AN OVERVIEW OF HEAD IMPACT PROTECTION RESEARCH RELATED TO AIRPLANE CABIN INTERIOR PANELS

STEPHEN SOLTIS
AIRCRAFT ENGINEERING DIVISION
FEDERAL AVIATION ADMINISTRATION
LAKEWOOD, CA

ABSTRACT

This paper reviews recent research activities conducted by the National Institute for Aviation Research (NAIR) at Wichita State University under a grant from the Federal Aviation Administration (Hooper, 1998). The research activities were structured to define an analytical methodology that could be used as a design aid for structures that need to comply with the head impact protection injury criteria found in Federal Aviation Regulations, 14 CFR 25.562 (14 CFR 25, 1998). This paper reviews the results of a series of airplane seat static and dynamic tests, analytical simulations of those seat dynamic test, the resultant design curves, and analytical methodology that could be used in the design of energy absorbing structures.

INTRODUCTION

The Federal Aviation Regulations (FARs), 14 CFR 25.562, define airplane seat dynamic performance standards that include both structural and occupant impact injury criteria. The Head Injury Criteria (HIC) that is also found in the Federal Motor Vehicle Safety Standard, 49 CFR 571.208, is one of the occupant injury criteria that must be met when showing compliance with the airplane seat dynamic performance standards (49 CFR 571, 1998). 14 CFR 25.562 requires that should head impact occur on an interior component in the airplane, the maximum value of the HIC integral (Equation 1), based on the occupant's resultant head acceleration time history, must not exceed 1000. The HIC value is a function of the magnitude of the acceleration and the duration of the acceleration for all possible sample time intervals within the total head strike interval.

$$HIC = \left[(t_2 - t_1) \left\{ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)\,dt \right\}^{2.5} \right]_{\max} \tag{1}$$

Compliance with HIC has sometimes been a challenging task for airplane interior designers particularly in the design of bulkheads or structures located directly in front of first row seated airplane passengers. It was found during seat dynamic tests that head strikes with a contemporary airplane bulkhead located forward of the seated airplane passengers resulted in HIC values in excess of 1000. A design procedure for airplane cabin interior energy absorbing structures was desired and needed.

BULKHEAD DESIGN PROCEDURE

The bulkhead design procedure illustrated in Figure 1 makes use of design experience, analytical tools, and static tests in the design of a candidate airplane bulkhead. Component impact tests using a simulated headform device could be used to obtain an early HIC evaluation and to gain confidence in the proposed bulkhead design. A full-up airplane seat and bulkhead certification test to the requirements found in FAR 14 CFR 25.562 would then be conducted to demonstrate HIC compliance. Successful compliance with the HIC requires no further testing and the airplane seat and bulkhead can be installed in the airplane. Failure of the airplane seat/bulkhead HIC test would require careful analysis of the test data and the analytical prediction. A bulkhead design modification may be warranted. This validation/certification cycle can be repeated from the beginning or at some intermediate level dependent upon the outcome of the initial certification test, the test data and analytical review, and the confidence placed on the new design of meeting the HIC.

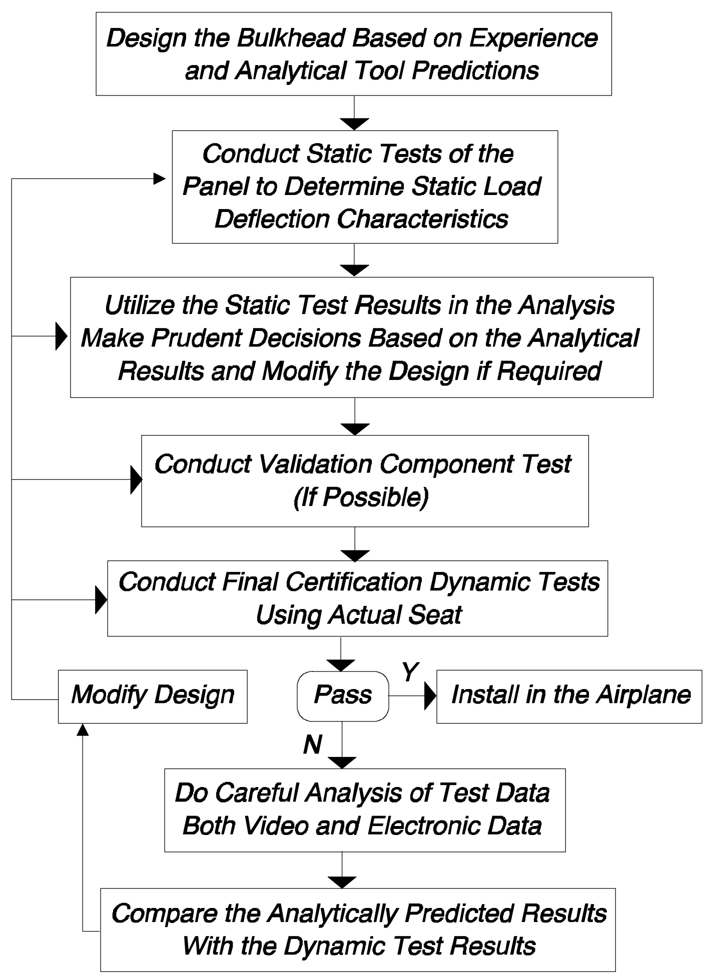


Figure 1 - Outline of Bulkhead Design Procedure

RIGID BULKHEAD BASELINE TESTS

Test Configuration

A series of baseline tests were conducted at the NAIR to establish a test protocol, define the test and configuration parameters that influence the HIC value, and evaluate the potential of using padding to minimize the HIC value. These test were conducted as shown in Figure 2 with a rigid seat and a rigid bulkhead to remove the variable of seat deformation and its potential effect on the HIC value. Padding was added to the impact surface. A 49 CFR 572, Subpart B, anthropomorphic test device (ATD) was used in all the tests to simulate the seat's occupant (49 CFR 572, 1998). That ATD represents a 50th percentile male occupant and it is commonly known as a Hybrid II dummy.

