AEROSPACE RECOMMENDED PRACTICE	ARP5765™	REV. A
	Issued 2012-10 Revised 2015-12 Superseding ARP5765	

(R) Analytical Methods for Aircraft Seat Design and Evaluation

RATIONALE

The changes in this revision represent the latest agreement obtained by the SAE SEAT Committee to provide the most current information on the topic. Specifically, this revision adds three new sections: Seat System Verification and Validation, Model Use, and Documentation of V&V and Model Use. Preexisting sections of the document have been revised to improve clarity and provide additional information or correct errors.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) defines a means of assessing the credibility of computer models of aircraft seating systems used to simulate dynamic impact conditions set forth in Federal Regulations §14 CFR Part 23.562, 25.562, 27.562, and 29.562. The ARP is applicable to lumped mass and detailed finite element seat models. This includes specifications and performance criteria for aviation specific virtual anthropomorphic test devices (v-ATDs). A methodology to evaluate the degree of correlation between a seat model and dynamic impact tests is recommended. This ARP also provides testing and modeling best practices specific to support the implementation of analytical models of aircraft seat systems. Supporting information within this document includes procedures for the quantitative comparison of test and simulation results, as well as test reports for data generated to support the development of v-ATDs and a sample v-ATD calibration report.

1.1 Purpose

This ARP aims to supplement the information provided in the FAA Advisory Circular (AC) 20-146. In general, assessing the credibility of modeling and simulation (M&S) is accomplished through the processes of Verification and Validation (V&V), which are rapidly evolving disciplines within the computational world. The recommended methodology for the successful design and evaluation of aircraft seats using analytical methods is a building block approach comprised of the following steps: software verification, v-ATD calibration, material characterization, subsystem tests, seat system validation, and sensitivity analysis. The v-ATD calibration is seen as the most critical component of the above approach, and as such, the v-ATD performance criteria is a separate section of this document (Section 3). To support the development of v-ATDs, a series of tests of physical ATDs was accomplished and the test information is provided for the Hybrid II (Appendix B) and FAA-Hybrid III (Appendix C). To aid in the completion of the six steps outlined above, the final primary section of the document contains recommended practices for both physical testing and numerical modeling (Section 5).

The uses of M&S in aircraft seat design and evaluation are numerous and begin in the early phases of any development program. Computer aided engineering tools that allow M&S of prototype designs are readily available. The use of M&S here allows tradeoffs to be conducted, evaluation of injury risks, investigation of potential failure areas, and the selection of successful design parameters. Beginning in these early phases will also help develop the future test plans to increase the odds of a successful seat system validation. Once a baseline seat is identified, M&S may be used for determining the critical cases for which testing may be necessary. Using M&S here will potentially reduce the number of required developmental and certification tests. After a baseline seat system is validated, M&S may be applied to investigate installation specific issues and minor modifications without the need to retest.

While there are several advantages of using M&S, it must also be recognized that there are several limitations. Successful validation depends on the quality of the reference test data, modeling techniques and interpretation of the correlation results. The M&S process discussed here relies heavily on the use of test data, and as such, physical testing is still required. Even with a model that is valid for the intended use, there are compliance situations where simulation cannot be applied and further testing will still be required. For example, if the model shows that a design modification significantly increases the stress in critical components where there are no redundant load paths, then a retest may be necessary to ensure that a failure does not occur.

This document is focused on providing guidance to the various stakeholders involved in the M&S process, who may each have different objectives in mind. These stakeholders include the software developers, seat suppliers, seat integrators (usually airframe manufacturers and their certification staff), and regulatory agencies. Their respective primary areas of concern roughly correspond to the different levels of the model validation process. The code developers need to understand the documentation requirements for the code verification and document the limitations of the code. v-ATD model developers need to understand the v-ATD calibration procedure amongst other things, in order to develop models that are useful for customers.

End users for a code or model (v-ATD) also need to understand clearly the limitations and its impact on their final objective and results before using the models. For example, some v-ATDs may be certified to be conditionally compliant which then the end user has to understand the implications of the conditions on his or her results.

The seat suppliers are primarily interested in developing accurate seat models in hopes of reducing the development cycle and the number of certification tests. The airframe manufacturers depend on the integrity of these models to produce reliable interface loads and are responsible to certify the seat for installation into the aircraft. The certification staff and regulatory agencies are concerned with the configuration control of the final product and how M&S relates to a safe and certified system. Thus the goal of this recommended practice is to offer to the seat community a set of potential criteria that may be used to support the creation and documentation of a valid seat system or subsystem in order to support certification efforts and to inform, and potentially streamline, the design process.

1.2 Units

In this document U.S. customary units (in-pound) and International System of Units (SI) are provided. In all cases, the in-pound units take precedence and the SI (metric) units provided are approximate and conservative conversions. Those who routinely use SI units in practice should ensure that the conversions are accurate.

1.3 Coordinate Systems

The coordinate systems in this document are consistent with SAE J211-1. Reference to x, y, and z dimensions are in the seat or ATD coordinate system and follow standard naming convention.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 AS8049B, Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft

2.1.1.2 SAE J211-1, 2007-07, Instrumentation for Impact Test - Part 1 - Electronic Instrumentation

2.1.1.3 SAE J211-2, 2008-11, Instrumentation for Impact Test - Part 2 - Photographic Instrumentation

2.1.1.4 Gowdy, V., DeWeese, R., Beebe, M., Wade, B. et al., "A Lumbar Spine Modification to the Hybrid III ATD For Aircraft Seat Tests," SAE Technical Paper 1999-01-1609, 1999, doi:10.4271/1999-01-1609

2.1.1.5 Bhonge, P. and Lankarani, H., "Finite Element Modeling Strategies for Dynamic Aircraft Seats," SAE Technical Paper 2008-01-2272, 2008, doi:10.4271/2008-01-2272

2.1.2 Code of Federal Regulation (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-0000, www.gpoaccess.gov.

2.1.2.1 Title 14 Part 23 (§14 CFR Part 23) Airworthiness Standards: Normal, Utility, and Acrobatic Category Airplanes

2.1.2.2 Title 14 Part 25 (§14 CFR Part 25) Airworthiness Standards: Transport Category Airplanes

2.1.2.3 Title 14 Part 27 (§14 CFR Part 27) Airworthiness Standards: Normal Category Rotorcraft

2.1.2.4 Title 14 Part 29 (§14 CFR Part 29) Airworthiness Standards: Transport Category Rotorcraft

2.1.2.5 Title 49 Part 572, Anthropomorphic Test Devices, Edition 10-1-88

2.1.3 Federal Aviation Administration (FAA) Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

2.1.3.1 FAA AC 20-146 Methodology for Dynamic Seat Certification by Analysis for use in Parts 23, 25, 27, 29 Airplanes and Rotorcrafts, 2003

2.1.3.2 DOT/FAA/AR-05/5 Development and Validation of an Aircraft Seat Cushion Component Test Volume 1

2.1.3.3 DOT/FAA/AR-11/24 Certification by Analysis: Hybrid II and FAA Hybrid III Virtual Anthropomorphic Test Devices Validation and Verification Methodology

2.1.3.4 FAA AC 25.562-1B, Dynamic Evaluation of Seat, Restraint Systems and Occupant Protection on Transport Airplanes, 2006

2.1.3.5 DOT/FAA/AR-2,11: Human Factors Associated with the Certification Of Airplane Passenger Seats: Seat Belt Adjustment and Release

2.1.3.6 Metallic Materials Properties Development and Standardization (MMPDS - 08), 2013

2.1.4 Industry Publications

2.1.4.1 Bathe KJ, Finite Element Procedures, Prentice Hall publication, 1996

2.1.4.2 Mark's Standard Handbook for Mechanical Engineers, 10th edition, 1999

2.1.4.3 Standard Test Methods for Tension Testing of Metallic Materials, Standard E8 / E8M -09 American Society for Testing Material, 2008

2.1.4.4 Standard Test Methods for Flexible Cellular Materials, - Slab, Bonded, and Molded Urethane Foams, Standard D3574-03, American Society for Testing Material, 2003

2.1.4.5 ASME V&V10-2006, Guide for Verification and Validation in Computational Solid Mechanics, 2006

2.1.4.6 Sprague MA and Geers TL, A Spectral-Element Method for Modeling Cavitation in Transient Fluid-Structure Interaction, International Journal for Numerical Methods in Engineering. 60 (15), 2467-2499. 2004

2.1.4.7 Belytschko T, Liu W, Moran B, Nonlinear Finite Elements for Continua and Structures, John Wiley and sons Publication, 2000

2.1.4.8 Bhonge PS and Lankarani HM, Evaluation of the Input Parameters for the Finite Element Modeling of Aircraft Seats using Component Level Validation, International Journal of Vehicle Structures and Systems, March 2011

2.1.4.9 Moorcroft D, DeWeese R, and Taylor A, Improving Test Repeatability and Methods, The Sixth Triennial International Fire & Cabin Safety Research Conference, Oct 25-28, 2010

2.1.4.10 Olivares G, Acosta JF, and Yadav V, Certification by Analysis I and II, FAA Joint Advanced Materials and Structures (JAMS) Center of Excellence Technical Review Meeting, Seattle May 2010

2.1.4.11 Buechler MA, McCarty AS, Reding D, Maupin RD. Explicit Finite Element Code Verification Problems, IMAC Conference & Exposition on Structural Dynamics XXII, 2004

2.1.4.12 On Fracture Locus in the Equivalent Strain and Stress Triaxiality Space, Bao and Wierzbicki, International Journal of Mechanical Sciences, 46 (2004) 81-98

2.1.4.13 "A Comparative Study on Various Ductile Crack Formation Criteria", Bao and Wierzbicki, Transactions of the ASME, Vol. 126, July 2004

2.1.4.14 "Dependence of ductile crack formation in tensile tests on stress triaxiality, stress and strain ratios", Yingbin Bao, Engineering Fracture Mechanics 72 (2005) 505-522

2.1.4.15 "A comprehensive failure model for crashworthiness simulation of aluminum extrusions", H. Hooputra, H. Gese, H. Dell, and H. Werner (2004), International Journal of Crashworthiness, 9:5, 449-464, doi:10.1533/ijcr.2004.0289

2.1.4.16 ABAQUS User's Manual

2.1.4.17 LS-DYNA User's Manual 971, May 2007

2.1.4.18 "The Second World-Wide Failure Exercise: Benchmarking of Failure Criteria Under Triaxial Stresses for Fibre-Reinforced polymer Composites", M J Hinton and A S Kaddour, 16th International Conference on Composite Materials

2.1.4.19 "Crashworthiness Analysis with Enhanced Composite Material Models in LS-DYNA Merits and Limits", K. Schweizerhof, K. Wiemar, Th. Munz, Th. Rottner

2.1.4.20 "Verification and Validation in Scientific Computing", William L. Oberkampf and Christopher J. Roy

2.1.4.21 Plastic Deformation and Ductile Fracture of 2024-T351, Jeremy Daniel Seidt, Ohio State University Dissertation 2010

2.1.4.22 Allowables-Based Flow Curves for Nonlinear Finite-Element Analysis, J.D. Pratt, ASM International Journal of Failure Analysis and Prevention 01/2007

2.2 Definitions

2.2.1 ANALYST

The individual creating and running the computer simulation.

2.2.2 CALCULATION VERIFICATION

The process of determining the solution accuracy of a particular calculation (ASME V&V10-2006).

2.2.3 CALIBRATION

The process of adjusting physical modeling parameters in the computational model to improve agreement with experimental data (ASME V&V10-2006).

2.2.4 CODE

The computer implementation of algorithms developed to facilitate the formulation and approximate solution of a class of problems (ASME V&V10-2006).

2.2.5 CODE VERICATION

The process of determining that the numerical algorithms are correctly implemented in the computer code and of identifying errors in the software (ASME V&V10-2006).

2.2.6 CONCEPTUAL MODEL

The collection of assumptions and descriptions of physical processes representing the solid mechanics behavior of the reality of interest from which the mathematical model and validation experiments can be constructed (ASME V&V10-2006).

2.2.7 ERROR

A recognizable deficiency that is not due to a lack of knowledge (ASME V&V10-2006).

2.2.8 INTENDED USE

The specific purpose for which the computational model is to be used (ASME V&V10-2006).

2.2.9 MODEL

The conceptual, mathematical, and numerical representations of the physical phenomena needed to represent conditions and scenarios. Thus, the model includes the geometrical representation, governing equations, boundary and initial conditions, loadings, constitutive models and related material parameters, spatial and temporal approximations, and numerical solution algorithms (ASME V&V10-2006).

2.2.10 PREDICTION

The output from a model that calculates the response of a physical system before experimental data are available to the user (ASME V&V10-2006).

2.2.11 REALITY OF INTEREST

The physical system and its associated environment to which the computational model will be applied (ASME V&V10-2006).

2.2.12 SENSITIVTY ANALYSIS

The general process of discovering the effects of model input parameters on the response features of interest using techniques such as analysis of variance (ANOVA) (ASME V&V10-2006).

2.2.13 SIMULATION

The computer calculations performed with the computational model (i.e., “running the model”) (ASME V&V10-2006).

2.2.14 UNCERTAINTY

A potential deficiency in any phase or activity of the modeling, computation, or experimentation that is due to inherent variability or lack of knowledge (ASME V&V10-2006).

2.2.15 VALIDATION

The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (ASME V&V10-2006).

2.2.16 VERIFICATION

The process of determining that a computational model accurately represents the underlying mathematical model and its solution (ASME V&V10-2006).

3. VIRTUAL ANTHROPOMORPHIC TEST DEVICE (v-ATD) CALIBRATION

A primary component affecting the response of an aviation seat system is the ATD. The majority of the compliance data channels are either directly measured from the ATD (e.g., HIC, lumbar load, etc.) or greatly affected by the ATD (e.g., floor reaction load). As such, it is imperative for the virtual representation of the ATD to be of as high fidelity as possible. To this end, the purpose of this section is to provide a methodology for evaluating the fidelity of an aviation v-ATD. This evaluation is broken into four parts: mass and geometry evaluation, sub-assembly evaluation, pelvic shape evaluation, and dynamic response evaluation. While this section is primarily for v-ATD developers, it contains important information regarding the limitations of this evaluation and how that affects seat system verification and validation.

3.1 Mass and Geometry Evaluation

The virtual Anthropomorphic Test Device (v-ATD) should meet the specifications cited in Title 49 of the Code of Federal Regulations (CFR) Part 572 as appropriate for the physical ATD it is meant to represent. These specifications reference drawings that provide geometry and mass distribution parameters, location of joints and their range of articulation, length, mass, and center of gravity for each segment, assembled dimensions, and general external shape. The mass and dimensions of the v-ATD should fall within the acceptable range cited in the specifications. Where the specifications do not cite a dimensional tolerance, it can be assumed that the tolerance is equal to ±0.1 inches (±2.54 mm) of the nominal value.

3.1.1 Sensor Locations

Per SAE J211-1, in order to measure multi-axial accelerations, each acceleration transducer axis must pass within 0.394 inches (10.0 mm) of the point of interest (e.g., the head CG), and the center of the seismic mass of each accelerometer should be within 1.181 inches (30.0 mm) of that point. The orientation of the measurement axis should not be greater than 5 degrees from the reference axis.

Load cell sensors should match the location indicated on the drawing to within 0.2 inches (5.08 mm). The orientation of the measurement axis should not be greater than 2 degrees from the reference axis.

3.2 Sub-Assembly Evaluation

The ATD specifications include static and dynamic sub-assembly tests. The results of simulations of these tests using the v-ATD (or sub-assemblies) should fall within the tolerance ranges cited in the specifications.

3.2.1 Hybrid II ATD

3.2.1.1 Hybrid II Regulations

The Hybrid II is defined in §49 CFR Part 572 subpart B. The following regulations define the sub-assembly evaluations:

Head - §49 CFR Part 572.6
Neck - §49 CFR Part 572.7
Thorax - §49 CFR Part 572.8
Lumbar spine, abdomen, and pelvis - §49 CFR Part 572.9
Limbs - §49 CFR Part 572.10

Since no tolerance is given for the probe velocity in §49 CFR Part 572.8 and §49 CFR Part 572.10, it is suggested to use the tolerance cited in subsections §49 CFR Part 572.34 and §49 CFR Part 572.35.

3.2.1.2 Hybrid II Pelvic Compression

In order to determine the amount of material under the ischial tuberosities, a simple static compression test can be evaluated. For the Hybrid II physical ATD, place the pelvis buttocks up onto a 5.362 inches (136.19 mm) tall pedestal that bolts to the lumbar load cell mounting surface of the pelvis as shown in Figure 1. Place a 75 pound (34 kg) object onto the pelvis and wait 5 minutes. Measure the distance from the top surface of the pelvis to the bottom surface of the pedestal. This distance must be between 10.402 inches (264.21 mm) and 10.802 inches (274.37 mm).

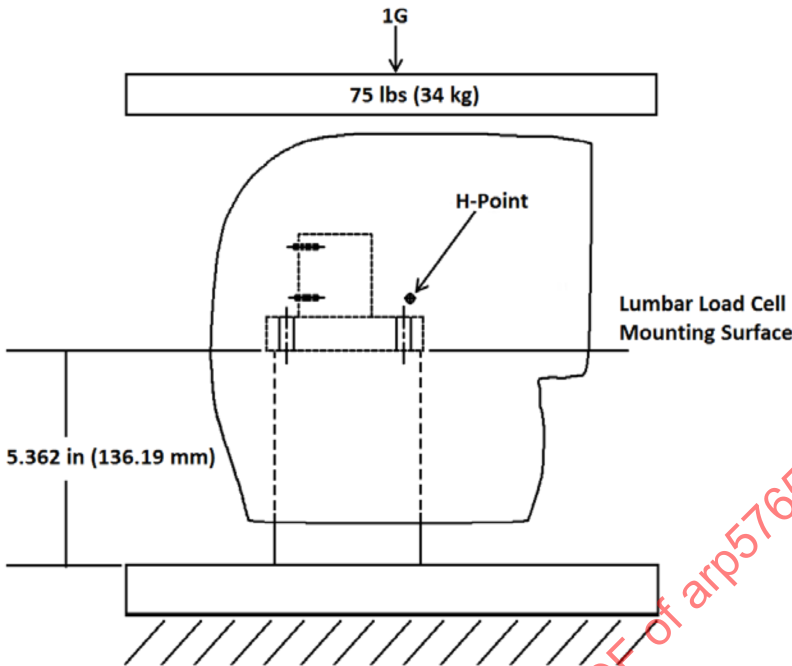

Figure 1 - Pelvis compression illustration

For the Hybrid II v-ATD, the pedestal may be simulated by locking the pelvis (i.e., allowing 0 degrees of freedom) such that the lumbar load cell mounting surface is 5.362 inches (136.19 mm) above a reference plane. A 75 pound (34 kg) object should be placed above the pelvis and gravity should be applied to load the object onto the pelvis. A rectangular plate with width and depth greater than the size of the pelvis is sufficient. Once equilibrium is reached, the distance measurement can be made; it is not necessary to simulate the 5 minute wait time. Equilibrium can be shown with a plot of the position of the 75 pound (34 kg) object or the contact force between the object and the pelvis.

If the lumbar load cell mounting surface is not explicitly modeled in the v-ATD, the pedestal height can be modified to account for the distance between the mounting surface and the H-pt. This distance is 1.344 inches (34.14 mm) for the Hybrid II.

3.2.2 FAA Hybrid III ATD

3.2.2.1 FAA Hybrid III Regulations

The FAA Hybrid III ATD contains parts from the Hybrid II and Hybrid III ATDs. Details on the construction of the ATD can be found in SAE 1999-01-1609. As a composite ATD, not all specifications listed in the CFR will be applicable. To evaluate the FAA Hybrid III sub-assembly tests specified in §49 CFR Part 572 subpart B and §49 CFR Part 572 subpart E are used, however neither thorax test is applicable. The following regulations define the applicable sub-assembly:

Head - §49 CFR Part 572.32
Neck - §49 CFR Part 572.33
Lumbar spine, abdomen, and pelvis - §49 CFR Part 572.9
Limbs - §49 CFR Part 572.35

3.2.2.2 FAA Hybrid III Pelvic Compression

In order to determine the amount of material under the ischial tuberosities, a simple static compression test can be evaluated. For the FAA Hybrid III physical ATD, place the pelvis buttocks up onto a 5.362 inches (136.19 mm) tall pedestal that bolts to the lumbar load cell mounting surface of the pelvis as shown in Figure 1. Place a 75 pound (34 kg) object onto the pelvis and wait 5 minutes. Measure the distance from the top surface of the pelvis to the bottom surface of the pedestal. This distance must be between 10.222 inches (259.63 mm) and 10.362 inches (263.19 mm).

For the FAA Hybrid III v-ATD, the pedestal may be simulated by locking the pelvis (i.e., allowing 0 degrees of freedom) such that the lumbar load cell mounting surface is 5.362 inches (136.19 mm) above a reference plane. A 75 pound (34 kg) object should be placed above the pelvis and gravity should be applied to load the object onto the pelvis. A rectangular plate with width and depth greater than the size of the pelvis is sufficient. Once equilibrium is reached, the distance measurement can be made; it is not necessary to simulate the 5 minute wait time. Equilibrium can be shown with a plot of the position of the 75 pound (34 kg) object or the contact force between the object and the pelvis.

If the lumbar load cell mounting surface is not explicitly modeled in the v-ATD, the pedestal height can be modified to account for the distance between the mounting surface and the H-pt. This distance is 1.320 inches (33.53 mm) for the FAA Hybrid III.

3.2.3 ES-2re ATD (Reserved)

3.3 Pelvis Shape Evaluation

The shape of the ATD's pelvis can significantly affect how it interacts with the seating surface. The following procedure is used to evaluate the v-ATD pelvis shape:

3.3.1 The physical ATD used for this evaluation should have a pelvis that is new or in good condition (no deterioration of the foam or rubber flesh). The joint stiffness for all joints should be adjusted per AS8049B.

3.3.2 The seat cushion material used for this evaluation should be a soft, open cell foam with a low initial stiffness (DAX 26 or equivalent per ASTM D3574-11), at least 4.0 inches (101.6 mm) thick, and have x and y dimensions that are greater than or equal to the x and y dimensions the seat pan defined in Figure 2.

3.3.3 The finite element (FE) representation of the seat cushion should have the same dimensions as the actual cushion, material properties that are based on measured material properties for that cushion, and appropriately defined FE parameters (such as mesh density and time step). The material properties should be determined by a quasi-static test that loads the center of the physical cushion with a round flat platen, 8.0 inches (203.2 mm) in diameter. Only the loading portion of the response is needed for the purposes of this procedure. The FE cushion model should be evaluated by simulating the quasi-static test of the physical cushion. The force on the plate calculated by the cushion model should be within 5% of the measured force for cushion engineering strain values of 10, 20, 30, 40, 50, 60, 70, and 80%.

3.3.4 Position the physical ATD as specified in §49 CFR Part 572.11 for checking dimensions (other than the head position which should be at the nominal location) and measure the H-point location (x and z) and pelvis orientation (angle about the y-axis) when seated on a rigid surface and when seated on the cushion. The rigid surface should have a pan angle of 0 degrees, a back angle of 0 degrees, and a footrest height 16.0 inches (406.4 mm) below the pan-back intersection for the no cushion seatings. Note that the foot rest height must be adjusted (by the difference in the H-pt heights, with and without the cushion) after the cushion is installed to maintain the same pelvis and upper leg angle for both conditions. For consistency in the location of the x component of the H-pt, apply approximately 20 pounds (88.96 N) to the ATD's knees and keep the upper legs horizontal by supporting them just behind the knees while lowering the ATD into the seat. Seat and measure the ATD three times with no cushion and three times with the cushion (six total seatings). Calculate the H-pt vertical height difference by subtracting the average H-pt z-position on the rigid surface from the average H-pt z-position with the cushion. Calculate the H-pt horizontal depth difference by subtracting the average H-pt x-position on the rigid surface from the average H-pt x-position with the cushion. The pelvic orientation should be within 2 degrees for all six seatings and the average angle should be recorded.

3.3.5 Perform a simulation with the v-ATD in the same position as specified in §49 CFR Part 572.11 for checking dimensions (other than the head position which should be at the nominal location) with a 1 G vertical load applied. Determine the H-point location (x and z) and pelvic orientation (angle about the y-axis) when seated in equilibrium on a rigid surface and when seated on the cushion. Note that the foot rest height must be adjusted (by the difference in the H-pt heights) after the cushion is installed to maintain the same pelvis and upper leg angle for both conditions. Calculate the H-pt height difference by subtracting the H-pt z-position on the rigid surface from the H-pt z-position with the cushion. Calculate the H-point depth difference by subtracting the H-pt x-position on the rigid surface from the H-pt x-position with the cushion. The difference between the average H-pt height difference of the ATD and the v-ATD should be no greater than 0.2 inches (5.08 mm). The difference between the average H-pt depth difference of the ATD and the v-ATD should be no greater than 0.2 inches (5.08 mm). The difference between the average pelvis orientation (angle about the y-axis) of the ATD and of the v ATD when seated on either the rigid surface or the soft cushion should be no greater than 2 degrees.

3.4 Dynamic Response Evaluation

Existing ATD specifications and calibration tests do not directly evaluate the ATD's response to all of the loading conditions that can occur during aircraft seat dynamic tests. To ensure that v-ATDs adequately emulate the physical ATDs when subjected to these unique loading conditions, comparisons with results of representative full scale sled tests are needed. The test parameters specified herein are designed to produce the range of ATD articulation, force application points and force magnitudes that are typical of those observed during tests of actual aircraft seats. To minimize as many variables as possible, a rigid seat and restraint systems with fixed anchorages are used.

3.4.1 General Dynamic Response Test Requirements

3.4.1.1 Each test condition should be repeated a minimum of three times.

3.4.1.2 Use a rigid seat with the anchorage geometry, contact surface locations, and load cell location as shown in Figure 2.

3.4.1.3 The contact surfaces should be rigid, flat, and smooth. The seat pan and floor should be covered with two layers of Teflon sheet.

3.4.1.4 The ATD used for these evaluations should meet its design and calibration specifications as defined in §49 CFR Part 572. The ATD should be clothed per AS8049B. Clothing may be cut away as necessary to avoid obscuring photometric targets.

3.4.1.5 Photometric target markers should be placed as called for in Table 2 and SAE J211-2.

3.4.1.6 Place the ATD consistently in the seat per AS8049B.

3.4.1.7 Restraint systems should use 2 inches (50.8 mm) wide nylon webbing, and have fixed anchorage points.

3.4.1.8 Adjust the lap belt pre-tension per AS8049B (about 5 pounds (22.2 N)).

3.4.2 Dynamic Response Test Setup Documentation

3.4.2.1 The surface geometry in contact with the ATD and the location of the belt anchors and guides should be documented.

3.4.2.2 The restraint system geometry (length, width, thickness and location of both rigid and flexible components) should be documented.

3.4.2.3 The restraint system pre-tension or slack values should be documented.

3.4.2.4 The initial position of significant ATD anthropometry landmarks defined in Table 2 and all photometric target markers used to track those locations should be documented. Also, the position of photometric reference targets used for scaling and/or validation per SAE J211-2 should be documented. The origin for these measurements should be the intersection of the seat back and seat pan at the seat centerline.

