NASA/TM–2020-220571

Occupant Response Analysis of a Full-Scale Crash Test of a Fokker F28 Fellowship Aircraft

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March 2020

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1.0 ABSTRACT

In this report, the capability of component fuselage testing and finite element models (FEMs) to predict occupant injury risk when applied to full-scale aircraft crash testing was evaluated. Component level and full-scale crash tests of a Fokker-F28 aircraft were performed in conjunction with representative FEM simulations. Lumbar spine injury risk, calculated through Anthropomorphic Test Device (ATD) outputs measured in the full-scale test, was compared with predictions made by component level testing and simulations. A quantitative assessment of FEM prediction accuracy was made using the International Organization for Standardization (ISO) Technical Report (TR) 16250 curve comparison methodology. Lumbar load injury risk measured in the full-scale test configuration was found to be significantly higher than in the component tests performed. The FEM provided a closer prediction of occupant injury risk than component testing but exhibited limitations in the multi-axis load environment. This work will help inform the application of component testing and FEM simulation when used to evaluate aircraft crashworthiness.

2.0 INTRODUCTION

In June of 2019, the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) conducted a full-scale crash test of a Fokker F28 MK1000 aircraft as part of a cooperative agreement with the Federal Aviation Administration (FAA). To study occupant response, a wide diversity of twenty-four Anthropomorphic Test Devices (ATDs, a.k.a. crash test dummies) were utilized for this test. These ATDs provided a means to evaluate occupant injury risk throughout the aircraft during a realistic crash event. Due to the significant cost, time, and facility requirements necessary to perform full-scale crash testing, aircraft crashworthiness is typically evaluated through component level testing (i.e. vertical drops of fuselage subsections or isolated seat tests) and Finite Element Model (FEM) simulations. The full-scale crash test provided a unique opportunity to study the effectiveness of these approximation methods.

Prior to performing the full-scale crash test of the Fokker F28 aircraft, two component tests were conducted at LaRC. The two tests were performed under vertical only loading conditions and consisted of the Forward and Wingbox Section of a Fokker F28 aircraft with a full suite of ATDs [1]. The data collected from these tests allowed for a direct comparison to crashworthiness data collected in full-scale tests of the same aircraft.

In conjunction with component testing, FEMs are a common tool used to bridge the gap between simplified test conditions and the full-scale crash environment. Finite element analysis (FEA) provides a relatively quick and low-cost alternative to full-scale testing. Extrapolating upon simplified test conditions used to develop the FEM allows for evaluation of crash conditions not feasible through test. Though providing significant potential to aid in crashworthiness evaluations, FEM model accuracy must be fully characterized before it is used to quantify the crashworthiness of an aircraft. Generally developed and calibrated through limited material and component level tests, comparison to a full-scale test condition provides a means to evaluate the validity of these models when used within the dynamic crash environment. An FEM of the Fokker F28 aircraft was developed from material and component models originally created using the fuselage section test data [2] and simulated in the full-scale test condition. The accuracy of predicted ATD responses was assessed to determine applicability of the FEM, as calibrated against component tests and used within the full-scale crash environment.

3.1 METHODS - Component Testing

In the component tests the Forward and Wingbox Sections were isolated and dropped from a height of 14-ft at the Landing and Impact Research (LandIR) Facility at NASA LaRC. The Forward Section was dropped onto a level soil bed with an impact velocity of 28.9-ft/s. The Wingbox Section was dropped with a 5° forward pitch between the vehicle section and the soil bed at an impact velocity of 29.1-ft/s. The Wingbox Section was pitched forward to induce a horizontal loading component onto the ATDs through the rotation of the structure at impact. The pre- and post-test state of the Forward and Wingbox Section tests is shown in Figure 1. The Forward Section exhibited failures in the structural frames of the fuselage and floor. The Wingbox Section, containing reinforced structure under the floor to handle loads transferred into the fuselage from the wings during flight, exhibited little deformation on impact with minor structural failures.

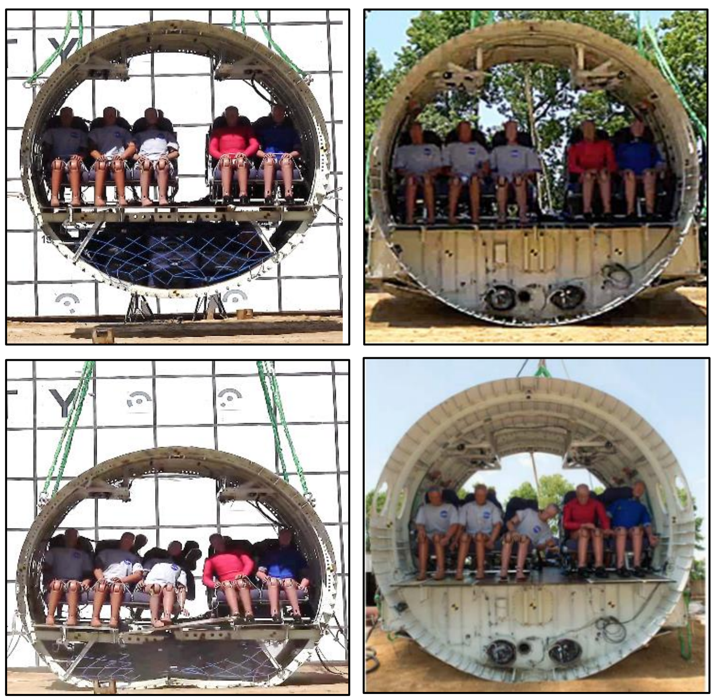


Figure 1. Pre- (upper) and Post- (lower) Test Photographs of Fokker F28 Component Tests: Forward Section (left) & Wingbox Section (right)

Two rows of seats were arranged in a triple-double configuration within each fuselage section. The triple seats were arranged on the starboard side and double seats on the port side. The seats used were previously flown on an in-service Boeing 737 and certified under AC 25.562 [3]. ATDs were fitted into each seat according to the layout provided in Figure 2, which also shows the location of each section within the aircraft. All ATDs were positioned in a neutral upright posture, 90° knee – 90° hip, except the FAA Hybrid III 50^{th} in 8C of the Wingbox Section which was positioned into a braced posture (hip rotated forward with head on the seatback). All ATDs were restrained using lap belts. Belts were tightened until no more than two fingers could be fit between the belt and pelvis on each ATD.

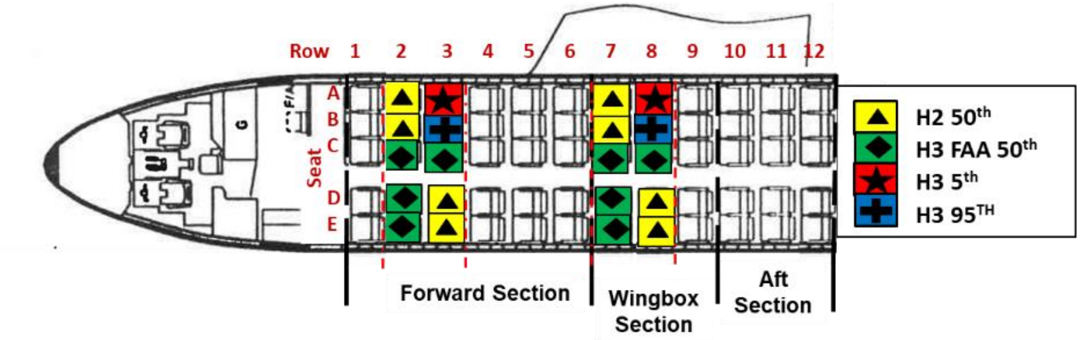


Figure 2. ATD Layout of Fokker F28 Component Tests

3.2 METHODS - Full-Scale Test

The full scale-crash test was performed by swinging the Fokker F28 aircraft from a height of 100-ft, onto a level 2-ft deep soil bed. Prior to reaching the soil bed, the swing cables were released using pyrotechnic cable cutters, resulting in a free fall boundary condition of the aircraft at impact. The aircraft impacted the soil bed with a 65.3-ft/s horizontal and 31.8-ft/s vertical velocity. Vehicle attitudes were: pitch = 0.38° nose down, roll = 4.3° Starboard side down, and yaw = 2.58° nose left. Figure 3 shows pre- and post-test photographs of the crash test. Airframe skin failures were observed across the underbody of the aircraft. Deformation was observed throughout the fuselage. Though there was floor deformation, no egress limiting intrusion into the aircraft cabin was observed. Structural damage has yet to be fully characterized and will be reported once the aircraft is completely disassembled. A detailed description of the test article, setup, and structural results is provided in Littell (2020) [4].

Figure 3. Pre- (upper) and Post- (lower) Test Photographs of Fokker F28-Full Scale Tests: External/Airframe (left) & Internal/ATDs (right)

The triple-double seating configuration used in the component tests was used in the full-scale test. Twenty-four ATDs were included in this test as described in Figure 4. These ATDs were obtained from NASA, the FAA, the National Highway Safety Administration (NHTSA), the US Army Research Laboratory, and the ATD manufacturer Humanetics®. All ATD's were positioned in the neutral posture except the Hybrid II ATD in seat 6B which was in the braced posture. ATDs were restrained within the seats using lap belts as they were in the component tests.

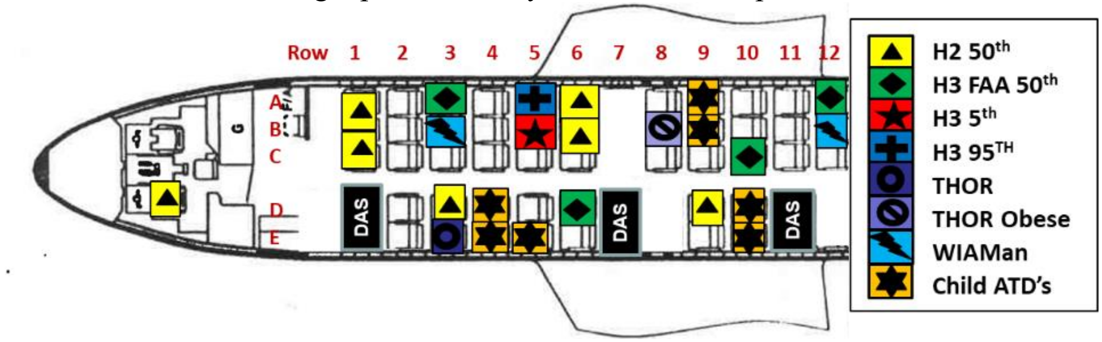


Figure 4 ATD Layout of Fokker F28 Full-Scale Test

3.3 METHODS - Vehicle FEM Development

A FEM of the Fokker F28 aircraft was developed using an existing NASTRAN [5] model of the aircraft and previously developed Forward and Wingbox Section FEMs calibrated from the component tests [2]. This was achieved by mapping the structural mesh and material definitions from the previously developed component FEMs to the remaining aircraft geometry defined by the NASTRAN model. The resulting FEM contained all structural components of the aircraft tested. The seats, ATDs, and data systems were represented by point masses rigidly fixed to the aircraft at the attachment points used in test (Figure 5). Additional information on the development of the vehicle and the test environment FEM is provided in Jackson et al. [6].

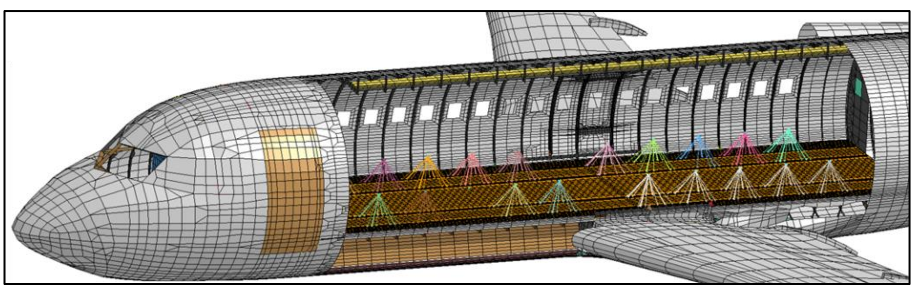


Figure 5. Fokker F28 Vehicle FEM

3.4 METHODS - Occupant FEM Development

To reduce simulation run time, the seat and ATD FEMs were developed and simulated separately from the full vehicle. Each seat grouping (ex. Row 2-Port Side) was modeled individually, with these individual models being referred to as "breakout" occupant FEMs. Each breakout occupant FEM included two rows of seats, the row containing the ATDs under investigation and the next forward row. This approach was necessary to account for the interaction between the ATD and forward row's seatbacks (Figure 6). The seat and belt FEMs used in this analysis were originally developed and calibrated during analysis of the fuselage component tests [2]. The seat FEM was developed from a CAD geometry provided by the seat manufacturer, B/E Aerospace (now Rockwell Collins). The material models representing the foam components of the seat cushion were developed and calibrated through static compression and dynamic impact tests of foam coupons. The seat FEM used to represent the forward row was reduced to the structural components affecting ATD contact with the seatback, i.e. the seat foam and armrests were removed, to reduce computational costs. A *CONSTRAINED_ROTATIONAL_JOINT definition was applied between the seatback and base structure to represent the rotational compliance of the reclining mechanism.

Figure 6. Seat Breakout FEM

Breakout occupant FEMs were developed for each seat group containing an adult Hybrid or THOR 50th ATD. Simulations were limited to these configurations by the ATD FEMs currently available to NASA. The Hybrid II and FAA Hybrid III 50th ATD's were simulated using the Hybrid III FAA 50th version 1.2.3 FEM [7] (Figure 7). The FAA Hybrid III has the straight spine of the Hybrid II ATD and is considered a valid surrogate for predicting lumbar loads by the FAA for seat certification [8, 3]. Though considered accurate for predicting lumbar response, the FAA Hybrid III cannot be assumed to be a valid surrogate for prediction of head-neck response of the Hybrid II due to geometric and material differences of parts making up this region within the two ATD configurations.

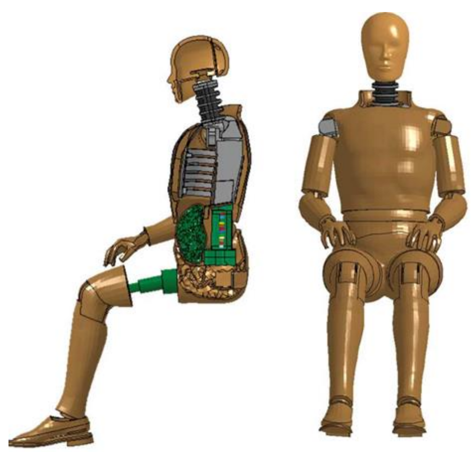


Figure 7. FAA Hybrid III FEM

The Hybrid III 5th and 95th ATD's were simulated using the Hybrid III 5th version 7.05 [9] and LSTC Hybrid III 95th beta version 3.03 [10] FEMs respectively (Figure 8). The THOR 50th ATD was simulated using THOR version 2.1 FEM publicly released by NHTSA [11] using material parameter and mesh adjustments made to improve stability and correlation of the model within the aerospace loading environment [12, 13].

Figure 8. Hybrid III - 5th, -95th, and THOR FEMs

Prior to performing simulation, the ATD FEMs were positioned into each seat to match the tested condition (Figure 9). To accomplish this, the ATD FEM was first oriented in the neutral upright posture. A pre-load simulation was then performed to load the ATD into the seat under gravity. This simulation was run out to 150-ms, the minimum amount of time required for the ATD to reach a steady state under gravitational acceleration. During this time the lap belts were tightened to a steady load of 10-lb using a combination of retractor and pretensioner elements. Though difficult to quantify the belt tightness achieved through the two-finger method used in test, a 10-lb tension force was chosen as a baseline approximation of the test conditions. The position of the ATD was fine-tuned using 3D scan data taken of the aircraft interior prior to test. Scans were taken using the FARO® FOCUS system and post-processed to create stereolithography (STL) meshes of each seat group using the FARO® SCENE software. The developed STL mesh was then superimposed on the breakout occupant FEM and the ATD was repositioned for optimal alignment.