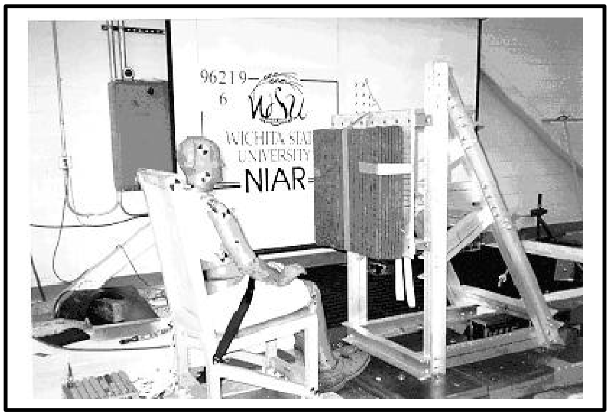


Figure 2 – Typical Baseline Test Setup

Seat set back from the bulkhead, which is defined as the horizontal distance between the head impact surface and the intersection point of the seat back and seat bottom cushion surface planes, ranged from 81.28 cm. (32 inches) to 93.98 cm. (37 inches). Those dimensions are typical of airplane installations. The ideal test pulse used in this test series was that defined in 14 CFR 25.562 (b)(2) and it is illustrated in Figure 3 along with an actual test pulse.

Summary of Results

Table 1 summarizes the baseline tests results along with the types and thickness of the padding materials used in those tests. The ATD's head impact velocity ranged from 12.84 m/sec. (42.1 ft/sec.) to 15.00 m/sec. (49.2 ft/sec.) that is consistent with the velocity change of 44 ft/sec. (13.4 m/sec.) defined in 14 CFR 25.562 (b)(2). The ATD's head path and head impact angle as depicted in Figures 4 and 5 were also measured in this test series. The head impact angle can influence the HIC value in that it can change the reaction mode of the impacted surface. If the head strikes the impact surface where the head's vertical axis is predominately vertical, the primary load on the impact surface will be compression. Should the head strike the impact surface where the head's vertical axis is predominately horizontal, the primary load on the impact surface will be a combined shear/ friction load. Most head impact conditions result in combined compression and shear/friction loads acting on the impact surface.

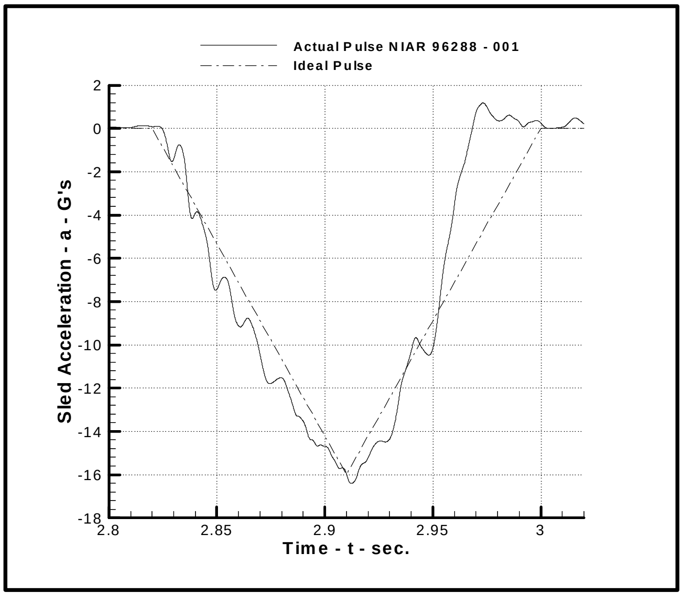


Figure 3 – Ideal and Typical Test Pulses

Table 1 also summarizes the ATD's measured peak head acceleration levels and the resultant HIC values that ranged from 2352 to 4645. A HIC value less than 1000 is desired. Figure 6 illustrates a typical acceleration time history of the center of gravity (C.G.) of the ATD's head.   The acquired time history curve was analyzed using Equation 1 to obtain the HIC value.

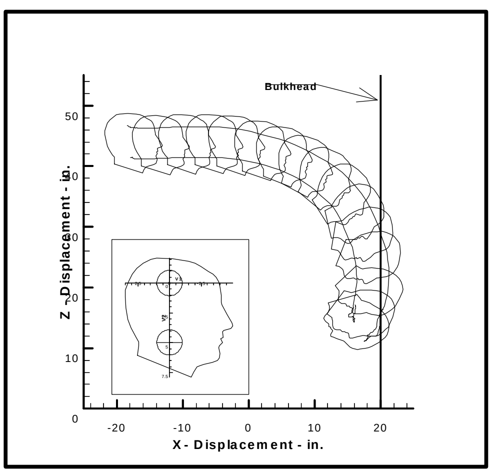


Figure 4 – Example of ATD Head Path

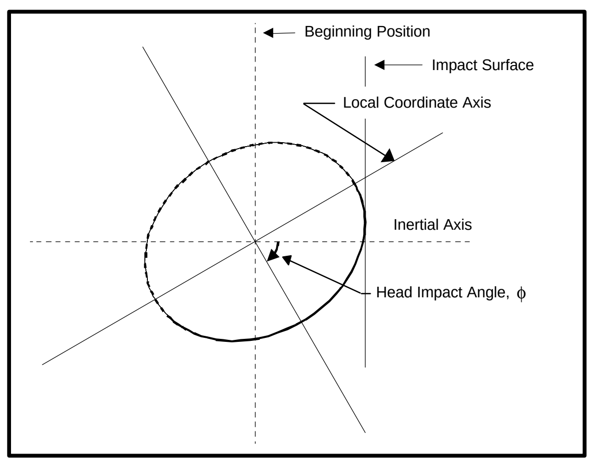


Figure 5 - Illustration of Head Impact Angle

Baseline Test Findings

The baseline tests provided some insight into the challenges associated with meeting the HIC and identified some of the more important parameters that influence the HIC value. The HIC values calculated from the baseline test are much higher than the limit (not to exceed 1000) found in 14 CFR 25.562. These tests showed that the padding and foam materials were ineffective in absorbing the head impact energy. The padding thickness used in the baseline tests may also be inappropriate for practical application in airline interiors. It should be noted however that the baseline test series only evaluated some common padding and foam materials and other materials not identified or evaluated may yield different results. Also found is that the HIC value is sensitive to ATD head orientation relative to the strike surface at the time of impact.

