MODELING OF OCCUPANT RESPONSE ON SIDE-FACING AIRCRAFT SEATS

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ABSTRACT

This paper addresses the injury and pass/fail criteria as well as the kinematics of occupants on side-facing aircraft seats. To demonstrate *equivalent level of safety* for these seats compared to the conventional forward-or-aft seats, a number of side-facing seat impact sled tests were conducted using a SID with three-point restraint system on a rigid divan-type couch with a rigid bulkhead in order to maximize the potential for injuries. For multi-occupant tests, a Hybrid II ATD was utilized as a second occupant. Analytical models were developed supporting the test results. A set of parametric studies were then conducted to identify proper restraint systems and seating configurations to protect the occupants.

INTRODUCTION

In the field of business jets, side-facing seats are quite popular. Many business people, who are the main users of such jets, prefer to relax on these couch type seats during flight and also to sit opposite their interlocutors at meetings, which are held during the flight (Sperber, 1997). Certification of these side-facing aircraft seats (individual and couch type) has presented new challenges to the aircraft industry. Dynamic certification of new side-facing seats (SFS) has become mandatory under Federal Aviation Regulation (FAR) 25.785: "*... a side-facing seat must provide the same level of occupant protection as a forward- or aft-facing seat with a safety belt and shoulder harness, and in general provide the protection provision of 25.562.*" 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 was 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. However, AC 25.562-1A, states that, "*The injury criteria of 25.562 are not adequate to demonstrate the* ***equivalent safety*** *of side-facing seats. To demonstrate equivalent safety fully in the absence of such specified criteria, the applicant must use other* ***injury criteria*** *which may be derived from the automotive industry, which uses* ***side-impact anthropomorphic test devices or dummies (ATD's)***." 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. The eventual goals of this research are to identify appropriate injury criteria and to identify a suitable side impact ATD for aircraft SFS certification. In addition a set of design guidelines was sought that would allow a simplified certification procedure using standard forward facing ATD's.

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INJURY AND PASS/FAIL CRITERIA

The side-impact ATD’s used by the automotive industry in dynamic testing includes Side Impact Dummy (SID), European Side Impact Dummy (EuroSID I) and Biofidelic Side Impact Dummy (BioSID) (SAE advisory report 1). The research program described in this paper examines the response of the SID. The SID is adapted from the Hybrid II 50th percentile male test ATD in an attempt to give it biofidelity in lateral impact. University of Michigan Transport Research Institute (UMTRI) developed it for NHTSA (National Highway Traffic Safety Administration) in 1979. Head, neck and neck bracket design is from Hybrid II 50^{th} percentile male test dummy design. Upper torso was redesigned to give calibrated responses to impacts from the left or right side with reversal of certain interior components. Arms omitted to prevent flailing and complication of torso response, are replaced by foam blocks under the torso jacket. Rib cage has five pairs of spring steel ribs with energy absorbing damping material. An adjustable shock absorber controls motion. Lower torso, modified from Hybrid II, responds to impacts at hip rotation centers from left or right side. The Legs are of Hybrid II design. Major biofidelic deficiencies are the lack of a shoulder load path, no elasticity in the thoracic compliance, and a very heavy rib mass. Figure 1 shows the SID and its instrumentation (SAE Advisory Report 3).

