr[3]	+119.	-6.03/+0.26	455.
Beech 1900	-1730.	-1.88/+94.4	2460.
Metro III[4]	-1680.	-0.20/+87.7	2560.
Rigid	-1700.	-6.56/+144.	2590.

Notes: 1. Sign convention for bending moments: + = flexion; - = extension.
2. Aero Commander seat structure failed at 0.092 s.
3. Aero Commander seat structure failed at 0.054 s.
4. Metro seat structure failed at 0.139 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 condition for seat strength. The 10-deg yaw in the 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 floor warping conditions. 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, "all of the seats separated from their floor- and wall-mounted seat tracks." 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." [10] Confirming the need for energy absorption in the vertical direction, the NTSB estimated that the average acceleration along the vertical axis of the aircraft during initial impact ranged from "19.8 to 35.7 g" and that "the vertical velocity change was about 42 feet per second." The report states further that "some injuries, such as aortic ruptures, were typical of a severe vertical deceleration."

Returning to the matter of seat retention, the NTSB reported that in a 1980 crash of a Swearingen Metro aircraft, "Despite the integrity of the cabin area, all of the 13 occupied passenger seats separated from their attachments during the impact sequence, leading to the (11) fatal and (2) nonfatal injuries to the passengers." [11] Although passenger seat configuration remains basically the same in the current Metro III aircraft, attachment hardware has been improved.

CONCLUSIONS

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 could 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 12 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 [13]. Impact velocities were approximately 44 ft/s, and deceleration levels, 9 to 16 g. Head impacts predicted by computer simulations 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 as described in Fig. 1, the 26-g deceleration level appears to mandate the use of upper torso restraint for all seats in the aircraft.

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 [14, 15], and those that have actually been installed in aircraft have demonstrated beneficial results [16, 17].

Seat retention has been a problem in accidents involving commuter aircraft. The floor deformations produced by the Aero Commander drop test indicate that the 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 floor warp conditions.

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.
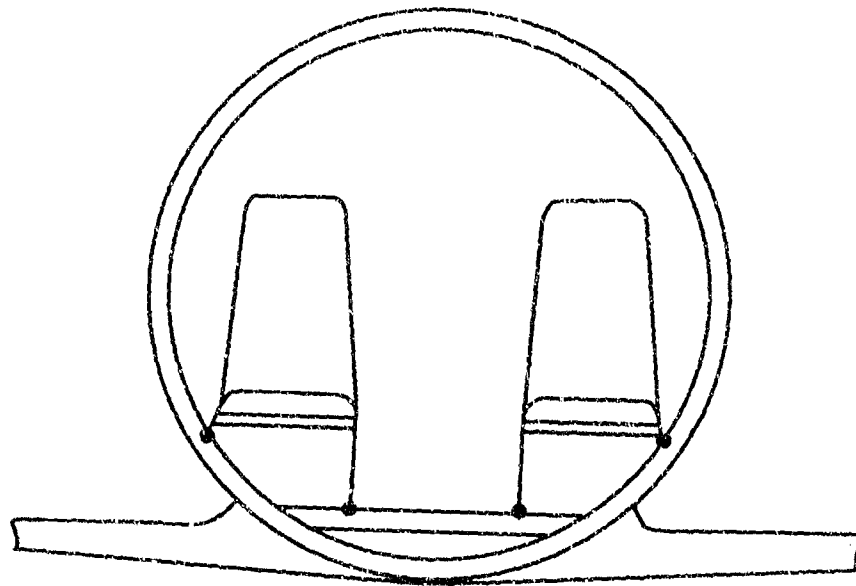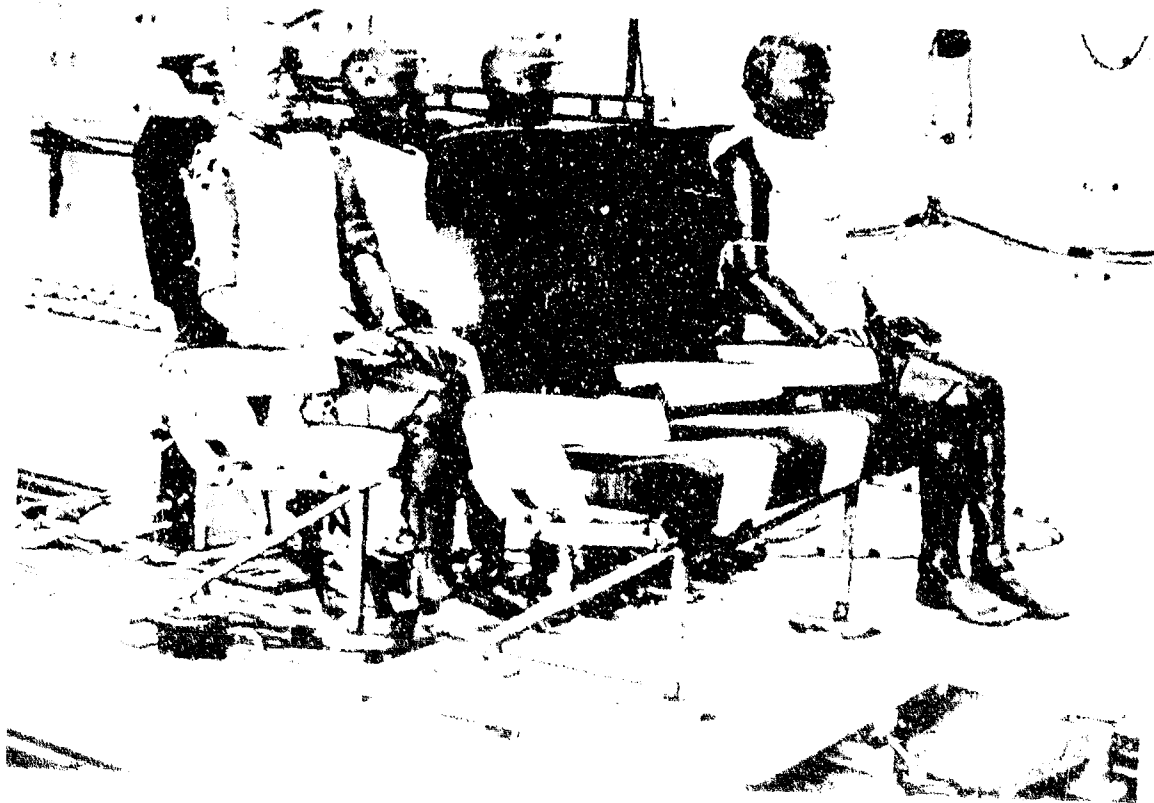
Fig. 11 Sidewall/floor-mounted seat configuration.

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

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