NASA/TM-2008-215115

Test-Analysis Correlation for Space Shuttle External Tank Foam Impacting RCC Wing Leading Edge Component Panels

Karen H. Lyle
Langley Research Center, Hampton, Virginia

March 2008

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-2008-215115

Test-Analysis Correlation for Space Shuttle External Tank Foam Impacting RCC Wing Leading Edge Component Panels

Karen H. Lyle
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

March 2008

Available from:

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Test-Analysis Correlation for Space Shuttle External Tank Foam Impacting RCC Wing Leading Edge Component Panels

Karen H. Lyle

NASA Langley Research Center

Abstract

The Space Shuttle Columbia Accident Investigation Board recommended that NASA develop, validate, and maintain a modeling tool capable of predicting the damage threshold for debris impacts on the Space Shuttle Reinforced Carbon-Carbon (RCC) wing leading edge and nosecap assembly. The results presented in this paper are one part of a multi-level approach that supported the development of the predictive tool used to recertify the shuttle for flight following the Columbia Accident. The assessment of predictive capability was largely based on test-analysis comparisons for simpler component structures. This paper provides comparisons of finite element simulations with test data for external tank foam debris impacts onto 6-in. square RCC flat panels. Both quantitative displacement and qualitative damage assessment correlations are provided. The comparisons show good agreement and provided the Space Shuttle Program with confidence in the predictive tool.

I. Introduction

Following the Space Shuttle Columbia Accident, NASA formed an independent board (identified as the Columbia Accident Investigation Board) that was chartered to determine the cause(s) of the accident. The board concluded that the physical cause of the accident was the impact of a 1.7-lb piece of External Tank Foam on the left wing leading edge, see Figure 1. The Columbia Accident Investigation Board (CAIB) made several recommendations for improving the NASA Space Shuttle Program in Volume I of the final report, Ref. [1]. Two recommendations directly related to structural impact analysis are:

- *Initiate a program designed to increase the Orbiter's ability to sustain minor debris damage by measures such as improved impact-resistant Reinforced Carbon-Carbon and acreage tiles. This program should determine the actual impact resistance of current materials and the effect of likely debris strikes.*
- *Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive corrective action, such as on-orbit inspection and repair, when indicated.*

An extensive experimental and analytical program was developed to address these recommendations. Specifically, a multi-center analysis team, referred to as the Damage Threshold Team, was formed with membership from NASA Langley, NASA Glenn, NASA Johnson, and The Boeing Company. The team's charter was to: 1) use physics-based state-of-the-art codes to simulate debris impacting the Space Shuttle Wing Leading Edge Reinforced Carbon-Carbon (RCC) Panels; 2) validate modeling approaches through test-analysis correlation; and 3) utilize validated modeling approaches to assist in investigating issues not possible to test, (e.g., performing parameter studies, simulating additional scenarios, and establishing worst case scenarios). A number of papers have been written describing the work, Refs. [2-17].