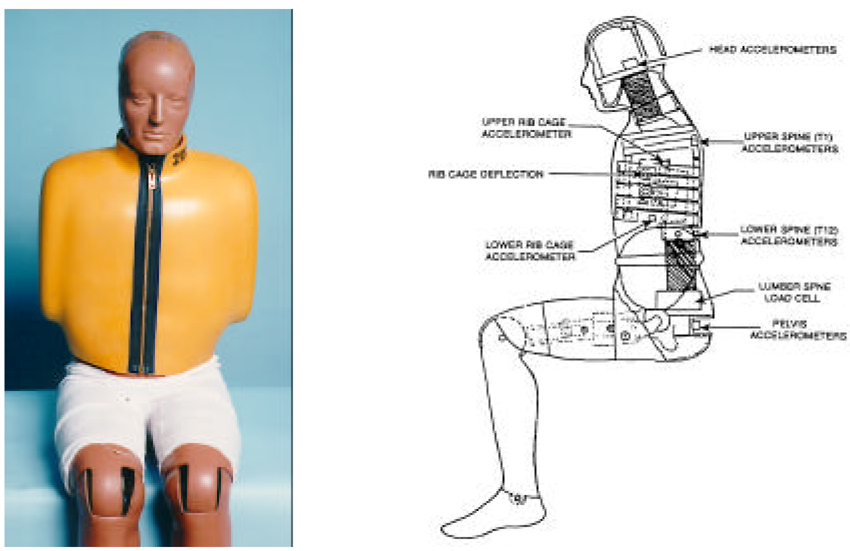


Figure 1. Side impact ATD SID with its instrumentation used in dynamic testing.

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. 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 (SAE Advisory Report 2). 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. Since SID for which this criterion was established and the Hybrid II and III have 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 differences in time of occurrence, to determine an average acceleration response of the ATD (see 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 or the 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 ATD, not to exceed 2,250 lb. (10 KN)

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

Lateral neck moments: As measured by BioSID or Hybrid III, not to exceed 354 in-lb. (40 N-m).

Lateral neck forces: As measured by BioSID or Hybrid III, not to exceed 250 lb. (1.1 KN).

FAA Regulation Criteria

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

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

Where: a(t) is the instantaneous resultant acceleration of head CG in G's, and
t_1 and t_2 are arbitrary 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) (for Test 1 condition only).

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

The methodology used to develop the research protocol is shown in the Figure 2. A preliminary test series was conducted to study occupant kinematics and 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 Civil Aeromedical Institute (CAMI) in Oklahoma City, OK, USA. The results of these tests were then used to validate the occupant model. A series of parametric studies were then conducted to analyze the occupant behavior in various environments.

Dynamic side-facing seat tests were conducted at CAMI using their horizontal deceleration type impact sled, shown schematically in Figure 3 (Desjardins, 1991). A typical deceleration pulse is shown in Figure 4.

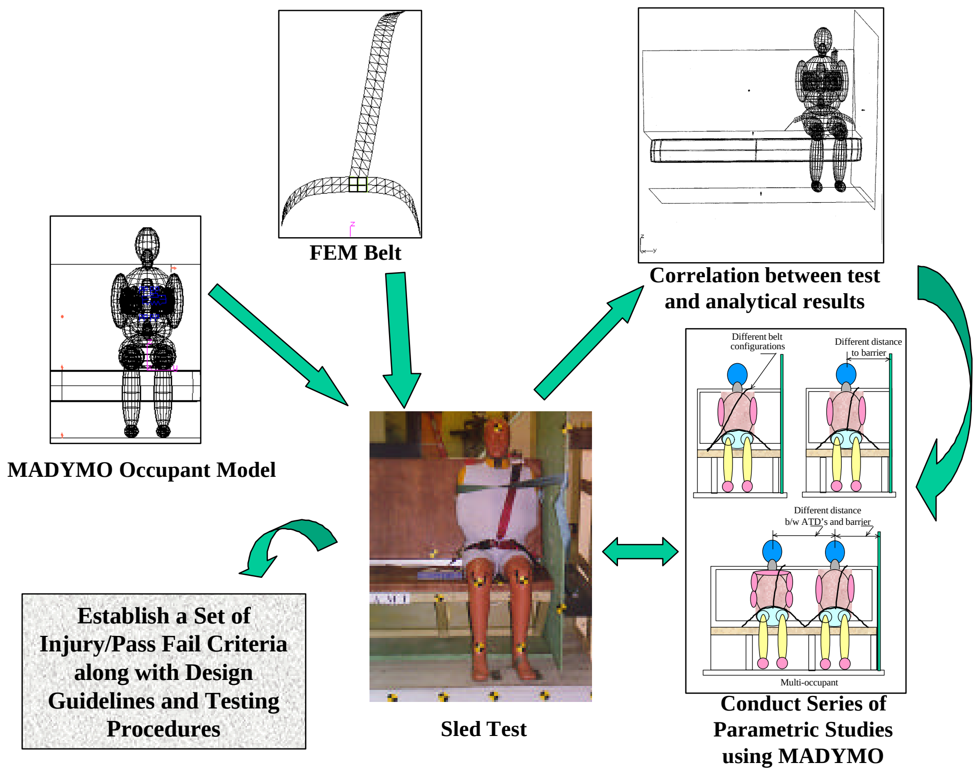
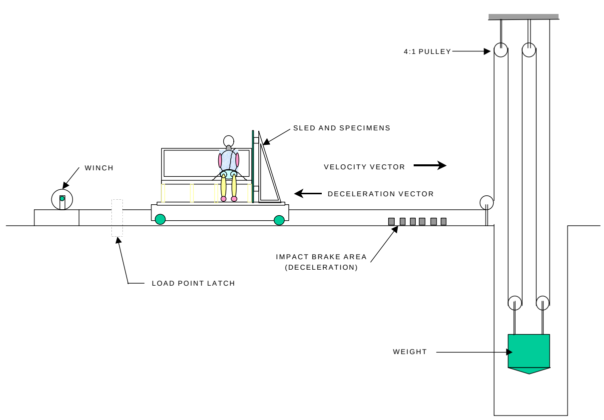


