

Component Characterization of an eVTOL Reference Model for Crashworthiness Studies

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ABSTRACT

Researchers at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) have conducted a series of structural component and seat level tests to improve finite element model (FEM) characterization of a representative vertical take-off and landing (eVTOL) test article developed by NASA. A full-scale dynamic test was conducted on the representative eVTOL test article in November of 2022. The test article represented a high wing, six passenger eVTOL design concept and is referred to as the lift plus cruise (LPC) test article. The full-scale test identified limitations in the analytical models used to predict aircraft structural response, in particular the composite material models did not effectively capture brittle failure of the structure which were measured during dynamic loading. To better understand the mechanism behind the composite material failure mechanisms observed and to improve the FEM, intact sample specimens of the composite airframe structure were recovered from the test article post-test and used in material characterization testing. In addition, the seat configurations used in the LPC test article were further studied using isolated seat and anthropomorphic test device (ATD) drop tower testing.

Dynamic compression tests and three-point bend tests, conducted at varied impact speeds, were performed on the recovered frame section specimens. Additional testing was conducted to characterize the material properties of the forming foam, which remained in the frames after fabrication. These tests were used to improve characterization of the damage and failure parameters of the composite material model used in the FE model of the LPC test article. Seat level tests were conducted on the seats used in the LPC test article using acceleration pulses inclusive of current general aviation and rotorcraft certification load levels as well as conditions representative of those measured at the seat base during the LPC test.

The structural material models and seat environment models of the LPC test article FEM were calibrated using the generated component test data. The updates made to these models were then integrated into the LPC FEM and simulated in the full-scale test condition. Results demonstrated the effectiveness of component testing to improve predictive capability of composite aerospace structural models within the crash and dynamic loading environments. Demonstration of the LPC FEM response across an accumulation of coupon, component, seat environment, and full-scale test levels provides confidence in the predictive capability of this model for future use in the study of occupant safety within eVTOL relevant crash environments.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Revolutionary Vertical Lift Technology (RVLT) project has been working to develop new technologies and methodologies to improve electric Vertical Take-off and Landing (eVTOL) design for the public good. One thrust of

this effort has been to develop methodologies to better characterize vehicle safety within crash loading environments and to develop technologies which can help mitigate occupant injury risk during dynamic loading events. As part of this effort the RVLT project designed, fabricated, and tested a representative eVTOL airframe cabin in a full-scale crash impact environment [131]. This test was used to assess the response of the lightweight all-

composite airframe structure to crash loading conditions and to evaluate the capability of energy absorbing structures to improve occupant safety. The test also served as a valuable data point for evaluating the capability of finite element models (FEM) to predict the crashworthiness of a lightweight composite vehicle structure [2].

The airframe test article was based on the NASA Lift plus Cruise (LPC) concept vehicle architecture [3]. An image of this vehicle concept is shown in Figure 1. The vehicle design includes high wings with multiple rotors, a large cabin capable of seating six occupants, and a lightweight composite material structure. The LPC architecture was selected as the basis for the airframe test article due to having similar features with production eVTOL aircraft. In addition, the vehicle concept is open source.



Figure 1. NASA Lift Plus Cruise (LPC) concept vehicle.

The initial FEM of the LPC design was generated using manufacturing design specifications and coupon level material test data on representative flat panel samples. The initial FEM development process and the results from correlation to the test full-scale test is described in [2]. The initial vehicle FEM poorly predicted failure within the composite skin material making up the airframe structure. Post-test analysis concluded this poor predictive accuracy was due to limited characterization of the damage and failure parameters within the composite skin material model obtained from the coupon level data. Although it was shown that these parameters could be directly tuned within the vehicle to better match the full-scale test response, the question remained whether the FEM could have better predicted the test if component level test data was available. Thus, a component level test campaign was conducted to determine the predictive potential of the full-scale vehicle FEM.

STRUCTURAL COMPONENT CHARACTERIZATION

Overview

Post-test specimens were cut from the LPC test article for component level testing and material model characterization. The LPC test article was first visually inspected to identify undamaged sections for specimen

removal. The sections were then cut out from the test article and specimens were gathered. These specimens included composite skin material coupons that were cut from a section of skin behind the C-pillar, sandwich composite beam specimens (composite skin with foam core) that were cut from the B-pillar, and foam core specimens that were removed from the lower center longeron (LCL). The subcomponent specimens were tested under both static and dynamic conditions to better understand the material/structural response and to generate material properties to improve the vehicle FEM.

Composite Material: Coupon Testing

The 1-in by 10-in composite coupons (removed from behind C-pillar) were speckle coated for use with three-dimensional digital image correlation (3D-DIC) and tested using a screw-driven MTS table-top machine, with a loading condition of 0.1 in/min until failure. The axial strain in the gage section was measured using 3D-DIC and plotted versus stress. Results from these tests were compared to the pre-test coupons that were created from flat sample panels (Figure 2).

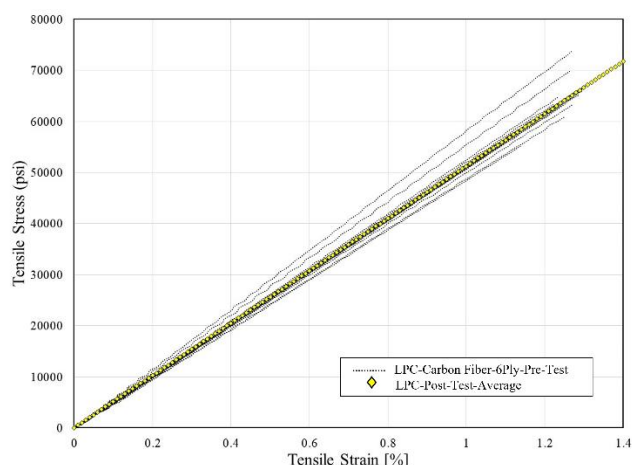


Figure 2. Post-drop test vs pre-test composite coupon comparison.

The stress-strain response measured on the post-test composite coupons from the LPC skin showed minimal variability across the samples tested and was consistent with the results measured from the flat panel samples [2]. These results verified consistent as-fabricated composite skin material response in the tested vehicle compared to the material used to characterize the stiffness of the composite skin material model. Thus, updates to the stiffness parameters of the material model were not required.

Beam Structure: Three-point Bend Testing

Dynamic three-point bend tests were conducted on the sandwich composite specimens which were cut from the B-

pillar of the post-drop test LPC test article. The specimens were speckle coated for 3D-DIC. The specimens were tested using a 14-ft drop tower, with a 115-lb impactor and a drop height of 1.5-ft and 3.5-ft to achieve a desired 10-ft/sec (herein called “low speed”) and 15-ft/sec (herein called “high speed”) impact velocity. The three-point bend test fixture consisted of two 2-in. diameter rollers spaced 12 in. apart, with a 1-in. diameter fixed roller in the middle (Figure 3). Two accelerometers were mounted to the impactor to record acceleration along the impact direction, with a sample rate of 50KHz. A pair of high-speed cameras in a stereo configuration (for 3D-DIC) were positioned to view the impact and measure the deformation and in-plane strain during the event, with a frame rate of 2,500 frames/sec and a resolution of 2.4 mega-pixels (MP).