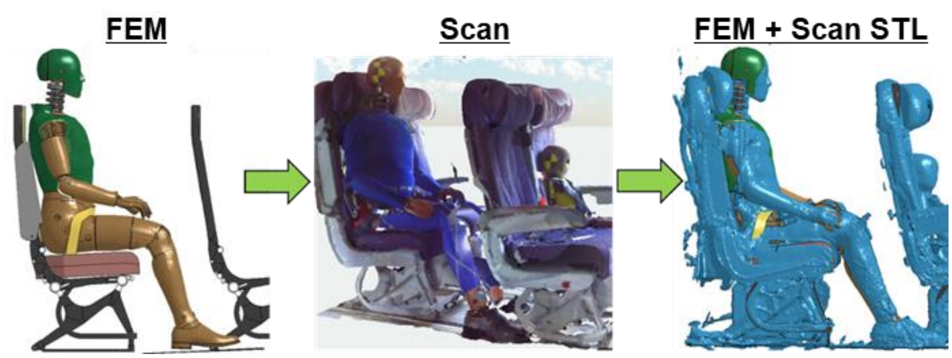


Figure 9. Occupant FEM Positioning Methodology

A total of nine occupant breakout FEMs were developed, these were made up of five starboard and four port side seat rows (Figure 10). Nine FAA Hybrid III ATDs were modeled, including one braced ATD in seat 6B. The braced ATD was positioned through a set of pre-load simulations in which the pelvis was held in place while a prescribed displacement was applied to the lower neck of the ATD to rotate the torso into the correct position. One Hybrid III 5th and one Hybrid III 95th ATD was simulated in Row 5 Starboard. The THOR ATD was simulated adjacent to a FAA Hybrid

III in Row 3 Port. In the breakout occupant FEMs which contained multiple ATDs, contacts were defined between adjacent ATD arms to accurately simulate interaction during flail.

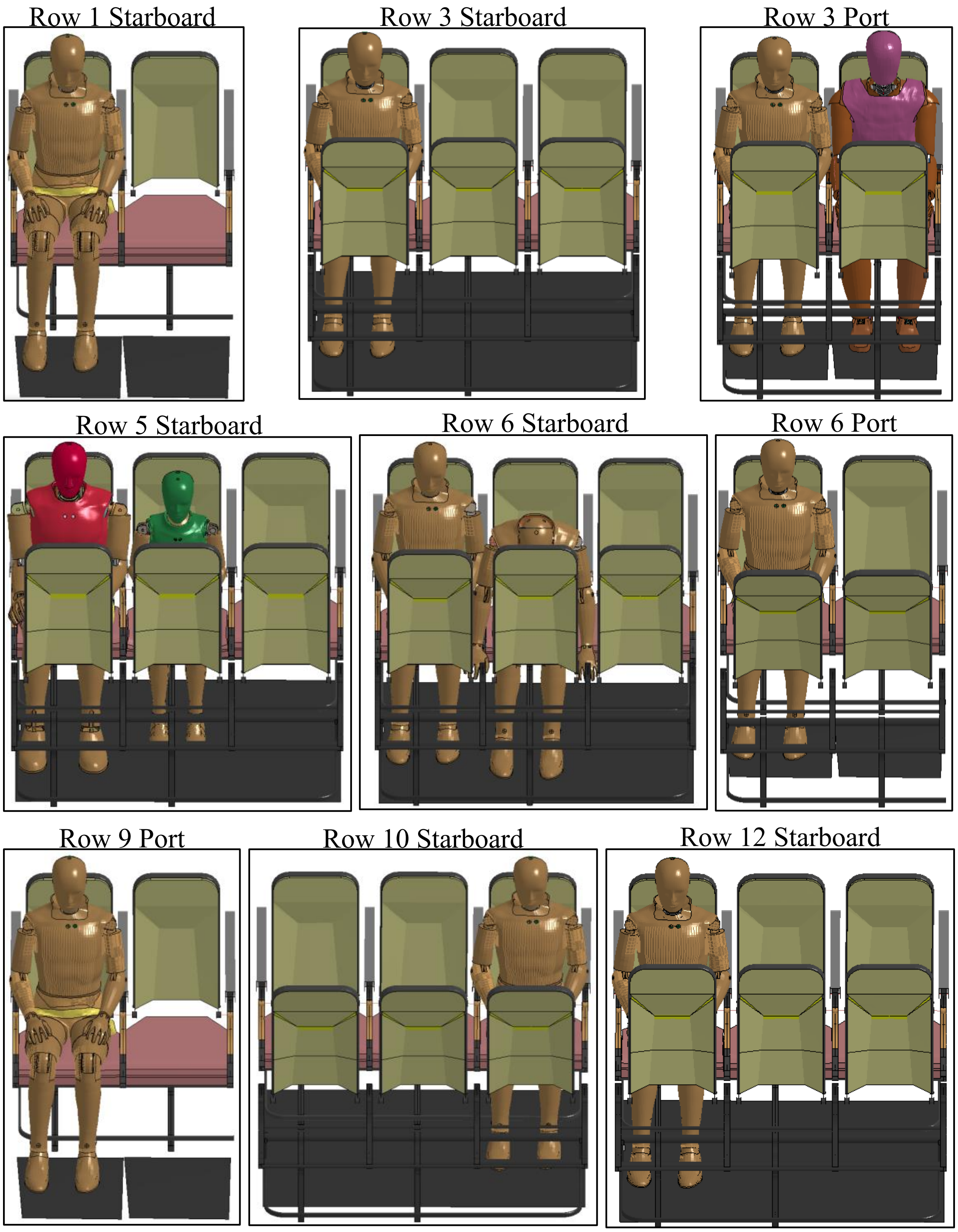


Figure 10. Breakout Occupant FEMs

Each breakout occupant FEM simulation was driven using the seat base kinematics predicted by the full-scale vehicle impact simulation. The predicted linear acceleration and rotational velocity components at the seat accelerometer location were prescribed to the breakout occupant FEM at a node that represents the seat accelerometer location. This node was rigidly attached to the floor attachment points of the seat. Simulation were carried out for up to 150-ms. All simulations were performed using LS-DYNA [14] SMP Version R10.1.0 double precision using eight processors on a Linux computer cluster. Simulation runtimes ranged from 24 to 72-hrs depending on the quantity and variant of ATDs in the seat group.

3.5 METHODS - Evaluation Methodology

In the full-scale aircraft test, 711 channels of data were collected, while 145 channels were collected for each component test. All data was sampled at 10 kHz and filtered according to the crash test specification outlined in SAE-J211 [15]. This data set was reduced for comparative analysis of predicted ATD response between the two test methods and simulation. To evaluate the differences in predicted occupant injury risk between both test configurations and FE analysis, the lumbar load responses of the Hybrid II and Hybrid III 50th FAA ATDs were compared between the full-scale test, component test, and FEM predictions. Although a multitude of ATDs and ATD responses were measured, the lumbar load of the straight spine Hybrid II/III 50th was selected to quantify injury risk due to its standardized use in current certification requirements [16]. The additional ATD channels collected were used to correlate the breakout occupant FEMs to the full vehicle test using a quantitative methodology.

To evaluate accuracy of the breakout occupant FEM, the correlation to each measured ATD response was quantitatively scored using the ISO/TR-16250 curve rating methodology [17]. This standardized curve comparison methodology scores the correlation between two curves on a scale between 0 (no correlation) and 1 (exact match). Correlation is calculated as a function of phase, shape, and peak value between the two compared curves. In this analysis, a score of 0.5 or greater was considered an adequate prediction of ATD response. Scores for each predicted response were tabulated to quantify FEM prediction accuracy in terms of ATD type, channel, and location within the vehicle. The 0.5 threshold used in this analysis was previously defined based on a blind comparison between subject matter experts in aerospace crashworthiness, qualitative assessment of breakout occupant FEM correlation adequacy, and computed ISO/TR-16250 scores [18].

Correlation between the breakout occupant FEMs and full-scale test were evaluated over two distinct loading phases. The primary loading phase occurred over the first 100-ms of the crash event. During this timeframe, the energy from the vehicle impact was transferred through the vehicle and seat structure and into each ATD. The critical loading along the spine of each ATD occurred during this timeframe. A full quantitative evaluation of all ATD responses was made over this primary loading phase. The secondary loading phase occurred over the subsequent 50-ms timeframe as the ATD upper bodies flailed and the ATD heads impacted the forward seatbacks, loading the head and neck of the ATDs. In certain cases, this contact occurred during the first 100-ms post impact, and the primary evaluation phase was adjusted to end before this contact occurred. The ability of the breakout occupant FEMs to capture this secondary load was evaluated in terms of head and neck correlation within the Hybrid III (5th, FAA 50th, 95th) and THOR ATD. The Hybrid II response was not compared in this evaluation, as the FAA Hybrid III FEM does not provide a representative surrogate for predicting head-neck response of this ATD configuration. Evaluation of the secondary response correlation was made qualitatively and did not include ISO analysis. High variability in response was observed in test, limiting the value in performing ISO analysis for this loading phase.

4.1 RESULTS - Vehicle Simulation Predictions

A comparison between average seat acceleration predicted by simulation and measured in both component and full-scale tests is provided in Figure 11. Average accelerations were computed by averaging linear acceleration measured from time of impact through 100-ms for each seat location. Overall, the simulation was found to slightly under predict vertical acceleration and over predict horizontal acceleration. The simulation did provide an improved prediction of the average seat vertical acceleration in the full-scale crash versus those from the component surrogate tests. Accuracy of the predicted seat accelerations are essential to accurate breakout occupant FEM predictions as they are used to drive these models. Additional detailed analysis of the full vehicle simulation correlation can be found in Jackson et al. [6].

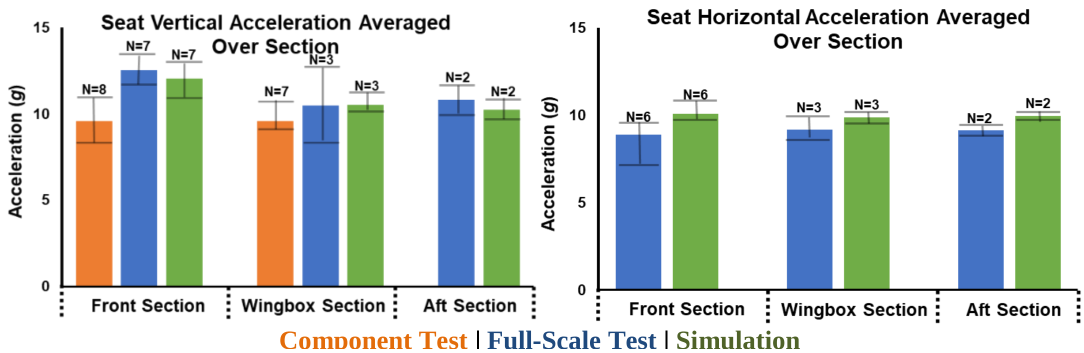
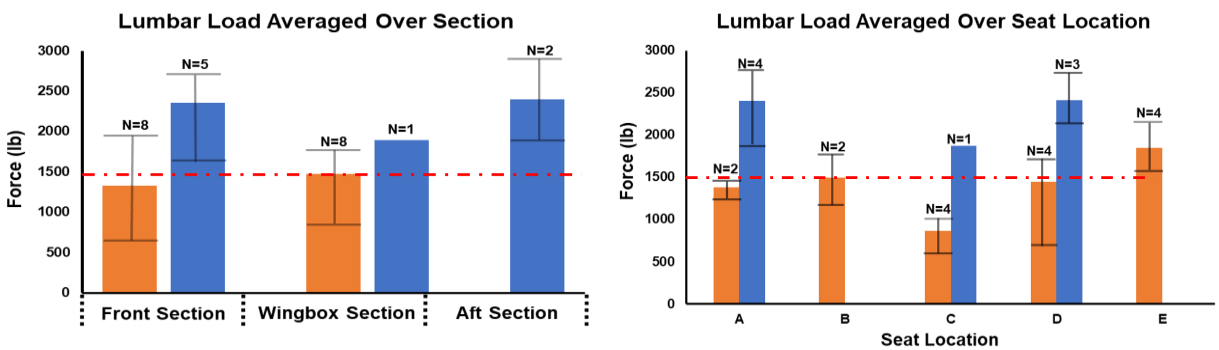


Figure 11. Comparison of Seat Accelerations Averaged over Section between Component Test, Full-Scale Test, and FEM Simulation

4.2 RESULTS - Component and Full-Scale Testing

The compressive lumbar loads measured in the Hybrid II and FAA Hybrid III ATD's were larger in the full-scale test than the component tests of the Forward and Wingbox Sections (Figure 12). Although experiencing wide variability in both test configurations, all compared lumbar loads were above the 1500-lb injury limit in the full-scale test while the average peak load measured in the component tests were below that limit. Key differences between the test article and test conditions likely influenced these findings. The increased airframe stiffness provided by the full-aircraft structure would have allowed a more direct load transfer into the ATDs. In addition, the combined loading vector of the full-scale test changes the kinematics of the ATD as load is transferred through the seat into the spine box. Forward motion may lead to a more direct alignment between the ATD and the front seat pan support tube located at the front of the seat, and this alignment of the ATD and seat would increase the compressive load into the spine compared to uniaxial vertical acceleration into the compliant seat foam center. In the component tests, the Wingbox Section was shown to induce larger lumbar loading than the Forward Section. This trend was not observed in the full-scale test. In the full-scale test, the Wingbox Section impacted first as its structure extended lowest on the airframe. The aircraft pitched down relative to the wingbox causing an increased vertical impact velocity at the Forward Section of the aircraft. The delay between horizontal and vertical impact accelerations caused by this vehicle motion would have also moved the ATD pelvis closer to the forward structure of the seat concurrently with peak vertical loading. Lastly, the failures in the frame structure between seat tracks, observed in the Forward Section during the component tests, hypothesized to be responsible for reduced ATD loads [1], were not observed in the full-scale test. The luggage used in the component test is hypothesized to have point-loaded the structure on impact, initializing failures of the subfloor structure, whereas the luggage surrogate foam used in the full-scale test spread the load across the floor more uniformly.



Component Test | Full-Scale Test

Figure 12. Comparison of Peak Lumbar Load Measured in Component and Full-Scale Test

In all test configurations, the lowest lumbar loads were measured in seat C. This location is the aisle seat in the triple seat configuration and was cantilevered from the inner seat track support by a distance of 22-in. The cantilevered seat allowed the seat pan support tubes to plastically deform under load, thus absorbing a portion of the crash energy through the structural deformation rather than transferring directly to the ATD. This seat structure deformation was observed in both test configurations (Figure 13).

Figure 13. Seat Deformation in Component (left) and Full-scale Test (Right)

Due to the effect of seat location on ATD response, direct comparisons between ATDs tested in the full-scale and component tests can only be made at three locations. Within the Forward Section of the aircraft, a direct comparison can be made between the Hybrid II ATD in seat 1A and 3D in the full-scale test and 2A and 3D respectively in the component test. Comparison of lumbar load response at these locations (Figure 14) shows significantly higher loads in the full-scale test ATDs. In addition to the larger peak load, the full-scale test exhibited significant tension loads following initial compression not observed in the component tests. The Hybrid II seated in seat 3D within the component test exhibited a delay in onset and significantly lower peak load than that observed in the full-scale test. In the component test, failures of the floor members were observed below seat 3D; this caused it to sink farther into the floor than all other seats within the test. As similar failure did not occur in the full-scale test, this likely contributed to the degree of difference observed between test configurations at this seat location.

