The Use of LS-DYNA in the Columbia Accident Investigation and Return to Flight Activities

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Abstract

During the launch of the Space Shuttle Columbia on January 16, 2003, foam originating from the external tank impacted the shuttle's left wing 81 seconds after lift-off. Then on February 1st, Space Shuttle Columbia broke-up during re-entry. In the weeks that followed, the Columbia Accident Investigation Board had formed various teams to investigate every aspect of the tragedy. One of these teams was the Impact Analysis Team, which was asked to investigate the foam impact on the wing leading edge. This paper will describe the approach and methodology used by the team to support the accident investigation, and more specifically the use of LS-DYNA for analyzing the foam impact event.

Due to the success of the analytical predictions, the impact analysis team has also been asked to support Return to Flight activities. These activities will analyze a far broader range of impact events, but not with just foam and not only on the wing leading edge. The debris list has expanded and so have the possible impact locations. This paper will discuss the Return to Flight activities and the use of LS-DYNA to support them.

Introduction

The Space Shuttle is a very complex machine consisting of 4 main components: the Orbiter, the Shuttle Main Engines, the External Tank, and the Solid Rocket Boosters. More than 2.5 million parts, 230 miles of wire, 1,060 valves, and 1,440 circuit breakers are required to construct this machine. At launch, the Space Shuttle weighs approximately 4.5 million pounds. With the use of the Solid Rocket Boosters and Shuttle Main Engines, this mass is accelerated to an orbital velocity of 17,500 miles per hour or 25 times faster than the speed of sound in just over eight minutes [1]. Figure 1 shows the launch of the Columbia on January 16, 2003.

The launch of STS-107 on January 16,2003

The Solid Rocket Boosters provide approximately 85% of the total thrust. The remaining 15% comes from the three Shuttle Main Engines. These engines use liquid hydrogen and oxygen that is stored in the External Tank. Due to the extremely low temperatures of the propellants, special foam insulation is required to prevent the fuels from boiling and ice from accumulating externally. It is a piece of this foam, which broke off 81 seconds after lift-off, that impacted the Orbiter's left wing leading edge, created a breach in the thermal protection system, and ultimately lead to the breakup of the shuttle during re-entry [1]. Please see reference [2] presented at this conference for more details concerning the Space Shuttle Columbia Tragedy.

Details of the Debris Strike

A detailed review of the foam impact event shows that the impact event occurred 81.7 seconds after launch. The foam debris appeared to have originated from the left bipod (–Y) ramp area of the external tank. It was estimated that the foam was 21 to 27 inches long, 12 to 18 inches wide, and weighted roughly 1.63 pounds. The foam appeared to be tumbling at a minimum rate of 18 Hertz and had an impact velocity of 625 to 840 feet per second (416 to 573 miles per hour) [1].

Impact Analysis Team

In the days that followed the Columbia break-up, various investigation teams were formed to analyze many different aspects of the event. In an effort to determine the severity of the foam impact, an Impact Analysis Team was formed comprising of personnel from Boeing Philadelphia, Boeing Seattle, NASA Glenn and NASA Langley.

Analysis Details

To provide an accurate analysis of the foam impact event, three areas needed to be developed: material properties of the foam, material properties of the reinforced carbon-carbon (RCC) material which makes up the leading edge and a detailed finite element model of the leading edge with supporting substructure. Once these three requirements were met, accurate predictions of the foam impact event could be generated using LS-DYNA.

Foam Material Model

As previously described, the foam impacted the leading edge in the vicinity of 625 to 840 feet per second. At the time, foam material behavior was not understood at these high impact rates. It was also not understood how low temperatures and low atmospheric pressure (conditions that existed at the time of the impact event) would influence the foam material properties. In order to develop the required foam material properties, NASA Glenn and NASA Langley performed multiple tests. Results from these tests were used to develop a validated material model within LS-DYNA.