3.4.3 Dynamic Response Test Data Requirements

3.4.3.1 The data reported should all be in engineering units versus time with 1 KHz sampling frequency for position and 10 KHz for all other channels. Electronic data should be recorded for a minimum of 300 ms after impact. Position data (derived from high speed video) should be recorded for the period of significant occupant response.

3.4.3.2 Record and process all electronic data per SAE J211-1. Neck force and moment data recorded should be translated to the occipital condyle location. Perform a tare correction on the seat pan force and moment data to compensate for the forces and moments induced by the mass attached to the load cell. Record seat pan forces in the local (seat pan) coordinate system. Seat pan moments recorded should be translated to the top of the seating surface at the center of the seat pan.

3.4.3.3 Record and process all photometric data per SAE J211-2. The accuracy of photometric length calculations should be determined per SAE J211-2 and reported. The origin for the position data should be the intersection of the seat back and seat pan at the seat centerline.

3.4.4 Specific Test Requirements

A minimum data set for each test condition should be defined such that the relative importance of each type of measurement is considered. Occupant kinematics are given the highest priority since they are directly related to head strike potential, and are the product of the forces and accelerations measured. Forces produced are next in priority since they directly assess occupant interaction with restraint systems and seating surfaces. Acceleration measurements are lowest in priority and typically only used to provide a means of comparing occupant response for regions of the body where kinematic or force measurements are not possible.

3.4.4.1 Specific Test Requirements for Forward Facing ATDs

- The minimum data set to be gathered for each test condition is defined in Table 3 with an X notation. Cells left blank are intentionally blank.

- Scenario 1: Forward facing test with a 2-point belt and without a toe stop. The input acceleration pulse is the 16 G, with a velocity change of 44 ft/s (13.41 m/s) defined in Part 25.562 for the horizontal test condition.

- Scenario 2: 60 degree pitch test with a 2-point belt. The input acceleration pulse is the 19 G, with a velocity change of 31 ft/s (9.45 m/s) defined in Part 23.562 for the combined horizontal-vertical test condition.

- Scenario 3: Forward facing test with a 3-point belt. Adjust shoulder belt to produce 1.25 inches (31.75 mm) of initial slack. The input acceleration pulse is the 21 G, with a velocity change of 42 ft/s (12.8 m/s) defined in Part 23.562 for the horizontal test condition. The geometry of the 3-Point restraint system should be such that the shoulder belt to lap belt attachment point is 4 inches (101.6 mm) to the right of the ATD centerline.

- Scenario 4: Forward facing test with a 4-point belt. Adjust shoulder belt to produce 1.25 inches (31.75 mm) of initial slack. The input acceleration Pulse is the 21 G, with a velocity change of 42 ft/s (12.8 m/s) defined in Part 23.562 for the horizontal test condition.

3.4.4.2 Specific Test Requirements for Side Facing ATDs (Reserved)

3.4.5 Simulation of the Dynamic Evaluation Tests

3.4.5.1 Each of the tests specified in 3.4.4 should be simulated using the v-ATD being evaluated. Simulation parameters should reflect the general and specific test requirements specified in 3.4.1 and 3.4.4. However, the actual values recorded per 3.4.2 should be used to compensate for setup variability. The v-ATD should be positioned in the equilibrium position that most closely matches the pre-test location of the ATD. This will require some engineering judgment since v-ATD dimensions typically vary somewhat from the ATD. The difference in achieved ATD initial position and test acceleration pulse during each repeated test should be minimal. The v-ATD developer is encouraged to use the initial conditions and sled pulse from one of the repeated tests as the input to a single simulation to compare to the repeated tests. However, if the variability of the test initial positions or sled pulses cause a poor test-simulation comparison, the v-ATD developer may run additional simulations using the specific test inputs for the simulation. The v-ATD developer and anyone reviewing the results of the v-ATD evaluation is encouraged to use engineering judgment during each phase of creating the model and the reviewing the results.

3.4.5.2 Simulation parameters not directly measured during the tests should be derived as follows:

- Static and dynamic force-deflection characteristics of the restraint used for the tests should be determined by a component test. This should include loading, unloading and hysteresis characteristics.
- The average friction coefficient between the ATD and the contact surfaces should be in the range of 0.2 to 0.5. Since friction is in practice difficult to quantify, this nominal value will be assumed for consistency.
- A value of 0.35 should be used for the average friction coefficient between the ATD and the restraint system. Since friction is in practice difficult to quantify, this nominal value will be assumed for consistency.

3.4.5.3 Simulation data produced should meet the same requirements and have the same data origins as the test data specified in 3.4.3 to facilitate direct comparison.

3.4.6 Comparison of Test and Simulation Results

The comparison of model results to full scale tests should be done using automated error metrics. For each test and simulation pair, calculate the error for the parameters being evaluated using the procedures contained in Appendix A. The maximum error for each parameter should be calculated from three repeated test and simulation pairs. If one simulation is used to match three (or more) tests, that simulation should be compared to each test. If individual simulations are executed for each test, only the matched test and simulation should be compared.

3.4.6.1 Forward Facing ATD Test and Simulation Comparison

The minimum data channels considered necessary to fully evaluate the dynamic performance of ATD are listed in Table 3. The parameters in Table 3 were examined to determine the type of evaluation (peak, curve shape, or both) that was appropriate for each data channel. Maximum values for acceptable error on the peak are specified in Table 4, with a notation that the peak of interest is either positive or negative. The number listed in each cell is the relative error (expressed as a percentage) for accelerations and forces or magnitude error (expressed as a scalar in inches (millimeters) or degrees) for position and angles. Maximum values for curve shape error are specified in Table 5. The number listed in each cell is the Sprague and Geers comprehensive error (expressed as a percentage). For each parameter identified in Tables 4 and 5, the error between each test and simulation result should be calculated and the maximum error from the repeated tests should be recorded. Standard rounding practice should be employed.

3.4.6.2 Side Facing ATD Test and Simulation Comparison (Reserved)

3.5 Compliance Criteria

In order to be considered fully compliant, a v-ATD must meet all requirements in 3.1 to 3.4 with no deviations from the specified maximum error values. No distinction is made between over and under predicting. A v-ATD that cannot meet all of the defined requirements may be deemed conditionally compliant with corresponding limits imposed on the use of the model. The effect of any deviations from the specified requirements should be addressed. The determination of conditionally compliant, the specification of the v-ATD's limitations, and the use of a conditionally compliant v-ATD will require sound engineering judgment, and the rationale of these decisions should be thoroughly documented. If the seat system model will be used to support certification, it is recommended that the user engage the regulatory authority early in the process to ensure the acceptance of the v-ATD.

3.5.1 Conditionally Compliant Examples (non-exhaustive list)

1. A v-ATD that meets all performance requirements in dynamic test scenarios one, three, and four, but cannot meet the performance requirements for scenario two, would only be approved for simulations matching the restraint and load application direction of scenarios one, three, and four.

2. A v-ATD with acceptable correlation for a significant portion of the head path in scenario one could be approved on the condition that the model can only be used in installations where the head path is prevented from exceeding the correlated area by external factors such as structural monuments.

3. A v-ATD that does not meet the shoulder belt loads for scenarios three and four could be allowed with the proper application of engineering judgment. For instance, if the v-ATD greatly over-predicts the belt load, it would not be appropriate for a simulation focused on determining head path since the extra belt load would most likely shorten the head trajectory. Conversely, if the v-ATD significantly under-predicts the shoulder belt load, the v-ATD may be best used in a head path simulation, where it would likely produce a conservative result. However this v-ATD would not be recommended for situations where the belt loads are close to the regulatory limits.

3.6 Documentation

Documentation showing compliance with all evaluations contained in this section should be available to all users of the v-ATD. This documentation should be analogous to the certification report that accompanies a physical ATD. An example v-ATD calibration report is contained in Appendix D. As with physical ATDs, it is important to have configuration control over the v-ATD. As such, all documentation should make clear the version of the v-ATD, the software platform that was used, and what parameters can be updated without invalidating the model. All evaluations detailed in this section need to be included in the documentation, as specified below.

3.6.1 Software and Hardware Platform Documentation

As in all computational models, the numerical accuracy of the v-ATD may be dependent on the specific configuration of the hardware and operating system used. In addition, it is a common experience that results of any computational software may deviate with release of newer versions of the same software. Therefore, the v-ATD developer should ensure that, regardless of the release versions of software, the performance of the v-ATD meets the requirements defined in this document. When the v-ATD has been calibrated, either to the complete or partial calibration set defined in 3.1 to 3.4, documentation should be provided by the v-ATD developer to the end-user that includes the version of the v-ATD, the version of the simulation software, the operating system, and the computer hardware platform that accomplished the calibration.

3.6.2 Mass and Geometry Evaluation Documentation

The following mass and geometry information should be included in the v-ATD calibration report:

- Table of external dimensions - citing the specification, tolerance, and actual value

- Table of total and segment weights - citing the specification, tolerance, and actual value

- Table of the centers of gravity for segments - citing the specification, tolerance, and actual value
- Table of sensor location of v-ATD in comparison to physical ATD, including notation of the node, joint, or body used to calculate the output

3.6.3 Sub-Assembly Evaluation Documentation

The following sub-assembly information should be included in the v-ATD calibration report:

- Specification, test results, and corridor plots (where appropriate)

3.6.4 Pelvis Shape Evaluation Documentation

The following pelvis shape evaluation documentation should be included in the v-ATD calibration report:

- Table of measurements versus test data
- Details of foam properties as used

3.6.5 Dynamic Response Evaluation Documentation

The following dynamic response evaluation information should be included in the v-ATD calibration report:

- Table 4 and Table 5 error information with simulation results
- Plots of data for each channel
- Details of belt properties as used

3.6.6 Conditionally Compliant v-ATD Documentation

For models that do not meet all the requirements, the documentation should clearly list the limitations and intended use of the v-ATD. The effect of any deviations from the specified requirements should be addressed.

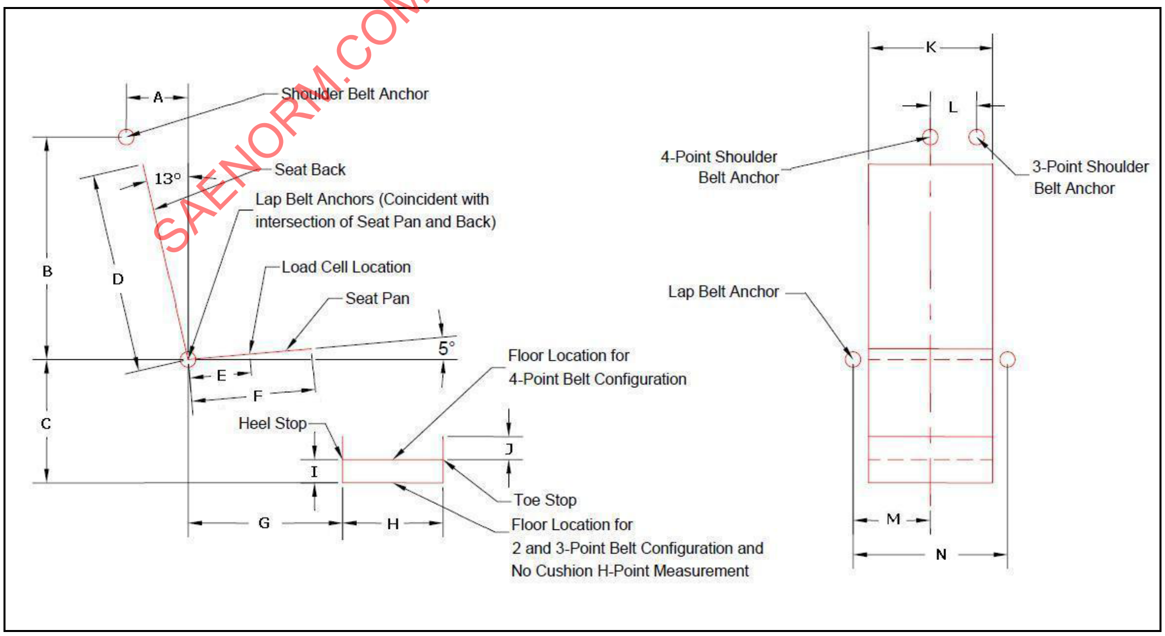

Figure 2 - Seat dimensions

Table 1 - Seat dimensions

Dimension	Letter	Distance (mm)	Distance (inch)
Shoulder Belt Anchor Depth	A	203	8
Shoulder Belt Anchor Height	B	737	29
Seat Pan-Back Intersection Height	C	406	16
Seat Back Length	D	660	26
Pan-Back to Load Cell Center	E	203	8
Seat Pan Length	F	406	16
Pan-Back to Heel Stop Length	G	508	20
Heel Stop to Toe Stop Length	H	330	13
Floor Height (4-pt Belt Configuration)	I	76	3
Toe Stop Height	J	76	3
Seat Width (minimum)	K	457	18
Seat Centerline to 3-pt Shoulder Belt Anchor	L	178	7
Seat Centerline to Lap Belt Anchor	M	254	10
Lap Belt Anchor Width	N	508	20

Table 2 - ATD anthropometry landmarks

#	Name	Definition	Measured Point
1	H-point	Intersection of a line passing through both hip joints and the midsagittal plane of the ATD	Measured at the surface of the hip flesh
2	Head CG	Intersection of a line along the y-axis passing though the head Center of Gravity and the midsagittal plane of the ATD	Measured at the surface of the head flesh
3	Knee	Intersection of the centerline of the knee pivot and the midsagittal plane knee	Measured at the surface of the knee pivot bolt head
4	Ankle	Intersection of the centerline of the ankle pivot and the midsagittal plane of the ankle	Measured at the surface of the ankle pivot bolt head
5	Shoulder	Intersection of the centerlines of the shoulder horizontal pivot and the fore-aft pivot	Measured at the surface of the shoulder flesh.
6	Elbow	Intersection of the centerline of the elbow pivot and the midsagittal plane of the elbow	Measured at the surface of the elbow pivot bolt head for the Hybrid-II or the outboard surface of the elbow flesh for the FAA Hybrid-III
7	Wrist	Intersection of the centerline of the wrist pivot and the midsagittal plane of the wrist	Measured at the surface of the wrist flesh
8	Pelvis Angle	The angle that the x-axis of the lumbar spine load cell makes with the Seat x-axis	Measured using auxiliary markers placed at known locations relative to the pelvis coordinate system
9	Head Angle	The angle that the x-axis of the head accelerometer array makes with the Seat x-axis	Measured using auxiliary markers placed at known locations relative to the head coordinate system

NOTE 1: When the ATD is in a typical seated posture, the location of each of the defined points can be estimated by adding half the breadth (width along y-axis) of the ATD or joint to the measured point's y-dimension.

NOTE 2: At a minimum, photometric targets should be placed at measured points 1 through 5 and as necessary to calculate head angle and pelvis orientation throughout the test.

NOTE 3: The seat coordinate system does not include the seat pan angle. In the current rigid seat configuration, the seat coordinate system is equivalent to the sled or laboratory coordinate systems for the 0 degree test conditions.

Table 3 - Dynamic calibration data set - forward facing ATD

Channel Description	Forward Facing 2-Point Belt	Forward Facing 60 degree 2-Point Belt	Forward Facing 3-Point Belt	Forward Facing 4-Point Belt
Sled Ax	X	X	X	X
Upper Neck Fx *			X	X
Upper Neck Fy *			X	
Upper Neck Fz *			X	X
Upper Neck Mx *			X	
Upper Neck My *			X	X
Chest Ax (CFC 180)			X	X
Lumbar Fz		X		
Lumbar My		X		
Right Lap Belt Load	X		X	X
Left Lap Belt Load	X		X	X
Right Shoulder Belt Load				X
Left Shoulder Belt Load			X	X
Seat Pan Fx	X	X	X	X
Seat Pan Fz	X	X	X	X
Seat Pan My	X	X	X	X
Head CG X Position	X	X	X	X
Head CG Z Position	X	X	X	X
H-point X Position	X		X	X
H-point Z Position	X	X		
Knee X Position	X			X
Knee Z Position	X			X
Ankle X Position	X			
Ankle Z Position	X			
Shoulder X Position			X	X
Shoulder Z Position			X	X
Opposite Shoulder X Position			X	
Opposite Shoulder Z Position			X	
Head Angle	X			X
Pelvis Angle	X	X		X

* FAA Hybrid III only

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Table 4 - Maximum allowable peak error for forward facing v-ATD**

Channel Description	Forward Facing 2-Point Belt		Forward Facing 60 degree 2-Point Belt		Forward Facing 3-Point Belt		Forward Facing 4-Point Belt	
Upper Neck Fx *					10%	-	20%	-
Upper Neck Fy *					30%	-		
Upper Neck Fz *					15%	+	30%	+
Upper Neck Mx *					25%	-		
Upper Neck My *					10%	+	20%	+
Chest Ax (CFC 180)					10%	-	10%	-
Lumbar Fz			10%	-				
Lumbar My								
Right Lap Belt Load	10%	+			10%	+	10%	+
Left Lap Belt Load	10%	+			10%	+	10%	+
Right Shoulder Belt Load							10%	+
Left Shoulder Belt Load					10%	+	10%	+
Seat Pan Fx								
Seat Pan Fz	25%	-	10%	-	25%	-	10%	-
Seat Pan My	20%	-	10%	-	10%	-	20%	-
Head CG X Position	0.5 inches (12.7 mm)	+			1.75 inches (44.45 mm)	+	0.25 inches (6.35 mm)	+
Head CG Z Position							0.3 inches (7.62 mm)	-
H-point X Position	0.25 inches (6.35 mm)	+			1.25 inches (31.75 mm)	+	0.5 inches (12.7 mm)	+
H-point Z Position	0.2 inches (5.08 mm)	+	0.1 inches (2.54 mm)	-				
Knee X Position	0.5 inches (12.7 mm)	+					0.5 inches (12.7 mm)	+
Knee Z Position								
Ankle X Position								
Ankle Z Position								
Shoulder X Position					2.0 inches (50.8 mm)	+	0.5 inches (12.7 mm)	+
Shoulder Z Position							0.5 inches (12.7 mm)	-
Opposite Shoulder X Position					0.5 inches (12.7 mm)	+		
Opposite Shoulder Z Position								
Head Angle							8 degree	-
Pelvis Angle	7 degree	-	3 degree	+			5 degree	+

* FAA Hybrid III only

** Column with plus or minus denotes peak of interest is either a global maxima or minima

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Table 5 - Maximum allowable curve shape error for forward facing v-ATD

Channel Description	Forward Facing 2-Point Belt	Forward Facing 60 degree 2-Point Belt	Forward Facing 3-Point Belt	Forward Facing 4-Point Belt
Upper Neck Fx *			10%	10%
Upper Neck Fy *			30%	
Upper Neck Fz *			20%	25%
Upper Neck Mx *			40%	
Upper Neck My *			10%	40%
Chest Ax (CFC 180)			10%	15%
Lumbar Fz		15%		
Lumbar My		25%		
Right Lap Belt Load	15%		10%	10%
Left Lap Belt Load	15%		10%	10%
Right Shoulder Belt Load				10%
Left Shoulder Belt Load			10%	10%
Seat Pan Fx	20%	5%	15%	10%
Seat Pan Fz	20%	5%	15%	10%
Seat Pan My	20%	10%	10%	15%
Head CG X Position	10%	10%	10%	10%
Head CG Z Position	10%	15%	30%	10%
H-point X Position	10%		20%	10%
H-point Z Position	10%	15%		
Knee X Position	10%			10%
Knee Z Position	10%			10%
Ankle X Position	15%			
Ankle Z Position	20%			
Shoulder X Position			15%	15%
Shoulder Z Position			40%	15%
Opposite Shoulder X Position			10%	
Opposite Shoulder Z Position			75%	
Head Angle	10%			10%
Pelvis Angle	10%	20%		10%

* FAA Hybrid III only

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4. SEAT SYSTEM VERIFICATION AND VALIDATION

The purpose of a model is to accurately represent a real world system, where the accuracy required is dependent on the intended use of the model. The process used to evaluate the accuracy of the computer model in representing both the real world and the underlying mathematical model is called the verification and validation (V&V) process. The V&V process generates evidence and establishes credibility that the computer model has the adequate accuracy and level of detail to support certification by analysis (CBA), and this evidence is included in a Verification and Validation Report (VVR). This section provides suggestions for the information to be included in VVR.

By following the V&V process, the modeler improves the likelihood that the model will accurately predict the response of the seat system and will generate the necessary documentation to substantiate its use for certification. The method recommended in this section is based on the ASME Guide for Verification and Validation in Computational Solid Mechanics (ASME V&V10-2006), with modifications that tailor this guidance to better apply to aviation seats. The suggested V&V approach is shown in Figure 3. Activities are shown in plain text, and the products of these activities are shown in rounded boxes. First, the reality of interest is defined, which is the physical system and its associated environment to which the computational model will be applied (i.e., its intended use). While the intended use of the model will affect many decisions, the basic concepts of V&V are the same regardless of model use. Next, the physical system is abstracted into a conceptual model, which includes the descriptions of the physical processes and assumptions.

At this point in the process, two parallel paths are formed to separate modeling and simulation (M&S) activities from physical testing activities. In the M&S branch, the conceptual model is described by a set a set of mathematical equations and modeling data that approximate the physical reality. The terms code, model, and simulation have specific, complementary definitions taken from ASME V&V10-2006. Code refers to the computer implementation of algorithms, i.e., software. The model is the conceptual, mathematical, and numerical representation of the physical phenomenon. The simulation is the execution of a model. Thus a model can be run multiple times, often with minor changes to initial conditions, generating multiple simulation results.

The first step is to determine whether the software solves the model properly. This process is called code verification. Next, it is important to determine that the numerical error, from the time step and mesh resolution (for finite element models), is low. This process is called calculation verification. The results of the model are then quantitatively compared to the results of the physical experiment. When acceptable agreement is observed, the model can then be used to predict the system response to an untested, but similar, scenario. Sensitivity analysis is recommended to guide the extent of extrapolation and to define limitations on the model.

This method is applied to a model that is intended to show full seat system compliance to one or more of the three basic test configurations (combined horizontal-vertical, structural, or occupant injury). This method also applies to component models which are intended to show some specific behavior. The method includes baseline material characterization along with traceability of material properties, component level response (when applicable), use of calibrated v-ATDs, and integrated seat system responses which includes the interaction with the v-ATD. Sensitivity analysis is recommended throughout the process to determine the sensitivity of model inputs that are difficult to measure (e.g., friction) or inputs that are not known with high certainty.

Verification and validation of a complete seat model is a complex task whereby the exact steps cannot be directly provided as they can be for the v-ATD. It is important to use engineering judgment to identify the parameters of importance and how they should be evaluated. In cases, where the models are to be used for certification purpose, it is important to obtain concurrence from the regulatory authorities on how to proceed toward validation. It is likely that the specifics will be customized depending on the specific seat model and the availability of test data.

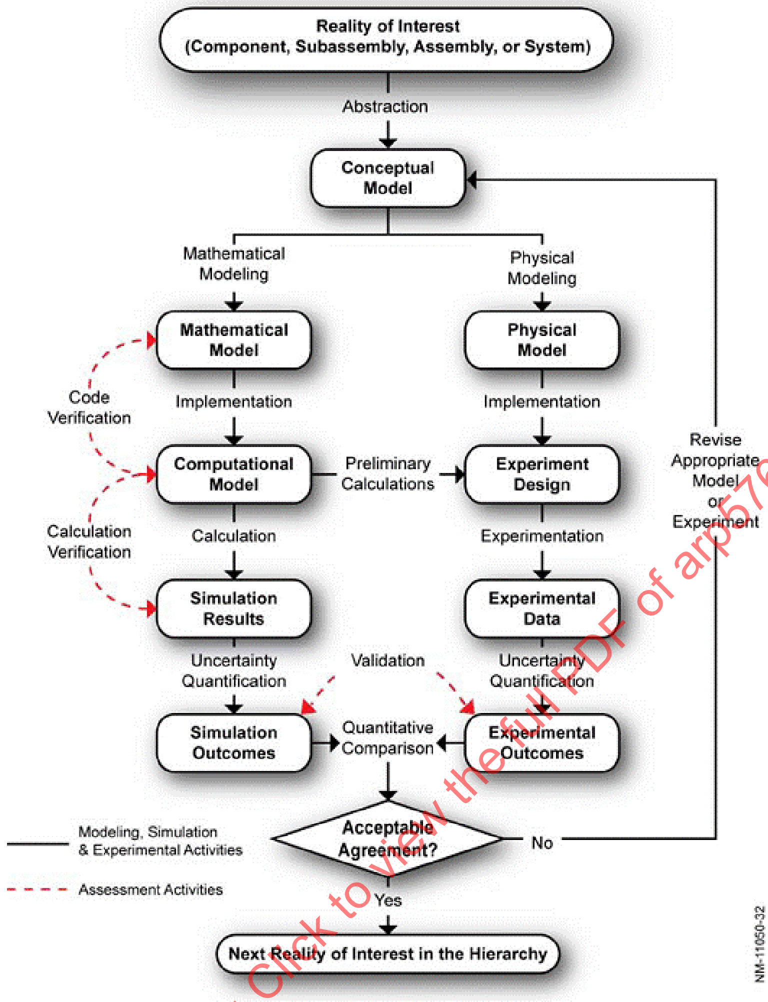


Figure 3 - ASME V&V10-2006 process map (ASME V&V10-2006)

Top level guidance is provided in FAA advisory circular AC 20-146 which describes the use of computer modeling analysis within seat certification. This includes general guidance on how to validate the computer models and under what conditions the models may be used in support of certification. This section is intended to complement the FAA guidance by providing an overview of several areas to consider when developing a validation plan and evaluating a model. Because verification and validation are rapidly evolving and are highly dependent on the specific problem, this section should be considered a starting point and updates or modifications of the process may need to be considered.

4.1 V&V Plan, Reality of Interest, Intended Use, and System Response Quantities

Prior to model development, it is useful to generate a V&V plan that includes a description of the reality of interest and intended use of the model, definition of the system response quantities of interest, selection of metrics to compare computed results with experimental measurements, code and solution verification requirements, definition of the accuracy requirements, and specification of validation experiments. This will allow the modeling and testing groups to coordinate physical testing requirements. The document can also be used in initial discussions with a regulatory agency if the work is going to be used for certification.

The first piece of the V&V Plan is to define the reality of interest and intended use of a model. The reality of interest includes both the system and the environment to be modeled. An example at the top level of the system hierarchy is a fully loaded triple place passenger seat under combined horizontal-vertical test condition as defined in 14 CFR 25.562. The reality of interest could also be at the component level. The intended use is application domain over which the model is expected to make predictions. A few examples are a model for initial seat development, a full seat system model for use in a certification package, and a model of part of the seat to show joint stresses. Once the reality of interest and intended use of the model is defined, they are abstracted into a conceptual model. The conceptual model is the collection of assumptions and descriptions of physical processes representing solid mechanics behavior of the reality of interest from which the mathematical model and validation experiments can be constructed (ASME V&V10-2006). From this, the appropriate modeling details, system response quantities (SRQs), and accuracy requirements will be a natural extension. Certification requirements will tend to be more stringent than internal developmental requirements.