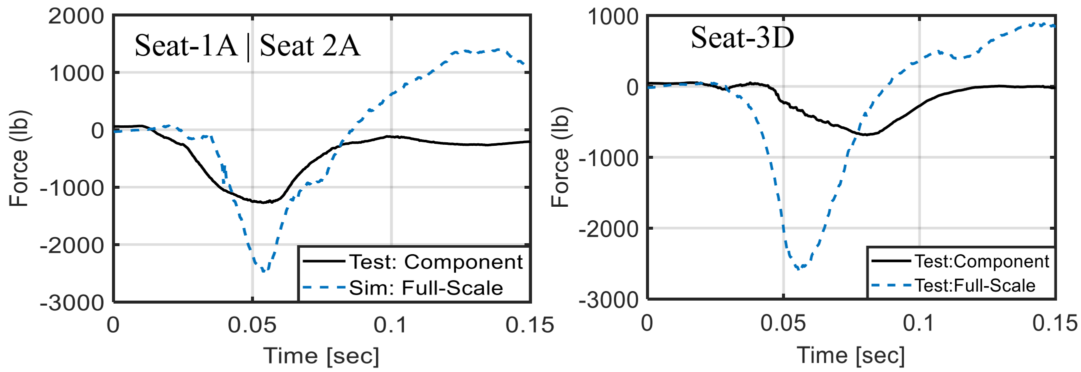


Figure 14. Comparison of Lumbar Load Response between Forward Section Component and Full-Scale Test

The Hybrid II ATD seated within 9D provides a single data point for Hybrid II/FAA Hybrid III response within the Wingbox Section of the full-scale test. This location can most closely be compared with the Hybrid II ATD seated within 8D on the Wingbox component test. Comparison of lumbar load response between these two ATD's demonstrates much closer load response than those observed in the Forward Section of the aircraft (Figure 15). Load onset and peak value closely match between the two test configurations. The more similar response in the Wingbox Section may be attributed to similarities in the loading of the Wingbox between the full-scale and component tests. The component test of the Wingbox Section induced combined horizontal and vertical loading into the ATDs through an angled impact vector. In addition, there was less load transfer variability in the Wingbox Section as the stiff understructure matched between the test configurations, as opposed to the differences in luggage surrogate used in between tests of the Forward Section of the aircraft. Lastly, the timing of impact was more similar in the Wingbox as this section was the first to contact the ground in the full-scale test, while there was a delay between initial impact and Front Section contact with the ground in the full-scale test.

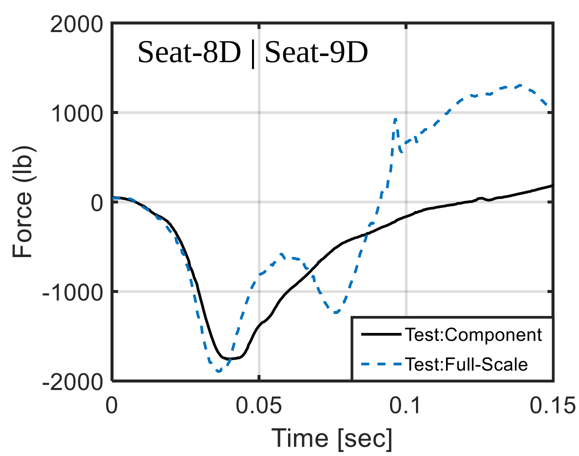


Figure 15. Comparison of Lumbar Load Response between Wingbox Section Component and Full-Scale Test

4.3 RESULTS – Breakout Occupant FEM Lumbar Load Predictions

The full-scale test simulation prediction accuracy of the Hybrid II and FAA Hybrid III lumbar loads varied across each section of the aircraft (Figure 16). Lumbar load was predicted closely in the Wingbox Section while slightly under predicted in the Aft Section. The lumbar load was over predicted in the Forward Section of the aircraft. These differences followed trends in vehicle simulation accuracy, with the seat accelerations being most closely predicted in the Wingbox Section of the aircraft, while the greatest discrepancies in predicted seat acceleration are found in the Forward Section. These discrepancies in the seat acceleration predictions are hypothesized to be a primary driver of lumbar load over-prediction in the Forward Section of the aircraft.

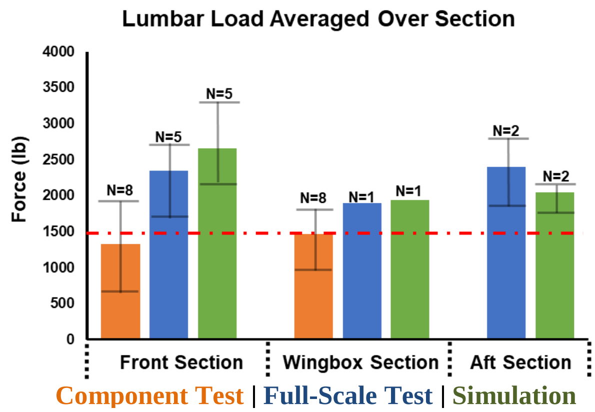


Figure 16. Comparison of Peak Lumbar Load Predicted by FEM Simulation and Measured in Component and Full-Scale Test

In comparrison between the full-scale test and simulation, the shape of the Hybrid II/FAA Hybrid III ATD lumbar load response is well predicted by the breakout occupant FEM in the Forward Section of the aircraft (Figure 17). The phasing and slope of the load response is closely captured by the FEM at each seat location. The FEM exhibits an over-prediction of initial peak load towards the front of the aircraft in rows 1-3. The FEM closely matches the initial lumbar peak in 6A and under-predicts peak load in 6D.

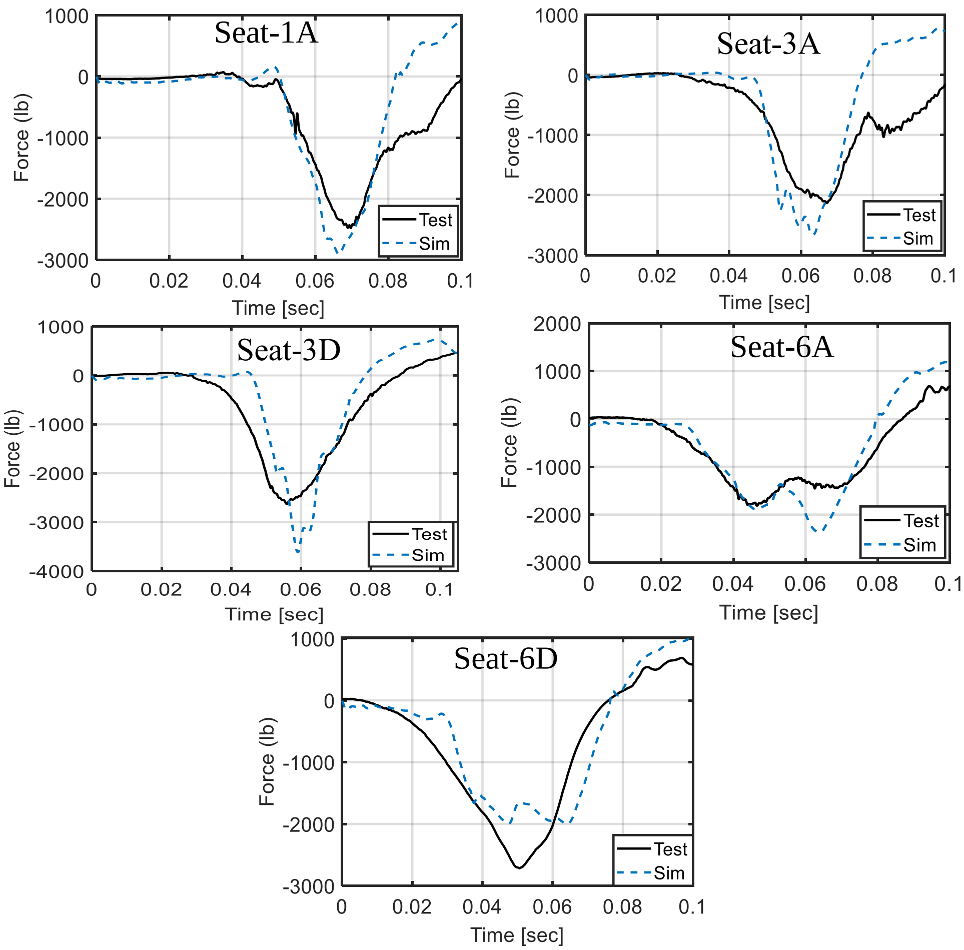
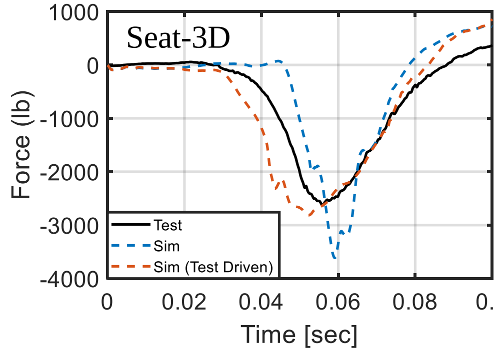
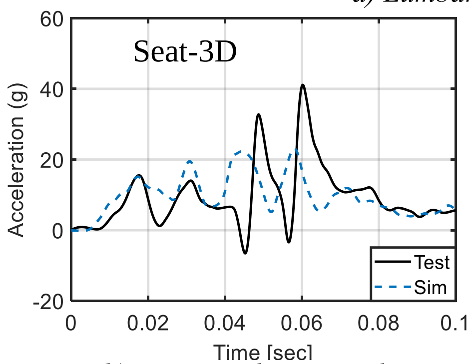


Figure 17. Comparisons of Lumbar Load Response across Forward Section of the Full-Scale Aircraft

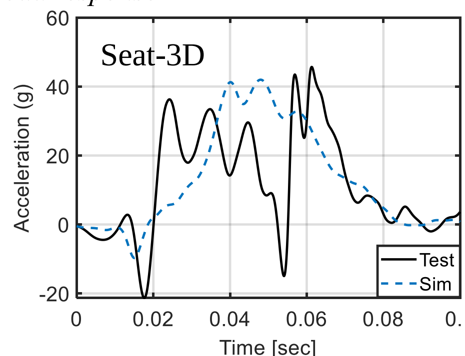
The ATD simulations in row 3 are the largest contributors of average lumbar load over-prediction in the Forward Section of the aircraft, with the largest over-prediction (991-lb) occurring in seat 3D. To evaluate the effects of the boundary condition accuracy on this over-prediction, a comparison was made between breakout occupant simulations driven from the vehicle FEM and test measured seat accelerations (Figure 18). When driven from the seat accelerations measured in test, lumbar load over-prediction was reduced by 185-lb. Though exhibiting similar energy and peak value, the vertical acceleration predicted by the vehicle FEM exhibits a delayed rise. This delay aligns with a similar delay seen in compressive lumbar load in the ATD FEM when driven by the FEM predicted acceleration. The delay in vertical acceleration results in a more forward excursion of the ATD within the seat at peak lumbar compression than that observed in the test acceleration driven simulation (Figure 19). The altered kinematics of the ATD as the vertical acceleration is driven into the spine is hypothesized to be partly responsible for the over-prediction of lumbar compression.



a) Lumbar load response



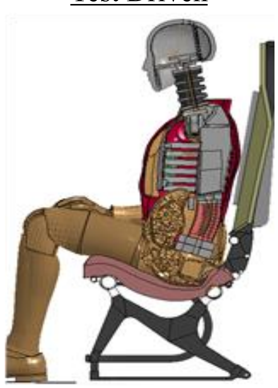
b) Horizontal seat acceleration



c) Vertical seat acceleration

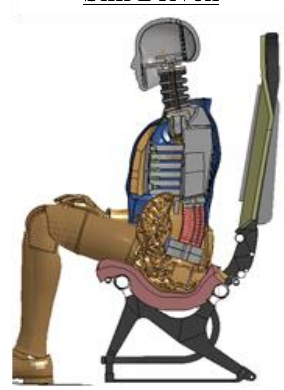
Figure 18. Lumbar Load Response Comparison between Test and Simulation Driven Acceleration Conditions – seat 3D

<u>Test Driven</u>



T=50 ms (test driven peak)

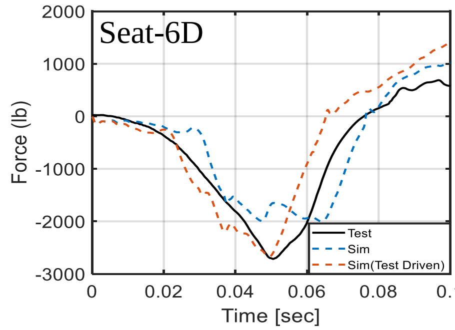
<u>Sim Driven</u>



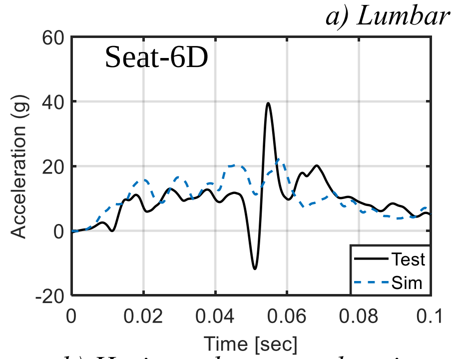
T=60 ms (sim driven peak)

Figure 19. Kinematic Response Differences at Peak Lumbar Loading between Test and Simulation Driven Acceleration Conditions – Seat 3D

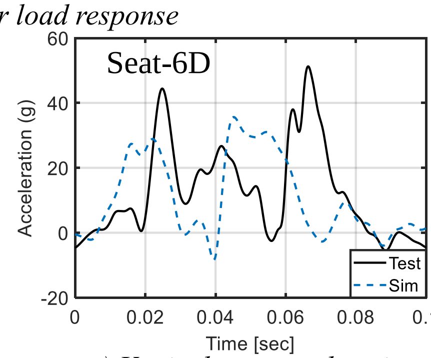
The prediction of lumbar load response of the FAA Hybrid III in seat 6D is the only under-predicted lumbar load found within the Forward Section. In this seat the predicted accelerations which are driving the breakout occupant FEM exhibit an opposite correlation trend from that seen in seat 3D. The seat vertical acceleration occurs earlier in the vehicle FEM prediction than the test (Figure 20). When driven from the seat acceleration measured in the test, the peak lumbar load is increased bringing the ATD model prediction to within 45-lbs compared to the 713-lb under-prediction observed when driven from the vehicle FEM predicted accelerations.



a) Lumbar load response



b) Horizontal seat acceleration



c) Vertical seat acceleration

Figure 20. Lumbar load Response Comparison between Test and Simulation Driven Acceleration Conditions – Seat 6D

The lumbar load response of the Hybrid II seated in the Wingbox section in seat 9D is closely predicted by the breakout occupant FEM (Figure 21). The phasing of the response is also closely predicted. The FEM does fail to capture oscillation in load observed in the test response but does capture the unloading and transition into tension loading well.

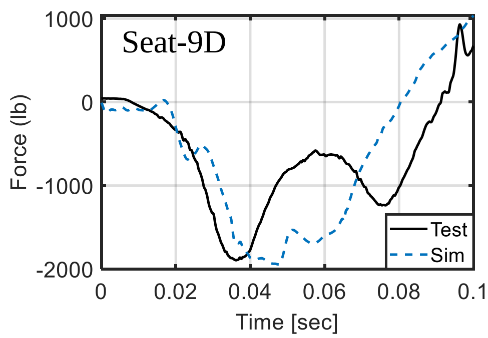


Figure 21. Comparisons of Lumbar Load Response across Wingbox Section of the Full-Scale Aircraft

The breakout occupant FEM was found to under-predict lumbar load measured in both seat locations tested within the aft section of the aircraft (Figure 22). The largest under prediction of peak lumbar load was observed in the rear of the aircraft in seat 12A. The FEM also exhibited the poorest correlation to response shape in this section, with peaks occurring later in 10C and early in 12A. Unloading occurred earlier in the FEM at both seat locations.