Figure 3. Three-Point Bend Test Setup

The dynamic three-point bend tests conducted on the sandwich composite specimens were simulated to calibrate the damage and failure parameters of the composite skin material model as well as to evaluate simplifying assumptions which were made in the vehicle model to optimize computation time. A representative model of the test conditions was generated. The indenter and end support structures were modeled using rigid shell elements with curvatures matching the test fixture. Impact conditions were simulated by applying the measured impact velocity to the indenter model. Three model configurations of the sandwich composite specimens were developed. The first (baseline) model of the sandwich composite specimen was isolated from the LPC vehicle FEM and only included the composite skin material, as the internal foam which was added during fabrication to form the composite foam was not originally included. The composite skin material was represented by the `*mat_laminated_composite_fabric` material model within LS-Dyna, using shell elements with `*part_composite` to define the composite layup. The forming foam was added to the second model to evaluate its potential effect on composite response. A `*mat_crushable_foam` model was developed to represent the forming foam using material specifications provided by the vehicle fabricator. Element erosion properties were added to the foam material model using `*mat_add_erosion`

to represent crack propagation identified during testing. Element erosion was calibrated through both three-point bend and dynamic foam test simulations to effectively capture crack formation while also eliminating early erosion of the foam under compressive load. A final value of 1% tensile strain was selected for erosion of the foam elements. The third model included the foam material as well a more refined mesh. The mesh was refined from a 0.5-in to 0.25-in element length. Both the addition of forming foam and mesh refinement increased required computation time and thus would not have been efficient to examine within the full-vehicle FEM. All simulations were carried out using LS-DYNA MPP version R14.0 single precision on a Linux computer cluster. The three model configurations compared to the low-speed dynamic impact test at peak deflection are shown in Figure 4.

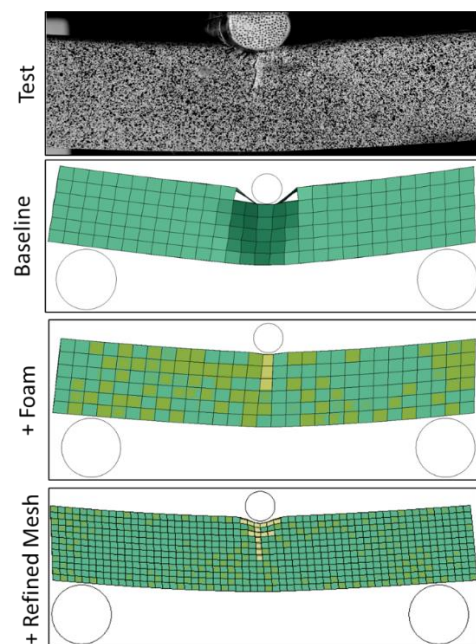


Figure 4. Low-Speed Three-Point Bend Test and Simulations at Peak Deflection

Both the forming foam and mesh refinement were found to influence the damage predicted in the composite skin when subjected to the dynamic three-point bend test conditions. The addition of the forming foam was found to reduce the extent of predicted damage. The mesh refinement was found to result in improved prediction of composite skin crack shape and extent when compared to what was measured in testing. Although additional mesh refinement may have led to further improved crack propagation prediction, 0.25-in mesh length was the smallest mesh length capable of allowing the full LPC vehicle simulation to be completed in a reasonable timeframe (<1 week). In addition to examining predicted composite damage, acceleration time histories were compared between test and simulation for each model configuration.

Comparison of predicted impactor acceleration for each model configuration simulated in the low- and high-speed three-point bend test conditions is shown in Figure 5. The baseline model configuration, taken from the LPC vehicle FEM, did not predict the measured impact acceleration. The baseline model was found to underpredict impact acceleration and to poorly represent acceleration shape. The addition of the forming foam significantly increased the stiffness of the model which resulted in an overprediction of acceleration in both the high- and low-speed impacts. The forming foam limited the prediction of specimen failure in the high-speed impact condition, identified by the drop-off in test measured acceleration at approximately 0.003 s. The inclusion of foam with the refined mesh model resulted in the closest overall prediction of acceleration time history in both test conditions. Mesh refinement reduced the peak impact acceleration, resulting in a close prediction of peak acceleration in both test conditions. Acceleration shape was also closely matched in the low-speed test condition. In the high-speed test condition, the refined mesh model did not predict acceleration shape. The poor prediction of acceleration shape in the high-speed test configuration was due to the model not effectively representing the composite brittle failure observed in testing.

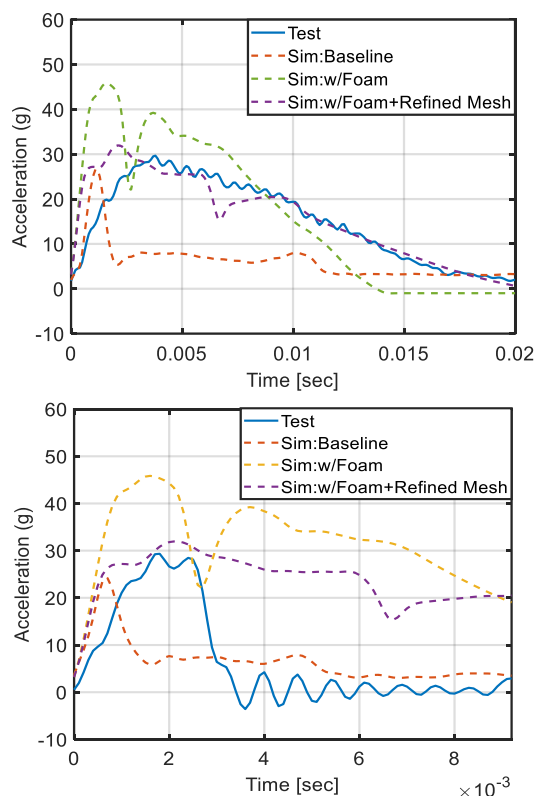


Figure 5. Test and Simulation Acceleration Response in Low-Speed (top) and High-Speed Three-Point Bend Test.

Forming Foam: Compression Testing

Once the forming foam was identified as having a tangible effect on the composite sandwich material response additional testing was conducted to better characterize the material for inclusion within the LPC vehicle FEM. The foam core specimens that were removed from the lower center longeron were tested under both static and dynamic loading conditions. The test specimens consisted of cylindrical plugs which were cut from the forming foam (Figure 6).



Figure 6. Foam-only plugs isolated from as-fabricated specimens.