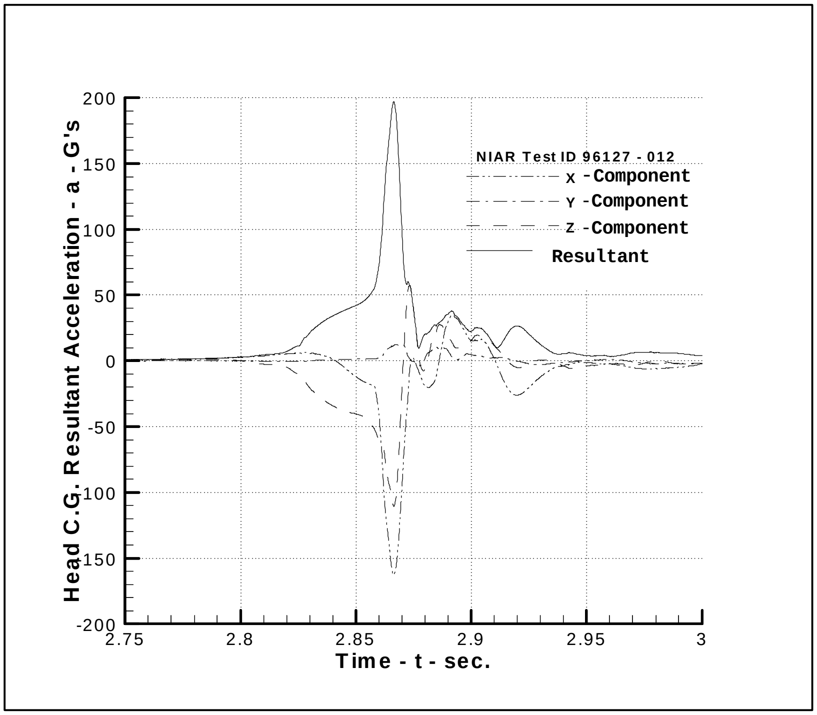


Figure 6 – Typical Head C.G. Acceleration Time History

SHEET METAL PANEL BULKHEAD STUDIES

Scope

Aluminum sheet metal panel bulkhead studies were conducted as part of a building block process to provide some additional insight in identifying some of the more important parameters that influence the HIC value. A summary of the aluminum sheet metal panel bulkhead studies that included analytical computer model simulations, static tests, and dynamic tests follow.

Table 1 – Summary of Rigid Bulkhead Baseline Tests

Test #	Padding Material(s)	Padding Thickness (in.)	Seat Set Back (in.)	Test G[*1] (G's)	Head Impact Velocity (ft./sec.)	Head Impact Angle (°)	Head C.G. Peak Acc. (g's)	*HIC*	$\Delta t = t_2 - t_1$ (ms)
96127-001	No Bulkhead	-	-	17.0	-	-	-	-	-
96127-002	No Bulkhead	-	-	17.0	-	-	-	-	-
96127-003	FR 3703[*2]	2.00	33.0	16.9	-	-	-	-	-
96127-004	FR 3502[*3]	2.00	33.0	16.6	-[*4]	-	-	-[*4]	-
96127-005	FR 3703	3.12	32.0	15.6	43.1	18	274	4645	6.7
96127-006	FR 3502	3.00	32.0	15.6	42.1	10	203	2647	7.4
96127-007	FR 3502	2.00	37.0	15.6	46.8	48	251	2537	6.3
96127-008	FR 3703	3.00	36.0	16.4	46.6	32	276	3400	3.9
96127-009	FR 3502	3.00	36.0	16.4	49.0	27	188	2601	9.2
96127-010	FR 3502+3703[*5]	1.00+2.00	36.0	16.6	48.5	25	245	3709	6.7
96127-011	Ensolite II+III[*6]	1.00+1.00	37.0	16.3	49.0	36	231	2715	7.1
96127-012	Ensolite II+III	2.00+1.00	36.0	16.4	49.2	29	197	2719	8.8
96219-001	FR 3502[*7]	2.00+2.00+2.00	35.0	16.7	45.9	32	191	2850	9.5
96219-002	(FR 3502+3503) [*7]	(1.00+2.00)+3.00	35.0	15.6	46.4	29	168	2481	10.8
96219-003	FR 3502	1.00+2.00	35.0	17.0	47.1	29	196	2691	7.7
96219-004	Ensolite II+III	2.00+1.00	35.0	16.9	47.0	24	193	2352	9.5
96219-005	FR 3703[*8]	3.00+3.00	35.0	17.0	47.3	31	190	2937	9.4
96219-006	FR 3502+3703	1.00+3.00	35.0	16.1	45.9	28	198	2624	8.8

Comments:

[*1] A minimum of 16.0 G is required for FAR Part 25.
[*2] Unmodified General Plastic LAST-A-FOAM 3 lb./cu. ft. [12].
[*3] Unmodified General Plastic LAST-A-FOAM 2 lb./cu. ft.
[*4] Accelerometer cable failed. No HIC data recorded.
[*5] Outer layer comprised of softer FR 3502 while the inner layer comprised of FR 3703.
[*6] For Ensolite, the lower number corresponds to softer (lower density) material.
[*7] Three, two-inch thick foams are glued together and perforated by ¾ inch diameter holes at 3 inch pitch.
[*8] Foam is perforated by 2 inch diameter holes at 3 inch pitch.