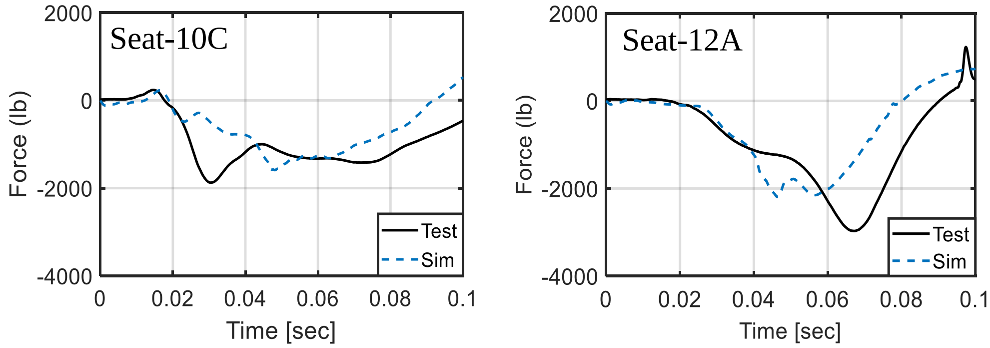


Figure 22. Comparisons of Lumbar Load Response across Aft Section of the Full-Scale Aircraft

4.4 RESULTS – Breakout Occupant FEM Correlation

The Humanetics® FAA Hybrid III FEM best predicted the response of the FAA Hybrid III and Hybrid II ATD along the vertical direction (Z-axis) (Table 1). Within the breakout occupant FEMs developed, the mean computed ISO 16250 score for each vertical response was above the 0.5 threshold for adequate correlation between test and simulation. The closest correlation was found in the lumbar spine and chest vertical acceleration response. The opposite was found along the horizontal direction (X-axis) with mean ISO scores in this direction all falling below 0.5. There were no clear trends observed between aircraft section and overall breakout occupant FEM correlation of either ATD. Modeled using the FAA Hybrid III FEM, the Hybrid II predictions were found to be less accurate across simulations. The lumbar load response of the Hybrid II was best predicted, as expected due to this region most closely matching the FAA Hybrid III configuration.

Table 1. FEM Simulation ISO Correlation Scores Calculated for the FAA Hybrid III and Hybrid II ATDs

Seat	Head AX	Head AZ	Chest AX	Chest AZ	Pelvis AX	Pelvis AZ	Spine FZ	Neck FX	Neck FZ	Neck MY
					FAA Hybrid III					
3A	0.57	0.53	NA	0.84	0.34	0.60	0.79	0.47	0.55	0.5
6D	0.42	0.64	0.55	0.67	NA	N/A	0.69	0.40	0.66	0.41
10C	0.28	0.54	0.29	0.75	N/A	N/A	0.57	0.19	0.52	0.49
12A	0.56	0.67	0.35	0.69	0.57	0.76	0.61	0.33	0.59	0.32
Mean	0.46	0.60	0.40	0.74	0.46	0.68	0.67	0.35	0.59	0.43
					Hybrid II					
1A	0.57	0.56	0.41	0.77	0.35	0.77	0.73	N/A	N/A	N/A
3D	0.44	0.63	0.48	0.77	0.37	0.7	0.74	N/A	N/A	N/A
6A	0.33	0.61	0.41	0.82	0.27	0.66	0.78	N/A	N/A	N/A
6B*	0.3	0.59	0.62	0.56	0.26	0.39	0.59	N/A	N/A	N/A
9D	0.43	0.63	0.27	0.67	0.4	0.41	0.56	N/A	N/A	N/A
Mean	0.41	0.60	0.44	0.72	0.33	0.59	0.68	N/A	N/A	N/A

*Braced Position

The simulation of the braced Hybrid II (6B) exhibited worse correlation compared to upright positioned Hybrid II in same seat row. The predicted lumbar load response in particular scored much lower in the braced ATD FEM. During test the braced ATD was held in position using a rope strapped over the ATD back to the seat below. Though the positioning was approximated in simulation, the load applied with these ropes was not modeled. The force applied by this rope would have changed both the initialized load within the lumbar spine and the response of the ATD, particularly as it rebounded off the seat, and thus likely contributed to the discrepancy observed in the predicted response. Although the simulated response of the braced ATD exhibited lower correlation scores than the upright ATD next to it, the FEM was shown to capture the kinematic response of the ATD against the forward seat (Figure 23). Both test and simulation demonstrate similar impact with the seat tray followed by significant neck extension as the impact load drives the ATD forward and downward.

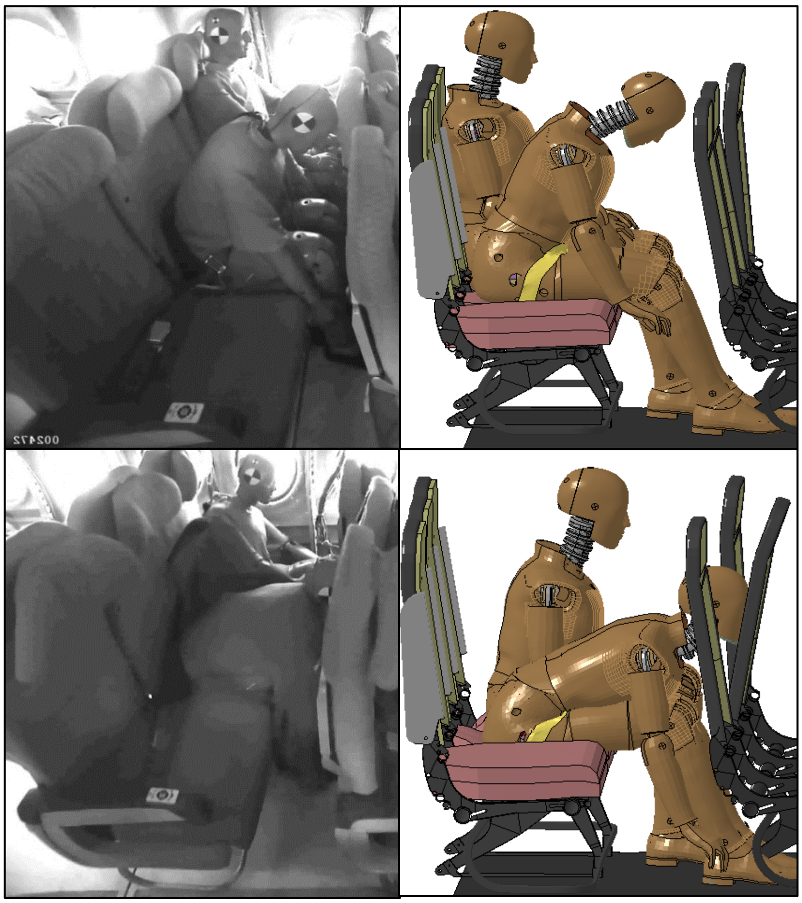


Figure 23. . Kinematic Response Comparisons of Braced ATD between Test and Simulation: Initial Position (Top) and Peak Neck Extension (Bottom) – Seat 6B

During the primary impact phase, energy from the crash event is transferred into each ATD through the pelvis and its interaction with the seat. Correlation of ATD response is dependent on the accuracy of this interaction. In general, vertical response of the Hybrid II and FAA Hybrid III pelvis acceleration was well predicted by the breakout occupant FEM. This finding corresponds with close correlation in the lumbar spine, chest, neck, and head responses along this direction. The horizontal correlation of the pelvis is lacking, corresponding with poor correlation across responses in this direction. A closer look at this correlation shows the breakout occupant FEM to over-predict pelvis horizontal acceleration towards the front of the aircraft while under-predicting horizontal response in the rear (Figure 24). Interestingly this trend in the pelvis horizontal acceleration matches that observed in the lumbar spine compressive load. The pelvis vertical acceleration is over-predicted in both the forward and rear aircraft locations but exhibits close correlation to the phase and shape of this response.

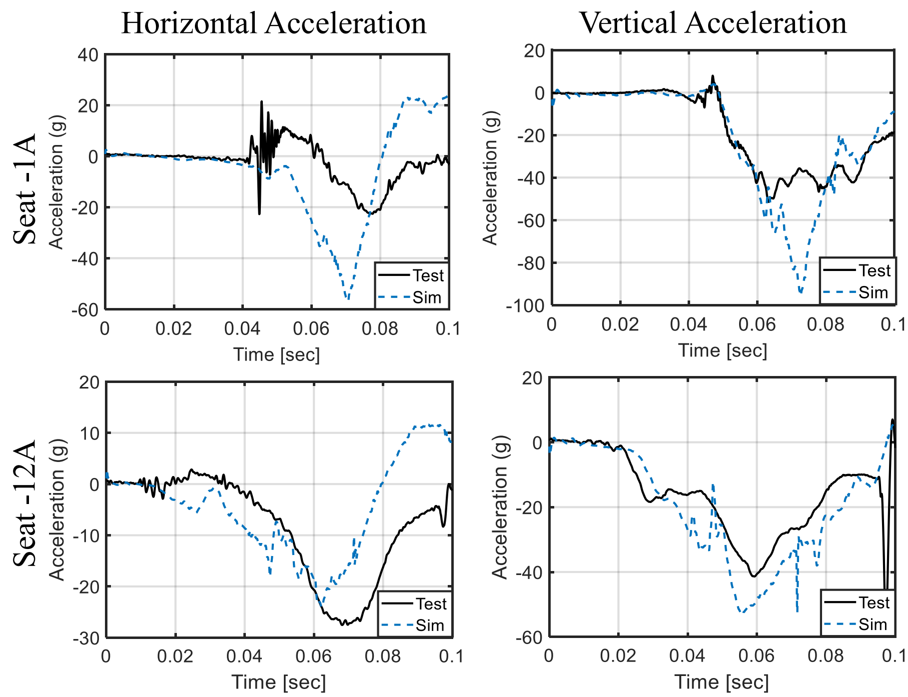


Figure 24. Comparison of Pelvis Acceleration Predictions across Length of Aircraft

The effect of the horizontal pelvis acceleration correlation is demonstrated in the kinematic response differences observed between seat 1A and seat 12A FEMs (Figure 25). In seat 1A the over-prediction of horizontal pelvis acceleration corresponds with the ATD being driven farther forward in the seat than that in seat 12A. The predicted peak pelvis horizontal acceleration in seat 12A is similar to the measured acceleration in seat 1A. Although test video is not available to verify, it is likely the positioning of the pelvis and lumbar spine at peak loading within the tested ATD in seat 1A is more similar to that simulated in seat 12A due to these differences in pelvis horizontal response.

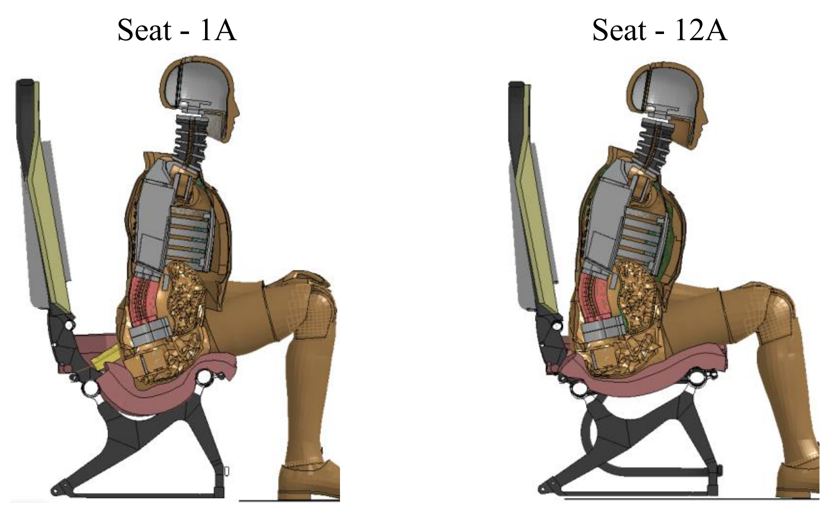


Figure 25. Kinematic Response Comparison between Seat 1A and Seat 12A at Simulated Peak Pelvis Acceleration

Simulations of the Hybrid III -5th, -95th, and THOR 50th resulted in similar correlation trends to those observed in the FAA Hybrid III (Table 2). All breakout occupant FEMs exhibited the closest correlation along the vertical direction. The poorest correlation was observed in the pelvis horizontal response. These results indicate that the primary vertical load was accurately transferred through the seat FEM to the various ATD FEMs while there was a systemic inadequacy in the components of the breakout occupant FEM that drive horizontal response. The Hybrid III 95th exhibited the poorest correlation overall while the 5th exhibited the highest. Seated next to each other, these two ATD's were driven from the same acceleration pulse, and discrepancies in correlation accuracy are likely due to differences in predictive capabilities of the ATD FEMs. Correlation plots for all ATD response comparisons is provided in appendix A.

Table 2. FEM Simulation ISO Correlation Scores Calculated for the Hybrid III 5th, Hybrid III 5th, and THOR 50th

Seat	Head AX	Head AZ	Chest AX	Chest AZ	Pelvis AX	Pelvis AZ	Spine FZ	Neck FX	Neck FZ	Neck MY
					Hybrid III 95th					
5A	0.34	0.57	0.19	0.67	0.27	0.48	0.66	0.16	0.53	0.27
					Hybrid III 5th					
5B	0.63	0.46	0.71	0.61	0.51	0.78	0.67	0.40	0.70	0.31
					THOR 50th					
3E	0.69	0.58	N/A	N/A	0.24	0.73	0.51	0.48	0.48	0.35

4.5 RESULTS – Correlation to Secondary Impact

The ability of the developed breakout occupant FEM to accurately predict the secondary loading event between the ATDs and the forward seatback was inconsistent. The FEM simulations were not able to precisely predict the timing of the contact between ATD and seatback in any of the compared seat locations. Simulation of the FAA Hybrid III in seat 3A, 6D, and 12A exhibited the closest approximation of the head strike timing for this ATD configuration (Figure 26). The simulated ATD at each of these locations predicted the time of contact with the seat back within 10-ms of that observed in test. In seat 3A and 6D, this timing corresponds with a similar peak resultant head acceleration between test and simulation. In 12A the simulation greatly over-predicts head acceleration resulting from that contact. The FAA Hybrid III in seat 10C does not appear to have impacted the forward seatback in the test, as the sharp spike in head resultant acceleration associated with this contact was not observed. The FEM simulation predicts head contact in seat 10C at a similar approximate time to the contact observed for the other FAA Hybrid III ATDs in the aircraft. Internal video focused on this seat location was lost, making it difficult to determine the source of this discrepancy between test and simulation.

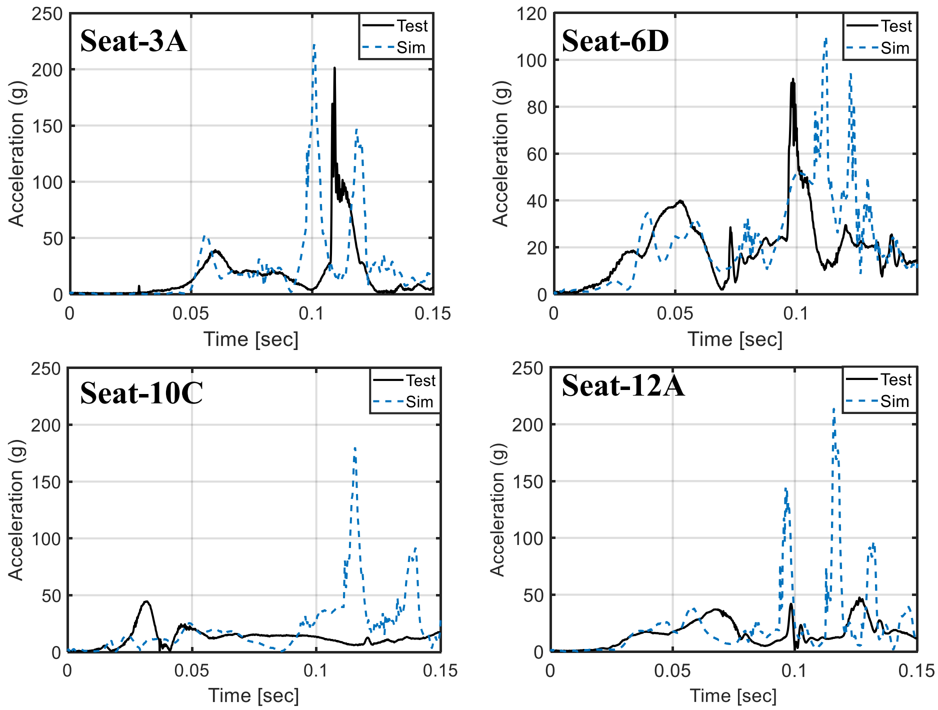


Figure 26. Comparisons of FAA Hybrid III Head Resultant Acceleration Response through Secondary Impact

Similar to the FAA Hybrid III FEM predictions of secondary impact, the Hybrid III -95th,-5th, and THOR FEMs all over-predicted the head resultant acceleration induced during secondary impact with the forward seatback (Figure 27). The timing of contact is closely predicted by the THOR and Hybrid III 95th FEM while it is predicted to occur earlier by the Hybrid III 5th FEM.

