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Use of a Simplified Model to Evaluate Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions

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12. Abstract

The Federal Aviation Administration (FAA) requires that aircraft seating systems protect occupants in the event of an emergency landing. During the combined longitudinal-vertical impact, the seat bottom cushion significantly affects the loads transferred to the occupant's spine, and therefore the risk of injury. Previous testing revealed test-to-test lumbar load variability as high as 18%, which was hypothesized to arise in part from variation within foam material properties. In this study, a high-rate load frame was used to measure cushion force-deflection behavior, and those data were then used as inputs to a computational model to estimate the effect of cushion-property variability on predicted lumbar load. 13 credibility factors were used to support a determination that the model was adequate for answering the question of interest. While the loading curves varied by as much as 23%, the predicted peak lumbar load varied by no more than 7.4%. These findings suggest that test uncertainty due solely to differences within cushion material properties is lower than that from other sources of uncertainty in full-scale sled tests.

13. Key Word

Seat Cushion Replacement, Foam, Lumbar Load, Dynamic Test Uncertainty

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List of Abbreviations

Acronym	Abbreviation Explained
AC	Advisory Circular
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ASME	American Society of Mechanical Engineers
ATD	Anthropomorphic Test Device
CAMI	Civil Aerospace Medical Institute
COU	context of use
FAA	Federal Aviation Administration
FE	finite element
H-pt	hip point
QOI	quantity of interest
SQA	Software Quality Assurance
V&V	Verification and Validation
v-ATD	virtual Anthropomorphic Test Device
VVUQ	Verification, Validation, and Uncertainty Quantification

BACKGROUND

The Federal Aviation Administration (FAA) requires that aircraft seating systems protect occupants in the event of an emergency landing (Emergency Landing Dynamic Conditions, 14 CFR §25.562). Dynamic testing is required by these regulations to substantiate the safety of seating systems. One of the two dynamic tests required is a primarily vertical impact with a minimum impact velocity of 35 ft/s, a peak deceleration of 14 g, and an impact angle of 30° from vertical. In this test, the principal injury measurement is the compressive load in the lumbar spinal column, which has a regulatory limit of 1500 lb. During this impact, the seat bottom cushion significantly affects the loads transferred to the occupant's spine and therefore the risk of injury.

Development of a seat cushion replacement methodology was identified as a goal of streamlining the certification process in response to the Wendell H. Ford Aviation Investment and Reform Act (2000). As a result, the FAA Civil Aerospace Medical Institute (CAMI) Biodynamics Research Team has supported numerous research projects focused on seat bottom cushions over the past 20+ years (Hooper & Henderson, 2005; DeWeese, 2006; Moorcroft, 2010; Taylor, 2012; DeWeese, 2013; Taylor, et al., 2017; DeWeese et al., 2021; Taylor and Moorcroft, 2023; Hellstrom et al., 2024). A recent project sought to validate a streamlined methodology for seat cushion replacement via a rigid seat test. However, large test uncertainty obscured the differences between the tested cushions (DeWeese et al., 2021). For example, repeated tests on one of the cushion designs produced peak lumbar loads that differed by 18% despite tightly controlled ATD placement (Table 5 in DeWeese et al., 2021). The primary goal of this current project was to use a simplified computational model to estimate the test uncertainty due solely to variation in measured cushion material properties. This evaluation included intra-sample variability, i.e., comparing force-deflection curves from repeated testing of the same cushion sample, and inter-sample variability, i.e., comparing force-deflection curves from testing of different samples of the same cushion design. A secondary goal was to provide an example of communicating the credibility of a numerical model to a decision maker.

Project Scope

Previous certification-style dynamic sled testing revealed substantial lumbar load variability (sample-to-sample and test-to-test). To have confidence in seat cushion replacement methodologies, the FAA needs to quantify the contribution of cushion variability to overall test variability. Computational modeling and simulation can isolate the various sources of variability while holding other sources constant. This will allow researchers to estimate how much variability of a cushion's properties affects the lumbar load and the risk of passenger injury.

SLED TESTS

As documented in DeWeese et al. (2021), tests using a Hybrid II Anthropomorphic Test Device (ATD) and a 14 g sled pulse were run on multiple samples of various cushions. For the current study, one configuration from that project was selected: a rigid seat with a flat aluminum seat pan and a wood build-up that matched the contour of seat cushion "D" (Figure 1). This cushion is composed of an approximately 2-inch-thick top layer of medium-density, high-initial-stiffness foam and an approximately 2-inch-thick bottom layer of closed-cell flotation foam with a density of 2.2 lb/cu ft[1]. From that larger test series, three cushion samples were selected for this project (D4, D5, and D6). The sled tests from these tests yielded normalized lumbar loads of 1594 lb, 1708 lb, and 1581 lb, respectively. These tests corresponded to CAMI tests A12007[2], A12008, and A12010. To check the generalizability of the results, a second cushion, B4, which yielded a lumbar load of 1346 lb (test A12005), was also evaluated in this project. That cushion was composed of an approximately 2-inch-thick top layer of medium-density, high-resiliency foam and an approximately 2-inch-thick bottom layer of high-density, progressive-stiffness foam.

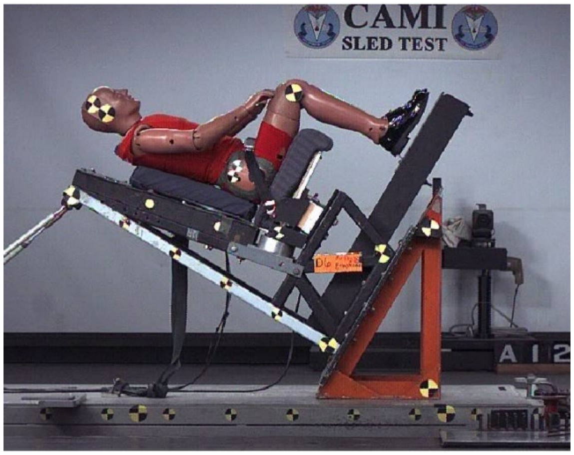

Figure 1: Side View of Dynamic Sled Test A12007

COMPONENT TESTS

Component tests were run in an MTS Landmark high-rate load frame (model # 661.20H-02; Eden Prairie, MN), to generate force-deflection curves for the numerical model.

Component Tests Setup

The aluminum-and-wood seat pan used in the sled tests was mounted in the high-rate load frame to reproduce the sled-test boundary conditions, including load cell location (Figure 2). An eight-inch diameter platen was used to compress the cushion. This platen is called out in ASTM D3574 (ASTM International, 2017) for cushion testing. Its 50.27 in^2 area is similar to the compressed area of the ATD (~50 in^2), which was estimated based on a crushed honeycomb (Figure 3). The cushions were attached to the seat pan via Velcro (Figure 4) as was done in the sled tests. The zero position was established by manually raising the ram until a 10 lb pre-load was on cushion

[1] Thickness was measured within the cushion region loaded by the ATD pelvis during the sled test (i.e., centered under the ischial tuberosities).

[2] Per CAMI naming convention, sled tests are denoted with an "A", high-speed load frame tests start with "M", and simulations start with an "S". The first two numbers are the year, and the last three numbers are the sequence from that year. For example, A12007 denotes the seventh sled test conducted in 2012.

D6. All subsequent tests used the same crosshead and ram position. Due to cushion variability, the resulting pre-loads ranged from 5 lb to 12 lb.

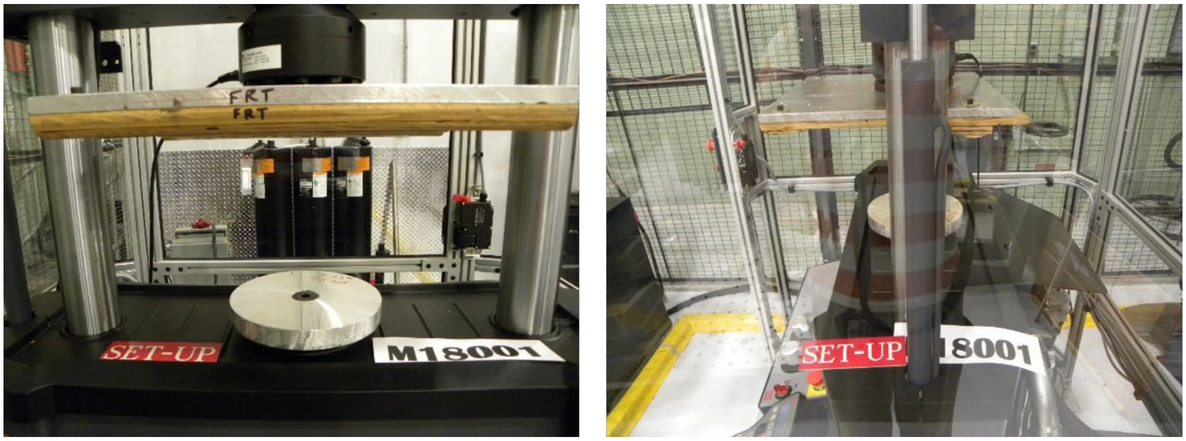

Figure 2: Front (L) and Side View (R) of Seat Pan Mounted in Load Frame

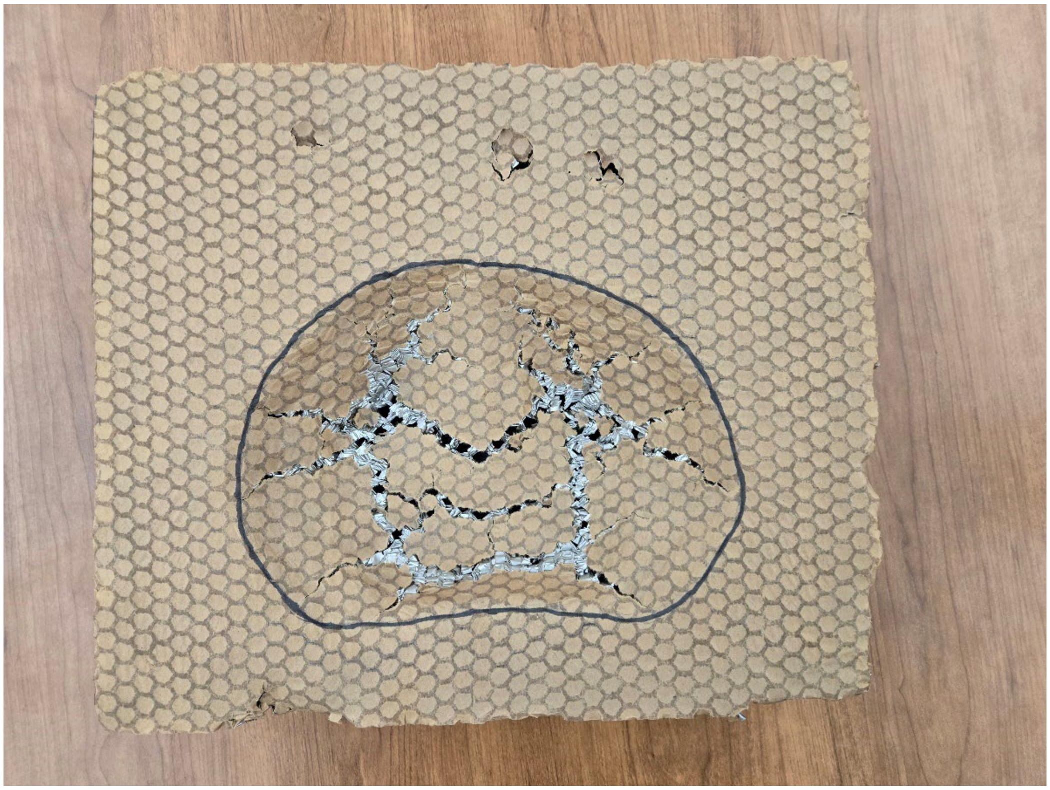
Figure 3: 14” by 11.8” Honeycomb Compressed by ATD Pelvis

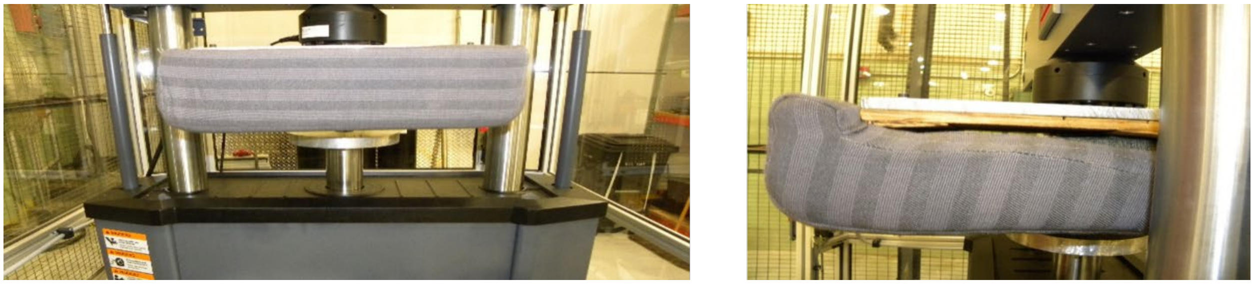

Figure 4: Front (L) and Side (R) View of Cushion Attached to Seat Pan

During the sled test (A12010), an average pelvic vertical velocity of 50 in/s (4.17 ft/s) was calculated based on photometric tracking of the pelvis (Figure 5). Based on this and the results of preliminary load frame tests, a ram velocity of 4 ft/s was selected for the component tests. The target seat pan load was 3000 lb since the lumbar load limit is 1500 lb and pan force is typically about twice that of the lumbar load (DeWeese, 2006). Previous testing suggested that the foam force-deflection curve may be in the asymptotic region at 3000 lb (Hooper & Henderson, 2005). As a result, all tests were run in displacement control, and the peak compression distance was gradually increased to minimize the risk of overloading the frame. Once a distance produced a peak of 3000 lb, that distance, 3.3", was fixed for all subsequent tests. The final procedure was defined as follows, with the displacement vs. time input graphically shown in Figure 6:

1. Zero displacement
2. Zero load cell
3. Dwell for 0.5 seconds
4. High speed acquisition initiated
5. Low speed acquisition initiated
6. Max/min acquisition initiated
7. High speed up: 3.3" at 4 ft/s
8. Dwell for 0.01 seconds
9. High speed down: 3.3" at 4 ft/s
10. Dwell for 0.5 seconds

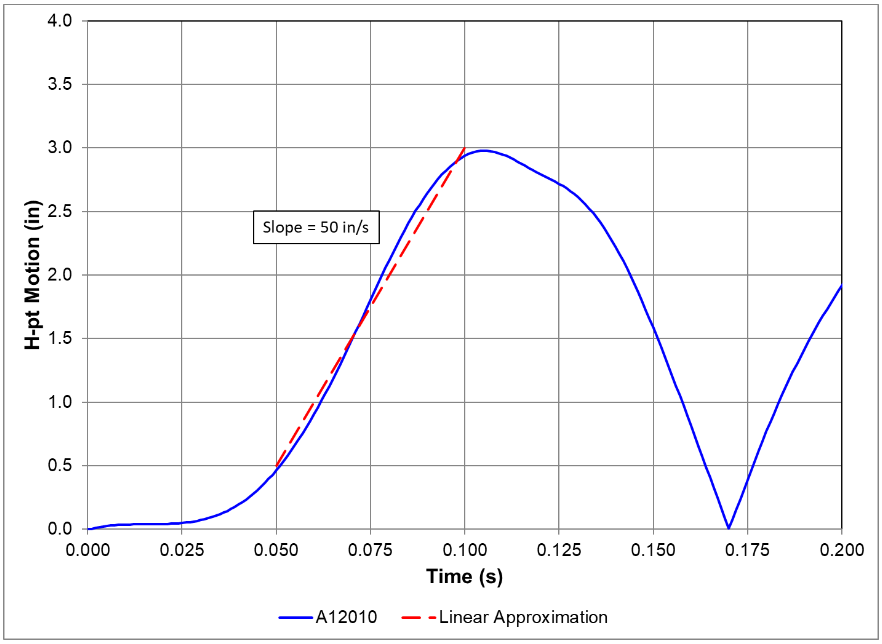

Figure 5: H-pt Motion vs Time for Test A12010

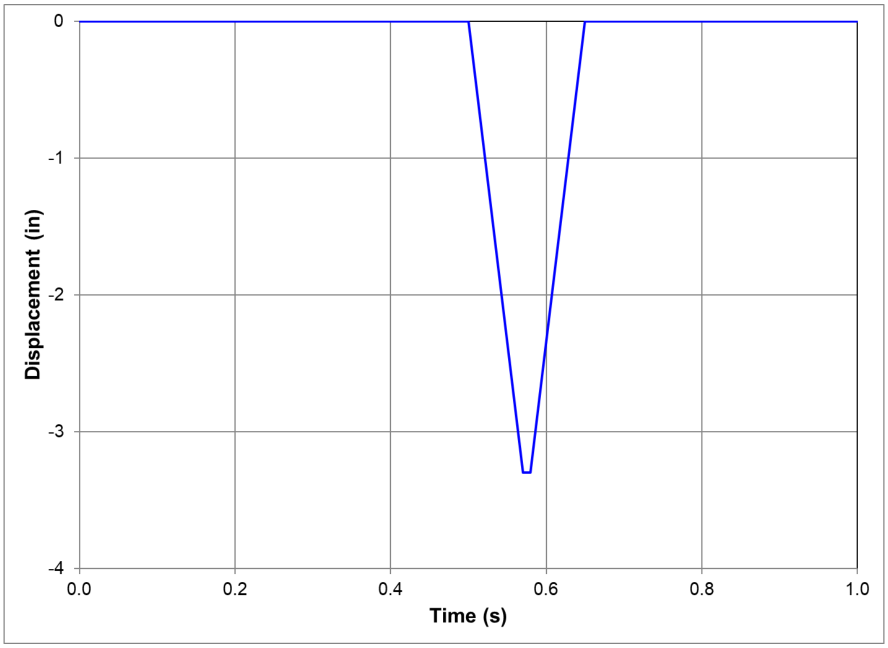

Figure 6: Displacement vs Time Input to Load Frame

The resulting loading rate is a reasonable representation of the seat pan force measured in the sled test (Figure 7). Note that the load frame curve was time-shifted to align the start of loading.