The static tests were conducted using a screw-driven MTS table-top machine with a loading rate of 0.1 in/min until densification occurred. Stress-strain response of each foam specimen was calculated from the MTS machine force-displacement output (Figure 7). The crush stress of the tested foam plugs ranged between 200 to 350 psi. An average stress-strain response curve was calculated from the measured data and used as input for the *mat_crushable_foam material model generated to represent the forming foam.

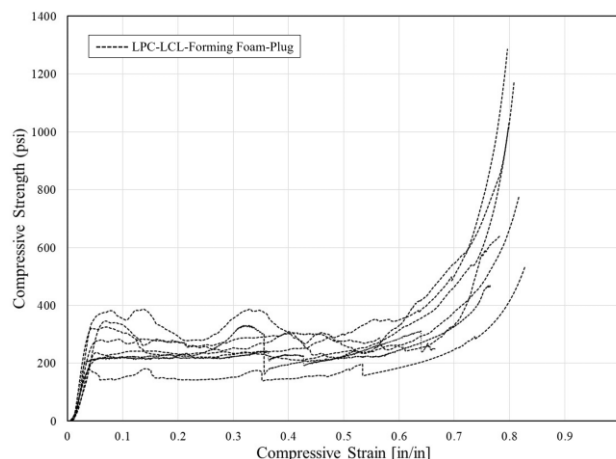


Figure 7. Forming Foam Stress-Strain response.

The dynamic test was conducted using the 14-ft drop tower with a 117.5-lb impactor and a drop height of 1-ft to achieve a desired 8-ft/s impact velocity. Two accelerometers were mounted to the impactor to record acceleration along the

impact direction, with a sample rate of 10 kHz. A pair of high-speed cameras in a stereo configuration were positioned to view the impact and subsequent deformation and failure, as well as to measure the displacement and in-plane strain during the event (using a speckle pattern on the impactor), with a frame rate of 10,000 frames/second.

A representative FEM of the forming foam dynamic impact test was generated. The geometry of the foam block tested was replicated and meshed with 0.25-in length solid elements as was used in the three-point bend model. The updated foam material model, generated from the static test data, was used in simulation. As mentioned in the three-point bend simulation analysis, the foam element erosion parameters were calibrated to accurately represent both the response measured in the dynamic foam compression test as well as that measured in the three-point bend test. Post-calibration, the forming foam model was found to produce close prediction of the acceleration time history measured on the impactor during test (Figure 8). Acceleration was closely predicted during the onset of crush through the steady state crush phase of the impact. The foam model exhibited a sharper unload response than that measured during test due to the inherently non-physical nature of element erosion. This limitation was balanced with the necessity to effectively capture tensile material failure response in the three-point bend test condition.

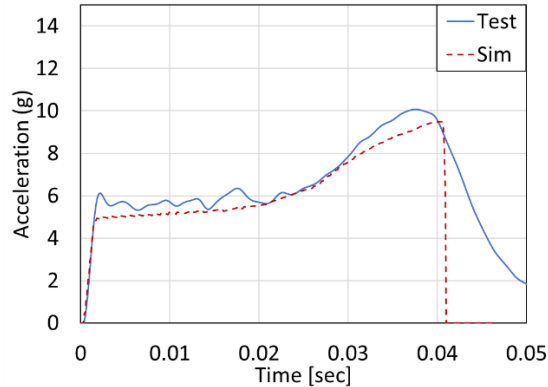


Figure 8. Dynamic Compression of Forming Foam Acceleration Correlation.

Beam Structure: Material Model

After the forming foam material model was characterized using the static and dynamic test data additional effort was put into improving the response of the sandwich composite material response within the three-point bend test environment. The preliminary evaluation of the three-point bend test model showed the inclusion of forming foam and mesh refinement resulted in close prediction of peak acceleration measured during test, but the model was limited in its prediction of specimen failure within the high-speed test condition. To improve prediction of specimen

failure, the element erosion parameters within the *mat_laminated_composite_fabric material model used to represent the composite skin material were calibrated.

Strain based element erosion is controlled within the *mat_laminated_composite_fabric material model through the ERODS parameter. Previously only a maximum effective strain limit was available within this material model. A recent update to LS-Dyna allowed directionally independent strain erosion limits to be set. This updated capability was utilized to improve model fidelity in predicting crack propagation within the composite skin material.

Initial values for the strain limit parameters in each direction were set using strain data measured on the test specimens during the three-point bend tests using 3D-DIC. Strains measured at the crack tip during impact (Figure 9) were used to determine a minimum strain to erosion value. Failure strain limits in each direction (tension, compression, shear) were then balanced to produce the crack propagation response measured in test while also limiting the non-physical energy loss associated with element erosion. This parameter balancing produced the following strain at element erosion limits: tension – 1.2%, compression – 15%, and shear – 30%. For the composite structure element erosion was specified when strain limit conditions were met in 25% of the composite material layers.

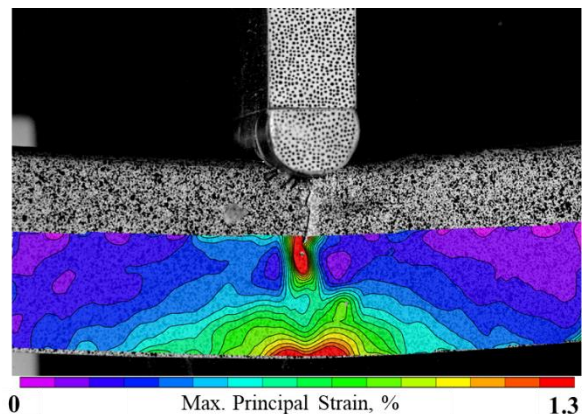


Figure 9. Principal Strain Measurement From 3D-DIC.

Calibration of the element erosion parameters within the composite skin material model resulted in improved prediction of the impactor acceleration time history during the three-point bend test conditions (Figure 10). Improved prediction of crack propagation led to close prediction of the acceleration drop-off in the high-speed impact test associated with the specimen failing approximately 0.004 s after impact. Peak acceleration associated with initialization of composite damage was also well predicted by the model in both impact speed conditions. Structural

damage without full specimen failure was predicted in the low-speed impact test, as demonstrated by close representation of post-peak acceleration response. These results provided confidence in the predictive capability of the calibrated material model to delineate between brittle failure and sub-failure damage.