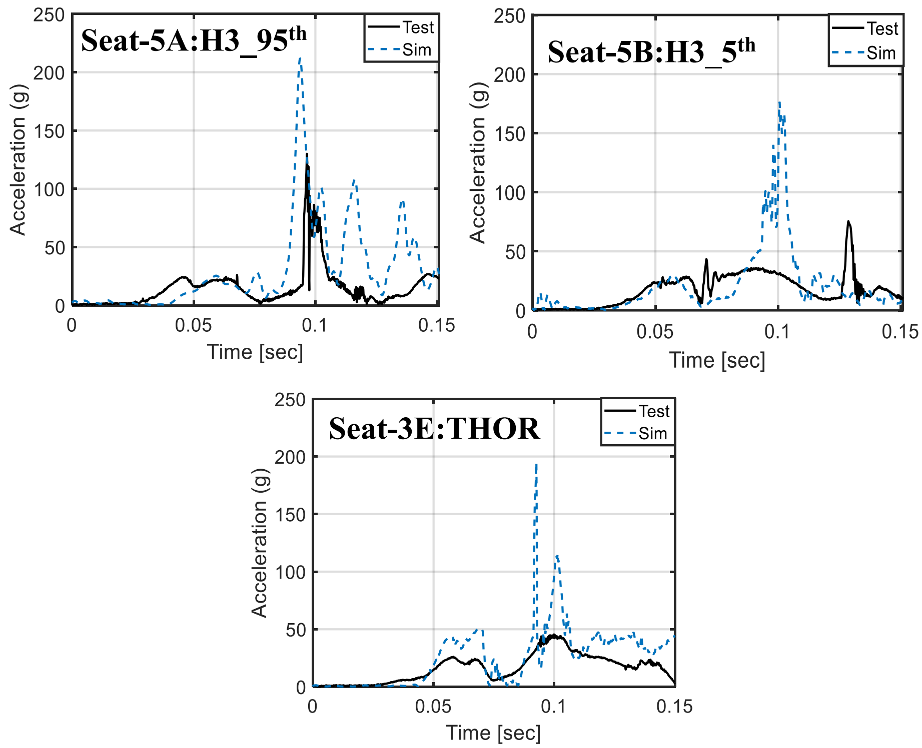


Figure 27. Comparisons of Hybrid III -95th, -5th, and THOR Head Resultant Acceleration Response through Secondary Impact

The head resultant accelerations predicted by the FEMs of each ATD evaluated during secondary impact exhibit a similar range of peak values, with most contact producing close to 200g of peak acceleration. The accelerations measured during the full-scale test exhibited significantly larger variability. The Hybrid III FAA head contact with seat 3A produced resultant accelerations close to the 200g range while the Hybrid III FAA seated in 12A exhibited less than 50g on contact. This variability is hypothesized to be dependent on inconsistent flexibility in the rotation of the seatbacks throughout the test article. During the test, high variability in seatback flexibility was observed both pre- and post- contact. This variability affected timing of contact, due to variations in seatback position, as well as energy transferred into the ATD due to variability in stiffness. The most significant example of this seatback variability was observed in seat 2E and 2D. The contact between the Hybrid II in seat 3D and the 2D seatback resulted in a full 90° rotation of the seatback (Figure 28). This rotation resulted from failure of the seatback reclining mechanism. The seatback in 2E, on the other hand, barely rotated upon contact with the THOR in 3E. The lack of rotational flexibility of the 2E seatback resulted in the THOR head being wedged under the tray table. Capturing this variability would require individual tuning of each seatback within the FEM. Though this process may have improved correlation, it would limit the applicability of these findings beyond the specific conditions of the seats used in this test.

a) Pre-Impact *b) Post-Impact*

Figure 28. Seatback Rotation Variability Observed in Row 2 Port Seats

The Hybrid II ATD seated in 9D had no forward adjacent seat row and thus provides a means for test to analysis comparison of secondary loading response without seatback contact. Although the head and neck components of the Hybrid II ATD differ from the FAA Hybrid III ATD configuration used to simulate it, the resultant head acceleration response was reasonably predicted throughout the initial and secondary loading phases (Figure 29). This similarity in inertial response further indicates the differences observed between test and simulation where there was head strike with the seatback arose from variability in the seatback stiffness not captured by the FEM. Comparison of kinematic response between test and simulation within seat 9D shows the FEM closely predicted the inertial motion of the ATD (Figure 30).

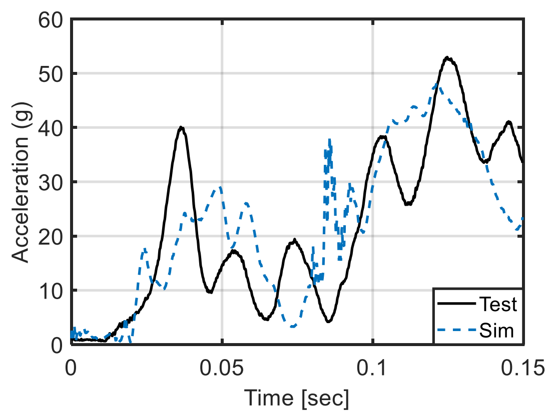


Figure 29. Comparison of Head Resultant Acceleration Response through Secondary Loading without Seatback Contact – Seat 9D

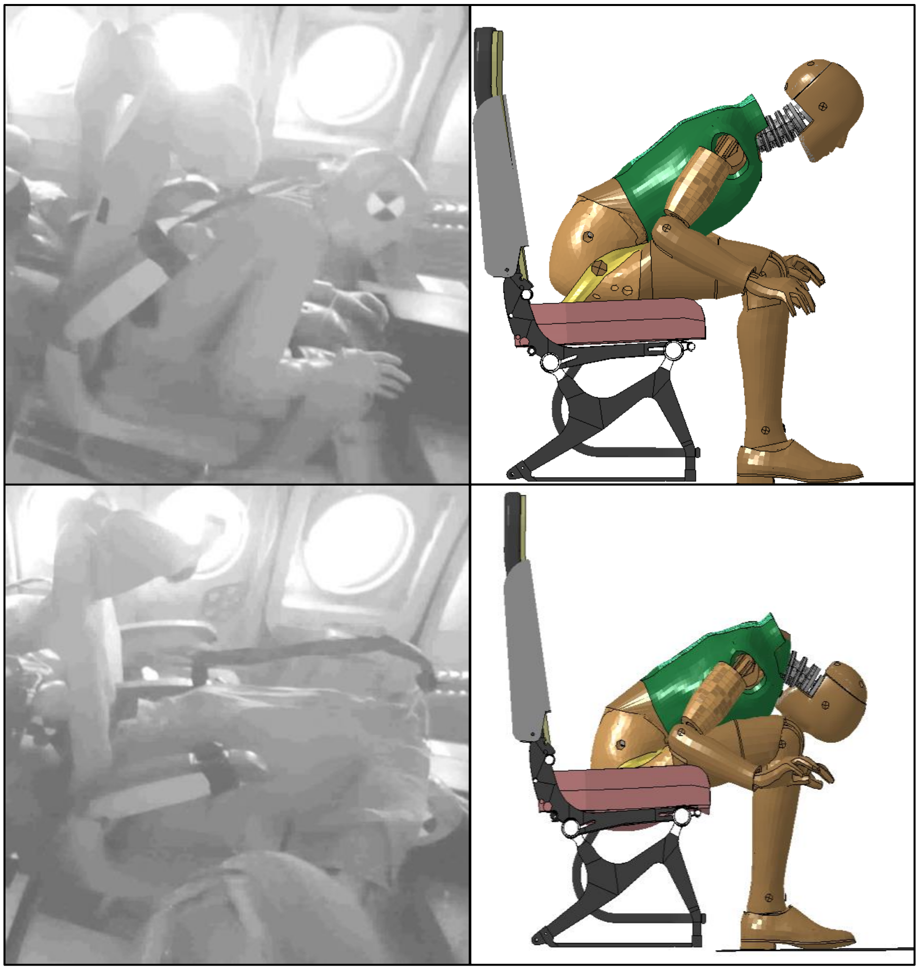


Figure 30. Kinematic Response Comparisons between Test and Simulation – Seat 9D

5.0 - DISCUSSION

Component tests of the Fokker F28 fuselage sections were found to be overly compliant in airframe stiffness, which resulted in an under-prediction of occupant injury risk expected in the full-scale crash environment. The Forward Section test exhibited significant structural deformation and failure. The increased structural stiffness imparted by the complete aircraft structure and uniform luggage foam surrogate under the Forward Section floor structure are hypothesized to account for lack of structural failures observed in this region during the full-vehicle test. Though no failure was observed in the seat rail frames during the full-scale test, investigation into damage in the subfloor station components is ongoing as the vehicle is disassembled. The effect of luggage surrogate on structural response will be verified once this investigation is complete. In addition to the reduced structural compliance, the horizontal velocity imparted to the ATDs during the full-scale crash likely drove the increase in occupant injury risk. These effects highlight key differences between component and full-vehicle testing which must be accounted for when using sub-scale testing to predict aircraft crashworthiness.

The FEM simulations of the full-scale crash test provided closer predictions of average seat acceleration and ATD peak lumbar loads measured during the full-scale test than those approximated by the component tests. The predictive accuracy of the full-vehicle FEM was an important factor in predicting lumbar loads as the breakout occupant FEMs were driven using seat acceleration time histories predicted by the full-vehicle FEM simulation. The breakout FEMs were driven using the simulated seat accelerations in order to evaluate the capability of the developed vehicle and occupant FEMs to be used together to predict occupant injury risk for dynamic impact conditions not tested. Because of this, modeling error in the full-vehicle FEM was compounded through the simulation of the breakout occupant FEMs.

Vehicle predictions of the seat accelerations at the front of the aircraft exhibited a delay between the rise of vertical and horizontal acceleration on impact [6], with the peak vertical acceleration occurring later in the simulation than test. This delay caused the ATD FEMs to move more forward in the seat, driving the spine-box into alignment with the front seat pan support tube during peak vertical load. When driven from test accelerations, in which the timing of the horizontal and vertical accelerations were closer aligned, the forward motion of the FEM prior to vertical loading was reduced along with predicted lumbar loads. This methodology brought predictions closer to those measured in test. The relationship between forward motion in the seat and lumbar loading is hypothesized to partially drive differences in lumbar load observed between the full-scale and component tests due to the lack of horizontal loading in the latter.

Overall, the breakout occupant FEMs provided adequate prediction of vertical responses within each ATD simulated as demonstrated by the ISO 16250 correlation scores. Horizontal responses were poorly predicted. These results indicate that the vertical loads were being correctly transferred through the seat structure into the ATD FEMs while the combination of factors affecting horizontal response are not being accurately accounted for. The transfer of horizontal acceleration from the seat into the ATD occurs through the lap belt and friction between the ATD and the seat/floor. Unknown variables, which affect this horizontal load transfer, include belt tension applied during the qualitative tightening process, position of the belt on each ATD pelvis, which was difficult to discern through the 3D scans due to the small thickness of the belt, and coefficients of friction between ATD and the seat/belts. All factors likely contribute to the horizontal prediction errors observed. Future efforts will work to better quantify these unknown parameters to improve FEM correlation.

The correlation of the Hybrid II ATD to the FAA Hybrid III FEM was found to be limited, particularly in the horizontal response of the head and pelvis. Part differences between these two ATD configurations likely drive these discrepancies. The pelvic flesh and neck parts of the Hybrid II ATD and the FAA Hybrid III FEM are different [19]. Though considered to provide similar loading into the lumbar spine under vertical loading, differences in pelvis shape between the two ATD's affect belt routing and thus motion along the horizontal plane. The neck of the Hybrid II ATD is made of a single rubber material while the FAA Hybrid III has a segmented neck designed to capture the flexibility of the human neck in flexion and extension. The physical difference resulted in a stiffer head-neck response in the Hybrid II ATD, which was not captured using the FAA Hybrid III FEM.

The Hybrid III 95^{th} FEM exhibited the poorest correlation overall. This FEM was developed by geometrically scaling the Hybrid III 50^{th} FEM [20]. Though providing approximate size and mass of the 95^{th} ATD, this FEM has not been validated to ensure it matches the actual part size or materials used in the 95^{th} ATD. Additional work, beginning with validating the geometry and material properties, is needed to improve the predictive capability of this FEM before being used to confidently predict ATD response.

The Hybrid III 5^{th} FEM used in this analysis was developed by the ATD manufacturer Humanetics®. Since this ATD is currently defined within automotive certification requirements, the FEM has been extensively validated through use in the automotive crash environment. Though the 5^{th} ATD FEM has not been validated extensively in the vertical impact direction, the model exhibited the closest correlation to test of all ATD FEM's in this analysis. These results provide confidence in the use of the Hybrid III 5^{th} FEM in the aerospace crash environment.

The THOR FEM exhibited similar correlation to the FAA Hybrid III FEM. The pelvis and lumbar-spine vertical responses are well predicted while horizontal responses are poorly predicted across the ATD. Improved definition of unknown environmental variables that are driving the horizontal response, discussed for the FAA Hybrid III FEM correlation, would be expected to improve the THOR FEM correlation as well. In addition, previous FEM evaluation efforts have primarily focused on uniaxial loading, with material calibration being performed to match response in isolated horizontal and vertical load conditions. Response under combined horizontal-vertical loading has not been thoroughly validated. Future developmental work on this FEM should focus on calibration within a controlled multi-axial load environment to improve confidence in its predictive capability for aerospace crashworthiness.

The breakout occupant FEM prediction of secondary head impact, head strike with the forward seatback, exhibited similar peak resultant head acceleration values across simulated ATD types and seat locations. Secondary response measured in the full-scale test data exhibited much larger variability. The variability in head strike timing and peak acceleration value observed in the test is consistent with high variability in seatback flexibility observed during the crash event. In the onboard high-speed video, flexibility between the seatbacks and seat structure was observed throughout the cabin. The amount of rotation observed as the airframe decelerated was variable between seats, with some seats exhibiting a quick forward rotation followed by a rebound while others continued forward for an extended period. The extent of this rotation had a direct effect on the timing and location of the secondary impact with the ATDs. In addition, the rotational velocity of the seatback, in both magnitude and direction, would directly affect energy transferred into the ATD head form and thus measured acceleration. This variability in stiffness could be due to a variety of factors, including effects of the ATDs seated in that row to previous wear on the reclining mechanism of each seat. This variability in seatback stiffness was not captured in the breakout occupant FEMs; a nominal value was used to represent the average seatback response observed. Though manually tuning each seatback FEM to match rotation observed in the test would improve correlation of secondary impact, the results would be specific to the condition of the seats tested and not extensible to a nominal vehicle configuration. A full characterization of seatback flexibility, the components affecting it, and what drives the variability observed in test is necessary to correctly implement seatback flexibility and accurately predict secondary impact loading.

