

Evaluation of Composite Airframe Dynamic Impact Modeling Using Hawker 4000 Fuselage Drop Test Data

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Abstract

Two drop tests of partial Hawker 4000 fuselage sections were conducted at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) to characterize the response of representative composite aerospace structure to dynamic impact loads. Test conditions were selected to induce damage into the composite structure in order to study material failure within a composite fuselage and evaluate the capability of finite element (FE) model analysis to predict that failure. The tests were simulated using FE models which were generated to isolate the effect of developmental data availability on predictive capability.

FE Models of the tested fuselage sections were generated using two limited data sets. The first model configuration was reverse engineered from the test article with no information related to design or fabrication details which would be known only by the manufacturer. The second model was generated from data provided by the manufacturer but without additional material characterization test data. Models were developed using these methodologies for each fuselage section tested. A third model was generated using input data and lessons learned from the first two models. Correlation of each model to the tests conducted was evaluated in terms of damage, deformation, and cabin acceleration measurements.

Correlation between the developed models and the tested fuselage sections indicated that the reverse engineered model predicted the composite damage and cabin acceleration measured during test though it was limited due to lack of detail in the composite layup changes through the structure. The model developed using manufacturer specifications did not predict damage, due to limited material and component model characterization data, but it did predict acceleration on par with the reverse engineered model. Model capability and limitation sources identified were verified through correlation of a final model which was developed by combining the individual data sets. The combined model demonstrated that the addition of calibrated composite material models to accurate composite layup definitions and detailed geometry led to improved correlation of damage and acceleration response within the composite fuselage structures.

INTRODUCTION

Improved weight efficiency achieved through use of the composite airframe structure has contributed to the advancement of electrified aerospace transportation and the burgeoning electric vertical take-off and landing vehicle industry. With the increased use of structural composites comes the challenge of modeling these complex material systems to predict structural failure within dynamic impact environments. Composite materials have unique failure mechanisms such as skin delamination, sandwich material

fracture, and sandwich to skin bond failure. Details of the fabrication methodology such as layup composition, bond location, and infusion techniques may additionally affect failure response of the composite structure.

To evaluate the effect of failure mechanisms and fabrication variables on computational modeling a test to analysis comparative study was performed. To generate test data of a composite aerospace structure a partial fuselage of a Hawker 4000¹ aircraft was obtained by researchers at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC). The Hawker 4000 fuselage section received was composed of a sandwich composite skin with no external frame or stringer support which made it ideal for isolating composite structural response under dynamic loading. The fuselage was sectioned into thirds. This was done to generate two test articles from the fuselage while also allowing for component specimen extraction for isolated material characterization testing. The forward and aft sections were used as drop test articles while the middle section was utilized for component testing used in computational model development. An image of the full fuselage and cut out test article sections is shown in Figure 1. Drop tests of each fuselage section were conducted with impact condition selected to induce large sections of composite damage into the structure for model correlation. This work builds upon drop testing of a Hawker 4000 fuselage conducted at the National Institute of Aviation Research (NAIR) in 2018 [1], by focusing on the effect of composite failure on structural response of the fuselage.



Figure 1. Hawker 4000 fuselage section: original fuselage (left), forward section (middle), and aft section (right)

Two unique computational models, a reverse engineered model and a model generated from manufacturer provided specifications, were developed for both the forward and aft test sections of the Hawker 4000 fuselage. These models were developed and analyzed independently to identify the effect of available input information on the predictive capability of finite element (FE) models used to analyze composite structures in dynamic impact conditions. The models were evaluated with respect to the prediction of composite failure, deformation under load, and cabin acceleration measured during the test of each test article. Afterwards, a combined model was generated which utilized data from both development processes. The combined model was used to verify findings from the isolated model correlation and to demonstrate FE model capability given both fabrication details and material model calibration data.

METHODOLOGY – DEVELOPMENT OF REVERSE ENGINEERED MODEL

Material models were generated for the reverse engineered test article models through material characterization testing performed using sample specimens cut from the Hawker 4000 fuselage. The first

¹*Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.*

material characterization test performed was a static three-point bend test of the carbon composite material. The forward-most section of the Hawker 4000 fuselage contained a 2-in. flange composed of the carbon composite material with no sandwich honeycomb (Figure 2). Sample specimens, measuring approximately 2 in. x 14 in. x 0.4 in., were cut from this flange, and used in the three-point bend testing to characterize the carbon composite material. Three-point bend testing was used in material characterization, rather than tensile coupon testing, due to the inability to procure a flat coupon specimen from the fuselage geometry.



Figure 2. Hawker 4000 forward composite flange (left) and cut test specimens (right).

The three-point bend tests were performed using a servo hydraulic test machine with a test fixture consisting of two 2-in. diameter rollers spaced 12 in. apart, with a 1-in. diameter fixed roller in the middle. Tests were performed with a controlled vertical displacement speed of 0.25 in./min. A total of four specimens were tested, two in the concave direction and two in the convex direction with respect to the indenter motion. A representative model of the test conditions was generated. The indenter and end support structure were modeled using rigid shell elements with curvature matching that of the test fixture. The test articles were modeled using solid elements with a mesh size of 0.1 in. and the *Mat 59: Composite Failure Solid material model. All component simulations described in this manuscript, unless otherwise specified, were carried out using LS-DYNA SMP version R10.10 single precision on a Linux computer cluster. The moduli and strength parameters of the composite material model were calibrated through simulation to replicate the force displacement data recorded in test. Calibrated model correlation to test data is shown in Figure 3. Localized strain measurements, gathered during test using Digital Image Correlation (DIC), were also compared between test and simulation to verify realistic bending behavior of the developed model. The test calibrated model accurately predicted the linear force-displacement response of both types of configurations tested, from initial deformation through the onset of material failure.

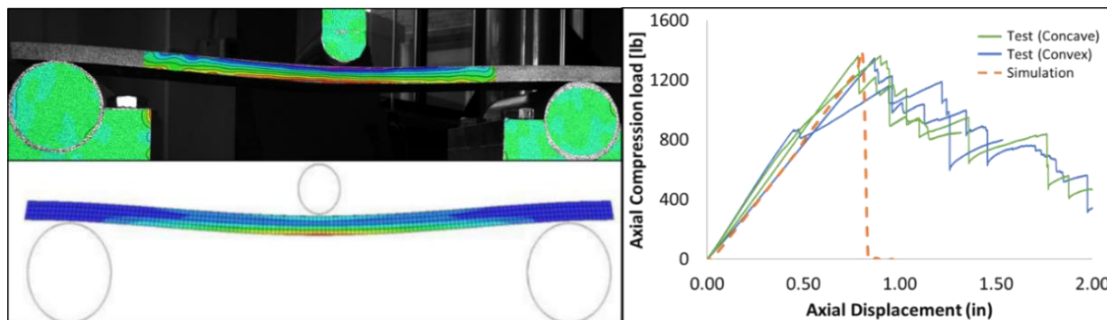


Figure 3. Three-point bend of composite flange specimen: test and simulation setup (left) and force displacement data correlation (right).

The next material to be characterized was the honeycomb core material within the composite skin of the fuselage. The fuselage contained both filled and unfilled honeycomb core material. Specimens of each type were cut from the center fuselage section. Three variations of specimens were gathered, one with both composite skins attached, one with a single composite skin, and one with the core only. Each represented a different boundary condition on the core and were tested to identify effects of skin bonding on measured material response. Example specimen variations are shown in Figure 4. The specimens were cut into 2-in. cubes with specimen thickness varying between 0.6 in. and 1 in. depending on specimen configuration. Static compression tests were performed on each specimen to characterize stress-strain response of the honeycomb material.

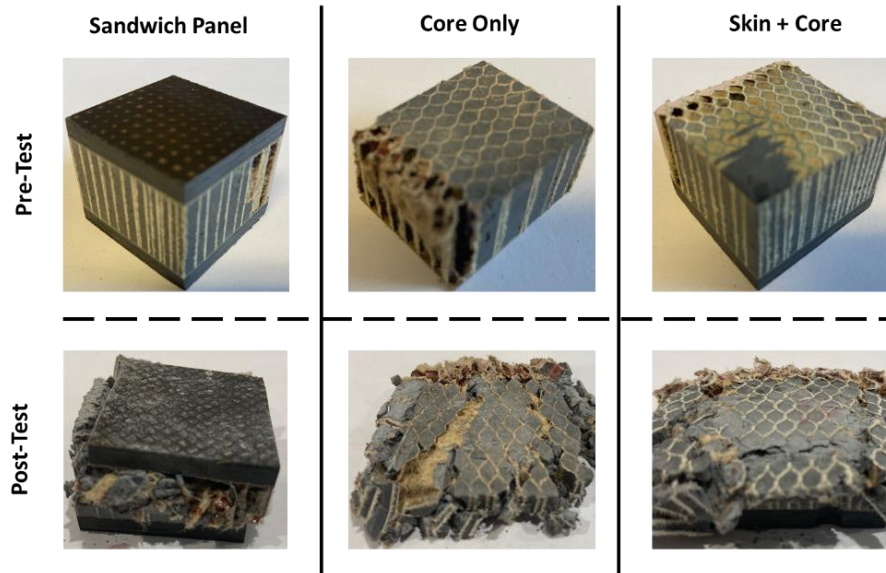


Figure 4. Honeycomb sandwich specimens.