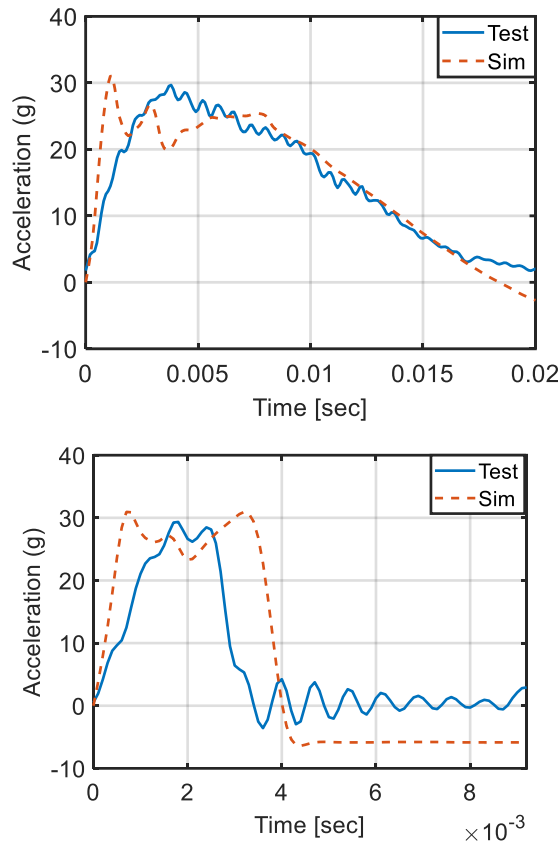


Figure 10. Updated Model Correlation to Acceleration in Low-Speed (top) and High-Speed Three-Point Bend Test.

Beam Structure - Compressive Damage Assessment

After calibration of the composite skin material model erosion parameters a dynamic compression test of the sandwich composite was used to assess the failure response predictions of the material under compressive loading. A vertical impact test was conducted on a sandwich composite specimen cut from the B-pillar of the LPC test article. The dynamic test was conducted using the 14-ft drop tower with a 115-lb impactor and an impact velocity of 10-ft/s. The specimen was arranged parallel to the impact velocity to produce a compressive crush force into the length of the specimen. Specimen length before and after the test was measured to characterize the extent of material failure during impact. This test was simulated using the calibrated composite sandwich model oriented to match the test condition. Change in simulated component length post-

impact was compared to that measured in test. A change in length of 0.94 in was measured on the specimen compared to a change in length of 1.03 in predicted by simulation. The close prediction of specimen compression during dynamic loading provided confidence that the calibrated composite and forming foam material models accurately represented the stiffness of the sandwich composite during compressive loading. The use of element erosion in FEM analysis results in non-physical loss of the material structure, this can negatively affect correlation, particularly in compressive loading conditions in which the eroded material may still provide resistance in the physical environment. Thus, some overprediction of specimen compression was expected. The difference in change of length of less than 10% between test and simulation provided confidence that the calibrated element erosion limits were reasonable for predicting response within a compressive loading environment.

SEAT COMPONENT CHARACTERIZATION

Seat Testing Overview

A series of seat-level drop tower tests were conducted with the goal of characterizing ATD responses under varied vertical impact loading conditions and seat environments. These tests were conducted with the Hybrid III –5th, FAA 50th, and 95th ATDs. Tested seat environments included, generic aluminum and composite seat buckets mounted to rigid aluminum frames, commercial off the shelf (COTS) seats, and a NASA energy absorbing (EA) seat design. All ATD's were seated in a 90° knee - 90° hip upright posture during testing, with 3D-Scans taken of the test environment pre- and post-test for positioning verification. Three- and four-point belts were used in testing depending on the seat configuration. Belt loadcells, accelerometers on the seat pan and impacting plate, and a full ATD instrumentation suite were included in each test. Figure 11 shows an example test configuration of the Hybrid III FAA 50th in the generic composite seat bucket.

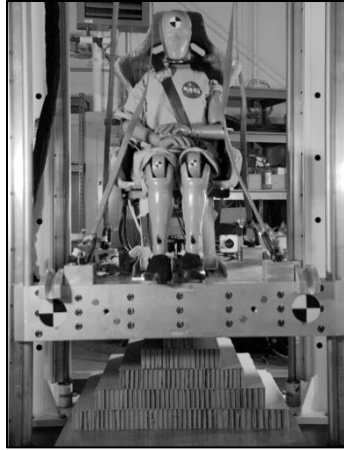


Figure 11. Hybrid III FAA 50th ATD in Seat Drop Tower Test Configuration.

Tests were conducted using a 30 ft drop tower with acceleration pulses generated using cardboard honeycomb stacks. Tested impact conditions included 10 g, 19 g, 30 g, and 42 g acceleration pulses which were generated to approximate vertical loading environments from a lightweight helicopter impact, emergency landing conditions defined by the Federal Aviation Administration (FAA) for general aviation and rotorcraft (14 CFR 23.562 and 27.562), and the LPC test respectively [4Error! Reference source not found.-6]. Figure 12 shows example test measured acceleration pulses.

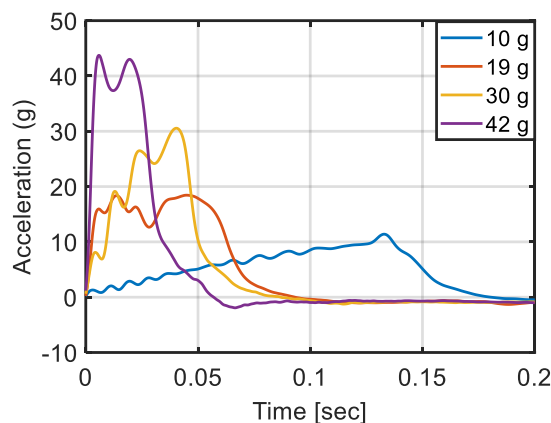


Figure 12. Seat Drop Tower Test Acceleration Pulses.

Seat Modeling Assumptions

The seat testing provided a much-needed data set with which to characterize the seat models used in the LPC test article model. Prior to the LPC test the seats had not been individually tested, thus modeling of the seats and seat to ATD interactions was based solely on established modeling practices and experience. There were four different seat configurations used in the LPC test: a generic aluminum

seat, a generic composite seat, a NASA designed EA composite seat, and a COTS seat. When modeling these seats, the following simplifying assumptions had been made: the generic composite and aluminum seat buckets were modeled as rigid and the frames connecting the seat buckets to the floor were simplified using rigid connections except in the case of the COTS and NASA EA seats. The isolated seat testing was used to evaluate each one of these assumptions and to characterize the predictive accuracy of the ATD models within the seated environments.

The first assumption evaluated using the seat level drop testing was that the seat frame connecting the bucket to floor was effectively rigid and could be modeled using rigid constraints between the floor and seat base. This assumption was assessed by comparing the acceleration time histories measured on the seat pan to those measured on the floor. Results from the seat testing showed the seat base and floor accelerometers to produce nearly identical results for these seat configurations in each of the impact conditions tested. An example comparison of measured floor and seat base accelerations for the 30 g test condition is shown in Figure 13. The acceleration shape and magnitude are closely matched between measurement locations. These results indicated that there was no meaningful deformation of the seat frame which would alter loads transferred into the occupant from the floor and thus the rigid attachment assumption used in the model was valid.