One of the impact tests that were performed consisted of shooting a foam cylinder, 3.00 inches in length and 1.25 inches in diameter, at a target mounted on load cells. Figure 2 shows the foam at several times during the impact event. The foam actually compresses from 3.00 inches to 0.50 inches and then returns to its original length. This specific set-up allowed for load time history data to be measured. The test set-up was modeled and the impact event simulated in an effort to create material properties of the foam. Figure 3 shows the FEM of the test set-up and figure 4 shows the comparison between the measure impact data with the predicted impact data. Since the data was filtered at 2400 Hz, getting an exact comparison was not possible. However, the predicted data, also filtered, does show good correlation, although slightly conservative. Please refer to "Material Modeling of Space Shuttle Leading Edge and External Tank Materials for Use in the Columbia Accident Investigation" [3] (also presented at this conference) for details on the development of the foam model.

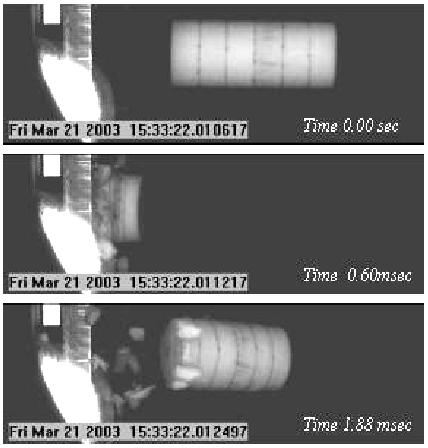

Figure 2. Time snap-shots of a foam impact test

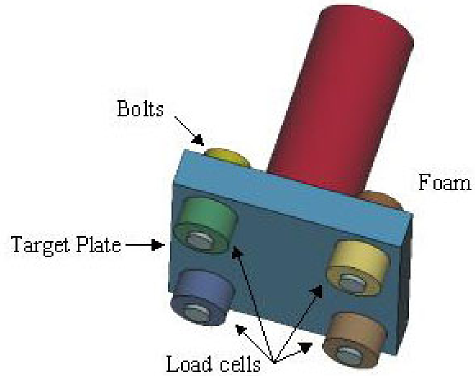

Figure 3. FEM of the test set-up

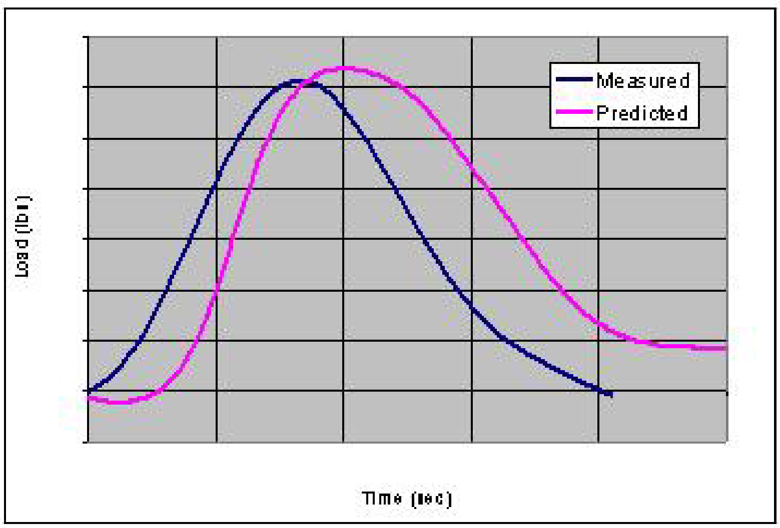

Figure 4. Comparison between the measure impact data with the predicted impact data

RCC Material Model

Another material that needed model development was the RCC, or reinforced carbon-carbon, material used on the Space Shuttle's leading edge. The RCC material itself is very unique. RCC fabrication actually starts with a rayon cloth graphitized and a phenolic resin. After being cured, the laminate is pyrolized to convert the resin to carbon. The laminate is then impregnated with furfural alcohol in a vacuum chamber, cured and pyrolized again to convert the furfural alcohol to carbon. The process is repeated several times until the desired carbon-carbon properties are achieved. The final product provides a great thermal barrier. However, in the presence of oxygen and high temperatures, the RCC material is highly susceptible to oxidation. To avoid this situation, the RCC is coated with silicon carbide [4]. Material properties for the RCC material were developed through testing. Please refer to references [3] and [5] for details on the RCC material model development.