The system response quantities can be split into three groups: primary, support, and threshold. A primary SRQ would be a required channel, such as head resultant acceleration, HIC, or lumbar load, or any quantity that can be considered critical in evaluating the system, such as floor reaction loads in a structural test. A support SRQ is a channel that provides additional confidence that the model is an accurate representation of the reality of interest. In a scenario where HIC needs to be evaluated, support channels could be head impact velocity and head impact angle. A threshold channel is one that is expected to be very low. An example is lap belt load in a combined horizontal-vertical test. During the critical part of the physical test, the belt load is essentially zero. A simple threshold can be defined to show that the model output does not grossly contradict the test data. For any of the three types of SRQs, engineering judgement can be used to determine specific channels for evaluating the reality of interest and intended use. In general, the SRQs can differ greatly between a structural test, an injury criteria test, and a combined horizontal-vertical test. The analyst is encouraged to discuss the collection of support and threshold channels with the test laboratory. Related recommendations are contained in 7.1.

4.2 Verification

Verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution (ASME V&V10-2006). This is a critical step that precedes validation, as it is important to minimize/eliminate errors before progressing. Verification is broken into two components, code verification and calculation verification.

4.2.1 Code Verification

Code verification is the process of determining that the numerical algorithms are correctly implemented in the computer code and of identifying errors in the software (ASME V&V10-2006). It helps to ensure the mathematical model and the solution algorithms are working correctly, i.e., the code solution predicts the analytical solution. This is generally performed by the code developer for commercial off the shelf software during the formulation of the code as well as any subsequent updates, such as during the development of new element, material or contact formulation. Code verification should include a robust software quality assurance system that ensures the traceability of code performances for various release versions. The software performance should be verified on commonly used operating systems and hardware platforms and the end-user should be made aware of any limitations. The code developer should provide the end-user with a theoretical manual that describes the basic software algorithms including formulations for element types, material models, contact methods, etc.

The user is encouraged to verify that the code is tested and complies with acceptable closed form or analytical solution. While the code developer should evaluate all of the implemented algorithms, the end-user should focus on the aspects of the code that are utilized in the individual simulation. As an example, in a seat model that is simulated with a multipurpose commercial code, only the algorithms that are related to structural dynamics need to be evaluated, while the algorithms that are related to fluid dynamics could likely be ignored.

A suite of explicit code verification problems is contained in Reference 2.1.4.12.

4.2.2 Calculation Verification

Calculation verification, also called solution verification, is the process of determining the solution accuracy of a particular calculation (ASME V&V10-2006). The goal of calculation verification is to show that the numerical errors (due to incomplete spatial or temporal convergence) in the system response quantities (SRQs) of interest are minor compared to the validation requirements. Evaluation of spatial convergence is necessary in components that are in the critical load path.

4.2.2.1 Temporal Discretization

The dividing of the total time of a simulation into smaller segments is called temporal discretization. Each segment is typically referred to as a time step, denoted as Δt below. The stability of explicit integration methods depends on the time step; if it is too large for a given element size L (minimum characteristic length in the model) the method fails, either due to stability issues or poor accuracy. If the element size is smaller than required, the solution time becomes impractical, thus diminishing the effectiveness of the method. Additional guidance such as critical time step for a given model is provided in 7.2.2.2.

In theory, the most numerically efficient solution is obtained when an integrating time step equivalent to the stability limit is chosen. Commercial codes, such as MADYMO, LS-DYNA3D, PamCrash, and RADIOSS, attempt to offset the problems of numerical instability by regulating and constantly updating the time interval used throughout the analysis. The time step may be recomputed at each cycle based on the changing mesh size. Nonphysical mass can also be added to the structure in order to artificially increase the time step, thereby reducing the run time. Use of mass scaling require defining a time scale factor, typically in the range of 0.6 to 0.9. The time step, including any scale factor, should be reported in the VVR.

4.2.2.2 Spatial Discretization

The finite element analysis technique divides a continuum into finite elements (volumes, surfaces, and line segments) which are interconnected at a discrete number of points, called nodes, and solves the boundary-value problem. The number of elements and the types of elements used will greatly affect the accuracy of the result. For example, a coarse mesh can produce erroneous results. Construction of a model includes a trade-off between the accuracy of the solution, and the amount of time it takes to run the simulation. Typically, the applicant uses the coarsest mesh that produces a sufficient level of accuracy. As such, evaluation of spatial convergence is necessary in components that are in the critical load path. The criteria used to determine that the discretization was sufficient to resolve the physics of interest should be provided in the VVR.

A quasi-quantitative estimate of the spatial convergence can be generated based on two or more mesh refinements. If the results of the numerical solution do not change significantly from the refinement, the mesh is likely close to the asymptotic region. Exact calculation of the spatial convergence error of an explicit structural analysis is a non-trivial pursuit that is an ongoing research activity.

To aid the end-user in this verification process, 7.2 contains information on standard industry practice that will help the modeler to manage the sources of error and methods to properly discretize the physical structure to reduce modeling error.

4.3 Validation

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (ASME V&V10-2006). The ability of the model to represent a physical phenomenon is evaluated by comparing the model predictions with physical test data. This process relies on high quality test data and a quantitative comparison of test and simulation results.

4.3.1 Test Data

In order to generate high quality test data for the purposes of modeling a dynamic sled test, modifications to the basic requirements of AS8049B are needed. Section 7.1 provides detailed recommended practices for generating high quality test data. Early and good communication between the test engineer and engineering analyst provides an opportunity to determine the desired data and the prioritization of that data based on available resources.

All tests conducted for model validation should be documented to sufficient detail to allow for the recreation of the test. Test documentation in a certification package may be sufficient for full scale sled tests. Component and material characterization tests will require unique documentation, which should include geometry, initial and boundary conditions, loading rates, and photographs. Additional guidance is provided in 4.5 and 7.1.2.

4.3.2 Validation Metrics

A validation metric is a mathematical calculation that defines the distance between an experimental value and a simulation value. This provides a quantitative evaluation of the agreement between the test and simulation. Appendix A describes one method to calculate the error between the results of a numerical simulation and the results of a physical test. Unless otherwise specified, for each required channel two features should be evaluated; magnitude error and curve shape error. Time histories should be evaluated at the beginning of the onset of the test pulse and throughout significant system response, often the motion of the anthropomorphic test device(s), as seen in the physical test. Channel inputs should have consistent units, appropriate sampling rates (minimum 10,000 Hz for electronic instrumentation data and 1,000 Hz for photometric data) and equal time lengths. Test and simulation position data needs to have the same global origin (typically the SRP). If necessary, units, data set length, and origin offsets can be corrected during post-processing.

4.3.3 Uncertainty and Sensitivity Analysis

4.3.3.1 Error and Uncertainty

All tests and numerical models contain errors and uncertainties. Error is a recognizable deficiency that is not due to a lack of knowledge (ASME V&V10-2006). Typical sources of error include numerical solution error (see 4.2.2) and human error, such as incorrect placement of sensors. Uncertainty is a potential deficiency that is due to inherent variability (aleatory uncertainty) or lack of knowledge (epistemic uncertainty) (ASME V&V10-2006). Uncertainty in similar tests exists because of the differences in material tolerances, initial conditions, material properties, differences between test facilities, and differences in ATDs, among others. Uncertainty in the numerical simulation exists because of input parameters, types of hardware, and software, among others. Some of the variability, such as material properties, affects both the physical model and the numerical model.

Ideally, the uncertainty in the model and experiment is explicitly quantified. This requires repeated testing, knowledge of the material variability, knowledge of manufacturing tolerances, sensor accuracy and calibration data, and other information. When that information is unavailable, subject matter experts could be used to estimate the range of experimental or numerical values. The explicit method provides greater confidence in the results of the uncertainty quantification.

4.3.3.2 Sensitivity Analysis

Sensitivity analysis is closely related with uncertainty analysis; while the latter studies the overall uncertainty in the conclusions of the study, sensitivity analysis tries to identify what source of uncertainty weighs more on the study's conclusions. The practitioner will find that disciplined use of the tools and techniques in sensitivity analysis will provide insight that cannot readily be understood by ad-hoc cause and effect studies. Typically, problems of complexity addressed in this document are non-linear in nature and multivariable. The multivariable model inherently leads to a multi-dimensional solution space, which can be difficult to understand without these methods.

Quite often, some or all of the model inputs are subject to sources of uncertainty, including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This uncertainty imposes a limit on our confidence in the response or output of the model. Good modeling practice requires that the modeler establish confidence in the model. This requires, first, a quantification of the uncertainty in any model results (uncertainty analysis); and second, an evaluation of how much each input is contributing to the output uncertainty.

Sensitivity analysis addresses the second of these issues, performing the role of ordering by importance the strength and relevance of the inputs in determining the variation in the output. “Sensitivity analysis is the general process of discovering the effects of model input parameters on the response features of interest using techniques such as analysis of variance (ANOVA)” (ASME V&V10-2006).

Furthermore, sensitivity analysis can be useful for a range of purposes, including:

- Model simplification - fixing model inputs that have no effect on the output, or identifying and removing redundant parts of the model structure.
- Increased understanding of the relationships between input and output variables in a system or model.
- Enhancing communication from modelers to decision makers (e.g., by making recommendations more credible, understandable, compelling or persuasive).
- Finding regions in the space of input factors for which the model output is either maximum or minimum or meets some optimum criterion.
- Testing the robustness of the results of a model or system in the presence of uncertainty.
- Uncertainty reduction: identifying model inputs that cause significant uncertainty in the output and should therefore become the focus of attention if the robustness is to be increased.
- Searching for errors in the model (by encountering unexpected relationships between inputs and outputs).
- In general, most sensitivity procedures adhere to the following outline:
- Quantify the uncertainty in each input (e.g., ranges, probability distributions). Note that this can be difficult and many methods exist to elicit uncertainty distributions from subjective data.
- Identify the model output to be analyzed (the target of interest should ideally have a direct relation to the problem tackled by the model).
- Run the model a number of times using some Design of Experiments (DoE), dictated by the method of choice and the input uncertainty.
- Using the resulting model outputs, calculate the sensitivity measures of interest.

In some cases this procedure will be repeated, for example in high-dimensional problems where the user has to screen out unimportant variables before performing a full sensitivity analysis. Sensitivity analysis is recommended to guide the extent of extrapolation and to define limitations on the model (Reference 2.1.4.21). Sensitivity analysis is recommended throughout the model validation process to determine the sensitivity to model inputs that are difficult to measure (e.g., friction) or inputs that are not known with high certainty (Reference Figure 4).

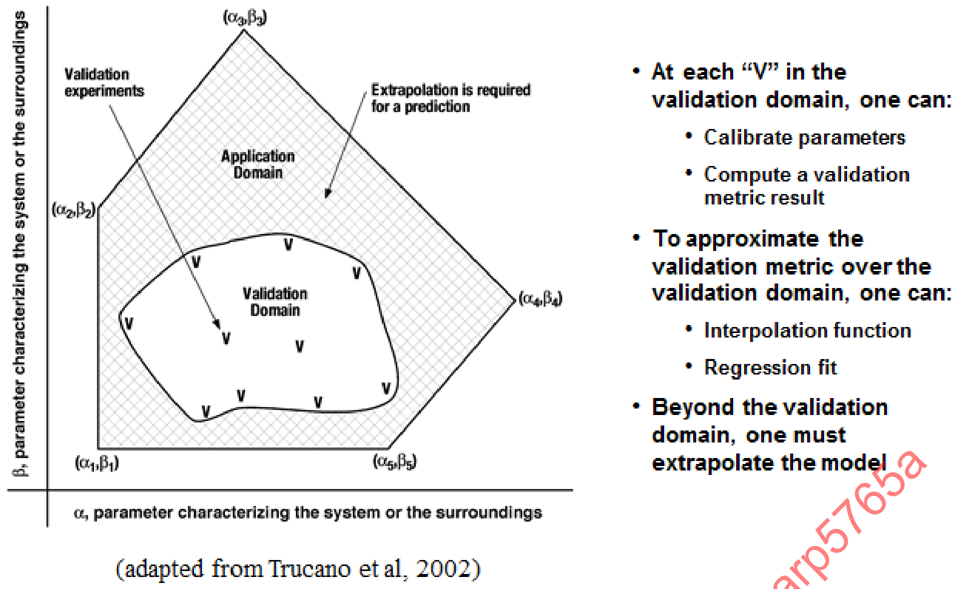


Figure 4 - Application domain (extrapolation) versus validation domain (Reference 2.1.4.21)

There are varieties of methods available to perform a sensitivity analysis. The choice of methods should be sufficient to match the complexity of the problem. In its basic form, a sensitivity, Design of Experiments and ANOVA analysis can be performed in popular spreadsheet programs. Alternatively, commercially available software tools are available to streamline the setup, execution, data collection and analysis of the study. Most of these tools also provide the ability to develop a pseudo-model (often referred to as response surface model or RSM) which is useful for understanding the extrapolation into the Application Domain of interest.

Sensitivity analyses can be used to document the sensitivity of the model to different parameters or differing initial conditions. This includes checking the sensitivity of the model for extrapolation and for the justification of specific model inputs where the data was not explicitly known.

An example of the sensitivity of the model to a parameter is the effect of the seat bottom cushion material property (input parameter) on the hip displacement and lumbar load (output parameters). The uncertainty of the foam material properties can be quantified by carrying out more sled tests, running multiple material characterization tests (see Example E1 and E2 in Appendix E), to better understand the load deflection characteristics of the foam, and by determining the rate sensitivity of the foam (refer example in Appendix E). Sensitivity analysis may have to be run at component level (to evaluate say material models) or system level (to evaluate global or specific response). Example E4 in Appendix E shows an example of system level sensitivity where the pretension in restraint was used to observe effect on maximum head excursion.

An example of sensitivity analysis to justify an uncertain model input is the selection of friction between a seat cushion and the v-ATD in a horizontal condition. Multiple values of friction coefficients, such as 0.0, 0.3, and 0.5, can be simulated. If the model results, such as head x-motion, are insensitive to the applied friction coefficients, then the typical value of 0.3 can be considered acceptable.

An example of sensitivity analysis for model extrapolation is evaluating the initial position of the head and the location of any structures which might be struck. The initial model should match these positions within the tolerance, however, future applications may change the SRP and seat geometry such that the initial head location might change. A sensitivity analysis could be conducted to determine what effect these variations have on the impact velocity and resulting HIC calculation.

4.4 Material Characterization

The characterization of materials is inherently important to the resulting system response and takes on a critical role for dynamic load cases where large displacements or permanent deformations are very common. Complicated materials such as strain rate sensitive foams and dedicated energy absorption techniques may be incorporated. There are three model inputs that affect material performance: material properties, constitutive models, and element formulation.

4.4.1 Material Properties

To predict the dynamic response of a seating system, a full load-deflection or stress-strain curve may be needed in addition to the basic material properties such as elastic modulus, yield strength, ultimate strength, and poison's ratio. These properties can be referenced from standards such as the Metallic Materials Properties Development and Standardization (MMPDS), obtained using known and accepted standard test methods such as American Society of Testing Materials (ASTM), or obtained from company proprietary methods accepted by a regulatory agency. MMPDS also provides typical stress strain curves for most of the material covering plastic range. Additional resources on metallic material characteristics are available in References 2.1.4.22 and 2.1.4.23.

Commonly used standard test methods to characterize metallic and non-metallic materials are:

- ASTM E8, ASTM D3039 - Tensile test
- ASTM E9, ASTM D3410, ASTM D6641, ASTM D5467 - Compression test
- ASTM D3518 - Lamina shear testing
- ASTM D7078 - V-notch Shear Test
- AS8043 - Seat belt pull test
- ASTM D3574-03 - High speed cushion compression test
- DOT/FAA/AR-05/5,I Development and Validation of an Aircraft Seat Cushion Component Test - Volume I

Regardless of the source of the material data, the following details should to be documented:

- Source of the data
- Reliability and Repeatability of data
- Statistical basis for material properties (percentile and confidence level)
- Failure criteria
- Directionality of test data (tension, compression, shear)
- Orthotropy of material data (longitudinal, long transverse, short transverse)

4.4.2 Constitutive Models

The selection of constitutive model, also referred to as material model, can affect the accuracy of the simulation output, especially for non-metal parts. When choosing between multiple constitutive models, It is recommended to evaluate the effect with coupon level or component level simulations.

4.4.3 Element Formulation

The type of element used to model a component also affects the structural response. For instance, a 3-node membrane element does not include bending, whereas a shell element does. Depending on the component to be modeled, bending may or may not be important. The types of elements, along with the justification for their use, should be documented. Additional guidance is provided in 7.2.3.

4.5 Subsystems

As a practical approach, it may be difficult to model complex structures in detail such as joints, fittings, restraint systems, and seat-to-aircraft interfaces. In these cases, subsystem testing may be needed to characterize the performance of these components and structural details so that deformation, elongation, or failure is accurately predicted. Validation of subsystems is achieved by performing coupon, component, and/or subassembly tests and correlating key performance characteristics such as load, deformation, or failure to the numerical model.

It is recommended to carry out component level or subsystem level testing and modeling to understand system behavior such as material properties (especially rate sensitive materials), behavior of joints, friction factors, and stress concentrations. Understanding the response of subsystems such as seat cushions, occupant restraints, v-ATDs, and any special seat mechanisms is recommended before running a full seat system simulation.

It is recommended to model and simulate the material characterization test to confirm that the selected material model is reproducing the physics observed in the test. This may require calibration of the FE input parameters such as element formulation, element type, time step scale factor, element length, and material model. At the end of each analysis, a system response such as force or displacement is compared with the physical test result at different levels such as at 25, 50, 70, 80, and 90% loading.

The use of component testing and simulation is extremely important for the use of non-metallic parts or parts which may fail during a full-scale test. It is only by characterizing the behavior beyond the elastic region that any confidence in the model can be obtained. This technique helps to ensure that complex structures can be accurately modeled and their response predicted. Special features of a seat may require development of a unique fixture to determine their behavior.

Subsystem validation adds another layer of confidence to the fully integrated seat model. For instance, if the material models for individual foam layers was calibrated, then simulating a component test of a cushion composed of multiple foam layers, along with the cushion cover, adds confidence that the calibrated properties are correct. High fidelity subsystem models provide a good base for the full system model, however interactions between different subsystems means that the full system model may not have the same fidelity as the subsystems.

Component test/models validation should be performed to characterize the following:

- Behavior of critical joints and attachments
    - Seat fitting to seat track
    - Complex joints
    - Composite bonded structure
- Discrete energy absorbers
- Seat cushion behavior
- Restraint system and it's attachment
- Structure to be assessed for head impact

4.6 Seat System

After verification and subsystem validation, the seat model is compared to a dynamic test of the same test condition and similar installation specifics as the intended use of the model to show that the model reproduces the same dynamic behavior as the physical seat system. The sled pulse from the physical test should be used in the model. Channels that are critical to system performance should be identified and acceptable error limits specified. The computer model is considered validated if acceptable agreement between analysis and test data can be shown for those parameters critical to the application of the model. The calculation methods are detailed in Appendix A. Test data used to validate the model should be included in the VVR.

4.6.1 v-ATD Calibration

Use of an appropriate v-ATD is an essential element of generating an accurate seat system model. The recommendation for calibration of the v-ATD was presented in Section 3 of this document. The end-user is responsible to ensure that the v-ATD performs to the level that is needed for qualification purposes and should understand the limitations in the event the v-ATD is conditionally compliant. Models utilized for certification purposes should clearly declare any conditionally compliant areas for the v-ATD and the affect it has on the outcome of the results.

H-pt height comparison: In order to facilitate comparison of the H-pt location between a physical ATD and the v-ATD, the ATDs should be measured in a baseline configuration. Position the ATD as specified in 49 CFR Part 572.11 for checking dimensions and measure the H-point location (x and z) when seated on a rigid surface. The rigid surface shall have a pan angle of 0 degrees with horizontal and a back angle of 0 degrees with vertical. The difference in the H-pt height between the physical and numerical ATDs should be documented.

4.6.2 Initial Conditions

As with all models, it is important that the initial conditions of the full seat system are accurate. Loads associated with floor misalignment should be evaluated. This shall be checked via measured data after the preloads and before the sled pulse is initiated. Pre-stresses and strains that affect system performance should also be evaluated. These are typically seen in joints and restraints.

Agreement between the test and simulation for the initial position of points on the seat and ATD is a crucial step in having a high fidelity simulation. These points should have unambiguous definitions. Figure 5 and Figure 6 show an example of these locations.

Example hard points on a typical Part 25 PAX seat are: forward seat track fitting, aft seat track fitting, front tube, aft tube, belt anchor point, floor height, and seatback hinge point. For most of these points, knowledge of the location in all three dimensions is beneficial. For these points, the acceptable difference between the test and model should match manufacturing tolerances.

Other, more ambiguous (soft) seat points can also be useful. Example points are the top of the seatback, the forward most point of the seat frame, points on the seat cushions, points on the restraints, and points on the armrest. Careful notes should be taken regarding the exact location of the measured point (pictures can often aid in this). Due to the nature of these points, the tolerance is less strict compared to the hard points. Some points, such as the buckle location, are only necessary if the buckle is explicitly modeled.

Likewise, for the ATD, both hard and soft points should be evaluated. Hard points include the head CG, H-point, knee bolt, and ankle bolt. In general, a tolerance of 0.5 inch on the initial position of these points is recommended. Under certain conditions, an important dimension will need a more strict tolerance, e.g., H-point X and Z in a down load scenario and head CG in an injury criteria scenario. Because of the lack of manufacturing tolerances on the Hybrid II ATD pelvis, the initial position comparison of the H-pt height (z-axis) should be corrected for the baseline difference between the physical and numerical ATDs, as described in 4.6.1. Soft points include the shoulder joint, wrist joint, and most forward or aft location of the shoe. As with the seat soft points, the tolerance is less strict compared to the hard points. For side facing seats, points along the mid-line of the ATD may be of additional value.

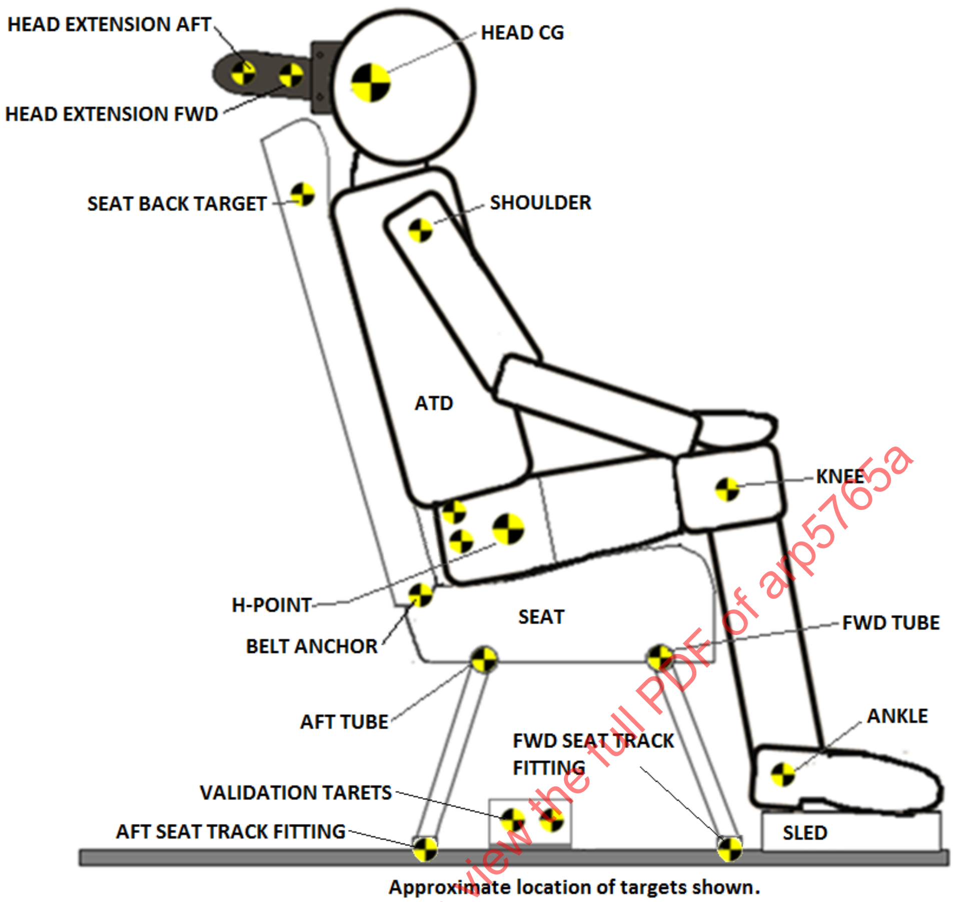


Figure 5 - Typical seat and ATD pre-test positions of interest

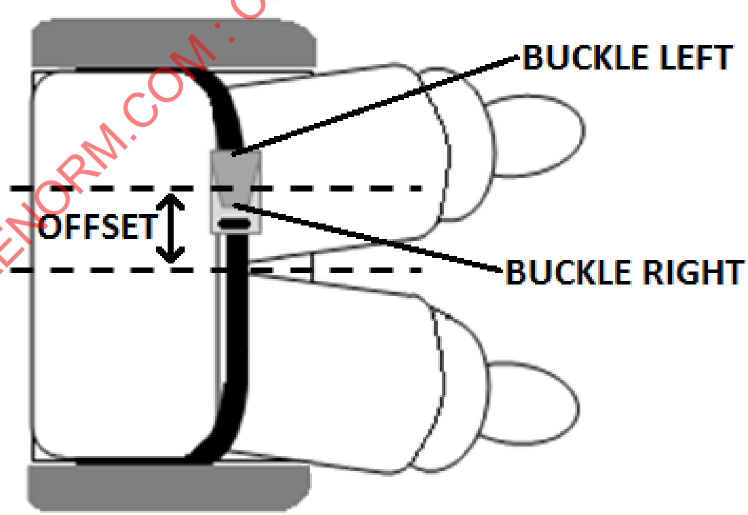


Figure 6 - Lap belt positions of interest

4.6.3 Model Output Pre-Checks

Once the simulation terminates, global modeling parameters should be evaluated including mass scaling, hourglass energy, energy balance, and penetrations. Section 7.2 provides recommendations for each. A qualitative comparison of the model predicted occupant and seat kinematics with test videos can provide an initial check on the simulation results.

4.6.4 Seat System Response Quantities

As discussed in 4.1, system response quantities can be separated into primary, support, and threshold categories. All quantities used to show compliance to AS8049 are primary channels and should be evaluated; however primary channels are not necessarily limited to compliance channels. Support and threshold channels are used to provide additional confidence and should be evaluated when appropriate. The analyst is encouraged to request the collection of channels beyond the regulatory minimum with the testing laboratory.