Results from the static compression tests of the unfilled and filled honeycomb core specimens are shown in Figure 5. The response of the sandwich panel and facesheet + core specimens was similar while the core only specimen differed. Without the laminate skin to stabilize the honeycomb boundaries of the honeycomb, the stability of the core under compressive load was altered. This effect was most pronounced in the unfilled specimens. The substrate of the filled specimens re-enforced the core stability and thus limited the effect of the facesheet boundary. Based on the finding that the facesheet altered honeycomb crush response under vertical loading, a model of the honeycomb sandwich specimen configuration was generated for material model calibration. The honeycomb core was modeled as a single layer of solid elements with material model *MAT 126: Modified Honeycomb. A single element thickness was used in the honeycomb model because multiple layer element thickness models were found to produce unrealistic crush behavior in preliminary simulations. The sandwich panel model was simulated in the tested conditions and the material model parameters along the axis of compression were calibrated to match the tested material response. Parameters defining response in the remaining directions were calibrated through subsequent three-point bend test correlation. Unique material parameter sets were generated for both the filled and unfilled honeycomb material. Comparison between the test data and simulation results for both the unfilled and filled honeycomb is shown in Figure 5. The developed material models closely tracked the stress required to initiate crushing of the honeycomb core as well as the stress-

strain response during crushing. Results provided confidence in using the developed material model to predict the honeycomb material response under compressive load normal to the sandwich surface. Next, testing was conducted to characterize the bending load response of the honeycomb sandwich composite.

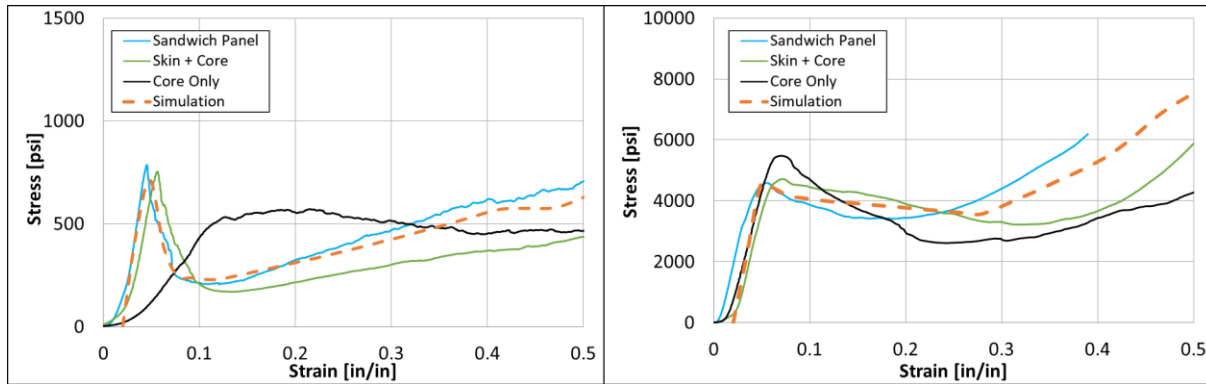


Figure 5. Stress strain correlation results for unfilled (left) and filled (right) honeycomb compression tests.

Static three-point bend tests of the sandwich composite were conducted to calibrate the integrated material system models. Four composite sandwich sections measuring approximately 15 in. x 2 in. x 1 in. were cut from the middle section of the Hawker 4000 fuselage. Static three-point bend tests were conducted on each specimen using the same method described for the flange specimen three-point bend tests. A representative model of the test configuration was generated using the component models developed from the composite shell and honeycomb tests. The test and representative model configuration are shown in Figure 6. Initially the honeycomb and composite shell elements were joined using shared nodes. During calibration it was found that this limited prediction of rotation and re-orientation of the honeycomb during specimen bending which was observed during test. To represent the glued bond between honeycomb and composite skin, the shared nodes were replaced using tied contact with failure between the face surfaces of each part. There were four distinct phases of loading measured in the force-displacement response of the sandwich specimens during the three-point bend tests. The first phase was elastic compression of the sandwich composite, indicated by a linear increase in compressive force with displacement. Correlation to this response required minimal tuning as it was driven by previously calibrated stiffness parameters of the component materials. High-speed photogrammetry of the tests indicated the first two drops in compressive load were caused by isolated shearing of the honeycomb material at the outer edges of the specimen. The shape and magnitude of the response curve over this time were used to calibrate the parameters defining shear stiffness within the honeycomb material model. After the second drop the honeycomb material re-oriented with the bending of the sandwich composite allowing compressive force to increase as displacement progressed. This behavior was achieved by implementing the tied contact between honeycomb and composite skin. The final drop in compressive load, occurring after displacement of approximately 2.25 in., was caused by honeycomb shearing which spread through the center of the specimen followed by delamination of the skin. The timing of this response was used to tune the element failure parameters of the honeycomb material model. With thorough calibration of the honeycomb material model and the part constraint definition, the composite sandwich model closely replicated each distinct loading phase measured in test.

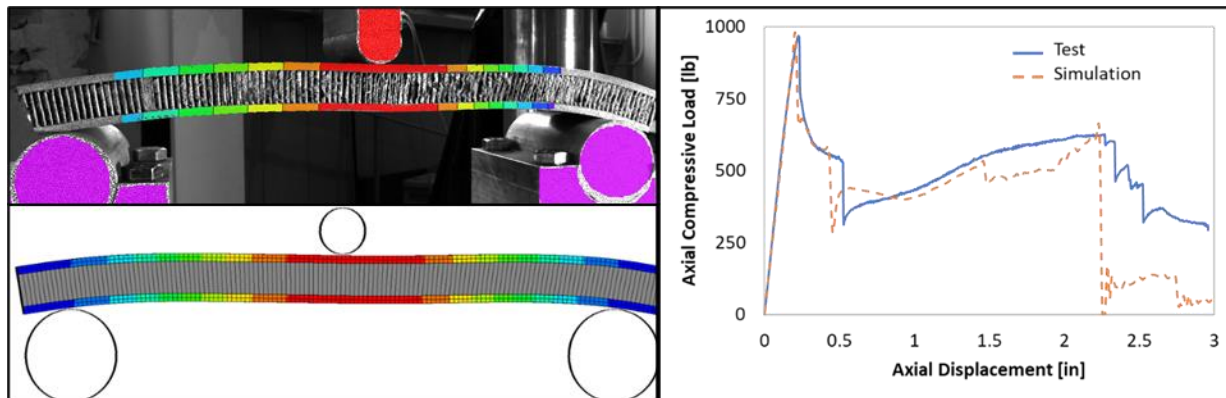


Figure 6. Three-point bend of composite sandwich specimen: test and simulation setup (left) and force displacement data correlation (right).

After developing the component material models through static test correlation, the predictive capability of the models under dynamic loading conditions were verified using dynamic three-point bend tests performed on specimens of both the carbon composite flange and carbon composite honeycomb sandwich. The same three-point bend test fixture used in the static tests were used in the dynamic test configuration. For the dynamic test a 100-lb. mass was fixed to the indenter which was dropped onto the test specimens with an impact speed of 10 ft/s. This boundary condition was represented in the FE model by applying a point mass and initial velocity to the indenter component. A picture of the test and simulation of the sandwich composite dynamic three-point bend test is shown in Figure 7. The response of the test specimens under dynamic load was quantified by vertical acceleration measured on the indenter mass. The component models, which were calibrated to the static tests, were shown to closely predict the acceleration of the indenter as it crushed both the carbon composite flange and honeycomb sandwich specimens. The composite flange exhibited a linear increase in acceleration which peaked at approximately 15. After peak acceleration the carbon composite began to fail which led to a sharp drop in acceleration. The linear acceleration slope, peak acceleration, and time of failure were all captured by the representative model. The sandwich composite exhibited linearly increasing acceleration to approximately 8 g, followed by a two phased drop in acceleration. This tiered acceleration drop mimicked the stress strain response observed in the static three-point bend testing which was driven by shearing of the honeycomb. After significant shearing and compression of the honeycomb, the carbon composite shell also failed. The sandwich composite model accurately predicted the shape, phase, and peak response of the indenter as it induced these multiple failure responses in the sandwich material. These results provided confidence that the material models of the Hawker 4000 fuselage, calibrated under the static test conditions, were effective at predicting dynamic impact response up to and through component failure.

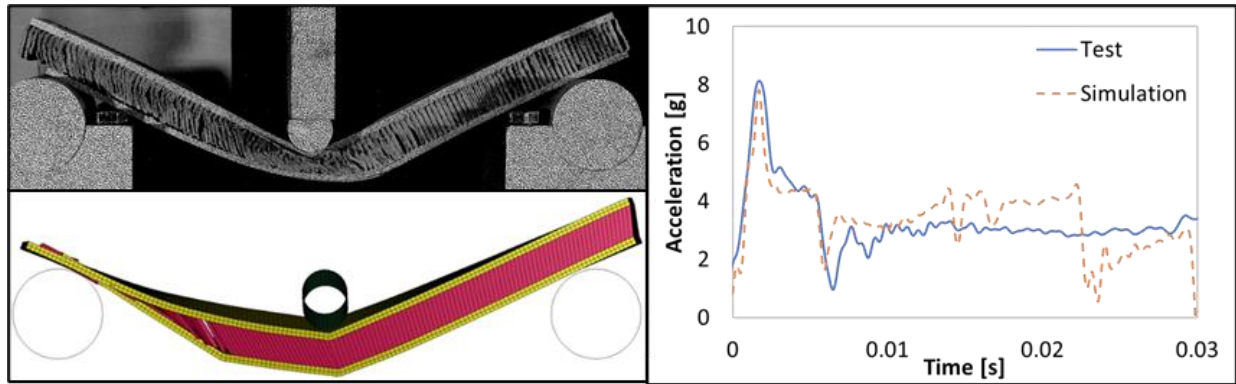


Figure 7. Dynamic three-point bend of composite sandwich specimen: test and simulation setup (left) and acceleration time history correlation (right).