6.0 CONCLUSIONS

In this study, comparisons of ATD response predictions were performed to assess the capability of using simplified test methods and finite element modeling to predict aircraft crashworthiness. Component fuselage section tests were performed under vertical impact conditions matching the full-scale crash test, but lacked a representative horizontal loading component. Differences in structural compliance and lack of horizontal loading was found to drive significantly lower lumbar injury risk predictions in the component tests than those observed in the full-vehicle test. FEM simulations, using models calibrated from component tests, were found to provide a closer prediction of lumbar injury risk but lacked good correlation in the horizontal direction. Predictive limitations of component testing and FEM simulations were characterized. This characterization will aid in the development of improved test and FEM methodologies as well as inform the need for test and FEM fidelity standards for certification of aerospace vehicle crashworthiness.

7.0 REFERENCES

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Appendix A.

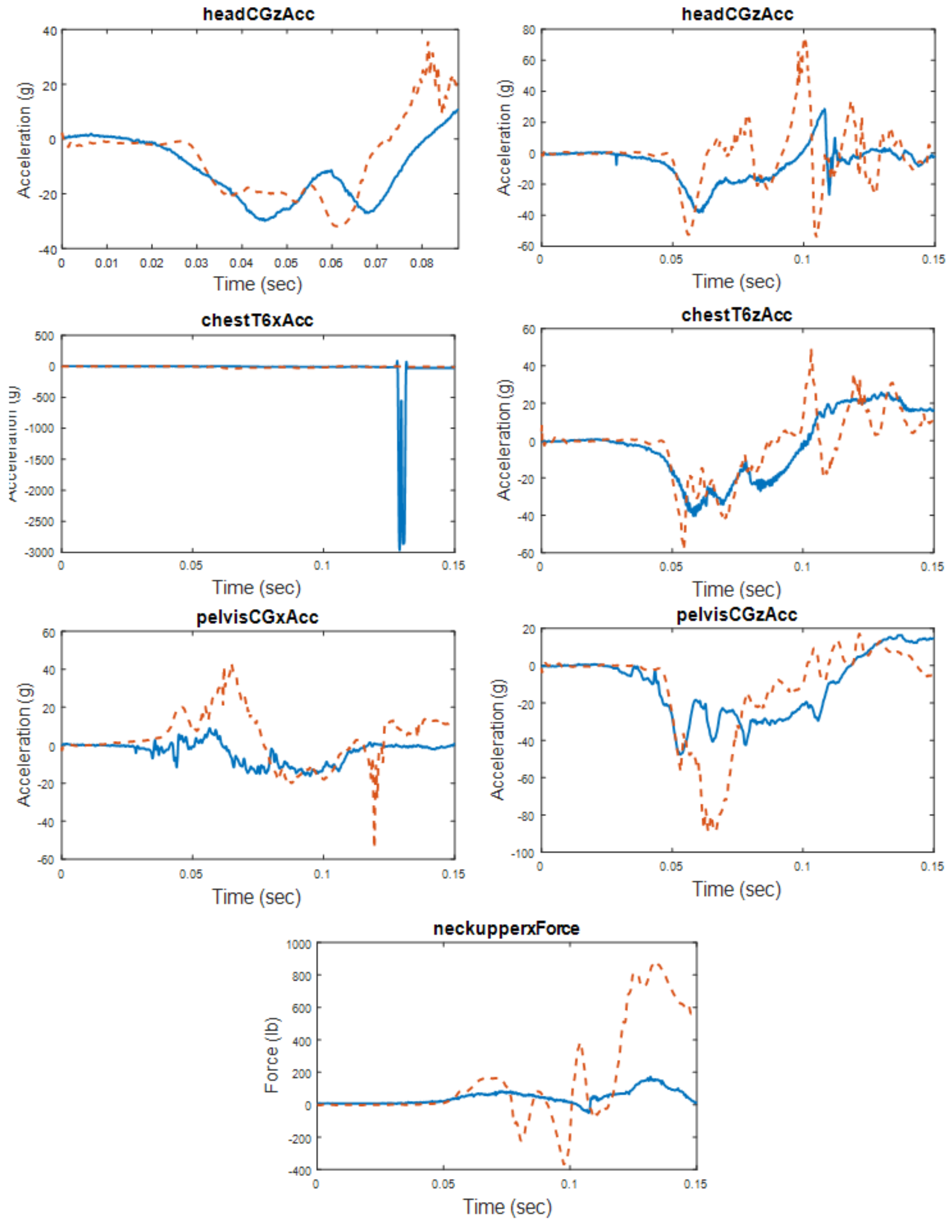

Figure 31. Seat 1A - Hybrid II Primary Impact Correlation Results (Simulated with FAA Hybrid III FEM)

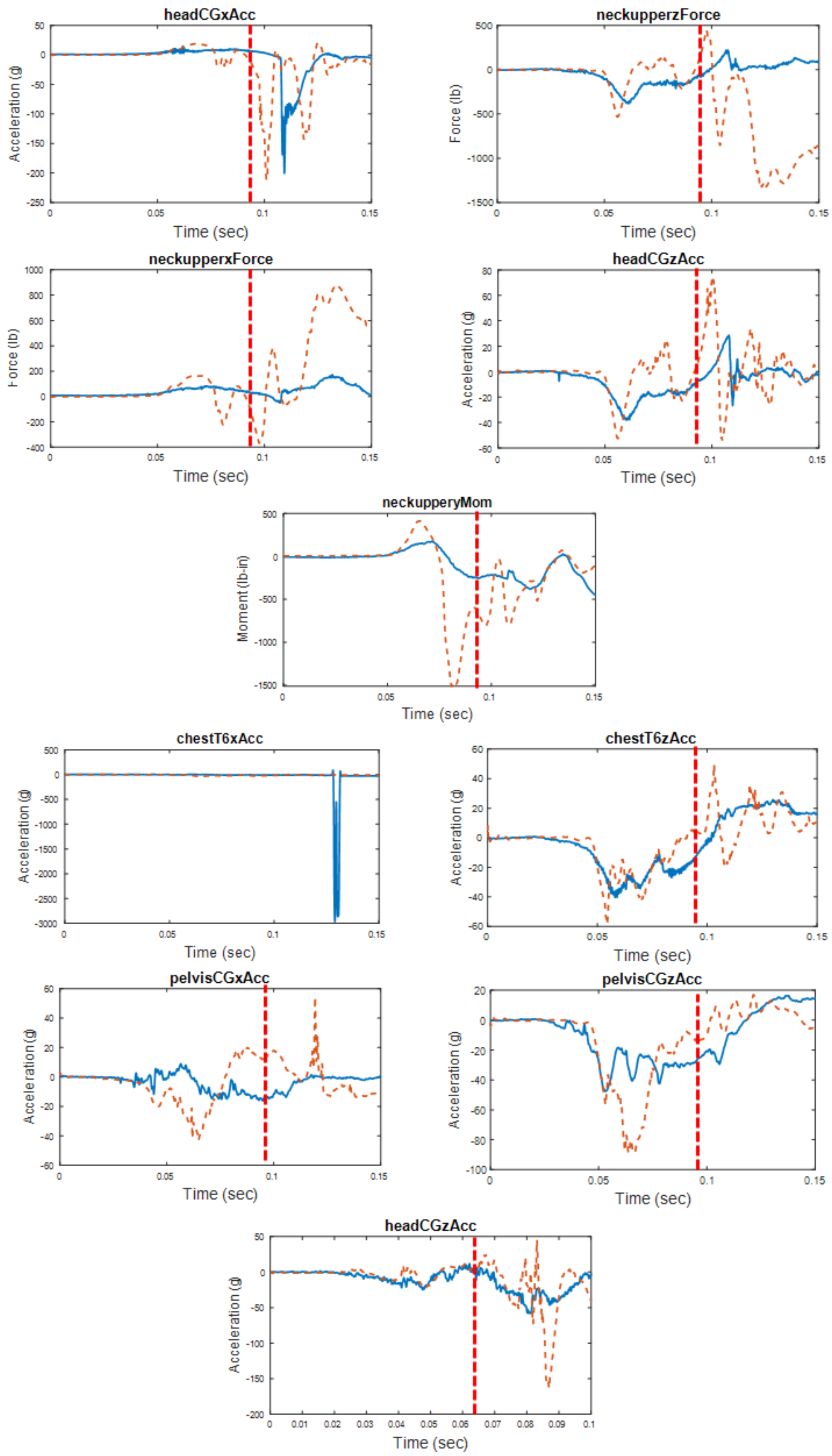

Figure 32. Seat 3A – FAA Hybrid III Primary & Secondary Impact Correlation Results

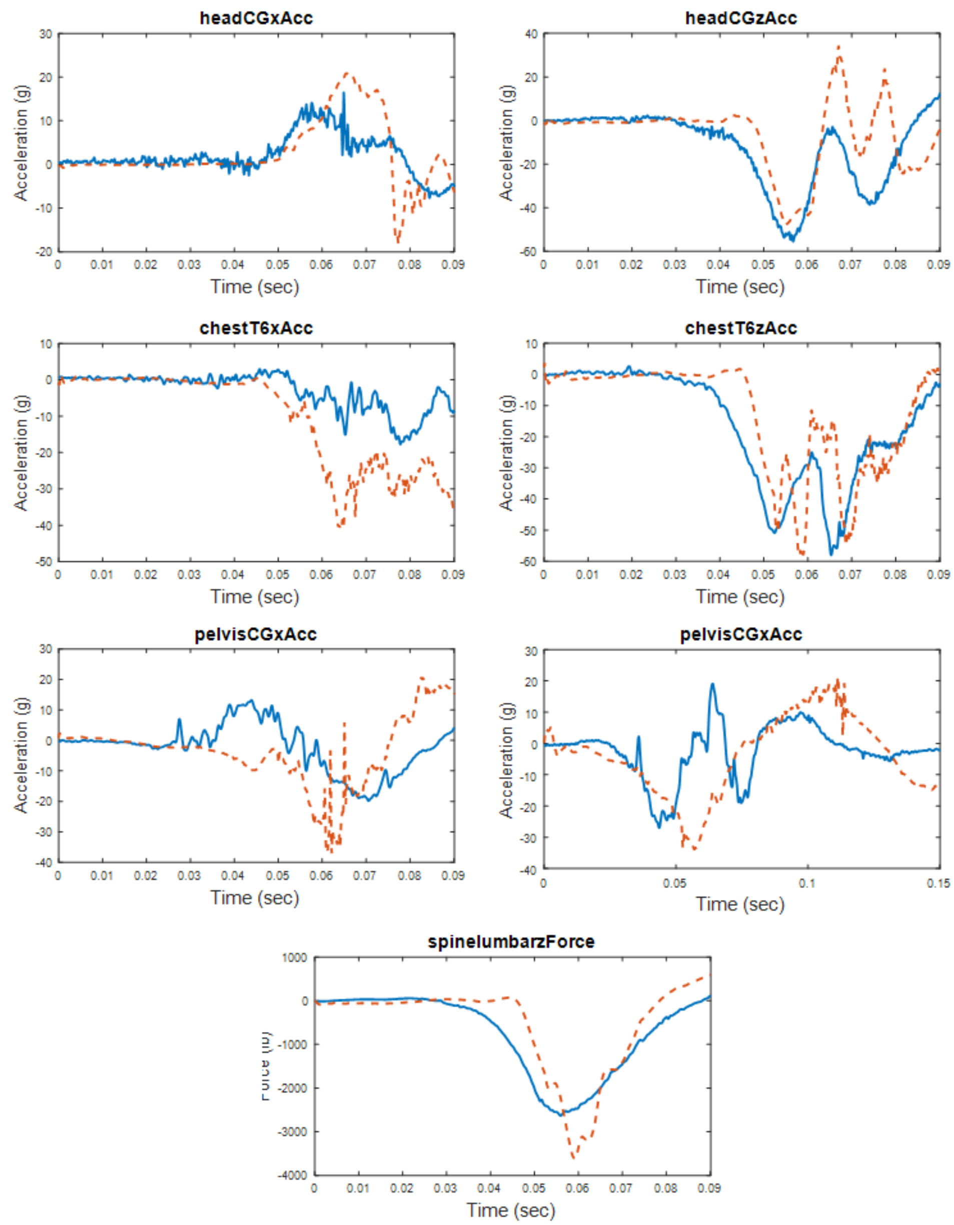

Figure 33. Seat 3D - Hybrid II Primary Impact Correlation Results (Simulated with FAA Hybrid III FEM)