All evaluated channels should correlate within the defined tolerances for peak error (Table 4) and curve shape error (Table 5) using the metrics defined in Appendix A. For channels not defined in those tables, the primary channels should correlate within 10% for both peak and curve shape error following the intent of FAA AC 20-146. Engineering judgment is emphasized, as there may be times where different limits would be appropriate. Support channels should also be evaluated with the magnitude and curve shape metrics defined in Appendix A, using engineering judgment to determine suitable limits. The method of evaluating threshold quantities, as described in Appendix A, does not require the definition of specific limits.

For any of the three types of SRQs, engineering judgment should be used to determine the specific channels to evaluate for the reality of interest and intended use. In general, the SRQs can differ greatly between a structural test, an injury criteria test, and a combined horizontal-vertical test. Using a basic, purely forward facing, Part 25 passenger seat as an illustrative example, typical channels for the three test conditions are described below.

For the combined horizontal-vertical test condition (Table 6), lumbar load is a compliance channel and hence a primary channel. Additionally, the vertical component of the floor reaction load, for all seat attachment points, is needed to show that the primary load path is modeled accurately. When available, occupant trajectory, such as pelvic vertical motion, and lumbar bending force can be used to support the evaluation. Belt loads are essentially zero throughout the critical portion of the test and are not typically measured. The simulation belt loads can be compared to either measured loads or the assumption of zero loads using a simple threshold is used to show that there is no anomaly in either the test data or simulation data.

Table 6 - Typical channels for horizontal-vertical test condition (Part 25 PAX seat)

Primary	Support	Threshold
Lumbar Fz	Occupant Trajectory	Belt Load
Floor Reaction Fz	Lumbar My	

For the structural test (Table 7), the floor reaction loads for the highest loaded legs are primary channels, both in the horizontal and the vertical direction. The floor reaction loads for the other legs are typically lower in magnitude and are therefore support channels. The lateral component of the load is likely to be minor in comparison to the horizontal and vertical directions and is considered a threshold channel. Because the belt loads are part of the primary load path, this channel is considered a primary quantity. Occupant motion can be used to provide supporting evidence that the structure is properly loaded and that the measured reaction forces are correct for the right reasons. Loads associated with floor misalignment should also be evaluated. This shall be checked via measured data after the preloads and before the sled pulse is initiated.

Table 7 - Typical channels for structural test condition (Part 25 PAX seat)

Primary	Support	Threshold
Floor Reaction Fx, Fz, and Fr for highest loaded legs in tension and compression	Floor Reaction Fx, Fz, and Fr for all other legs	Floor Reaction Fy
Belt Loads	Occupant Trajectory	Peak strain in structural members in the primary load path

For the injury criteria test (Table 8), multiple channels are needed to show that the occupant motion and interaction with surrounding structures is accurate. Several channels are also available to provide supporting evidence for example Head Acceleration Ax and Az are the support channels for Head Resultant Acceleration and HIC. Unlike the previous two conditions, the head trajectory is now considered a primary response, particularly if this model is going to be used to show that the head does not contact any aircraft structures.

Figure 5 shows an example of the qualitative comparison of the head impact location

Table 8 - Typical channels for injury criteria test condition (Part 25 PAX seat)

Primary	Support	Threshold
Head Resultant Acceleration and HIC	Floor Reaction Fx and Fz	Floor Reaction Fy
Head X and Z motion	Head Acceleration Ax, Az	Head Acceleration Ay
Belt Loads (belt payout if present)	Pelvic acceleration and/or Knee Motion	
Femur Fz[1]	Target Seatback Motion	
Impact Location[2]	Head Impact Velocity and Angle[3]	

1 – Femur Fz should correlate if the applicant and ACO determine that it should be evaluated

2 – Qualitative evaluation

3 – Single value only, no shape evaluation

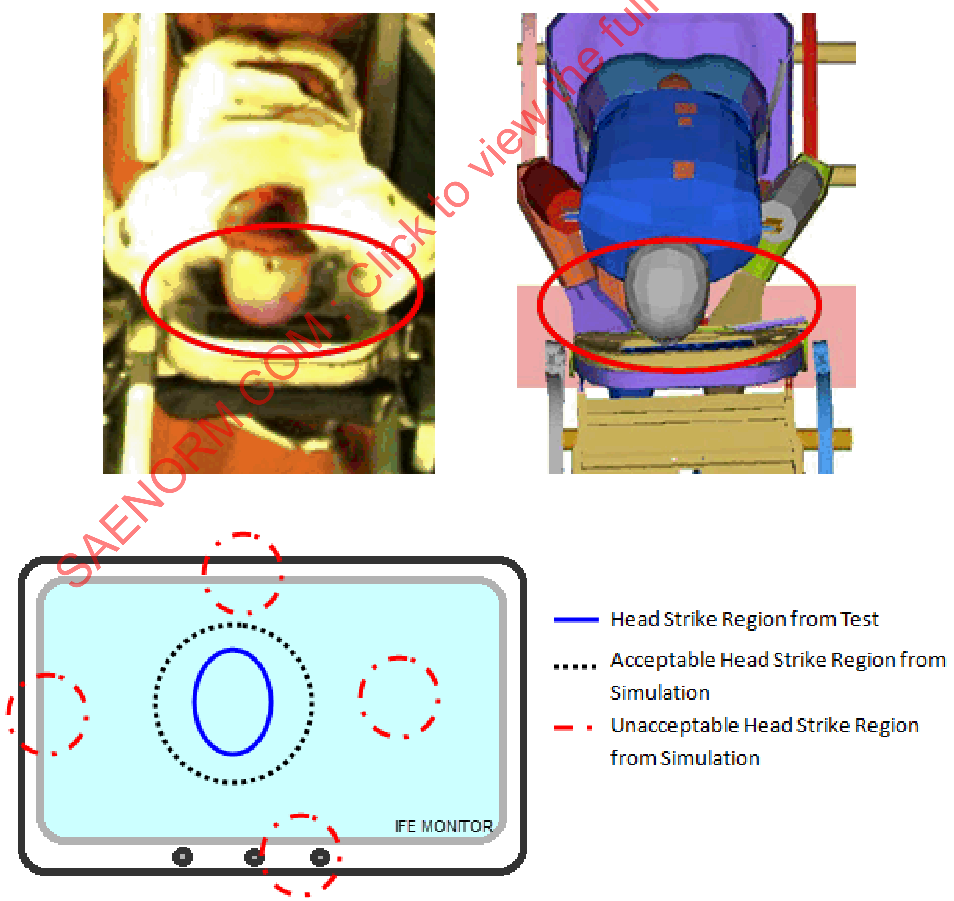


Figure 7 - Qualitative comparison of head impact location

5. MODEL USE

Given a model that has been validated for the intended use, the analyst will use the model to evaluate the seating system in lieu of physical tests, within seat development or a seat certification program. For seat development, the uses of modeling and simulation are widespread. For certification, a more conservative approach is suggested. FAA AC 20-146 provides guidance for when M&S could be used to reduce or replace physical tests or show compliance with federal regulations focusing on modeling in support of testing (worst case scenario design, installation, or head strike potential) and modeling instead of testing (change to seat design, change to installation).

The model used for prediction should be identical to the model used in validation with modifications only due to the specific extrapolation of interest. For example, if the goal of the model is to predict the impact of changing the seat pitch, then the only difference between the validation simulation and the model use simulation should be the seat pitch. No other changes to the model are legitimate (with the exception of the pulse, see 5.4 and 7.2.7).

The specifics of model use will vary based on the specific intent. This section is intended to provide general guidance on the use of a model that has been validated for an intended use.

5.1 Hardware and Software

Model use simulations should be performed on the same hardware and software platform on which the validation was conducted. If a different software version and/or hardware platform is used from the initial validation, the validation model should be reevaluated.

5.2 Verification

In general, the same time step and mesh should be used for model use simulations as was used for the validation simulation(s). In some cases, the change in the model will necessitate a new time step or mesh. For example, changes to a seat pan such as the addition of holes or reinforcements, will require a new mesh be generated and this mesh may require a different time step. Changes to the material properties may also require a different time step if the stiffness or material density is significantly different. The user is encouraged to follow the recommendations in 4.2 when the changes to the model have a potential to affect the time step or mesh.

5.3 Subsystems

When using the model to substantiate changes to the seat design, use of subsystem models is encouraged. Subsystem models should be verified and validated (see Section 4).

5.4 Load Application

Model use simulations should apply the sled pulse in the same manner (acceleration versus deceleration) as was used in the validation simulation(s). Additionally, the user is recommended to use the same pulse as was used in the validation simulation(s). Regardless of the application method and specific profile selected, the applied pulse must meet the requirements of the pertinent regulation. Additional guidance is contained in 7.2.7.

5.5 v-ATD

Model use simulations that utilize a v-ATD should use a calibrated v-ATD, per Section 3 of this document, and the v-ATD should be identical to that of the validation simulation(s). The end-user is responsible to ensure that the v-ATD performs to the level that is needed for qualification purposes and should understand the limitations in the event the v-ATD is conditionally compliant. It is important that any limitations inherent in the v-ATD not adversely impact the results of the model use simulations.

5.6 Initial Conditions

v-ATD positioning: The positioning of the v-ATD should match that used in the validation systems when possible. Changes to the seating structure may require a new seating position. Section 7.2.8 provides additional guidance.

Floor deformation: The means of applying structural deformation should match that used in the validation simulation(s). Additional guidance is provided in 7.2.8.

Restraints: Fitment of the restraints and any required preloads or slack should match that used in the validation systems when possible. Changes to the seating structure may require a new fitting of the restraints. Additional guidance is provided in 7.2.4 and 7.2.8.

Clamping: Preloads related to clamping of one part to another should match those used in the validation simulation(s).

5.7 Limitations

It is recommended to evaluate how the assumptions/simplifications of the model might affect the output of the computational model, the interpretation of the results, and the relevance to the purpose of the study. For instance, if a buckle is not explicitly modeled, then certain aspects of the restraint system cannot be evaluated with that model. If loads in the structure or loads transferred to the aircraft are increased compared to the loads measured in the validation simulations, then the risk of structural failure should be addressed. Significant changes to the material or mechanism of load transfer of the seat-to-floor attachments from the certificated baseline seat design (which includes the seat-to-track fitting and track substantiated under TSO-C127x), will require a new series of dynamic tests and are not candidates for certification by analysis.

AS8049 Compliance Requirements: Table 9 lists assorted compliance requirements defined in AS8049. 'Not Practical' means that with the state of the art of today's modeling, it is either not possible or not practical to use the dynamic modeling to answer these questions. If a dynamic model is used as part of the certification, another means of compliance with these paragraphs of the requirements would have to be developed. 'Possible' means that it can be accomplished with the dynamic model, but is not a guarantee of success and may not necessarily be accomplished. For instance, for determining the post-test deformation measurements, it may be necessary to conduct an additional implicit analysis to apply the restoring force to get the seat back to its nominal resting position. If this cannot be done, then showing these data would then be 'Not Practical'.

Table 9 - AS8049 compliance requirements

Compliance Requirement SAE #	Requirements	Can be Demonstrated by Numerical Analysis	Comments
5.3.9.13	Live vest retrieval	Not Practical	
5.4.1	Seat structure remain attached	Possible	The model will have to demonstrate that it properly predicts failure
	Prediction of primary structural damage	Possible	Damage prediction may be possible by comparing maximum stress/strain data with accepted values, however, this is just predicting damage and not failure, would need to determine acceptability
	Deformation, crippling, shear buckling	Possible	
5.4.2	Occupant restraint system remains attached	Possible	Belt path and location should be evident when reviewing the occupant kinematics
	Damage prediction: fraying, tears	Not Practical	These would require a very fine mesh and other techniques to simulate fiber layup and typically beyond the capability of most restraint system models
	Buckle release and damage to components affecting buckle release	Not Practical	This would require detailed modeling of the buckle and its operation/mechanism and is generally beyond most dynamic models
	Seat Belt Payout	Not Practical	While the payout itself is not a requirement, it can be important to measure this quantity to aid in the assessment of the belt performance. Since the buckle and ring connectors are not modeled at this time, belt slippage and payout cannot be determined.
5.4.3	Seat permanent deformation within quantitative limits (C/B ratio, seat pan rotation, seat permanent deformation). Reference 3.5 of AS8049B.	Not Practical	The final resting portion of the seat can be determined, but a subsequent analysis would need to be conducted to apply the restoring force. Because this restoring force cannot be readily applied or the floor unwarped, the final permanent deformation point cannot be determined. However, a conservative approach may be to use the maximum dynamic displacement and compare that with the warped configuration to determine an estimate of the permanent deformation. Consideration must be given here if the permanent deformation cannot be determined as this will severely limit the application of the model for structural evaluations.
	Deployable Items affecting egress (tray tables, leg rests, video monitor, etc.)	Possible	As long as the action is modeled appropriately
	Stowable seats near exits or exit path	Possible	The seats would be modeled and validated as regular seats
5.4.4	HIC not to exceed 1,000	Possible	Part of the kinematic determination of the v-ATD
	Post-test delethalization, sharp edge evaluation	Not Practical	This would require a significantly small mesh in all areas, or running the model many times increasing mesh density in areas were failure was predicted. A better alternative would be to determine areas of where damage occurs and conduct specific testing on those objects for evaluation
5.4.5	Upper torso restraint loads not to exceed 1,750 pounds	Possible	Part of the loads determination
5.4.6	Lumbar load not to exceed 1,500 pounds	Possible	Part of the loads determination
5.4.7	Upper torso restraint remains on ATD during impact	Possible	Belt path and location should be evident when reviewing the occupant kinematics
5.4.8	Pelvic restraint remains on ATD pelvis during impact	Possible	Belt path and location should be evident when reviewing the occupant kinematics
	Submarining	Possible	Belt path and location should be evident when reviewing the occupant kinematics
5.4.9	Femur load not to exceed 2,250 pounds	Possible	Part of the loads determination
5.4.10	Retention of items of mass	Not Practical	While the items of mass will be included, the details regarding how they are attached and the fitting mechanisms with their associated strengths to the seat are not included

5.8 Factor of Safety

To account for the testing uncertainty, conservatism can be incorporated into validation and model use via a factor of safety. For example, repeated testing of seat cushions show a typical variance about ±125 pounds when testing parameters are tightly controlled. Assuming the uncertainty is normally distributed, the standard deviation is 41.67 pounds (6 standard deviations within the 250 pound range). Based on this standard deviation, there is a 95% confidence that the true load is below the regulatory limit of 1,500 pounds if the measured or simulated load is no greater than 1,430 pounds. Therefore, it is recommended that only seat configurations with dynamic test data that yield spine loads below 1,430 pounds should be used for validation. Likewise, for model use, it is recommended that only models that produce a lumbar load below 1,430 pounds be used. Note that models can exceed 1,430 pounds in the validation phase.

Table 10 - Example peak lumbar loads

	Validation	Model Use
Model under predicts	Test = 1,400 pounds, Model = 1,350 pounds	Model = 1,380 pounds or less
Model over predicts	Test = 1,400 pounds, Model = 1,450 pounds	Model = 1,430 pounds or less

Given two dynamic tests with the same desired deceleration profile, the maximum HIC values will likely vary. Therefore, a precise match between the test derived HIC and the analytical HIC is not realistic. However, the maximum analytical HIC value should correlate to within 100 HIC units of the maximum test derived HIC value. The applicant is encouraged to generate conservative HIC prediction models. One method to add conservatism to the process is to incorporate test uncertainty as a factor of safety in validation and model use. Using the same process as above and assuming a typical variance of ±200 HIC units, the 95% confidence HIC value is 890. Therefore, it is recommended that only seat configurations with dynamic test data that produce a HIC value below 890 should be used for validation. Likewise, for model use, it is recommended that only models that produce a HIC value below 890 be used. Note that models can exceed 890 in the validation phase.

Table 11 - Example HIC values

	Validation	Model Use
Model under predicts	Test = 850, Model = 800	Model = 840 or less
Model over predicts	Test = 850, Model = 900	Model = 890 or less

5.9 Sensitivity Analysis

If the conclusions of the analysis are significantly dependent on the assumptions and/or simplifications in the model, the analyst should conduct a sensitivity analysis of the parameters associated with those assumptions and/or simplifications. Sensitivity analysis is recommended to guide the extent of extrapolation and to define limitations on the model as well as to determine the sensitivity of model inputs that are difficult to measure (e.g., friction) or inputs that are not known with high certainty.

5.10 Post-Processing and Results

Provide channels as per AS 8049 from the model use simulation(s) following SAE J211 for sample frequency and filtering. If a quantity is derived from a numerical model, the means of obtaining the results should be documented. Primary channels should be compared to the regulatory limit to determine whether the design/installation passes. The primary and support channels should also be compared to the validation simulation(s) results to determine how much the values have changed. Significant differences should be addressed, specifically to determine if the simulation is erroneous and to evaluate the effect of the differences on the system performance.

6. DOCUMENTATION OF V&V AND MODEL USE

It is important to document the model development, verification and validation activities, and model use. Documentation should include the rationale for the selected equations, list the assumptions, and discuss the results and uncertainties. Enough detail should be included to determine the correlation between the physical seat and numerical model. The level of detail required in each section will depend on the complexity of the concept and its impact on the model response. In many cases a simple paragraph or table providing the information may be sufficient. Likewise, referring to attached documentation will also satisfy the requirements.

The context of the mode use, i.e., the goal of the project, should be discussed as this will guide what components are needed for the analysis and which can be safely excluded. The sections provided below are meant to be a guideline on the types of information to include in the report; they may not be relevant or important to every model. There may be other items of interest to include in the report and some of the below items may already be documented in the seat certification plan. Use engineering judgment on which sections apply.

The term 'provide rationale' is used throughout this section. This simply means to state the source or reasoning behind a specific choice. For example, the rationale for the selection of MMPDS A basis material data could be that the part in question is a structural member in the primary load path, but is only expected to experience elastic deformation. It is not meant to go into a scientific study or justification, just to document the reasoning behind making certain choices.

A sample report is available at the following website: ftp://ftp.tc.faa.gov/actlibrary

6.1 Executive Summary

The purpose of the executive summary is to provide a concise, high-level overview of the entire report so that a reader can quickly understand the modeling and simulation conducted. The items in the executive summary should be included in more detail elsewhere in the report. The summary should include the following:

- Briefly state the modeling approach and summarize the type(s) of analysis(es) conducted in the computational modeling study (e.g., rigid body or FEA; static or dynamic, implicit or explicit).

- Briefly summarize the model at a high level (number of seat places, impact direction, orientation, etc.).

- If the seat is for a family of seats, describe other applicable seat models.

- State the vendor of the commercially available analysis code.

- Discuss the simulation results (and experimental validation) and their implications for certification (i.e., the comparisons were acceptable except for which variables).

- Summarize the model limitations or conversely, the conditions where the validation is applicable.

- Summarize the conclusion(s).

6.2 Introduction

Discuss the purpose and scope of the analysis, as this will dictate the relevant details necessary for review. Give a brief description of the type of seat test and configuration. The details provided in this section should correspond to the objectives of your analysis (i.e., calculate lumbar load for a 14G down test in a two-place transport category seat).

6.3 Numerical Implementation

Provide the following details regarding the software used in the numerical implementation of the analysis.

- Provide the name (including version number) of the software used to solve the model(s).
- Provide configuration control information such as platform, operating system, software build, etc.
- Provide details on the solver routine used including whether the solution is implicit or explicit.
- If a v-ATD is used, provide the following information on the v-ATD
  - Specify the ATD (i.e., Hybrid II, FAA-Hybrid III, etc.)
  - Provide the version number of the v-ATD
  - Describe the compliance of the v-ATD with regards to Section 3
  - Describe any limitations of the v-ATD
  - Attach v-ATD calibration report

6.4 Seat System Geometry

Provide a high level description of the seat to be used and where it will be installed as it pertains to the configuration being analyzed. This could include information on the degree of overhang, the seat place width, or seat pitch.

Provide details regarding the seat geometry that was modeled, such as CAD drawings or other dimensional details. Describe the critical components that are in the load path for the specific scenarios that were tested and to be modeled. Describe the restraint system used and any additional features. This may include load limiters, inflatables, or shoulder harnesses.

6.5 Material Models and Material Properties

Provide details for the material models (constitutive laws) used to describe the mechanical behavior of the seat and reference the solver material identification. Provide a rationale for the constitutive model chosen to represent the material behavior. Provide the material properties (input data) used in those material models and state how the data were obtained. Referring to the solver manual will reduce documentation, but may delay acceptance.

For each material, reference the material inputs necessary to fully characterize the relevant mechanical behavior of the material. This may include:

- Source of material inputs which could include
  - Provide a reference if obtained from literature
  - Test description, e.g., uniaxial tensile test, compression test, etc.
  - Sample condition, e.g., geometry, processing, heat treatment
  - Protocol, e.g., loading rate, frequency, mean strain
  - Environment, e.g., temperature, humidity
  - Obtained characteristics, e.g., force, torque, displacement, time

- o Derived force-displacement or stress-strain-curves, etc.
- o Method(s) used to compute the material properties from the test data (statistical basis)

- Material law coefficients
- Elastic modulus
- Ultimate tensile strength
- Plateau stresses and elastic strain limits
- Strain at break
- Viscoelastic properties

The materials used in the testing should represent the design details of the parts of interest, to the extent possible.

6.6 Mesh (System Discretization)

Provide the following details regarding generation of the mesh:

- Element types used in the analysis
- Mesh density
- Element quality for the different element types in the model, such as aspect ratio, Jacobian, and crash time step
- Mesh refinement or adaptive meshing used.

It is recommended to provide figures depicting the mesh at relevant scales, especially in transition regions or regions of complex geometry and regions of high stress or strain. For critical parts, overlay CAD data with FE to show geometric conformity.

Mesh Convergence: For implicit/static analysis on a component level model provide a convergence analysis (tabular or graphical representation) to demonstrate that the results are independent of the element size. For explicit analysis, provide a rational stating how the results are mesh independent.

If portions of the seat were modeled with differing discretizations, analysis methods or simplifications, describe and provide a rationale for these differences (e.g., conducted part component tests and replaced with beam elements, non-structural part not in the load path, etc.). If seat has unique geometric features that might affect the analysis (e.g., seat pan contour) then describe how those were or were not accounted for in the model. Finally, regarding the method of construction, please include relevant information on limitations and assumptions as related to the geometry.

6.7 Boundary and Initial Conditions

Provide information regarding the conditions that were imposed on the system. These might include, but are not limited to, the boundary and loading conditions, initial conditions, and other constraints that control the system. These items may include:

- The acceleration pulse from the test.
- The location of any ballast weight.
- For a structural simulation, describe how the floor warpage was applied to the model.

- Provide a description of the initial conditions included in the model such as pretension application and pre stresses included in the components.

- State the contact conditions in the model, including friction.

- Describe the model control parameters, including: units, time step, start/stop times, global damping.

6.8 Post-Processing and Results

SAE J211 should be followed for any data collection and AS8049B should be followed for any seat system testing.

Provide the following:

- Describe the computational model output. If applicable, describe any post-processing calculations done to arrive at your output. Data channels necessary for validation processed according to SAE J211.

- Energy balance (include sliding interface energy).

- Mass scaling used.

- State whether any elements have exceeded a failure criterion and the details of such failure.

- Provide the values and graphically display the location(s) of critical stresses, strains, forces, or displacements.

If multiple loading modes were modeled separately (static warparge, then dynamic pulse), discuss the implications of superposition of stress or strain states for each loading mode (e.g., location, direction, and phase of the critical stresses or strains).

6.9 Validation

Provide information regarding the methods employed to validate the computational model. Validation of the seat system model establishes the level of accuracy and predictability of the model and defines the limitations of the model. The results of a validation study serve to support your choice of constitutive relationship, material properties, meshing, and contact. The following format for presenting that information is suggested.

Compare the simulation results to the test data for the primary, support, and threshold channels, when available, as described in 4.6. Specify the type of information that can be gained from the validation experiment and its relationship to model predictions and accuracy.

Describe the physical test conditions used for the model validation study. This could include:

- Any component tests conducted.

- The final full scale seat dynamic test.

- Include information and rationale for items like which component or subsystem selected, boundary and loading conditions, and initial positions.

- Any structural failures that occurred during the testing.

Describe the locations on the seat or ATD where the experimental measurements were acquired. For example, if additional photo targets were placed on the ATD describe those locations.

Describe the boundary and loading conditions used for the model and describe how they relate to the validation experiment.

State the primary, support, and threshold channels. For primary channels, calculate the error metrics according to appendix A and list in a table. Inclusion of plots is encouraged. For the support and threshold channels, show that the test and simulation results are similar to the extent that it is useful. Provide a kinematic comparison to demonstrate that the model is able to capture relevant behavior.

Include in the discussion the relevance of the seat system test to other possible test scenarios (i.e., same seat family with different leg spacing), implications of model and experimental assumptions on the results, limitations on the agreement between the validation model and experiment, and the extent of predictability of the seat system model.

6.10 Model Use

Document the intent of the model use. Document all changes to the model including rationale for any changes to material models, contact algorithms, friction factors, etc. Provide the results of the model use simulation(s) including channels as per AS8049. Results may be presented in more than one format (e.g., table, graph, and plot).

It is recommended to provide details regarding how the assumptions/simplifications described in the previous sections might affect the output of the computational model, the interpretation of the results, and the relevance to the purpose of the study.

6.11 Limitations

Discuss key limitations of the model. This section is not focusing on a description of the model, but on the inherent limitations of the model, for example, a baggage bar was modeled using beam elements so failure cannot be predicted for this member. This should include items not compared per 5.7 and under which conditions can the model be applied.

If the conclusions of the analysis are significantly dependent on the assumptions and/or simplifications in the model, report on a sensitivity analysis of the parameters associated with those assumptions and/or simplifications.

6.12 Conclusion

Summarize the computational study with respect to the purpose of the study and how the study relates to the regulatory submission. Discuss the results in the context of the modeling objectives and their implications on seat performance. For example, discuss how any failures are noted and how the model would be used to assess any failures that may not have occurred during the system testing. Additionally, address the following points:

- Discuss any inconsistencies between the modeling results and the modeling assumptions and simplifications.
- Discuss the sensitivity of the results to variations in modeling parameters (e.g., material properties, boundary conditions, geometry).

State the overall conclusions of the computational modeling study and whether the objective(s) have been met.

7. BEST PRACTICES FOR TESTING AND MODELING

The purpose of this section is to provide recommended practices that will assist in the development and evaluation of an aviation seat model. The testing subsection provides guidance on how to conduct a dynamic sled test in order to provide the seat engineering analyst with as much information as is reasonable. These efforts go beyond those recommended in AS8049B, as the purpose of tests conducted in accordance with AS8049B are different than tests run in order to provide data for validation of computer models. The modeling subsection provides the industry's current best practices for the development of aviation seat models. Because analytical methods are rapidly evolving, these best practices are expected to change with time and should not be considered a requirement.

7.1 Testing Best Practices

In addition to the requirements in AS8049B, several modifications of a full-scale sled test protocol are needed to provide optimal data for the purposes of modeling a dynamic sled test. In general, more data is needed than a test or simulation engineer may initially realize. This is particularly true for simulations of previous tests where only limited data have been collected. Modeling of these scenarios can be difficult as the parameters necessary to ensure a valid simulation were not measured. While it may not be feasible to perform all of the items listed here, the more information that is available, the better chance there is to accurately replicate the sled test results. Early and good communication between the test engineer and engineering analyst provides an opportunity to clarify what data is needed and allows the test engineer to prioritize the collections of this data based on available resources.