After material characterization, model geometry of the forward and aft test article sections was generated from three dimensional (3D) scans of the Hawker 4000 fuselage. An image of the 3D scan and generated FE models is shown in Figure 8. An outer mold line (OML) was isolated from the scans across the forward and aft test section locations. Large openings in the forward and aft test sections were included within the OMLs. Surface geometries were then constructed from the extracted OMLs. A mesh template was generated on the surface geometries using 0.9-in. quadrilateral shell elements. Solid elements representing the carbon composite skin and honeycomb interior were then extruded from the template mesh to match the thickness of each component measured on the test articles. The composite skin was extruded to a thickness of 0.19 in. and the honeycomb was extruded to a thickness of 0.75 in. Each component part mesh was separated and the tied contact card developed during the sandwich three-point bend testing was implemented between the carbon composite and honeycomb parts. The material models developed in the component tests were used to define the respective material sections within the reverse engineered models of each test article.

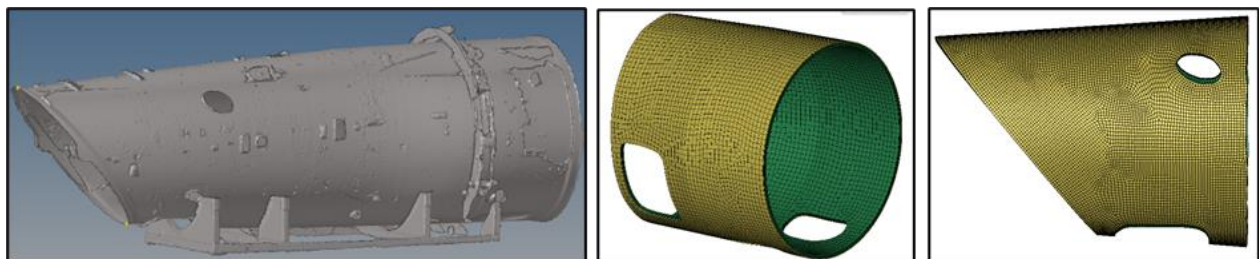


Figure 8. 3D Scan of Hawker 4000 Fuselage Section (left) and reverse engineered models developed from scan: forward section model (middle) and aft section model (right).

Ballast mass and instrumentation which were included in each test article were replicated within the developed FE models. A schematic of the test article mass and instrumentation setup is shown in Figure 9. The forward test article section included 14 ballast blocks each weighing 25 lb. The ballast blocks were attached to the test article using aluminum c-channels mounted across the test article length at approximately 72 in. above the belly. This mass was represented in the reverse engineered FE model using point masses rigidly fixed to the composite sandwich elements through constrained nodal rigid bodies (CNRBs) defined at the c-channel mounting locations. Accelerometers were installed along the belly, sidewall, and ballast mass locations within the test article. The belly and sidewall accelerometers were

mounted to the interior skin of the test article while the ballast mass accelerometers were fixed to the test article through the c-channel attachment. Accelerometers models were included at each representative location using CNRB attachments. The forward section test article weighed 760 lb. with all ballast mass and instrumentation included. The developed FE model weighed 740 lb. the slight difference in model and test article weight can be attributed to geometric simplifications made in the reverse engineering process. Although the mass of the FE model could have been artificially altered by adjusting material model density, this step was not taken because there was not enough information gathered from the test article to determine whether artificially adding mass across the entire structure would improve or worsen the estimation of test article CG.

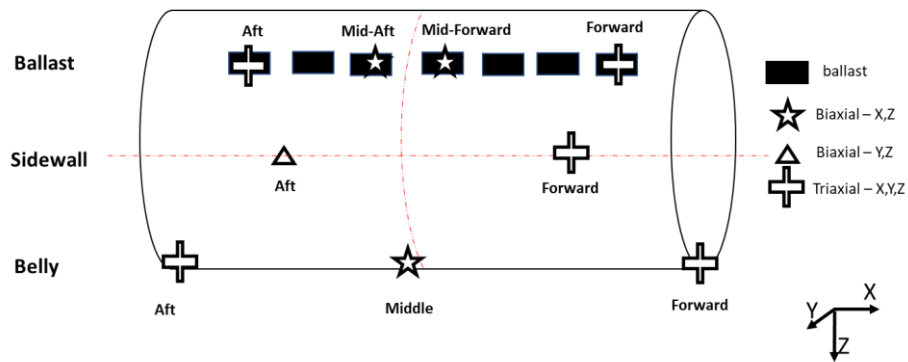


Figure 9. Schematic of forward section ballast mass and instrumentation locations.

The aft section test article included eight 25-lb. ballast blocks attached to aluminum c-channels mounted at the approximate center of the test article. Accelerometers were added along the length of the c-channel as well as mounted to the ceiling and belly of the test article. A schematic of the test article mass and instrumentation setup is shown in Figure 10. Mass and instrumentation of the aft section test article was matched in the reverse engineered model as it was in the forward section. The aft section test article weighed 490 lb. with all ballast mass and instrumentation included. The reverse engineered FE model weighed 484 lb.

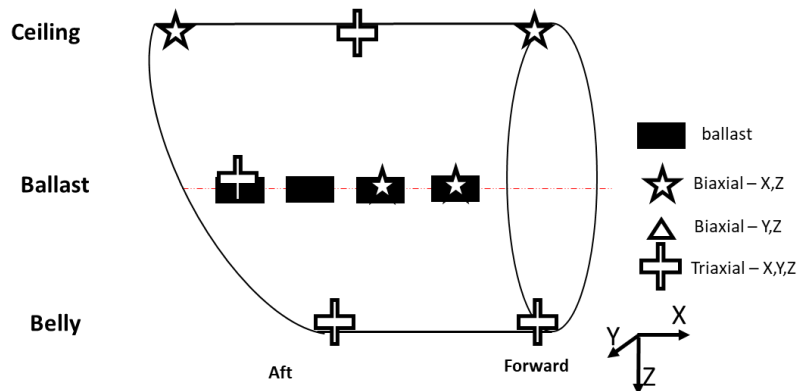


Figure 10. Schematic of aft section ballast mass and instrumentation locations.

METHODOLOGY – DEVELOPMENT OF MANUFACTURER SPECIFICATION MODELS

In parallel to the reverse engineered model development, FE models of the test articles were generated using only manufacturer design specifications. A static loads model of the Hawker 4000 fuselage along with a list of component materials was provided by Textron Inc. A representative FE models of each test article for use in dynamic impact analysis was developed using the provided model and information with no knowledge from the reverse engineering data set. First the forward and aft test sections were isolated from the provided fuselage model. The isolated section models are shown in Figure 11. The manufacturer specification models contained greater geometric detail than what was included in the reverse engineered models which were limited in their fidelity by the 3D scan conversion process. No re-meshing of the manufacturer provided model was performed. The forward and aft section models were composed of shell elements with mesh density varying from 0.2 in. to 3.4 in.

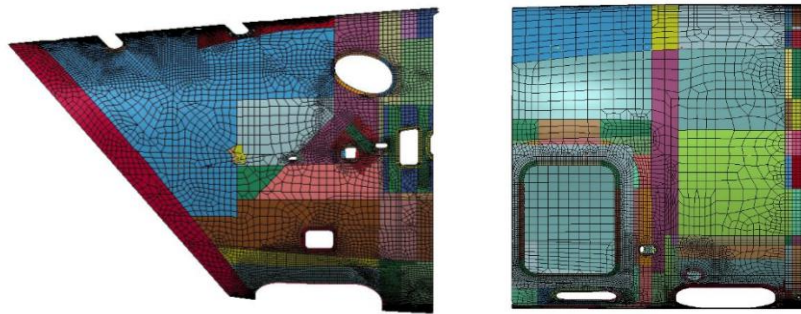


Figure 11. Manufacturer specification models of aft (left) and forward (right) section test articles.

Linear material property specifications for the component materials within the Hawker 4000 test article were provided by the manufacturer. These specifications included density, elastic moduli, shear moduli, and Poisson's ratio. Component materials included carbon fiber tape and weave, as well as filled and unfilled honeycomb variations. Material models of each component were generated using *Mat 58: Laminated Composite Fabric. Material strength parameters were not provided in the manufacturer specifications; thus, these values were estimated from previously derived and publicly available material model parameters of similar stiffness composite material [2]. Composite layup definitions, including material orientation and thickness, were defined for each shell element part within the manufacturer specification models using the *Part Composite card within LS-Dyna.