Figure 2. Flow diagram for Side-facing aircraft seats.



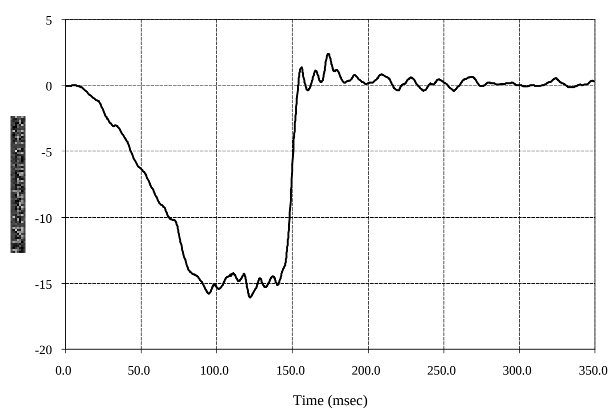
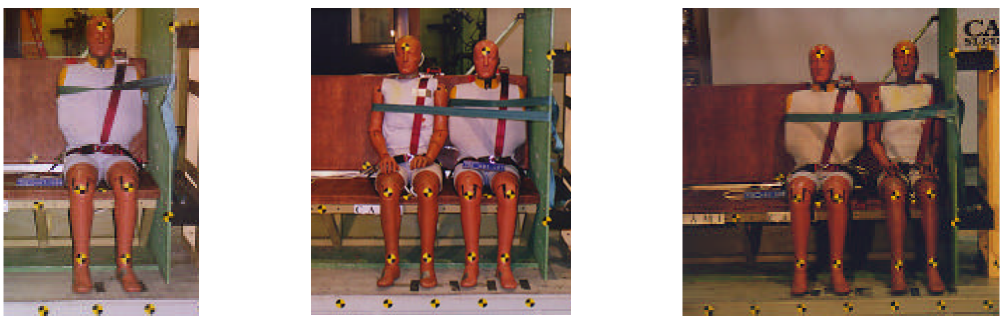


Figure 3. Schematic of CAMI sled test facility. Figure 4. Typical deceleration pulse at CAMI.

FAR Part 25.562 Type II tests were conducted with no misalignment, with an initial velocity of 44 ft/sec (13 m/s). 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. 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. A SID ATD was used during the single occupant tests and the distance between dummy 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 as shown in Figure 5.



SID | SID and Hybrid II | Hybrid II and SID

Figure 5. Single and multi-occupant tests with SID.

SIDE-FACING SEAT TESTS WITH SID

The first series of tests were accomplished using the SID, which is considered the simplest of the three side impact ATD's (Viano, 1987). The goals of these tests were to determine the affect 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 SID ATD; the second set from A97061-64 is multi occupant, with SID sitting beside the barrier and the third set from A97065-67 is also multi occupant, with HII sitting besides the barrier. 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. The tests A97055 to A97057, single occupant with ATD centerline distance to barrier – 15 in. (0.38 m), and A97058 to A97060, single occupant with ATD centerline distance to barrier – 12 in. (0.3 m), are for the same set of conditions and were repeated aiming at a more statistically reliable data. To ascertain the same, statistical analysis is performed using a standard T test, normal distribution, and a 90% confidence level. It was found from the calculations that 90 % of the tests run with these parameters will have a TTI falling into the interval of $91 < \mu < 101$. For the series A97058-60 similar analysis was performed which resulted in a interval of $57 < \mu < 70$, and predicts that 90% of tests run in this condition fall into this interval.

