IDENTIFICATION OF POTENTIAL INJURIES TO OCCUPANTS ON SIDE-FACING SEATS IN AIRCRAFT ACCIDENTS

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ABSTRACT

The existing seat dynamic performance standards in the Federal Aviation Regulations (FAR's) have been developed with the primary focus on forward or aft-facing seats, and are not appropriate for the evaluation of potential injuries to occupants seated on side-facing seats (SFS). The purpose of this study was to examine the injury criteria utilized by the automotive industry to assess injuries due to side impact accidents, and to investigate the potential applicability of these methods for side-facing seats in civil aircraft. Several sled tests had been conducted with single and double occupant with the test conditions complying with the 16G, 44 ft/s (13.41 m/s) horizontal impact specified in 14 CFR 25.562. Various side impact injury criteria were evaluated in the tests, including the Thoracic Trauma Index (TTI), Viscous Criteria (VC), rib deflection and pelvis acceleration. Analytical models were developed supporting the test results. Parametric studies had been performed with the validated analytical models to study various factors affecting the injury criteria. Neck loads for the various seating and belt configurations for Hybrid III and SID-H3 or Franken SID (US DoT-SID with Hybrid III head and neck), (MADYMO, 2001), was evaluated by analytical simulations. Inflatable restraint systems were used in reducing the neck injury values below the proposed tolerance limits. Analysis of the data acquired from the tests and observations related to injury parameters from all ATDs are presented. Through the conclusion, most suitable injury criteria are identified. Seating and restraint system configurations that provide maximum protection for occupants on SFS were also identified.

Aircrafts, Side-Facing Seats, Injury Criteria, Side Impact ATD, Restraint System

THE USE OF SIDE-FACING seats (SFS) in business jets is becoming increasingly more popular. Executives prefer to relax on couch-type seats while sitting opposite their business associates during in-flight meeting (Sperber, 1997). Certification of the SFS has become mandatory under FAR 25.785, requiring *equivalent level* of occupant protection as compared to a forward or aft- facing seat. Passengers seated on side-facing seats experience different dynamic response compared to those on forward or aft-facing seats in an aircraft accident. The regulations established by Amendment 25-64 were developed from a database of forward-facing seat test results, and no specific guidelines for the certification of SFS were given. Advisory Circular (AC) 25.562 does not specify a method of compliance nor the injury/pass-fail criteria for side-facing seats but recommendation is made to use the injury criteria as well as side-impact anthropomorphic test devices (ATD's) from the automotive industry. It is important to note that, although AC25.562 suggests the use of criteria from the automotive industry, the situation for aircraft SFS is quite different from the automotive side impact (Marcus, 1983), as no structure intrudes the side part of the ATD in an aircraft SFS and the nature of soft tissue injury is quite different compared to automotive counterpart.

This study details some of the injury criteria that might be used for the evaluation of the injuries for passengers on SFS. These include the acceleration-based criteria such as pelvic acceleration and thoracic trauma index (TTI (d)), compression-based criteria such as rib deflection and viscous criteria (V*C), and

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load-based criteria such as the lateral abdominal, illiac and pubic symphysis forces. For evaluating these injury parameters, a series of SFS type sled tests were conducted at the FAA Civil Aeromedical Institute (CAMI) utilizing a rigid divan type couch, with a rigid bulkhead in order to maximize the

potential injuries. Tests were conducted for different lap belt spacing, distances to barrier and distance between ATD's. A three point restraint system consisting of polyester webbing with a shoulder retractor was utilized. The generated data were compared in the level of biofidelity, instrumentation, and in predicting the potential injuries to an occupant in a SFS. Neck injury (other than whiplash) had not been a dominant occupant injury mode in automobile accidents and thus neck injury research had been limited. With the proliferation of sideward facing seats in business jet aircrafts new emphasis has been placed on the definition of human tolerance limits for lateral loading impact conditions. FAA has proposed the tolerance limits for lateral loads and moments. In this research we have used this proposed neck injury criteria evaluation to test the pass-fail criteria. Through the conclusion, the related injury and pass-fail criteria along with the most appropriate testing procedure for certification of these seats with some design guidelines to meet this certification are outlined.

Fig. 1 - Side Facing Seat in jet aircraft

POTENTIAL INJURY CRITERIA

The side-impact ATDs used by the automotive industry in dynamic testing includes Side Impact Dummy (US DoT-SID), European Side Impact Dummy (EuroSID-1) and Biofidelic Side Impact Dummy (BioSID) (SAE advisory report 1).

The automotive industry has developed many injury criteria that can be used to evaluate the potential for occupant injuries in automobile side impact situations. A number of these injury criteria have been used in the certification of automobile side impact protection. Others have been used solely for research purposes (SAE Advisory Report 2). These injury criteria along with current FAR 25.562 criteria need to be evaluated to determine if they are useful as a means of evaluating potential injuries in side facing aircraft seats. A comprehensive list of these potential injury criteria is listed below.

FMVSS 214 CRITERIA (docket no. 88-06):

Pelvic Acceleration: The potential for pelvis fracture was evaluated using the criterion established in FMVSS 214 for side impacts in automotive industry (Shams *et al*, 1995). The criterion provides for a limit of 130G for the lateral acceleration of the pelvis. Basically US Dot-SID was used to establish this criteria, but with Hybrid II and Hybrid III having identical pelvis construction, the criterion can be appropriately applied to sled tests and simulations using these ATDs.