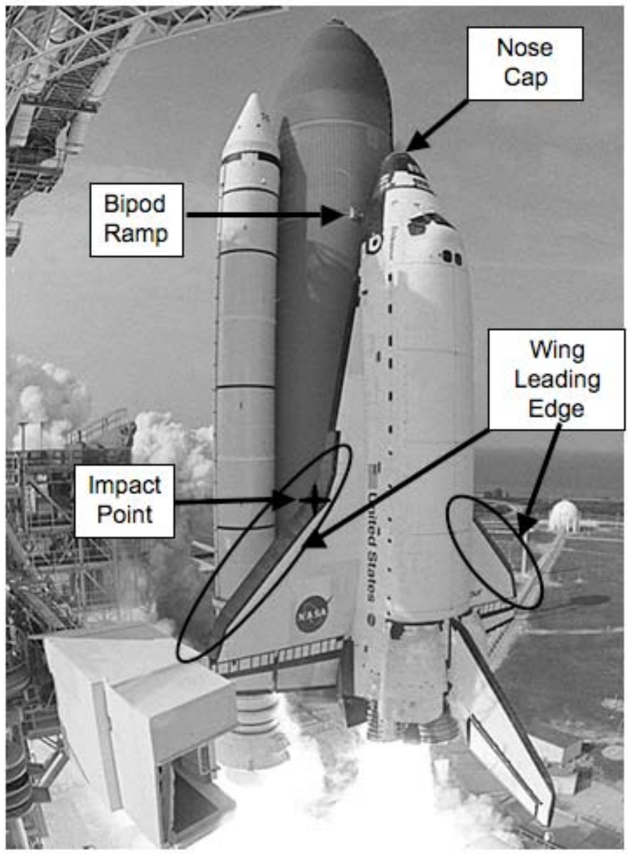

Figure 1. Photograph of a RCC Wing Leading Edge Panels.

II. Background

The highest reentry heating areas of the NASA Space Shuttle are protected with a specially processed reinforced carbon-carbon (RCC) material. Both the wing leading edge and the nosecap assembly are fabricated from the RCC material, see Figure 1. To begin fabrication of RCC material, a precursor woven fabric is layered such that all plies are alternating in the 0 and 90 degree directions. During the processing, silica is infused in the outer 2-to-3 laminae, and the resulting laminate is heated in an inert environment to form a silicon-carbide (SiC) coating. This silicon-carbide coating is needed to protect the Space Shuttle Orbiter's wing leading edge during the high heating experienced on re-entry of the orbiter through the Earth's atmosphere. The processing creates voids in the carbon-carbon (C/C) substrate and micro-cracks in the SiC coating. These substrate voids and coating cracks result in a material with a highly complex stress-strain and failure behavior.

The Damage Threshold Team developed a comprehensive analysis and test plan to enhance understanding of RCC material when impacted by potential ascent debris. A 3-Level testing and model validation approach based on increasing structural complexity was developed. Briefly, the Level-1 testing concentrated on material characterization; the Level-2 effort focused on component impact testing; and the Level-3 (and most complex) element contained debris impacts onto actual flight hardware. The primary objective of this testing was to provide high quality data to enable validation of simulating the impact of various debris types onto RCC material. For these studies, the RCC material was tested in a pristine, or as-fabricated, state. This means that the material had not been aged by exposure to an actual or laboratory simulated reentry heating environment.

This paper summarizes the results of an extensive Level-2 study designed to evaluate the accuracy of simulating foam impacts onto RCC plates in a controlled test environment. BX-265 is an insulating foam used on the external tank, see Figure 2. The release of the BX-265 predecessor on the Bipod Ramp (BX-250) was determined to have been the physical cause of the Space Shuttle Columbia accident.

Figure 2. Insulating foam on Space Shuttle External Tank.

III. Testing Program

Level-2 component testing was performed at the NASA Glenn Research Center to provide RCC component level impact data for correlation with detailed finite element models. The component-level testing program encompassed a wide range of projectile materials including foams, ice, and gap filler. The results in this report are limited to cylindrical BX-265 foam projectiles impacting at 45-degrees on 19-ply, flat RCC plates, see Figure 3. The foam projectiles were nominally 1.5 inches in diameter and 3 inches long, with a mass of 3.00 grams. The RCC plates were 6 x 6 inches with a nominal thickness of 0.233-inches. The panels were constrained on the upper and lower surfaces along the perimeter with aluminum half-round rods located 0.16 inches from the four edges. The following information was recorded for each test: plate thickness; projectile mass and velocity; pre- and post-test photographs; pre- and post-test non-destructive evaluations (NDE); and high-speed digital video. The digital video data was processed using a commercial photogrammetry system to produce displacements, see Ref. [15]. Details about this test series can be found in a comprehensive test report, Ref. [14].