Analytical Simulations

Analytical simulations of a seat and bulkhead were conducted at NAIR using a MADYMO (MADYMO, 1994) seat/occupant computer model as depicted in Figure 7. The seat and the lower bulkhead were modeled using rigid planes. The 50th percentile male MADYMO model was used to simulate the seat occupant. The seat occupant was attached to the rigid seat with an elastic lap belt. Two bulkhead models were used. One bulkhead model used finite structural elements to model the bulkhead. The other defined the overall stiffness characteristics of the bulkhead. Dynamic tests were used to validate the MADYMO seat/occupant computer model. The input acceleration used for the MADYMO analyses was an idealization of a typical test pulse measured in the dynamic test series.

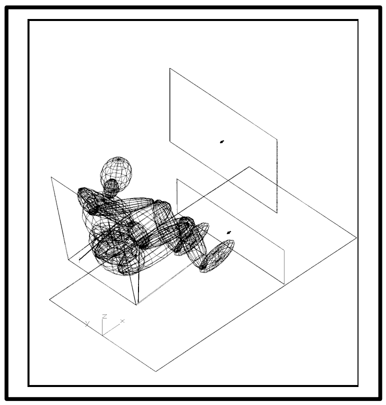


Figure 7 - Example of MADYMO Seat/Occupant Computer Model

Parameter MADYMO analytical studies were performed to determine the stiffness characteristics of a sheet metal bulkhead panel that would meet the HIC criteria. Figures 8 and 9 summarize the results of this initial MADYMO analytical study and indicate that a sheet metal panel thickness of .20 cm. (.08 inches) or less is required to achieve a HIC value less than 1000. The MADYMO simulations indicate that bulkhead panel deformations of at least 6 cm. (2.4 inches) are necessary to achieve a HIC value less than 1000.

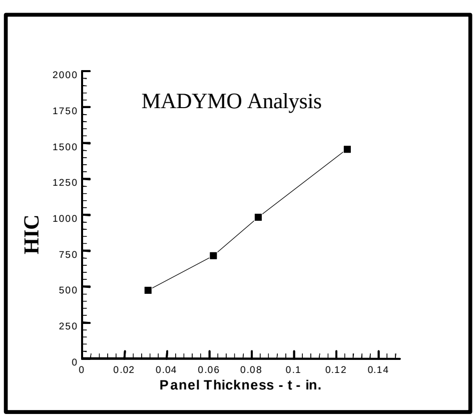


Figure 8 – HIC vs. Panel Thickness

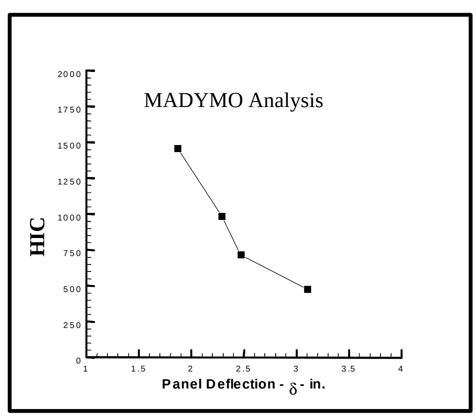
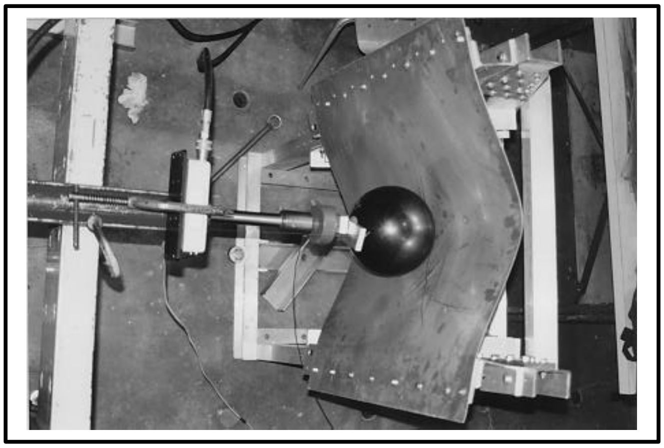


Figure 9 – HIC vs. Panel Deflection

Static Tests

Static tests of aluminum sheet metal panel bulkheads were conducted to determine the stiffness characteristics of those panels. The sheet metal panel bulkheads were mounted on a support frame. The panels were statically loaded using a bowling ball attached to a hydraulic cylinder as shown in Figure 10. A load cell and a string pot were installed in series with the hydraulic cylinder to measure the load deformation characteristics of the panels. A typical load/deformation curve for a static test is shown in Figure 11. The measured stiffness characteristics of the sheet metal panel bulkheads were used as input to the aforementioned MADYMO seat/occupant computer model.



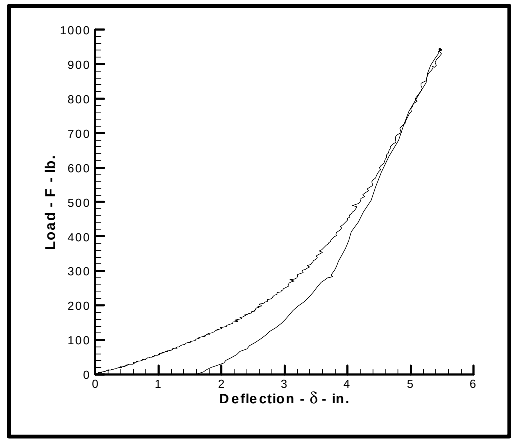


Figure 10 – Typical Panel Static Test

Figure 11 – Typical Load/Deflection Curve

Dynamic Tests

Dynamic tests were conducted at the NAIR with sheet metal panel bulkheads to evaluate their effectiveness in providing head impact protection and to provide a dynamic test database that would be used to validate the MADYMO seat/occupant computer model. These tests were conducted with the rigid seat and the sheet metal panel bulkheads mounted in the same fixture that was used in the static tests. Padding was added to the impact surface of most of the sheet metal panel bulkheads. A 49 CFR 572, Subpart B, anthropomorphic test device (ATD) was used in all the tests to simulate the seat's occupant. The ideal test pulse used in the test series was that defined in 14 CFR 25.562 (b)(2) and illustrated in Figure 3. A typical dynamic test setup is shown in Figure 12.