Thoracic Trauma Index (TTI(d)): The TTI is an acceleration based criterion which uses the maximum value of the near-side rib and spinal acceleration, irrespective of the differences in time of occurrence, to determine an average acceleration response of the ATD (Cavanaugh *et al*, 1990, 1994). Thoracic Trauma Index, TTI(d), as measured by a side impact ATD should not exceed 85G. This limit corresponds to an AIS (Abbreviated Injury Scale) of 3 representing serious injury to the thoracic region, and is evaluated as:

$$TTI(d) = \tfrac{1}{2}\,(RIB_G + T12_G) \qquad (1)$$

where: RIB_G is the larger of the peak acceleration of the upper and lower rib (chest) in G's,

$T12_G$ is the peak acceleration of the 12 thoracic or the lower spine in G's.

Draft ECE 95 Criteria:

Viscous Criteria (V*C): It is evaluated from the product of the velocity of deformation and the instantaneous compression of the chest region of ATD (Lau and Viano, 1986).

$$V^*C = \max\left(\frac{D\dot{D}}{T_\circ}\right) \qquad (2)$$

where: D is deflection of the rib(s) or chest,

$\dot{D}$ is velocity of deformation of the rib(s) or chest,

T_o is half of undeformed width of the torso or chest.

(V*C) is a measure of the soft tissue injury induced by excessive deformation of the chest. It is rate sensitive and corresponds to potential injuries that are not addressed by compression criteria (Viano and Lau, 1988).

Rib Deflection: The lateral compression of rib-to-spine deformation should not exceed 1.6 in. (42 mm).

RESEARCH CRITERIA:

Pubic symphysis forces: As measured by the EuroSID-1 ATD, not to exceed 2,250 lb. (10 KN)

Lateral abdominal forces: As measured by the EuroSID-1 ATD, not to exceed 560 lb. (2.5 KN)

FAA REGULATION CRITERIA:

Head Injury Criteria (HIC): shall not exceed 1000. The HIC is defined (Gurdjian, 1953, 1964) by

$$HIC = \left[(t_2 - t_1) \left\{ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right\}^{2.5} \right]_{max} \quad (3)$$

where: a(t) is the instantaneous resultant acceleration of head CG in G's,

t_1 and t_2 are times in the pulse which maximize the HIC value.

Compressive load*:* Measured between the pelvis and the lumbar column not to exceed 1,500 lb. (7 KN)

Femur load: The axial compressive load in each femur of the ATD shall not exceed 2,250 lb. (10KN)

Shoulder Strap Load: For a three-point restraint system, the tension in the shoulder strap must not exceed 1,750 lb. (7.8 KN)

Restraint Retention: Upper torso restraint strap must remain on the occupant's shoulder during the impact.

Submarining: Lap safety belt must remain on the occupant pelvis during the impact, and no submarining is allowed.

NEW CRITERIA REQUIRED TO ESTABLISH AN EQUIVALENT LEVEL OF SAFETY:

Body-to-body contact: Contact between the head, pelvis, or shoulder area of one ATD on the adjacent seated ATDs is not allowed during the tests conducted in accordance with FAR 25.562(b)(1) and (b)(2). Incidental contact of the leg, feet, arms and hand that will not result in incapacitation of the occupants is acceptable. Contact during rebound is allowed. This requirement is due to the lack of information on injuries from body-to-body contact. Since very little is known, the standard simply does not allow the contact.

Body-to-wall/furnishing contact: If the sofa is installed aft of a structure such as an interior wall or furnishing that may contact the pelvis, upper arm, chest, or head of an occupant seated next to the structure, a conservative representation of the structure and its stiffness must be included in the tests.

Support*:* The occupant's pelvis must remain supported by the seat base throughout the test.

SIDE-FACING SEAT RESEARCH PROGRAM

To develop the research protocol the following methodology was used. Preliminary sled tests was conducted to study the kinematics of the occupants in side facing seats and to establish a baseline for occupant modeling. A preliminary model was then developed using the occupant simulation software MADYMO to arrive at a test matrix. A series of sled tests were conducted based on this at the CAMI in Oklahoma City, Oklahoma, USA. Dynamic side-facing seat tests were conducted at CAMI using their horizontal deceleration type impact sled.

FAR Part 25.562 Type II tests were conducted with no misalignment, with an initial velocity of 44 ft/sec and a 16G-deceleration pulse at a peak of 90ms. To attain maximum level of occupant contact and deceleration and to eliminate a possible glancing impact, the tests were conducted without yaw. For the tests, a steel 3-place couch with no energy absorbing features was used. A rigid impact barrier made of a 0.5-in. (0.013 m) thick aluminum plate with multiple I-beam back supports was installed at the forward end of the couch to maximize the potential for the injury. The three point restraints, with

a lap belt and shoulder harness of polyester webbing, supplied by Aircraft Belts Inc. were used for all the tests. US DoT-SID, EuroSID-1 and BioSID ATD's were used during the single occupant tests and the distance between the ATD and the rigid barrier was varied according to the range of couch sizes expected in aircraft. A Hybrid II was used during the double occupant tests to maximize the impact loading on the ATD's. Figure 2 shows the typical sled test setup configuration.

