

Test and Analysis Correlation of Form Impact onto Space Shuttle Wing Leading Edge RCC Panel 8

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Abstract

Soon after the Columbia Accident Investigation Board (CAIB) began their study of the space shuttle Columbia accident, “physics-based” analyses using LS-DYNA were applied to characterize the expected damage to the Reinforced Carbon-Carbon (RCC) leading edge from high-speed foam impacts. Forensic evidence quickly led CAIB investigators to concentrate on the left wing leading edge RCC panels. This paper will concentrate on the test of the left-wing RCC panel 8 conducted at Southwest Research Institute (SwRI) and the correlation with an LS-DYNA analysis. The successful correlation of the LS-DYNA model has resulted in the use of LS-DYNA as a predictive tool for characterizing the threshold of damage for impacts of various debris such as foam, ice, and ablaters onto the RCC leading edge for shuttle return-to-flight.

Introduction

During the Columbia Accident Investigation Board (CAIB) investigation, various teams from industry, academia, national laboratories, and NASA were requested by Johnson Space Center (JSC) Orbiter Engineering to apply “physics-based” analyses to characterize the expected damage to the shuttle thermal protection system (TPS) tile and Reinforced Carbon-Carbon (RCC) material, for high-speed foam impacts. The forensic evidence from the Columbia debris eventually led investigators to conclude that the breach to the shuttle TPS was caused by a large piece of External Tank (ET) foam that impacted and penetrated the lower portion of a left-wing leading edge RCC panel. The precise location of the impact was narrowed down to the left-wing RCC panel 8. Consequently, the CAIB sanctioned a foam impact test onto RCC panel 8 in July 2003 at Southwest Research Institute (SwRI) in San Antonio, Texas. In the test, a 1.67-lb. block of foam was shot from a large compressed-air gun and impacted panel 8 at a velocity of 777 ft/s at an angle of incidence of 25.1 degrees in an attempt to simulate the scenario observed approximately 82 seconds into Columbia’s flight. The impact resulted in a large 16-in. x 16-in. hole in panel 8.

Chapter 11 recommendation 3.3-2 of the CAIB report [1] requests that NASA initiate a program to improve the impact resistance of the wing leading edge. The second part of the recommendation is to ...“determine the actual impact resistance of current materials and the

effect of likely debris strikes.” For Return-to-Flight, a team consisting of personnel from NASA Glenn Research Center, NASA Langley Research Center, and Boeing Philadelphia was given the following task: to develop a validated finite element model of the shuttle wing leading edge capable of accurately predicting the threshold of damage from debris including foam, ice, and ablaters for a variety of impact conditions. Since the CAIB report was released, the team has been developing LS-DYNA models of the RCC leading edge panels, conducting detailed materials characterization tests to obtain dynamic material property data, and correlating the LS-DYNA models with data obtained from impacts tests onto RCC panels. Other documents that have been authored by the team can be found in References 2- 5.

To begin validating LS-DYNA predictions, test and analysis correlations were performed for selected full-scale RCC panel impact tests. In particular, the correlation study for the panel 8 impact test at SwRI, which produced the most damage to date, will be described in this report.

Experimental Program

Description of Test

A foam impact test onto RCC panel 8 was conducted in July 2003 at SwRI in San Antonio, Texas. In the test, a 1.67-lb. block of foam with a cross-section of 11.5 x 5.5 inches was shot from a large compressed-air gun and impacted panel 8 at a velocity of 777 ft/s at an angle of incidence of 25.1 degrees. The primary purpose of the test was to determine if a piece of foam traveling at the estimated velocity of the foam that struck Columbia’s wing could breach an RCC leading edge panel.

The pre-test setup of panels 5 through 10 with T-seals between panels is shown on the test-rig at SwRI in Figure 1. The end of the gun barrel can also be seen in the figure. The gun barrel was rotated (clocking angle) such that the front edge of the foam would align with the RCC panel to produce as much contact surface as possible. High-speed picture and photogrammetry data were captured as well as time history data from strain-gages and accelerometers.

Summary of Test Results

The most obvious result from the test was the large 16-in x 16-in hole in panel 8 that is illustrated in Figures 2 – 3. Also, the RCC fragments from the hole that were created by the foam impact were collected and are illustrated in Figure 4. The ruler at the right side of the figure measures 12 inches in length.