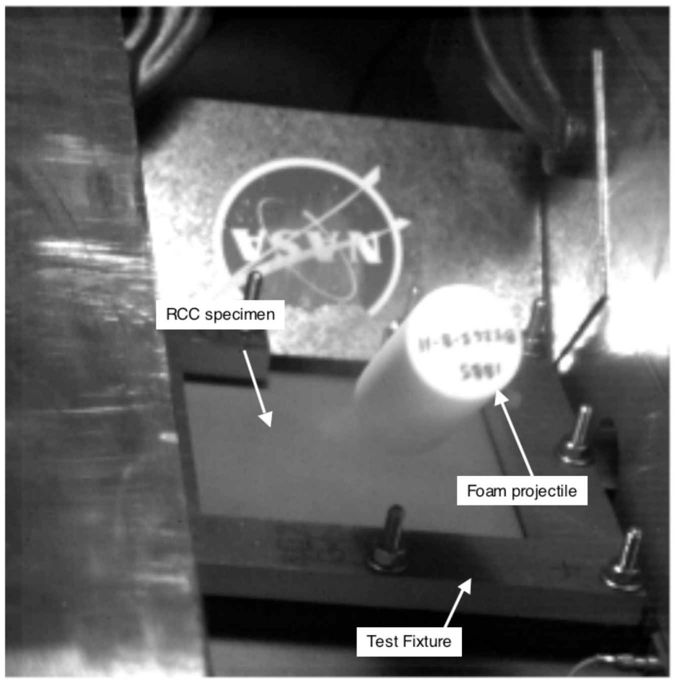

Figure 3. Photograph of 45-degree foam impact onto RCC 6-in.square RCC plate.

Critical damage is defined to be damage such that the shuttle cannot re-enter the Earth's atmosphere safely. The initial testing was performed when the Shuttle Program established that the critical damage threshold was set as a through-crack (visible damage) in the RCC material. However, as the testing progressed, more was learned about the behavior of RCC material with various types of damage when subjected to re-entry heating conditions. Based on this new information, the Shuttle Program reduced the threshold for acceptable damage to NDE-detectable (internal) damage. The test series highlighted in this document focused on obtaining data to understand the behavior of RCC for the initial definition of critical damage; however, the focus for the correlation accuracy is the later NDE-detectable damage limit. The experimentally determined threshold velocities for the 6x6-inch plates should not be used to extrapolate to the thresholds for full-scale panels, T-Seals, or the nosecap assembly.

At the time that these studies were performed, the only substantial material property data available was for RCC smeared **laminate** properties generated during the shuttle development, Ref. [18]. However, the material properties of the SiC are shown to vary substantially between the SiC coating and the C/C substrate. The SiC coating has a high compressive strength and very little tensile strength. The compressive and tensile stress-strain curves are much more alike for the C/C substrate. In addition to the strength differences, the density of C/C is much lower than that for the SiC coating. However, for these correlation studies, no through-the-thickness variations was allowed to enable usage of the documented laminate material properties and test article specific laminate test data. Since the measured RCC failure properties are known to vary significantly, a material input parameter uncertainty assessment was conducted to understand the importance of the various material modeling parameters, Ref. [2]. The material characterization effort was further complicated by the fact that the RCC material was very scarce. This scarcity of material required several compromises to be made based on the team's collective engineering judgment. The primary compromise dealt with the fact that plate-specific material properties were obtained by cutting coupon specimens from impacted plates. Care was taken to cut from areas where no damage was detected using NDE methods. Non-dimensionalized comparisons of failure data from Ref. [18] with post-impact data are shown in Figures 4 and 5, for tension and compression, respectively. The impacted material, although cut from areas with no NDE-detectable damage, appear significantly weaker than the material tested for inclusion in Ref. [18]. The idea that the impact might have affected the material properties, even though the NDE did not detect any damage, was considered. However, because of the scarcity of the RCC material, the use of post-test material was deemed to be an appropriate compromise. Since no pre-impact material failure properties were obtained for the panels used in this test series, it was virtually impossible to assess the effect of the impact on the material properties.