Finite Element Model

A detailed finite element model of the shuttle's leading edge and substructure was the 3rd requirement for the impact analysis. At the time, only a coarse mesh model existed. This was a NASTRAN loads model, which did not explicitly model such details as the mounting hardware. To generate the detailed FEM, CATIA models, Pro E models, and 2-D drawings were used. The preprocessors PATRAN and TrueGrid were utilized to generate the required mesh. Figure 5 shows some of the meshed parts. In the end, a FEM consisting of over 400 individual parts was created. The final model resembled the test set-up at Southwest Research Institute, see figure 6.

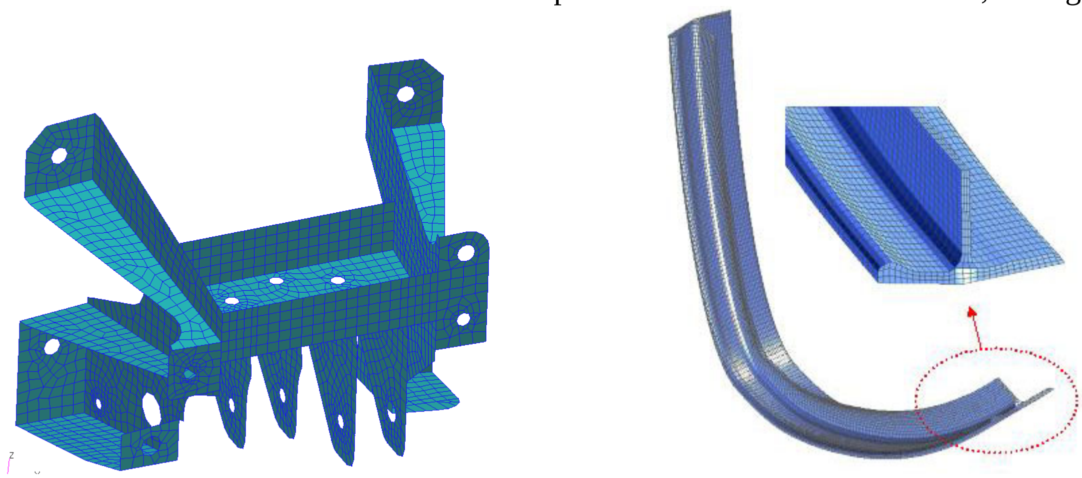

Figure 5. Meshed geometry (left: Lug; right: T-seal)

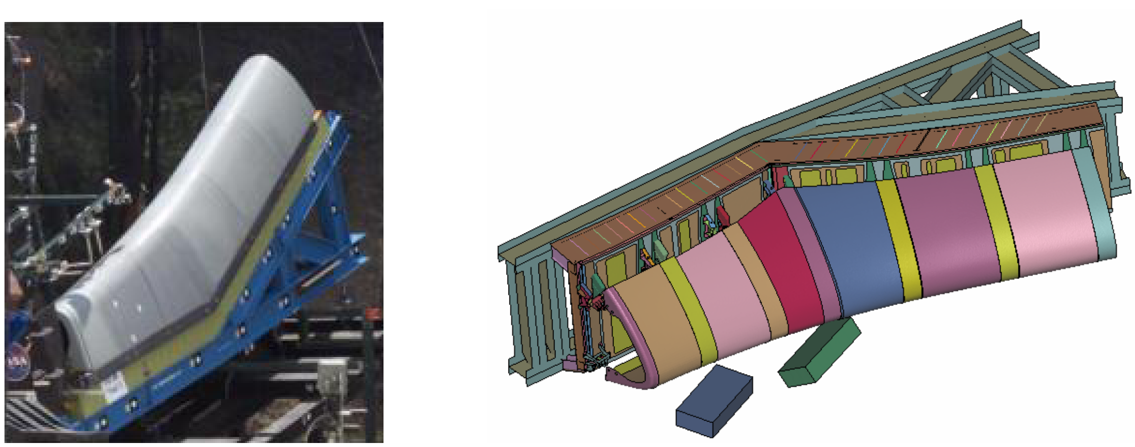

Figure 6. Comparison of test set-up and FEM (various foam orientations shown)