In addition to high-speed photographic data, photogrammetric measurements were made of the panel behind the area of the foam impact. Strain gages, accelerometers, and load cell transducers were used on the test article to obtain time histories of the impact event. Photogrammetric and strain gage data will be used in the report to compare with the LS-DYNA simulations.

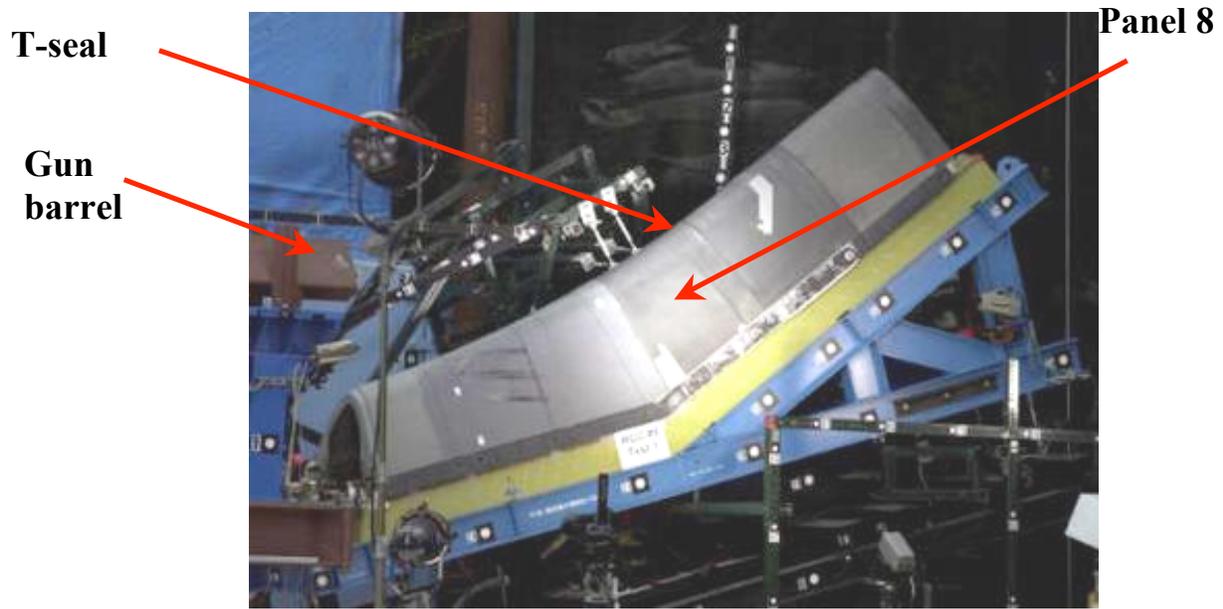


Figure 1. Pre-test set up at SwRI with panels 5 through 10 and associated T-seals on test-rig.

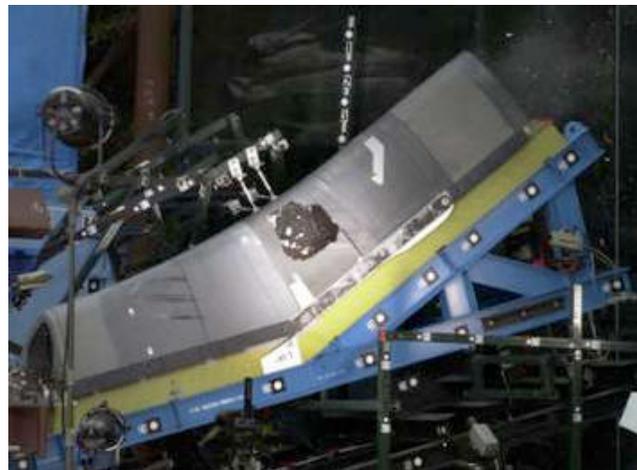


Figure 2. Post-test photo illustrating the large hole in RCC panel 8.



Figure 3. Close-up photograph of the damage to RCC panel 8.



Figure 4. The major RCC fragments from the impact test.