Based on this analysis, the variation of pelvic acceleration and TTI for the tests A97055-60 as a function of the distance of the SID ATD to the barrier is shown in Figure 6. It is evident that the pelvic acceleration is much lower than the severe injury level (130 G) for both the distances to the barrier. For a 15-in (0.38 m) barrier distance TTI value marginally failed the required criteria. The change of the distance of the barrier to 12-in. (0.30 m) reduced TTI well below the severity level (Hargrave, 1989). HIC is above the tolerance threshold for all the cases, but the purpose of these tests was not to meet the HIC requirement, but rather to investigate the configurations that would meet TTI and pelvic acceleration criteria. For the tests from A97061-64 the injury parameters measured were below the threshold, but as observed from the video data the body-to-body contact might render a significant issue. Moreover it can be inferred that as the variables like ATD distance to barrier, distance between ATD's and lap belt spacing decreases, the acceleration values are lowered. For the subsequent tests ATD positions were interchanged to evaluate the body-to-body impact TTI as the SID is instrumented for one side impact only. The TTI value is above the threshold as can be compared between the tests A97061 and A97067.

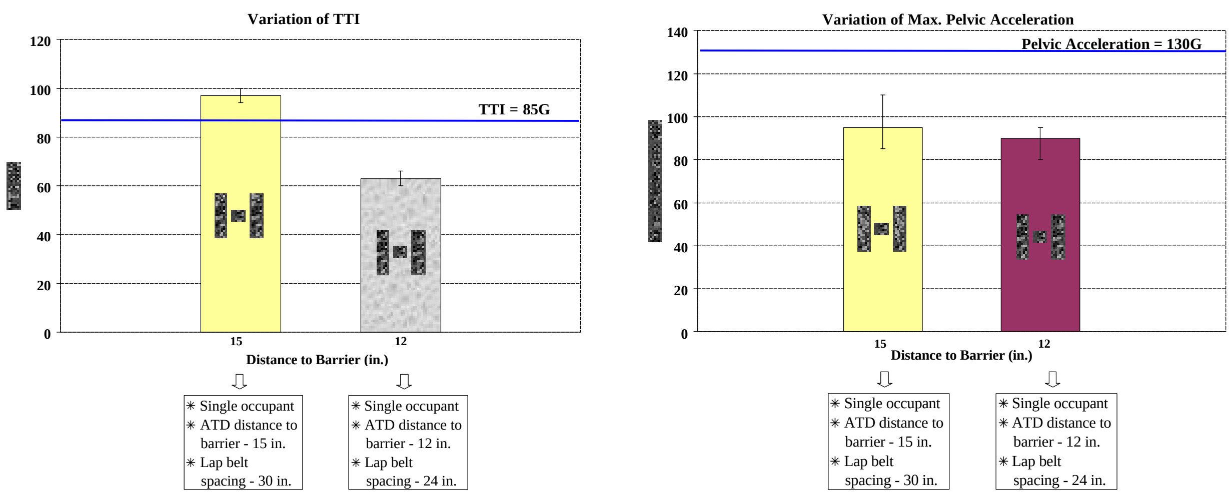
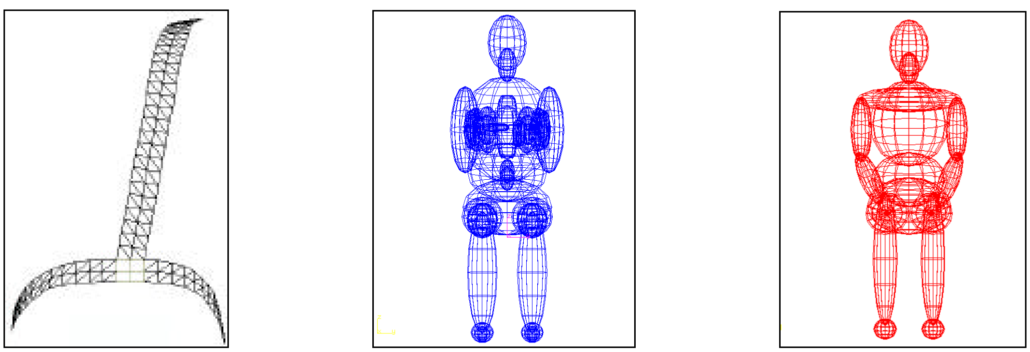