Since the model consisted of so many parts, along with an aggressive schedule, a team of modelers was used. A great deal of communication was required amongst the team members so that in the end, all of the pieces fit together. The assembly of the various part meshes was greatly simplified by leveraging LS-DYNA's tied contact capability. Use of tied contacts allowed two meshes to be constrained to one another without requiring the nodes to be equivalenced. LS-DYNA's joint constraint capability was also utilized to represent the pin connections between parts, such as a T-seal with its associated substructure- see figure 7.

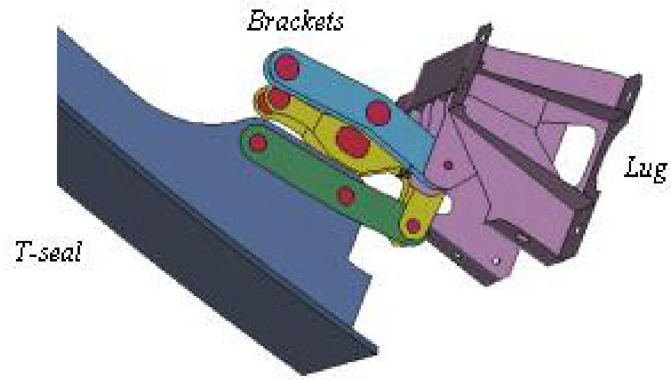

Figure 7. Picture of a modeled joint: rigid materials that fill the fastener holes are used to create revolute joints between brackets, lug, and T-seal (other brackets shown used for adjacent panels)

Impact Simulations

Even before material models for the foam and RCC were developed, CAIB wanted to understand panel 'vulnerability', and the influence of foam impact speed, orientation and size on impact load. This information was being supplied to the testing community that was performing impact tests in parallel with the analysis.

For these first sets of analyses, panel 8 was selected as the target structure. This selection was based on a 'best guess' of impact location and available panel geometry. During the analysis of the impact event, the panel was constrained at the mounting holes. Specifically, filling the holes with a rigid material and then constraining their movements in both translation and rotation created the required boundary condition. By constraining the 'filled hole' instead of a single node, point loads and localized deformations were eliminated.

Reviewing the pictures of the foam impact event, it appeared that a thick dust cloud was generated as a result of the impact event, see figure 8. This observation, along with the estimated foam size and impact speed, was used for the initial set of impact analyses. To simulate the thick dust cloud, the foam was initially modeled using Eulerian elements along with an equation of state. Eulerian elements, unlike Lagrangian elements, do not deform (LS-DYNA does allow the user to control the deformation), but allow the mass to move between elements. Thus Eulerian elements do not get 'skewed', which would reduce time step. It also enables the analysis to accurately predict large non-linear behavior or 'splattering' events. Results from the initial set of analyses are shown in figure 9.