Finite Element Simulation

The units used in the LS-DYNA model for length, mass, and time were inch, pound/g, and seconds. In these units, the acceleration of gravity, g , is 386.4 in/s^2 . The main shuttle Orbiter coordinate system was also used. For this example, the outer mold line (OML) surfaces of the RCC panel plus flanges and ribs were obtained from solid models and meshed using quadrilateral shell elements by Boeing and Glenn Research Center (GRC). The foam debris velocity was primarily along the global Orbiter X-axis with a resultant velocity of $9,300 \text{ in/s}$ (775 ft/s) used in the model.

Before the test at SwRI, pre-test LS-DYNA models were constructed by Boeing Philadelphia to assess the likely damage. However, no failure criterion was used in the initial pre-test predictions. For the model described in this paper, Mat58 (MAT LAMINATED COMPOSITE FABRIC) [6] with failure was used as the material model for the RCC. The RCC material parameters required for Mat58 are discussed in Reference 3 and are based on available RCC material data. There is a wide variation in the RCC material properties for as-fabricated material. Panels that have been flown exhibit some mass loss, which further degrades the RCC material strength. In addition, the material is considerably stronger in compression as compared to tension. The RCC material properties for the LS-DYNA model were chosen to be average as-fabricated values. The failure strain for the model was approximately 0.006. The RCC material is a “tough” brittle material with a typical panel of 19-ply of fabric laid up in alternating 0/90 layers. The thickness of the 19-ply RCC material is nominally 0.233 inches and the density of RCC is approximately 100 lb/ft^3 . The manufacturing process to make RCC from Rayon cloth is a complex multistage process [7]. The material is laid up and then heated without oxygen to drive out all volatile materials except the carbon. In a final process silica is added into the furnace to produce SiC-rich material in the outer two layers through a diffusion process. The failure model in the LS-DYNA Mat 58 material is a cumulative damage model [8].

The foam model for the projectile was the Mat 83 MAT_FU_CHANG_FOAM model [6]. Strain rate effects were found to be important in the foam material at the velocities in question. High strain-rate data for the Fu-Chang model was generated in a specially configured and

instrumented 14-ft. bungee-assisted drop tower at the Impact Dynamics Research Facility at NASA Langley that can achieve strain rates of over 400/s. The high strain-rate data were directly input into the Fu-Chang model. The Poisson ratio of the foam is assumed to be zero. The weight density of the foam for this simulation was calculated from the weight and size of the foam block used in the test at SwRI and was found to be approximately 2.0 lb/ft³.

An exploded view of the LS-DYNA model is shown in Figure 5. The model consists of a single panel 8 with a foam projectile and neglected the adjacent RCC panels and the T-seals that fill the gaps between RCC panels. There were a total of 25 designated parts in the LS-DYNA model. The model used 59,360 shell elements to represent the RCC panel and 11,636 solid elements to represent the foam projectile. The shells make use of lamination theory and are modeled to have the actual number of plies for each area (part) modeled. The nominal size of the RCC shell elements was chosen to be approximately 0.2 inch on a side. From LS-DYNA parametric studies performed on the RCC Panel 6 impact test conducted in June 2003 at SwRI, the boundary conditions removed from the area of the impact do not significantly affect the damage. Thus, whether the panel is held in place or is completely unrestrained, the predicted damage was about the same. In this panel 8 model, the bolt holes in the flanges were filled with a rigid material that was completely restrained.