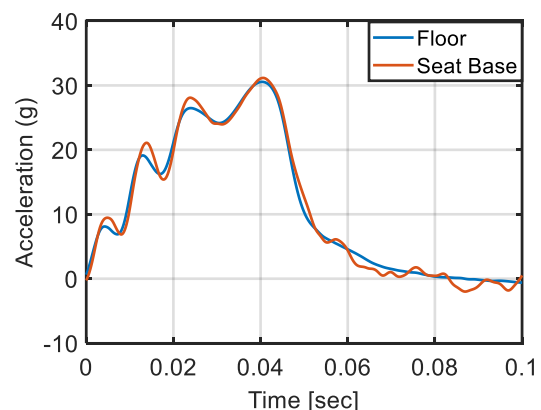


Figure 13. Acceleration Measured at Seat and Floor Base Locations.

The next assumption evaluated was the use of rigid material models to represent the aluminum and composite seat buckets. A comparison between lumbar force measured using the Hybrid III 5th ATD in the aluminum and composite seats when subjected to the 19 g acceleration pulse is shown in Figure 14. The composite seat was shown to produce a much higher lumbar load response compared to the aluminum seat in the same loading condition. The geometry of the two seat pans, in the load path between

impact and lumbar spine of the ATD, were essentially the same. The difference in lumbar load measurement can thus be attributed to the difference in material makeup of the two seats. The noted influence of seat material indicated the assumption of rigid material models for the composite seat bucket was not valid.

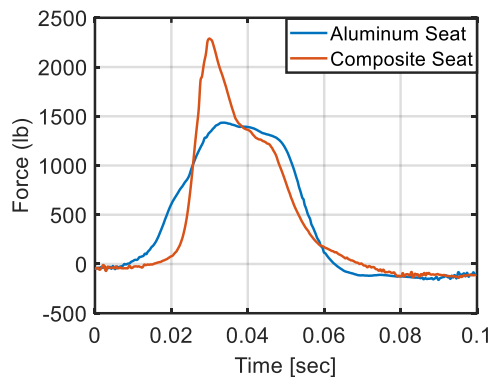


Figure 14. Lumbar Force in Different Seat Types

Occupant Model Assessment

After evaluating the simplifying assumptions used in the previously generated LPC seat models, representative models of the seat-level drop tower test configurations were generated to assess the predictive capability of the occupant models. Based on the findings that the seat bucket material affected occupant loading, the material models used in the previously generated seat models were updated from rigid to elastic. The LSTC Hybrid III -5th version 160920_V2 [7], -50th version 151214_BETA [8], and -95th version 151214.V3.03_BETA [9] were integrated into the seat models and positioned to match the tested configurations. The acceleration time histories measured on the floor were used to apply the impact boundary conditions to the model. Figure 15 shows the model generated of the Hybrid III FAA 50th ATD in the composite bucket seat, shown previously in Figure 11.



Figure 15. Model of Seat Test Environment.

A comparison between peak lumbar force values predicted by the generated FEMs and those measured in testing is shown in Table 1. Tests of the composite seat with the Hybrid III FAA 50th ATD were not simulated due to test induced damage to the seat. Each occupant FEM was found to closely predict peak lumbar force response across the complete range of impact acceleration conditions and seat types tested. All predicted values were within 10% of that measured in test and all but two cases had predicted values within 5%. No clear trend could be established in the data between test configuration and model accuracy. Lacking any trend with test configuration, the variations in modeling error can most likely be attributed to inherent test variability, such as slight position changes which occur during the drop tower test event which are not fully captured in the simulation.

Table 1. Lumbar Force Predictions

Impact Configuration		Lumbar Force		
Pulse (g)	Seat	Test (lb)	Simulation (lb)	Difference (%)
50 th	10 Aluminum	730	747	2.33
	19 Aluminum	1705	1624	4.75
	30 Aluminum	2484	2627	5.76
	42 Aluminum	4387	4320	1.53
	19 NASA EA	1369	1315	3.94
	30 NASA EA	2411	2524	4.69
95 th	19 Aluminum	1824	1857	1.81
	30 Aluminum	2710	2830	4.43
5 th	19 Composite	1545	1546	0.06
	30 Composite	2288	2061	9.92
	30 Aluminum	1435	1405	2.09
	30 NASA EA	1342	1354	0.89

Response time histories between test and simulation were also compared to evaluate FEM correlation throughout the impact event. As an example, lumbar force time history comparisons between test and simulation for each ATD in the 30 g aluminum seat test configuration is shown in Figure 16. This was the poorest correlated condition for the Hybrid III - 50th and -95th ATD FEMs and the second poorest correlated condition for the Hybrid III 5th ATD FEM. Although there are slight discrepancies in peak lumbar force for each of these cases the overall response shape is very close. Loading slope and time to peak is matched in each simulation. The largest discrepancy observed was in the unloading slope of the 50th ATD which was greater in simulation. This difference is associated with differences in spinal configurations between the FAA ATD configuration used in test and the automotive ATD configuration FEM which was available for simulation. Outside of this one aspect the generated models were found

to effectively replicate the ATD response across each condition evaluated. These results provided additional confidence in using the update seat models within to predict occupant responses in vehicle level analyses.

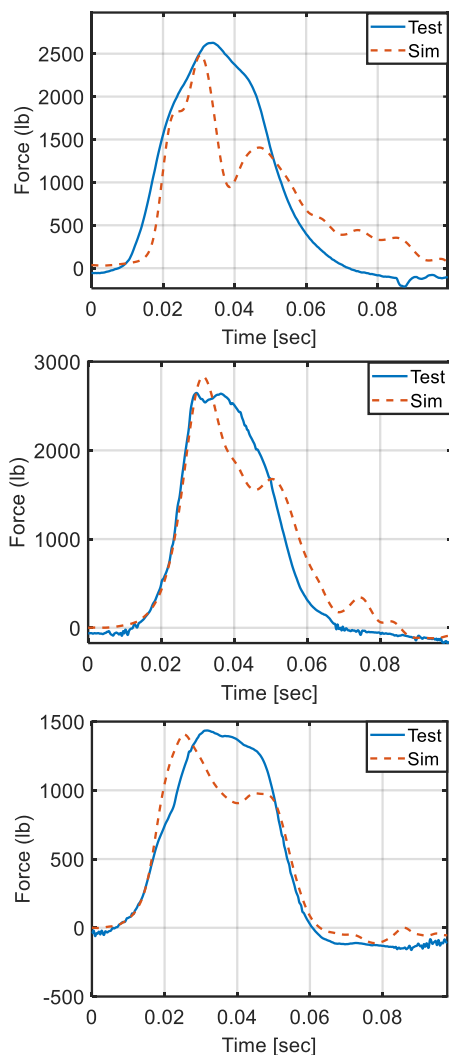


Figure 16. Lumbar Force Correlation of Hybrid III – 50th (top), 95th (middle), 5th (bottom) in 30 g Test Configuration.