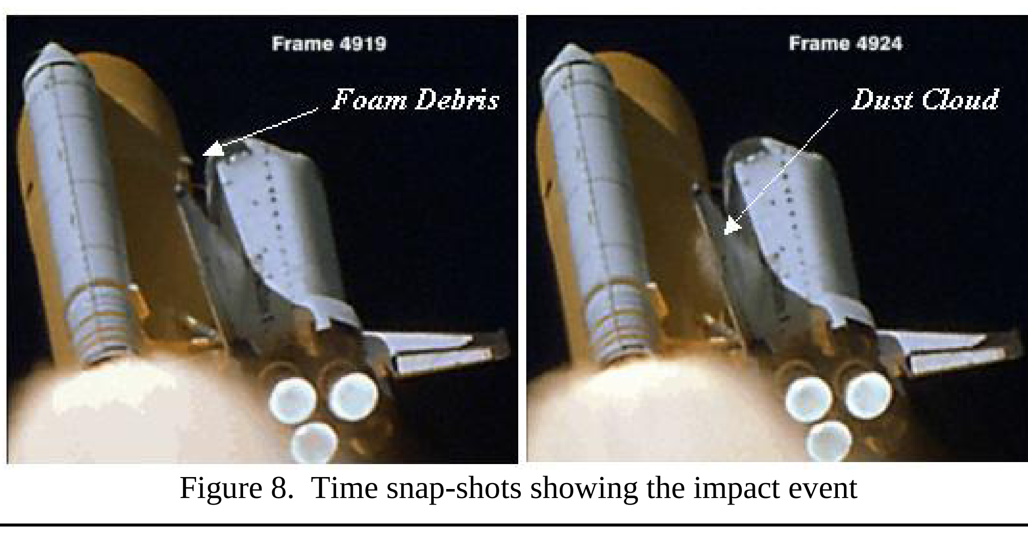

Figure 8. Time snap-shots showing the impact event

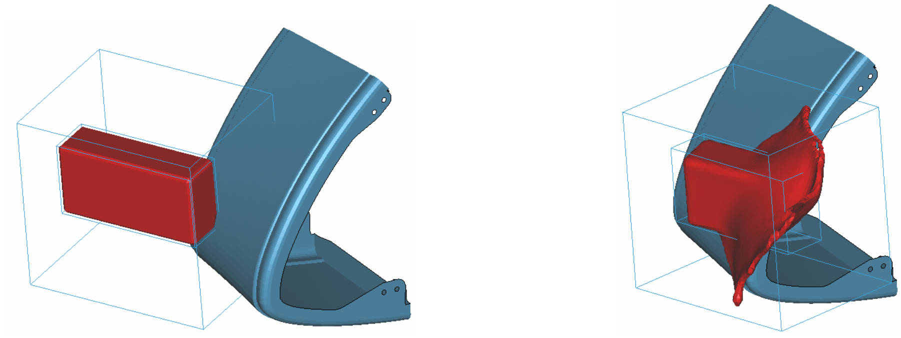

Figure 9. Simulation of a foam impact event using Eulerian Elements and an equation of state to represent the foam

As the foam testing and material model development progressed, the foam was modeled using Lagrangian elements with elastic material properties. Although using elastic material properties was not completely accurate, it was more accurate than the initial approach using a fluid-like behavior. Results with the new foam material model were noticeable different, see figure 10.

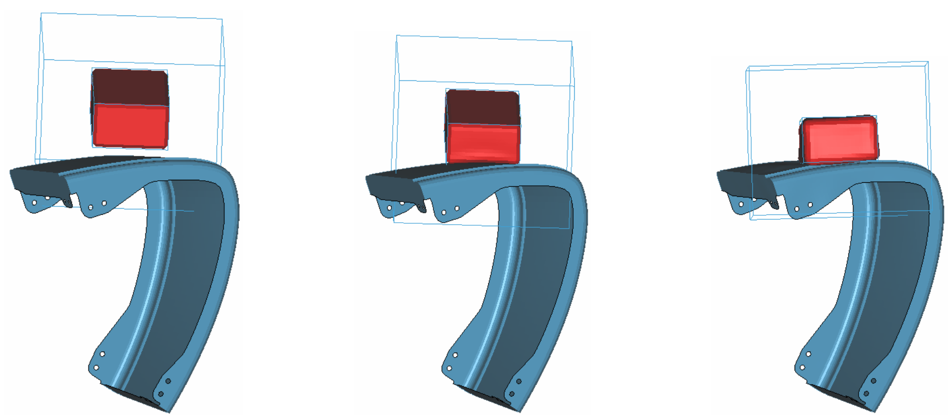

Figure 10. Simulation of a foam impact event using Eulerian Elements and elastic material properties to represent the foam