7.1.1 Consistent ATD Pre-Test Position

Care in positioning the ATD is important since initial position affects the kinematics and measured parameters. The ATD installation procedures in AS8049B are a good starting point for achieving consistent ATD placement. However some aspects of the installation procedure are not defined sufficiently to ensure a fully reproducible initial position. In order to provide a seating methodology that can be easily replicated by the engineering analyst, the following additional steps can to be taken.

7.1.1.1 For forward tests or when determining the 1-g pre-load position for a down load test, the amount of force pushing the ATD into the seat back while it is being lowered into position should be controlled (Reference 2.1.4.10). Prior to the ATD contacting the bottom cushion and until it is lowered completely into place, an approximately 20 pound (89 N) force should be applied continuously to the lower sternum of the ATD and the upper legs should be kept horizontal by supporting them just behind the knees. References to the sequence and a pictorial guide to achieve a consistent ATD position are available in Reference 2.1.4.10. The v-ATD should be positioned using the same force in a similar manner.

7.1.1.2 For all tests, the initial orientation of the pelvis about the y-axis should be documented. Normally the stiffness of the lumbar spine and the pelvis and thigh flesh contact will inherently result in the pelvic X-axis being approximately parallel to the upper leg when the ATD is placed in a typical aircraft seating position. If the pre-test pelvis orientation differs significantly from this nominal orientation then the cause (such as binding in the femur ball joint or degraded flesh components) should be determined and corrected. One way to facilitate this measurement is to scribe lines on the side of the pelvis that are parallel and perpendicular to the pelvic load cell mounting surface. If these scribed lines also intersect with a line passing through the femur balls (the H-point) then they can be useful in placing targets from which the pelvis position and orientation can be determined (Reference 2.1.4.10). Specialized electronic sensors are also available to measure the initial pelvis orientation.

7.1.1.3 When positioning the ATD for a down load test, it is important that the pelvis position and orientation matches the recorded 1-g position as closely as possible. Ideally, the x-location should be within 0.2 inches (5.08 mm), the z-location should be within 0.1 inches (2.54 mm), and the angle about the y-axis should be within 2 degrees. These values should be considered a goal and will not always be achievable in a reasonable amount of time.

7.1.2 Test Documentation

Accurate and complete dimensional information about the seat, interior components, restraint systems, and occupant position is a critical component to building a valid model. Documentation of initial preloads, post-test deformations and failures are also important.

7.1.2.1 Seat and Interior Mockup Measurements

- While detailed drawings of the seats tested are usually available to the engineering analyst, an easily identifiable point on the seat should be measured to relate the seat position to the rest of the sled setup. The positions of any adjustable seat features should also be noted. If drawings are not available, then the location of seating support surfaces (seat pan and back), belt anchors/guides, and cushion dimensions should be determined. If the floor is deformed prior to the test, then sufficient measurements should be made to compare the pre-test position with the virtual representation of the seat after floor deformation is applied.

- The location of the floor or any other surfaces included in the test setup that the occupants may interact with should be noted. After floor deformation, the position should also be noted.

- Knowledge of the length and position of all belt segments, even an approximation, will facilitate the placement of belts on the v-ATD. The segment lengths of non-adjustable portions can be obtained from belt assembly drawings if available; otherwise they should be measured. The pre-test length of any adjustable segments, including segments attached to inertia reels, should always be measured. If measurement of the segment lengths pre-test is not practical then an alternative is to mark the belt prior to test and then measure post-test. In addition to segment lengths, pre-test measurements of the location of the anchor, buckle, and at least one intermediary point for each segment, will further improve the accuracy of virtual belt placement. For a shoulder belt, the centerline of the belt at the top of the shoulder is a very useful intermediate point. The pre-test belt location measurements should be done after any floor deformation is applied if the deformed position will be the initial condition for the simulation.

- Post-test deformation of pertinent seat features should be documented to compare with model predictions. The post-test seat measurements should be done before restoring the floor if the deformed position is the final condition for the simulation.

7.1.2.2 ATD Position

- Measure the pre-test position of the ATD(s). The points and angles measured should be those that are readily found on the v-ATD. The most useful points to measure are anatomical landmarks such as the Head CG and joints such as the H-point, knee, and ankle, all of which can be directly compared with v-ATD features. Typically, in a physical test, the surface or target marker attached to a joint or landmark is measured, while for the v-ATD, the joint or body centerline is reported. Documentation of what specifically has been measured will make it possible to relate the location between the physical system and the numerical system.

- Often direct access to the H-point marker is obstructed due to armrests or the lap belt. In this case, the location can be derived from other accessible targets attached to the pelvis. If no pelvis targets are accessible then the H-point location can be estimated from the Head CG and knee location using ATD anthropometry data. Note that this estimation method may not provide enough precision to adequately determine if the ATD is in correct 1-g preload Z location for down load tests. Some means of directly measuring the initial pelvis Z location will need to be devised for those tests.

- Basic length measures can also be useful, such as the distance between the knee centerlines, the distance between the elbows, and the distance between the feet. As with all measures, it is important that these distances can be replicated in the simulation with precision. Specifically, this means that distances should be between hard points that are readily located on both the physical system and the numerical system.

- For tests with floor deformation, measuring the ATD position before and after deformation provides important information for setting up and evaluating the simulation. If post deformation, but pre-impact, measurements are impractical, the results of photometric analysis at time zero may be substituted.

- While not a substitute for pre-test measurements, pre-test pictures provide additional information, such as the placement/orientation of the arms, hands, and feet, which are not easily accounted for by pre-test measurements. Setup pictures before and after floor deformation may also aid in capturing details of the effect of pitch and roll on the ATD. The pictures can also be a reality check if there appear to be large errors in the measurements. For global pictures, a purely perpendicular angle is best. Close-up pictures may also be useful when extra detail is necessary.

7.1.2.3 General Documentation

- Post-test notes and photographs documenting specific damage and deformation details will provide valuable information about failure modes to the engineering analyst.

- Record floor reaction load offset due to floor deformation (per AS8049B paragraph 5.3.8.6).

7.1.3 Dimensions of the Tested ATD

ATDs are produced within dimensional tolerances. Several dimensions of the specific ATD used should be measured so that the v-ATD can be compared to the actual dimensions of the ATD tested. In some circumstances, the data may be post-processed to account for the deviation (see, for example, 4.6.1).

7.1.3.1 Sitting Height

If a head path test is to be modeled, the sitting height of the ATD should be measured per the applicable CFR procedure. The measured height should fall within the tolerance specified in the regulation. (Note: The FAA-Hybrid III should meet the Hybrid II requirement.)

7.1.3.2 H-point Location

If a down load test is to be modeled, determine the height of the H-point with the ATD seated on a flat, rigid surface, posed in the position called for in the CFR sitting height procedure. One way to facilitate this measurement is to mark the point on the pelvis flesh that intersects a line passing through the femur ball centers. For a forward facing test, the depth (x-position) on the H-point should be determined using the same procedure outlined above.

7.1.3.3 Shoe Thickness

If there are significant differences in shoe thickness between multiple physical ATDs, then measure the distance from the ankle pivot to the bottom of shoe for each shoe. If the same model of shoe is used for all physical ATDs, then a single reference measurement is sufficient.

7.1.4 Motion Analysis

Accurate position and velocity time histories derived from tests are very useful in validating models.

7.1.4.1 General Recommendations

- Follow the recommendations contained in SAE J211-2 and ARP5482 to ensure that the data produced is as accurate as possible and that the error bounds for the data is quantified. These error bounds are needed to properly interpret comparisons between test and simulation results.
- Depending on the photometric technology employed, additional measurements of the ATD and sled setup may be required to provide the geometric information necessary to derive position or angular data from the test videos.
- Cut and tape down ATD clothing to avoid obscuring photometric targets during the test.
- Tape wires and belt ends that could move in front of photometric targets and interfere with target tracking.

7.1.4.2 Target Point Placement Considerations

- Head: It is important that the targets placed on the ATD head are at a known location with respect to the ATD anthropometry. This will allow precise correlation with v-ATD's that are based on the same anthropometry. The head CG is one of the most common landmarks to use. Note that on most ATDs, there is a small hole drilled in the skull on a line passing through the head Y-axis at the CG location. This is to facilitate placing targets on the head using a pin.
- Shoulder: Due to the bi-directional articulation of the shoulder and the clavicle to which it is attached, it can be difficult to precisely relate the position of a target attached near the shoulder pivot to fixed anatomical landmarks in a v-ATD. If a target is placed on the arm with its center at approximately the Y-axis of the shoulder's rotational joint, then its motion can be used to estimate the shoulder's motion. This data can still be useful for model correlation as long as the inherent measurement uncertainty is taken into account.

- H-point: The motion of the H-point during a test is very useful in validating a model since the motions of the other parts of the occupant are linked to it. Unlike the head, there is no simple landmark to use for applying a target marker at the H-point location. Hybrid II and FAA Hybrid III ATDs have an access hole that is near the H-point but this cannot be used reliably to locate a target marker. The ATD pelvis drawings define the relationship between the hip ball centers and accessible features such as the lumbar spine mounting surface and instrument cavity cover mounting surface (Reference 2.1.4.10). By referring to these drawings, the points on each side the pelvis that lie on a line passing through the centers of the hip joints can be located. Unfortunately, on many seats the H-point is not visible during a sled test because of armrests and/or lap belts. Since the distance from the knee joint to the H-point is fixed, the knee pivot location (which is usually visible) can be used to estimate the H-point forward motion.

- Knee and Ankle Pivots: The targets placed on the knee and ankle should be centered on their pivot axis and firmly attached to the structure and not to the rubber flesh. Mounting the target to a lightweight disc that is attached to the pivot bolt is a good means of accomplishing this (Reference 2.1.4.10). Since the FAA Hybrid III ATD's ankle is a ball joint, a lightweight bracket attached to the leg structure that positions a target at the pivot's Y-axis is needed.

- Restraint System: Target markers attached to shoulder straps that may pay out of an inertia reel during a test are particularly useful in quantifying restraint system performance. The marking technique should take into account that straps may twist during loading, potentially obscuring a flat target attached directly to the webbing. Ideally the markers should be placed between the belt guide and the ATD's shoulder to avoid interfering with the guide. Since webbing transducers are often installed at this same location, integrating the target marker with the load cell may have some advantages.

- Auxiliary Targets: These targets are used when it is anticipated that the H-point or head CG targets will be obscured for a portion of the time of interest or when there is interest in calculating the rotation of the object. The auxiliary targets are attached to or placed on the same body segment as the obscured target and can be used to calculate the virtual location of that target. For the ATD head, a rigid, lightweight extension can be affixed rigidly to the skull cap with at least two targets on it in order to maintain sufficient visible points throughout the test. For the pelvis, targets are placed above and behind the H-point such that the lap belt does not obscure them.

- Virtual Targets: When a target becomes obscured, the virtual position of the target can be calculated based on the position of non-obscured targets (the auxiliary targets) and the known geometric relationships between all points. It typically takes two visible auxiliary targets to determine the location of the virtual target. This location can then be compared to the location of the primary target when no obscurities occur to get a complete tracking of the target.

- Angular Position: Some commercial off the shelf photometric software can calculate angular position based on a single target if certain conditions related to resolution, contrast, and target size are met. Alternately, angular position can be determined from the position of at least 2 points attached to a rigid body if the rotation is in a plane perpendicular to the camera. Given the geometric relationships between the two points, the angular displacement is a simple trigonometric calculation. If the initial orientation of the rigid body is known, then the displacement can be readily converted to position.

- Curve Fitting: ARP5482 generally discourages using curve fitting methods to derive the location of temporarily obscured targets, particularly when determining peak excursion values. However, interpolation or curve fitting methods, when properly employed, can produce data that is very useful for model validation. For targets that are moving in a relatively smooth trajectory, physics-based curve fitting methods that use higher order derivatives to determine interpolation points can reliably predict the location of obscured points while producing a smoothed velocity time history.

- Overhead Cameras: If an overhead camera is used to generate y-axis data, targets should be placed along joint centerlines or the midline of the head. Care should be exercised when placing the targets to ensure that the x-axis location of the target can be readily identified in the v-ATD.

7.1.5 Additional Data to Consider

Depending on the capabilities of the test lab and the configuration for the specific tests to be run, it may be possible to collect some additional channels of data. These channels would be in addition to those normally required for compliance with the test setup. These channels can be used by the engineering analysts as an aid in validating the model by giving additional insight into the response of the system.

7.1.5.1 Whenever the FAA-Hybrid III ATD is used, the upper neck 6-axis load cell should be used. This will aid in troubleshooting any issues with head-neck motion and contact with the head. If a lower leg strike is anticipated, the upper and lower tibia load cells should be used to measure this contact load.

7.1.5.2 During the vertical test, measurements of the seat pan and seat cushion compression are important. A triaxial accelerometer should be placed on the lower side of the seat pan. This accelerometer will measure the motion of the seat pan relative to the seat and will allow a transmissibility calculation. Alternatively, cushion deformation could be directly obtained using a string-pot.

7.1.5.3 In cases where multiple ATDs are used for ballast and are not instrumented (i.e., structural only tests), consideration should be given to providing at least basic instrumentation to these ATDs to collect lumbar loads and head accelerations to determine how the additional occupants are interacting with the seating system.

7.1.5.4 The use of strain gauges on the structural components of a seat provides data to support the evaluation of the seat model. It is advised to review the structural load path thoroughly and determine key locations which are known to produce high stresses either through classical analysis methods, analytical models, or through experience gained from prior testing. Different types of strain gages are available: single grid gage is used to obtain the stress state (when known to be uniaxial), whereas for a biaxial stress state a two- or three-element rosette is required in order to determine the principal stresses. The analyst is advised to review literature available from the strain gage manufacturer to get details on installation, type of gages, data collection accuracy and stability of the gage for the experiment.

7.2 Modeling Best Practices

This section provides guidelines for modeling structural and non-structural materials, methods for simulating initial test conditions such as pitch and roll, the application of the sled pulse and gravity, and output control.

7.2.1 Overview of Numerical Methods for the Dynamic Analysis of Mechanical Systems

Representing a physical system with a computational model requires a thorough knowledge of the system and relies on an approximation of the underlying reality. The methods used are limited by modeling theory, numerical approximations, material and system characterization, and the accuracy of test data. The essential task in a dynamic analysis is the formulation of the equations of motion for a system. These equations are in the form of a set of differential equations, coupled with algebraic equations, which are solved by integration.

The mathematical modeling of the impulse loading or impact of mechanical systems is a complex task. Mathematical models for this physical phenomenon must be idealized approximations and the postulated dynamic behavior must be validated by suitable experiments. While the solutions are an approximation to the underlying partial differential equations, when utilized properly the results are useful for predicting the behavior of a seat system.

7.2.1.1 Mathematical Analysis Approaches

The equations of motion can be solved either explicitly or implicitly. The explicit method has unknowns on only one side of the equation and therefore can directly solve the equations by integration. The implicit method contains coupled sets of equations with unknowns on both sides and uses an iterative technique to obtain a solution. Explicit analysis methods are well suited to simulate short duration dynamic events such as impact and crash. Conversely implicit analysis methods are well suited to long duration static/quasi-static events such as sheet metal spring back after forming.

In general, there are two explicit numerical methods employed in dynamic analysis of mechanical systems: multibody analysis and finite element analysis (FEA). The multibody technique simulates the gross motion of systems of rigid bodies connected by kinematical joints. The system is defined by the mass of bodies, the length of segments, the degrees of freedom of joints, and contact between bodies. The contact formulation is defined such that a body can penetrate another body to emulate deformation. The FEA technique divides a continuum into finite elements (volumes, surfaces, and line segments) which are interconnected at a discrete number of points, called nodes, and solves the boundary-value problem. This technique provides detailed information about a structure, such as the position and velocity of nodes and the stresses and strains of elements.

The multibody technique is typically used when the user is mainly interested in the kinematics of the system. It provides a faster analysis but without detailed information about the structural deformation and potential failure of the system. The FEA technique is used when a user wants to perform a more in-depth analysis of the structural behavior of the system such as local structural deformation and stress distribution. A combined multibody-FEA approach can also be used, allowing for the efficiencies of each method to optimize the speed of the analysis.

7.2.1.2 Integration Methods

Numerical methods use discretization of time and space (i.e., the governing equations are solved at certain discrete locations and instants of time). Methods for integrating the discretized equations of continuum mechanics are called explicit (forward Euler method) if displacements at some time $t+\Delta t$ in the computational cycle are independent of the acceleration at that time (where Δt is the time step). In the implicit (backward Euler method) scheme, the displacement at any time $t+\Delta t$ cannot be obtained without knowledge of the acceleration at the same time. The implicit method has unconditional stability which allows for larger time steps. The explicit method has conditional stability which requires small time steps. Impact problems typically contain large stress or velocity gradients, which necessitate very small time steps.

The Central Difference Scheme is the most commonly used scheme for explicit modeling. In this scheme the equilibrium relation (Equation 1) is regarded as a system of ordinary differential equations with constant coefficients, and finite difference expressions are used to approximate accelerations or velocities in terms of displacements.

External force = Inertia force + Damping force + Elastic force or Internal force (Eq. 1)

The most important advantage of the explicit integration scheme is that it does not require a factorization of the stiffness matrix in the step by step solution. It leads to an algorithm which can be easily programmed, does not require any matrix inversion, and is suitable for a fast parallel computing.

In implicit methods, equilibrium is achieved at each time using an iterative procedure. Thus the accuracy of the method depends largely on the solution procedure and convergence tolerances specified. These methods are efficient for structural dynamics problems with low to moderate frequency content whereas explicit methods are much more efficient for high frequency and shorter duration applications. Common implicit solution methods are Houbolt, Wilson Theta, Park Stiffly stable method, and the Hilbert-Hughes-Taylor scheme.

7.2.1.3 Components of a Numerical Model

Having introduced the basics of numerical methods, the rest of this section will detail the principle components of building an aircraft seat model for use in dynamic impact simulations. Whether using FEA or multibody techniques, creating a model requires assigning global parameters, performing the discretization of the geometry, defining the material parameters, assigning initial and boundary conditions, and controlling the model output. These components define the geometry and physical properties of the structures, the environment, and how all the structures interact in the environment.

7.2.2 Global Parameters

7.2.2.1 System of Units

A consistent system of units must be used in the analytical method to yield correct results. Table 12 lists several sets of consistent units and Table 13 lists two examples. A simple check, based on Newton's Second Law of Motion, is:

$$1 \text{ (force unit)} = 1 \text{ (mass unit)} * 1 \text{ (acceleration unit)} \quad \text{(Eq. 2)}$$

$$1 \text{ (acceleration unit)} = 1 \text{ (length unit)}/((1 \text{ time unit})\ \text{^}2) \quad \text{(Eq. 3)}$$

Table 12 - Sets of consistent units used in analytical models

Mass	Length	Time	Force	Stress	Energy
kg	m	s	N	Pa	J
g	mm	ms	N	Mpa	mJ
kg	mm	ms	KN	GPa	KN-mm
tonne	mm	s	N	MPa	N-mm
lbf-s**2/in	in	s	lbf	Psi	lbf-in
slug	ft	s	lbf	Psf	lbf-ft
Kgf-s**2/mm	111 mm	s	kgf	kgf/mm²	kgf-mm

Table 13 - Examples of consistent units used in analytical models

System	Material	Density	Young's Modulus
Metric (mm-kg-ms)	Aluminum	2.79E-06	73.08
US (in-lbf-s)	Aluminum	2.63E-04	1.03E+07

In some codes, the v-ATD has fixed units which will necessitate the use of a specific system of units. If the units employed in the model are different than the units of the test data, then the simulation units should be post-processed to be consistent with the test data units. This also applies for data set length and origin offsets. Proper and consistent rounding practice should be employed.

7.2.2.2 Time Step

The division of the total time of a simulation into smaller segments is called temporal discretization. Each segment is typically referred to as a time step, and denoted as Δt in Equation 4. The stability of explicit integration methods depend on the time step; if it is too large for a given element size L (minimum characteristic length in the model) the method fails, either due to stability issues or poor accuracy. If the element size is smaller than required, the solution time becomes impractical, thus diminishing the effectiveness of the method.

The critical time step for a given model according to the Courant stability condition is:

$$\Delta tcr = 2/\omega = L/C \quad \text{(Eq. 4)}$$

where:

ω = natural frequency of the system

C = sound speed through the material ($\sqrt{(E/\rho)}$)

E = material's Young's modulus,

ρ = material density

This condition requires that the time step is small enough to ensure that a sound wave may not cross the smallest element during one time step. The speed of sound in steel and aluminum is approximately 16,404.2 ft/s (5,000 m/s). Therefore, if in a given seat model the minimum element length is 0.197 inches (5.0 mm), the computed time step size would be 1e-6 s. The minimum element length in a model will change during the simulation as elements are compressed or elongated. As a result, most codes have a variable time step feature that modifies the time step as the critical element lengths change. Occasionally, the simulation time step is controlled by only a few small or stiff elements in the model. When this happens, it is typically useful to remesh the controlling elements. In the case of extreme compression, which is often seen in seat bottom cushions, some codes can automatically remove elements when the length becomes a small fraction of the initial length to avoid extremely small time steps or calculation instabilities.

The user should utilize a suitable code specific stability criterion, such as a time step scale factor. In codes that use a time step scale factor, a value of 0.9 is recommended for most common applications. In the case of high rate sensitive materials such as foams, it is common to use a scale factor between 0.6 to 0.7.

7.2.2.3 Mass Scaling

In FE modeling, mass scaling is the process of adding nonphysical mass to the structure in order to increase the time step, thereby reducing the run time. Mass scaling can be accomplished using the automatic mass scaling parameter employed in most crash codes. There are multiple techniques to accomplish mass scaling, such as adding non-structural mass, nodal mass distribution, and selective mass scaling. It is recommended that the overall mass scaling should not exceed 5% for critical seat components. For non-critical seat components, an increase in mass of up to 10% is acceptable. For quasi-static simulations, it is acceptable to increase the mass scaling up to 10% since the kinetic energy is small.

Rigid body techniques do not use mass scaling.

7.2.2.4 Damping

The use of global damping is not recommended.

7.2.2.5 Element Quality Criterion

When using the FE technique, the element quality will affect the accuracy of the solution. This is especially important when running a structural stress analysis. To maintain accuracy in nodal displacements and stress flow in the structural components, special attention should be paid to the element type, shape, and function. The seat components should have no duplicate elements and have proper connectivity between nodes. It is recommended that the minimum and maximum quadrilateral element angle should be 45 and 135 degrees, respectively. For triangular element, the minimum should be 20 and the maximum should be 120 degrees. The use of 3 node triangular elements or 4 node tetrahedron or 6 node pentahedron (wedge) elements should be as minimal as possible near critical structural areas. The following recommendations are suggested to create good element shape for structural analyses.

Table 14 - Element quality criteria

Items	Quadrilateral or Shell Elements		Hexahedron or Solid (Brick) Elements	
	95% of Elements	5% of Elements	95% of Elements	5% of Elements
Aspect Ratio	<=5	<=10	<=5	<=10
Face Skew	<=45 degree	<=60 degree	<=45 degree	<=60 degree
Face Warpage	<=10 degree	<=21 degree	<=10 degree	<=21 degree
Jacobian	>= 0.7	>= 0.5	>= 0.7	>= 0.5

7.2.3 Physical Discretization

Physical discretization refers to the decomposition of a system into assemblies, subassemblies, parts, and when using FEA, the finite elements. The seat system can be separated into structural components, such as metallic components, non-structural parts, such as seat cushions and restraints, and the v-ATD. Each of these components can further be divided into parts, such as the side frames, tubes, spreaders, and legs. In the multibody approach, the components are represented by one or more bodies with a defined surface. The focus is on the macro motion of the assembly, such as the global seat frame motion. In the FE approach, each piece and part is further divided into nodes and elements, called a mesh, and the stress and strain of the part under loading can be determined.

In general, the multibody seat model can be easily generated; however a large number of assumptions must be made to simplify the structure. The response of the seat can be modeled via simple bodies or surfaces, articulated by rotational or translational kinematic joints. For example, the dynamic performance of a machined leg may be represented by several bodies connected by a rotational joint. The model can replicate the sliding forward or upward motion of the seat frame as well as the rotation of the seat pan and seat back and even provide an estimate of the floor reaction loads. Nonlinear translational and torsional spring-dampers can be utilized for modeling hinges such as the connection between the seat frame and seat back.

In order to discretize a part in FEA, additional engineering judgment is required. Typically, surface data in CAD is used as the starting point for developing a mesh. The surface data is then split into a finite number of elements. The number of elements and the types of elements used will greatly affect the accuracy of the result. These characteristics will be guided by the type of material (i.e., structural versus non-structural), criticality (i.e., primary load path versus non-load bearing), accuracy required (i.e., developmental simulation versus simulation intended for compliance) and available computational power. Many books have been published that contain detailed information on generating a finite element model (see, for example, References 2.1.4.1 and 2.1.4.8). The following subsections provide additional guidance on generating a seat model mesh.

7.2.3.1 Modeling of Structural Seat Components

Structural seat components can be modeled using 1-D beam/bar elements, 2-D shell elements, and 3-D solid elements depending upon the geometry and criticality. The selection of a particular element affects the physical phenomenon that an element can capture along with the accuracy and time required for a solution. General guidance on the appropriateness of elements for a given geometry can be found in FE books, several of which are listed in the references section (see 2.1.4), as well as in the manuals for FE codes. Some basic information is contained below.

Beam elements are useful for modeling springs, certain sections of seat systems such as hydro lock and other components with one dimension significantly larger than the other two. The elements can have 6 degrees of freedom (DOF) or 3 DOF. Furthermore, a cross section can be defined for the beam which will affect the calculated stresses. Cross sections include rectangular, tubular, W, C, T, Z, and I shapes, among others.

Shell elements are useful for components that are relatively thin in one dimension, such as torque tubes, seat pans, and other sheet metal parts. As with beams, there are numerous options that affect the calculated stresses. For example, some shell elements do not consider out of plane stress or strain. Shell elements are meshed as either triangular or quadratic. Triangular elements are stiffer and sometimes prove more costly computationally, but are useful for complex geometry or mesh transition regions and regions with hourglassing (see 7.2.9.2 for more information about hourglassing). When using shell elements it is recommended to define the center plane of the shell elements at the mid-surface (wherever possible) of the part geometry. A typical example of a torque tube shell model extraction on mid-surface is shown in Figure 8.