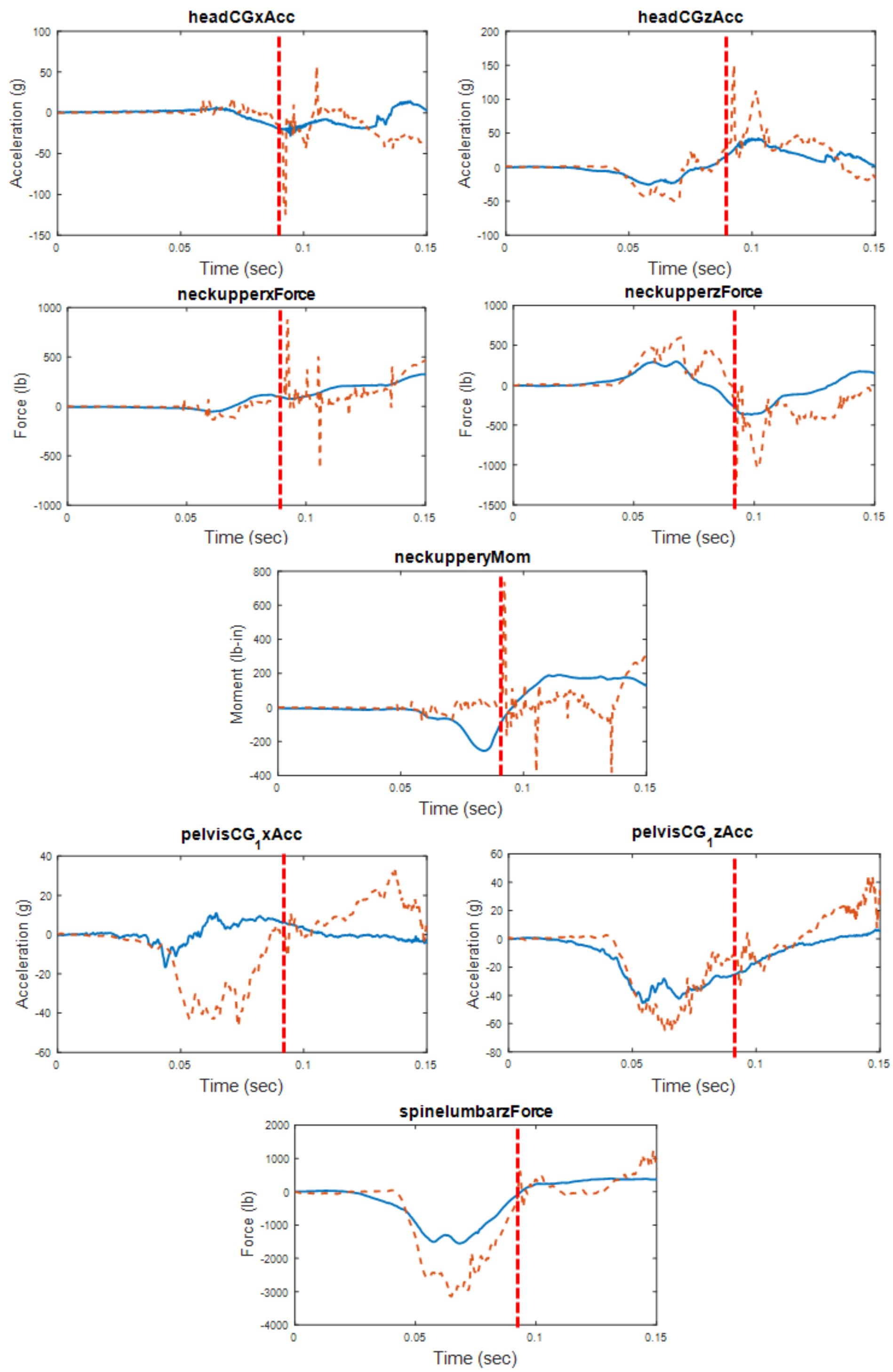

Figure 34. Seat 3E – THOR Primary & Secondary Impact Correlation Results

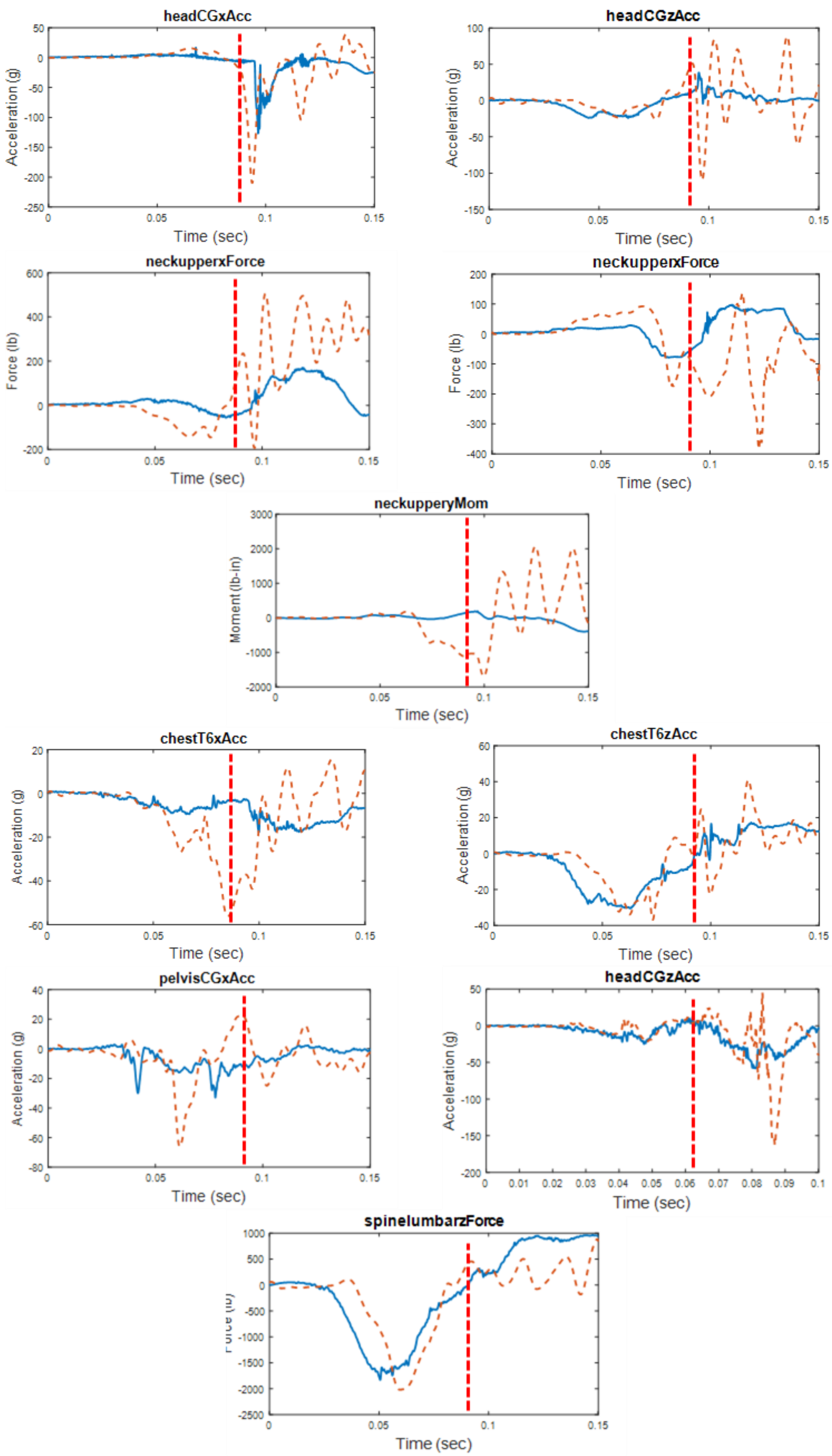

Figure 35. Seat 5A – Hybrid III 95th Primary & Secondary Impact Correlation Results

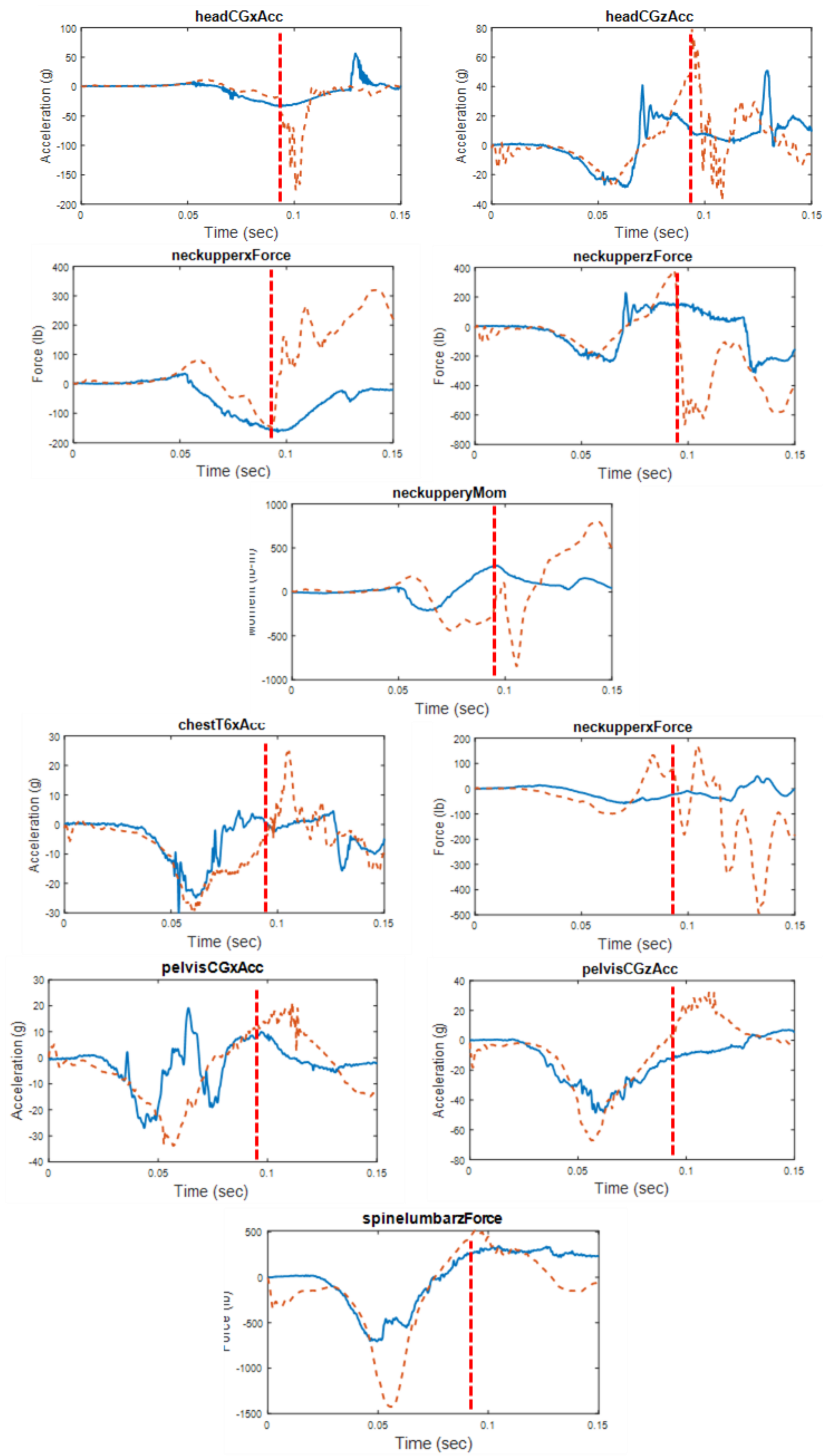

Figure 36. Seat 5B- – Hybrid III 5th Primary & Secondary Impact Correlation Results

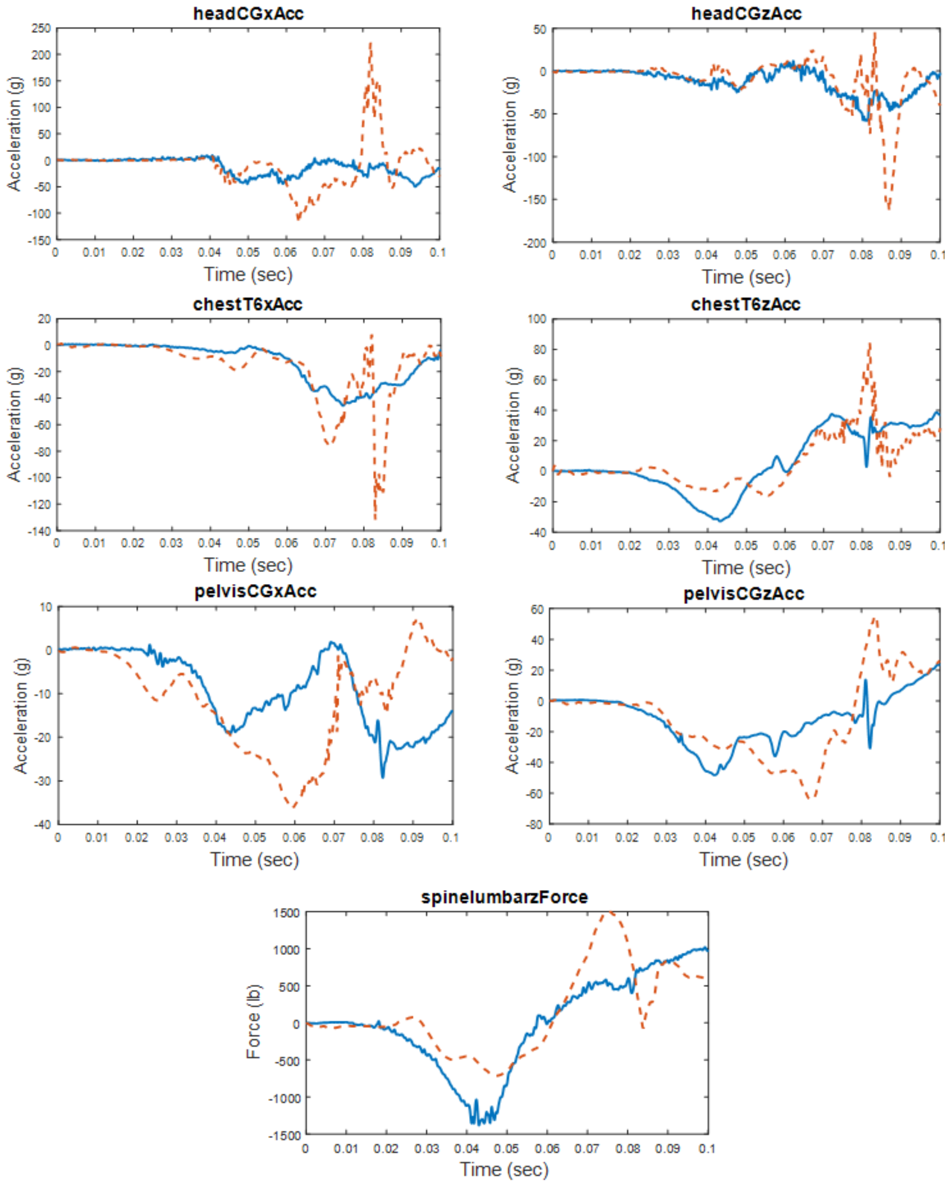

Figure 37. Seat 6A - Hybrid II Primary Impact Correlation Results (Simulated with FAA Hybrid III FEM)

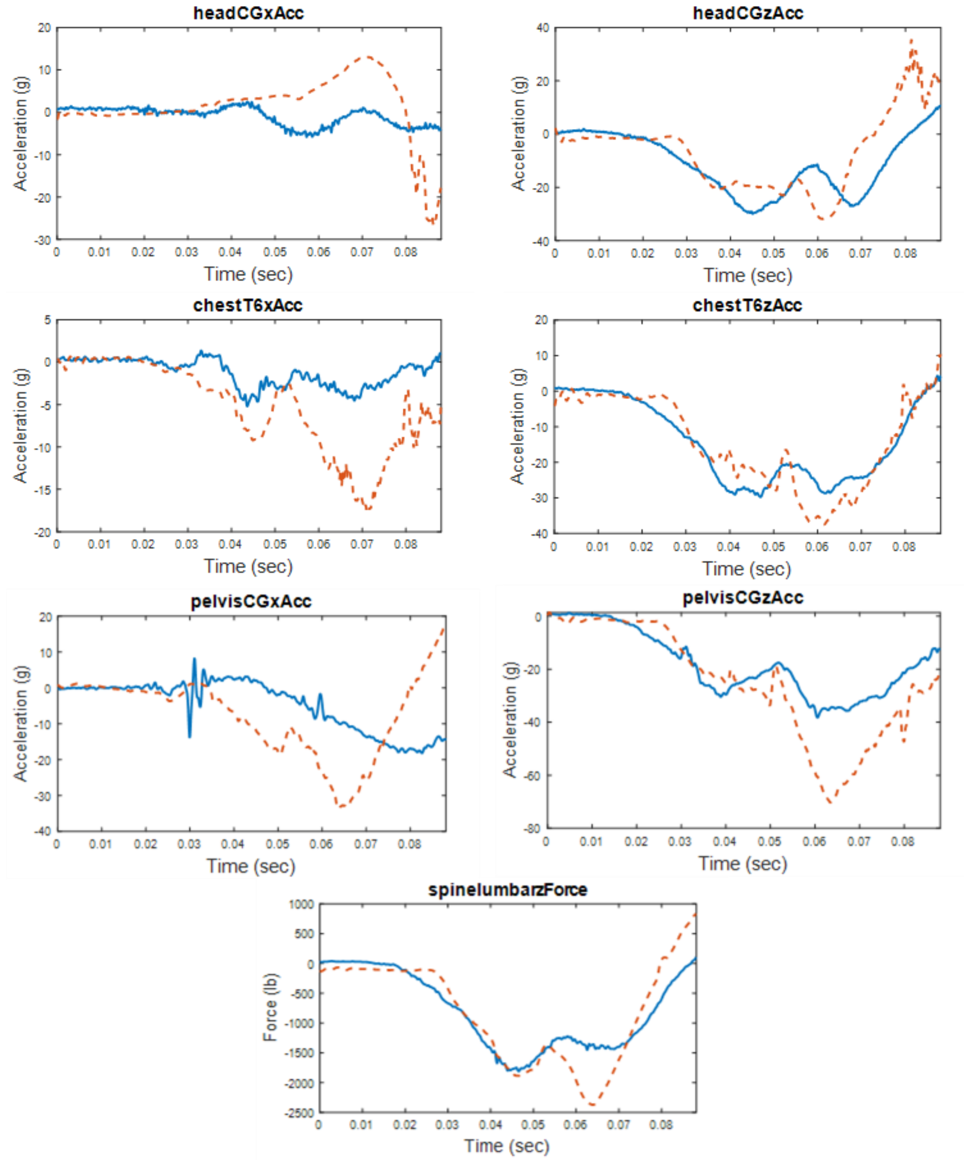

Figure 38. Seat 6B - Braced Hybrid II Primary Impact Correlation Results (Simulated with FAA Hybrid III FEM)