Ballast mass and instrumentation was added to the manufacturer specification models of the forward and aft test sections in the same manner they were included within the reverse engineered models. CNRBs were used to attach the ballast mass and accelerometer models to the fuselage skin matching the configuration used in each test article. The complete manufacturer specification model of the forward test article section weighed 753 lb. compared to the 760 lb test article weight. The aft test article section model weighed 485 lb. compared to the 490 lb test article. The mass of the manufacturer specification models was closer to the test articles than achieved in the reverse engineered models due to improved fidelity in geometry and composite layup variation achieved from the manufacturer specifications.

METHODOLOGY – DEVELOPMENT OF TEST ENVIRONMENT MODEL

The impact surface used to test both the forward and aft section test articles of the Hawker 4000 fuselage was a 3.3-in. thick steel plate with load cells mounted on each corner between the plate and concrete

surface on which it rested. The load cells were included below the impact surface in order to measure the total force imparted into test article during the impact event. The force measurements allowed for verification of the impact boundary condition applied within the model.

The impact surface was modeled using three different methods to determine the most realistic way to replicate the boundary conditions of the test. All three methods included a model of the steel plate and pedestal load cells, modeled using solid elements with an elastic material model of steel. The models differed in how they represented the boundary at feet of the steel plate. The first model fully constrained the feet of each pedestal load cell in space using a nodal constraint. The second model included a rigid wall contact below the feet. The third model included a solid element model of the concrete surface below the steel plate with the concrete model using an elastic material model. The concrete model was fixed in space using a nodal constraint along the bottom of the part. An automatic surface contact was applied between the concrete and steel plate in the third model configuration. Each boundary condition model was simulated using the reverse engineered forward section model in the tested configuration. A schematic of each model and resulting comparison of measured to predicted force in the platform load cells is shown in Figure 12. In the nodal constraint boundary condition model, oscillation frequency in the predicted load cell force is close to double what was measured. These results indicated the motion of the steel plate was over constrained at its boundary with the nodal constraint boundary condition. Both the rigid wall and elastic element boundary condition improved the frequency of the predicted force in the platform load cell. Both the rigid wall and elastic element contact boundary conditions only constrain motion of the steel plate in the downward direction which is more realistic to the tested condition. In both models load cell force was well predicted over the first 0.2 seconds post impact. After this time the force oscillations predicted by both models dampens out at a faster rate than was measured. The primary load transfer from plate into the test article occurred before 0.2 seconds and thus differences after this timeframe were not considered essential to prediction of the impact response of the test article. Based on the results of the boundary condition evaluation, the rigid wall contact setup was used to model the test environment as it provided a simpler model then the elastic element contact while also providing realistic prediction of load during the impact event.

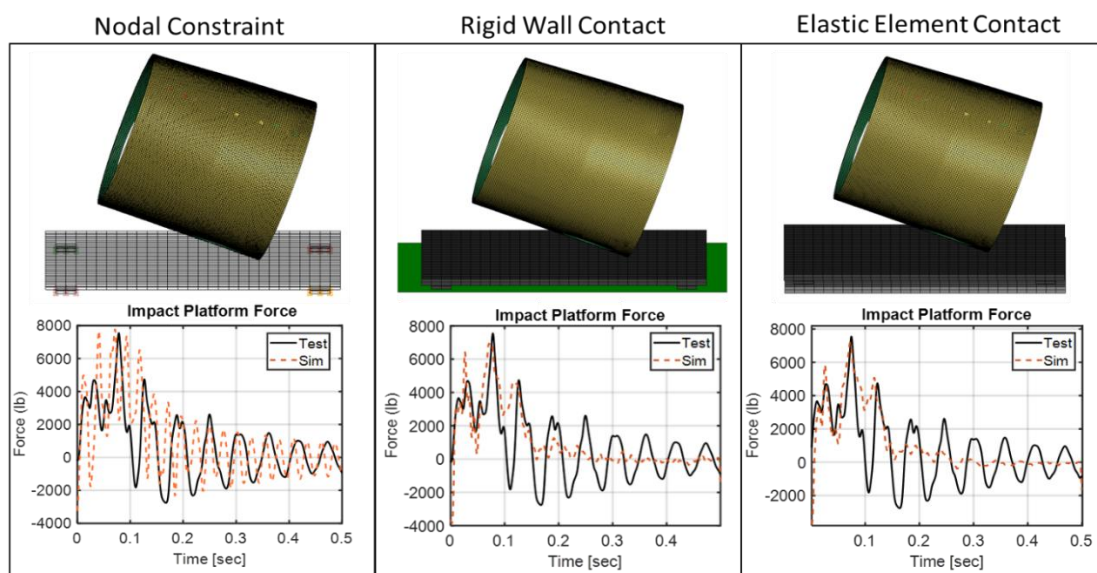


Figure 12. Comparison of model boundary conditions on impact force predictions.

RESULTS – FORWARD SECTION TEST MODEL CORRELATION

Impact conditions for the tests performed on the Hawker 4000 fuselage sections were defined with the intention to induce composite structure failure during impact. A nominal impact speed of 30 ft/s was selected for each test. Vehicle orientation and total ballast mass was selected based on prediction of composite failure using pre-test simulations of the reverse engineered models. For the forward section test the test article was dropped from a height of 14 ft. with a downward pitch of 20 degrees. The impact conditions were verified using highspeed photogrammetry. An image of the forward test article at impact with angle and velocity measurements is shown in Figure 13. The measured impact conditions of the forward test article were 30 ft/s vertical velocity with a downward pitch of 19.7 degrees.

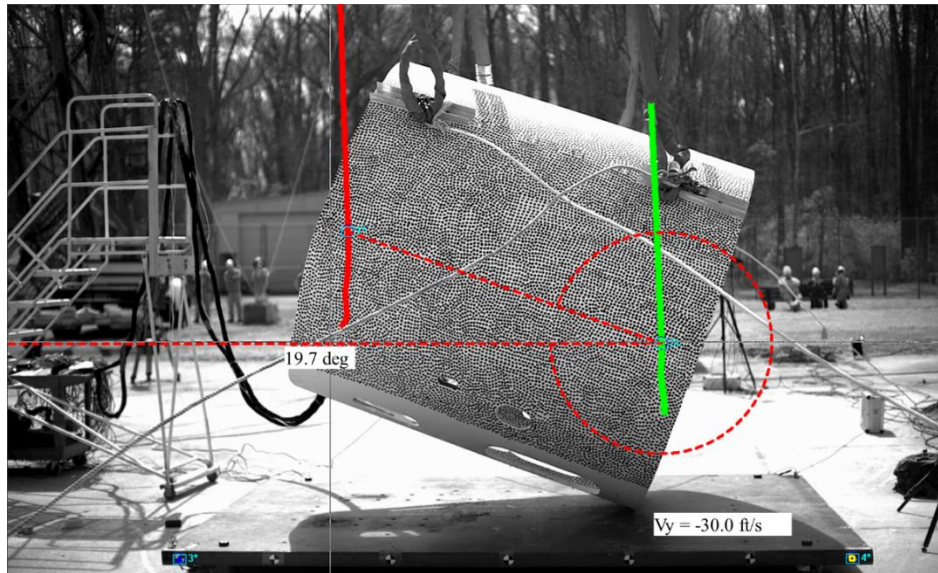


Figure 13. Forward section impact conditions.

The measured impact conditions were implemented within the forward section models and the test was simulated using LS-DYNA SMP version R13.10 single precision on a Linux computer cluster. The LS-DYNA solver was changed in the test article simulations from what was used in the component analysis due to an update of the Linux computer cluster used. Comparative simulation between R10.10 and R13.10 was conducted with the reverse engineered forward section model. Results showed no significant change in predicted response. Simulations were carried out to a termination time of 0.25 seconds using eight processors. The reverse engineered model had an approximate run time of six hours while the manufacturer specification model had a run time of four hours. The increased run time in the reverse engineered model was driven by the multi-layer solid element configuration used to represent the composite sandwich, opposed to the shell element *Part_Composite definition used in the manufacturer specification model.

The forward section test article showed failure of the composite structure along the impact edge of the test article during the impact event. The impacting edge experienced delamination to both sides of the impact centerline, forming a “w” shape in the composite structure. The region behind the impact edge also flattened during the impact, exhibiting delamination of the composite sandwich up to the midline of the test article. At peak deflection the fuselage took on a slight oval shape. An image of the test article, reverse engineered model, and manufacturer specification model at peak deformation is shown in

Figure 14. Damage to the composite structure along the impact edge up to the front midline of the test article was predicted by the reverse engineered model, though the distinct “w” shape observed in test was not replicated. The manufacturer specification model did not predict material failure within the composite structure. Simplifying the representation of the multi-material sandwich composite using shell elements with *Part_composite definition prevented prediction of the component delamination failures which occurred during test. In addition, more pronounced bowing of the fuselage into an oval shape was observed in the manufacturer specification model than what was observed in both the test and reverse engineered models.

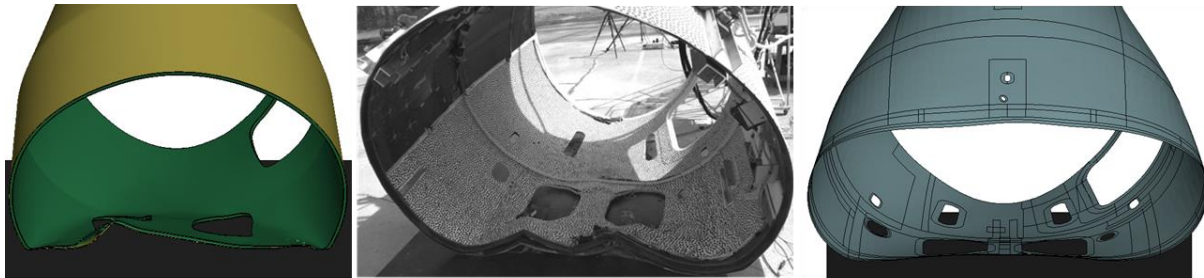


Figure 14. Composite damage observed in forward section test article (middle) and predicted in reverse engineered (left) and manufacturer specification (right) models.