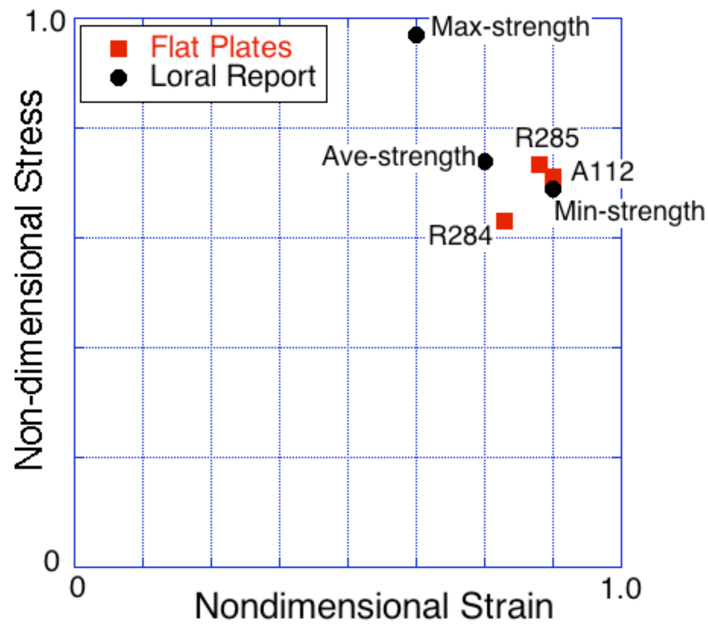

Figure 4. Nondimensional tensile stress-strain failure values for test RCC panels and as-fabricated design data.

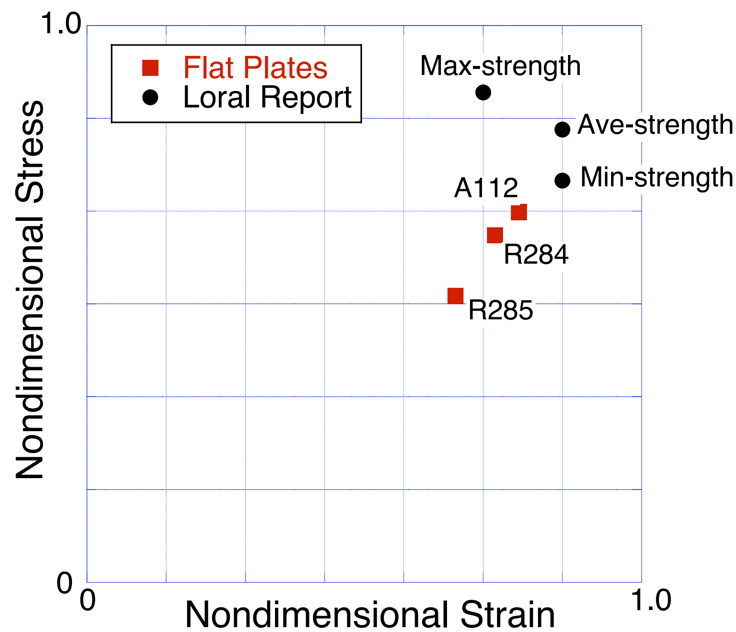

Figure 5. Nondimensional compressive stress-strain failure values for test RCC panels and as-fabricated design data.

Prior to impacts on the RCC plates, extensive material characterization testing of the BX-265 foam projectiles was also performed. This testing included static crush and tensile testing, as well as moderate strain-rate crushing in a drop tower. Analytical material models were validated by correlation with impact tests of the foam projectile on load cells. Details about the debris testing and modeling can be found in Reference 5. The BX-265 load curves used to describe the foam response are shown in Figure 6 for two strain rates, along with the unloading curve. The foam is weak in tension and fails at 80 psi.