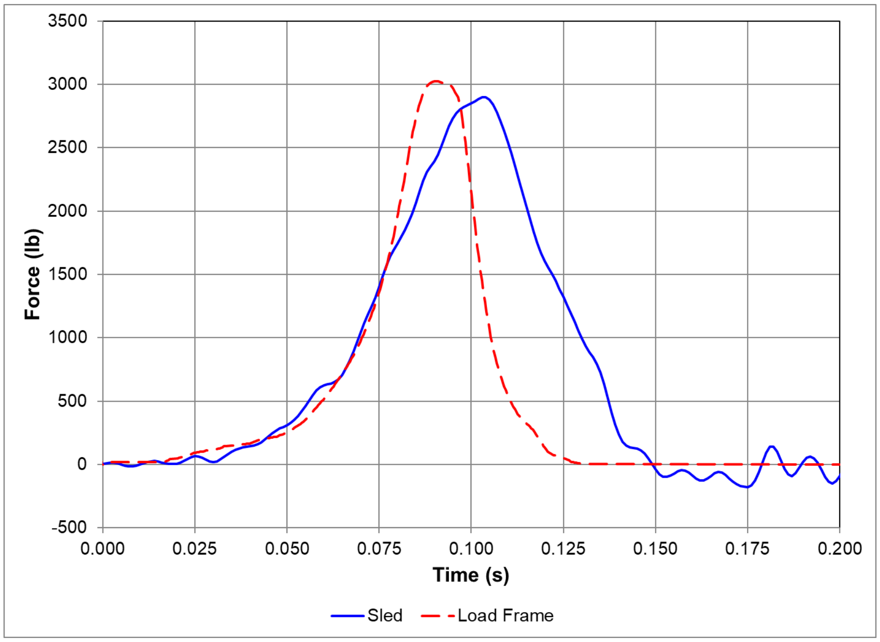

Figure 7: Force vs Time for Sled Test (A12010) and Load Frame Test (M18007)

Five cushion samples were tested with the load frame: D2, D4, D5, D6, and B4. Four of these samples were the actual cushion samples tested in the 2012 sled test series (D4, D5, D6, and B4). The last sample, D2, was not previously tested. All samples were stored in the same location from their acquisition in 2012 through testing in 2018. Details on the test parameters are in Appendix A: Load Frame Test Matrices.

The cushion samples were allowed to relax for 5 minutes to 15 minutes between most tests. To determine whether time was a factor in cushion performance, sample D5 was allowed to relax for a minimum of 24 hours between tests. This cushion was tested between 1700 and 1730 local time each day for four consecutive days (Tuesday through Friday). The four tests were M18016, a null test (failure of data acquisition), M18017, and M18018. The sample was then tested on the following Monday morning, 64 hours later, due to the weekend (M18019), and lastly, 26 hours later (M18020). Temperature and humidity for all tests were within the parameters for the Hybrid II per 14 CFR 572: 66°-78°, 10%-70% humidity (Anthropomorphic Test Devices, 2022).

Component Tests Results

Cushion D6 was tested seven times, as four tests were used to determine the final compression target that would yield 3000 lb. Figure 8 shows crosshead displacement vs. load cell force for the seven tests. The stiffness of the curves decreases with test sequence, although this trend does not persist for the final two curves. The first test to the target load of ~3000 lb (M18005) produced a slightly higher peak load (3077 lb) than the subsequent tests (3016 lb and 3027 lb) and is slightly stiffer.

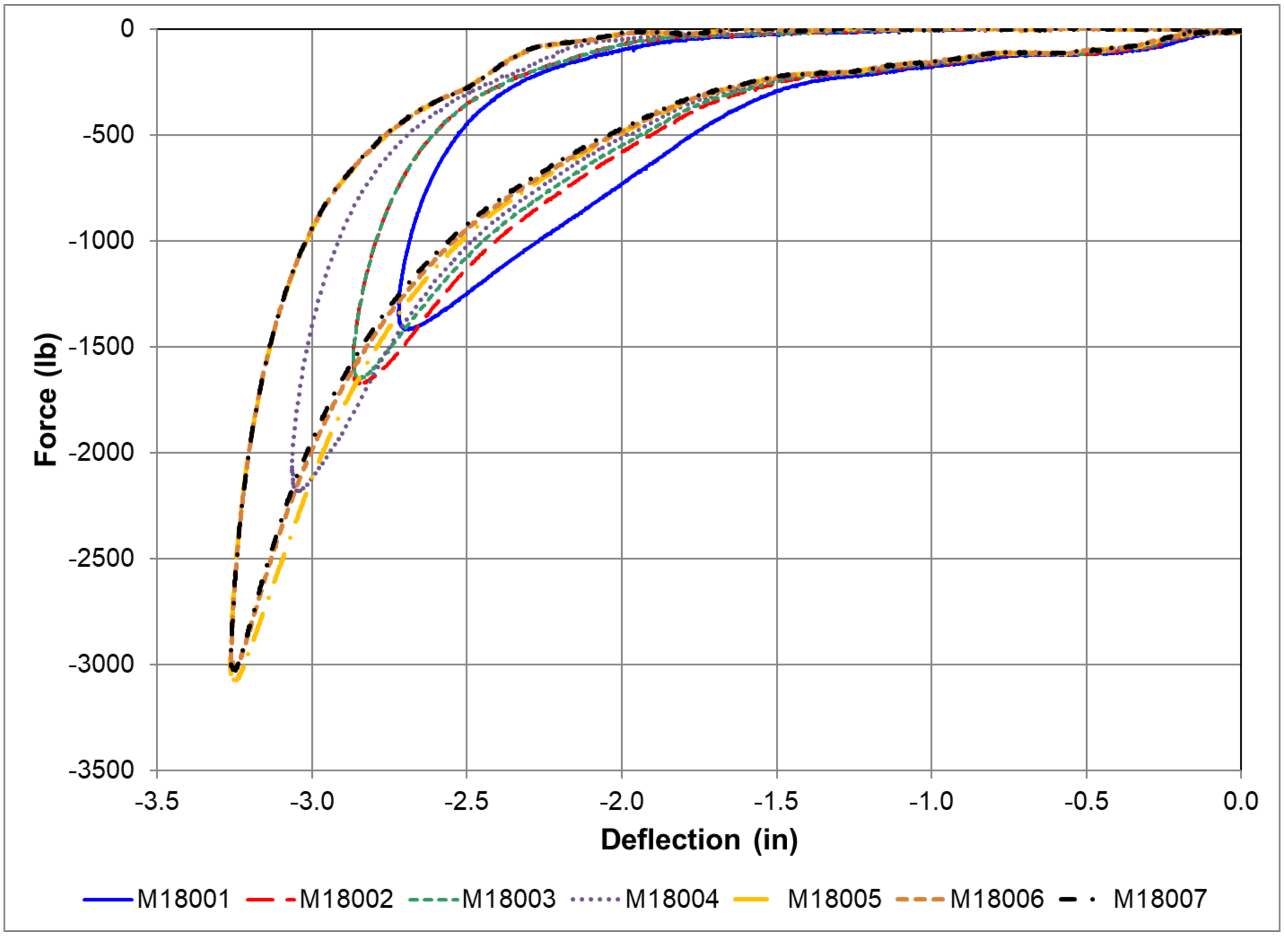

Figure 8: Force-Deflection for Cushion D6

Cushion D4 was tested four times (Figure 9). There is a noticeable change in stiffness between the first test and the three subsequent tests. The first test peaked at 3251 lb, followed by peaks of 3148 lb, 3123 lb, and 3079 lb.

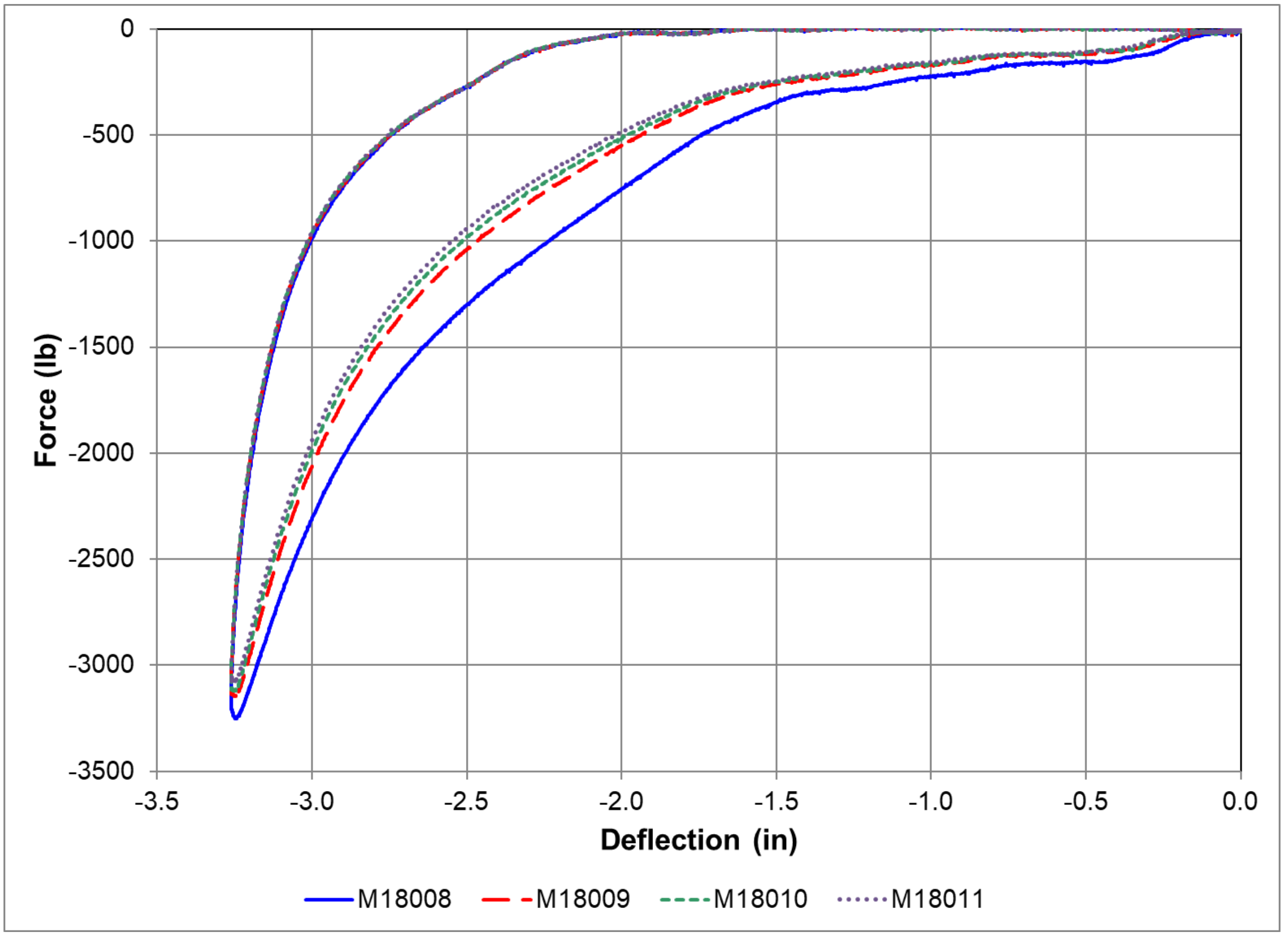

Figure 9: Force-Deflection for Cushion D4

Cushion D2 was tested four times (Figure 10). As with sample D4, there is a significant change in stiffness between the first test and the subsequent tests. The first test peaked at 2829 lb, followed by peaks of 2745 lb, 2765 lb, and 2796 lb.

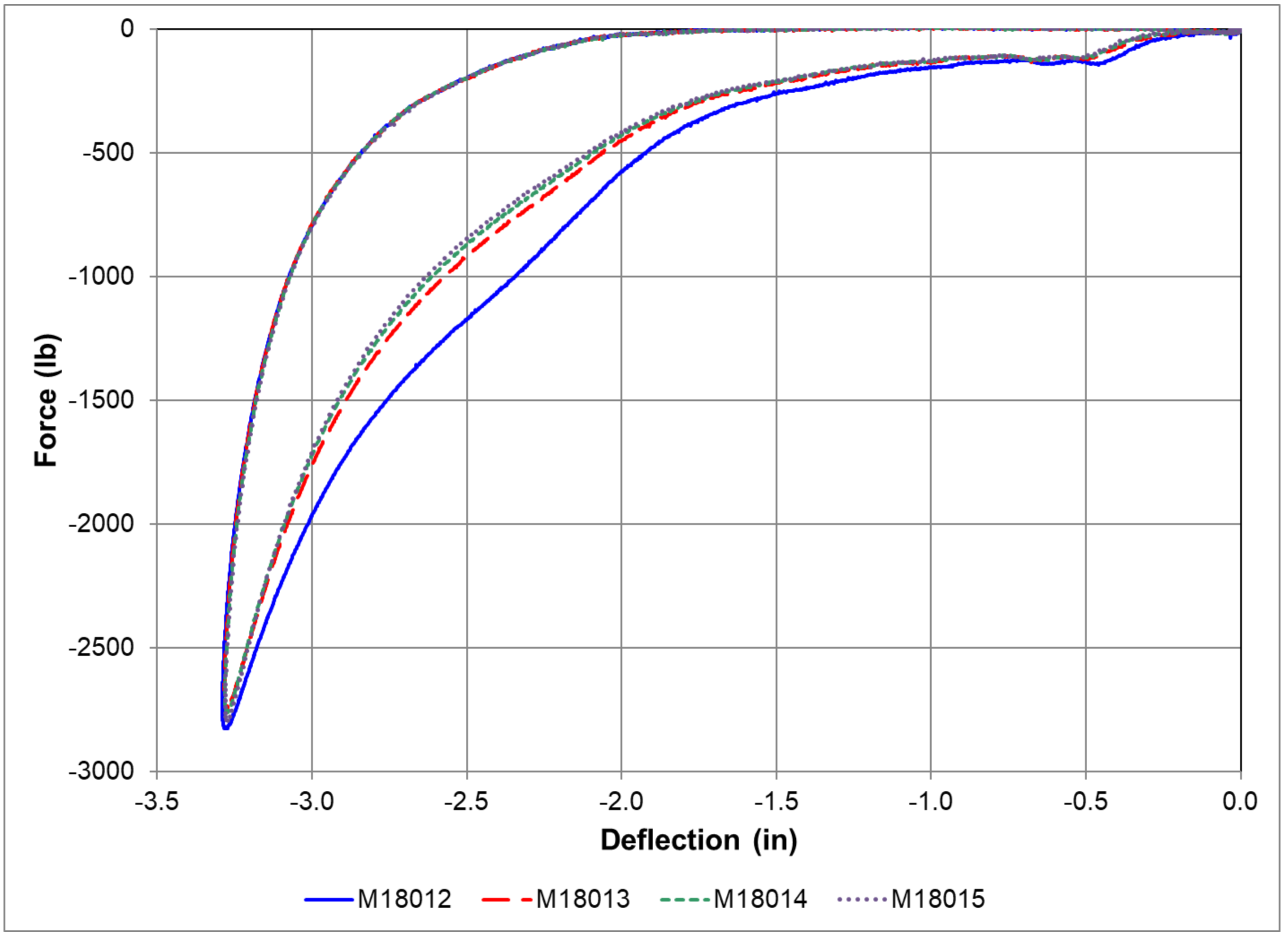

Figure 10: Force-Deflection for Cushion D2

Data was recorded for five tests of cushion D5 (a sixth test, the second in the sequence, did not generate any data as the data acquisition did not activate). As with cushions D2 and D4, there is a noticeable change in stiffness between the first test and the subsequent tests, while the remaining tests are mostly similar (Figure 11). The first test peaked at 3266 lb, followed by peaks of 2861 lb, 3023 lb, 2761 lb, and 2600 lb. Test M18018 is stiffer than test M18017, while all the previous tests showed a decrease in stiffness by sequence.