TESTS WITH US DOT-SID:

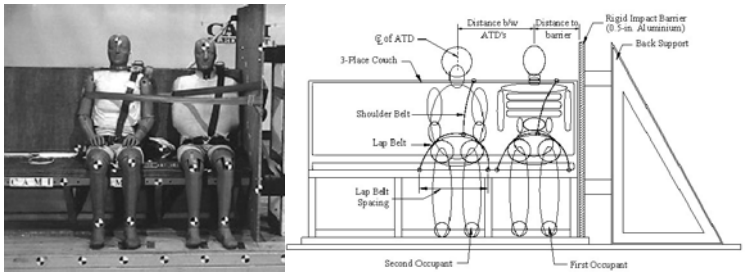


Fig. 2 - Typical sled test setup configuration

Tab. 1 - Summary of SFS tests with US DoT-SID

CAMI Test #	ATD Type & Order	Distance to Barrier (in.)	Distance Between ATDs (in.)	Lap Belt Spacing (in.)	Max Pelvic Acc. (G's)	TTI (G's)	HIC
A97055	SID	15 [0.38m]	n/a	30 [0.76m]	92.7	93.5	1872
A97056	SID	15 [0.38m]	n/a	30 [0.76m]	84.1	96.9	1851
A97057	SID	15 [0.38m]	n/a	30 [0.76m]	108.5	99.7	2206
A97058	SID	12 [0.31m]	n/a	24 [0.61m]	87.3	60.6	1825
A97059	SID	12 [0.31m]	n/a	24 [0.61m]	94.9	62.9	1957
A97060	SID	12 [0.31m]	n/a	24 [0.61m]	80.8	67.8	2196
A97061	SID & HII	12 [0.31m]	24 [0.61m]	24,24 [0.61m,0.61m]	89.8	62.2	1433
A97062	SID & HII	12 [0.31m]	18 [0.46m]	21,21 [0.53m,0.53m]	93.1	64.1	1442
A97063	SID & HII	12 [0.31m]	18 [0.46m]	21,21 [0.53m, 0.53m]	86.8	68.5	1711
A97064	SID & HII	9 [0.23m]	18 [0.46m]	18,18 [0.46m, 0.46m]	35.3	32.9	1451
A97065	HII & SID	9 [0.23m]	21 [0.53m]	18,24 [0.46m, 0.61m]	47.5, 53.3	**, 61.4	**, 1916
A97066	HII & SID	9 [0.23m]	24 [0.61m]	18,30 [0.46m, 0.76m]	48.9, 68.5	**, 79.1	300, 1061
A97067	HII & SID	12 [0.31m]	24 [0.61m]	24,24 [0.61m, 0.61m]	107, 54.9	**, 103.9	1840, 4252

* All the tests utilize a rigid impact barrier

The first series of tests were accomplished using the US DoT-SID, which was considered the simplest of the three-side impact ATD's (Viano, 1987). The goals of these tests were to determine the effect that ATD spacing and belt configuration had on pelvic acceleration and TTI. These tests were broadly classified into three sets with the first set, from A97055-60 with single occupant US DoT-SID ATD; the second set from A97061-64 was multi occupant, with US DoT-SID sitting beside the barrier and the third set from A97065-67 was also multi occupant, with HII sitting besides the barrier. A summary of all the test and their results are presented in Table 1. Each configuration was repeated three times to provide statistically reliable data. The data channels that were collected from this test include: pelvic acceleration, shoulder and right lap belt forces, upper chest, lower chest and lower spine accelerations for evaluating TTI and head acceleration for evaluating HIC.

By using a systems approach, dynamic testing of the side-facing seat was modeled using the MADYMO analysis tool (Ashkenazi and Arcan, 1993). The simulations were performed in three separate phases. In the first phase, models were generated to obtain at a preliminary test matrix for conducting sled tests using MADYMO belt models. In the second phase, simulations were performed to validate the model against a set of tests performed at CAMI. In the final phase, parametric studies were conducted with variation of different design variables such as lap belt spacing, occupant-to-occupant distance, occupant-to-barrier distance, lap and shoulder belt anchorage point and effect of 10 deg. yaw. The couch, barrier and the floor were modeled as rigid planes of same dimensions as of sled tests. The rigid couch was represented as two rigid planes that are fixed in space. One plane modeled as the seat pan while the other modeled as the seat back. A three-point restraint system was modeled using belt properties that were representative of the system used in the sled tests. The belt was modeled using the finite membrane elements since it possesses nearly zero bending stiffness

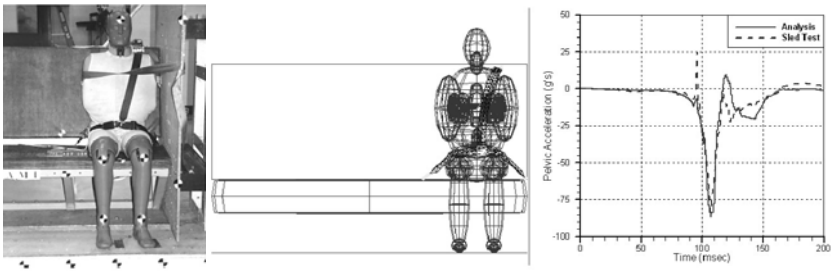


Fig. 3 - Validation of MADYMO model with sled test results

MADYMO simulations were validated, shown Figure 3, with that of SFS sled tests and further analyses were performed with different seating conditions and parameter variations to study other configurations. Different lap belts spacing like 24-in. (0.61m), 20-in. (0.51m) and 16-in. (0.4m) were considered to analyze the body displacement envelope. These studies were conducted to identify the most suitable belt spacing for which the body-to-body contact could be minimized. Even by moving the lap and shoulder belt anchorage point from left to right the occupant was not restrained completely. Hence, body-centered belt wrapping was analyzed in which the lap belt completely wraps the pelvis, with the anchorage at the back of torso. This yielded better result, as the occupant torso was completely restrained. The next set of tests was analyzed for multi-occupant seating, to evaluate the body-to-body forces for lap belt spacing of 20 in. (0.51 m) and 16 in. (0.4 m). The TTI values were much lower than the threshold value of 85 G and the effect of lap belt spacing were not significant, as the lower torso alone is restrained resulting in a significant effect on the pelvis acceleration.