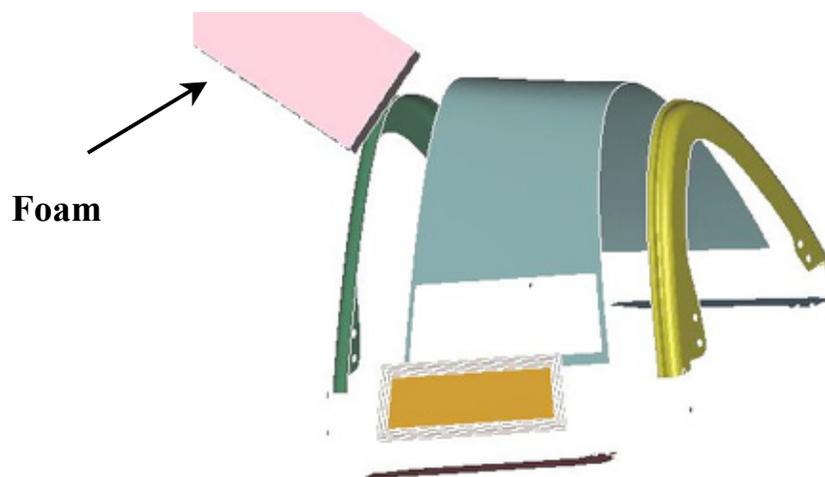


Figure 5. Exploded view of parts of the LS-DYNA model including foam, left and right ribs, front and back flanges or spars, main panel, and front lower doubler region.

Test and Analysis Correlation

Structural Deformation and Failure

The deformed model at approximately 6 ms after impact is shown in Figure 6. The “picture panel” area (in red) at the bottom of the panel is a doubler region with ply drop-offs forming the “frame.” The damage did not extend into the doubler region. Qualitatively, the damage shown in Figure 6 correlated quite well with the size and shape of the actual hole observed post-test (see Figure 3). The RCC debris that was collected post-test is illustrated in Figure 7 from the back side of the panel with the photogrammetric targets. In Figure 8, damage progression is shown at 5 ms after foam impact. The broken pieces in the simulation show a remarkable similarity to the actual pieces collected and shown in Figure 7. Failure of a brittle material is chaotic and depends on local imperfections, residual strains, and thicknesses of the material. The simulation assumes

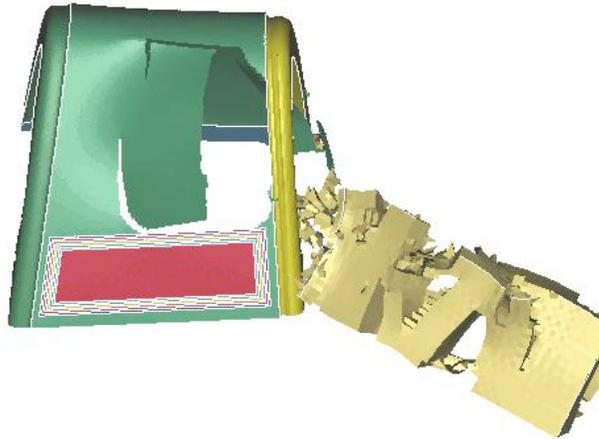


Figure 6. LS-DYNA model showing foam and panel breaking apart 6 ms after impact.

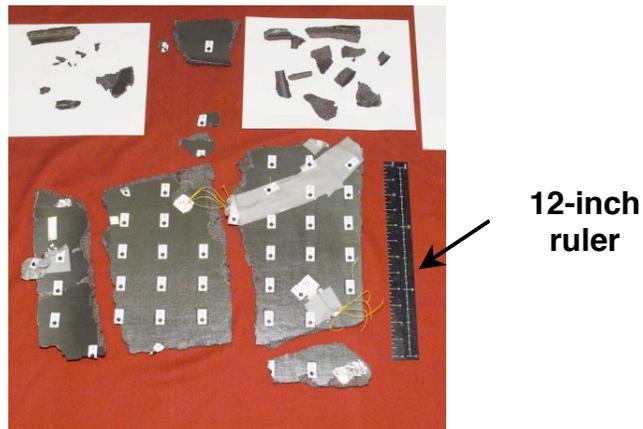
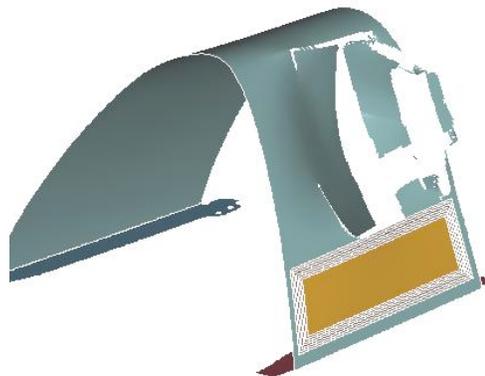


Figure 7. Panel debris showing photogrammetric targets on the back side. The black ruler on the right is 12 inches long.