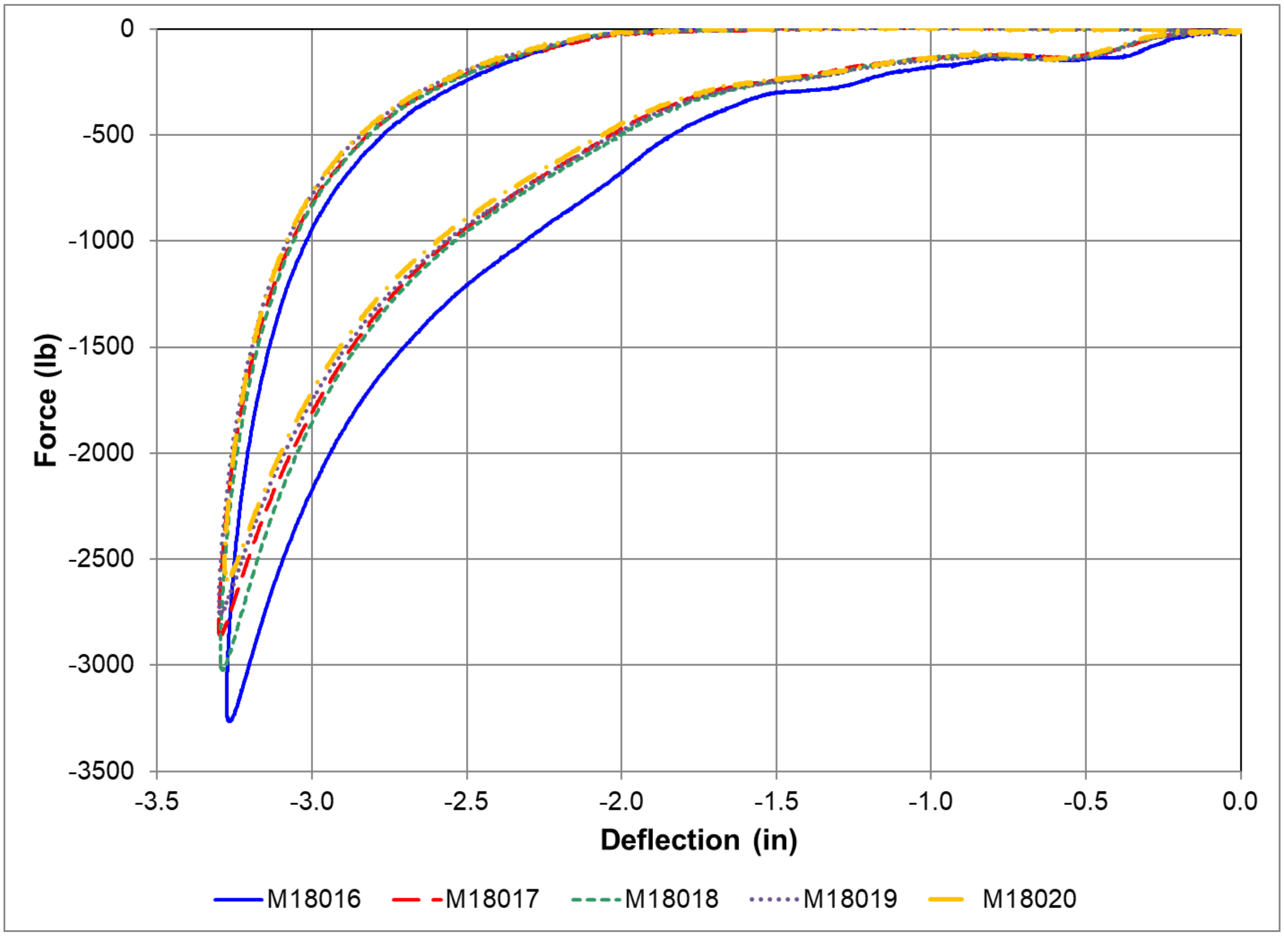

Figure 11: Force-Deflection for Cushion D5

Figure 12 shows a cross-plot of the four samples of the D cushion type. For each sample, the second test approaching 3000 lb was used. In the case of samples D2 and D4, this was the second load frame test. For sample D5, this was the third load frame test as the second test did not generate data. For sample D6, this was the 6th load frame test since the first 4 tests were used to determine the distance necessary to reach 3000 lb. As noted above, samples D4, D5, and D6 were also previously tested on the sled. All four samples have a similar load-deflection from zero to 1.0”. Sample D4 has a higher stiffness than the other samples from 1.0” to 2.75” but is similar to sample D6 from 2.75” to 3.25”. Samples D2 and D5 have virtually identical curves for the full 3.25” of compression.

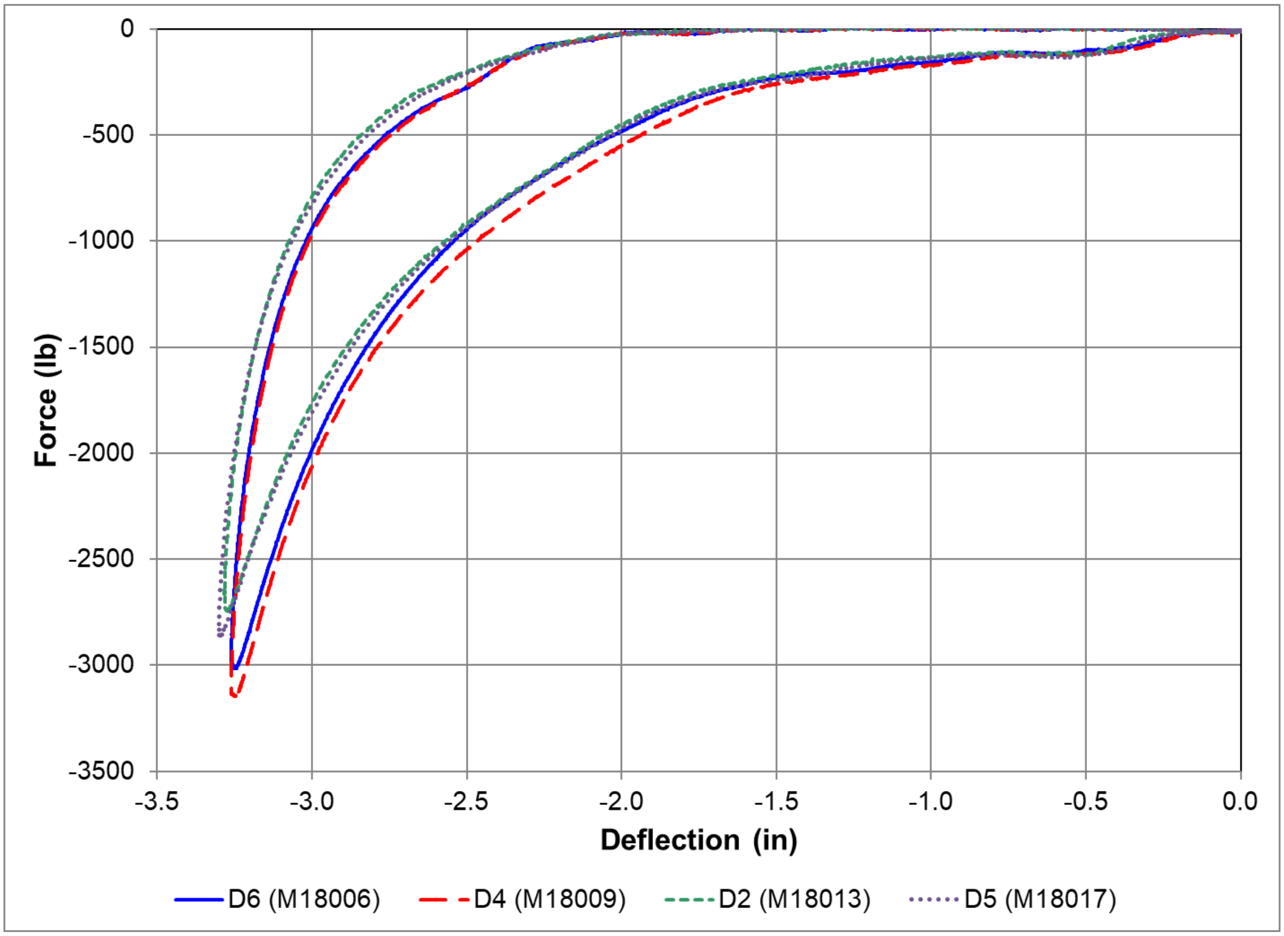

Figure 12: Force-Deflection Cross Plot of D Cushions

To determine if intra-sample trends were limited to the foam build-up used in the D cushion type, a separate cushion build-up was tested. Sample B4 was tested 4 times (Figure 13). The same intra-sample trend was observed, where tests two, three, and four produced very similar curves, and test one is distinct. The test peaks were 2809 lb, 2844 lb, 2845 lb, and 2878 lb.

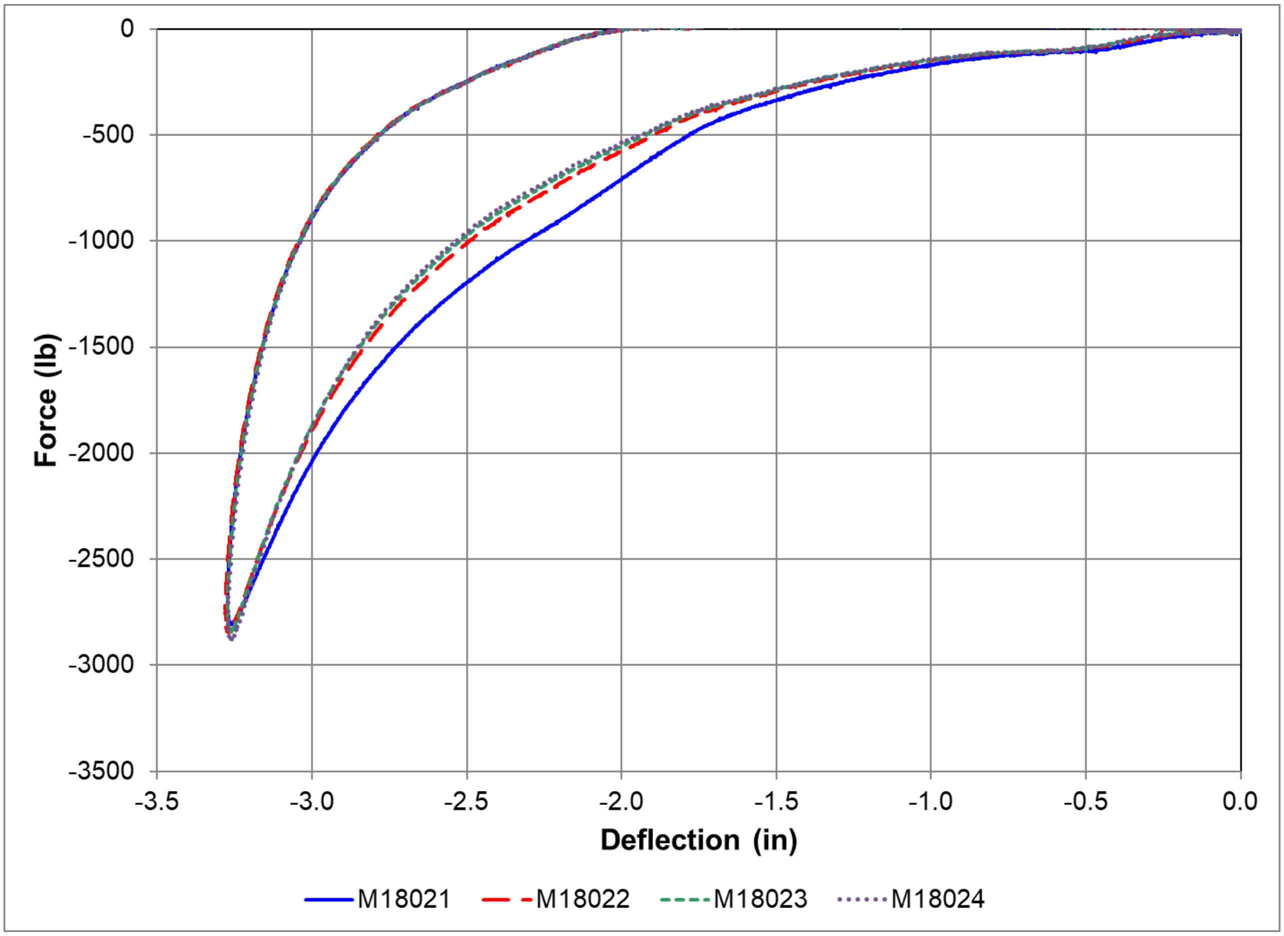

Figure 13: Force-Deflection for Cushion B4

Overall, the tests showed a consistent pattern. The initial load frame test on each sample generated the stiffest curve. This trend held for cushions with and without an earlier sled test and held for tests separated by 5 minutes as well as tests separated by 24 hours. While this trend suggests an initial set[3] by the cushion, it should be noted that sled tests run on identical samples do not exhibit a consistent trend in lumbar load as a function of sequence. For example, DeWeese (2006) ran repeated tests on 3 cushions, yielding a range of sequence effects, as test A04035 had a lower lumbar load than test A04036 (1173 lb vs 1187 lb), test A04062 was higher than test A04063 (1195 lb vs 1172 lb), and three tests of a third foam produced loads of 1200 lb, 1130 lb, and 1151 lb (A04007, A05017, and A05033, respectively). Likewise, DeWeese et al. (2021) noted a range of different sequence effects in Table 4 (A11024>A11025>A11026) and Table 5 (A10002<<A10003<A10004>A10005). Subsequent comparisons in that paper show a similar mix of lumbar load responses when viewed via the lens of test sequence.

[3] This assumes that foams, particularly closed-cell foams, experience some permanent damage from being loaded to densification.

NUMERICAL MODEL

The impact of the force-deflection curve variance on lumbar load was evaluated by use of a simplified numerical model in Madymo release 2406 (Siemens; Munich, Germany). The cushion was initially modeled using a multibody approach, but that representation did not reproduce the observed response adequately. It was therefore replaced with a finite element (FE) model. Stress-true-strain curves derived from the load-frame data were used to define each cushion sample. All inputs to the model used metric units since the virtual Anthropomorphic Test Device (v-ATD) is defined in metric.

Cushion Data Post-processing

The MTS data (time, distance, force) was post-processed for use in the simulations. The raw data was collected at 24,576 Hz[4] in English units (inches and pounds) and recorded in the first quadrant (positive displacement - positive load). The data were then subsampled by a factor of 10[5], duplicates of displacement were removed, and nonmonotonic displacement points were removed (Figure 14). The data was then split into loading and unloading curves and converted to metric units (meters and Newtons). Next, the data was placed in the 3rd quadrant (negative-negative), and stress vs true strain was calculated (Figure 15). Stress was defined as the load divided by the area of the platen (50.27 in^2 = 0.0324 m^2). True strain was calculated as the natural log of one plus engineering strain $\varepsilon_t = \ln(1+\varepsilon_{eng})$, where engineering strain was calculated as the displacement divided by the cushion's nominal initial thickness (4 in = 0.1016 m). For the loading curves, a few points at the end were deleted to remove the roll off and allow for smooth extrapolation (Figure 16). For the unloading curve, the data were trimmed beyond approximately -1.4 true strain, as model instabilities were observed with curves that extended beyond that. All data after the load cell first returned to zero after the peak were also deleted from the unloading curve. Lastly, one first quadrant data point was added to each curve to prevent the unloading curve from exceeding the loading curve (which causes the simulation to abort), following the advice of Madymo tech support. For the loading curve, this value was (0.04652, 50000), and for the unloading curve, it was (0.04652, 15000) for all cushions.

[4] Because this was the first use of this high-rate load frame for the present application, the highest available sampling rate was selected. Based on our experience in this project, we could have run at sampling rates that match sled test sampling, such as 10 kHz or 20 kHz for instrumentation, or possibly even the 1000 Hz typically used for photometrics.

[5] Except for M18005, which was subsampled by 5 because it gave better agreement with the raw curve.

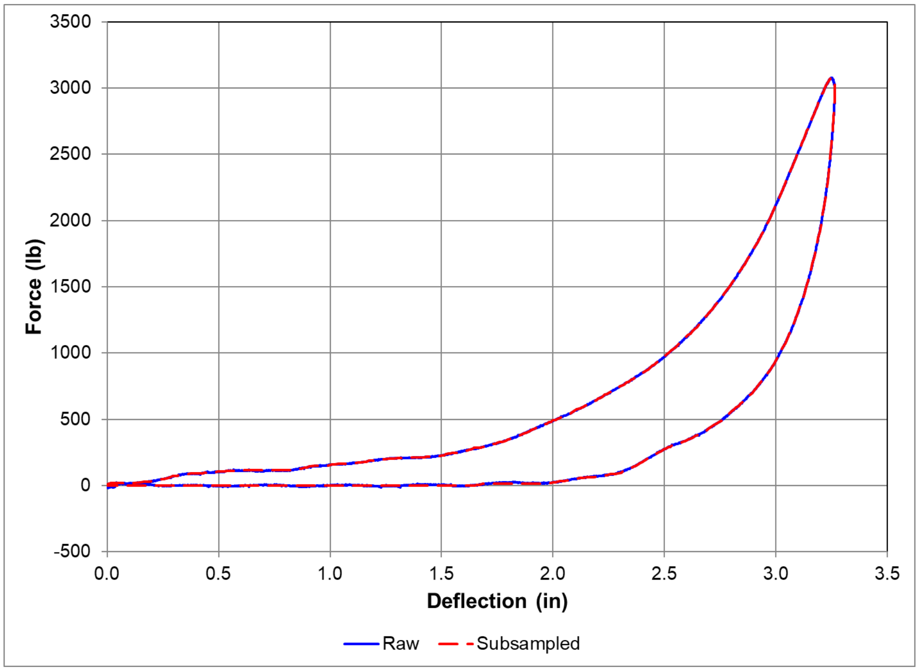

Figure 14: Raw vs Subsampled Force-Deflection Data from Test M18005

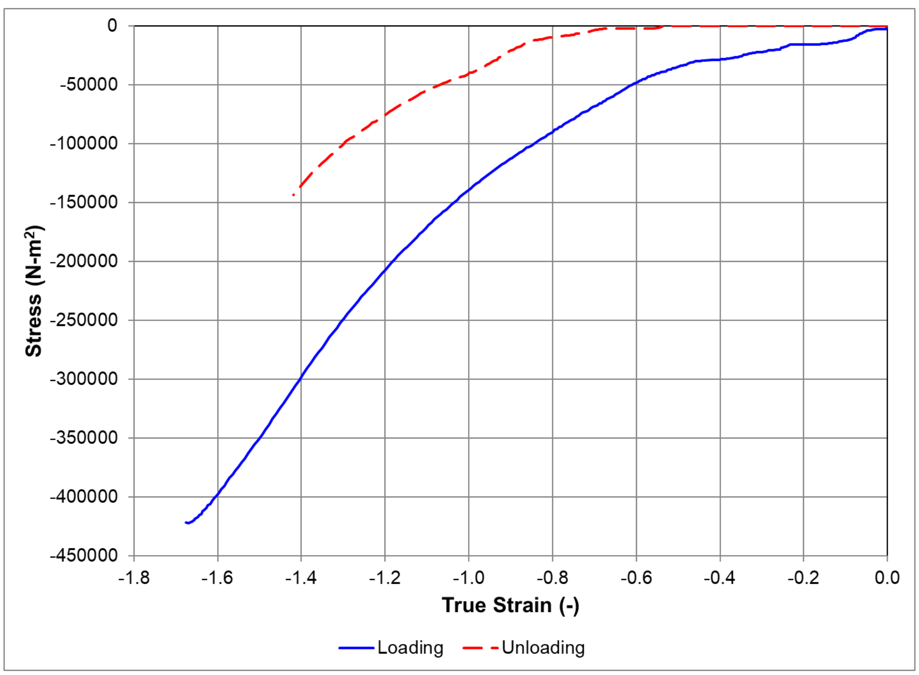

Figure 15: Loading (Blue) and Unloading (Red) True Strain vs Stress for Test M18005