The dynamic tests conducted with the sheet metal panel bulkheads demonstrated that they were effective in absorbing some of the impact energy. The ATD's peak head acceleration and the resultant HIC value were reduced when compared to the rigid bulkhead. Typical ATD head C.G. acceleration time histories for both a rigid and an aluminum sheet metal panel bulkhead are shown in Figure 13. The added padding was also effective in reducing the ATD's peak head acceleration when compared to an unpadded sheet metal panel bulkhead. However the padding increased the duration of the ATD's head acceleration with an end result that the HIC values were comparable for both the unpadded and padded sheet metal panel bulkheads. A summary of the dynamic tests results for the aluminum sheet metal panel bulkheads can be found in Table 2.

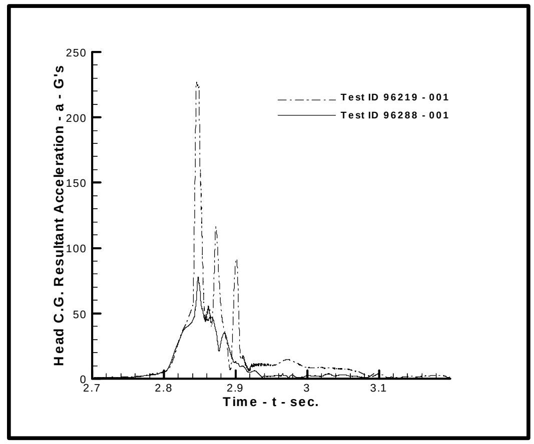


Figure 12 – Typical Panel Test Setup

Figure 13 – Rigid vs. Sheet Metal Bulkhead

Table 2 – Summary of HIC Results for Aluminum Sheet Metal Panels

Test ID	Padding Material	Panel Thickness (in.)	Seat Set back (in.)	Test Pulse (G's)	Head Impact Angle (°)	Head Impact Velocity (ft/sec.)	Head C.G. Peak Acc. (G's)	*HIC*
96288-001	FR 3502[1]	0.063[2]	35	16.4	33	46.6	77.9	559
96288-002	FR 3502[1]	0.071[2]	35	16.0	34	46.5	77.8	674
96288-003	FR 3502[1]	0.04[2]	35	15.7	-	-	68.3	491
96288-004	None	0.063[2]	35	16.6	38	45.1	142.5	694
96288-005	FR 3502	0.063[2]	35	16.5	32	45.9	88.7	619

[1]3 in. thick foam perforated by 2 in. diameter holes at 3 in. pitch.
[2]Al 2024-O sheet

AIRPLANE CABIN CLASS DIVIDER PANELS

Scope

Airplane cabin class divider panel studies were also conducted as part of a building block process. These studies were used to evaluate actual airplane components. They were structured to assess the divider panel's static and dynamic impact characteristics, to provide an additional dynamic test database that would be used to validate the MADYMO seat/occupant computer model, and to investigate modifications to the divider panels that might reduce the HIC value. The divider panels were aluminum or nomex honeycomb core/fiberglass face sheet structures that were covered with carpet material as depicted in Figure 14. An overview of a typical airplane cabin class divider panel is shown in Figure 15. A summary of the airplane cabin class divider panel studies that included static tests, dynamic tests, and analytical computer model simulations follow.

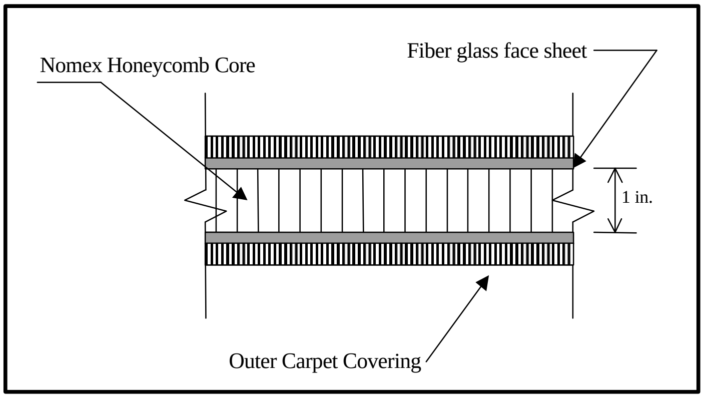


Figure 14 – Typical Divider Panel Construction

Figure 15 – Typical Divider Panel

Static Tests

Static tests of the airplane cabin class divider panels were conducted to determine the stiffness characteristics of those panels. The airplane cabin class divider panels were initially mounted using their airframe attachments however it was found that additional support was required to prevent premature localized structural failures. Additional support was provided along the sides of the divider panels that eliminated the structural failures. Some of the divider panels were modified by cutting vertical slits through the fiberglass facing sheets. This modification reduced the bending stiffness of the divider panel in the ATD's head strike area.

The divider panels were then statically loaded using the bowling ball attached to a hydraulic cylinder as shown in Figure 16. A load cell and a string pot were installed in series with the hydraulic cylinder to measure the load deformation characteristics of the divider panels. Typical load/deformation curves for three tests are shown in Figure 17. The measured stiffness characteristics of the airplane cabin class divider panels were used as input to a MADYMO seat/occupant computer model that simulated the airplane cabin class divider panel installations.