Video footage of the impact event shows the foam both translating and rotating. However, the tests being performed at Southwest Research Institute were only translating the foam and there was some concern that these tests would not be reproducing the actual event. Our next task was to understand the importance of foam rotation on impact load. To provide some insight, 3 different cases were analyzed: no rotation, slow rotation, and fast rotation. Results from the analyses, figure 11, show that the rotation did have a noticeable influence on the resulting load.

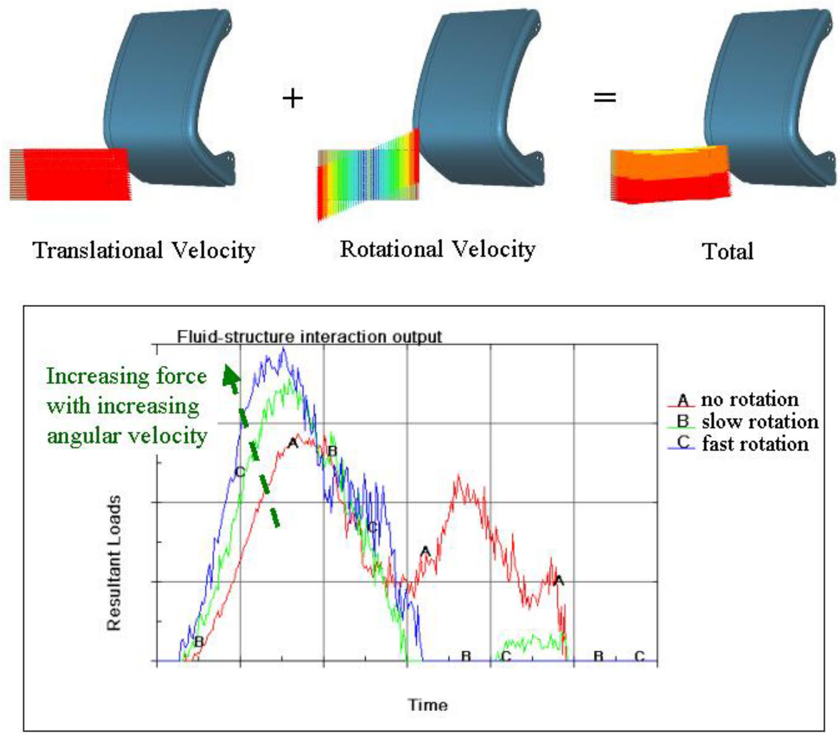

Figure 11. Effects of foam rotation investigated

As more of the finite element model was developed, larger models were used in the impact analysis. One such analysis consisted of Panels 6 & 7, T-seal 7 & 8, and supporting substructure. This specific configuration was chosen because it represented a concurrent test. Results from the test were used to validate the model. Figure 11 shows the finite element model used. A detailed comparison between the test and the analytical simulation was performed by NASA Langley [6,7].

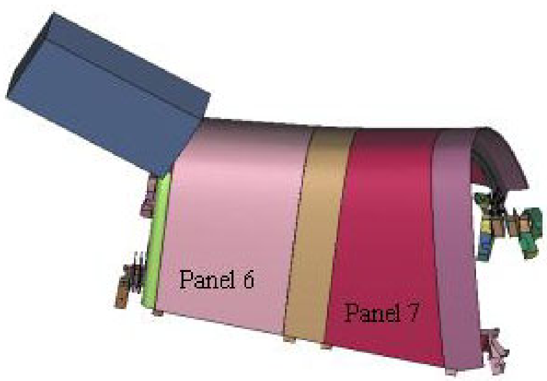

Figure 11. FEM used for the panel 6-impact analysis

On July 8th, 2003, another foam impact was performed at Southwest Research Institute. In the test, a 1.67-pound piece of fuel-tank foam insulation was shot at more than 530 miles per hour at Panel 8. The foam impact blew open a 16-inch hole, yielding what one member of the Columbia investigation team called the "smoking gun" that proves what brought down the spacecraft.