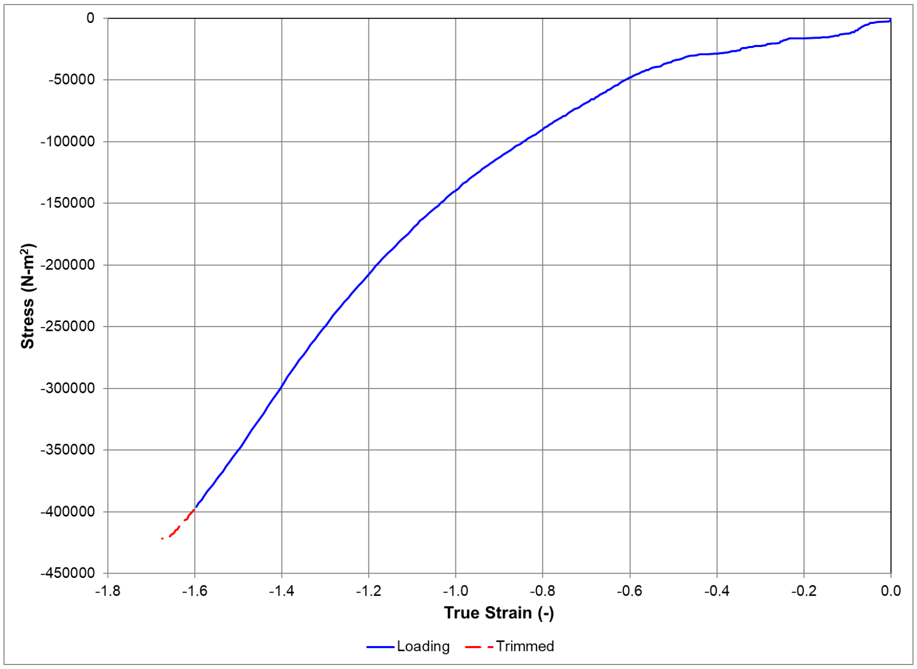

Figure 16: M18005 Loading Curve Showing Trimmed Area (Red)

Model Setup

All models used the base Madymo Hybrid II (d_p57250el) v-ATD. This v-ATD is a standard multibody representation with detail included in the chest and pelvis to better capture belt interactions. Madymo provides a simple application model (e_p572el.xml) for the Hybrid II v-ATD that is the v-ATD in a rigid seat exposed to the 16 g longitudinal pulse. This model is based on the rigid seat configuration defined in SAE International Aviation Recommended Practice (ARP) 5765B (2021). Modifications to the application model were made to more closely match the configuration used for CAMI test A12010 and to replace the multibody cushion with a finite element cushion. The model contains two systems: seat and ATD (Figure 17). The seat system comprised three planes (seat back, seat pan, and floor) and the seat bottom cushion. The default seat back was retained, which is similar in size to the physical seat (25.1” tall by 19.7” wide for the model vs 33” tall by 20” wide for the CAMI seat). In the physical test, a fabric-covered shim was included to properly position the ATD. The shim was represented by a rigid plane in the model, since loading on the seat back is assumed to be minimal in this crash condition. Both the model and the real seat back were oriented with a 13° recline. The wood portion of the seat pan in the rigid seat is 15.75” wide and 16.0” deep, and the seat bottom cushion is 18.0” wide and 19.0” deep (Figure 18). To simplify the model, the finite element seat bottom cushion was defined as 19.0” wide and 19.0” deep. The thickness of the cushion design ranged from 2.5” at the aft edge to 5” in the front. The cushions were approximately 4” thick in the region that was loaded during the sled tests and load frame tests; thus, the FE cushion was simplified to a uniform 4” thickness. This was considered acceptable because the pelvis does not translate during the loading portion of the event (i.e., the pelvis remains in the portion that is approximately 4 inches thick from the onset of the test through the time of peak lumbar load). To avoid instabilities, the seat pan plane (representing both the wood and aluminum pan of the physical seat) was made slightly larger (21.6” deep by 20.9” wide) based on a recommendation by Madymo tech support. Both the seat pan and seat cushion were pitched 5° to match the physical seat configuration. The floor plane was defined using a size large enough that the ATD feet were supported, and the Z-position was set such that the ATD hip point (H-pt) to ankle distance matched the sled test (14.5”). Bracket joints were used to connect the planes to inertial space, allowing for load cells to be defined for each. No lap belt was included because previous work indicated negligible effect in this orientation (Moorcroft, 2014). This assumption was evaluated with the baseline model (M18006), and the addition of a lap belt only changed the peak lumbar load by 0.06%.

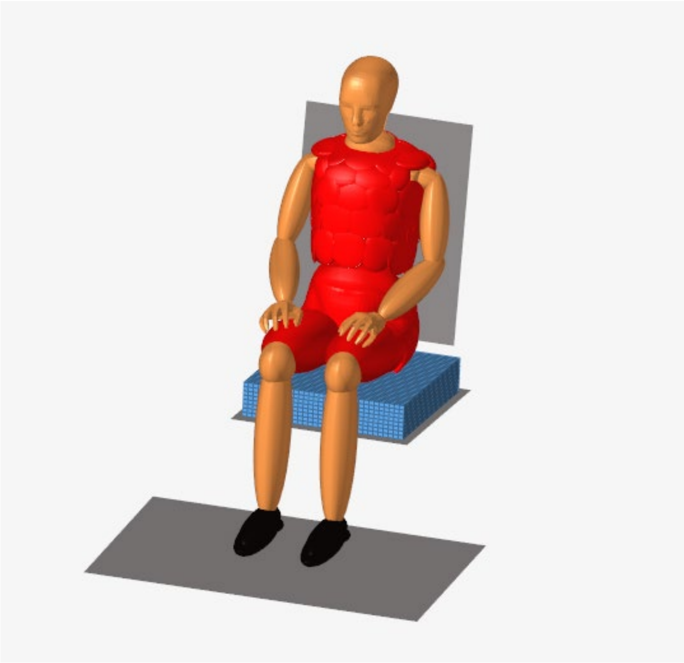

Figure 17: Hybrid II v-ATD in Simplified Seat

Figure 18: Underside of Seat Cushion and Seat Pan

Five contacts were defined:

- Multibody-multibody contact between the seat back (shim) and thorax-pelvis group
    - Contact_force.char using the characteristics of the second surface (thorax-pelvis) and a friction coefficient of 0.3
- Multibody-multibody contact between the floor and v-ATD shoe group
    - Contact_force.char using the characteristics of the second surface (shoe) and a friction coefficient of 0.4
- Multibody-FE contact between the pelvis group and the FE cushion
    - Contact_force.kinematic with a friction coefficient of 0.3
- Multibody-FE contact between the FemurKnee groups (left and right) and the FE cushion
    - Contact_force.kinematic with a friction coefficient of 0.3
- Multibody-FE contact between the seat pan and the FE cushion
    - Contact_force.kinematic with a friction coefficient of 0.5

During model development using a flat seat pan, an initial value of 0.3 was used for the friction coefficient for each contact based on the recommendations in ARP5765B. In these initial simulations, the shoes and seat bottom cushion moved more than what was observed in the overall sled test program. The friction coefficients for those contacts were therefore increased until the simulated motion better matched these general test observations. For the seat bottom cushion-to-seat pan contact, this represents the hook-and-loop connector in the physical setup. The shoe-to-floor friction represents the tread of the shoe. For the other contacts, the friction represents fabric (on the seat bottom cushion and seat back shim) interaction with the ATD clothing. These coefficients should be interpreted as calibrated modeling parameters.

Control Parameters

The simulation was run with repeatability enabled, using 8 processors, and the Euler integration method. Each simulation was run from -0.4 seconds to 0.2 seconds with a time step of $1.0E^{-6}$. For the FE cushion, the time step selection method was set to accurate, and a reduction factor of 0.9 was defined.

Finite Element Cushion

To build the FE cushion, a rectangular block (19”x19”x4”) was created using Altair HyperMesh 2025 (Siemens; Munich, Germany). The solid geometry was meshed with 8-noded hexahedron elements. The final mesh was 32x32x8 elements (Figure 19). This mesh was selected based on the results of a Grid Convergence Study detailed in Appendix B. In Madymo, the cushion used the 8-node solid element (property.solid8) with the advanced strain formulation turned on, along with the full integration method. The foam material property was selected (material.foam) with a damping coefficient of 0.05, data type log (to account for the true strain input), and a density of 49.3 kg/m^3 estimated from the measured cushion assembly weight (2.57 lb = 11.43 N). The characteristic material was defined using the loading and unloading curves from the load frame test (as described in Cushion Data Post-processing section above). A damping coefficient of 0.05 was defined, along with hysteresis model 1 and a hysteresis slope defined by the last data point of the loading and unloading curves (ranging from $5.9E^5$ to $2.0E^6$).

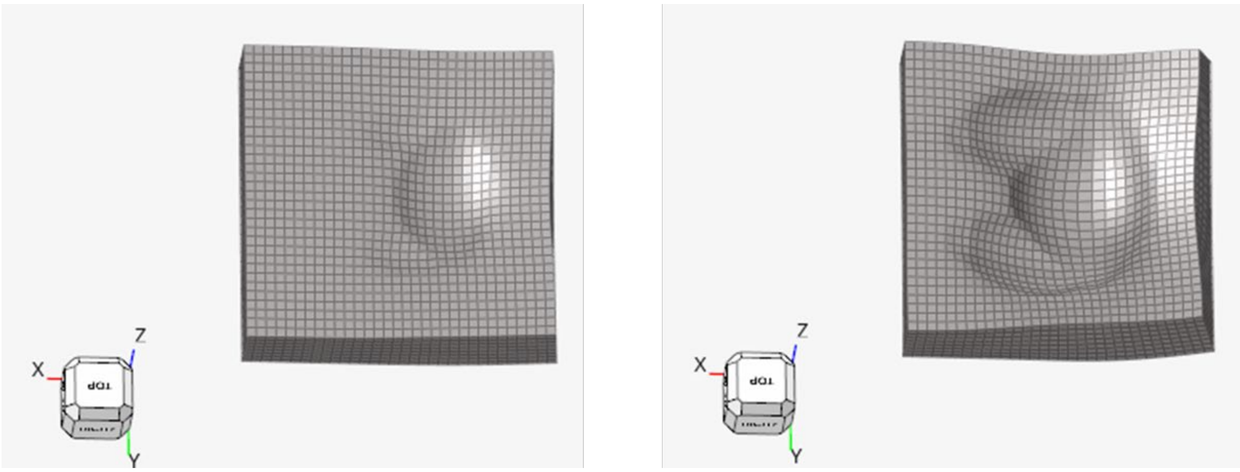

Figure 19: Finite Element Cushion at t=0 (L) and Max Lumbar Load (R) in Simulation S18006

Sled Pulse

In the physical combined longitudinal-vertical sled test, the seat is pitched up 60° and experiences a longitudinal impact. Running this test comprises three phases. The first phase is to determine the "1-g" position of the pelvis with the seat flat (i.e., no pitch). This involves lowering the ATD into the seat (-1 g) while applying approximately 20 lb of force to the chest to push the ATD into the seat back (Moorcroft, 2010). The second phase involves forcing the ATD into the same pelvis position and angle in the pitched seat as measured in the upright seat. The third phase is to run the impact, where the ideal Part 25 pulse is an isosceles triangle with a peak of 14 g and a duration of 0.160 s.

At time zero of the sled test, gravity affects the ATD based on the pitch angle: acceleration in the x-direction (Ax) equals the negative sine of 60° times 1 g, and acceleration in the z-direction (Az) equals the cosine of 60° times 1 g. During the impact, the longitudinal component of the sled pulse, sled(i), is added to the gravitational component, where "i" is the moment in time:

- Ax(i) = sled(i)*cos(60) – sin(60)*1 g
- Az(i) = sled(i)*sin(60) + cos(60)*1 g

For the Madymo simulations, the seat was defined in a flat, upright orientation with the v-ATD placed just above the cushion with no initial penetrations (left pane of Figure 20) and the applied accelerations were rotated to produce the same motion as experienced in the physical tests. The simulations run for this project combined the first and third steps above. Since gravity and the sled pulse can be rotated in the middle of the simulation, the second step is not needed.

During the initial step, gravity was ramped from zero to -9.81 m/s^2 between -0.4 s and -0.3 s and held at that magnitude until time zero. The 20 lb force on the ATD chest was represented by a 2.5 m/s^2 acceleration into the seat[6]. This 0.4 s duration allowed the v-ATD to settle into the cushion and reach its "1-g" position (center pane of Figure 20).

[6] The component of the ATD above the lumbar load cell weighs approximately 75 lb. 2.5 m/s^2 is roughly one-quarter gravity. When applied to the torso, the result is approximately 20 lb.

During the final step, gravity is held at a constant value of -9.81 m/s^{2,} and the ideal pulse is applied with three data points: 0 m/s^2 at time 0, -137.34 m/s^2 (14 g) at time 0.080 s, and 0 m/s^2 at 0.160 s. The simulation was allowed to run until 0.200 s (right pane of Figure 20). These values for the sled pulse and gravity are rotated as described above, yielding the following inputs to the model (Table 1).

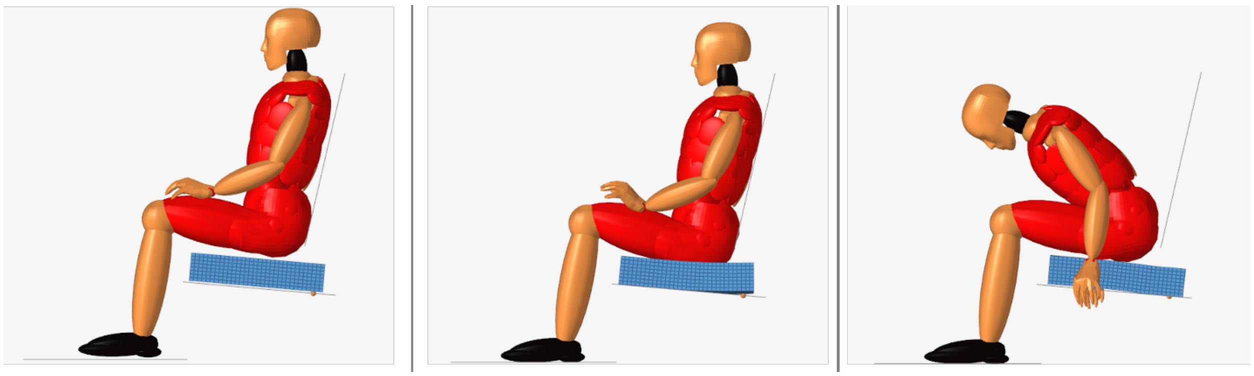

Figure 20: v-ATD at time -0.400 s (L), 0.000 s (C), and 0.200 s (R)

Table 1: Accelerations Applied to the v-ATD

Time (s)	X-direction (m/s^2)	Z-direction (m/s^2)
-0.400	0	0
-0.300	2.5	-9.81
-0.001	2.5	-9.81
0.000	8.496	-4.905
0.080	-60.174	-123.845
0.160	8.496	-4.905
0.200	8.496	-4.905

Model Output

Standard ATD outputs were generated, including: neck, lumbar, femur, and tibia loads and moments; head, thorax, and pelvis accelerations; and joint positions. Seat pan and floor load outputs and FE energy were also included. Multibody outputs were sampled at 10,000 Hz and filtered per SAE J211/1 (SAE International, 2022).

In the physical tests, all sensors were zeroed right before the impact began, i.e., the weight of the ATD is zeroed out of the seat pan load cell response. Because the simulations combined seating and impact into a single event, the simulation results were zeroed in post-processing at time zero. For position data, the physical tests used the seat pan–back intersection. Since the model was simplified, a fixed marker was added to the model with the same relative Z-position of the pan-back intersection to allow for a one-to-one comparison. As a result, the positions outputted by the model were shifted 4.74”.

MODEL CREDIBILITY

The American Society of Mechanical Engineers (ASME) published definitions related to the verification, validation, and uncertainty quantification (VVUQ) of computational models (VVUQ 1). They define credibility as "the trust, established through the collection of evidence, in the predictive capability of a computational model for a context of use" (ASME, 2022). The VVUQ 40 subcommittee published a framework for assessing credibility, denoted as V&V 40 (ASME, 2018)[7]. This framework allows for a structured method to answer the question of how much VVUQ is enough, as the cost must be balanced against the risk (Figure 21). A prior example of applying this approach to an aircraft seat model can be found in Moorcroft (2019).

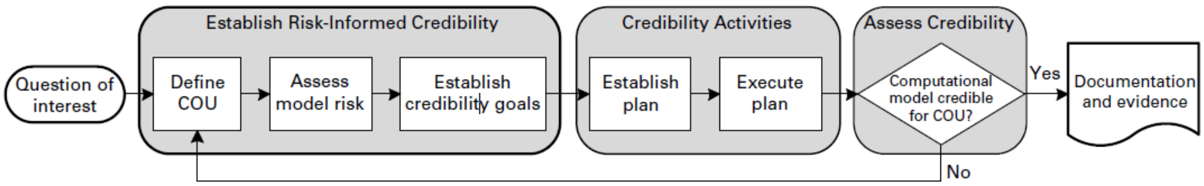

Figure 21: Risk-informed Credibility Assessment Framework (Figure 2.4-1 in ASME, 2018).

Question of Interest: Per VVUQ 1, "the question of interest is the specific question, decision, or concern that is being addressed. The question of interest is not solely focused on the M&S activities, but instead is the overall project goal." For this project, the question of interest is: How much does variability within foam material properties (i.e., sample-to-sample variability) affect lumbar load in a seat certification test?

Context of Use (COU): "The context of use, or context of model use, is the specification of the role and scope of the computational model used to address the question of interest" (ASME, 2022). For this project, the computational model will be used to estimate the change in lumbar load due to variability in foam material properties. The goal is to provide information that allows for a better understanding of certification test results.

Model Risk: Per V&V 40, "model risk is the possibility that the use of the computational model leads to a decision that results in patient harm and/or other undesirable impacts. Model risk is the combination of the influence of the computational model (model influence) and the consequence of an adverse outcome resulting from an incorrect decision (decision consequence)." For this project, the model risk is determined to be low.

Model Influence: Medium – while the results of the modeling will be used without follow-on testing, the model will not be used to directly evaluate seat designs.

Decision Risk: Low – an incorrect decision is unlikely to result in unsafe conditions, considering the numerous other sources of uncertainty in certification testing. This information will not be used exclusively when making any certification decisions.