Figure 6. Variation of Pelvic acceleration and TTI for different distance to the barrier.

MODELING AND ANALYSIS OF SID TESTS

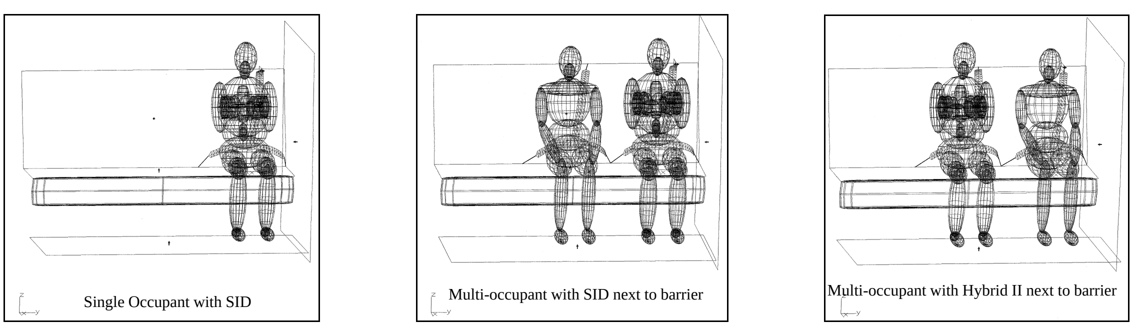
By using a systems approach, dynamic testing of the side-facing seat was modeled using the MADYMO analysis tool (Ashkenazi and Arcan, 1993). The simulations were performed in three separate phases. In the first phase, models were generated to obtain at a preliminary test matrix for conducting sled tests 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 MADYMO model of the couch/ATD/barrier test configuration is shown in the Figure 8. 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 the seat pan while the other modeled the seat back.

The floor and rigid impact barrier were also modeled by means of a rigid plane. An additional rigid body was placed below the seat to arrest the leg displacements in a manner similar to that observed during the sled tests. The contact forces between these planes and the ATD body is defined by appropriate loading and unloading curves. 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 as per MADYMO theoretical manual, 1996. The belt portions that are in contact with occupant are modeled by finite elements and these are connected to the conventional belt model, by which multi-directional sliding can be realized. This helps to simulate phenomena such as submarining and belt roll out yielding good simulations and much better results of the injury parameters. MADYMO ATD models of US DOT SID and Hybrid II as per MADYMO database manual (1996) were used as occupants in respective positions. These models are shown in Figure 7. Test pulses of the corresponding test deceleration pulses were digitized and put as acceleration in the input data. All simulations were carried out to 200 msec., which was beyond the influence of crash pulse. For analytical purpose, representative CAMI sled tests A97055, A97058, A97061, and A97067 were modeled and simulated, as the rest of the tests were duplication of these prescribed tests. The simulation models are shown in the Figure 8. Injury parameters like pelvic acceleration, TTI, HIC, belt forces and the body-to-body or body-to-barrier forces and belt forces are looked into. Sled test and analysis peak values of pelvic



3-point finite element belt SID Hybrid II

Figure 7. MADYMO models of Finite element belt, SID and Hybrid II.



Test A97058 Test A97061 Test A97067

Figure 8. MADYMO simulations for the tests at CAMI with Finite element belts.

acceleration and TTI show reasonable agreement as can be read from Figure 9. Similarly, the profiles of pelvic accelerations were compared and showed reasonable agreement, during the peak acceleration period and is less than the threshold value of 130G in all the cases as shown in Figure 10. The Figure 11 shows the comparison of upper, lower chest and spine acceleration profiles for the test A97058 as a typical test. The accelerations of the upper and lower chest are higher when compared to MADYMO, whereas the spine acceleration is lower for this test condition. Overall the TTI values fairly agrees with all the test conditions (within 10%) for which these three accelerations are used.