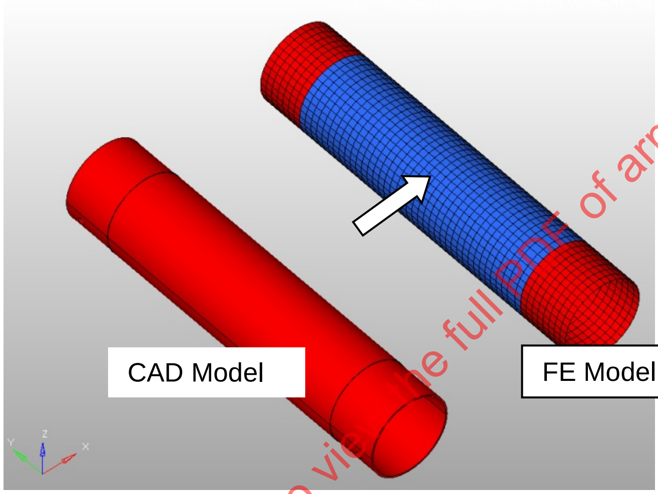


Figure 8 - Mid-surface extraction of a tube

Solid elements are useful for components that are relatively similar in size in all three orthogonal directions, such as thick section of seat frame or seat fitting. The elements can be 8-noded hexahedron (also known as brick), 6-noded pentahedron or 4-noded tetrahedrons, with various element formulations and options such as constant stress, options for the number of DOF, etc.

Shell and solid elements can have fully integrated or reduced integrated formulations, which affects stability and computational costs. Most of the time one point-integration elements are recommended rather than full integrated elements.

Representing complex shapes often requires a combination of element types. For example, the machined components shown in Figure 9 have varying thicknesses which make it difficult to properly capture the overall strength of the component. If this component is part of the primary load path, then advanced modeling techniques may be required in order to achieve the desired accuracy. One such technique, shown in the figure, is to use a combination of solid and shell elements. The web section is modeled using shell elements and the flange and the ribs are modeled using solid elements (Figure 9A and Figure 9B). Solid elements have only translational DOF at each node and no rotational DOF, while shell elements have both rotational or translational DOF at each node, thus it is necessary to maintain rotational continuity wherever shell elements connect to solid elements. For this purpose, it is recommended that one layer of shell elements be embedded into the solid mesh (with shared nodes). This layer of shell elements is also then moved to a separate part as shown in Figure 9C. Care needs to be taken to avoid over-predicting the stiffness due to the redundancy of some elements (which is needed for proper connectivity). It is also recommended that the modeler consult with the software manual to determine the availability of special commands to tie the rotational degree of freedom or specific solid elements with 6 DOFs per node.

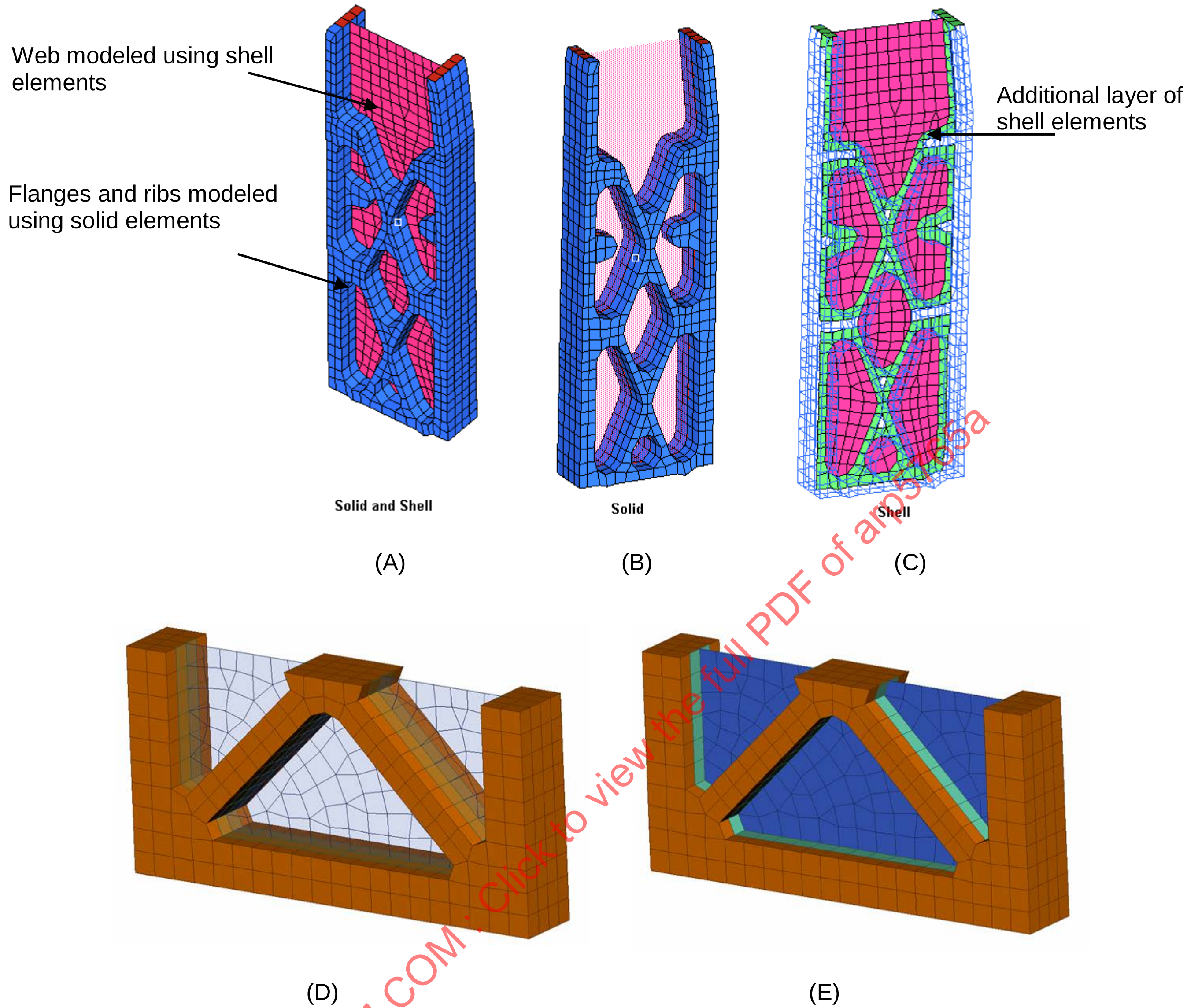


Figure 9 - Model of a seat frame section

7.2.3.2 Modeling of Holes in Structures

The recommended method for modeling holes is to use quadrilateral or hexahedron elements (sufficient to capture the geometry appropriately) around the hole as shown in Figure 10. This mapped area is often referred to as a washer. It is recommended to avoid triangular and pentahedron elements in the first layer around the hole (or a cutout section) since these elements may predict higher stress than the nearby elements. The analyst may choose to not model the hole in its entirety when it is sufficiently small and depending on the criticality of the load path.

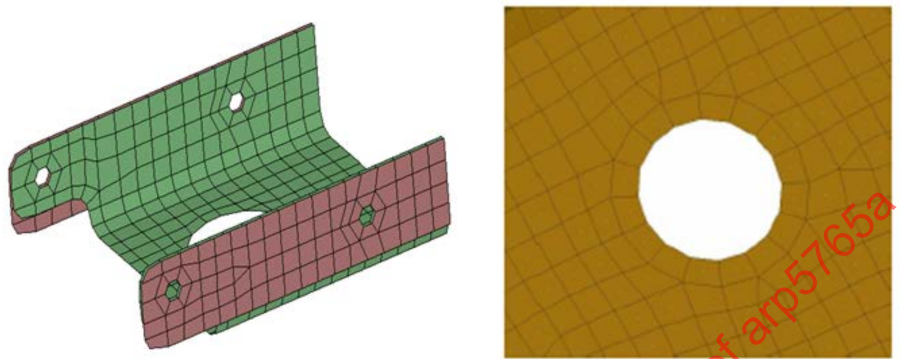


Figure 10 - Modeling of holes

7.2.3.3 Modeling of Joints

One of the trickier aspects of modeling a full aircraft seat is the modeling of joints. The majority of seat failures are observed in joints or related to the joints, and when compared to the size of a standard triple place passenger seat, an individual nut-bolt or screw connection is very small. There are two main options for modeling these joints: the first is to generate a simplified approximation using rigid body techniques or beam elements; the second is to explicitly model the actual hardware that constitutes the joint. The first method runs faster, however it cannot always capture all of the relevant physics. The second method can capture all of the physics, but can be computational slow since the mesh may be very fine if a bolt acts as a hinge.

Initially the analysis can be conducted using a rigid body approximation with dedicated modeling of joints. Similarly, rigid elements can be used in a FE technique combined with equivalent strength beam elements as shown in the top of Figure 11 (labeled A). In addition, general springs can also be used as connecting elements. If the joint is found critical in post-processing, it is recommended that the modeling of the joint is conducted by providing actual nut and bolt surfaces as shown in the modified FE model in the bottom of Figure 11 (labeled B). This technique helps to simulate bearing stresses and helps to model existing pre-tensions. This modeling method also provides a better representation of the shearing and bending behavior of the joint. Nodes on the common surfaces of the nuts and bolts can be merged or connected by rigid connections. An appropriate friction factor needs to be defined between the mating bolted surfaces.

Once the connections are defined, an eigenvalue analysis can be run to check for missed connections and unconstrained degrees of freedom.

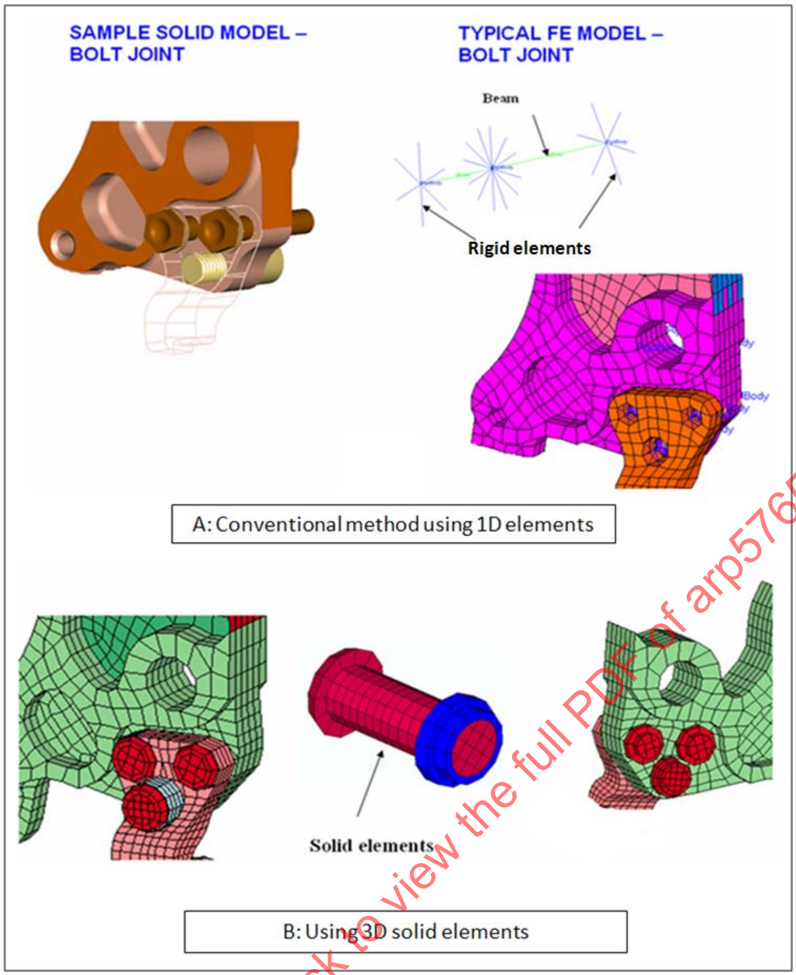


Figure 11 - Modeling of a joint

- Multi-Scale Modeling

In finite element analysis, the finite element mesh is sometimes too coarse to produce satisfactory results in a specific region of interest, such as the joint shown in Figure 11. In general, the transition between scales of the model resolution is addressed through sub-modeling. Sub-modeling is also known as the cut-boundary displacement method or the specified boundary displacement method. The cut boundary is the boundary of the sub-model which represents a cut through the coarse (or global) model. Displacements calculated on the cut boundary of the coarse model are specified as boundary conditions for the sub-model. Characteristics or state variables in addition to displacement may be used in the boundary exchange in order to improve the accuracy of the model. As an example, the global seat model may contain a coarse representation of a bolt using a one dimensional element. The local model could be set-up using three dimensional solid elements to better capture the contact, load condition and the resulting state of stress distribution within the fastener. The local model provides improved data accuracy, while allowing the global model to retain acceptable computation times.

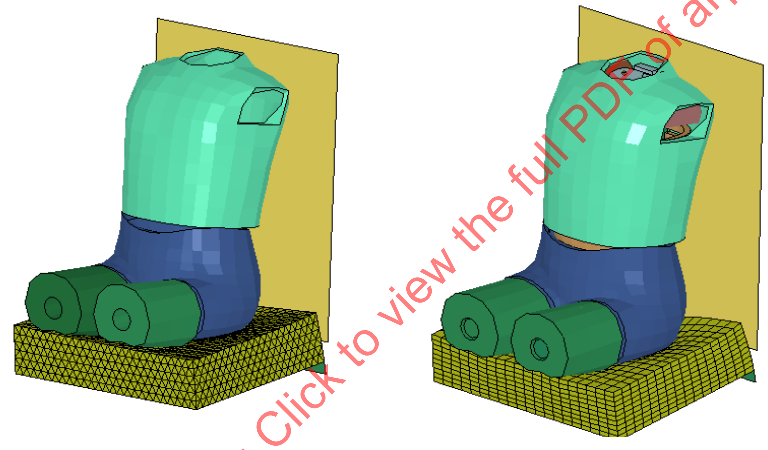
7.2.3.4 Track Fitting Modeling

The track fitting is in the primary load path and is very important for the calculation of floor reaction loads. It is recommended to evaluate the track fitting at the assembly level and in the full scale seat model. For the full scale seat, tests with floor deformation provide the most useful comparison. Both force and moment from the load cell should be collected for the correlation.

Depending on the level of accuracy required, either 'simplified' or 'detailed' modeling can be used in the simulation as described above. For the 'simplified' model, it is not necessary to model all the joint details as long as the correct rotational and translational degrees of freedom are considered. In order to evaluate failure, or if the fitting has complicated behavior such as yielding or flexibility, the 'detailed' modeling approach is recommended. The material of the fitting housing and stud should be validated first. If track failure is not a concern, the track can be modeled with a rigid material. If the stiffness of the track is crucial, then detailed modeling of the track is also recommended. All contacted surfaces between the fitting and track should be included in the model.

7.2.3.5 Modeling of Seat Cushions

When the detailed deformation of the seat cushion is not needed, for example in the early stages of the design, rigid body analysis techniques may be used where the load-deflection curve can be used directly to describe the contact force due to penetration of the v-ATD with the (rigid surface) seat. The fixed joint can also be used between the seat pan and the seat cushion to transfer the applied load to the cushion. For a more detailed analysis, 3 dimensional 8-node hexahedron (brick), or 4 or 10-node tetrahedral elements can be used to model the seat cushion as shown in Figure 12. If negative volume elements (see 7.2.9.1) are found in the cushion model, it is often useful to stiffen the foam material at high strains (i.e., strain hardening). It is recommended to carry out component tests and simulations to evaluate the effect of FE variables such as element type/formulation, mesh density, material model, etc., on simulation accuracy.



A: Tetrahedron elements B: Hexahedron elements

Figure 12 - Seat cushion modeling

7.2.3.6 Modeling of Restraints

Restraint systems can vary greatly depending on the type of aircraft and location of the seat. The most basic restraint system is a lap belt only restraint commonly found on Part 25 passenger seats. The restraint system is made up of the belt webbing, two anchors, and the buckle. In basic models, the anchors are considered fully rigid and the buckle may be ignored. More advanced models will contain explicitly modeled restraint hardware in order to more fully capture the true performance of the restraint system.

Additional components can be incorporated into the system, including shoulder belts, pre-tensioners, load limiters, various buckle designs, and inflatable restraints. Many codes contain elements, formulations, and simulated hardware (such as retractors) that are specifically designed to model restraint systems. It is recommended to perform component tests and/or simulations to evaluate the performance of complex restraint systems.

There are three methods available for modeling belt webbing (applicable to both lap belts and shoulder belts):

- Segment Belt: This belt consists of a chain of 1-D straight belt segments (see top row of Figure 13). The ends of a belt segment are called the attachment points. Attachment points are fixed points on bodies or in the reference space. The model accounts for slip of belt material from one segment to an adjacent segment, but only in the direction of the belt segment. These belts are typically attached directly to the v-ATD which does not allow the pelvis to slide above or below the belt and as such, no friction is defined. The belt stiffness is defined as a force-relative elongation function. Hysteresis of the belt material can be defined in the belt model.

- Finite Element Belt: Belt components can be modeled with 2-D membrane finite elements in order to predict complex behavior such as multi-directional belt slip, submarining, and roll-out (see center row of Figure 13). Slip is controlled by friction defined between the v-ATD and the belt. The belt stiffness is defined as a stress-strain function for the webbing material.

- Hybrid Belt: For this modeling approach a hybrid of Finite Element and segment belts are used to define the belt system (see lower row of Figure 13). The finite element portions of the belt are defined to model the contact areas where the belt can slide over the dummy surface in an arbitrary direction so that submarining and belt roll-out can be modeled. The segment belt approach is used at the anchor point locations in order to define the initial belt tension (or slack, when appropriate). It is important to match the material properties of the FE belt and segment belt since they are defined differently. This method is recommended because of the simplicity of adjusting the total length of the belt.

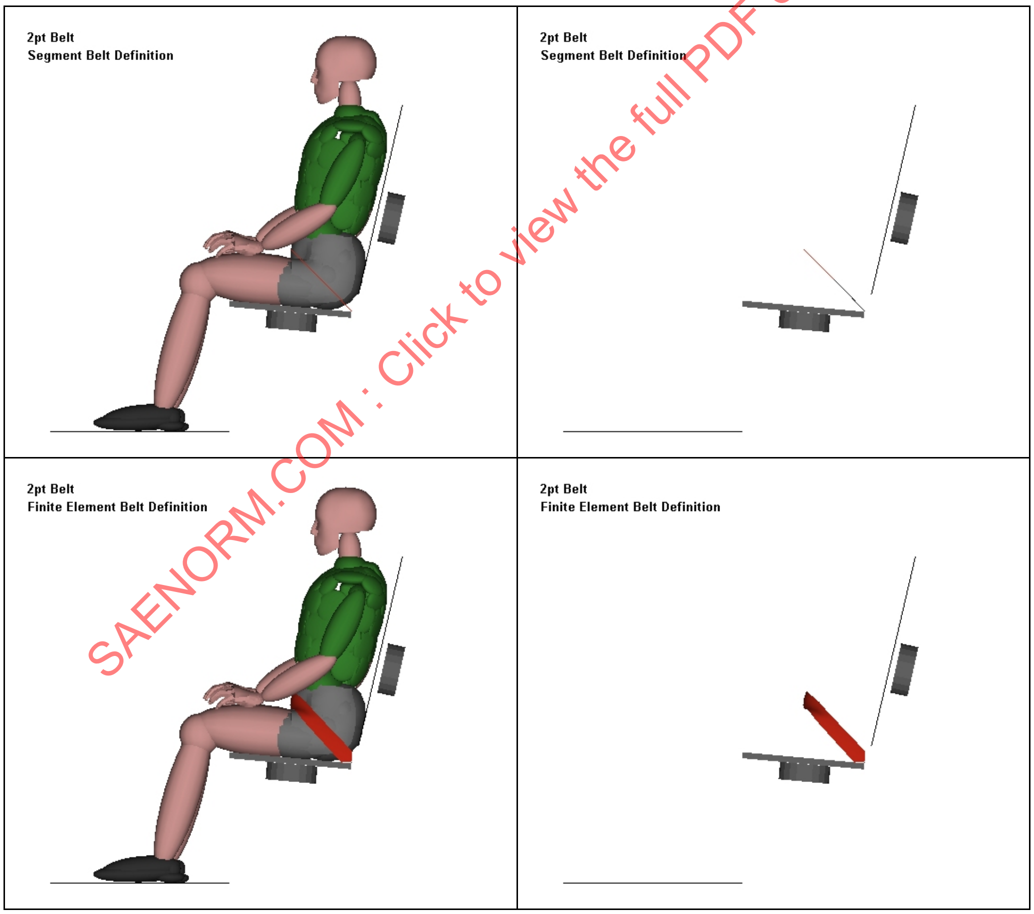


Figure 13 - Belt modeling techniques

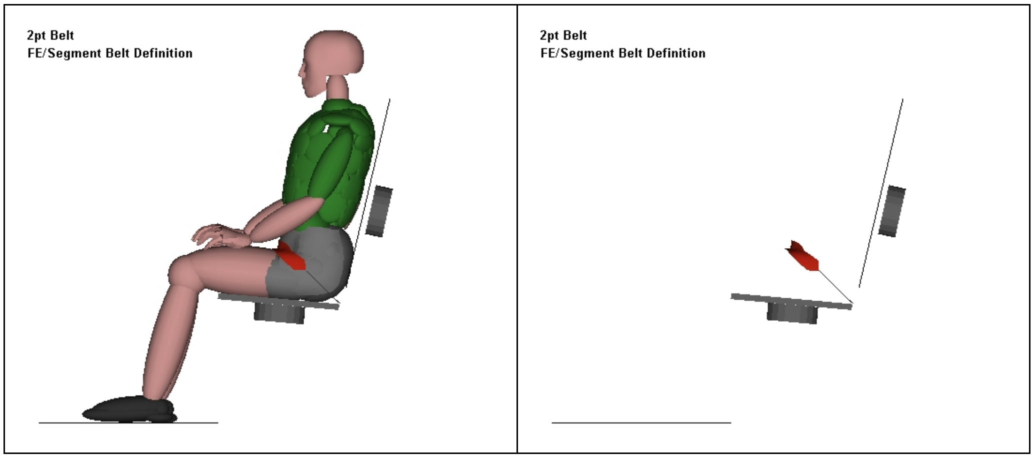


Figure 13 - Belt modeling techniques (continued)

7.2.4 Material Definition

Aircraft seat materials are divided in two basic categories: metallic material and non-metallic material. Non-metallic materials are further sub-divided into composites, plastics, woods, foam, fabric, and webbing. Material properties play an important role in dynamic design because they react kinetic energy from the impact event. In energy attenuating seats, components of the seats or separately installed mechanisms are designed with a purpose of absorbing some of the kinetic energy of the event through plastic deformation.

Material characterization data must be selected from sources that conform to accepted industry practices such as published ASTM or equivalent standards. The characterization data must be documented in sufficient detail so that the source can be verified. A material characterization test should be simulated to verify that the material model selected, model discretization, and element formulation are able to reproduce the physical behavior of the material.

7.2.4.1 Metallic Material

Under typical crash loading rates, common metallic materials have not shown rate sensitivity. A recommended source for metallic material data is the MMPDS Handbook (Metallic Materials Properties Development and Standardization) which provides mechanical properties such as Young's modulus, Poisson's ratio, ultimate strength, and engineering stress-strain curves. Mechanical properties for metallic material can be also generated by conducting tensile tests per ASTM E8/E8M. During testing, load-deflection (or load - engineering strain) data is collected. This data, or the engineering stress-strain data from the MMPDS Handbook should be converted to true stress, truestrain using Equations 5 and 6. The test data can also be used to determine the Young's modulus, Poisson's ratio, ultimate strength, and failure stress.

$$\sigma_{true} = \frac{P}{A_0}\left(e_{engineer} + 1\right) = \sigma_{engineer}\left(e_{engineer} + 1\right) \quad \text{(Eq. 5)}$$

$$\varepsilon_{true} = \ln\frac{L}{L_0} = \ln\left(e_{engineer} + 1\right) \quad \text{(Eq. 6)}$$

Equation 6 yields the true strain but nonlinear codes require that the plastic portion of true strain is separated from the elastic portion since the elastic strain is calculated internally using Young's modulus. Equation 6A shows logarithmic or true plastic strain. (ABAQUS User Manual section 23.1.1 also documented in LS/DYNA manual):

$$\varepsilon_{\ln}^{pl} = \ln\left(e_{engineer} + 1\right) - \frac{\sigma_{true}}{E} \quad \text{(Eq. 6A)}$$

where:

$$P = load$$
$$A_0 = original\_area$$
$$\sigma_{true} = true\_stress$$
$$\varepsilon_{true} = true\_strain$$
$$\sigma_{engineer} = engineering\_stress$$
$$e_{engineer} = engineering\_strain$$
$$L = final\_length$$
$$L_0 = original\_length$$
$$E = Youngs\_Modulus$$

The above equations should be used to convert engineering stress and strain to true stress and effective plastic strain and should be applicable for any plasticity material model for nonlinear FEA codes unless otherwise noted in the corresponding User's Manual.

In addition to plasticity curves, nonlinear material properties often include a failure criteria. It is important that if plasticity is used in the model, failure criteria must be converted using Equations 5 and 6A as well. For example elongation values are typically listed in engineering strain and so must be converted to logarithmic plastic strain using the above formulae. Failure criteria often mark the beginning of a softening curve or the point of element erosion. Incorrect failure criteria can have a significant effect on the outcome of the simulation.

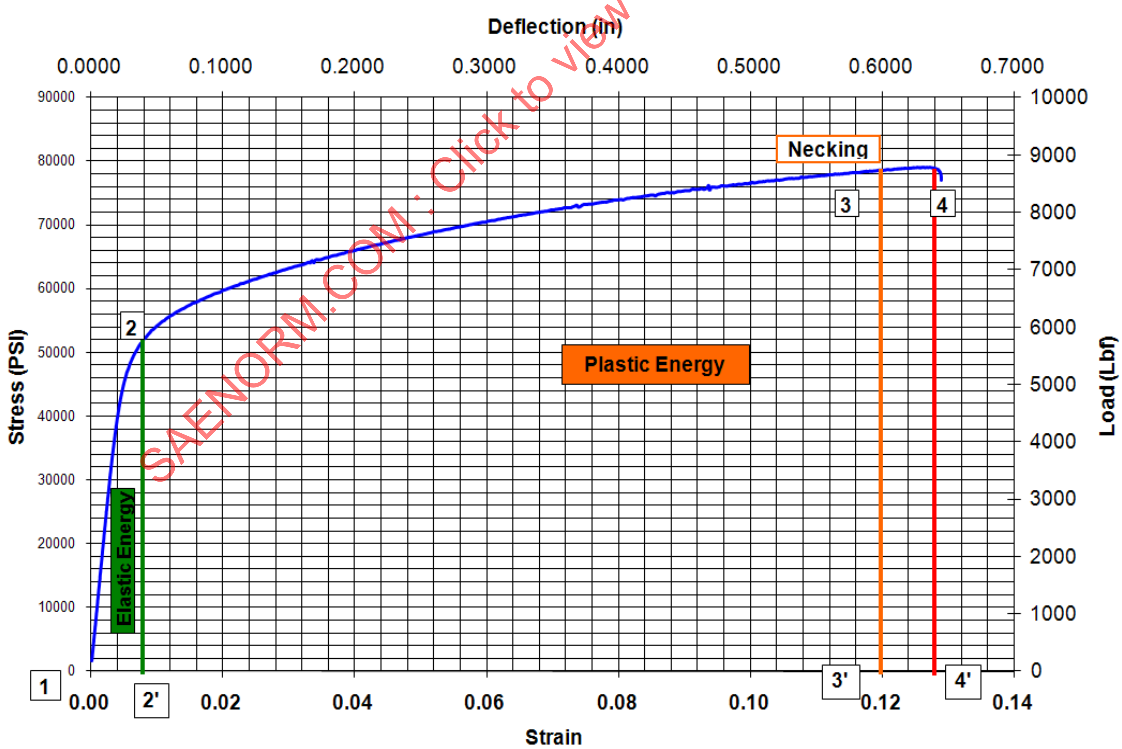


Figure 14 - Elastic and plastic energy in ductile material (AL 2024)

Figure 14 shows the tension stress strain curve for ductile material Aluminum (Al 2024), elastic and plastic energy stored as

Elastic energy available = Area under curve 1-2-2'-1

Plastic energy available = Area under curve 2'-2-4-4'-2'

where:

1. Start point of stress-strain or load-deflection curve

2. Yield stress (typically 0.002 offset) if yield point is not defined

3. Necking point

4. Ultimate tensile stress

This data is then used in the numerical model to predict structural failure. For a ductile material such as aluminum or steel, it is recommended to use the necking point as the fracture/failure stress, as once necking begins, the true stress is no longer equal to the effective stress. In the case of a tension test, the uniaxial stress state becomes a triaxial stress state once necking begins.