[7] This section provides an example of the type of information an applicant may want to submit to a decision maker for certification activities. It also includes additional detail on each aspect as this is the first known aviation report to apply this particular methodology.

Credibility Factors: V&V 40 defines 13 credibility factors that support a final determination on whether the model is adequate for answering the question of interest. These factors are grouped under three broad categories: verification (subdivided into code and calculation verification), validation, and applicability. For each credibility factor, V&V 40 provides example gradations of the activities that reflect the rigor of the exercise. Due to the low model risk, lower levels of graduation on the credibility factors are acceptable for this project.

Code Verification

ASME VVUQ 1 defines code verification as "the process of determining that the mathematical models are correctly implemented in the computer code and of identifying errors in the software."

Credibility Factor 1: Software Quality Assurance (SQA) – Medium Credibility

A formal vendor SQA package was not available for review. However, Madymo's maturity, widespread use in transportation safety applications, and stable performance in this study support a medium SQA credibility rating.

Credibility Factor 2: Numerical Code Verification – Medium Credibility

While a formal code verification document is not available, the routine use of Madymo in transportation industries to evaluate occupant safety suggests that the software is capable of providing accurate solutions. The implementation of the foam material properties was evaluated (see Material Model Verification in Appendix B).

Calculation Verification

Calculation verification, also known as solution verification, is, "the process of determining the accuracy of a particular numerical solution relative to an estimate of the exact solution of the computational model" (ASME, 2022).

Credibility Factor 3: Discretization Error – High Credibility

A grid convergence study was conducted on the finite element model of the cushion with an estimated error of 0.02% using the two finest meshes (see Grid Convergence Study in Appendix B). Madymo automatically tracks and adjusts, when necessary, the time step. No subcycles[8] were necessary with the time step that was selected for the model.

Credibility Factor 4: Numerical Solver Error – Low Credibility

No formal solver parameter sensitivity was performed. Solver parameters were documented, and in the case of the integration method for the solid FE elements, "full" was selected due to the presence of high hourglass energies with the "reduced" option. Simulation S18006 was run twice, changing only the filename, to check repeatability. The peak lumbar load was identical (through at least 3 decimal places).

Credibility Factor 5: Use Error – Medium Credibility

Key inputs and outputs were verified by the practitioner.

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[8] Finite element models will sometimes use a smaller time step than the multibody model (referred to as subcycles) to increase efficiency.

Validation

ASME VVUQ 1 defines validation as “the process of determining the degree to which a model represents the empirical data from the perspective of the context of use.”

Credibility Factor 6: Computational Model Form – Low Credibility

The influence of model form assumptions was not explored beyond the use of an FE model versus a multibody model for the seat cushion.

Credibility Factor 7: Computational Model Inputs – Medium Credibility

V&V 40 divides model inputs into quantification of sensitivities and quantification of uncertainties. When quantifying the model sensitivities, we are evaluating how much the model outputs change based on varying model inputs without needing to know the real-world distribution of the inputs. When quantifying the model uncertainties, we use the real-world distributions and propagate those uncertainties through the model. The latter approach is a more rigorous extension of the former. For this project, the uncertainty from the cushion material properties was propagated through the model, but no other model inputs were addressed.

Credibility Factor 8: Comparator Test Samples – Medium Credibility

Comparators, referred to as empirical data in VVUQ 1, provide the data against which simulation results are evaluated (ASME, 2018). For this project, the comparator is data from a sled test of the same cushion. V&V 40 divides comparator test samples into four components: quantity of test samples, range of characteristics of test samples, measurement of test samples, and uncertainty of test sample measurements.

- Quantity of test samples: Medium-low – three samples of the “D” cushion were tested, while only one sample of the “B” cushion was tested.
- Range of characteristics of test samples: Low – both cushions have similar construction and similar force-deflection curves.
- Measurement of test samples: High – all key characteristics of the test samples were measured.
- Uncertainty of test sample measurements: Medium – the load frame displacement and load measurements are highly accurate; however, the sled test data have significant uncertainties that are only estimated.

Credibility Factor 9: Comparator Test Conditions – Medium Credibility

V&V 40 divides test conditions into four components: quantity of test conditions, range of test conditions, measurement of test conditions, and uncertainty of test condition measurements.

- Quantity of test conditions: Medium – the cushions were tested at a single sled pulse, but that pulse is the certification required pulse test. As long as the results are not extrapolated too far, the limited test conditions are acceptable.
- Range of test conditions: Not applicable – this factor examines whether a range of test conditions, from nominal to extreme, is evaluated. As the question of interest relates only to certification conditions, this factor is considered not applicable.

- Measurement of test conditions: High – all key characteristics of the test conditions were measured.
- Uncertainty of test condition measurements: Medium-low – uncertainty on the sled test results is estimated based on past experience (see DeWeese et al., 2021).

Credibility Factor 10: Equivalency of Input Parameters – High Credibility

The types and ranges of all parameters of the computational model and those of the comparator were equivalent. The computational model outputs the same sensor data as the physical sled test, including the locations of the sensors.

Credibility Factor 11: Output Comparison – Medium Credibility

This credibility factor evaluates the similarity of the output types between the computational model and the comparator. V&V 40 divides output comparison into four components: quantity, equivalency of output parameters, rigor of output comparison, and agreement of output comparison.

- Quantity: High – Multiple outputs were compared.
- Equivalency of output parameters: High – the outputs were equivalent.
- Rigor of output comparison: Medium – deterministic validation metrics were used to compare the outputs.
- Agreement of output comparison: Medium Credibility - the model was compared to a representative sled test across five channels. The simulation peak lumbar load was 13.5% higher than the test peak, with a shape error of 10.5%[9]. Both error values were within the predefined acceptance criteria. Additional details are found in the Model Validation section of Appendix B.

Applicability

ASME VVUQ 1 defines applicability as, “the relevance of the evidence from the verification, validation, and uncertainty quantification activities to support the use of the computational model for a context of use.”

Credibility Factor 12: Relevance of the quantities of interest (QOI) – High Credibility

The QOIs from the validation activities were identical to those for the COU.

Credibility Factor 13: Relevance of the validation activities to the COU – High Credibility

Since the validation test has the same boundary and initial conditions, including the sled pulse, as the certification test that is of interest for the COU, the relevance of the validation activities is high.

Credibility Assessment

The V&V 40 credibility framework provides a systematic method to guide the determination of whether a model is sufficiently credible for use in answering the question of interest. Once the model risk is defined, minimum levels of credibility can be assigned for each credibility factor,

[9] Both calculations were based on the methodology defined in AC 20-146A and SAE ARP5765B.

although engineering judgment is still recommended when evaluating whether the model is adequate. Current FAA seat certification requires a specific, idealized laboratory test. The computer models used to support seat certification can exactly replicate those test conditions, which allows for several credibility factors to be at the highest level (e.g., input parameters, output comparison type, relevance of QOI, and relevance of validation). For this model, the code verification credibility is medium, the calculation verification is a mix of low, medium, and high, and the applicability credibility is high (Table 2). For validation credibility, there was also a range of low to high factors. Most importantly, the primary channels were within the pre-defined accuracy requirements. Considering the risk and the achieved graduations on the credibility factors, the model is considered adequate for answering the question of interest.

Table 2: Achieved Credibility

Main Activity	Sub-Activity	Credibility Factor	Minimum Required Credibility	Achieved Credibility
Verification	Code	SQA	Medium	Medium
Verification	Code	Numerical Code Verification	Medium	Medium
Verification	Calculation	Discretization Error	Medium	High
Verification	Calculation	Numerical Solver Error	Low	Low
Verification	Calculation	Use Error	Low	Medium
Validation	Computational Model	Model Form	Low	Low
Validation	Computational Model	Model Input	Low	Medium
Validation	Comparator	Test Samples	Low	Medium
Validation	Comparator	Test Conditions	Low	Medium
Validation	Assessment	Equivalency of Input Parameters	High	High
Validation	Assessment	Output Comparison	Low	Medium
Applicability	N/A	Relevance of QOI	High	High
Applicability	N/A	Relevance of Validation Activities to COU	High	High

SIMULATION RESULTS

Eleven of the load frame results were simulated to allow for a comparison of the effect of cushion sample-to-sample variability on sled test lumbar load variability. For the eleven simulations, the only changes to the model were the cushion loading curve, unloading curve, and hysteresis slope. All other parameters used in the validation model were unchanged. The lumbar load at time zero ranged from 60.6 lb to 68.3 lb and was zeroed out. Table 3 contains the peak lumbar load for the 11 simulations.

Table 3: Simulation Matrix and Results

Simulation ID[10]	Reference Cushion	Reference Sequence	Reference MTS Data	Lumbar Load (lb)
S18005	D6	Test 5	M18005	1693.1
S18006	D6	Test 6	M18006	1697.8
S18008	D4	Test 1	M18008	1579.0
S18009	D4	Test 2	M18009	1668.4
S18012	D2	Test 1	M18012	1584.5
S18013	D2	Test 2	M18013	1655.2
S18016	D5	Test 1	M18016	1593.1
S18017	D5	Test 2[11]	M18017	1656.1
S18020	D5	Test 5	M18020	1661.4
S18021	B4	Test 1	M18021	1449.7
S18022	B4	Test 2	M18022	1533.5

Minimal stiffness difference across the full loading range

To evaluate how a small difference in the cushion's force-deflection curve affects the lumbar load, simulations S18005 and S18006 were compared (Figure 22), as the force-deflection data had substantial congruence (shape error of 4.2%[12], hereafter referred to as stiffness). The difference in peak lumbar load was 0.3%[13].

[10] This project used a naming convention for the simulations that is different than the typical CAMI methodology mentioned in footnote 2. To avoid confusion, the simulation ID matched the load frame test ID instead of denoting when the simulation was completed.

[11] A test was run in between M18016 and M18017, however the data acquisition did not trigger.

[12] The difference in the load frame force-deflection curve was estimated based on the loading portion of the curve. Since the Sprague and Geers comprehensive error referenced in the Model Validation section of the Appendix requires a consistent x-value, each curve was approximated by a 6th order polynomial (r^2>0.999) and expressed in 0.1" increments from 0" to 3.3".

[13] Using relative error biased towards the first referenced simulation (e.g. |S18005 – S18006| / S18005).

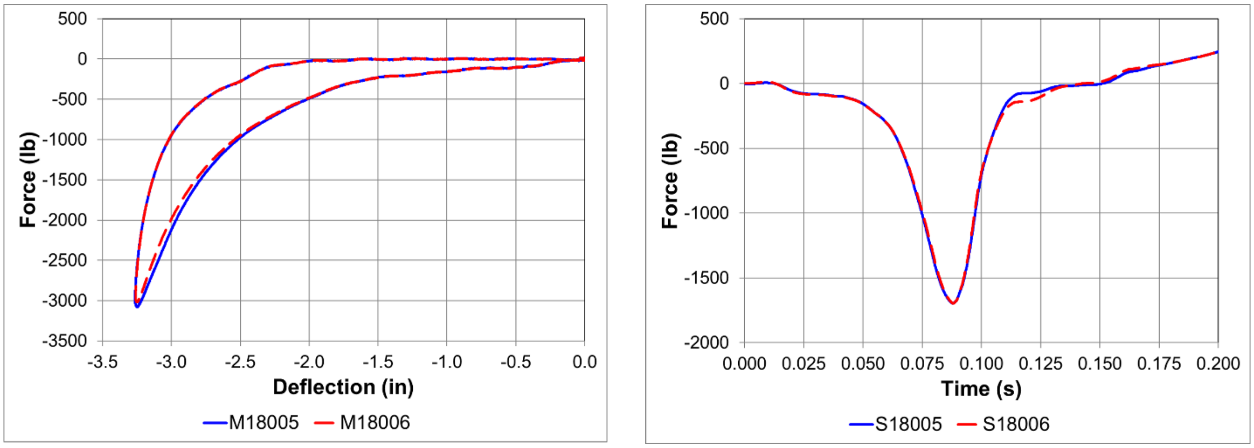

Figure 22: Load Frame (L) vs Simulation Lumbar Load (R) for Cushion D6

Large stiffness difference across the full loading range

The impact of a relatively large loading curve variance on lumbar load was estimated by comparing S18008 and S18009, which used MTS data from cushion D4 (Figure 23). The difference in stiffness is 11.7%. The difference in peak lumbar load was 5.4%.

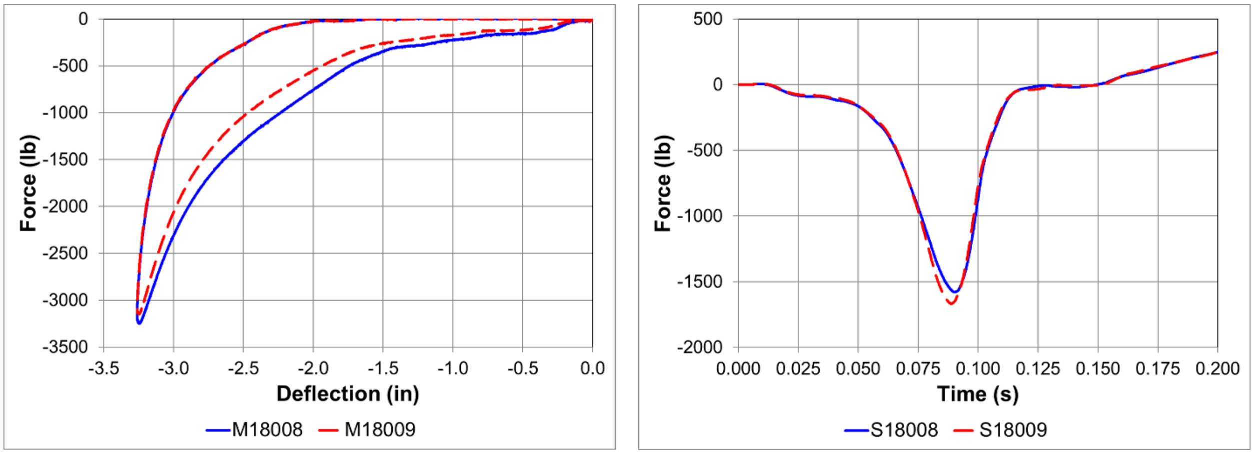

Figure 23: Load Frame (L) vs Simulation Lumbar Load (R) for Cushion D4

Similarly, the first test (M18012) and second test (M18013) for cushion D2 also included a large stiffness difference throughout (11.3%). The difference in peak lumbar load from simulations S18012 and S18013 was 4.3% (Figure 24).

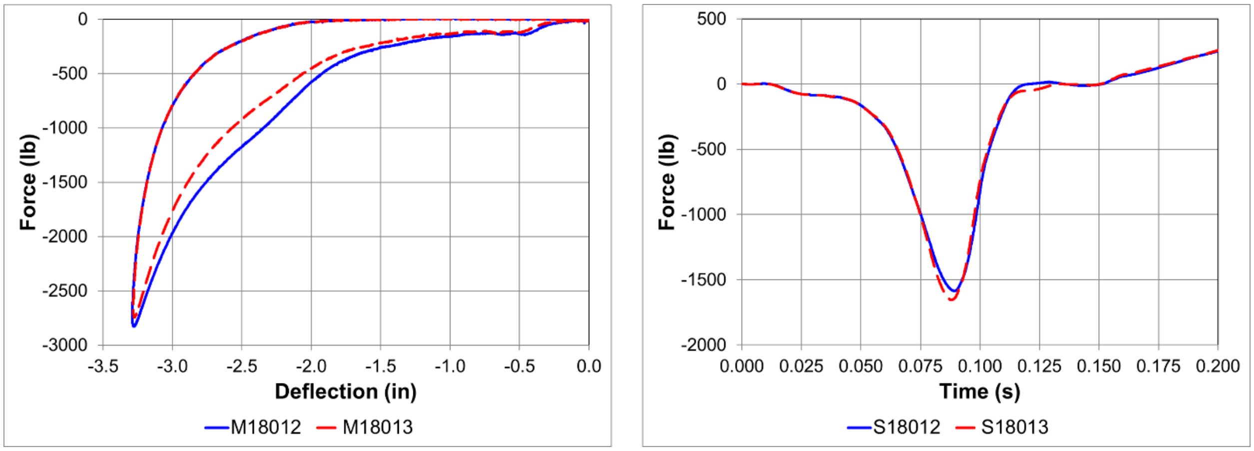

Figure 24: Load Frame (L) vs Simulation Lumbar Load (R) for Cushion D2

Large stiffness difference and difference in peak load

The first test of cushion D5 (M18016) and the fifth test (M18020) showed both a large stiffness difference (Figure 25) and a large difference in the achieved peak during the load frame test (3266 lb vs 2600 lb). The difference between the loading curve from M18016 and M18020 was 22.9%. The corresponding simulations differed in predicted peak lumbar load by 4.1%.

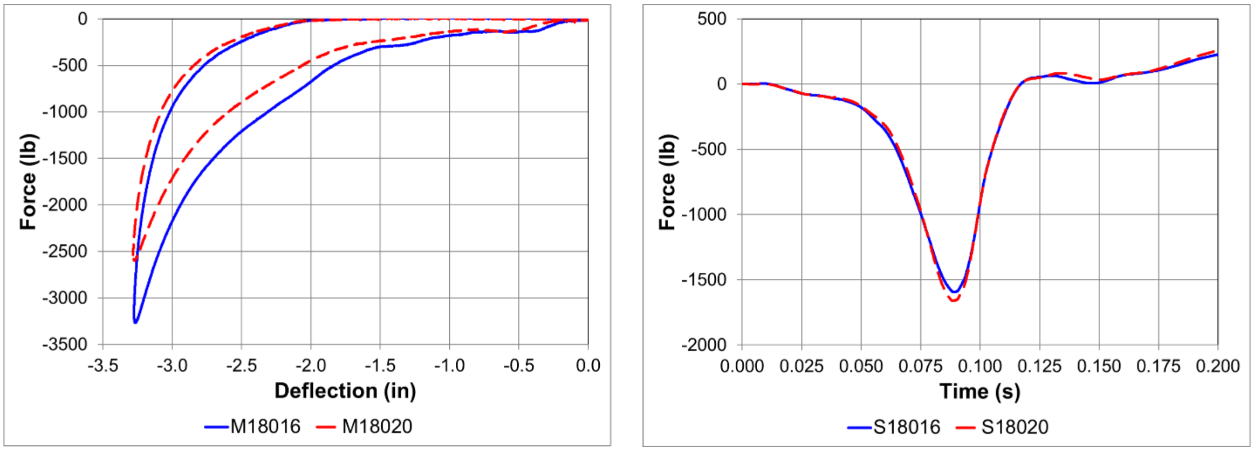

Figure 25: Load Frame (L) vs Simulation Lumbar Load (R) for Cushion D5

Stiffness difference only in the middle of the loading range

For cushion B4, the first (M18021) and second (M18022) tests overlay initially and at the end but show a stiffness difference in the middle of the curve from true strain of -1.5 through -3 (Figure 26). The difference in stiffness is 7.9%. The difference in peak lumbar loads for the simulations (S18021 and S18022) was 5.5%.