Motion of the test panels was measured using a full-field photogrammetry system, see Reference 15. The coordinate computations were based on a two-camera stereographic technique viewing the backside of the plate. This backside orientation would be representative of viewing impacts on actual full-scale RCC panels from the inner mold line (IML). The viewing area for the flat plate tests was set to 14 x 14 inches, see Figure 7. The grey SiC coating surface was speckled with black paint to provide contrast and thus enhance pattern recognition. The coordinate system was described by assigning “x” and “y” in the panel of the plate with “z” out-of-plane.

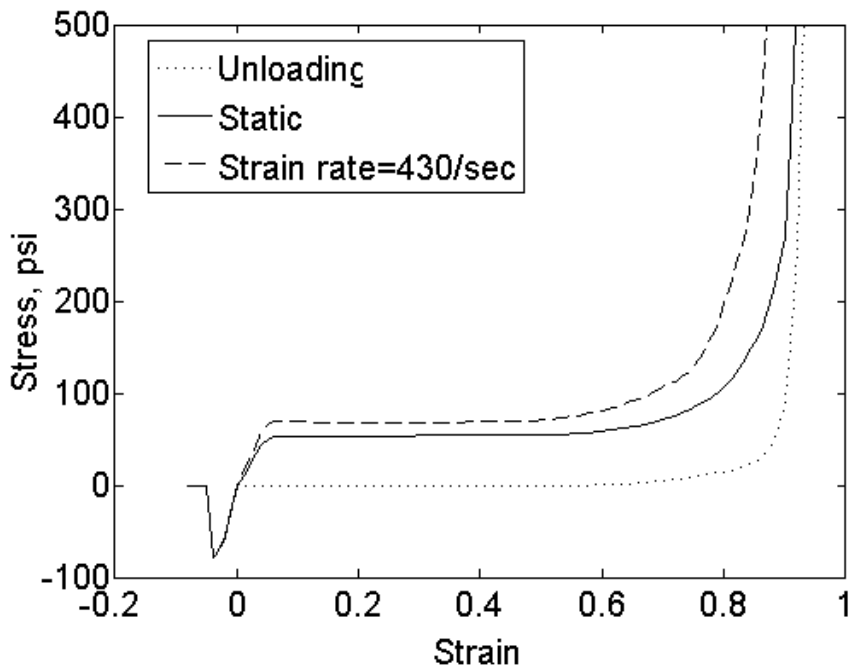

Figure 6. Analytical loading and unloading curves for BX265 foam model.

The photogrammetry technique divides the panel into a series of overlapping facets. Three facets have been highlighted in Figure 8. Each facet was 0.605 inches on a side and contained 11x 11 pixels. The plate coordinates were computed for the center of each facet, denoted by the smaller solid squares. The displacement was computed by subtracting the pre-impact coordinates from the time varying coordinates during the impact, see Figure 9. The displacements were then spatially smoothed to obtain the displacements used for the comparisons. Smoothing was accomplished by taking the median of a 5x5 area of facet center displacements, see Figure 10, and assigning this value to the center facet (red square). The software only calculated a median if 50 % of the facets contained reliable data. Thus, no results would be computed for facets with coating loss. For the results reported here, two smoothing passes of the facets were performed, see Figure 11. In general, the spatial smoothing was effective. However, the red oval in Figure 11 highlights the potential for anomalous values at the edges resulting from the smoothing process. The anomalies at the edges did not effect the assessment because the comparisons were performed for locations nearer the center.