VEHICLE MODEL EVALUATION

Updates to LPC Test Article FEM

The modeling approach findings and material model updates from the structural component tests and seat level tests were integrated into the FEM of the LPC test article. The first update made to the LPC test article FEM was the addition of the forming foam within the beam support structures of the vehicle model. Solid elements were meshed within each beam section to represent the foam

used. Void space was included at the joints of adjoining sections to represent the individual sections of foams which were assembled within the beam shape during fabrication. The forming foam was attached to the composite skin of the frames using tied coincident nodes. The forming foam elements added to the LPC vehicle FEM are shown in Figure 17. An eroding contact was added between skin and foam to maintain contact between the components throughout dynamic impact simulation. The material model of the forming foam and the calibrated parameters of the composite skin material model, generated from the component level test data, were also added to the updated vehicle FEM. Lastly the mesh of the LPC test article FEM was refined to match the 0.25 in element length of the calibrated component models.

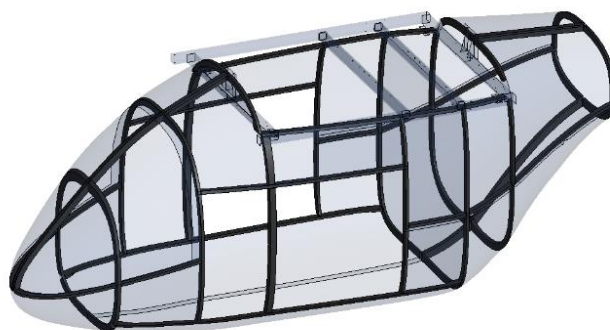


Figure 17. Forming Foam within LPC Vehicle.

The elastic material models for the composite and aluminum seat designs were added to the vehicle model to improve prediction of occupant loads as indicated by the seat level test analysis. In addition to updating the seat models, an ATD FEM of the Hybrid III – 10 year old (YO) configuration was generated. This FEM was generated to represent this ATD configuration which was included in the front starboard seat during the original LPC vehicle test. A FEM of the Hybrid III – 10 YO ATD was not publicly available, so this ATD had previously been represented in the LPC test article model as a simple point mass. Subsequent analysis of the LPC test simulation had shown the simplification of ATD weights as point masses to have a measurable effect on structural response predictions of the vehicle FEM [2]. Thus, to improve predictive accuracy a FEM of the Hybrid III – 10 YO ATD was generated by geometrically scaling a publicly available FEM of the Hybrid III – 6 YO [10] to the weight and dimension specifications of the Hybrid III – 10 YO. The remaining ATD configurations used in the test (two Hybrid III FAA 50th, one FAA Hybrid II 50th, one Hybrid III 5th, and one Hybrid III 95th) were represented in simulation using the publicly available Hybrid III models described in the seat level analysis section. The seated occupant model setup

used in the LPC test article simulation is shown in Figure 18.

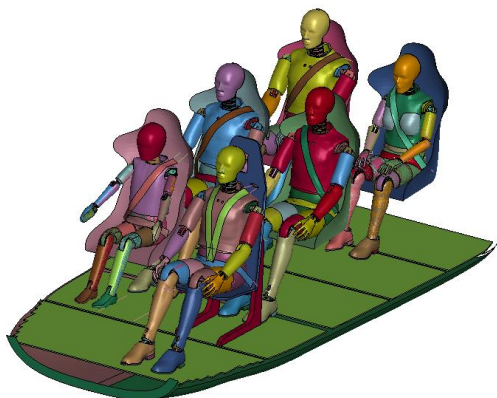


Figure 18. ATD Layout within LPC Vehicle.

Simulation of the LPC vehicle test was driven using test measured impact conditions [1]. The vehicle model was oriented with a 0.6° pitch and 2° yaw. An initial velocity of 38.1 ft/s in the horizontal direction and 31.4 ft/s in the vertical direction was prescribed. To simulate the impact environment a representative concrete surface model was generated below the initial vehicle location. Prior to velocity initialization the vehicle model was held in place at the lifting hardware attachment locations while the ATD models and vehicle structure were loaded under gravity for 0.5 s. Additional details on the LPC test modeling setup can be found in [2]. Simulation of the updated LPC test article model was performed using LS-DYNA MPP version 14.0 on a Linux Computer cluster. The simulation was carried out to a termination time of 0.3 seconds using 24 processors and had a run time of 108 hours. Both test and simulation data were filtered to SAE J211 recommendations for crash impact analysis [11].

Correlation of Structural Kinematics

The updates made to the structural models within the LPC vehicle FEM, based on the component tests conducted, resulted in prediction of the structural material failure responses observed during the test. During the test the B-Pillars collapsed under the weight of the representative overhead wing mass. This led to collapsing of the overhead mass into the occupant compartment. Additional brittle failure of the composite skin and beam sections were also observed throughout the vehicle structure as the overhead mass collapsed downward. A comparison of damage observed within the test article compared to that predicted by simulation is shown in Figure 19. The updated vehicle FEM was found to capture the primary material failure responses which drove gross vehicle kinematics and in cabin volume changes. B-pillar failure and aft cabin section collapse was closely predicted within the model. Additionally, the collapse of the front starboard cabin

section, due to the slight yaw at impact was predicted. The model did not predict all the skin tearing which was observed on the test article, though this did not limit its overall prediction of structural deformation and cabin intrusion.

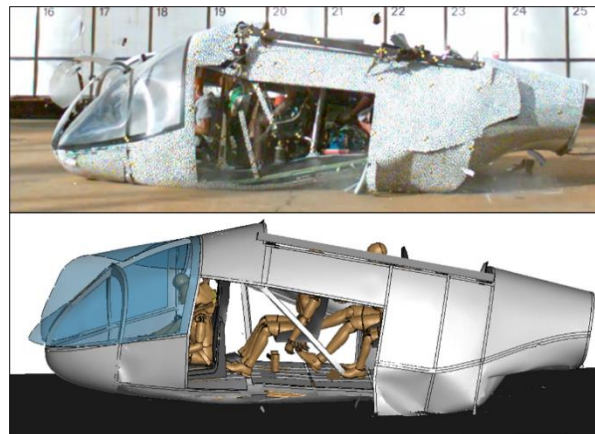


Figure 19. Structural Deformation Comparison between LPC Test and Simulation.

Correlation of Accelerative Loading Response

Kinematics of the test article structure were measured during testing using accelerometers attached to lifting hardware, the floor at each A-Pillar and rear cabin frame location, at the tail location, at the base of each seat, and under each seat pan. Each of these accelerometers was included within the vehicle FEM, as shown in Figure 20. Acceleration responses are compared at the lifting hardware and cabin frame locations as these locations best characterize the accelerative forces moving through the structure during impact. The starboard A-Pillar accelerometer separated from the structure during impact and thus was not included in the comparison. Acceleration predictions are shown only in the vertical direction because horizontal acceleration loading was minimal within the vehicle structure. Lastly the floor and seat acceleration response directly drive occupant load predictions and are thus effectively captured in the evaluation of occupant response predictions.