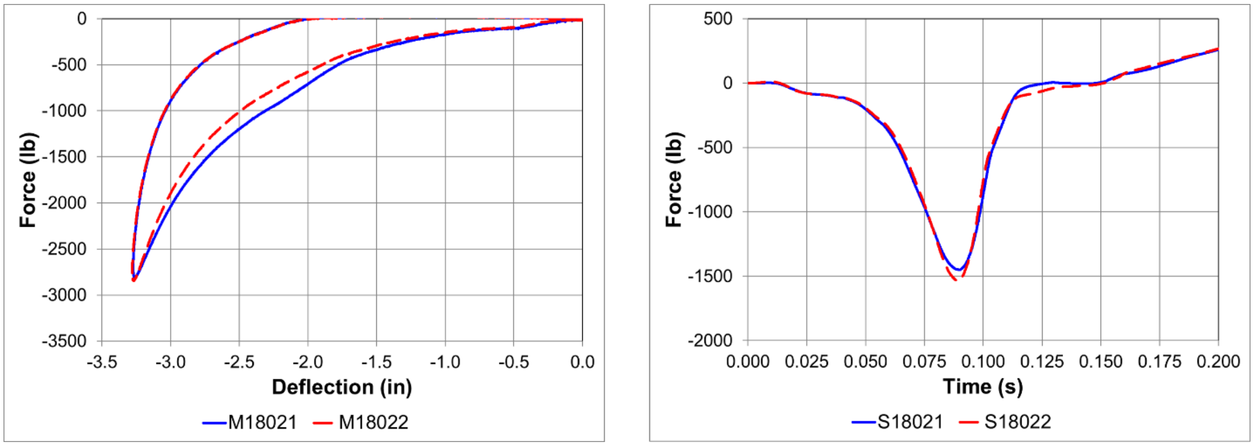

Figure 26: Load Frame (L) vs Simulation Lumbar Load (R) for Cushion B4

"D" Cushion

The second recorded test to the target load for all four "D" cushions was evaluated (Figure 27). The difference between the stiffest force-deflection curve (M18009) and the softest force-deflection curve (M18017) was 13.6%. The peak lumbar loads were 1697.8 lb (S18006), 1668.4 lb (S18009), 1655.2 lb (S18013), and 1656.1 lb (S18017). This resulted in a max difference of 2.5%.

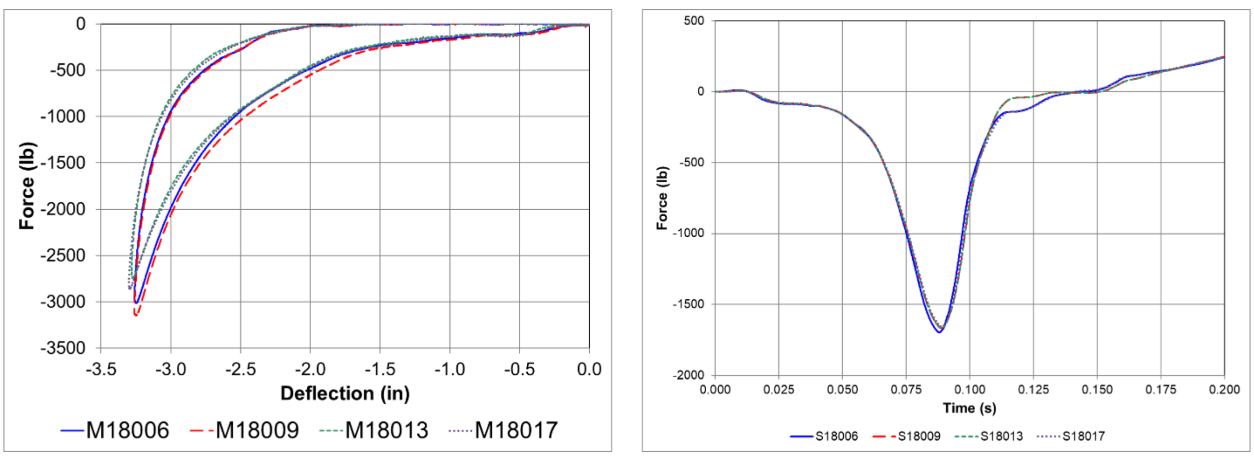

Figure 27: Load Frame (L) vs Simulation Lumbar Load (R) for "D" Cushion Cross Plot

Cushion D5 vs B4

The second test on cushion D5 was compared to the second test on cushion B4 (Figure 28). The two curves are very similar (shape error of 6.0%), although there is an important difference around 130 lb (Figure 29), which is the approximate weight of the ATD loaded into the seat during the "1-g" seating. In the physical tests, there was a 0.15" difference between the initial H-pt Z-position, which resulted in a peak lumbar load difference of 21%. For the simulations, using the second test for each (M18017 and M18022), the difference in peak lumbar load was only 7.4%. The difference in H-pt height at "1-g" was only 0.06".

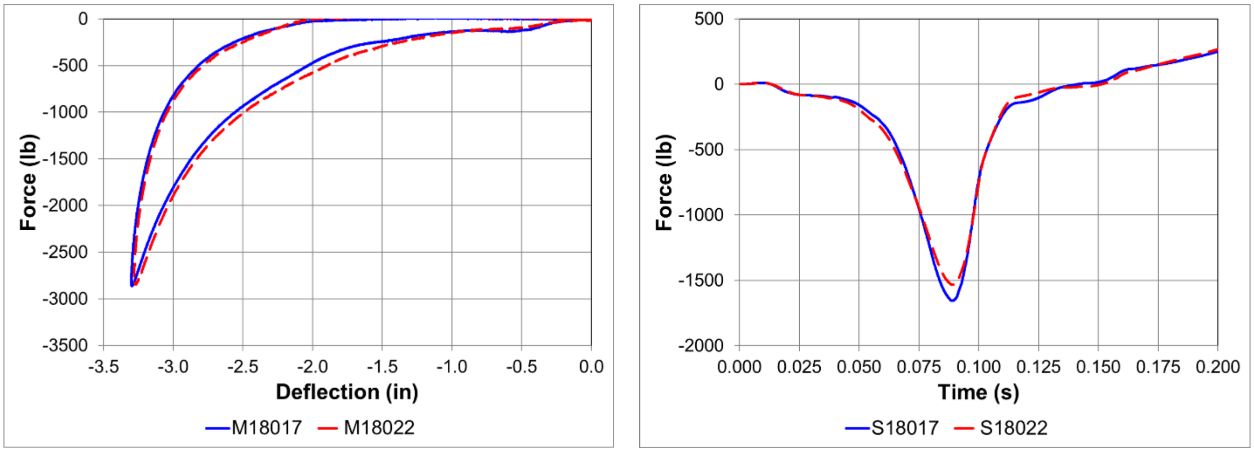

Figure 28: Load Frame (L) vs Simulation Lumbar Load (R) for Cushions D5 and B4

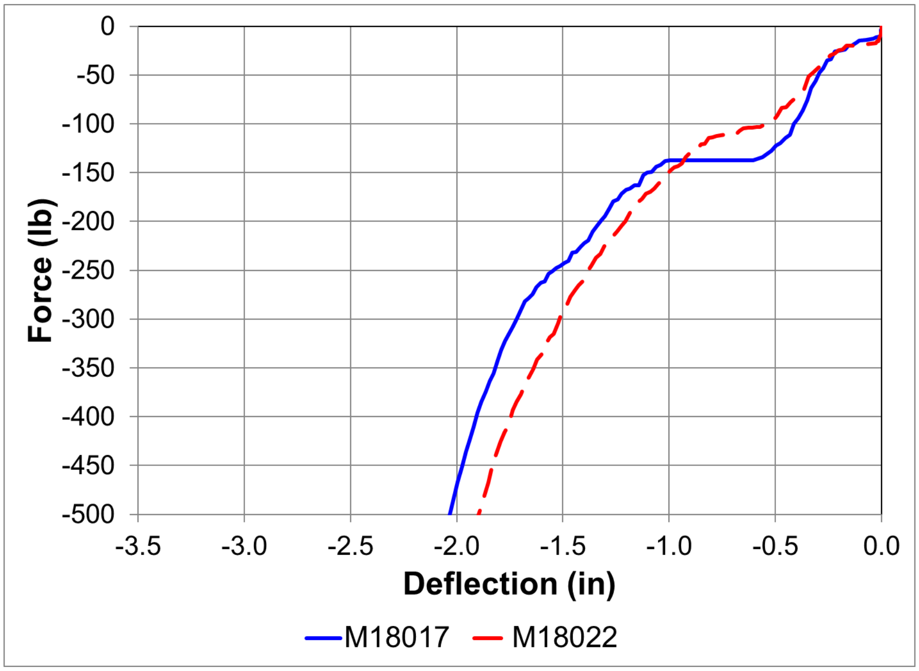

Figure 29: Closeup of Load Frame Results for D5 and B4

DISCUSSION

Previous testing found significant variability in peak lumbar load for the combined longitudinal-vertical configuration, even in tests using identical cushion samples (DeWeese et al., 2021). Test uncertainty included variability from the test methodology, presence or absence of a dress cover, ATD initial position, interaction with armrests, test article configuration (supported vs. cantilevered), and differences from the use of different ATDs of the same type. The goal of this project was to use a simplified model to observe the impact of sample-to-sample variability on predicted lumbar load. This was evaluated with three types of comparisons intra-sample, inter-cushion, and cushion-to-cushion.

Intra-sample Variability

Individual samples were repeatedly tested in the MTS load frame, allowing for the resulting force-deflection curves to be used in the model to estimate the amount of variability that may be due to intra-sample effects (Table 4). For cushion D4, the first MTS test (M18008) was compared to the second MTS test (M18009), resulting in a relative difference in lumbar load of 5.4% (relative error biased towards the highest load). For cushion D5, the first MTS test (M18016) was compared to the fifth MTS test (M18020), resulting in a relative difference of 4.1% (also biased towards the highest load). Similar comparisons were made between the first and second tests on cushions D6, D2, and B4, yielding relative errors of 0.3%, 4.3%, and 5.5%, respectively. These values are on the low end of similar comparisons of sled test data. For example, DeWeese (2021) included multiple comparisons of intra-sample variability (labeled as Test Uncertainty Due to the Test Method), with their Table 4 showing a 4.9% difference, Table 5 showing a 17.6% difference, and Table 6 showing between a 6% and 10% difference in observed lumbar load.

Table 4: Intra-sample Variability

Cushion	Simulation 1 Lumbar Load (lb)	Simulation 2 Lumbar Load (lb)	Relative Error (%)
D4	1579.0	1668.4	5.4
D5	1593.1	1661.4	4.1
D6	1693.1	1697.8	0.3
D2	1584.5	1655.2	4.3
B4	1449.7	1533.5	5.5

For the cushions tested in this project, the largest measured difference in force-deflection stiffness was 23% for the D5 sample (component tests M18016 and M18020). Propagating that difference through the model yielded only a 4.1% difference in predicted lumbar load from the corresponding simulations. If the simulations are accurate, this result suggests that the overall system (e.g., ATD in a dynamic sled test) attenuates the force-deflection difference, at least when measured by peak lumbar load. Consequently, a limited number of component tests may be sufficient to generate representative force-deflection data.

Inter-cushion Variability

Three samples of the D cushion were tested on the sled, allowing for a comparison of the sample-to-sample effects within a single cushion buildup (Table 5). Cushions D4, D5, and D6 were each tested on the sled, yielding a relative error of 7.4% when comparing the highest normalized lumbar peak (1707.7 lb for test A12008) and the lowest normalized lumbar peak (1581.3 lb for test A12010), and biased towards the higher load. For the simulations using the second recorded load frame test to the target load (i.e., M18009, M18017, and M18006), the relative error was only 2.5%, despite the 13.6% difference in force-deflection stiffness. Similar to the intra-sample variability, if the simulations are accurate, this data suggests that a limited number of samples may be sufficient to generate representative force-deflection data.

Table 5: Inter-cushion Variability

Test type	Cushion D4 Lumbar Load (lb)	Cushion D5 Lumbar Load (lb)	Cushion D6 Lumbar Load (lb)	Relative Error (%)
Sled	1594.1	1707.7	1581.3	7.4
Simulation	1668.4	1656.1	1697.8	2.5

Cushion-to-cushion Differences

To evaluate cushion-to-cushion variability, cushion D5 was compared to cushion B4 (Table 6). D5 was selected since it had the largest difference in peak lumbar load compared to the B4 cushion. The sled results showed a 21.2% difference, while the simulations only showed a 7.4% difference.

Table 6: Cushion-to-cushion Variability

Cushion	Cushion D5 Lumbar Load (lb)	Cushion B4 Lumbar Load (lb)	Relative Error (%)
Sled	1707.7	1345.5	21.2
Sim	1656.1	1533.5	7.4

Model Accuracy

The accuracy of the simulations can be inferred by two methods. Firstly, the validation exercises showed that the model overpredicts peak lumbar load by approximately 10%-15% for the conditions evaluated. The v-ATD evaluation resulted in an overprediction of about 10%, while the system validation evaluation resulted in the model overpredicting the lumbar load by 13.5% despite the pan force only overpredicting by 1.6%. However, several of the support channels showed larger errors in the system level evaluation. The similarity in the overpredictions between the simulations with no cushion and those with a cushion suggests that the underlying v-ATD model may be the cause of the deviation, although considering the large scatter that exists in sled testing, it is not conclusive that the model has 15% error (i.e., all that can be said is that the model differed from the single test data point by 10%-15%).

The second inference for model accuracy can be made by looking at the inter-sample and cushion-to-cushion variability. Multiple tests and simulations included the “D” cushion buildup. The relative error within the three simulations was about one-third that of the sled tests (2.5% vs 7.4%). For the cushion-to-cushion variability, the simulation deviation was again about one-third that of the test data (7.4% vs 21.2%). These results suggest that either the model is not sensitive enough to the force-deflection changes or there is more scatter in the physical tests than just the cushion properties. The pelvic motion data from the system validation exercise suggests the first explanation (i.e., not sensitive enough), while the large test scatter previously reported suggests the latter explanation.

LIMITATIONS

This study has several limitations. First, the computational model was intentionally simplified and used an idealized seat and cushion geometry. Second, only a limited number of cushion samples and two cushion designs were evaluated. Third, some model parameters and implementation details, including contact friction values and material-curve conditioning steps, were selected to obtain realistic motion and stable simulations rather than being measured independently. Fourth, model validation was performed against a single representative sled-test condition rather than across the full range of cushion responses studied. Fifth, the cushion samples were several years old prior to the load frame testing. Accordingly, the model is best interpreted as a tool for comparative sensitivity analysis within the studied configuration, not as a general predictor of lumbar load for arbitrary seat cushion designs or crash conditions.

CONCLUSION

The Federal Aviation Administration (FAA) requires that aircraft seating systems protect occupants in the event of an emergency landing. During the combined longitudinal-vertical impact, the seat bottom cushion significantly affects the loads transferred to the occupant's spine, and therefore the risk of injury. Previous testing revealed test-to-test lumbar load variability as high as 21%, which was hypothesized to arise in part from variation within foam material properties. In this study, a high-rate load frame was used to measure cushion force-deflection behavior, and those data were then used as inputs to a computational model to estimate the effect of cushion-property variability on predicted lumbar load. 13 credibility factors were used to support a determination that the model was adequate for answering the question of interest. The model was compared to a representative sled test across five channels. The simulation peak lumbar load was 13.5% higher than the test peak, with a shape error of 10.5%. Both error values were within the predefined acceptance criteria.

The high-rate load frame testing produced consistent results, with all samples exhibiting the same trend – the first load frame test was notably stiffer than subsequent tests. This trend held for a fresh cushion as well as cushions that were previously exposed to a dynamic sled test. The trend also held for load frame tests separated by 5 minutes and those separated by more than 24 hours. The largest observed difference in stiffness on the loading portion of the force-deflection curve was 23%.

The load frame-derived material properties were used in a simplified model of the seat cushion, along with the Madymo Hybrid II virtual Anthropomorphic Test Device, to predict the amount of lumbar load variation due solely to the cushion variability.

- The difference in predicted lumbar load due to intra-sample variability (i.e., simulating two force deflection curves for the same cushion sample) was as high as 5.5% for the 5 samples evaluated. Previous comparisons of sled tests observed differences between 4.9% and 17.6% for tests of the same cushion sample.

- The difference in predicted lumbar load due to inter-sample variability (i.e., simulating the force-deflection curves for multiple samples of the same cushion design) was 2.5% for three samples of the D cushions. In the corresponding sled tests, the observed difference was 7.4%.

A previous study identified multiple sources of test uncertainty in the combined longitudinal-vertical impact, such as test methodology, ATD positioning, seat configuration, and use of different test dummies, that resulted in significant variation in repeated testing. The findings of this report suggest that test uncertainty due solely to variation in measured cushion material properties is on the order of 5% and is lower than that from other sources of uncertainty in full-scale sled tests. This trend held for both intra-sample comparisons and inter-sample comparisons. The results of this research also suggest that a limited number of material characterization tests may be sufficient to produce data for numerical simulations of aircraft seat cushions.

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Appendix A: Load Frame Test Matrices

Tables 7-11 contain the test number, test date, start time, amount of rest between tests, prescribed maximum stroke, and achieved preload for the high-speed load frame tests.