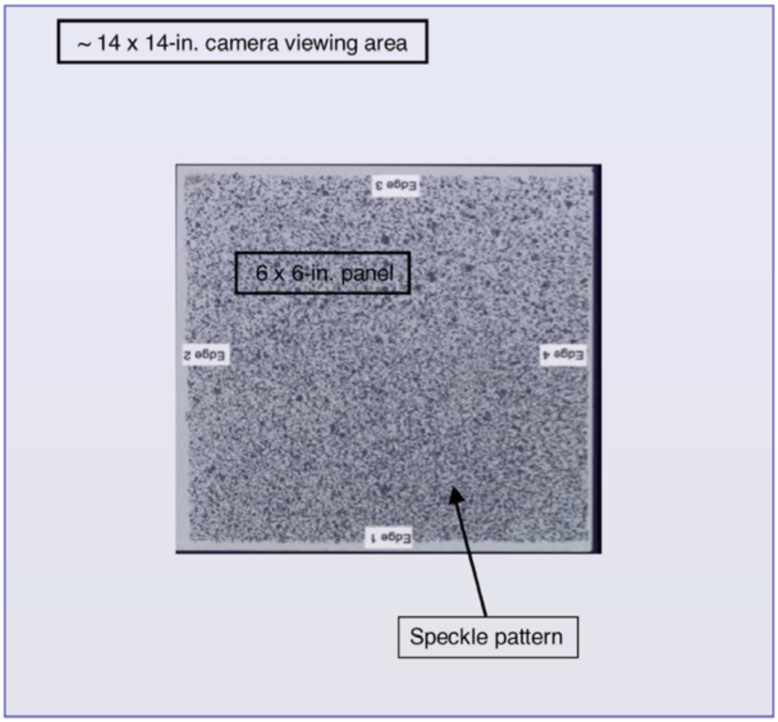

Figure 7. Relationship of test panel and camera viewing areas used in photogrammetry analysis. The camera viewing angle extended beyond the test panel to enable assessment of boundary conditions.

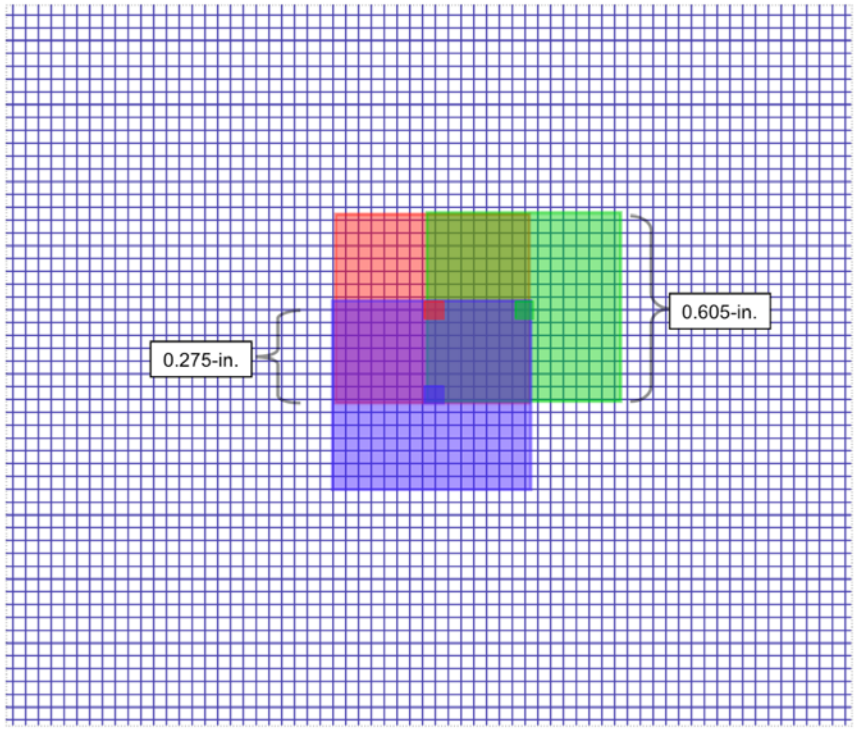

Figure 8. Schematic of pixel and facet configuration on panels.