SIDE-FACING SEAT TESTS WITH EUROSID-1:

Based on the results acquired using US DoT-SID, the second phase of testing was planned using EuroSID-1 to investigate if the injury criteria as measured from an EuroSID-1 ATD indicate a similar potential for injuries when compared to data acquired from previous series of tests conducted with a US DoT-SID. In addition to Thoracic Trauma Index (TTI), which was acquired with the previous US DoT-SID tests, the EuroSID-1 would provide:

- Rib deflection data to compute the Viscous Criteria (V*C) injury assessment for the thorax. The ATD has three rib deflection potentiometers and thus three data channels are used to compute V*C.
- Pubic force compression load and the lateral abdominal force

The test setup was a replicate of earlier series of tests done with US DoT-SID, to enable us to compare the biofidelity of both the ATDs. The configurations that were looked into are single occupant, impacting a rigid barrier and a padded wall of 1-in. thick IV3 foam. For multi-occupant tests, Hybrid II was seated next to EuroSID-1, with the two ATD's shoulders touching each other, in order to reduce the relative velocity of the Hybrid II. The last two tests utilize a body-centered restraint system. The summary of test results is presented in Table 2.

It was inferred from the test data that the effect of padding resulted in lower acceleration values of rib and pelvic, with no significant effect on the rib deflections. In general it was observed that the rib deflections are pretty high in all these tests, and in some cases the rib potentiometers are bottomed out although the viscous criteria was below the threshold of 1m/s. From this data it seems that the occupant was exposed to much slower rate of chest and rib compression but for a longer period. Therefore to restraint the lateral excursion of the occupant, subsequent tests were conducted with a body-centered belt in which the lap belt was wrapped around the pelvis with the shoulder harness anchorage behind the neck as shown in Figure 4. The essential difference between the conventional three-point restraint and the body -centered belt was, in the later, the belt wraps around the pelvis completely in the direction of impact. Because of this ATD was restrained, to a large extent resulting in no contact to the barrier when the centerline of ATD was at a distance of 16-in (0.4 m) from it. This configuration demonstrated reasonable potential to minimize the acceleration, compression and force based criteria.

Table 2. Summary of Euro SID-1 test results.

CAMI Test #	ATD Type & order	Distance to Barrier (in.)	Distance b/w ATD (in.)	Lap Belt Spacing (in.)	Max Pelvic Accel(g's)	TTI (g's)	Rib Deflections ($x10^{-3}$ m)			$V*C_{max}$ [3]
							Upper Rib	Middle Rib	Lower Rib	(m/s)
A98005[1]	EuroSID-1	15.75 [0.4m]	N/A	21 [0.53m]	105	64.9	45.0	39.9	36.8	0.74
A98006[2]	EuroSID-1	15.75 [0.4m]	N/A	21 [0.53m]	150	81.8	50.2	39.7	36.5	0.93
A98007	EuroSID-1&HII	15.75 [0.4m]	19.5 [0.5m]	21,20[0.53, 0.51m]	150	86.6	55.9	44.5	40.0	0.99
A98008	EuroSID-1&HII	12 [0.31m]	19 [0.48m]	21,21[0.51,0.51m]	77	44.5	59.0	46.2	40.9	0.68
A98009	EuroSID-1	19 [0.48m]	N/A	10 [0.25m]	33.8	44.7	0	0	0	-
A98010	EuroSID-1	16 [0.41m]	N/A	10 [0.25m]	45.2	46.7	0	0	0	-

[1] Padded wall of 1-in. thick IV3 foam. [2] Rigid barrier [3] Maximum value of upper, middle and lower rib is considered

For all the sled tests, US DoT-SID recorded higher rib acceleration as compared to EuroSID-1. This could be attributed to the arm and shoulder structure of the two ATD's, which differ significantly and the width of the EuroSID-1 ATD was more by 2-in (0.051m), as compared to US DoT-SID. Moreover, US DoT-SID was more sensitive to rigid barrier impacts and lacks biofidelity in chest compliance. Besides that, the US-Dot SID lacks a human-like chest deflection response, which was crucial to the injury indicating capabilities of an ATD, because of its rib cage design. The US-Dot SID dummy has a 9.8 kg near side-rib mass, which was approximately an order of magnitude greater than the effective human near-side rib mass. It produces impact responses that are nearly three times higher than the recommended human chest response. This was concluded when the rib acceleration profiles of the two ATDs are overlapped for similar test conditions. The US DoT-SID shows higher peak values and the impact occur much earlier than the EuroSID-1 ATD.

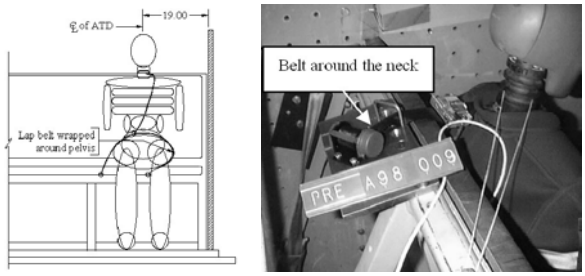


Fig. 4 - Body-centered Belt configuration.