Dynamic Tests

A number of dynamic tests were conducted at the NAIR with standard and modified (slit facing sheets) airplane cabin class divider panel installations. These tests were conducted to

Figure 16 – Typical Static Test

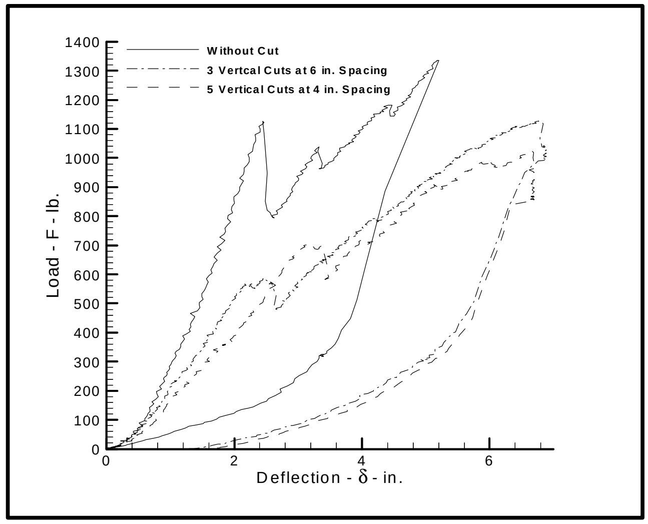


Figure 17 – Load/Deflection Curves for Divider Panels

evaluate the divider panel's effectiveness in providing head impact protection and to provide a dynamic test database that would be used to validate the MADYMO seat/occupant computer model that simulates the divider panel installations. These tests were conducted with the rigid seat and the divider panels were mounted in the same manner that was used for the static tests. A 49 CFR 572, Subpart B, anthropomorphic test device (ATD) was used in all the tests to simulate the seat's occupant. Seat set back from the divider panels ranged from 86.36 cm. (34 inches) to 91.44 cm. (36 inches) which is typical of airplane installations. The ideal test pulse used in the test series was that defined in 14 CFR 25.562 (b)(2) and illustrated in Figure 3. A typical dynamic test setup is shown in Figure 15.

The dynamic tests conducted with the airplane cabin class divider panel installations found that they were typically too stiff to provide the desired level of head impact protection and HIC value. The modified (slit facing sheets) airplane cabin class divider panel installations were

Table 3 – Summary of Dynamic Tests Results of Cabin Class Divider Panels

Test ID	Test Pulse (G's)	Divider Panel Modification	Seat Setback (in.)	Head Impact Angle (deg.)	Head Impact Velocity (ft/sec.)	*HIC*	*HIC* Window $\Delta t = t_1 - t_1$ (ms)
97191-001	16.7	No	36	53	44.9	823	19.0
97191-002	16.3	No	35	42	45.3	1394	12.5
97191-003	17.1	5 Vert. Slits	34	40	45.6	1132	22.4
97204-002	16.3	5 Vert. Slits	35	44	41.3	882	21.1

generally more effective in absorbing the impact energy. A summary of some of the dynamic test results for both the standard and the modified airplane cabin class divider panels can be found in Table 3. The effect of the modification can be seen by comparing the results of the dynamic tests of a standard and modified divider panel both tested with an identical (i.e., 35 inches) seat setback distance. The divider panel modification lowered the HIC value when compared to the standard divider panel.

<u>Analytical Simulations</u>

Analytical simulations of the airplane cabin class divider panel installations were conducted at NAIR using a MADYMO seat/occupant computer model like that depicted in Figure 7. The airplane cabin class divider panel installation models used the overall stiffness characteristics of the divider panels that were measured during the static tests.

Analytical simulations of selected dynamic test conditions were conducted to validate the airplane cabin class divider panel installation MADYMO models. The input acceleration used for the MADYMO analyses was an idealization of the measured test pulse for the dynamic test condition being simulated. Correlation with dynamic tests and model validation were considered accomplished if the occupant's overall kinematics were generally the same and specifically if the occupant's head C.G. acceleration time histories during impact were comparable considering pulse shape and peak G's magnitude. A comparison of the head C.G. acceleration time histories for a dynamic test and an analytical MADYMO computer simulation of that test is shown in Figure 18. Table 4 compares head C.G. acceleration peak values, the HIC values, and the integration intervals for the HIC calculations for dynamic tests and the MADYMO analytical predictions. The correlation level shown between the dynamic test results and the MADYMO predictions was considered adequate for validation of the MADYMO airplane cabin class divider panel computer model. MADYMO analytical studies were then used to determine the stiffness characteristics of airplane cabin interior panels that would provide an acceptable level of head impact protection and HIC value for the impact condition defined in 14 CFR 25.562 (b)(2).

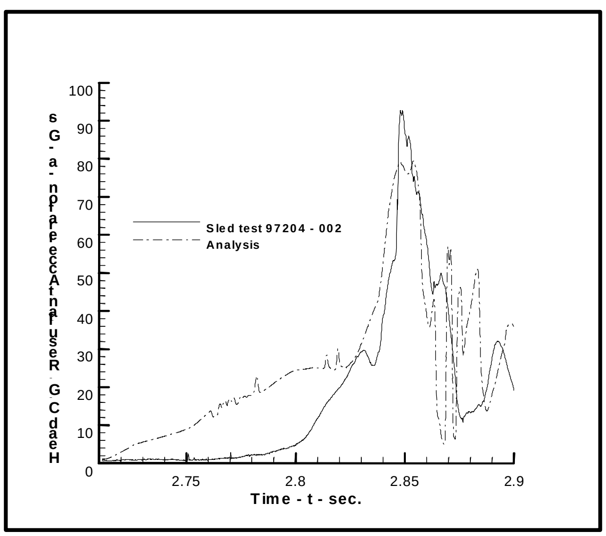


Figure 18- Comparison of Test and Analytical Head C.G. Accelerations

Table 4 – Comparison of Dynamic Tests and MADYMO Predictions

Data Comparison for Unmodified Divider Panel

	Head Impact Angle	Head Impact Velocity (ft/sec.)	Peak Head Acceleration (G's)	*HIC*	*HIC* Window $\Delta t = t_1 - t_1$ (ms)
Analysis Result	45°	45.9	133	1443	13.8