Table 7: Cushion D6 Test Matrix

Test Number	Test Date	Test Start Time	Rest (min)	Max Stroke (in)	Pre-load (lb)
M18001	July 9, 2018	1546	N/A	2.75	~10
M18002	July 9, 2018	1600	14	2.9	~10
M18003	July 9, 2018	1615	15	2.9	~10
M18004	July 9, 2018	1620	5	3.1	~10
M18005	July 9, 2018	1625	5	3.3	~10
M18006	July 9, 2018	1635	10	3.3	~10
M18007	July 9, 2018	1645	10	3.3	~10

Table 8: Cushion D4 Test Matrix

Test Number	Test Date	Test Start Time	Rest (min)	Max Stroke (in)	Pre-load (lb)
M18008	July 9, 2018	1708	N/A	3.3	5-6
M18009	July 9, 2018	1720	12	3.3	5-6
M18010	July 9, 2018	1735	15	3.3	5-6
M18011	July 9, 2018	1745	10	3.3	5-6

Table 9: Cushion D2 Test Matrix

Test Number	Test Date	Test Start Time	Rest (min)	Max Stroke (in)	Pre-load (lb)
M18012	July 10, 2018	1107	N/A	3.3	~3
M18013	July 10, 2018	1122	15	3.3	~3
M18014	July 10, 2018	1137	15	3.3	~3
M18015	July 10, 2018	1152	15	3.3	~3

Table 10: Cushion D5 Test Matrix

Test Number	Test Date	Test Start Time	Rest (hr)	Max Stroke (in)	Pre-load (lb)
M18016	July 10, 2018	1700	N/A	3.3	7
Null*	July 11, 2018	1700	24.0	No data	No data
M18017	July 12, 2018	1730	24.5	3.3	6
M18018	July 13, 2018	1730	24.0	3.3	4
M18019	July 16, 2018	0935	64.08	3.3	6
M18020	July 17, 2018	1120	25.75	3.3	5

* During the test run at 1700 on July 11, 2018, the data acquisition system failed to record.

Table 11: Cushion B4 Test Matrix

Test Number	Test Date	Test Start Time	Rest (min)	Max Stroke (in)	Pre-load (lb)
M18021	July 17, 2018	1550	N/A	3.3	10
M18022	July 17, 2018	1605	15	3.3	7
M18023	July 17, 2018	1620	15	3.3	0
M18024	July 17, 2018	1635	15	3.3	5

Appendix B: Model Verification and Validation

Material Model Verification

As a part of credibility factor 2 (numerical code verification), the implementation of the foam material model was evaluated. A typical method of evaluating the correctness of the mathematical implementation of a material model is to evaluate a single element that has a known solution. It is useful to note that this type of verification exercise only evaluates mathematical correctness. Evaluating physical correctness (i.e., does the model accurately represent the physical world) is left to the validation exercises. The foam model (property, material, and characteristics) was applied to a single element (3.15" x 3.15" x 3.15", density of 49.3 kg/m^3) that was compressed between two rigid planes of a size sufficient to eliminate edge effects using prescribed motion (Figure 30). The bottom plane was fixed, and the top plane moved downward such that 75% compression (1.39 true strain) was reached at 0.15 s. Only a loading curve was defined for the foam material, using a linear simplification of the cushion loading curve (0.0, 0.0; -1.4, -400000 N/m^2). Kinematic MB_FE contact was defined between the planes and the element, including a friction coefficient of 0.3. The simulation output matched the material input, demonstrating that the solver is correctly calculating the model response.

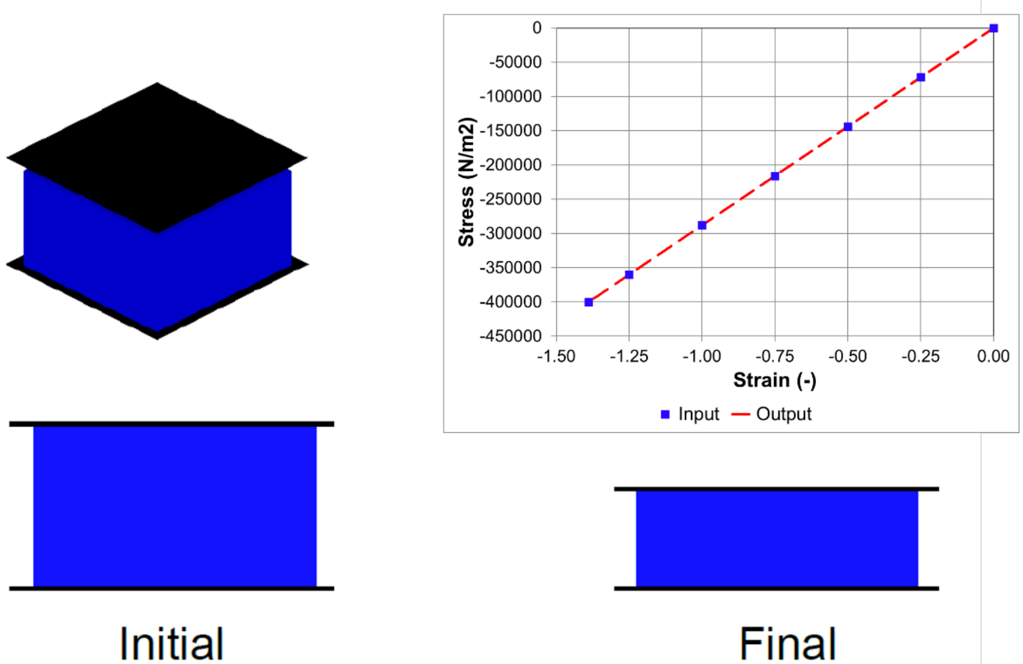

Figure 30: Material Model Verification

Grid Convergence Study

In support of credibility factor 3 (discretization error), a grid convergence study was conducted on the finite element model of the cushion. Discretization error was estimated using the baseline model (S18006) with four meshes employing element doubling, starting with an 8x8x2 element mesh and concluding with a 64x64x16 element mesh (Figure 31, Table 12). Relative errors were calculated for pairs of meshes biased towards the finer mesh. The error between the coarsest mesh (8x8x2) and the next mesh (16x16x4) was 7.77% [(1797.2-1657.5)/1797.2]. The next pair (16x16x4 vs 32x32x8) had a relative error of 0.20%, while the final pair had a relative error of 0.02%, suggesting that the solution is in the asymptotic region. Based on these results, the 32x32x8 element mesh was selected for the final model as it provided the best tradeoff between accuracy and computational run-time[14]. While it is possible that the optimal mesh could change with different material properties (i.e., in the other simulations), the similarity between the loading and unloading curves in this project suggests that risk is low.

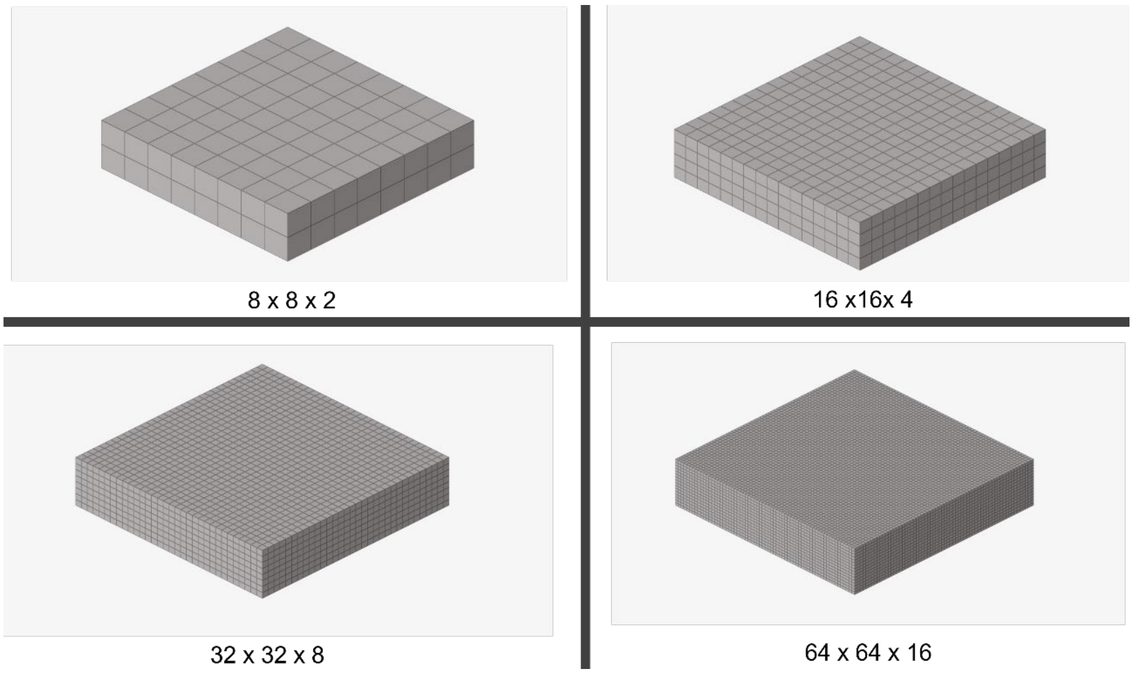

Figure 31: Meshes for Grid Convergence Study

Table 12: Numerical Solutions for Lumbar Load

Grid	Element Length on Contact Surface (in)	Lumbar Load (lb)	Relative Error (%)	Total CPU Time
8x8x2	2.36	1657.5	N/A	2 hr 36 min
16x16x4	1.18	1797.2	7.77	2 hr 39 min
32x32x8	0.59	1793.6	0.20	8 hr 17 min
64x64x16	0.295	1794.0	0.02	40 hr 57 min

Model Validation

As a part of the validation exercise, credibility factor 11 (output comparison) contains a subgroup for evaluating the level of agreement of the output comparison (i.e., how closely the simulation results match the physical data). ARP5765B (2021) provides general validation guidance for aircraft seat systems. The ARP defines three classes of channels: primary, support, and

[14] Running these simulations with 8 cores provided nearly linear thread scaling, as the elapsed time to run was nearly one-eighth the CPU time, for instance the 32x32x8 sim took 1 hour, 6 minutes, and 9 seconds.

threshold. Primary channels are those considered critical in evaluating the system. Support channels are less important but provide additional confidence that the model properly represents the physical response of the system. Threshold channels are those expected to be low, where it is only useful to check that the model response isn't grossly different than the test data. For the combined horizontal-vertical test configuration, the ARP recommends evaluating the following channels:

- Primary channels: lumbar Fz, floor reaction Fz
- Support channels: occupant trajectory, lumbar My
- Threshold channels: belt force

Since the original sled tests used a rigid seat, there were no floor reaction load cells. Additionally, those sled tests did not include a floor load cell. Because of this, the Z-component of the seat pan load was used instead. For occupant trajectory, the H-pt target is not visible during the sled test, but an auxiliary target was tracked. The initial position of the H-pt target was also recorded. No belt was included in the model, so no threshold evaluation was completed.

FAA Advisory Circular (AC) 20-146A (2024) and ARP5765B define the same methodology for comparing simulation results to test data. For position data, the peak is a simple difference: |Test – Sim|. For instrumentation data, the peak is compared using a relative error biased towards the test data: |Test – Sim| / Test. For both data types, the shape error is evaluated using the Sprague and Geers comprehensive error. That error is calculated using a series of integrals, which are approximated in a spreadsheet program using the trapezoidal method.

AC 20-146A provides default recommendations for the accuracy of critical channels. For the lumbar load, 10% is recommended for both the peak and shape. However, the AC notes that different levels of correlation may be agreed upon prior to the initiation of a program. Based on the risk defined for this project (low), the correlation levels for this project were set at 15% for primary channels for both peak and shape. For support channels, 30% was set as the requirement for load. The AC does not provide recommended accuracy requirements for occupant trajectory. In the v-ATD calibration section, the ARP lists a peak error of 0.1" for the Z-component of H-pt position with a 15% shape error and a 3° peak error and 20% shape error for pelvic angle. Since the v-ATD calibration is a tightly controlled test, it is reasonable to allow a greater discrepancy in the system validation. As such, 0.25" and 6° are defined for the peak error and 25% for shape error. Lastly, as noted in AC 20-146A:

> Failure to satisfy all validation criteria does not automatically preclude the model from being validated. The applicant and the certification branch engineer should evaluate whether the deviations impact the ability of the model to predict credible results and determine if deviations from the validation criteria are acceptable (FAA, 2024, section 8.4.1).

v-ATD Evaluation

The v-ATD subsystem was evaluated on a rigid seat without a seat bottom cushion, as recommended by ARP5765B, using the provided application model for the Hybrid II v-ATD (e_p572el.xml). This seat has a flat seat pan, as opposed to the 5° pan specified in ARP5765B. The provided model was modified to apply the ideal 14 g sled pulse, adjust the floor to match the

H-pt to ankle distance used in CAMI testing, and adjust the v-ATD limb positioning. The model parameters were the same as the baseline model defined above, except that the contact between the pelvis and the seat bottom is a multibody-multibody contact using the characteristics of the pelvis (kinematic contact type is not permitted for this contact type). The comparator, CAMI test A04072, is a nominal 14 g test with no seat bottom cushion and a 5° seat pan. The normalized peak lumbar load was 942 lb. Friction between the ATD, clothed in cotton shorts, and aluminum seat pan was not measured for the 2004 test. Friction testing conducted in 2023 for a separate project estimated the coefficient for cotton clothing on the ATD against a smooth surface (wooden desk) to be 0.17 (Hellstrom et al., 2025). The simulation was run three times, using friction coefficients of 0.1, 0.17, and 0.2 (Table 13). All three simulations produced lumbar loads greater than test A04072, with relative errors[15] ranging from 6% for the lowest friction coefficient to 11% for the highest.

In the simulations, the "1-g" position of the pelvis was 4.06" above the flat seat pan, which falls within the manufacturing tolerance for the Hybrid II (3.696" – 4.096"). A hand calculation can also be used as an additional check. Using the ATD weight above the lumbar load cell (approximately 75 lb) and ignoring dynamic overshoot, the minimum expected lumbar load is 909 lb (Taylor and Moorcroft, 2023). Based on these results, the Madymo Hybrid II v-ATD is considered acceptable for use in this test configuration.

Table 13: v-ATD Lumbar Load Without Cushion

ID	Pan-Pelvis Friction Coefficient	Lumbar Load (lb)	Relative Error (%)
Rigid01	0.1	998	5.9
Rigid017	0.17	1039	10.3
Rigid02	0.2	1050	11.3
A04072	Unknown	942	N/A
Hand Calculation	N/A	909	N/A

System Validation

To validate the overall system, sled test A12010 was simulated using the Madymo Hybrid II ATD. The test included cushion sample D6. The force-deflection curve from load frame test M18006 (6^{th} test in series) was chosen as the baseline cushion properties. The baseline model, S18006, was modified to use the pulse from test A12010 using the rotations defined above (Figure 32). Simulation data (S12010) was post-processed as specified above (Model Output).

[15] The relative error was calculated between the simulation result and test A04072, biased towards the test. No correction was applied for the difference in seat pan angle.

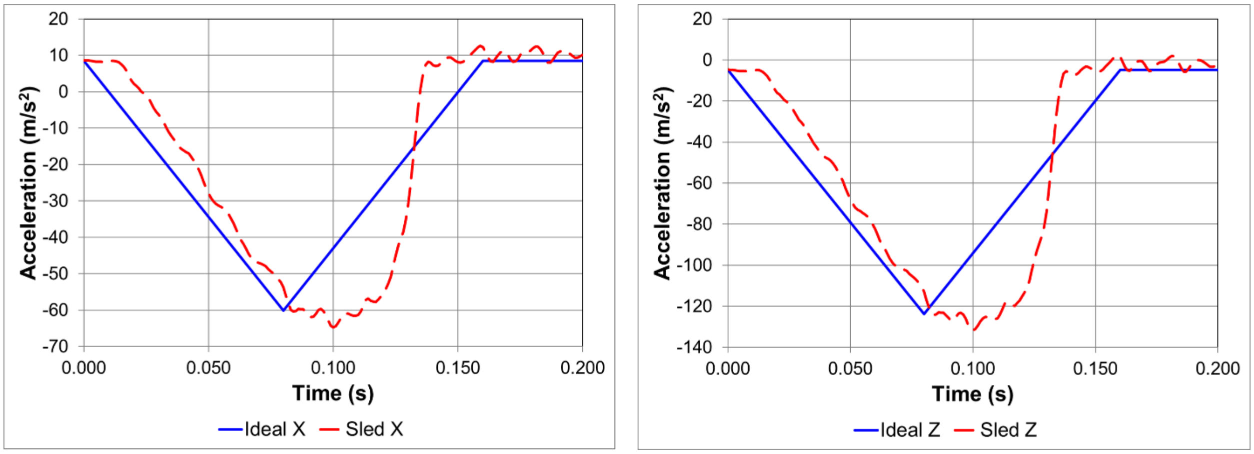

Figure 32: X-component (L) and Z-component (R) of Default Pulse and A12010

Figure 33 shows three time captures from test A12010: 0.000 s, 0.100 s, and 0.125 s. The ATD is upright through the peak lumbar load (0.102 s) and begins rotating forward. By 0.125 s, the relevant parts of the test have been completed.

Figure 33: A12010 at 0.000 s (L), 0.100 s (C), and 0.125 s (R)

Figure 34 shows four time steps from simulation S12010: -0.4 s, 0 s, 0.1 s, and 0.125 s, where the first 0.4 s was used to settle the v-ATD into the “1-g” position. Similar to the physical ATD, the v-ATD stays upright through peak lumbar load (0.0987 s) before rotating forward.