SIDE-FACING SEAT TESTS WITH BIOSID:

The tests were conducted to investigate if the injury criteria as measured from a BioSID ATD indicate a similar potential for injuries when compared to data acquired from previous series of tests conducted with a US DoT-SID and EuroSID-1. In addition to Thoracic Trauma Index (TTI), Rib deflections and Viscous Criteria (V*C) values acquired with the previous EuroSID-1 tests, the BioSID will provide:

- Illiac force
- Upper Neck Moment in x-direction and force in y-direction (for some of the tests)
- Larger Rib Deflections (up to 75 mm) compared to EuroSID-1

The test setup was a replicate of earlier series of tests at CAMI with EuroSID-1. Distance to barrier from the dummy was measured from the ATD centerline. A 3-point restraint was used with a standard lap belt installation and a single shoulder harness over the forward shoulder for tests A98014 and A98015. A 16-in. (0.41m) distance to barrier represents a 6.3-in. (0.16m) space between the ATD's forward shoulder and the barrier i.e. the width of BioSID is 19.4-in. as measured from shoulder arm to arm. A 1-in. (0.025m) thick pad was used on the rigid barrier in the region of head impact to prevent any damage to the BioSID head. A 1-in. (0.025m) thick pad was used on the rigid barrier in the region of lower leg to prevent any damage to the BioSID lower leg. A hip plug, made of styrofoam, of 2.85-in. (0.072m) outer diameter and a 0.5-in. (0.13m) inner diameter and a height of 2.5-in. (0.064m) was placed near the pelvis for all the tests on the side of impact. BioSID has five ribs in its upper chest. Therefore accelerometer locations are scaled from EuroSID-1 ATD and correspondingly placed on the BioSID ATD. This helps in comparison of acceleration and compression data for the EuroSID-1 and BioSID tests. A body-centered belt configuration, with lap

belt wrapped around the pelvis and a single shoulder harness was used for the tests A98011 and A98012. A summary of the test conducted at CAMI is shown in Table 3.

Tab. 3 - Summary of test conducted at CAMI with BioSID

CAMI Test #	ATD Type & order	Dist. to barrier (in.)	Lap Belt Spacing (in)	Test Pulse (G's)	Sled Vel. (ft/s)	Max. Pelvic Accel. (G's)	TTI (G's)	Rib Deflections ($x10^{-3}$ m)			Viscous Criteria (m/s)
								Upper Rib	Middle Rib	Lower Rib	
A98011	BioSID	16.00 [0.41m]	10 [0.25m]	16.1	45.1 [13.75m/s]	34.5	74.2	11.9	-	7.5	0.12
A98012	BioSID	16.00 [0.41m]	10 [0.25m]	15.5	45.0 [13.71m/s]	35.0	74.5	9.7	-	8.9	0.1
A98013*	BioSID	15.75 [0.4m]	21 [0.53m]	-	-	141.0	66.6	47.2	-	49.1	1.06
A98014	BioSID	15.75 [0.4m]	21 [0.53m]	16.4	45.2 [13.78m/s]	119.0	78.8	48.0	-	50.5	1.1
A98015	BioSID	15.75 [0.4m]	21 [0.53m]	16.4	45.1 [13.75m/s]	83.4	67.3	52.7	-	54.5	1.14

*Not a valid Test, as the hip plug was not placed near the pelvis of the BioSID ATD

OBSERVATIONS:

The following observations were made from these series of SFS tests.

1. Pelvic accelerations in general are less than 130 G except for those tests in which the ATD center-line distance to barrier is larger than 12-in. (0.31m) EuroSID produced higher pelvic acceleration when compared to BioSID and US DoT-SID
2. TTI results from similar test conditions with the US DoT-SID and EuroSID-1 were consistent but the values are in general a little lower for EuroSID-1 than the SID values
3. The rib deflections were in general quite large although V*C data usually were below the threshold in most cases. This might suggest that rib deflection limit could be a more suitable injury criteria to be used than the V*C for aircraft occupant injury evaluation on SFS's. With BioSID there were cases where the V*C was over the threshold value of 1 m/s.
3. Body-centered belt wrapping seams to be the most effective configuration as the occupant is laterally restrained. Body-centering lap belt with a shoulder attachment behind the ATD neck minimized the compression, acceleration and force based injury criteria.
4. Force based injury criteria like, the Illiac force, Pubic symphysis force and the abdominal forces are below the injury threshold values.
5. In case of multi-occupant seating, as the distance between ATD's decreases the acceleration criteria decrease. Although these criteria are below the threshold in most of the tests, the nature of body-to-body injury is found to be the most significant issue.

The examination of the video data of both the sled test and the simulation showed excessive head rotation that could lead to serious neck injuries. Taking this into account, neck injuries that could occur due to a side-facing seat configuration needs to be addressed.

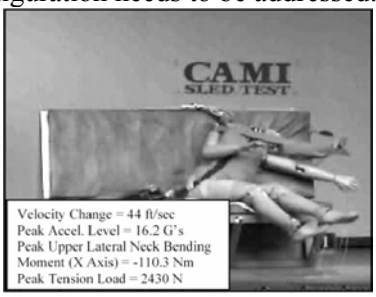


Fig. 5 – Sled test video of an occupant in SFS showing the excessive head rotation

NECK INJURY CRITERIA EVALUATION

There are no standard criteria specified for neck injury in standard aircraft regulations. The criteria which is being used in automotive industry has been recommended to be used in aircraft industry. It is important to note that, although AC25.562 suggests the use of criteria from the automotive industry, the situation for aircraft SFS is quite different from the automotive side impact, as no structure intrudes the side part of the ATD in an aircraft SFS and the nature of soft tissue injury is quite different compared to automotive counterpart.

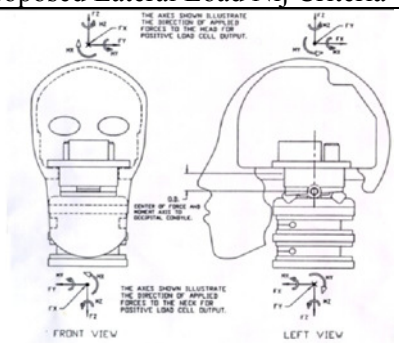
The FAA and NHTSA are initiating research tasks directed to further define tolerance limits for lateral neck loading. The following proposal has been made by Stephen J. Soltis, Federal Aviation Administration (Soltis, 2001). Two forms of candidate tolerance limits for lateral neck loading are

proposed. These limits are based on the maximum measured kinematics and load values that appear to reach the onset of minor injury and the threshold of serious injury.