Further analytical studies are conducted to study the probable contact forces between the barrier and occupant in case of single occupant and contact force between the occupants in case of multiple occupants. This will provide the information forehand to analyze the potential injuries pertaining to this type of seating. It can be inferred that the forces decrease as the lap belt spacing and ATD distance from barrier decreases. Simulations were extended to study the effect of 10-deg yaw on the system. No roll out is possibly observed and pelvic accelerations and TTI were further lowered. Although analysis shows reasonable correlation with the tests, several parameters including the belt properties, slipping and friction, etc. could affect the results.

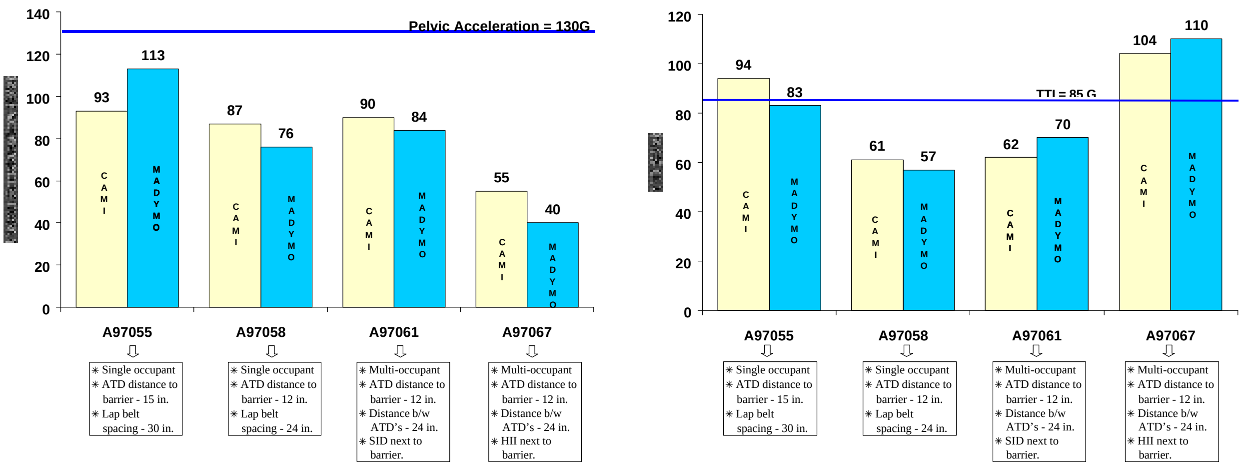


Figure 9. Comparison of pelvic acceleration and TTI peak values: Sled test with analysis.

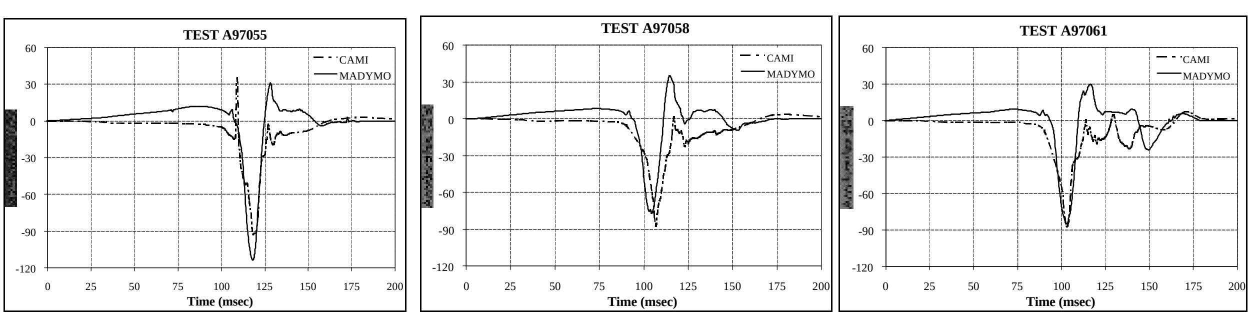


Figure 10. Comparison of pelvic acceleration profile: Sled test with analysis.