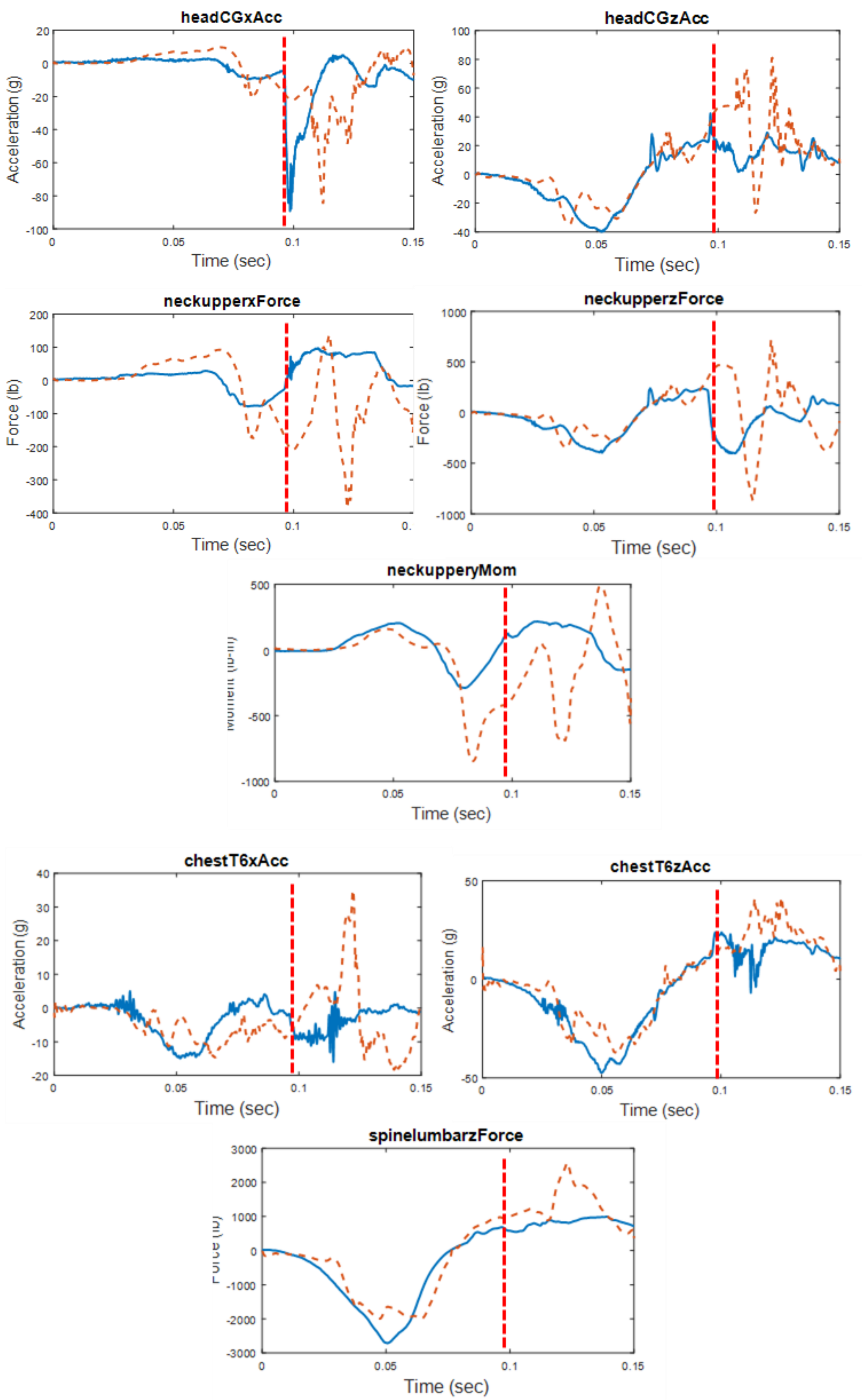

Figure 39. Seat 6D – FAA Hybrid III Primary & Secondary Impact Correlation Results

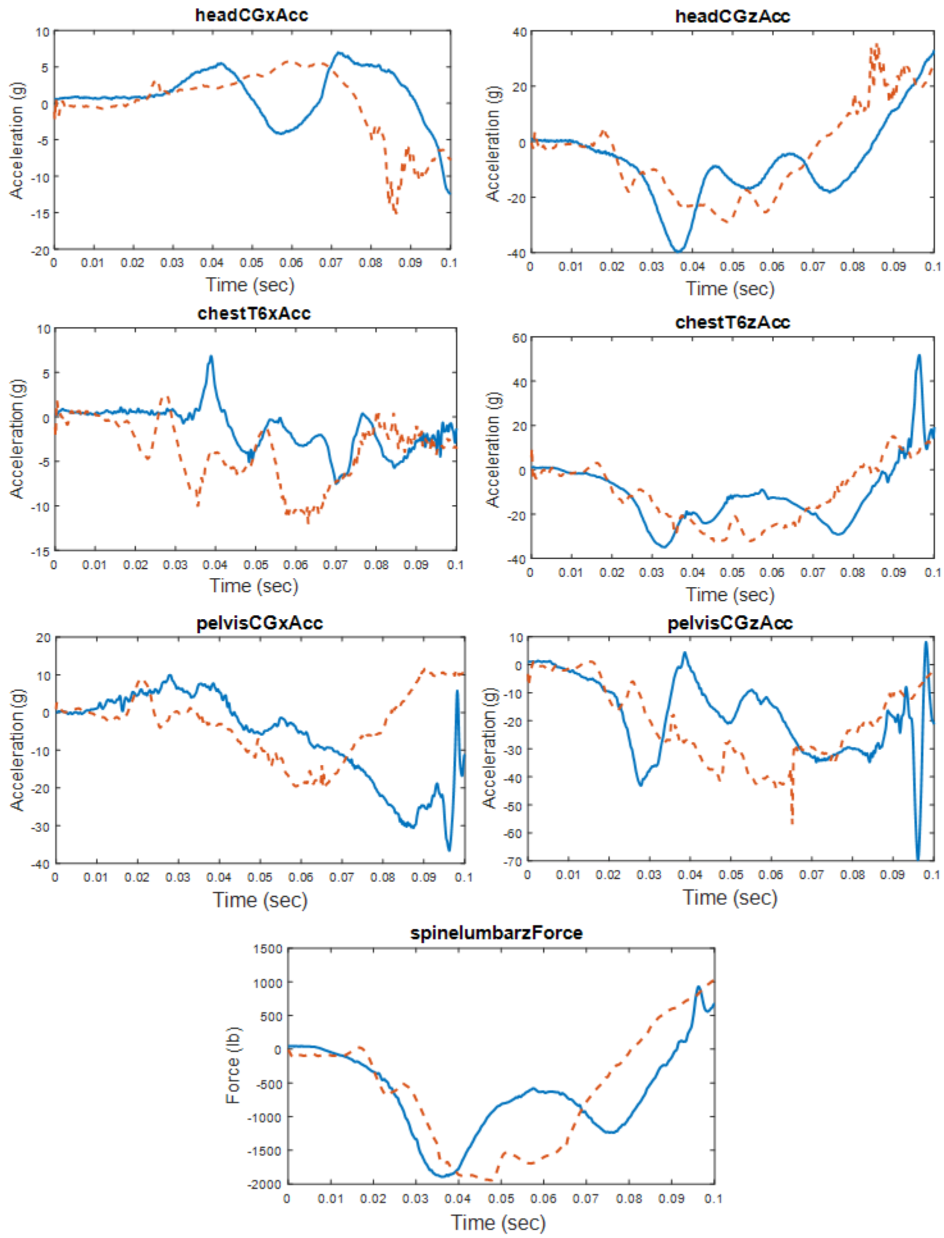

Figure 40. Seat 9D - Hybrid II Primary Impact Correlation Results (Simulated with FAA Hybrid III FEM)

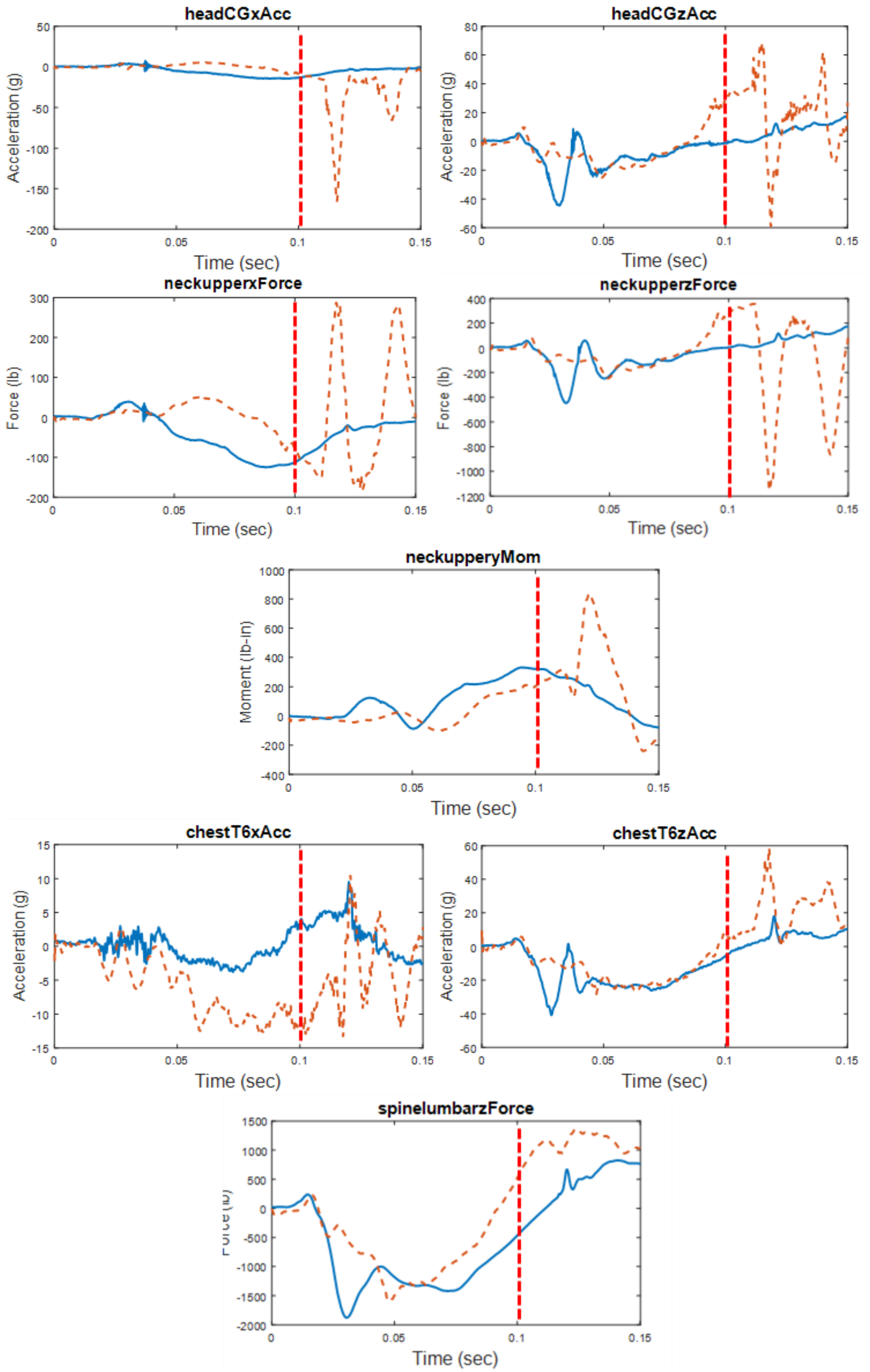

Figure 41. Seat 10C – FAA Hybrid III Primary & Secondary Impact Correlation Results

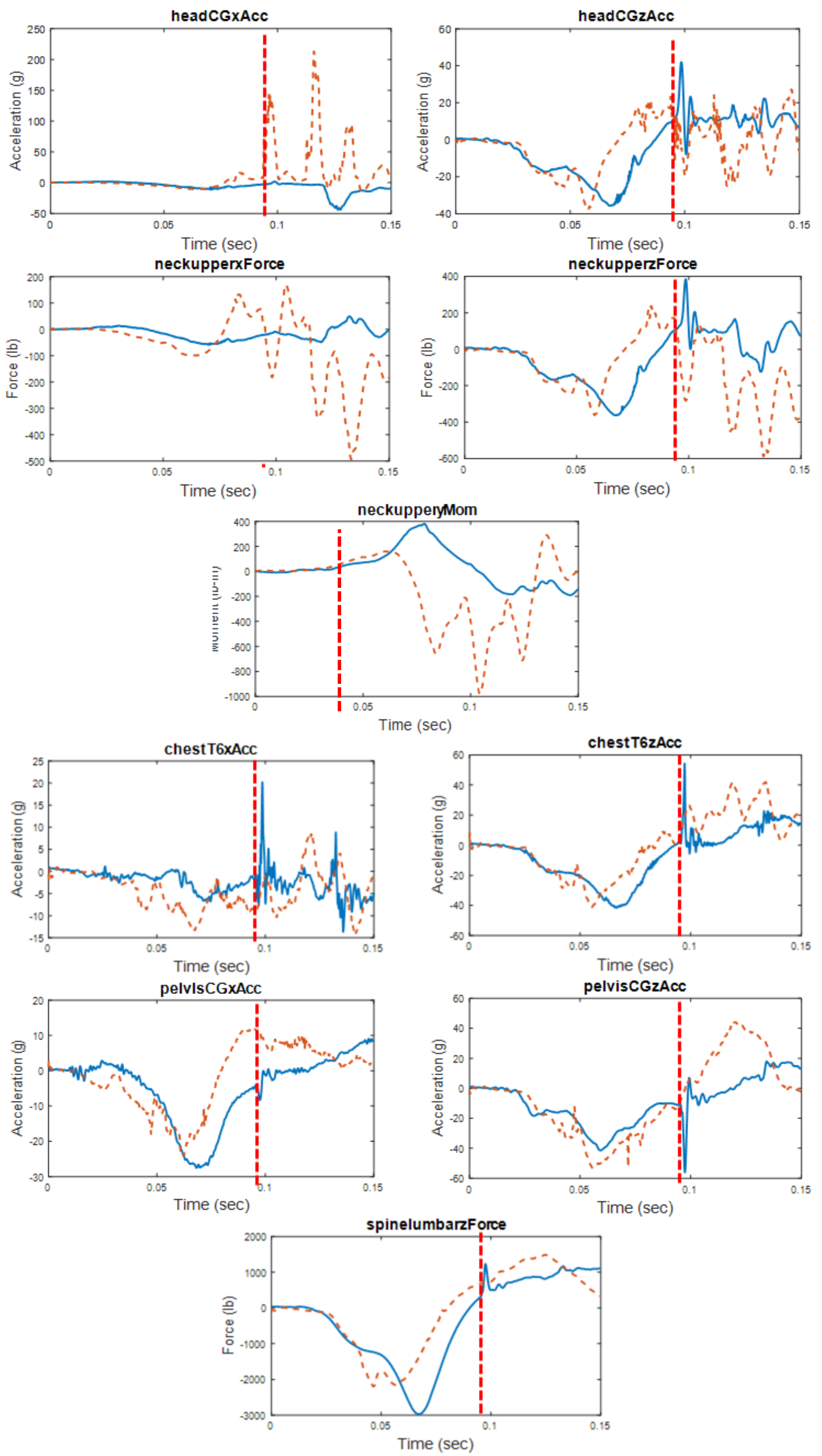

Figure 42. Seat 12A – FAA Hybrid III Primary & Secondary Impact Correlation Resul

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14. ABSTRACT
In this report, the capability of component fuselage testing and finite element models (FEMs) to predict occupant injury risk when applied to full-scale aircraft crash testing was evaluated. Component level and full-scale crash tests of a Fokker-F28 aircraft were performed in conjunction with representative FEM simulations. Lumbar spine injury risk, calculated through Anthropomorphic Test Device (ATD) outputs measured in the full-scale test, was compared with predictions made by component level testing and simulations. A quantitative assessment of FEM prediction accuracy was made using the International Organization for Standardization (ISO) Technical Report (TR) 16250 curve comparison methodology. Lumbar load injury risk measured in the full-scale test configuration was found to be significantly higher than in the component tests performed. The FEM provided a closer prediction of occupant injury risk than component testing but exhibited limitations in the multi-axis load environment. This work will help inform the application of component testing and FEM simulation when used to evaluate aircraft crashworthiness.

15. SUBJECT TERMS
Crash impact simulation; LS-DYNA; Test-analysis correlation

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