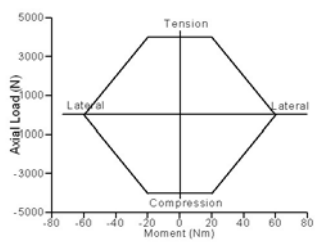
1. The first form is based on the kinematics response of the occupant.
   - Lateral neck flexion not to exceed 60 degrees. This angle is measured between the head anatomical vertical axis and the mid-sagittal plane of the ATD. Neck flexion was a cited concern by many of the researchers.
   - Peak linear acceleration not to exceed 36 G's measured at the C.G of the ATD's head.
   - Peak angular acceleration of the ATD's head not to exceed 2600 rad/sec^2.
   - Where head strike with structures or other obstacles occurs the kinematics based limits are not to be exceeded up to the point of head contact. During head contact HIC not to exceed 1000.
2. The second form of tolerance limits is based on the peak axial loads and moments measured at the neck of the occupant.
   - Lateral neck moment (Mx) not to exceed 536 inch-pounds (i.e., 487 inch-pounds (55 Nm) increased 10% to account for muscle strength) or 60 Nm measured at the upper neck load cell of an ATD.
   - The maximum axial loads not to exceed 940 lbs. force (4170 N) tension and 900 lbs. force (4000 N) compression.
   - Nij criteria using the NHTSA's intercepts with above lateral moment limit as shown in Table 4.

Table 4 - Proposed Lateral Load Nij Criteria

Dummy Size	Peak Limits		
50% Male	Tension (N)	Compression (N)	
	4170	4000	
	Nij Intercepts		
	Tension (N)	Comp. (N)	Lateral Moment (Nm)
	6806	6160	60



Hybrid III Upper Neck Load Cell Orientation



Proposed Lateral Load Nij Criteria

Based on recent studies with Hybrid III ATD, done in Civil Aeromedical Institute (CAMI), pass/fail neck injury criteria based on combination of maximum lateral bending moment (Mx), tensile force (Fz), and shear force (Fy) measured with the Hybrid III neck load cell has been developed. The upper neck orientation of the Hybrid III ATD is shown in Table 4. The following maximums have been proposed.

Lateral bending moment Mx	< 487 inch-lbs (55 Nm)
Tensile force Fz	< 1530 lbs (6806 N)
Compressive force Fz	< 1200 lbs (5338 N)
Lateral shear force Fy	< 250 lbs (1112 N)

When calculating the Nij, combined effect of axial load and lateral bending moment has to be considered. As shown in Table 4 the neck loads and moments should fall within the region marked by the polygon to pass the criteria. Or in other words, during the impact response period, the combination of Fz and Mx must be within the following limit:

$$\text{Nij} = \left(\frac{Mx}{487}\right) + \left(\frac{Fz}{1530}\right) < 1$$

PARAMETRIC STUDIES FOR STUDYING NECK LOADS

In the past most of the research activities have rightly focused on the more common injury modes that are associated with frontal impacts and forward facing seats. Lateral neck injury modes have not had much emphasis. However with the proliferation of sideward facing seats in business jet aircraft and the automotive industry's initiative to improve the occupant impact protection level for side impact automobile accidents new emphasis has been placed on the definition of human tolerance limits for lateral loading impact conditions. Parametric studies have been done with occupant sitting

next to the barrier and at the center of the couch. SID-H3 (Franken SID, FSID) Side Impact dummy has been used for the studies, it is similar to the US DoT-SID with the exception of the neck and the head. In this model, the head and neck of the Hybrid III dummy model is combined with the US DoT-SID model.

Parametric studies have been done using the validated analytical model to study the neck loads with different restraint system configurations and different occupant positions. Validation has been done with sled tests (using the US-DoT SID), as the parameters validated like pelvis acceleration, TTI and chest accelerations are common in both dummies, validation can be effective. Good correlation has been obtained in pelvic acceleration and TTI values. Different belt configurations used in the parametric studies are shown in Figure 6.

1. Mid Position (Buckle 1) 2.Right Position (Buckle 2) 3.Extreme Position (Buckle 3)
4.Body Centered 5. Body Centered with shoulder behind neck

Fig. 6 - Various Belt Configurations

Test Matrix along with the results, shown in Table 5, has been developed taking all the factors into consideration. First series of test set was done with single occupant by varying the distance to the barrier and the buckle types. Second series was done using body centered lap belt configuration and shoulder anchorage position behind the neck. Third series was used to study the effect of body-to-body contact on the neck loads by having two occupants sitting in the couch. Hybrid III has been used as the second occupant sitting away from the barrier with proper contacts given between the dummies. Distance between the dummies was varied to observe the effect on the neck loads. Polyester belt properties were given to the finite elements used in modeling the belt. Rigid properties had been given to the seat and the barrier to study for the worst-case scenario. A typical 16g, triangular acceleration pulse with a rise time of 90ms was applied for all the simulations.

Neck injury criteria were calculated according to the proposal given by the FAA, CAMI. In this research we have used the limits proposed by the FAA, CAMI as described earlier. Using Franken SID, loads and moments with respect to all the axes were obtained. We were mainly considered about the axial loads (Fz), lateral shear loads (Fy) and lateral bending moment (Mx). The loads and moments obtained for all the simulations are tabulated in Table 5 with the calculated Nij value. From the results we can clearly see that Nij value fails in all the cases. The lateral bending moment value has more effect on the Nij values than the axial loads. In all the cases the lateral bending moment was well over the critical limit proposed which is 487 inch-lbs (55 Nm). The axial load was well within the tolerance limit of 1530 lbs (6806 N) for tension and 1200 lbs (5338 N) for compression. But the combined effect of bending moment and axial load has to be considered in calculating the Nij value, which takes the value beyond 1.0. The lateral shear load was also over the limit in most of the configurations. With the use of body-centered lap belt configuration and shoulder anchorage behind the neck Nij has been reduced, but still the values were above the tolerance limit.