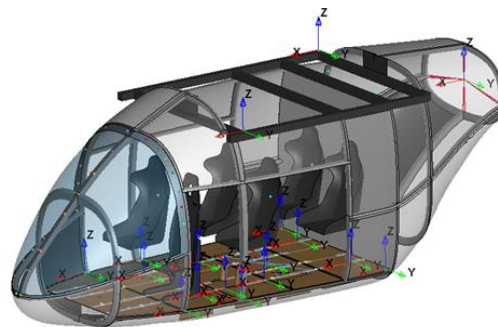


Figure 20. LPC Instrumentation Layout.

A comparison between vertical acceleration time history measured on the test article lifting hardware and predicted using the updated vehicle FEM is shown in Figure 21. The vehicle FEM was shown to closely predict the accelerative load transferred into the lifting hardware during vehicle impact with the ground. Over the first 0.075 seconds the phase, shape, and peak acceleration response was closely predicted by the model, though less oscillations can be observed in the simulated response compared to the test data. At 0.1 s there was a large spike measured in the lifting hardware acceleration which was not predicted by the vehicle FEM. This spike was correlated with the lifting hardware impacting the seated occupant environment, and not related to impact forces transferred through the vehicle structure.

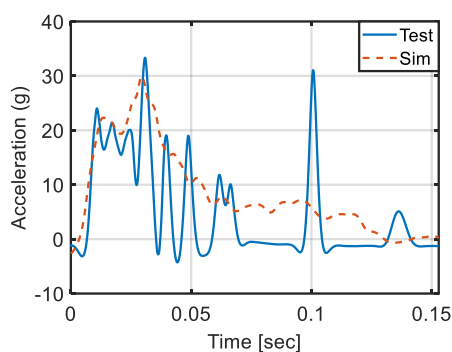


Figure 21. Lifting Hardware Acceleration.

A comparison between vertical acceleration responses measured on the test article airframe and predicted using the updated vehicle FEM is shown in Figure 22. In all locations both peak acceleration and acceleration shape were accurately captured by the model. At the front A-pillar the acceleration shape exhibited a sharp rise at vehicle contact, followed by a double peak and sharp drop-off with rebound. All aspects of this acceleration response were captured by the simulation. The aft section of the airframe measured different acceleration responses. On the aft starboard side, a slower oscillating rise in acceleration was recorded until approximately 0.025 s after which a drop-off occurred. The simulation predicted this same general response, though a greater rebound acceleration was predicted in the acceleration drop-off. On the aft port-side a low oscillating acceleration was measured until approximately 0.025 s at which point a large spike in acceleration was observed. The simulation response precisely matched this behavior in shape, phase, and magnitude. After the large acceleration spike, the aft portside accelerometer lost communication with the data acquisition system resulting in the flat acceleration value shown in the test to simulation comparison. The close prediction of the varying acceleration responses measured across the test vehicle structure provided confidence in the updated FEMs capability to predict vehicle structural kinematics during

complex loading environments influenced by both damage and failure responses within the structural material.

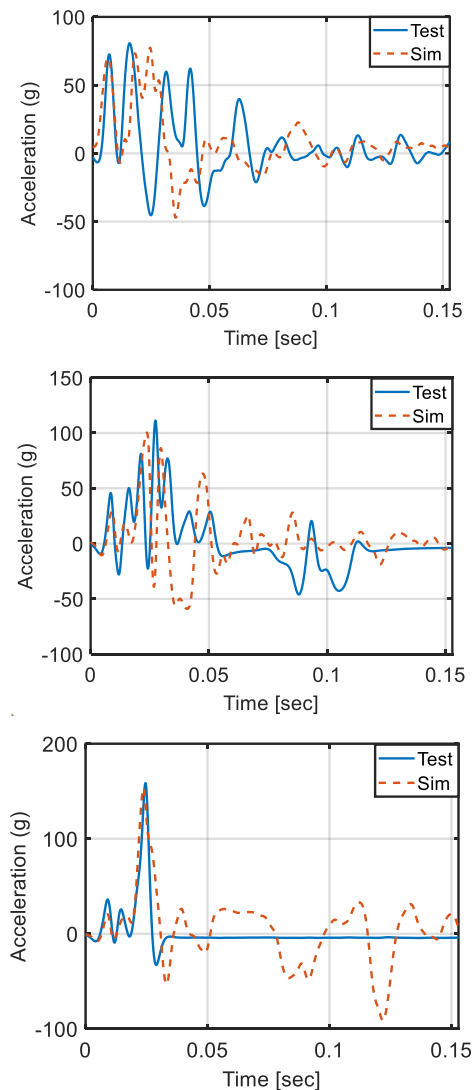


Figure 22. Airframe Accelerations: Front Portside (Top), Aft Starboard (Middle), Aft Portside (Bottom).

Correlation of Occupant Response

A comparison between measured and predicted lumbar compressive forces in the Hybrid III 50th ATDs seated in the middle row of seats is shown in Figure 23. The mid-starboard seat was a generic composite seat bucket with a rigid aluminum frame between seat and floor. The mid-portside seat was also a composite seat bucket but included a NASA generated EA design, which used composite crush tubes to attenuate the impact acceleration force. The differences in these two seat designs can be observed in the measured lumbar forces. The rigid seat frame produced a peak lumbar force of approximately 2300 lb, while the EA seat reduced peak lumbar force to approximately 1400 lb.

The test article FEM was found to accurately predict this seating effect on lumbar response. Although peak was not perfectly predicted in the starboard seat location, the increase in force with the rigid seat frame was. The peak was missed due to a sharp oscillation at the time of peak response which was not present in the test. Outside of this oscillation, the phase and shape of the force response was effectively captured by the mid-starboard occupant model. The mid-portside lumbar force was accurately represented by the representative occupant model across the full loading time history. Initial rise, peak, and drop-off in force, representing the crush initiation of the seat EA system, were all predicted by the FEM. After initial drop-off in force the secondary peak, representing the crush phase of the EA system, was also matched by the FEM. These results indicate that both the prediction of loads transferred to the seat by the vehicle structure, loads transferred through the EA system, and ATD response were all effectively captured by the FEM.