A series of analyses were performed prior to the test to assess a number of different parameters: impact location and foam orientation. The analytical results were then used to select the most critical impact location and foam orientation as to impart the most loads into the leading edge panel. These parameters were used to guide the test.

The pre-test predictions, using RCC material without failure activated showed very good correlation between high strain and locations of damage in the impacted panel. Immediately after the test, the analysis was rerun with RCC failure turned on and the damage correlated very well with the location and amount of damage in the panel 8, see figure 12. Again, NASA Langley performed a detailed comparison between the measured test data and analytical prediction [6,7].

Figure 12. Good correlation achieved between test and analytical prediction

Return-to-Flight

Due to the success of the team in generating and validating material models, creating mesh of complex structure, and then making realistic predictions in a relatively short period of time, the team was asked to support Return-to-Flight activities. Specifically, continue to investigate foam impacts with different sizes of foam, various impact velocities and several different impact locations. The debris list has expanded to include ice, ablators, and metallics. The target list has also expanded from panels and T-seals to the nose cone and chin panel.

Concluding Remarks

The Impact Analysis Team used LS-DYNA to assist with the Columbia Accident Investigation. Specifically, LS-DYNA was used to investigate the foam impact event on the Shuttle's leading edge. Both the foam and the RCC material models were complex in that they were non-linear, included strain-rate effects, and exhibited brittle failure. In the end, very good correlation was achieved between pre-test predictions and post-test results.

Acknowledgements

The authors wish to acknowledge the efforts from the others on the Boeing Team: Steve Choi, Chris Felker, Lee Firth, Ed Glembocki, Mark Higgins, Rick Luzetsky, Flavio Poehlmann-Martins, Pierre Minguet, & Mostafa Rassaian. The authors also wish to thank the CAIB and their staff, the astronaut core including Charles Camarda; Glenn Miller, Justin Kerr, and Ronald Baccus at JSC; Mike Dunham & Darwin Moon at Boeing Houston and the many other unnamed

individuals who contributed long hours during the Columbia accident investigation to make this effort possible.

References

1. Gehman, H. W., *et al*: Columbia Accident Investigation Board Final Report Volume I. U. S. Government Printing Office, Washington DC, 20402-0001, August 2003.
2. Melis, M; Carney, K; Gabrys, J.; Fasanella, E.; and Lyle, K.: A Summary of the Space Shuttle Columbia Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts. Proceedings of 8th International LS-DYNA User's Conference, Dearborn MI, May 2-4, 2004.
3. K. Carney, M Melis, *et al* "Material Modeling of Space Shuttle Leading Edge and External Tank Materials For Use in the Columbia Accident Investigation " Proceedings from 8th International LS-DYNA Users Conference, Dearborn MI, May 2-4 2004.
4. Kennedy Space Center's Science, Technology and Engineering Website, "Reinforced Carbon-Carbon Material", http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_sys.html#sts-rcc
5. Goldberg, R. and Carney, K., "Modeling the Nonlinear, Strain Rate Dependent Deformation of Shuttle Leading Edge Materials with Hydrostatic Stress Effects Included", 8th International LS-DYNA Users Conference, Dearborn MI, (2004).
6. Fasanella, E., Lyle, K., Gabrys, J., Melis, M. and Carney, K., "Test and Analysis Correlation of Form Impact onto Space Shuttle Wing Leading Edge RCC Panel 8", 8th International LS-DYNA Users Conference, Dearborn MI, (2004).
7. Lyle, K., Fasanella, E., Melis, M., Carney, K. and Gabrys, J., "Application of Non-deterministic Methods to Assess Modeling Uncertainties for RCC Debris Impacts ", 8th International LS-DYNA Users Conference, Dearborn MI, (2004).