Table 5 - Test Matrix for Parametric Studies

Test Set	ATD Type & Order	Distance to barrier	Distance Between ATD's	Lap Belt Spacing	Buckle Type	Shoulder Belt Position	Mx	Fz	Fy	Nij
1.1	FSID	12 [0.31m]	-	16 [0.41m]	1	-	-92	-3796	1024	2.223
1.2	FSID	12 [0.31m]	-	16 [0.41m]	2	-	-93	-3731	-1072	2.238
1.3	FSID	12 [0.31m]	-	16 [0.41m]	3	-	-57	-2635	1722	1.424
1.4	FSID	36 [0.91m]	-	16 [0.41m]	1	-	71	1949	1103	1.573
1.5	FSID	36 [0.91m]	-	16 [0.41m]	2	-	116	2129	1751	2.414
1.6	FSID	36 [0.91m]	-	16 [0.41m]	3	-	118	1822	2556	2.414
1.7	FSID	12 [0.31m]	-	20 [0.51m]	1	-	69	912	1608	1.395
1.8	FSID	12 [0.31m]	-	20 [0.51m]	2	-	-106	-2958	931	2.366
1.9	FSID	12 [0.31m]	-	20 [0.51m]	3	-	-95	-3626	1075	2.252
1.10	FSID	36 [0.91m]	-	20 [0.51m]	1	-	78	1516	1277	1.634
1.11	FSID	36 [0.91m]	-	20 [0.51m]	2	-	94	2106	1484	2.025
1.12	FSID	36 [0.91m]	-	20 [0.51m]	3	-	138	1657	2191	2.746
2.1	FSID	12 [0.31m]	-	BC	-	-	-110	-4443	-1035	2.650
2.2	FSID	36 [0.91m]	-	BC	-	-	82	1966	1463	1.782
2.3	FSID	12 [0.31m]	-	BC	-	BN	-72	-2385	1396	1.656
2.4	FSID	36 [0.91m]	-	BC	-	BN	58	1671	997	1.306
3.1	FSID & HIII	12 [0.31m]	24 [0.61m]	20 [0.51m] 20 [0.51m]	1	-	67 84	911 1662	1609 1480	1.357 1.772
3.2	FSID & HIII	12 [0.31m]	24 [0.61m]	16 [0.41m] 16 [0.41m]	1	-	-124 100	-4228 1897	1147 1513	2.869 2.090
3.3*	FSID & HIII	12 [0.31m]	24 [0.61m]	16 [0.41m] 16 [0.41m]	1	-	-125 116	-4059 1967	1238 1501	2.669 2.395
3.4	FSID & HIII	12 [0.31m]	18 [0.46m]	16 [0.41m] 16 [0.41m]	1	-	-106 76	-3539 1752	1184 1358	2.453 1.640

FSID Franken SID BC Body centered lap belt HIII Hybrid III dummy BN Behind neck shoulder anchoring * Rigid armrest is considered Tolerance Limits: Fz (compression)< 5338 N, Fz (tension) < 6806 N, Fy < 112 N, Mx < 55 N-m

This interest and effort to provide better occupant safety has led to the development of the all-new restraint system i.e. "Inflatable seat belt Restraint system". Inflatable seat belt restraint system falls under Inflatable Restraint System category (IRS). Inflatable seat belts were used for the occupants placed away from the barrier. After different iterations the best design for the inflatable seat belt has been developed. Body centered lap belt configuration and shoulder anchorage behind the neck combined with the inflatable seat belt restraint system provides the best result for the occupant placed away from the barrier. Side airbag has been designed and used to reduce the loads acting on the dummy placed next to the barrier. Side airbags considerably reduces the neck injury value well below the threshold of 1.0. Figure 7 shows the inflatable seat belt and the side airbag restraining the occupants.

Table 6 shows the neck injury values for 3-point restraint system and the inflatable restraint system. All the neck loads and moments were considerably below the critical values with the use of inflatable seat belt restraint system and side airbag. Neck injury criteria were below the threshold of 1.0 for both the ATDs.

Table 6 Comparison of the results obtained with and without inflatable restraint systems

Test Setup	FSID				Hybrid III			
	Fz	Fy	Mx	Nij	Fz	Fy	Mx	Nij
3-Point Restraint System	2009	1477	95	2.020	1855	1325	85	1.823
Inflatable Restraint System	946	843	34	0.754	735	914	42	0.880

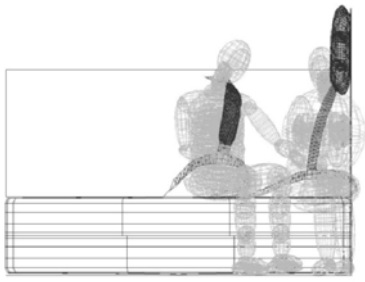


Fig. 7 - Inflatable restraint system

CONCLUSIONS

The purpose of the research project was to examine the methods utilized by the automobile industry to assess thoracic injuries due to side impact accidents, and to investigate the potential applicability of these methods for sided facing seats and sofas in civil aircraft. This knowledge may be used to develop crashworthiness standards for side facing seats. The following conclusions can be made from this study:

1. Acceleration based criteria depend on the relative velocity of the impact and the stiffness of the object impacted. Tests show that the pelvic accelerations were below the critical limit with the ATD centerline 15" (0.38m) or less from the rigid barrier. TTI values were below the critical limit when the occupant was 12" (0.31m) (or less from the barrier. But with 1" of IV3 padding on the barrier the ATDs gave good results when seated up to 15.75" (0.4m) from the barrier. These findings indicate that a seat design that places an occupant close to a padded supporting wall would be desirable.
2. Limiting compression-based criteria needed an opposite approach to limiting acceleration-based criteria. The padding used in this project had little affect on rib compression. Avoidance of contact with the wall was the only effective means of preventing rib compression demonstrated by the tests in this project. In order to have a balance between limiting acceleration and compression-based criteria, body centered restraint system had been used. With body centered restraint the translation of the ATD had been reduced considerably and thereby reducing the compression-based criteria. With this design the acceleration-based criteria could also be limited to acceptable levels. Other means of limiting the load on the ribs, such as an energy-absorbing wall, may also be useful in meeting both types of injury criteria
3. After analyzing all the data obtained from the sled tests, EuroSID-1 was found to be more reliable in measuring data. The results were repeatable and provide good correlation with the other side impact ATDs. SID lacks the ability to measure rib deflection and did not provide accurate lateral flail response when restrained by only the belts. This was primarily due to lack of a clavicle for the shoulder belt to bear on. The BioSID was least suitable, since lack of a second arm and the "farside" spine design prevents its use in evaluating body-to-body contact. Noisy nature of the acceleration data produced by the BioSID was also a concern. BioSID was not durable and repairs were necessary after each test.
4. Attempts to quantify the effects of body-to-body contact were not conclusive. When the H-II ATD was placed aft of the SID or EuroSID-1, both the acceleration and compression based criteria tended to be somewhat higher. However, limitations in the design of all current side impact dummies, which are only biofidelic when struck from one side at a time, prevent proper assessment of the potential for injures resulting from body-to-body contact. Further study using occupant-modeling codes may yield the information sought.
5. Study on the neck loads shows that more work needs be done on the interior to bring them below the tolerance limits. All the belt configurations failed, with body centered restraint

giving encouraging results. Inflatable restraint systems considerably reduced the neck loads but the practicality of the design of inflatable belt is of concern. Side airbags can be one of the solutions in reducing the neck loads for the occupant sitting next to the barrier.

REFERENCE

14 CFR 25, Code of Federal Regulations, Part 25 – Airworthiness Standards: Transport Category Airplanes, the Office of the Federal Register, National Archives and Records Administration, 2001.

Ashkenazi, Z., and Arcan, M., 1993 "Use of MADYMO to Investigate Impact on Occupants Sitting Laterally to the Direction of Travel" Tel AVIV University, Ramat AVIV, Tel AVIV, Israel.

Cavanaugh, J.M., and Malhotra, T.J., 1990, "Biomechanical Response and Injury Tolerance of the Pelvis in Twelve Sled Side Impacts", SAE Paper No 902305.

Cavanaugh, J.M., Timothy Walilko, Anthony Walbridge, Yue Huang, and Albert I.K., 1994, "An Evaluation of TTI and ASA in SID Side Impact Sled Tests", SAE Paper No. 942225.

Federal Motor Vehicle Safety Standard No.214, Side impact production docket no.88-06, notice 8 RIN 2127-AB86.

Gurdjian, E.S., Lissner, H.R., Latimer, F.R., Haddad, B.F., and Webster, J.E., 1953, "Quantitative Determination of Acceleration and Intercranial Pressure in Experimental Head Injury", Neurology 3, 417-423.

Gurdjian, E.S., Roberts, V.L., Thomas, L.M.,1964, "Tolerance Curves of Acceleration and Intercranial Pressure and Protective Index in Experimental Head Injury", J. of Trauma 6, 600.

Lau, V.I., and Viano, D.C., 1986 "The Viscous Criteria-Bases and Applications of an Injury Severity Index for Soft Tissues", SAE Paper No. 861882, 31st STAPP car crash conference, Warrendale, Pennsylvania.

MADYMO Database Manual Version 6.0, 2001, TNO, Delft, Netherlands.

Marcus, J.H., Morgan, R.M., Eppinger, R.H., Kallieris, D., Mattern, R., and Schmidt, G., 1983, "Human Response to and Injury from Lateral Impact", SAE Paper No. 831634.

SAE Advisory Report 1 Chapter 2 "Adult dummies: past and present".

SAE Advisory Report 2 Chapter 5 " Injury Assessment".

Shams, T., Zhao, Y.M., and Rangarajan, N., 1995, "Safety of Side Facing Seats in General Aviation Aircraft", SAE Paper No. 951164, Corporate and regional aviation meeting and exposition, Wichita.

Soltis, S. J., 2001 "An Overview of Existing and Needed Neck Impact Injury Criteria for Sideward Facing Aircraft Seats" The Third Triennial International Aircraft Fire and Cabin Safety Research Conference, Atlantic City, USA.

Sperber, M., Schuller, E., Schroth, C.J., 1997, "Crashworthiness of Side-Facing Seating Positions in Aircrafts, Biodynamics Stresses and Maximum Strain Criterion", SAE Paper No. 971456 Corporate and regional aviation meeting and exposition, Wichita.

Viano, D.C and Lau, I.V., 1988, "A Viscous Tolerance Criterion for Soft Tissue Injury Assessment", J. Biomechanics Vol. No.5, pp 387-399.

Viano, D.C., 1987, "Evaluation of the SID dummy criterion for side impact testing", 31st STAPP car crash conference, SAE Paper No #872208, Warrendale, Pennsylvania.