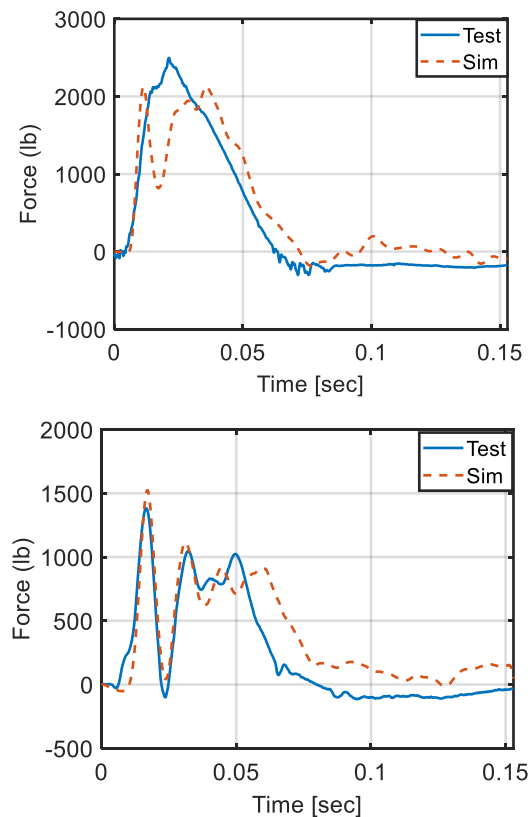


Figure 23. Hybrid III 50th Lumbar Force: Middle Starboard (top) and Middle Portside (bottom).

A comparison between measured and predicted lumbar compressive forces in the ATDs seated in the aft row of seats is shown in Figure 24. The Hybrid III 95th ATD was seated in the aft-starboard seat. The FEM closely predicted the lumbar compressive force shape of this ATD though it

overpredicted peak force. Damage to the floor structure was observed below this ATD within the test article post-test. Failure of the floor structure was not represented within the model and may have contributed to the overprediction of lumbar peak force in this location. The Hybrid III 5th ATD was seated in the aft-portside seat. The FEM closely predicted the lumbar peak force and initial loading response of this ATD. The FEM did overpredict the second load peak, though this did not result in overprediction of total peak load within the ATD. In general these ATD FEMs, which are not as commonly used as the Hybrid III 50th configuration, provided a reasonable prediction of occupant loading within the LPC test article environment.

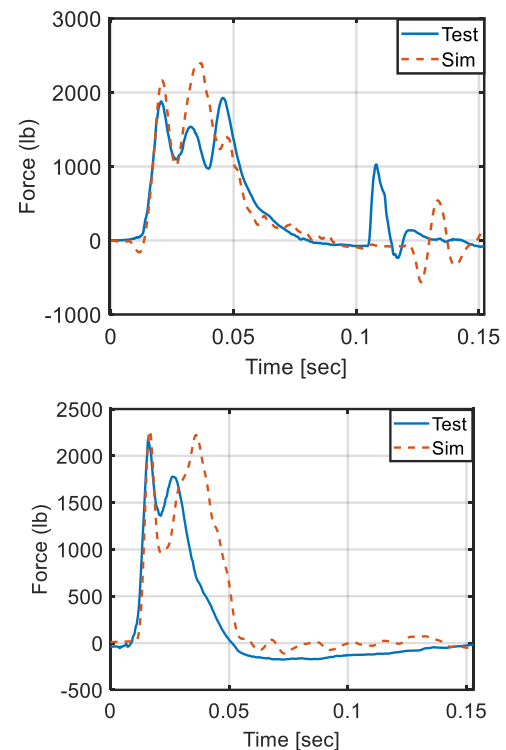


Figure 24. Lumbar Force: Hybrid III – 95th (Top) and -5th (Bottom).

CONCLUSIONS

The NASA RVLT project developed, fabricated, and tested the LPC vehicle design in a representative crash impact environment in part to provide a test bed for characterizing modeling techniques and to predict vehicle crashworthiness in an eVTOL relevant structural configuration. The pre-test simulation of the LPC test event was found to be limited by poor prediction of damage and failure characteristics of the composite skin material system. Component structural testing under dynamic load to failure was identified as the missing aspect of the model building block approach, necessary to properly characterize structural failure

response for full-scale crash impact prediction within the vehicle FEM. To fill in this gap, intact structural specimens were gathered from the LPC test article and subjected to additional dynamic test environments to better characterize their isolated material properties. This testing provided data to calibrate the component structures within the vehicle FEM within relevant dynamic loading conditions. Component level calibration led to improved representation of the complete vehicle response within the tested environment, and thus demonstrated the importance of component testing to produce a predictive FEM for assessing vehicle crashworthiness.

Component testing of the structural materials making up the LPC vehicle was used to evaluate simplifications made in the original LPC FEM modeling process and to calibrate the material properties of the primary structural material model. Results of this analysis demonstrated the need to refine the vehicle mesh and to include aspects of the fabrication process which were originally deemed not-structurally relevant within the vehicle FEM. In addition, new material modeling capabilities within LS-Dyna were leveraged using the component test data to improve prediction of brittle failure within the composite structure material model.

Seat level drop tower testing was conducted with the seat and adult ATD configurations used in the LPC vehicle. These tests were also used to evaluate key assumptions made in the original vehicle FEM development process. Analysis of the test data resulted in updates to the seat models to better represent the stiffness of the seat pans and correspondingly improve prediction of occupant loading.

Updates made to the seat and structural component models were integrated into the full-vehicle FEM and simulation of the LPC test was conducted to verify the effects of these changes on vehicle predictions. The updated structural material model led to close prediction of the structural damage observed within the test article during the impact event. This led to effective prediction of occupant compartment volume loss within the vehicle FEM. Additionally the updated vehicle FEM closely predicted the acceleration responses driven through the vehicle structure, which indicated the vehicle structural materials were effectively captured by the FEM. These results indicated that the component level testing and model calibration conducted using the structure of the LPC vehicle was effective in improving the capability of the vehicle FEM to predict damage and failure response of the composite vehicle structure within crash loading environments.

Within the updated vehicle FEM, the ATD models were found to predict the occupant loading levels measured during the test. These results indicated the loading transferred from the impact through the vehicle structure

and into the seat structures was effectively captured by the vehicle FEM. In addition, the close prediction of occupant load in each ATD and seat configuration indicated the seat environment models, characterized in the component drop testing, were valid within the full-vehicle impact environment. The demonstrated capability of the generated model to identify the differences in occupant loading due to the different seat environments and ATD configurations, provides confidence in using these models to identify means of occupant safety improvement through seat design optimization going forward.

The goal of the present study was to characterize the effectiveness of using component level testing to improve FEM representation of full-vehicle crash impact response in a condition at which the vehicle has demonstrated significant brittle failure within the composite structure. Results found that calibration of the composite model erosion parameters using component testing in relevant dynamic loading conditions, can produce material parameters which can effectively replicate brittle composite failure response in the full-scale vehicle environment. Additionally, the calibrated vehicle and seat environment models were shown to effectively predict occupant loading in this crash environment condition. To validate the predictive capability of the updated vehicle FEM, a second full-scale test of the LPC test article is planned. This test will be used to assess the predictive capability of the vehicle FEM outside impact conditions not previously tested. This work is intended to provide data on crashworthiness modeling approaches for composite vehicle structures to better characterize the applicability and limitations of these analyses for determining eVTOL vehicle safety.

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