Panel 8. LS-DYNA model, with panel ribs and foam removed for clarity, showing RCC debris pattern at 5 ms after foam impact.

a perfect orthotropic RCC material without imperfections and cannot be expected to accurately predict the actual shapes and sizes of the debris.

Photogrammetric test and analysis correlation

The displacements of targets on the backside of panel 8 were captured by high-speed video cameras. This photogrammetric data were analyzed in the region outlined by the square in Figure 9. Since the local axis system shown in Figure 9 did not align with the model axes, the photogrammetric data were processed to obtain a resultant displacement at each point for a given time. The resultant displacement is a scalar quantity independent of the coordinate frame. The experimental resultant panel displacements for the points at various times were then plotted as contour plots and compared with the LS-DYNA predicted resultant displacement contours. A typical comparison of test with analysis is shown in Figure 10 for a time of 1.8 ms after foam impact. The panel began to break up around 2.0 ms after foam impact.

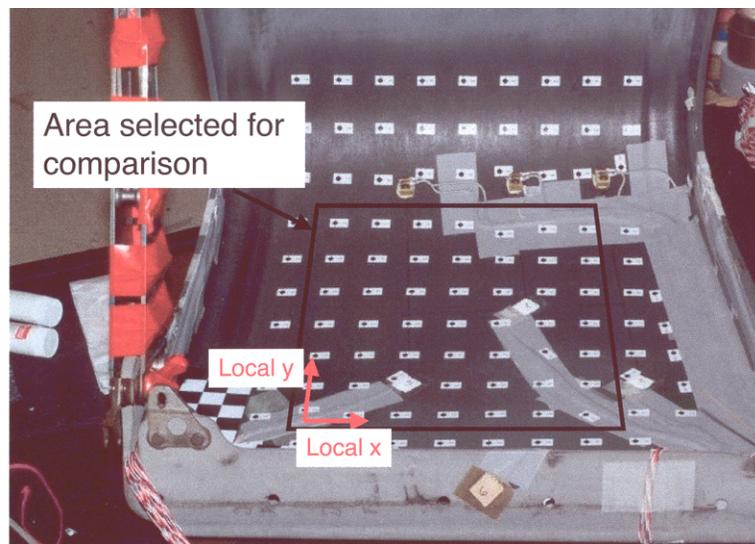


Figure 9. Photogrammetric targets on the back of Panel 8 in the SwRI test.

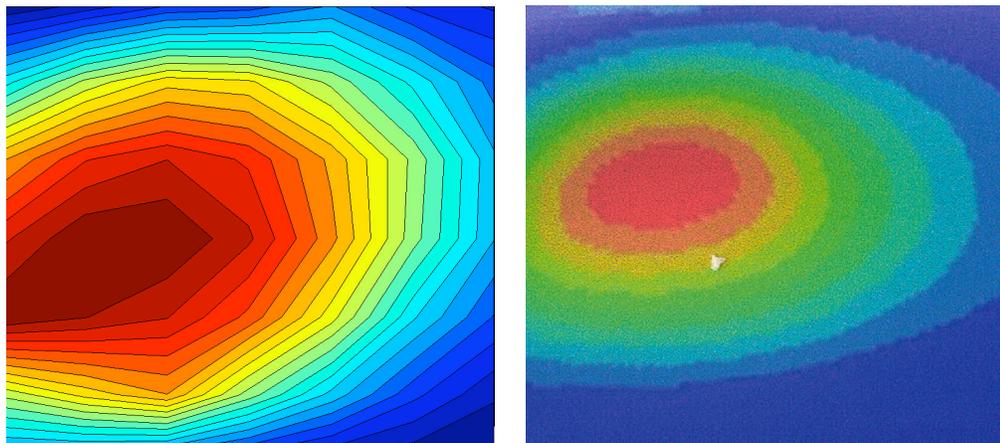


Figure 10. Measured (left) and predicted (right) deflection pattern at 1.8 ms after foam impact. The maximum deflection contour for both plots is 1.2 inches.