Displacement of the forward fuselage structure was measured during the test using three-dimensional digital image correlation (3D-DIC). Peak vertical displacement of the fuselage was compared between test and simulation in order quantify the effectiveness of each model in predicting changes in occupant compartment volume during impact. Comparison of vertical displacement at peak deflection in the test and each model is shown in Figure 15. The test measurement was limited to the area of test article perpendicular to high-speed video taken during the test and is thus compared along the horizontal face of the fuselage section. Both the reverse engineered model and manufacturer specification model predicted greater vertical displacement than what was measured in the test. The reverse engineered model predicted an equal overprediction of approximately 3 in. of displacement at the front and aft end compared to the test article. The overprediction of displacement at the front and aft end of the test article is likely due to increased damage in the floor of the model resulting in greater displacement of fuselage, while retaining similar overall shape to the test article. The manufacturer specification model showed much higher displacement towards the front end, compared to the test article while the aft end showed less relative change. This difference is driven by the increased deformation in fuselage shape predicted by the manufacturer specification model during impact. Rather than absorbing the impact energy through material failure, the manufacturer specification model deformed elastically at the point of impact, like a rubber ball, resulting in overprediction of deformation of the fuselage shape both downward and laterally. Though some bowing was observed in the test article during the test, it did not match the deformed shape predicted in the manufacturer specification model.

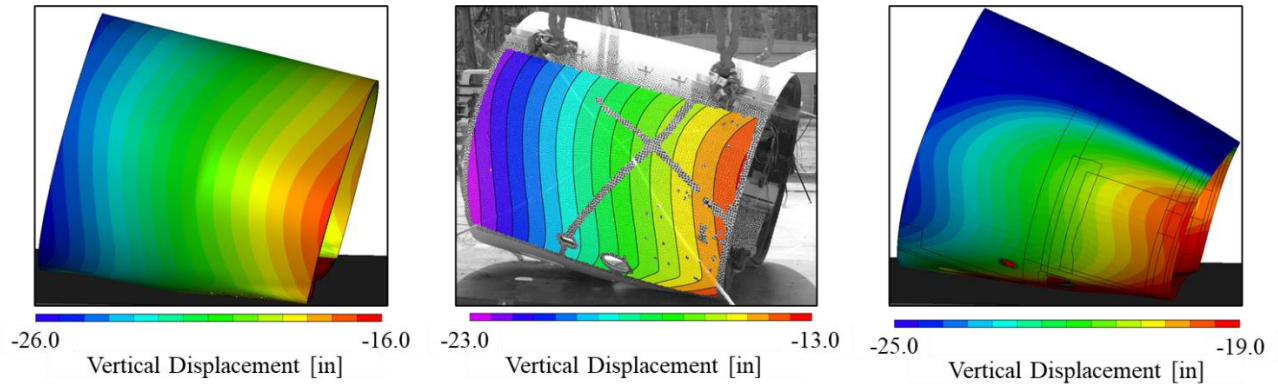


Figure 15. Vertical displacement measured in forward section test article (middle) and predicted in reverse engineered (left) and manufacturer specification (right) models.

Acceleration time histories recorded in the test article were compared to those predicted by the two representative models to quantify the capability of the model to predict energy transferred from the impact into the occupant compartment of the composite structure. Acceleration data was originally filtered using a Channel Frequency Class (CFC) 60 filter in accordance with SAE J211 guidelines [3]. The data produced was highly oscillatory which made comparison between test and simulation difficult. To improve data legibility a Butterworth low-pass filter with a 60 Hz cutoff frequency was applied to both test and simulation data. An example comparison between the CFC 60 and 60 Hz Butterworth filter applied to the forward port side ballast horizontal acceleration from test and simulations is shown in Figure 16. The lower cutoff frequency filter was found to retain overall shape and magnitude of the acceleration pulses while reducing the oscillatory responses recorded in both test and simulation data.

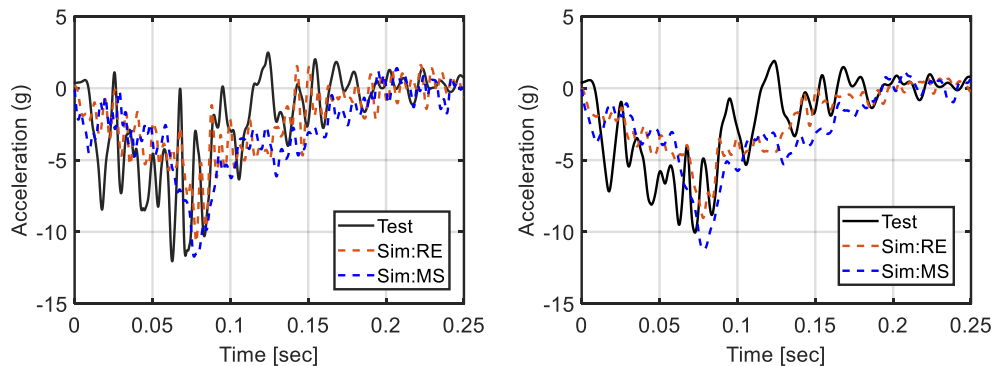


Figure 16. Comparison of CFC 60 filter (left) and 60 Hz Butterworth filter (right) applied to measured and predicted acceleration response.

The accelerometers attached to the ballast mounts provided the most consistent accelerometer time histories during the impact event to allow for comparison between test and simulation. The accelerometers mounted directly to the vehicle skin tended to record large signal oscillations and in certain cases became detached from the vehicle during the impact event. Acceleration time histories measured in test and predicted using simulation at the forward portside ballast location in the horizontal, lateral, and vertical directions are shown in Figure 17. The reverse engineered model and manufacturer specification model, denoted as RE and MS respectively, exhibited similar acceleration predictions

compared to the test data. Peak acceleration and time of peak was well predicted by both models in the horizontal direction. Neither model captured the initial rise acceleration measured during test and both models slightly underpredicted acceleration prior to the maximum peak in horizontal acceleration. The initial increase acceleration was also underpredicted by both models in the lateral and vertical directions as well, though overall the manufacturer specification model did a better job predicting peak initial acceleration. After the initial underprediction acceleration time history shape was predicted by both models in the lateral and vertical directions. Although the manufacturer model did not predict the structural damage observed in the test it provided an as accurate, if not slightly improved, prediction of acceleration response compared to the reverse engineered model of the forward test article.

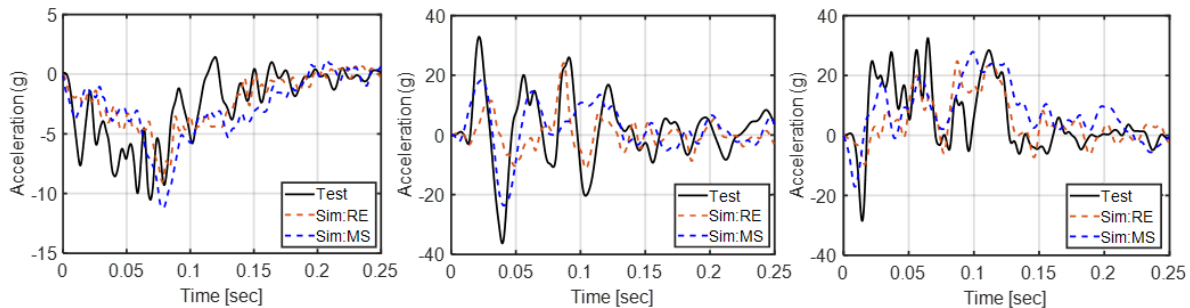


Figure 17. Forward section forward portside ballast acceleration: horizontal (left), lateral (middle), and vertical (right).

Acceleration time histories measured in test and predicted using simulation at the aft portside ballast location in the horizontal, lateral, and vertical directions are shown in Figure 18. Correlation to the horizontal acceleration time history was similar to that observed at the forward accelerometer location. Both models underpredicted initial acceleration but captured overall shape and peak acceleration response in the horizontal direction. The manufacturer specification model slightly overpredicted peak horizontal acceleration while the reverse engineered model slightly underpredicted this value. Lateral acceleration was highly oscillatory as it was in the forward accelerometer, due to the impact force being perpendicular to the recorded motion. Both models captured response at varying times in this direction, but neither were consistent across the evaluated period. Both models under predicted acceleration in the vertical direction, though both captured overall shape of the response in this direction. Similar to the results of the forward accelerometer comparison, differences between model type were not found to significantly alter acceleration time history correlation.