In some cases a high level of triaxiality may exist even before necking begins. Examples are material around fastener holes in preloaded bolts, swaged fastener collars, and even members that are loaded in compression. It has been found that failure strain is far from being constant and actually varies strongly with stress triaxiality. Triaxiality ratio is the ratio of Von Mises to hydrostatic stress as defined below:

$$\sigma_H = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3}$$

$$\bar{\sigma} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

$$Triaxiality\_ratio = \frac{\sigma_H}{\bar{\sigma}}$$

where:

$\sigma_1, \sigma_2, \sigma_3$ are principal stresses

σ_H is hydrostatic stress

$\bar{\sigma}$ is Von Mises stress

It has been shown experimentally that below a stress triaxiality ratio of -1/3 fracture will never occur regardless of the value of equivalent plastic strain (5). So a short cylindrical coupon in pure uniaxial compression (difficult to achieve) would be represented by a triaxiality ratio of -0.33. A coupon loaded in pure shear would have a triaxiality of 0.0, and a stress triaxiality of 0.4 corresponds to pure tension on a smooth round bar.

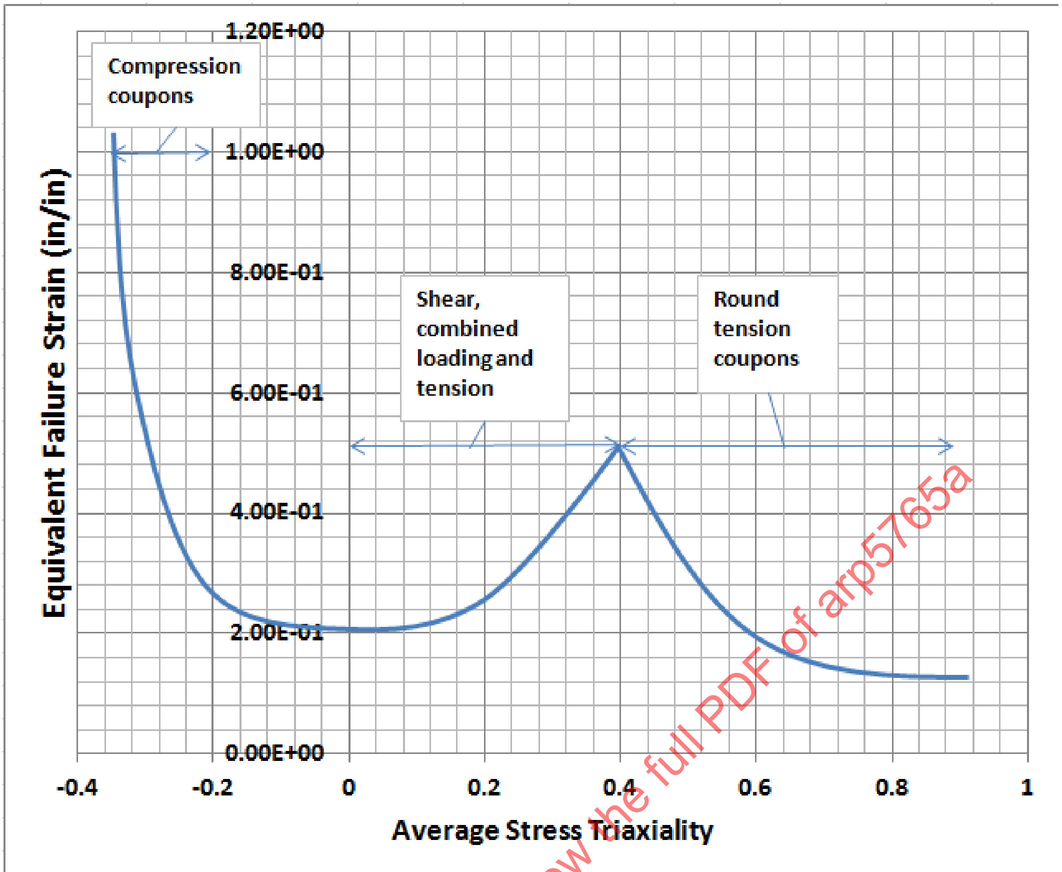


Figure 15 - Equivalent strain to failure versus average stress triaxiality (5)

It may be beyond the scope of most seat projects to define equivalent strain failure to this level of detail. However, knowledge of the true physics allows the user to approximate the equivalent strain to failure versus triaxiality curve with limited coupon data. By doing so the correct failure strain can be modeled for pure tension, while erroneous failure in compression can be avoided (more discussion in “Tension and Compression” section below). Modeling of states of pure shear, biaxial, and triaxial tension can be included if data exists. In most cases members are loaded in simple tension or compression. For simple tension the necking point can be used as a tensile failure criteria as discussed above. For simple compression, typically only yield and buckling are considered.

If tension fracture is to be simulated using element erosion, care should be taken to regularize stress localization. Failure simulation in FEA using element erosion is a mesh dependent capability. The finer the mesh, the earlier failure is likely to occur and the more rapidly it will progress. This is intuitive since a small element will result in a higher local stress when present in an area of high stress gradient. The erosion of a single element forms its own high stress gradient zone. Some nonlinear codes have regularization features which allow the user to modify erosion failure as a function of element size. These should be employed if progressive damage is to be simulated.

Anisotropic/Orthotropic Effects in Metals

Rolled metallic sheet and plate materials are not isotropic. Care must be taken to use the appropriate curve or parameters for longitudinal, long transverse, and short transverse material directions. In most cases the critical direction may be used if the transverse direction is not loaded, for example. If multiple directions are important, then appropriate material model must be selected to represent such a material, so that anisotropic/orthotropic effects can be captured.

Plasticity curves which are statistically based may be given as “typical”, “A” basis, or “B” basis. Typical values are simply a best fit of the data so that 50% of the population of values is expected to fall above the typical value. “A” basis is defined as the mechanical property value above which at least 99% of the population of values is expected to fall, with a confidence of 95%. “B” basis is the value above which at least 90% of the population of values is expected to fall with a confidence of 95%. It is important to keep in mind that if typical values are used with no margin of safety, there is a significant probability that failure will occur in the test. This is true for both plasticity curves and ultimate elongation values since yield can lead to ultimate failure in a nonlinear dynamic model. It is therefore recommended that a minimum of “B” basis values are used. If only typical values are available, it is recommended that a margin of safety be included.

Tensile and Compressive Behavior

True stress also accounts for reduction or expansion of the specimen cross section. True or logarithmic strain is used to modify engineering strain such that tension and compression stress-strain curves are more similarly shaped and avoid mathematically undefined quantities. So true stress and logarithmic strain correct the mathematical issues but do not completely account for physical differences in the material plasticity curves in tension and compression. For this reason data standards cited above (4.4) often include separate curves or parameters for tension and compression. However, most numerical material models do not include the ability to enter different plasticity curves for tension and compression. For codes that don’t include this feature, the analyst must determine whether the tension or compression stress-strain curve is critical for various segments of the model and apply the appropriate curve.

7.2.4.2 Cushion Material

Component testing is recommended to determine the load-deflection/stress-strain properties for seat cushion materials as they exhibit load rate sensitive characteristics. For aircraft seating applications, to predict lumbar load as per §14 CFR Part 2X.562 (b) 1, relatively high-loading rates around 30 in/s (0.762 m/s) are recommended to determine load-deflection characteristics. Servo hydraulic machines or comparable equipment can be used to derive the required data. The materials that seat cushions are typically constructed from exhibit highly non-linear behavior and the material model chosen should be able to represent these behaviors such as strain hardening, rate dependency, and hysteresis. While dynamic data collected at high-loading rates is needed in order to conduct the analysis, static data is also needed in order to determine the initial cushion deformation and stress distribution that is required to simulate the initial occupant position.

A procedure for determining some of the necessary properties as well as the test fixture and methodology for the cushion component tests is detailed in the FAA report “Development and Validation of an Aircraft Seat Cushion Component Test Volume - I”, DOT/FAA/AR-05/5.

7.2.4.3 Restraint Material

Restraint material such as nylon and polyester are not rate dependent. Force-deflection characteristics for restraint material are recommended to be derived from static tensile test data. The material model chosen can be checked for its ability to represent the restraint properly by simulating the component test used to derive the data.

The static material property data is important in order to apply the correct amount of pretension in the restraint system while setting up the initial position of the occupant.

7.2.4.4 Composite Material

Composite Laminate Materials

There are significant differences between composite models in various codes and even between various models within the same code. There are so many different features and failure criteria that only an overview of some of the basics will be discussed here. Material models for both shell elements and solid elements are available. One common feature among shell based models is the ability to assemble user defined lamina level engineering properties (E1, E2, E3, G12, G23, G31, v12, v23, v31) and a list of ply orientations into an elemental stiffness matrix. There are some models that require the user to assemble the stiffness matrix external to the code but the advantage of storing the stacking sequence internally is that once elemental strain values have been obtained, strain and stress at the lamina level can be determined. Solid materials have much less in common. Some codes include solid composite models which allow multiple lamina per element much like the shell models. This is convenient when large solid laminates need to be modeled. It allows solid modeling of individual lamina or the user can combine several lamina into a single element. Some codes also include failure criteria for solid models. Some are limited to fiber and transverse failure criteria while others include failure criteria for virtually all modes of failure and strain rate dependence.

Most of the progressive failure models for shells and solids employ some form of the Hashin criteria. Generally the Hashin Criterion separates various modes of failure as follows:

Tensile fiber mode:

$$e_f^2 = \left(\frac{\sigma_{11}}{X_t}\right)^2 - 1$$

Or sometimes:

$$e_f^2 = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\tau}{S_c}\right)^2 - 1$$

Compressive fiber mode:

$$e_c^2 = \left(\frac{\sigma_{11}}{Xc}\right)^2 - 1$$

Tensile matrix mode:

$$e_m^2 = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau}{S_c}\right)^2 - 1$$

Compressive matrix mode (transverse and shear loading):

$$e_d^2 = \left(\frac{\sigma_{22}}{2S_c}\right)^2 + \left(\frac{\tau}{S_c}\right)^2 - 1$$

Or sometimes:

$$e_d^2 = \left(\frac{\sigma_{22}}{2S_c}\right)^2 + \frac{\sigma_{22}}{Y_c}\left[\frac{Y_c^2}{4S_c^2} - 1\right] + \left(\frac{\tau}{S_c}\right)^2 - 1$$

where:

e_i^2 Are damage parameters which indicate failure if greater than or equal to zero

σ_{11} Fiber direction stress

σ_{22} Transverse direction stress

τ Shear stress

X_t Fiber tensile strength

X_c Fiber compressive strength

Y_t Matrix direction tensile strength

Y_c Matrix direction compressive strength

S_c Shear strength

A similar set of equations expanded to three dimensions is often used for progressive Hashin criteria in solid continuum elements. Note that these are heuristic equations which by no means guarantee accuracy for all potential layups or loading situations. They should yield reasonable results for typical layups under simple loading. The International Conference on Composite Materials has sponsored a series of "World Wide Failure Exercise" Benchmarks to determine the best composite failure theories available. Unfortunately none have proven to be outstandingly accurate. FEA vendors seem to have made do with Hashin in many cases (References 2.1.4.17, 2.1.4.18, 2.1.4.19).

Composite material models are typically elastic up to the point of failure initiation. After that point there are many variations on how the failure progresses. In the simplest case, the stress tensor in the failed direction for a specific failed lamina goes to zero. This progresses through the laminate until all of the lamina have failed. Typically, erosion (removal) of the element occurs at that point. This is a reasonable approximation for tensile failure but a very poor one for compressive or shear failure. Even instantaneous tensile failure can often result in unstable damage propagation across the model. This is due to the inherent noisiness of explicit time integration FEA. Element failure can result in a spike in the stress wave which then leads to failure of the adjacent element, and so on. A number of schemes have been developed to combat this problem. One is to include a failure strain so that final failure is extended over a finite strain:

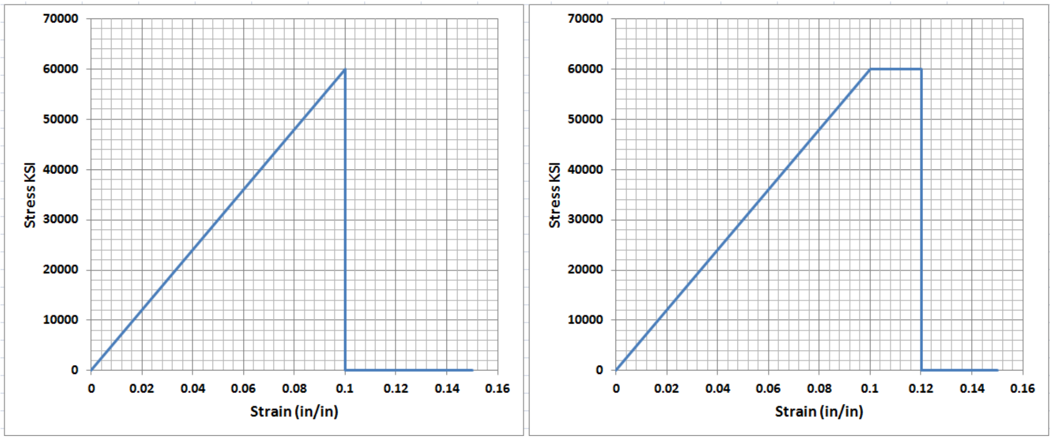


Figure 16 - Stress-strain curve for fiber tension (Reference 2.1.4.20)

Another method is to use a damage parameter which can provide an exponential softening curve:

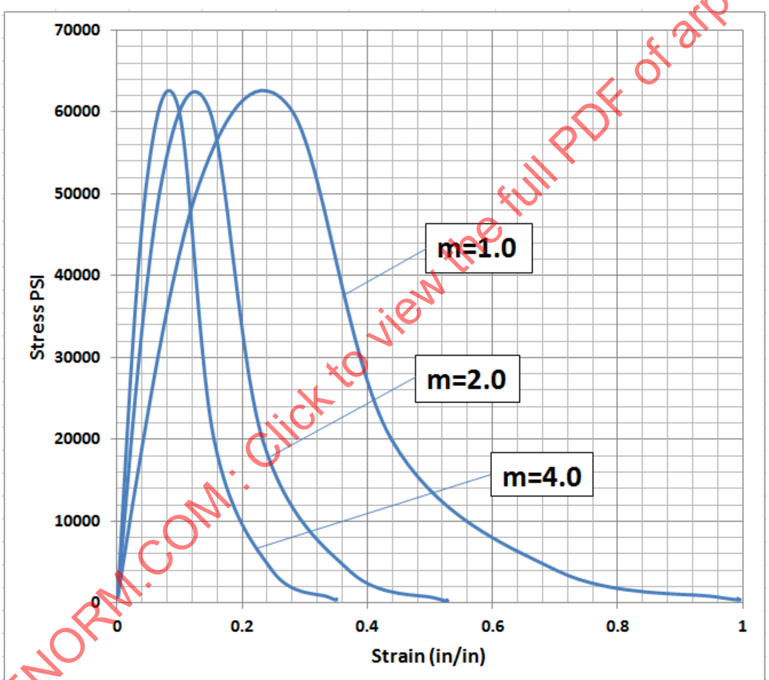


Figure 17 - Stress-strain curve using various "m" exponential parameter values for one material model

Another method is to include some sort of plasticity curve to prevent abrupt failure. Sometimes a lower limit of stress is specified so that after initial failure there is a drop in stress to some limited value. This is more often done in the case of shear or compression. The figure below shows and example for shear:

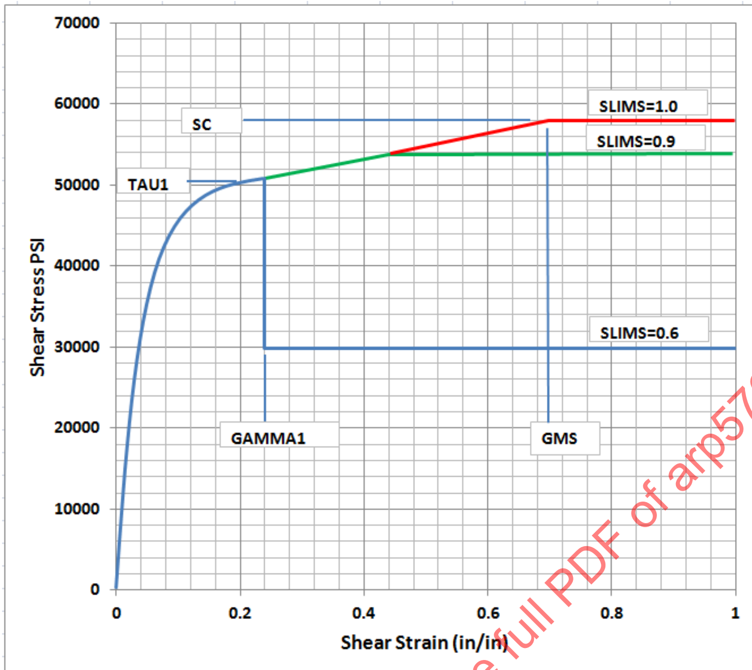


Figure 18 - Stress-strain diagram for shear

Yet another method is to average the stress values over a certain number of time steps.

The important thing to remember is that there are no perfect composite material models currently available. It is up to the user to perform element, coupon, and component level test-analysis correlation for all applicable failure modes to be sure that the model will represent the final seat test.

7.2.4.5 Failure Criteria

Failure criteria are not always differentiated in tension and compression. If there is a possibility of ductile failure, and failure is to be modeled, a simple material model which includes only a single failure strain value will not always serve the purpose. Many of the commonly used material models will invoke element erosion (deletion) when all integration points of that element have reached an effective plastic strain equal to a user-defined failure strain. However since the code does not differentiate between effective plastic strain in tension and compression, compressive strain will also cause element erosion. This is not the correct physical response since ductile materials do not fracture under pure compressive load. There are a variety of material models which avoid this problem either through definition of triaxiality ratio versus failure strain or through the use of failure models developed by Gurson, Wilkins, and others. Material models which are capable of applying different yield curves in tension and compression as mentioned above, do not necessarily have the ability to differentiate failure in tension and compression (References 2.1.4.13, 2.1.4.14, 2.1.4.15, 2.1.4.16).

7.2.4.6 Strain Rate Effects

The strain rate is another important factor for ductile materials since many materials show an increase in yield strength as a function of strain rate. There is also sometimes a reduction in elongation as a function of strain rate. The user must identify and account for these effects by providing appropriate rate-sensitive curves or by using appropriate scale factors that correct material yield point based upon applied strain rate. The choice of which method to use is dependent upon availability of strain rate data, capability of the simulation code in use and the modeling standards/best practices applied by the user. It is important to perform a single element or coupon level analysis of any ductile material model developed and compare the results against coupon test data. This should be done across the entire range of dependent physical quantities expected in the sled test.

7.2.5 Contact Definition

In order for bodies to interact in a model, the boundaries and interaction properties must be defined. This is referred to as contact. In general, contact can be defined between any components in a model. Many codes also allow for automatic contact definitions, where the code automatically activates contact between bodies that are a specific distance apart. In the multibody approach, contact is between surfaces. In the FE approach, contact can be between elements and nodes, elements and elements, or nodes and nodes. One side of the contact is referred to as the master side, with corresponding master segments/nodes, while the other side is referred to as the slave side, with slave segments/nodes. Typically the slave side has a finer mesh density or is the softer material. Most of the software codes use the proposed stiffness for contact based on average master and slave characteristics (combined characteristics), although options exist to limit the characteristics to either the master or slave side. Penetrations of contact intersections during the simulations have to be checked, specifically initial penetrations. Three general contact algorithms are: kinematic constraint, distributed parameter, and penalty stiffness. While all the methods are acceptable, it is recommended that the penalty stiffness method be used.

a. Kinematic Constraint Method or Lagrange Multipliers

In this contact algorithm the constraints are imposed into global equations by a transformation of the slave node displacement components along the contact interface. The transformation will distribute the slave node normal force component to adjacent master nodes.

b. Distributed Parameter Method

In this contact algorithm half of the mass of the slave surface area is distributed to the master surface area. The internal stress in each element determines a contact pressure distribution for the master elements that receives the mass. The acceleration is updated at the master surface and then impenetrable constraints are imposed on slave node accelerations and velocities to make sure the movement is along the master surface.

c. Penalty Stiffness Method

This is a very reliable and probably the widest used contact algorithm in implicit and explicit codes. This method uses normal interface non-linear springs and dampers between each of the nodes of the contact surface based on the Hertz theory. In multibody codes, a hysteresis damping function may be used to represent the energy loss in impact. This model assumes that the energy is dissipated by residual plastic deformation or internal damping of the bodies in contact. For FE codes, a stiffness modulus is computed for each master and slave segment based on the elasticity and the thickness property of each of the contacting elements. Care should be given in selecting spring stiffness as this affects penetration and time step.

7.2.5.1 Contact Normals

In order for two bodies to properly interact, it is important for the software to know what is considered inside the body and what is outside. This is accomplished by setting contact normals. The order that nodes are defined in an element will define the outward normal.

Some codes have a feature to automatically address this issue. Many graphical user interfaces are also set up to allow the user to quickly modify any incorrect normals. It is recommended that the analyst verify proper orientation during the mesh process to avoid future problems.

7.2.5.2 Contact Thickness

In order to properly account for interfaces when using shell elements, it is important to take into account the thickness of the parts at the contact level. This is separate from any thickness definition at the element level that is used to properly calculate stress and strains.

7.2.5.3 Contact Friction

The methods to determine static and dynamic coefficients available in the codes are based on a Coulomb formulation. Friction values can be selected from a standard handbook such as Mark's Standard Handbook for Mechanical Engineers. Since determining the coefficient of friction based on physical testing is difficult it is recommended to conduct a sensitivity analysis on critical friction parameters.

Contact between the seatbelt webbing and the v-ATD, as well as between the v-ATD and the seat cushions, is typically represented using surface-to-surface contact. A friction coefficient between the range of 0.2 and 0.5 is considered reasonable.

7.2.6 Load Application

Dynamic evaluation of a seat requires a load application, typically referred to as the sled pulse. This pulse (Figure 19) is defined in 14 CFR XX.562 (part 23, 25, 27, and 29 aircraft). This regulation specifies velocity change, rise time, and peak acceleration. AC 25.562-1b provides additional guidance by specifying an "ideal pulse" for the longitudinal and combined vertical/longitudinal test conditions. AC 23.562-1 and AC25.562-1b also call for one half of the velocity change to be achieved during the rise time period. Multiple types of facilities, or tracks, are used to produce the required sled pulse, including deceleration tracks, acceleration tracks (such as Hyge systems), and rebound tracks. Round robin testing has shown that all three types of facilities produce acceptable results. For ease of comparing results, it is recommended to model the type of facility that accomplished the physical tests. However the model can still be validated against test data when the pulse application is different.

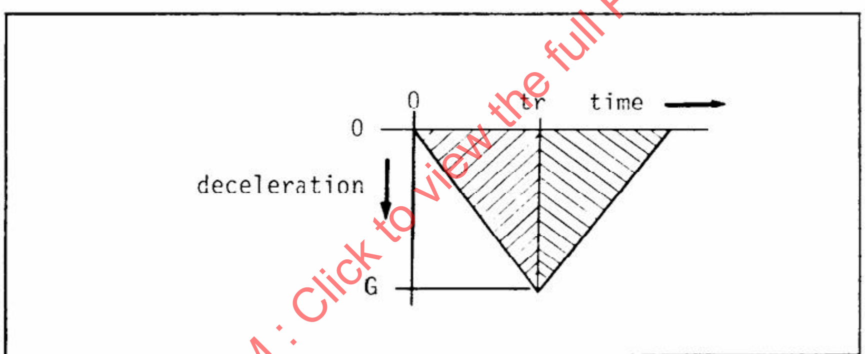


Figure 19 - Generic sled pulse

In addition to the sled pulse, the force of gravity (1-g) acts on the seat system during a dynamic test. Explicit codes currently in use do not assume the existence of gravity, thus gravity must be defined. Typically, in the pure horizontal test condition, the sled pulse will only act on the seat in the X-direction and gravity will only act in the Z-direction. For some tests, such as those for side facing seats, the sled pulse may act in the seat Y-direction. For a combined horizontal-vertical test (colloquially called a down load test), it is common practice to leave the model in a horizontal position and rotate the applied accelerations. To accomplish this, the defined accelerations in the X and Z direction are a geometric combination of the sled pulse and gravity. Likewise, yaw can be added to the horizontal sled pulse for a seat structural test by the geometric combination of the X and Y accelerations. For all applied accelerations, it is important to use consistent units.

In general, seat models are run for one of three purposes: design and development, validation, or generic modeling. The sled pulse used may be different for the three purposes. For design and development, it is recommended to apply a pulse that exceeds the regulatory requirement. This will provide additional confidence that the seat will perform satisfactorily during physical testing and is essentially a factor of safety. For a 16 g horizontal test, peak acceleration on the order of 16.8 g is often employed. Because different test facilities produce different shaped pulses and many facilities exceed the minimum required peak acceleration, there is a benefit to matching these characteristics when defining a developmental pulse. For validation exercises, it is recommended to use the exact pulse recorded in the physical test. For generic modeling, the ideal pulse is recommended, however any acceleration pulse that meets the regulatory requirements is acceptable.

- Ideal Pulses

In several test conditions, the ideal acceleration pulse, based on an isosceles triangle and the defined peak acceleration and rise time, does not induce the required change in total velocity and rise time velocity. This has not been an issue in physical tests, in part because many facilities are unable to produce the exact ideal pulse and tend to overshoot the required peak g's. For simulations, where the pulse can be defined exactly, this can become an issue. These deficiencies could result in a pulse that does not meet guidance and/or regulatory requirements. Table 15 summarizes the test condition requirements and achieved results required for the various aircraft designations (velocity, peak g's, rise time, final time, and calculated velocity changes). The final time assumes an isosceles triangle. Calculated velocities in a grey box do not meet the specified requirements, specifically the four Part 23 conditions and the vertical Part 27/29 condition.