Strain gage test and analysis correlation

A large number of strain gages were placed on the panels, ribs, and flanges for the impact test onto panel 8. The test-analysis correlation presented in this paper will concentrate on the five strain-gage rosettes on panel 8 near the foam contact region. The test data were processed to determine the local-x, or longitudinal strains, and the local-y, or lateral strains (see coordinate system in Figure 9). The five positions of interest of the strain-gage rosettes are shown in Figure 11 and are labeled from 1 to 5. The five elements in the finite element model that best corresponded to the experimental location are shown in Figure 12 labeled with the shell element number. The experimental strains are compared with the predicted strains on the inside (inner or 19th ply) of the selected shell element. The comparisons are shown in Figures 13 through 17.

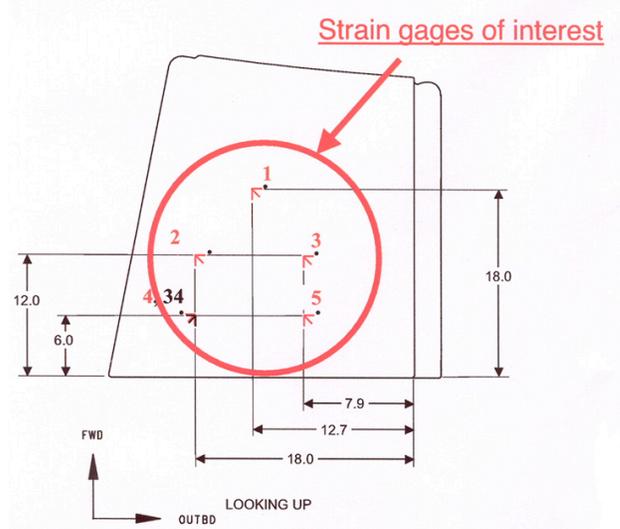


Figure 11. Strain gage locations in test drawing. The strain gages were on the inside of the panel.

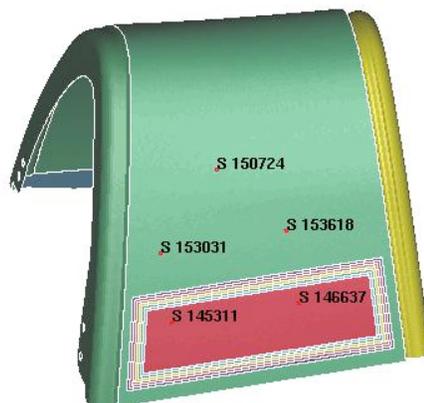


Figure 12. Locations of five elements that best correspond to the strain-gage locations 1 through 5 (see Figure 11).

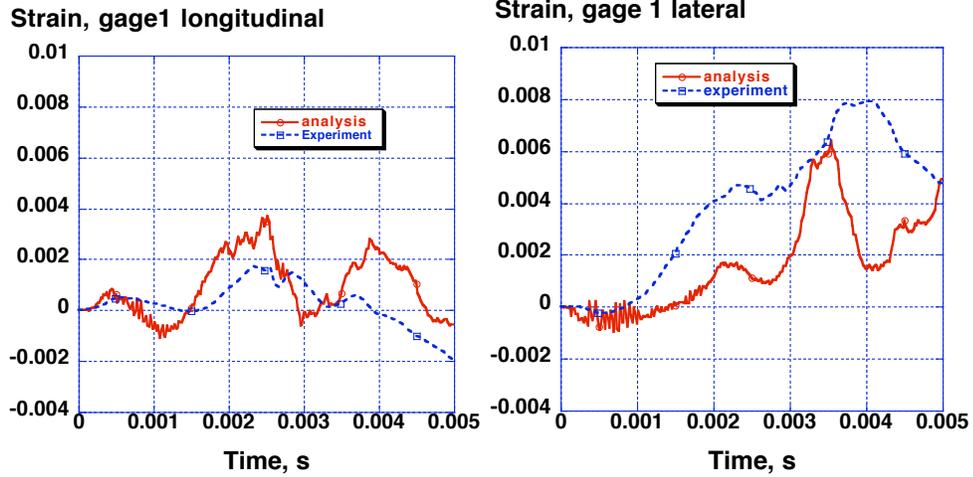


Figure 13. Strain comparisons for gage 1 location.