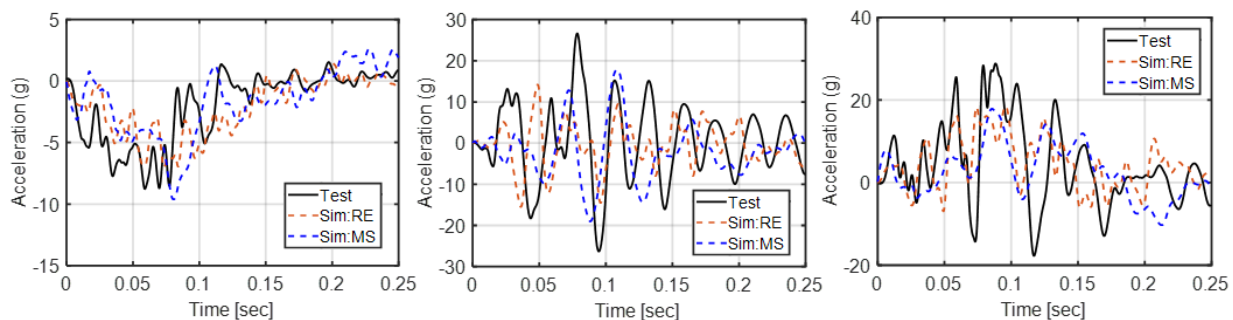


Figure 18. Forward section aft portside ballast acceleration: horizontal (left), lateral (middle), and vertical (right).

RESULTS – AFT SECTION TEST MODEL CORRELATION

The aft section test article was dropped from a height of 14 ft. with a nose up pitch of 20 degrees. The impact conditions were verified using highspeed photogrammetry. An image of the aft test article at impact with angle and velocity measurements is shown in Figure 19. The measured impact conditions of the forward test article were 26.7 ft/s vertical velocity with a downward pitch of 17.9 degrees. The test article rotated slightly during the drop which altered the impact conditions. The measured impact conditions were used to drive the aft test section simulations carried out using the same process and LS-DYNA solver used in the forward section simulations. The aft test section reverse engineered model had an approximate run time of three hours while the manufacturer specification model had a run time of four hours.

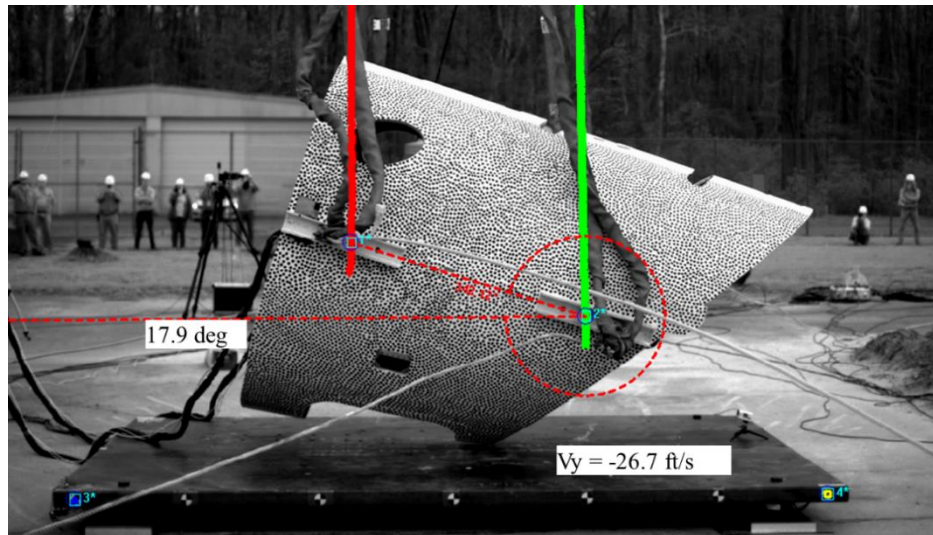


Figure 19. Aft section impact conditions.

During impact, damage to the aft section test article composite structure along the impacting edge was observed. The center of the impacting edge showed delamination and brittle failure of the composite skin and sandwich material extending across the length of the structure in this area. Failure of the material along the length of the impacting structure caused the fuselage to fold inward at the failure point producing a distinct triangular shape. The inward folding also led to sandwich delamination along the width of the impacting edge of the fuselage. An image of the aft test section reverse engineered model, test article, and manufacturer specification model at peak deformation is shown in Figure 20. The composite failure of the impacting structure was predicted by the reverse engineered model. The reverse engineered model predicted composite failure and sandwich delamination across the length of the impact region and accurately replicated the inward folding which resulted in the distinct triangular peak around the failure point. The manufacturer specification model was not capable of predicting the material failure, and like the forward section model it predicted more compression of the fuselage ring during the impact event.

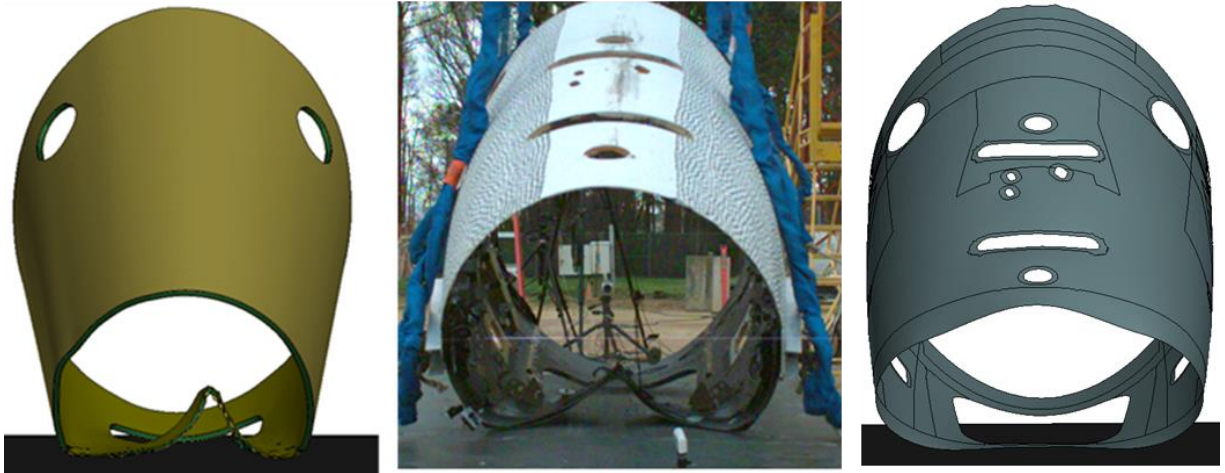


Figure 20. Composite damage observed in aft section test article (middle) and predicted in reverse engineered (left) and manufacturer specification (right) models.

Comparison of vertical displacement at peak deflection measured on the aft section test article and each representative model is shown in Figure 21. The reverse engineered model was found to predict similar vertical displacement to what was measured across the surface of the test article. Close prediction of structural displacement by the reverse engineered model corresponded with the accurate prediction of damage. Prediction of displacement across the compared surface also indicates realistic estimation of structural stiffness of the test article by the reverse engineered model. The manufacturer specification model underpredicted displacement towards the non-impacted bottom edge of the fuselage, this was caused by lack of failure prediction which prevented compression of the fuselage bottom into the impact surface. Displacement towards the top end of the test article was reasonably predicted. Although the manufacturer specification model did not predict the structural failure it compressed in a manner which produced similar vertical displacement on the impacting side of the test article.

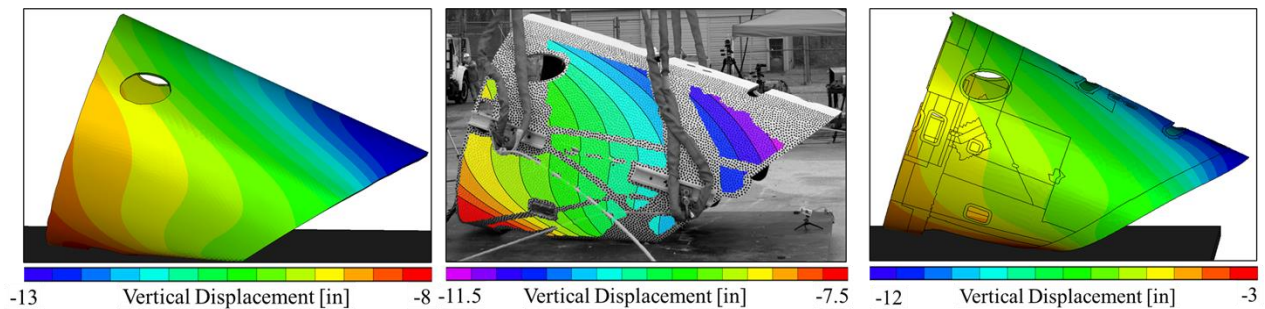


Figure 21. Vertical displacement measured in aft section test article (middle) and predicted in reverse engineered (left) and manufacturer specification (right) models.

Acceleration time histories measured in test and predicted using simulation of the aft test article at forward portside ballast location in the horizontal and vertical directions are shown in Figure 22. The lateral direction accelerometer was lost during test. In the horizontal direction the reverse engineered model predicted peak acceleration and acceleration shape during the impact event. The manufacturer specification model overpredicted initial peak acceleration in the horizontal direction. In the vertical direction the reverse engineered predicted acceleration shape but underpredicted peak acceleration. The

manufacture specification model also predicted acceleration shape and more closely predicted the initial acceleration peak. Neither model predicted the large acceleration spike of 45 g in the vertical direction which was recorded in the test accelerometer at approximately 0.03 s.