Table 15 - "Ideal" pulse + calculated velocity

Part	Seat	Direction	Required Velocity ft/s (m/s)	Peak G's g's	Rise Time s	Final Time s	Calculated Rise Time Velocity Change ft/s (m/s)	Calculated Total Velocity Change ft/s (m/s)
23	Crew	Horz	42 (12.80)	26	0.05	0.10	20.93 (6.38)	41.86 (12.76)
23	Crew	Vert	31 (9.45)	19	0.05	0.10	15.30 (4.66)	30.59 (9.32)
23	Pass	Horz	42 (12.80)	21	0.06	0.12	20.29 (6.18)	40.57 (12.37)
23	Pass	Vert	31 (9.45)	15	0.06	0.12	14.49 (4.42)	28.98 (8.83)
25	All	Horz	44 (13.41)	16	0.09	0.18	23.18 (7.07)	46.37 (14.13)
25	All	Vert	35 (10.67)	14	0.08	0.16	18.03 (5.50)	36.06 (10.99)
27/29	All	Horz	42 (12.80)	18.4	0.071	0.142	21.03 (6.41)	42.06 (12.82)
27/29	All	Vert	30 (9.14)	30	0.031	0.062	14.97 (4.56)	29.94 (9.13)

To correct the above deficiencies, several new "ideal" pulses have been defined such that the peak g's are held constant and the total velocity change meets the regulatory requirements. These pulses were designed such that one half of the velocity change was achieved during the originally specified rise time, in accordance with AC 25-562-1b. The intent was to minimize the difference between the isosceles triangle pulse and the new pulse, while providing the required velocity change. Changes to the rise time and final time were made in whole millisecond increments. Table 16 summarizes the new pulse recommendations along with the calculated velocity changes. For completeness, acceptable pulses from Table 15 are included.

Table 16 - New pulse recommendations

Part	Seat	Direction	Required Velocity ft/s (m/s)	Peak G's g's	Rise Time s	Final Time s	Calculated Rise Time Velocity Change ft/s (m/s)	Calculated Total Velocity Change ft/s (m/s)
23	Crew	Horz	42 (12.80)	26	0.049	0.101	21.34 (6.50)	42.28 (12.89)
23	Crew	Vert	31 (9.45)	19	0.049	0.102	15.60 (4.75)	31.20 (9.51)
23	Pass	Horz	42 (12.80)	21	0.057	0.125	21.25 (6.48)	42.26 (12.88)
23	Pass	Vert	31 (9.45)	15	0.055	0.129	15.62 (4.76)	31.15 (9.49)
25	All	Horz	44 (13.41)	16	0.09	0.18	23.18 (7.07)	46.37 (14.13)
25	All	Vert	35 (10.67)	14	0.08	0.16	18.03 (5.50)	36.06 (10.99)
27/29	All	Horz	42 (12.80)	18.4	0.071	0.142	21.03 (6.41)	42.06 (12.82)
27/29	All	Vert	30 (9.14)	30	0.030	0.063	15.44 (4.71)	30.43 (9.28)

7.2.7 Initial Conditions

7.2.7.1 v-ATD

- Positioning

Placement of the v-ATD should mirror the procedure defined in AS8049B. For modeling purposes, achieving equilibrium with the v-ATD, specifically the torso, is the most important facet of positioning the ATD. There are several methods listed below. Once equilibrium is achieved, the legs and hands may need to be adjusted to meet AS8049B guidelines. When test data is available, the position of the joints can be compared to the test data, factoring in any discrepancies found, as mentioned above. In cases where test data is not available prior to analysis, similar or existing seat configurations can be used to approximate the v-ATD position. Due to measurement errors and differences in segment lengths between the numerical and physical dummies, it may not be possible to have an exact match; however these differences should be minor. If large differences are seen, the data should be reevaluated and the segment lengths double checked. Also, it is important to remember the seating methods used in the physical test. It is more important to have the dummy in equilibrium and avoid dummy to dummy penetration than to match test data initial positions. Again, any significant differences should be evaluated to determine the most likely cause.

The Hybrid II ATD has no manufacturing tolerance on the H-pt height and the FAA-Hybrid III tolerance is fairly large. Because of this, significant variations can be found between physical dummies and numerical dummies. Also, wear and tear on a physical dummy can change this height. To quantify this difference, the physical dummy to be simulated should be placed on a rigid, flat surface and the z distance between the H-pt and the surface should be measured. A simulation of the process should also be completed and the results compared (similar to the process described in 3.3.4). In the simulation, it is important to make sure that gravity is defined and that the dummy is at equilibrium. Any differences between these heights will affect the initial position of the dummy and could affect the results of a simulation (particularly in a down load test configuration). In addition to the H-pt height, other segment lengths can vary a small amount based on the allowed tolerances. It is recommended that the user evaluate critical lengths to determine if the as-tested ATD is significantly different than the v-ATD; of particular importance is the H-pt height, the ATD sitting height, and the lower leg segment lengths, including the shoes (as discussed below). Additionally, the user should be aware that measurement uncertainty can affect the reported locations of ATD markers and may need to be factored into the above evaluations.

The most accurate way to achieve equilibrium is to replicate a typical physical seating of the ATD. Numerically, the v-ATD can be placed just above and in front of the seat and the standard 1-g of gravity can be applied in the vertical direction. Additionally, the torso can be pushed back into the seat with 20 pound (89 N) of force (as described in 7.1.1) with either a point load or an acceleration function. The downside to this method is that it can greatly increase the time it takes to set up and run a model. One method to minimize this impact is to split the simulation into two, where the ATD positioning is separated from the impact. While this is beneficial if the same simulation needs to be run numerous times with only changes that do not affect the ATD position, it is important to make sure that residual stress and strains in the seat cushion are retained.

Alternate seating methods exist. A prescribed motion can be defined such that the ATD properly deforms the seat cushion while ending in the location suggested by the test data. This method does not guarantee equilibrium and can be tricky if there are any discrepancies, as mentioned above. Another method is to place the v-ATD in the final location, resulting in initial penetrations, and define a contact that forces the cushion to conform. This method has the same limitations as the prescribed motion method and can also struggle with thick cushions. A typical method in the automotive industry is to place the v-ATD in the location defined by the test data (or vehicle drawings) and move or modify the properties of the seat cushion to force equilibrium. This method is not recommended for the aviation industry.

Regardless of the method employed, the equilibrium of the v-ATD should be verified by the analyst through review of energy balance or review of load/position time history plots or through animation of the simulation.

- Clothing

Per AS8049B, an ATD must be clothed during a sled test. The primary impact of the clothing on the results of the test is a function of the difference in the friction between the seat and either the ATD rubber flesh or the cloth material. Since this change in friction can be accounted for in a simulation without the need for explicitly modeling the clothes, it is recommended to not model any clothing during a standard impact simulation. Two possible exceptions to this are space applications (pressure suits) and military applications (additional mass from gear/clothing).

The typical v-ATD will have shoes modeled. However, it is possible that the sole height could be different between the physical shoes used and the default shoes on the v-ATD. It is recommended that the user should calculate the distance from the floor to either the knee or ankle joints and compare this distance between the physical test and the simulation. For significant deviations, the user may have to modify the v-ATD shoe or adjust the floor height.

7.2.7.2 Floor Deformations

The purpose of providing floor deformation is to demonstrate the integrity of the attachment of the seating structure to the airframe even though the seat or airframe may be deformed by the forces associated with the crash. Procedures for floor deformation including selection of specific pitch and roll configuration are defined in AS8049B. There are two common methods for applying floor deformation: two-stage and single event. Either method can be acceptable as long as the model is capable of producing the desired structural pre-loads in the seat, achieving the proper v-ATD initial position before applying the crash pulse, and minimizing noise in the simulation. Using either of the methods the analyst has to ensure that the initial conditions of the ATD match the physical test and the two-stage might be preferred when there is significant movement of the ATD during the pitch and roll event.

- Two-Stage Analysis

The two-stage analysis consists of two separate simulations. In the first stage/simulation, pitch and roll rotations are applied to the seat, typically by prescribing displacement of the floor track. In the second stage/simulation the crash event is simulated. The first stage can be performed using either implicit or explicit analysis and the second stage is done using the explicit method. The nodal positions and element output such as stresses and strains from the first stage are then used as the starting input conditions for the second stage of the analysis. To account for ATD position change due to physical pitch and roll event, the v-ATD should be placed in the seat (with the seat in the deformed condition) such that the initial condition of the v-ATD and seat position accurately simulates the actual test conditions.

The following is a step-by-step summary of the two stage analysis:

Step 1 - Position the v-ATD as per the initial position reference points taken during the physical test.

Step 2 - Conduct pitch and roll procedure.

Step 3 - The deformed shape co-ordinates and stresses of the seat are applied and the v-ATD position is again matched with the reference points taken during physical test after pitch and roll.

Step 4 - With these deformed shape co-ordinates and stresses incorporated into the entire system (seat + v-ATD), the acceleration pulse is then applied to simulate a dynamic event.

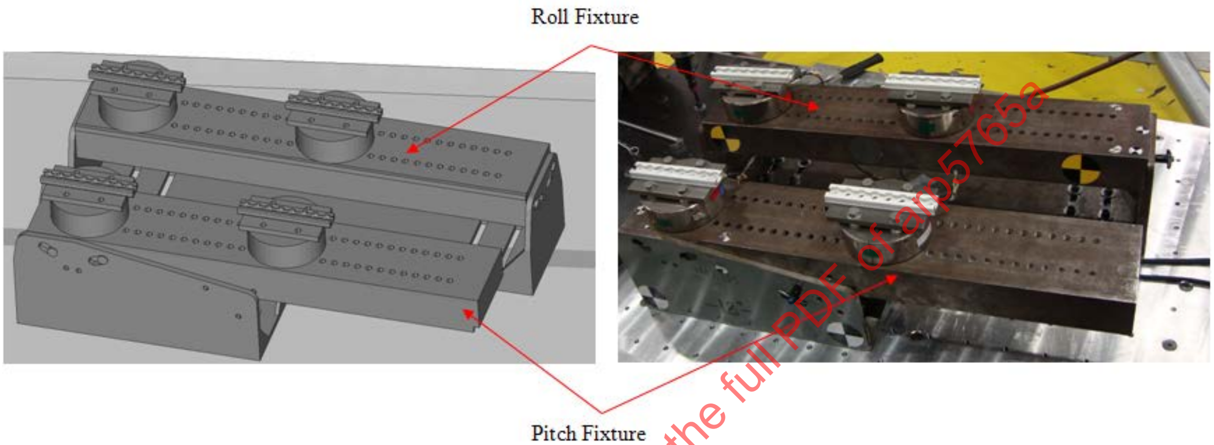


Figure 20 - Pitch and roll fixtures

Figures 20 and 21 show the floor deformation processes as described by the two-stage analysis.

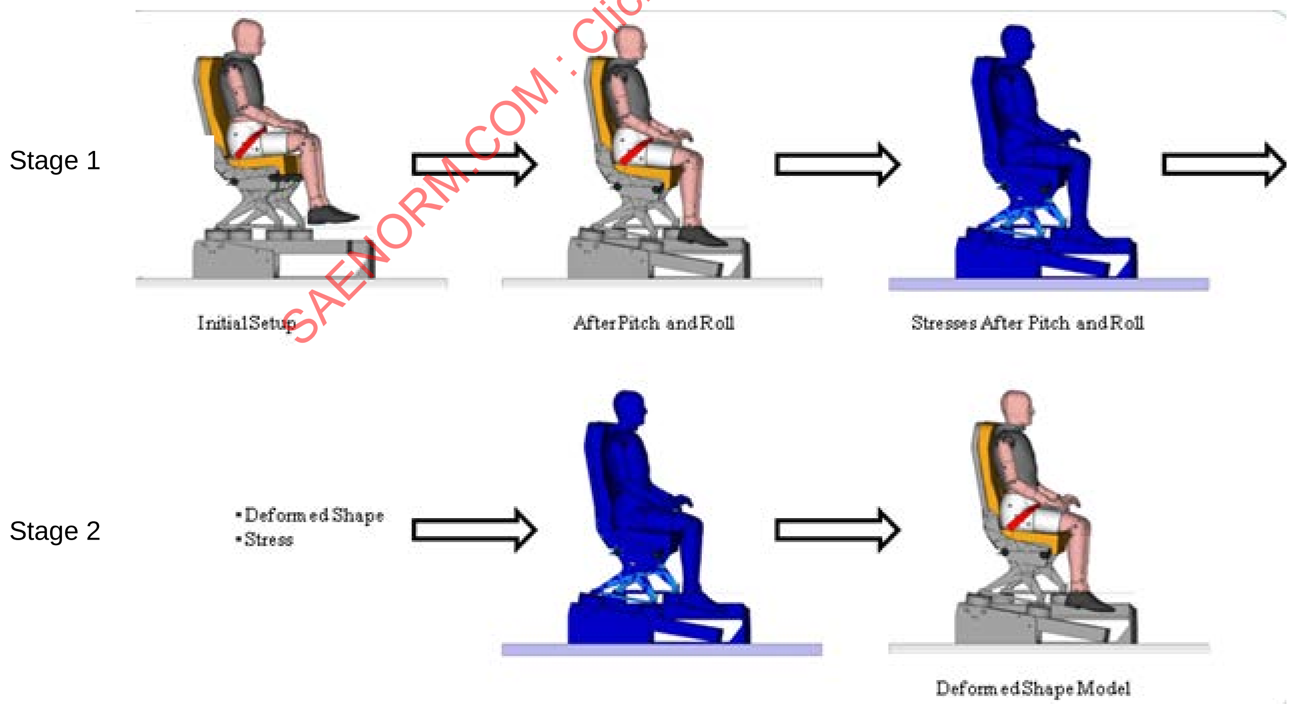


Figure 21 - Pre-simulation

- Single Dynamic Event Analysis

The single dynamic event involves the simulation of the floor deformation and conducting the crash analysis in one step. This typically involves setting the v-ATD in the seat, followed by a period of 50 to 150 ms of floor deformation to achieve the desired floor deformation and v-ATD position, and finally applying the crash pulse. In the physical test, FAA policy allows for reposition of the ATD after floor deformation in an upright posture. This could cause discrepancies in initial v-ATD position between the physical test and the simulation.

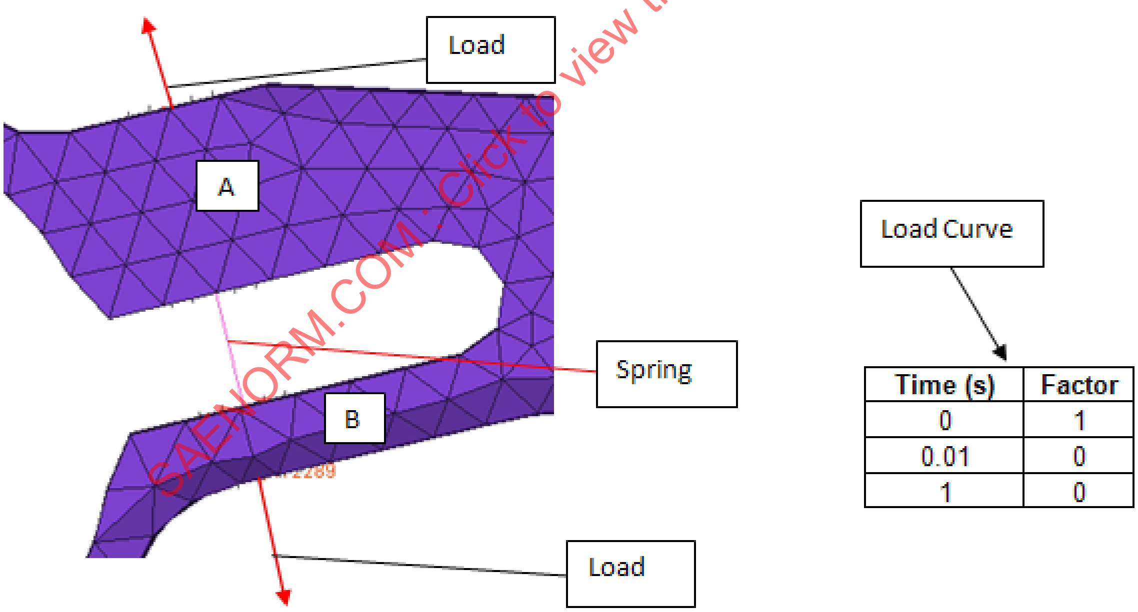
7.2.7.3 Restraint System Initial Condition

Restraint systems play an integral role in both the motion of the occupant and the loading into the seat. As such, it is important to properly define the initial condition of all restraint segments. For 2-point lap belts, AS8049B calls for the belt to be snug, but not excessively tight, which is commonly referred to as two fingers tight. FAA research has shown that this belt tension adjustment is in the range of 5 to 10 pounds (22.24 to 44.48 N) (DOT/FAA/AM-02/11). For shoulder harnesses, the properties of the inertial reel will determine both the pre-tension and payout and should meet AS8043. For developmental tests, the inertial reel can be emulated by 1 to 1.25 inches (25.4 to 31.75 mm) of slack.

The length of belt segments can also affect the belt performance. Fixed length segments of the belt should be modeled with the specified length (from seat drawings or physical measurements). For adjustable segments, obtaining the appropriate pre-tension will drive the length of the belt. Physical measurements of the adjustable belt segments, as recommended in 5.1.2.1, can be used as a reality check on the simulated length.

7.2.7.4 Clamping

A clamping preload can be applied on the spreader or leg to be held on to the cross tube firmly. This can be achieved in multiple ways. One of the methods is briefly described below.



Time (s)	Factor
0	1
0.01	0
1	0

Figure 22 - Clamping example

Sections A and B needs to be under load for the spreader/leg to hold on to the cross tube. This can be achieved as shown in Figure 22. A discrete spring with an offset value (refer to the respective code) has to be used in between the two sections and the load will be applied on these two sections at the start of the analysis. The equating forces will then be dropped to zero within a small period of time as depicted in the load curve and this will pull the two sections to draw closer to hold on to the cross tubes firmly.

7.2.8 Output Control

Output control is an important step in the modeling process. Results need to be thoroughly reviewed for accuracy since the output is used to generate reports to communicate the validity and meaning of the model.

7.2.8.1 Energy Balance

After running a model, the overall energy balance of the system should be reviewed. This gives insight into the overall response of the system to mechanical inputs and hence understanding the accuracy of the solution. The ratio of initial total energy and total energy at any point during the dynamic event should be in the range of 0.9 to 1.1.

7.2.8.2 Output Request

In many codes, output files are not generated automatically. The user needs to request each channel as required. It is recommended to request all data channels that are recorded during similar physical tests. Additional channels may also be useful for troubleshooting. It is useful for the time interval to be the same as the physical data. SAE J211-1 provides detailed information on instrumentation polarity, sampling rate, and filtering methods.

7.2.8.3 Output Definition

In order to properly compare test and simulation results, it is important to select the appropriate output location. Loads, accelerations, and positions are calculated at bodies (in a multibody solver) or nodes (in a FE solver). The simulation output should come from a location that matches the physical location of a physical sensor or marker as closely as is practical. Engineering judgment may be required, specifically for comparing physical markers on the flesh of the ATD (and the resulting position) with position data from a simulation, which may be calculated based on hard points (such as the v-ATD bone), a node on the v-ATD flesh, or even a non-physical spot attached to a MB body.

7.2.9 Common Errors

The following sections discuss common errors that may be encountered when creating models. This list is not exhaustive.

7.2.9.1 Negative Volume

Severe deformation of brick elements may sometimes cause the volume of the material to be calculated as negative and can occur without the program reporting an error. Negative volume in elements is widely observed in materials that are soft and that can undergo higher deformation (i.e., soft foams). When such errors occur, it is recommended to investigate the following remedies:

- Refine the local mesh
- Review material properties.
- Reduce time step scale factor
- Review element formulations.

7.2.9.2 Hourglass Energy

Hourglassing may be caused by coarse mesh or poor element quality. Inappropriate contact definition such as poor slave and master surface definition, incorrect modeling definition at connections, poor boundary conditions may also result in high hourglassing energies.

Hourglass energy (HE) in individual components can be determined by plotting the material energies from the component. It is recommended that for critical seat components the HE should be less than 5% of the internal energy (IE) and less than 10% of the IE for non-critical seat components.

Linear elements with reduced integration points are significantly more efficient than full-integration or 2nd order elements but are very sensitive to variations in element shape and susceptible to hourglassing (zero energy modes). Hence, refining the mesh or using full-integration elements can reduce hourglassing effects. If not addressed, excess hourglassing can significantly affect the accuracy of the results.

8. NOTES

8.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications nor in documents that contain editorial changes only.

PREPARED BY SAE AIRCRAFT SEAT COMMITTEE

APPENDIX A - METHODOLOGY FOR THE COMPARISON OF TEST AND SIMULATION WAVEFORMS

A.1 INPUT

This appendix describes a means for determining an error between test and simulation data. For each required channel, magnitude error and curve shape error should be evaluated. Channel inputs should have consistent units, appropriate sampling rates (10 KHz for electronic instrumentation, 1 KHz for photometric) and equal time lengths. Test and simulation position data need to have the same global origin and coordinate system. If required, units, data set length, and origin offsets can be corrected during post-processing.

Time histories should be compared beginning with the onset of the test pulse and through significant system response (often ATD motion) as seen in the physical test. The intent is to capture all the relevant data, while limiting the total length of comparison, especially if that added length involves a lack of motion/signal response since this will alter the metric results.

A.2 MAGNITUDE ERROR

A.2.1 Motion Data

For proper evaluation, motion data will be handled differently than force, acceleration, velocity, and moment data. Position data for the test and simulation should be offset by the test data initial position (I.P.) as seen in Figure A1. This approach will preserve any initial differences between the test and simulation results. To accomplish this, subtract the test data target I.P. from the entire time history of both the test data and simulation data. Once the data has been offset, the magnitude error, whether positive or negative, can be determined by a simple difference (Equation A1) of the most significant peak. If the channel has significant positive and negative peaks, both should be evaluated. The curve shape error should be determined using the Sprague and Geers comprehensive error (Equation A8).

$$Error = \left| Peak_{Test} - Peak_{Sim} \right| \quad \text{(Eq. A1)}$$

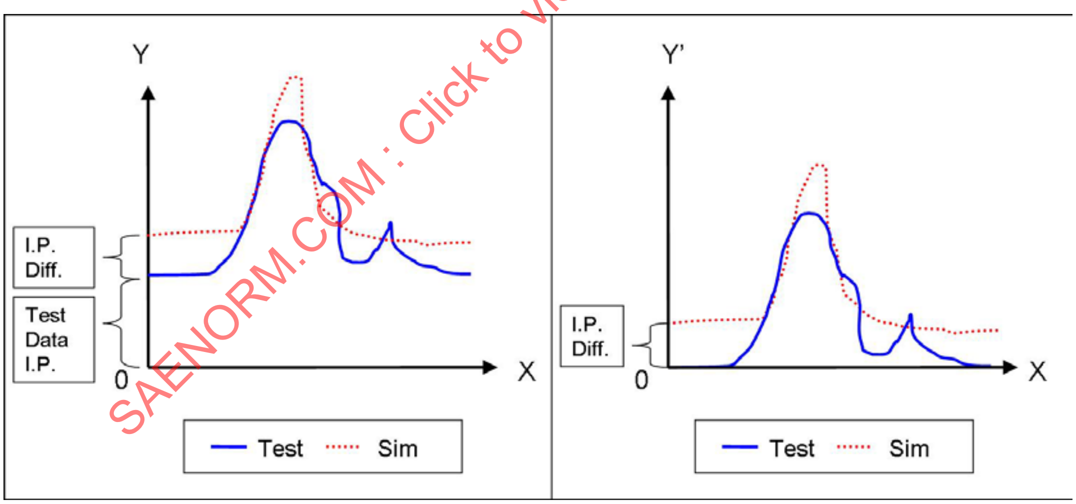


Figure A1 - Coordinate transform illustration

A.2.2 Electronic Data

For all other data types (force, moment, acceleration, velocity), the magnitude error should be calculated using a relative error calculation (Equation A2) on the most significant peak, whether positive or negative. If the channel has significant positive and negative peaks, both should be evaluated. The curve shape error should be determined using the Sprague and Geers comprehensive error.

$$Error = \frac{|Peak_{Test} - Peak_{Sim}|}{|Peak_{Test}|} * 100\%$$ (Eq. A2)

A.3 SHAPE ERROR

The curve shape error is calculated using the Sprague and Geers comprehensive error. Given two time histories of equal length, measured m(t) and computed c(t), the following time integrals are defined:

$$I_{mm} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m^2(t) dt$$ (Eq. A3)

$$I_{cc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} c^2(t) dt$$ (Eq. A4)

$$I_{mc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m(t) \cdot c(t) dt$$ (Eq. A5)

The magnitude error, biased towards the test, is then defined as:

$$M_{SG} = \sqrt{I_{cc} / I_{mm}} - 1$$ (Eq. A6)

The phase error is defined as:

$$P_{SG} = \frac{1}{\pi} \cos^{-1}(I_{mc} / \sqrt{I_{mm} I_{cc}})$$ (Eq. A7)

The comprehensive error is defined as:

$$C_{SG} = \sqrt{M_{SG}^2 + P_{SG}^2}$$ (Eq. A8)

Due to the relative simplicity of the error metric, it can be implemented into a spreadsheet program with little loss of accuracy. The integrals can be approximated by summations using the trapezoidal method.

$$\int_a^b f(t) dt \approx \frac{b-a}{2N} \sum_{i=1}^{N} [f(t_i) + f(t_{i+1})]$$ (Eq. A9)

where:

N is the number of intervals such that $\Delta t = \frac{b-a}{N}$

Because Equations A6 and A7 use ratios of the integrals, the coefficients cancel leaving, for example:

$$\frac{I_{cc}}{I_{mm}} \approx \frac{\sum_{i=1}^{N}[c(t_i)^2 + c(t_{i+1})^2]}{\sum_{i=1}^{N}[m(t_i)^2 + m(t_{i+1})^2]} \quad \text{(Eq. A10)}$$

A.4 THRESHOLD EVALUATION

A threshold evaluation is a simple observation denoting whether a signal exceeds a defined value (called a threshold). There are two versions of this evaluation, with the choice dependent on the characteristics of the physical test data. For a channel that is nearly zero during the critical phase of the event, a maximum load is defined (e.g., 100 pounds) and the simulation output is checked to make sure that it does not exceed that threshold during the critical phase of the event. For a channel that is non-zero, a maximum load greater than the peak seen in the physical test is defined. The maximum load can be a multiple of the test maximum (e.g., 1.1*test max) or simple addition (e.g., test max + 100 pounds).

A.5 REFERENCE

Sprague MA and Geers TL. *A Spectral-Element Method for Modeling Cavitation in Transient Fluid-Structure Interaction*. International Journal for Numerical Methods in Engineering. 60 (15), 2467-2499. 2004.