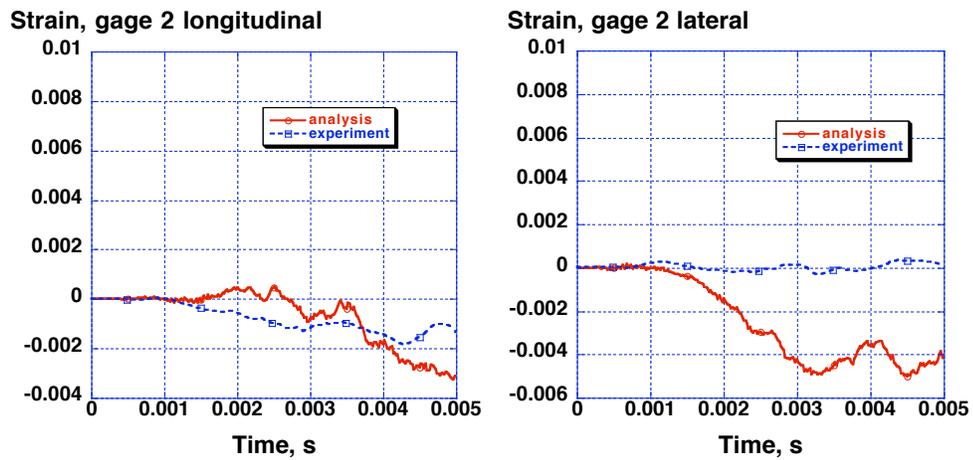


Figure 14. Strain comparisons for gage 2 location.

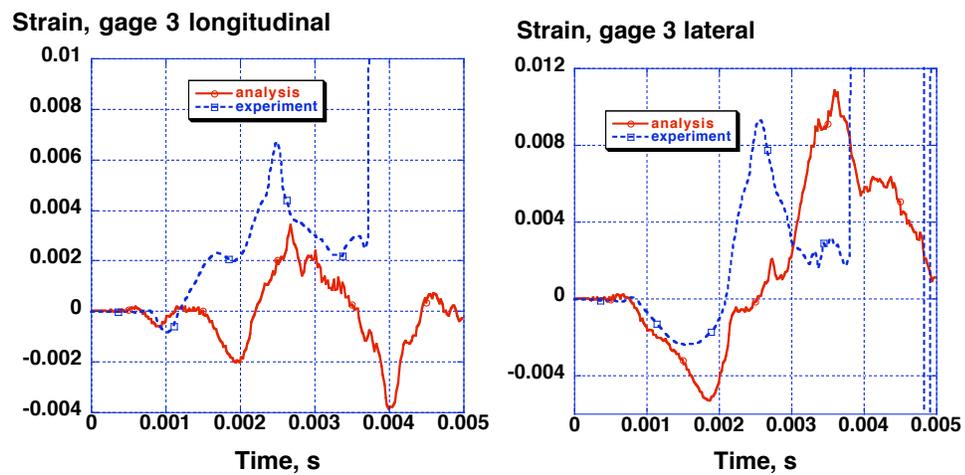


Figure 15. Strain comparisons for gage 3 location.