Data Comparison for Divider Panel with 5 Vertical Slits

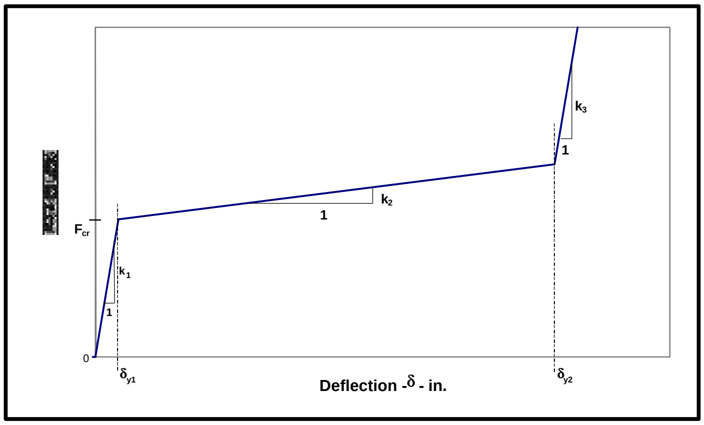
	Head Impact Angle	Head Impact Velocity (ft/sec)	Peak Head Acceleration (G's)	*HIC*	*HIC* Window $\Delta t = t_1 - t_1$ (ms)
Analysis Result	45°	45.9	80	831	27.8
Sled Test (97204-002)	44°	41.3	93	882	31.1

DESIGN GUIDELINES FOR HEAD IMPACT ATTENUATION

Softening Type Materials

The validated MADYMO model was used to determine the stiffness characteristics of an ideal airplane cabin interior panel that would provide an acceptable level of head impact protection and HIC value. Parameter studies that would define design curves that could be used as guidelines in the design of airplane cabin interior panels were performed. The MADYMO analyses initially considered structures that exhibit softening type stiffness characteristics. A softening type stiffness characteristic is one that initially exhibits little initial deflection for increasing load until the load reaches a level where the structure deforms extensively at a relatively constant load level until the structure bottoms out. Further increases in load produce little or no increase in deflection. Figure 19 illustrates a typical load/deflection curve for an ideal softening structure. An example of an actual softening type structure is shown in Figure 20. That figure shows that airplane cabin class divider panels exhibit load/deflection characteristics typical of a softening type structure.

The physical characteristics of an ideal load/deflection curve for softening cabin interior structures were determined using the validated MADYMO computer model. Figure 21 reflects the results of those analyses. That figure shows that an idealized cabin interior structure that deflects at a 2450 N (550 lbs.) load level for a minimum 5.5 cm. (2.2 inches) deflection would



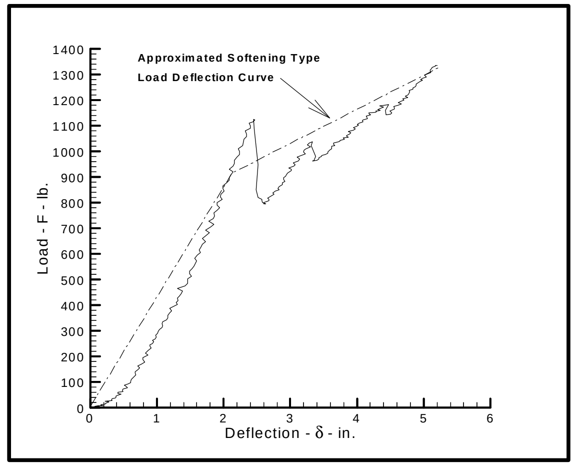
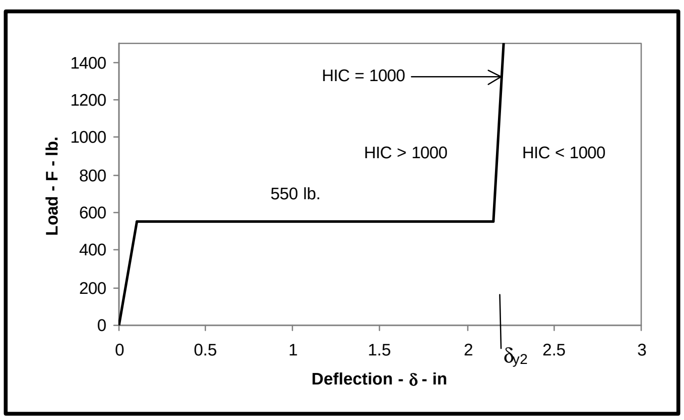


Figure 19 – Typical Load/Deflection Curve
Softening Type Structures

Figure 20 – Load/Deflection Curve
For Divider Panels

satisfy the HIC criteria and provide an acceptable level of head impact protection. Figure 22 shows a range of acceptable load/deflection characteristics for other softening type structures. Both Figures 21 and 22 can be used in the initial design stages of cabin interior structures. They can provide input to the design process by providing guidance regarding the desired stiffness characteristics of the structure.



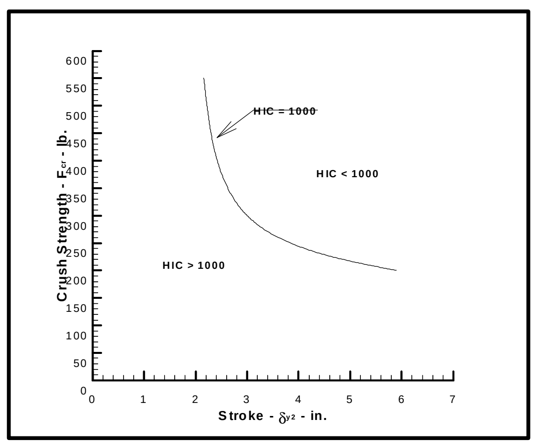
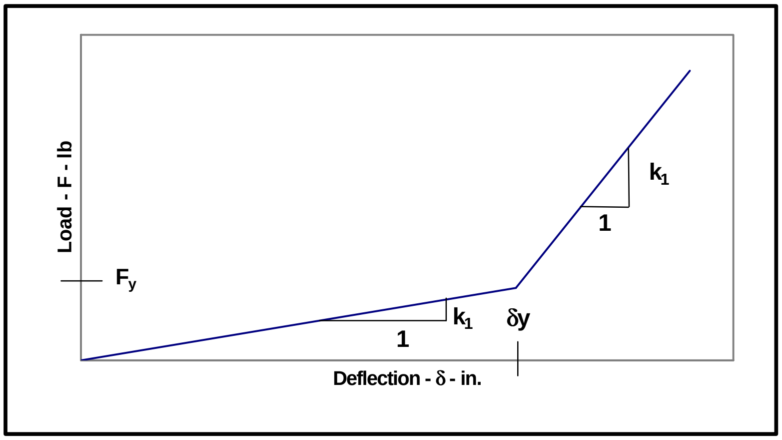