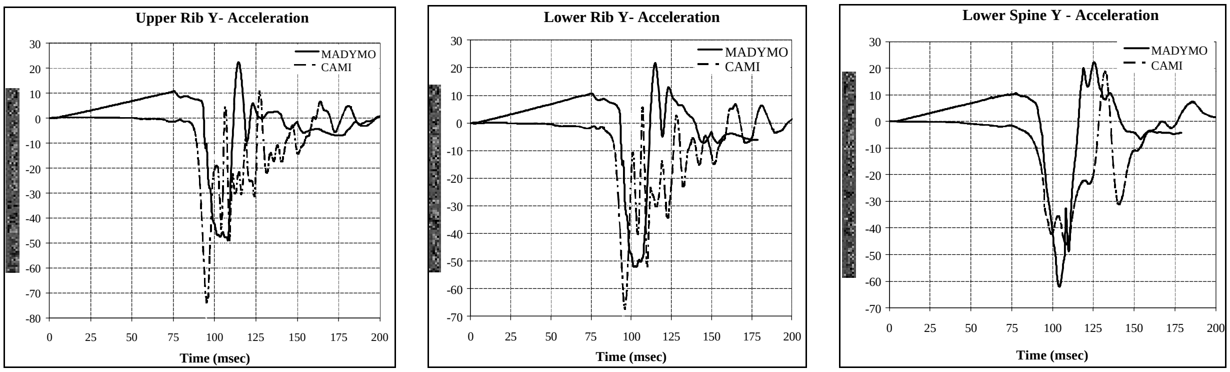
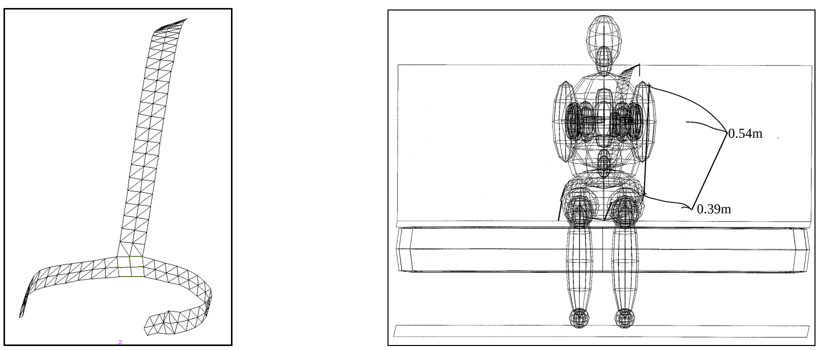


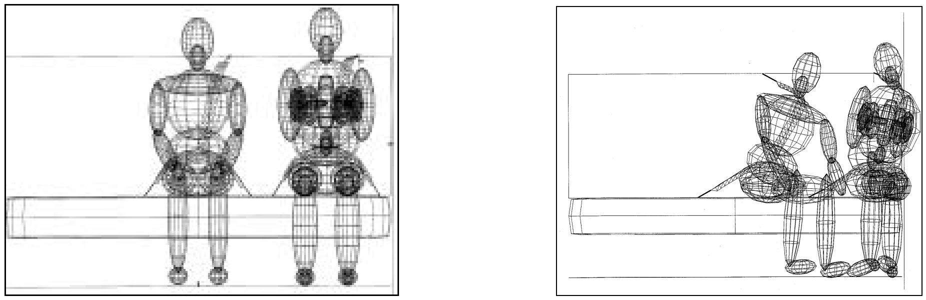
Figure 11. Comparison of chest accelerations profiles: Sled test with analysis.

Having validated the results of MADYMO simulations with that of SFS sled tests further analysis was 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. The belt with 16-in. (0.4m) lap belt spacing provided good results minimizing the lateral exertion, as the belt is closely wrapped around the body. 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 as shown in Figure 12. The next set of tests was analyzed for multi-occupant seating, to evaluate the body-to-body forces by placing the SID next to the rigid barrier for lap belt spacing of 20 in. (0.5 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.



Body-centered belt Body-envelope

Figure 12. MADYMO parametric studies with Body-centered belt.