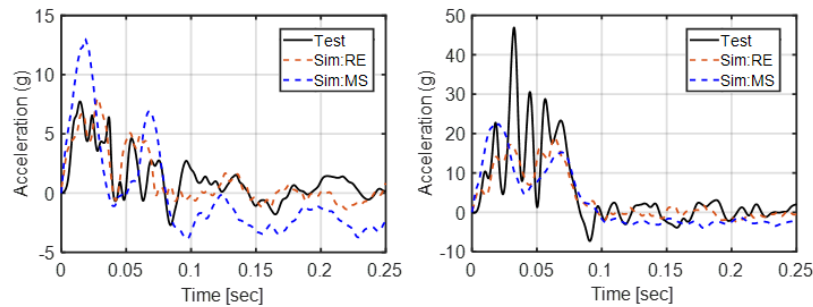


Figure 22. Aft section forward portside ballast acceleration: horizontal (left) and vertical (right).

Acceleration time histories measured in test and predicted using simulation of the aft test article at the aft portside ballast location in the horizontal, lateral, and vertical directions are shown in Figure 23. In the horizontal direction the models achieved similar correlation to that which was observed in the forward accelerometer location. The reverse engineered model predicted acceleration shape and magnitude with the exception of the initial acceleration spike which was underpredicted. The manufacturer specification model overpredicted acceleration magnitude resulting in an earlier rebound in acceleration. In the lateral direction both models predicted acceleration shape. The reverse engineered model under predicted acceleration magnitude while the manufacturer specification model predicted peak acceleration magnitude but overpredicted local acceleration spikes. In the vertical direction both models underpredicted the initial acceleration spike measured in test, though the manufacturer specification model came closer to predicting the peak value. During the second rise in vertical acceleration, the reverse engineered model predicted the acceleration shape and magnitude while the manufacturer specification model overpredicted peak acceleration. Unlike in the forward section model correlation, clear differences in acceleration time history correlation were identified in the aft section models. The manufacturer specification model predicted higher acceleration responses than the reverse engineered model in all cases. The higher acceleration prediction by the manufacturer model had a mixed effect on correlation, it generally resulted in the manufacturer specification model overpredicting peak acceleration but for the lateral direction it led to improvement in both shape and magnitude prediction. The reverse engineered model showed close overall correlation to the test response apart from underpredicting the initial acceleration spike.

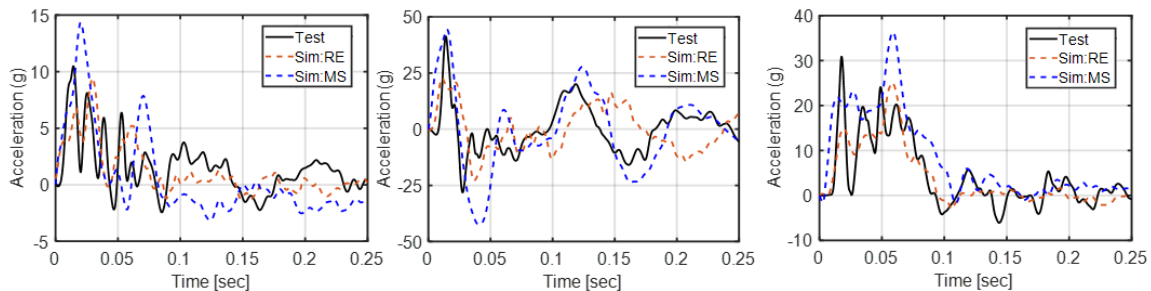


Figure 23. Aft section aft portside ballast acceleration: horizontal (left), lateral (middle), and vertical (right).

DISCUSSION

The reverse engineered and manufacturer specification FE models of the Hawker 4000 fuselage were developed utilizing unique data sets on the geometry, construction, and material characteristics of the fuselage which were obtained relative to the specific model configuration. During the model development process data was not shared between model configurations in order to identify benefits and limitations of each isolated data set used to produce the models. The isolated development methodologies produced mixed results with regards to predicting damage, deformation, and acceleration within the fuselage test articles during dynamic impact test conditions.

The reverse engineered models were developed using component tests and measurements of the Hawker 4000 test article with no knowledge of the fabrication process or manufacturer details. The geometry of the reverse engineered models was developed from 3D-scans and were thus limited in detail compared to the computer-aided design (CAD) geometry obtained by the manufacturer specifications. Component material testing performed on the test article allowed for in-depth material characterization. Material characterization testing led to the development of material models which were calibrated to predict component response through failure under both static and dynamic loading within the sandwich composite structure. Though the component material models were calibrated to test, detailed variations in the composite layup throughout the test article could not be replicated without manufacturer specification data. Lack of composite layup definition data limited precision in replicating mass distribution and material stiffness variability through the structure of the reverse engineered models.

The reverse engineered models were shown to predict the mechanism and location of the composite structural damage observed in both the forward and aft section test articles. Prediction of damage in the forward section model was limited by lack of prediction of the W shaped indentation observed in test and prediction of more damage across the length of the fuselage floor. Increased damage prediction across the floor of the fuselage led to overprediction of peak vertical displacement of forward fuselage section. The aft section test article closely predicted the triangular shape of the damaged section and the extent of damage measured in test. Close prediction of damage extent led to close prediction of peak vertical displacement by the aft section model. Differences in the prediction of damage extent and resulting displacement in the forward and aft section models can be attributed to different effects of imprecision within the composite layup distributions between these two sections of the test article. Based on the manufacturer specifications, the impacting surface of the forward test article was made up of 34 unique composite skin layups, the aft test article impacting surface was made up of three unique composite skin layups. Thus, the simplification of the composite skin as a single part in the reverse engineered models was more significant in the forward section.

Acceleration time history was well predicted by the reverse engineered models of the forward and aft section test articles. The models captured acceleration shape and peak acceleration in most locations across the length of the test article. The one consistent limitation of the acceleration predictions by the reverse engineered model was that initial the acceleration spike recorded in test was not captured. Improved mass distribution and composite layup definition from manufacturer specifications would likely improve acceleration prediction in the reverse engineered model.

The models generated using manufacturer specifications contained the precise geometry of test articles taken from the design CAD of the vehicle. The models also contained details on variability of composite layup throughout the structure. Detailed composite layup definitions allowed the models to closely

replicate material stiffness and mass distribution throughout each test article structure. The manufacturer specification models were limited in their material characterization. The material data provided by the manufacturer to develop the material models did not contain information on material damage or failure under dynamic load. In addition, as there was no component data to develop a validated composite sandwich model in relevant conditions, the model relied on simple shell element representation of composite structure. Shell element representation of the composite structure was effective for applying varying stiffness characteristics of the different composite layups across the structure but limited the capability of the models to predict failure within the sandwich composite.

The manufacturer specification models did not predict the composite failure which occurred in the forward and aft test articles. Lack of composite damage led to energy absorption through elastic compression of the fuselage ring in both test article model configurations. Greater compression of the ring shape predicted by the model led to overprediction of vertical deformation along the impacting edge in both the forward and aft section models. Lack of composite failure also led to underprediction of vertical displacement on the non-impacted side of the test article. Using only the material parameters provided in the manufacturer specifications limited the ability to characterize damage and failure properties in the developed material models. Limited material model characterization led to lack of failure prediction and subsequently poor prediction of vertical displacement within both models.

Although significant differences in failure and deflection shape existed between test and the manufacturer specification models, the models produced a reasonable prediction of the acceleration responses measured in test. The manufacturer specification model of the forward section test closely predicted acceleration shape and produced a closer prediction of peak acceleration than the reverse engineered model. The manufacturer specification model of the aft section test overpredicted peak acceleration in but did a better job of predicting initial acceleration than the reverse engineered model. The reasonable prediction of acceleration by the manufacturer specification model indicates prediction of acceleration load measured in the structure is more predicated on accurate representation of structural stiffness than composite failure prediction.

Post Test Findings - Combined Model Development and Correlation

After developing and examining the predictive capabilities of each developed model in isolation, a combined model was developed of the forward section test article which combined the data and lessons learned from each model to improve predictive capability. The combined model development began with the manufacturer specification model to retain the precise geometry and unique composite layup part definitions contained in that model. The manufacturer specification model mesh provided by the manufacturer was inconsistent in size and used a combination of triangular and quadrilateral shell elements. For the combined model, the geometry was re-meshed using quadrilateral shell elements with a consistent mesh length of 0.5 in. After meshing the shell geometry, the sandwich composite was split into its constitutive skin and core parts like what was done for the reverse engineered model. The inner and outer carbon composite skin was modeled using shell elements with *part_composite to define the 177 unique carbon composite parts which made up the test article inner and outer skins. The honeycomb core was modeled using solid elements which were extruded from the inner skin elements to the length of honeycomb core specified in each composite part defined by the manufacturer specifications. The tied contact with failure model developed in the reverse engineered model was used to bond the solid core

elements to the composite skin shell. The material model definitions developed for the reverse engineered model were applied to the materials defined within the combined model.

The combined model was simulated in the forward test condition using the impact plate model previously developed. Impact conditions were applied matching those measured in the test. Simulations were conducted using the same solver and number of processors used in the previously described model simulations. Simulation run time was approximately 24 hours, which was higher than the previous two models due to the increased complexity of the model. A comparison of damage predicted in the combined model to that which was observed during test at peak deformation is shown in Figure 24. The combined model predicted the “w” shaped damage progression from the point of impact across the impact edge. The model predicted similar delamination of the composite though the damage predicted did progress further out from the point of impact than what was observed in test at peak deformation. Overall, the prediction of composite failure was improved in the combined model compared to what was predicted in the models using the isolated data sets.