Figure 21- Load/Deflection Curve
For Ideal Softening Structure

Figure 22 – Softening Structural
Characteristics For HIC = 1000

Stiffening Type Materials

The MADYMO parameter studies also included structures that exhibit stiffening type stiffness characteristics. A stiffening type stiffness characteristic is one that initially exhibits large deflections at low load levels until the structure bottoms out. Further increases in load produce little or no increase in deflection. Figure 23 illustrates a typical load/deflection curve for an ideal stiffening structure. An example of an actual stiffening type structure is shown in Figure 24. That figure shows that sheet metal panel bulkheads exhibit load/deflection characteristics typical of a stiffening type structure.



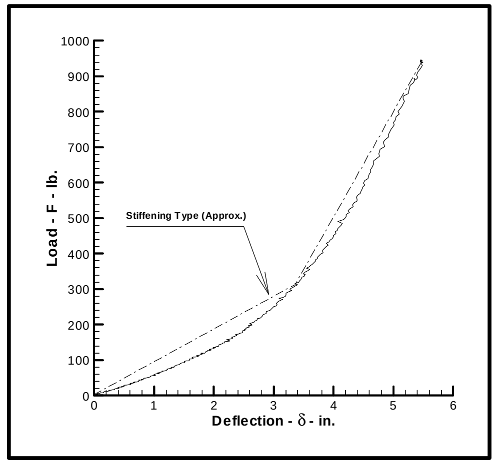
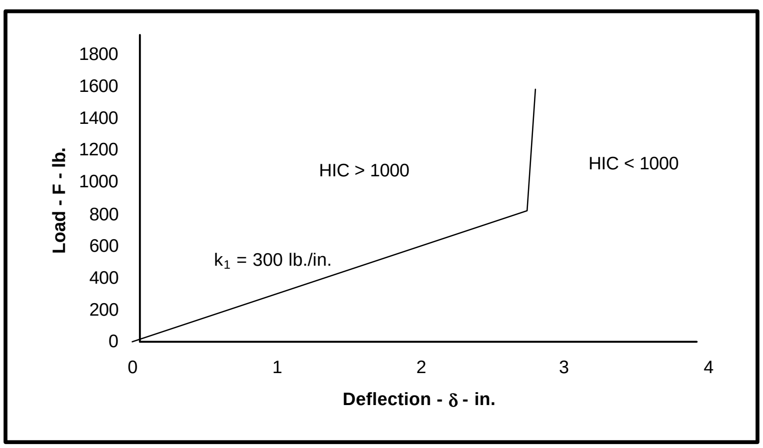


Figure 23 – Typical Load/Deflection Curve
Stiffening Type Structures

Figure 24– Load/Deflection Curve
For Sheet Metal Panels

The physical characteristics of an ideal load/deflection curve for stiffening cabin interior structures were also determined using the validated MADYMO computer model. Figure 25 reflects the results of those analyses. That figure shows that an idealized cabin interior structure that initially deflects at a 525 N/cm. (300 lbs./inch) loading rate for a minimum 7.0 cm. (2.8 inches) deflection would satisfy the HIC criteria and provide an acceptable level of head impact protection. Figure 26 shows a range of acceptable load/deflection characteristics for other stiffening type structures. Both Figures 25 and 26 can be used in the initial design stages of cabin interior structures. They can provide input to the design process by providing guidance regarding the desired stiffness characteristics of the structure.



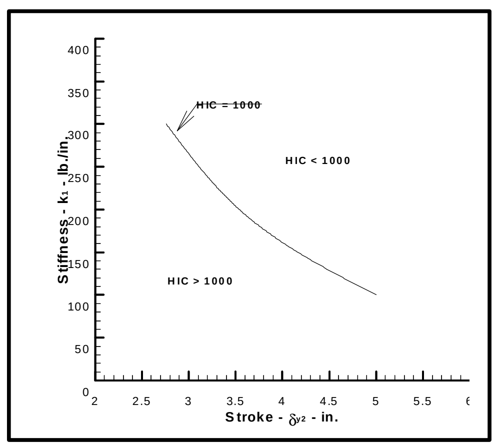


Figure 25 – Load/Deflection Curve
For Ideal Stiffening Structure

Figure 26 – Stiffening Structural
Characteristics For HIC = 1000

CONCLUSIONS

The research activities reviewed in this paper show that design and analytical procedures could be developed and used as design aids for structures that need to comply with the head impact protection injury criteria found in Federal Aviation Regulations, 14 CFR 25.562. Other specific findings include:

1. The rigid bulkhead baseline dynamic tests demonstrated that the common padding and foam materials used in these tests were ineffective in absorbing the head impact energy. Energy absorbing materials and/or structure (i.e., structural deformation) are required.

2. A design procedure for airplane cabin interior structures that makes use of static tests, dynamic sled tests, and MADYMO analyses has been defined and used to predict the effects of occupant head strikes and the resultant HIC value.

3. MADYMO analyses have been used to develop stiffness design curves for airplane cabin interior structures that may provide an acceptable level of head impact protection. Idealized stiffness design curves were developed for both softening and stiffening type structures

4. The analytical methods applied in this study have shown that for the impact condition defined in FAR 14 CFR 25.562 (b)(2) a minimum of 2.4 inches of structural deformation is required to provide an acceptable level of head impact protection and a HIC value less than 1000. That deformation value is consistent with other studies that found that 3-4 inches of structural deformation is required (Swearingen, 1996), (Boeing/ATA, 1991-1992), (Boeing/MGA, 1992).

A future demonstration program may lead to the design, fabrication, and certification of airplane cabin interior structures that could be placed in airline service.

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