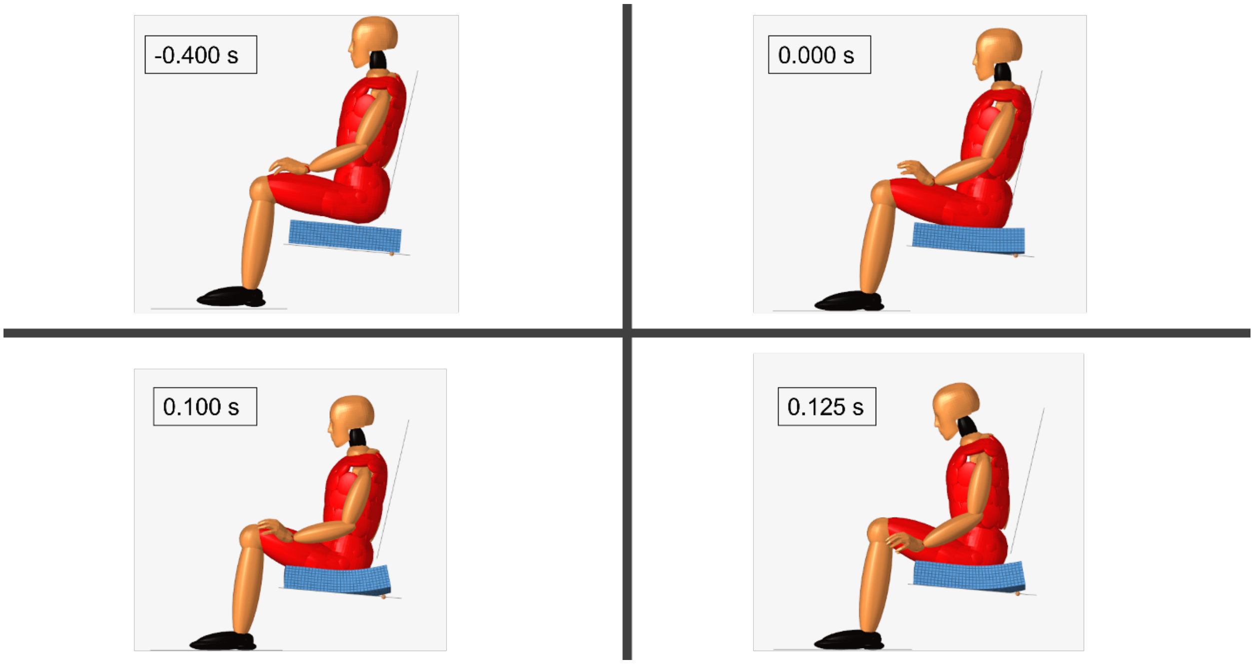

Figure 34: S12010 at -0.400 s, 0.000 s, 0.100 s, 0.125 s

Primary Channel: Lumbar Fz

The two Fz lumbar loads behave similarly, each peaking around 0.100 s, although the simulated lumbar load is narrower than the test result (Figure 35). The simulation peak load has a 13.5% higher magnitude than the test peak, with a shape error of 10.5%. Both error values are within the predefined acceptance criteria.

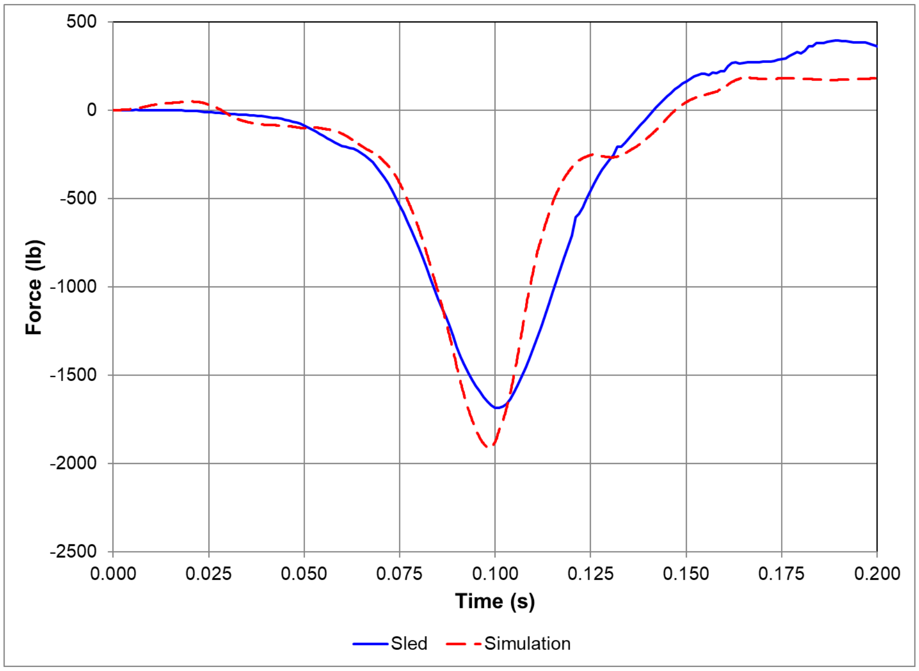

Figure 35: Validation Comparison - Lumbar Fz

Primary Channel: Seat Pan Fz

The two curves are similar, although the simulation result is narrower and has an earlier peak (Figure 36). The simulation peak load is 1.6% higher than the test peak, with a shape error of 10.6%. Both error values are within the predefined acceptance criteria.

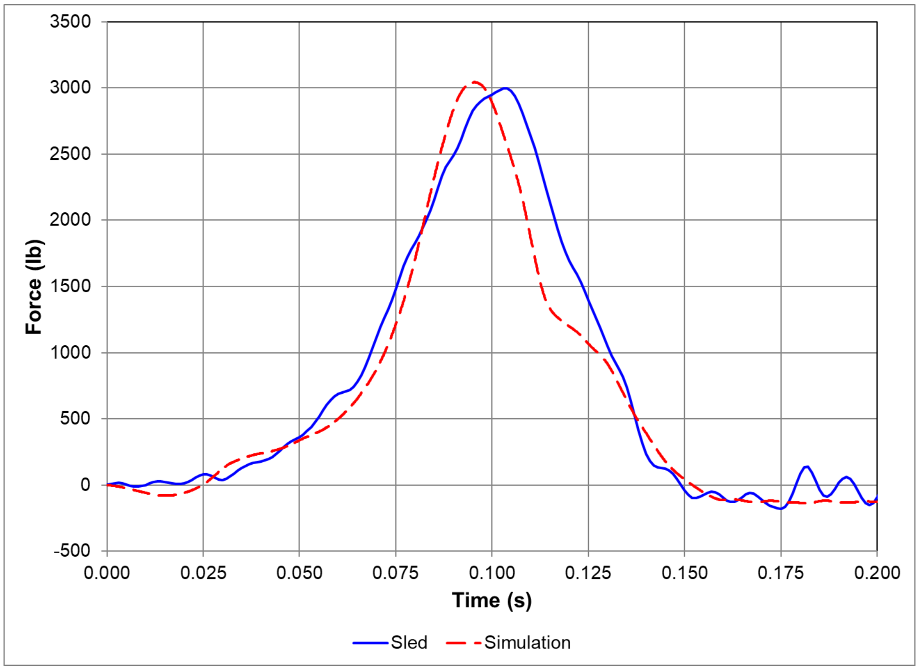

Figure 36: Validation Comparison - Seat Pan Fz

Support Channel: Lumbar My

The two curves deviate starting around 0.065 s, with the test data appearing to exhibit sensor drift (Figure 37). The simulation minimum moment is 109% lower than the test peak, with a shape error of 29.5%. The magnitude error falls outside the predefined acceptance criteria, but the shape error meets the requirement. Part of the reason that the shape error is so large is that the minimum moment in the sled test is relatively close to zero (-246.3 in-lb).

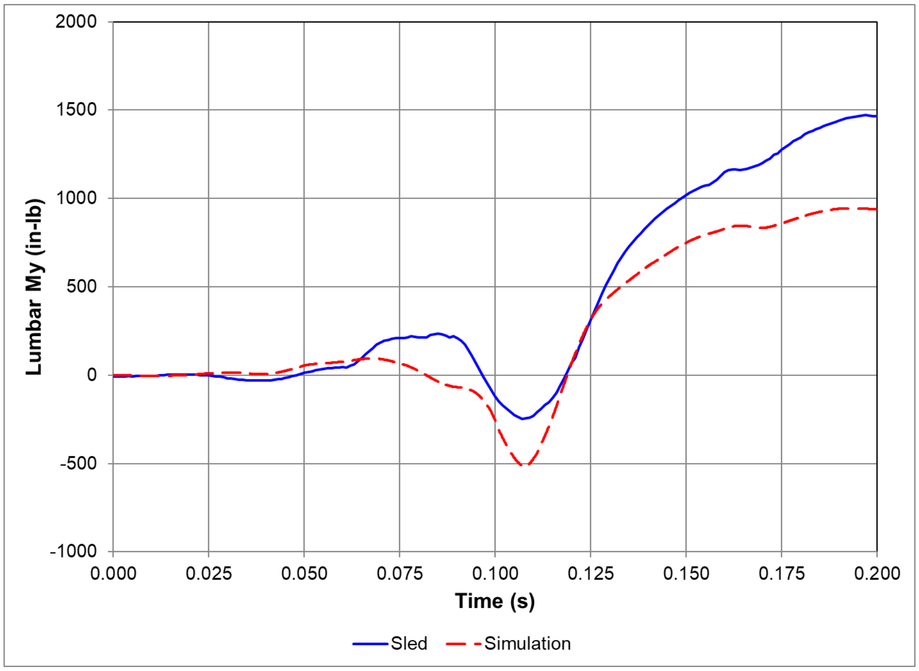

Figure 37: Validation Comparison - Lumbar My

Support Channel: H-pt Z-position

The two curves look similar (shape error = 8.0%), but the v-ATD in the simulation is 0.35" higher initially and doesn't compress the foam as much as seen in the physical test (Figure 38). The cushion is compressed nearly 75% in the sled test (2.98"), while the simulation only has about 50% compression (1.98"). Retaining the initial difference, the difference in the minimum values is 1.35". The peak error is outside the requirement, but the shape error is within the requirement.

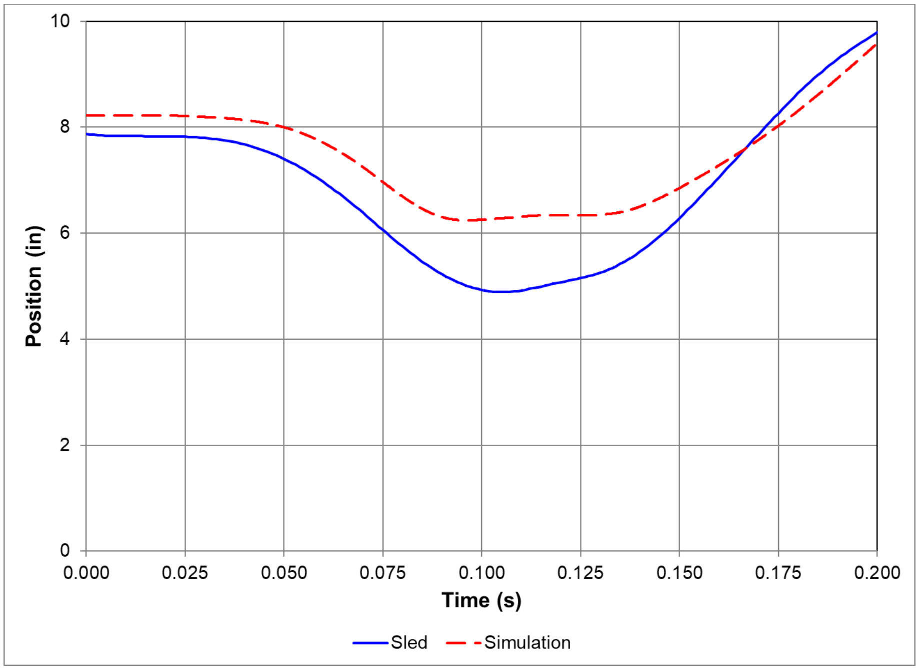

Figure 38: Validation Comparison - H-pt Z-position

Support Channel: Pelvic Angle

Both angles were zeroed at time equal to zero. The curves begin to diverge around 0.085 s, with the physical ATD rotating 14.2° while the v-ATD only rotates 3.5° (Figure 39). This phenomenon was previously observed in the Hybrid II v-ATD for a longitudinal test scenario (Moorcroft, 2006). The error on the peak is 10.7°, while the shape error is 71.2%. Both are outside the requirement.

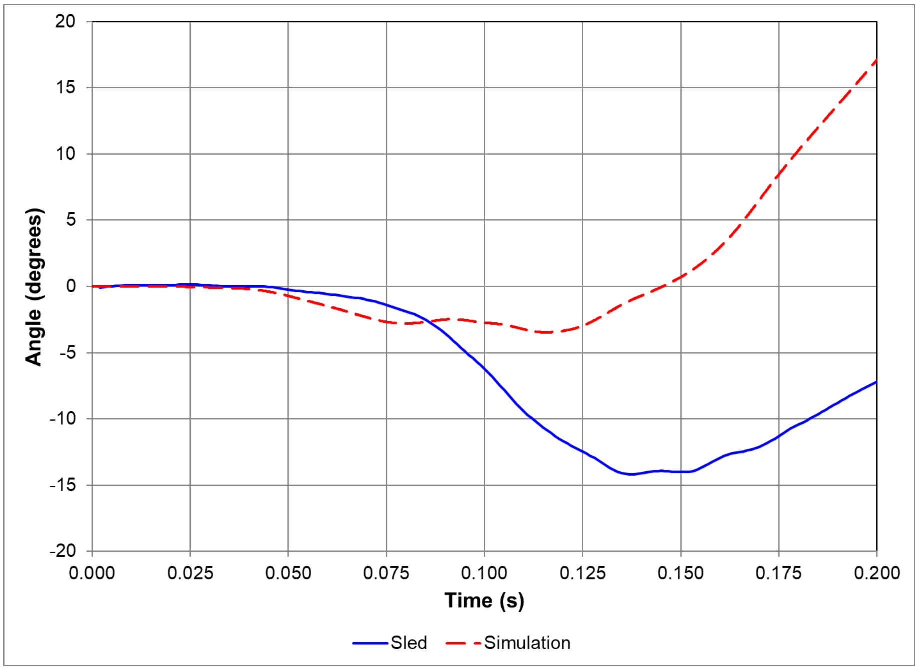

Figure 39: Validation Comparison - Pelvic Angle

Appendix C: Data Management Plan

Dataset and Contact Information

Title: Use of a Simplified Model to Evaluate Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions

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Funder: Federal Aviation Administration (faa.gov)

Grant/Contract(s): N/A

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Recommended Citation: U.S. Department of Transportation, Federal Aviation Administration. (2026). Use of a Simplified Model to Evaluate Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions [datasets]. https://doi.org/10.21949/1529736.

Project abstract

The Federal Aviation Administration (FAA) requires that aircraft seating systems protect occupants in the event of an emergency landing. During the combined longitudinal-vertical impact, the seat bottom cushion significantly affects the loads transferred to the occupant's spine, and, therefore, the risk of injury. Previous testing revealed test-to-test lumbar load variability as high as 18%, which was hypothesized to arise in part from variation within foam material properties. In this study, a high-rate load frame was used to measure cushion force-deflection behavior, and those data were then used as inputs to a computational model to estimate the effect of cushion-property variability on predicted lumbar load. 13 credibility factors were used to support a determination that the model was adequate for answering the question of interest. While the loading curves varied by as much as 23%, the predicted peak lumbar load varied by no more than 7.4%. These findings suggest that test uncertainty solely due to the differences within the cushion material properties is lower than that of the other sources of uncertainty in full-scale sled tests.

Project start date: 08-17-2022
Project end date: 09-30-2026

Data Description

This dataset contains component test data from a high-speed load frame and simulation results of a virtual anthropomorphic test device seated in a rigid seat subjected to a combined longitudinal-vertical impact. This data is created by physical experiments and model simulations. Physical sensors are a load cell and a linear variable differential transformer. The tests were conducted in 2018, and the simulations were run in 2026.

It is anticipated that Aircraft seat manufacturers and test laboratories will benefit from access to this data as they design and test real aircraft seats and restraints. This dataset will also provide a public record to support potential rulemaking.

Roles & Responsibilities

The FAA Aeromedical Research Division (see Contact Information) is responsible for generating the data and is responsible for managing the data initially. This division is responsible for managing the internal project management processes to ensure adherence to the published data management plan (DMP). This process requires management review and sign-off at project start and close-out.

This dataset is hosted by the National Transportation Library (NTL) at: https://ntl.bts.gov/ntl.

Standards Used

The data files collected are saved in a mix of common file formats, including xlsx, and proprietary formats. The common file formats can be opened using commonly available software, such as Microsoft Excel, or with freely available software, such as OpenRefine. The simulation animations (.h3d) can be viewed using the freely available HyperView player. The proprietary formats can be viewed using common physics-based simulation post-processors, such as MadPost from Siemens, HyperView from Altair, and LS-Prepost from Ansys.

Access Policies

These data files are in the public domain and can be shared without restriction. The data files contain no sensitive information.

Sensitive Data Policies

The data files contain no sensitive information.

Sharing Policies

These data are managed by the Transportation Library. The data are in the public domain and may be reused without restriction. Citation of the data is appreciated. Please use the following recommended citation: U.S. Department of Transportation, Federal Aviation Administration. (2026). Use of a Simplified Model to Evaluate Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions [datasets]. https://doi.org/10.21949/1529736.

Archiving and Preservation Plans

The dataset will be archived by the National Transportation Library at: https://ntl.bts.gov/ntl. Prior to archiving, the data are stored on the secured FAA networks and drives, which are backed up nightly. The US DOT systems are secured from outside users and backed up daily. The NTL Database meets all the criteria outlined on the “Guidelines for Evaluating Repositories for Conformance with the DOT Public Access Plan” page: https://doi.org/10.21949/1520563.

The dataset will be retained in perpetuity.

FAA staff will mint persistent Digital Object Identifiers (DOIs) for each dataset stored in the Biomechanics Test Database. These DOIs will be associated with dataset documentation as soon as they become available for use.

The DOIs associated with this dataset include: https://doi.org/10.21949/1529736

The assigned DOI resolves to the repository landing page for the “Use of a Simplified Model to Evaluate Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions” dataset, so that users may locate associated metadata and supporting files.

Applicable laws and policies

This data management plan was created to meet the requirements enumerated in the U.S. Department of Transportation's 'Plan to Increase Public Access to the Results of Federally-Funded Scientific Research' Version 1.1 https://doi.org/10.21949/1520559 and guidelines suggested by the DOT Public Access website https://doi.org/10.21949/1503647, in effect and current as of March 25, 2026.