Pre-simulation for multi-occupant Sample during Simulation

Figure 13. MADYMO parametric studies simulations.

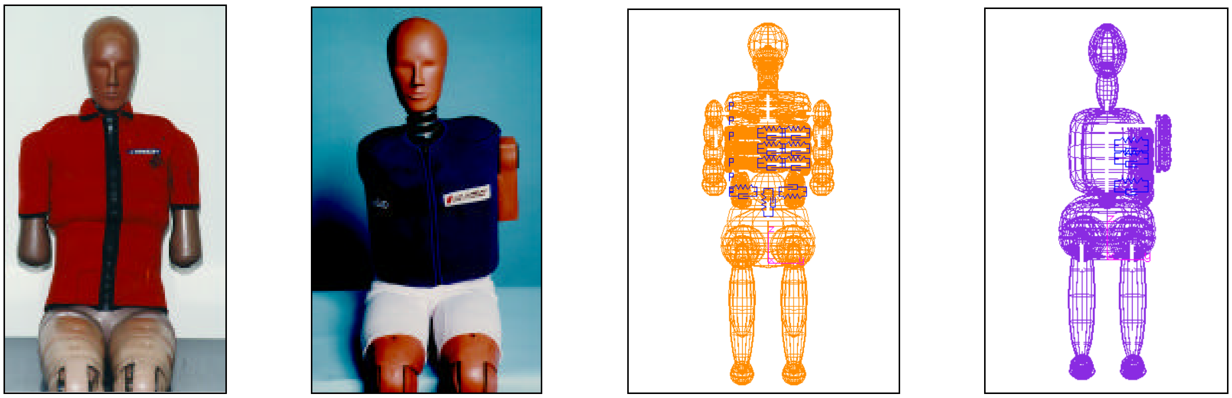
CONCLUSIONS

The purpose of this study was to understand the nature of crash injuries sustained by an occupant on a side-facing aircraft seat. This knowledge may be used to design crashworthiness standards for these seats with a higher degree of protection. The following conclusions can be made from this study.

For all the sled tests and the simulation conducted the resultant pelvic acceleration was below the threshold of 130G. Similarly the other acceleration based criteria, the TTI was also less than the injury threshold of 85G for an single occupant test with an ATD centerline distance of 12 in. (0.3 m) and a lap belt spacing of 24 in (0.61m). It was observed that the most significant parameter was the distance of ATD to the wall and as this distance increases, the ATD gains velocity resulting in higher acceleration values. Hence, for single seating, ATD centerline distance of 12 in. (0.3m) from the barrier would be an acceptable design. It is to be noted that these injury values are corresponding to the worst possible scenario, as a rigid bulkhead was utilized in all the sled tests and simulations. Besides these, the SID in general has been shown to be stiffer than the other side impact ATD's, and is quite sensitive to rigid barrier impacts. The study in general showed that for single SFS, it is possible to obtain a set of design guidelines on belt spacing, distance to bulkhead, shoulder restraint attachment point, belt geometry, belt stiffness, bulkhead properties, etc. for which TTI and pelvic accelerations are kept below the threshold. 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. Therefore, alternate means of minimizing the lateral excursion are explored, of which body-centered belt configuration yielded best results, restraining the occupant laterally. The study also revealed that MADYMO analytical studies using SID showed reasonable agreement with the experimental test results conducted at CAMI. The parametric studies with this analysis tool resulted in arriving at optimum design configurations such as the body-centered belt. Hence the occupant simulation codes can greatly reduce the number of full-scale sled tests.

The SID lacks a human-like chest deflection response, which is crucial to the injury indicating capabilities of an ATD, because of its rib cage design. (Viano, 1987). The principal measure of biofidelity of a test device is the human-like force deflection response and the acceleration-based injury criteria do not seem to provide enough insight into all modes of injury.

Thus the SID has the capability to measure only some of the injury criteria listed earlier and for the compression and viscous measures other side impact ATD's, such as EuroSID and BioSID that have these capabilities, are to be explored as shown in the Figure 14.



EuroSID ATD | BioSID ATD | EuroSID MADYMO Model | BioSID MADYMO Model

Figure 14. ATD and MADYMO model of EuroSID and BioSID.

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