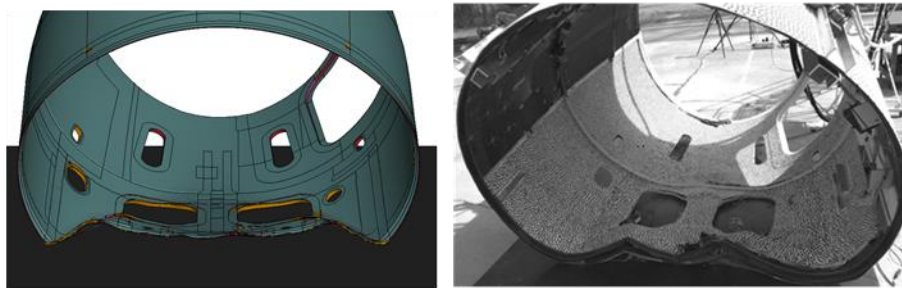


Figure 24. Composite damage observed in forward section test article (left) and predicted in the combined model (right).

Comparison of vertical displacement at peak deflection measured on the forward section test article and the combined model is shown in Figure 25. The combined model closely predicted vertical displacement along the impacting edge, which corresponds with prediction of the composite failure recorded in this region. The model underpredicted displacement at the aft end. Underpredicted displacement at the aft end could be caused by the combined model being slightly stiffer than the test article across its length.

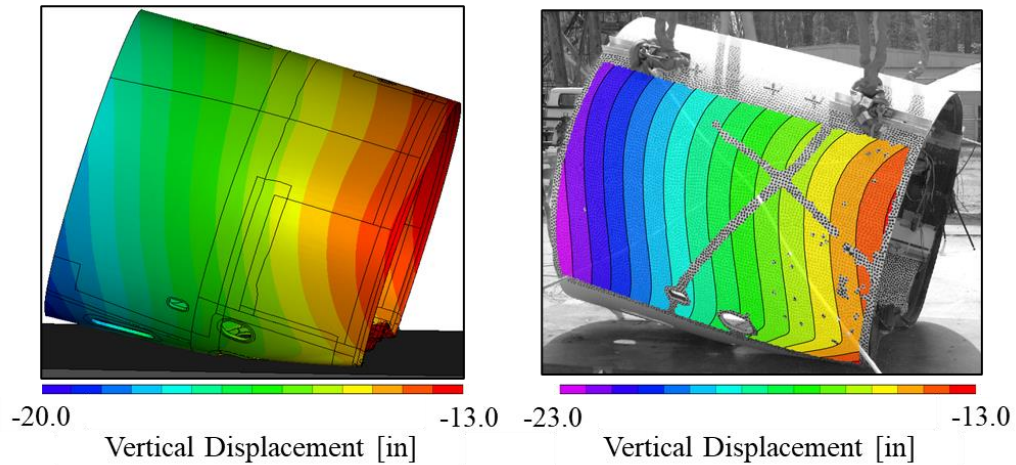


Figure 25. Vertical displacement predicted in the combined model (left) and measured in forward section test article (right).

Acceleration time histories measured in test and predicted by the combined model of the forward test article at the forward portside ballast location in the horizontal, lateral, and vertical directions are shown in Figure 26. Horizontal and vertical acceleration time histories were precisely predicted during the impact event. The combined model most notably improved prediction of the initial acceleration spike in the horizontal direction which was not captured in either of the isolated models. Lateral acceleration shape was predicted by the combined model while magnitude was underpredicted in this direction. The lateral acceleration shape prediction was improved compared to the isolated models while limitations in the prediction of lateral magnitude remained. The lateral direction is normal to the impact direction and accelerations measured in this direction were oscillatory without a clear acceleration pulse shape. Discrepancy in prediction of acceleration in this direction can be attributed to increased damping of the structure in the FE model.

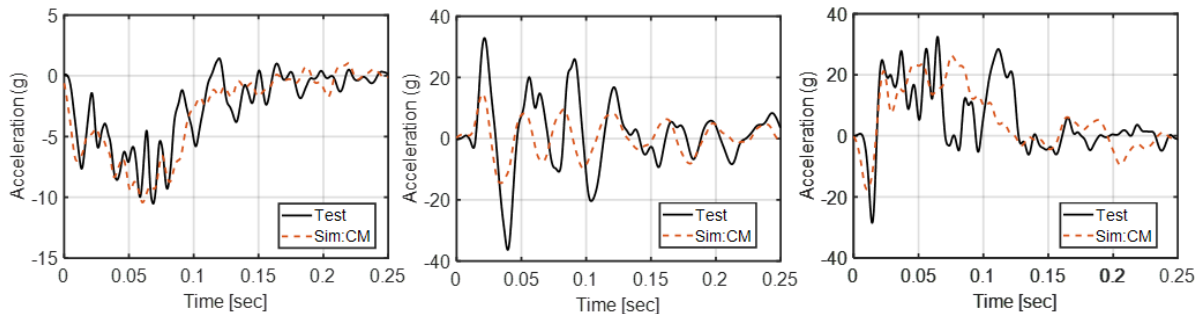


Figure 26. Forward section forward portside ballast acceleration: horizontal (left), lateral (middle), and vertical (right).

Acceleration time histories measured in test and predicted by the combined model of the forward test article at the aft portside ballast location in the horizontal, lateral, and vertical directions are shown in Figure 27. Horizontal acceleration was precisely predicted by the combined model similar to the correlation observed in the forward accelerometer location. Lateral acceleration was predicted during the first 0.1 seconds of impact though as the simulation progressed peaks in the oscillating acceleration response were underpredicted. The combined model underpredicted vertical acceleration in the aft

accelerometer which was out of family with the correlation achieved in the other directions and accelerometer locations with this model.

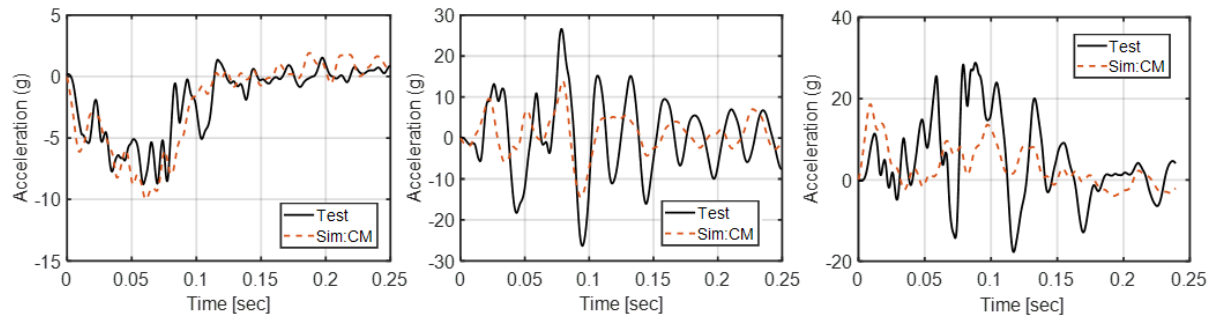


Figure 27. Forward section aft portside ballast acceleration: horizontal (left), lateral (middle), and vertical (right).

CONCLUSIONS

Dynamic impact tests of two Hawker 4000 composite fuselage sections were conducted to study FE modeling of carbon composite aerospace structures. The tests were performed with impact conditions selected to induce damage in the composite structure and thus evaluate the capability of FE models to predict damage and identify effects of damage on overall structural response. Unique FE models of the test articles were developed. One was developed through reverse engineering of the test articles and the other developed using manufacturer provided design specifications. Data from the two modeling techniques were initially not shared between models to produce separate models from which the effect of input data on model predictions could be examined. After studying each model in isolation, a third model was generated which was used to demonstrate FE model predictive capability when provided both manufacturing specifications as well as component calibration data.

Correlation between the developed models and tests performed showed that reverse engineering techniques were capable developing a model which could of predict general damage location and mechanism. The reverse engineering model was limited in the fidelity of composite layup variation defined within the model, which limited its capability to predict the extent of composite damage. Combining composite layup and geometry details from the manufacturer specifications with the reverse engineered material models improved prediction of damage extent. Manufacturer specifications alone were not sufficient to develop a model which predicted composite damage. The prediction of damage had a direct effect on predicted vertical displacement of the composite fuselages during impact and thus is essential to prediction of survivable volume analysis. Correlation to cabin acceleration was not clearly affected by damage prediction. In the forward section test, the manufacturer specification model, which did not predict damage, predicted cabin acceleration on par with the reverse engineered model which did predict damage. Although prediction of damage was not found to be essential to prediction of cabin acceleration, cabin acceleration correlation was improved in the model developed using both manufacturer specification details and reverse engineering data.

Comparison between FE models generated using reverse engineered techniques and manufacturer specification was conducted to inform future analytical efforts on the effect of input data availability on capability to predict response of composite structure under dynamic impact load. As composite materials become more prevalent within aerospace structural design, the importance in predicting the response of

these materials within dynamic loading environments grows. Understanding how modeling input data effects structural response predictions is an essential step in generating FE models which can be used to reliably analyze aerospace structures for design optimization and crashworthiness evaluation.

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