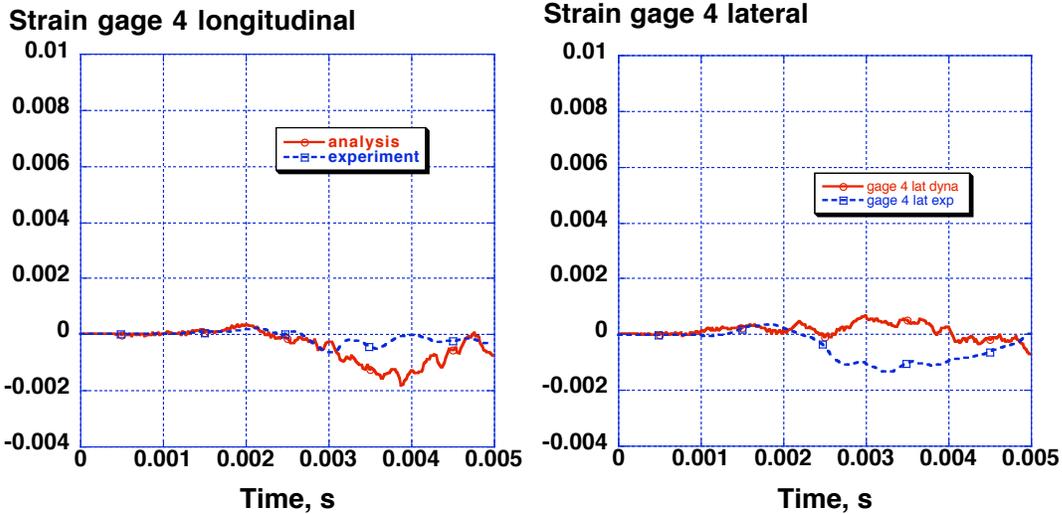


Figure 16. Strain comparisons for gage 4 location.

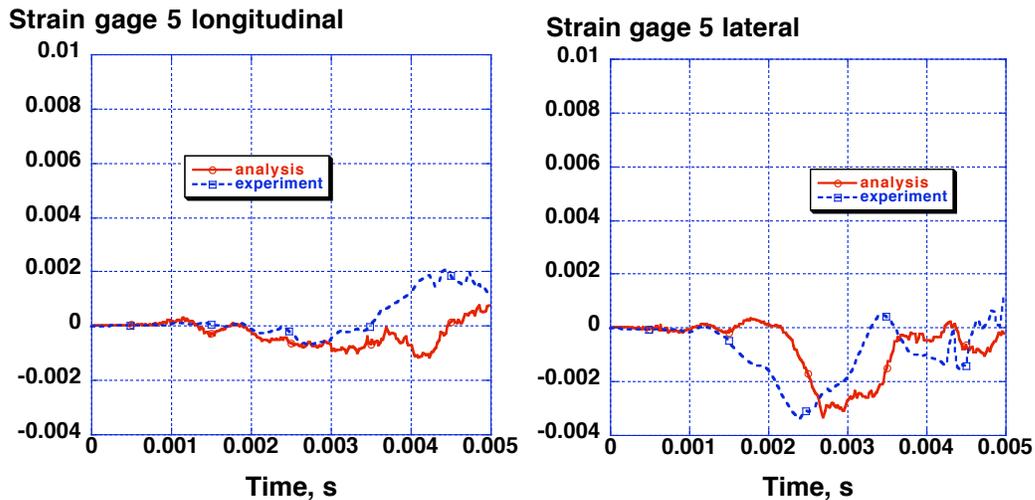


Figure 17. Strain comparisons for gage 5 location.

Discussion of Results

The amount of damage, including the resulting 16-in. square hole produced in panel 8 and the approximate shape of RCC debris, predicted by LS-DYNA correlate well with the experiment. Considering the brittle nature of the RCC material, the high speed of the impact, and the complexities of modeling the foam, the high level of agreement obtained is remarkable.

The resultant displacement data predicted by LS-DYNA was consistent with the experimental data and produced contours that approximated the overall pattern of deflection for each time interval. Since the experimental photogrammetric method has not been completely validated against a standard, the data should only be considered as qualitative.

The experimental strain data also correlate reasonably well the experimental data. There are many details that must be considered when comparing dynamic destructive stain data. First, the strain is likely to have high gradients from region to region. Consider that the strain gages are bonded onto the SiC outer layer. The SiC material is filled with micro-cracks and the

underlying RCC material is quite porous. The exact location of the cracks in the RCC does not correspond to the location of the cracks in the model. Thus, overall, the agreement is considered quite good.

Concluding Remarks

LS-DYNA was used to simulate the damage to the left-wing RCC panel 8 that occurred during an impact test in which a 1.67 lb. block of foam impacted the panel at 777 ft/s. The test was conducted at SwRI in June 2003 during the Columbia accident investigation. The LS-DYNA Fu-Chang foam model with rate-effects was used to characterize the foam material properties, and the MAT_LAMINATED_COMPOSITE_FABRIC with a cumulative damage failure model was used to characterize the complex RCC material. The LS-DYNA model results correlated well with the test both qualitatively and quantitatively. As a result, LS-DYNA “physics based” models are being used as predictive tools for characterizing the threshold of damage for impacts of various debris such as foam, ice, and ablators onto the RCC leading edge for shuttle return-to-flight.

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