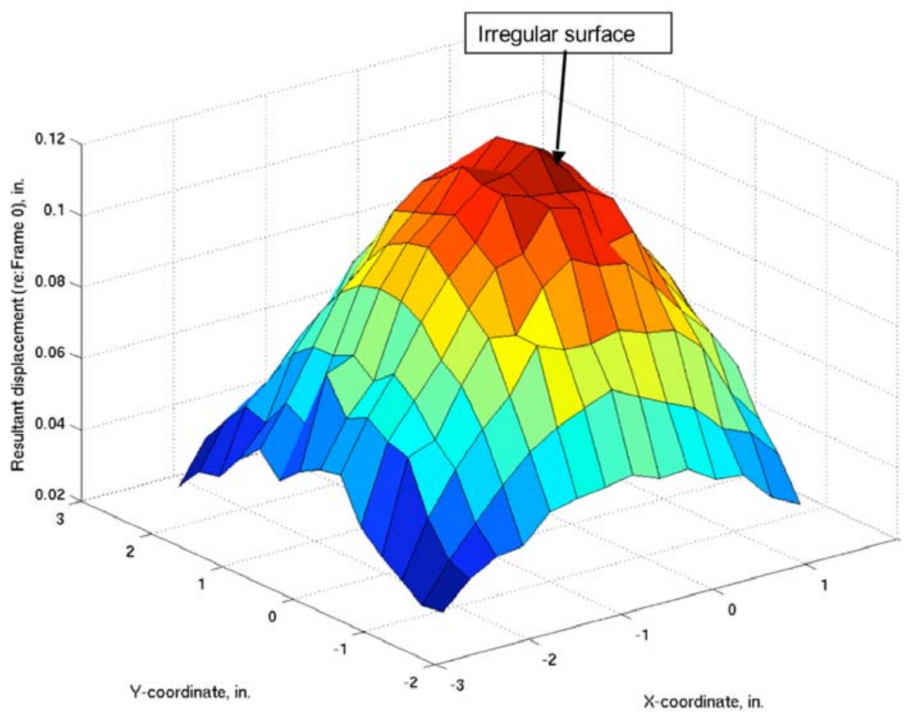

Figure 9. Raw instantaneous resultant deformation (i.e., without spatial smoothing).

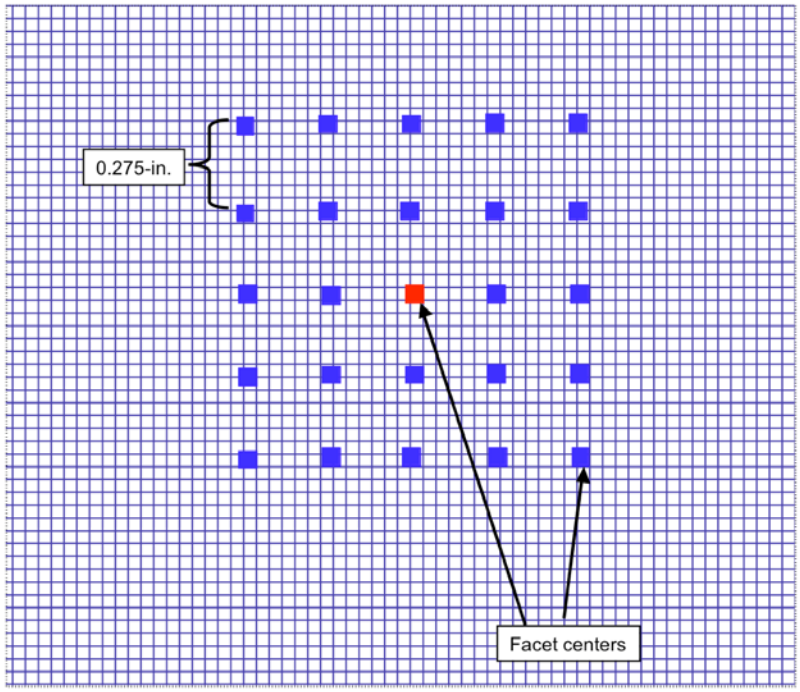

Figure 10. Facet configuration used for spatial smoothing of displacements.

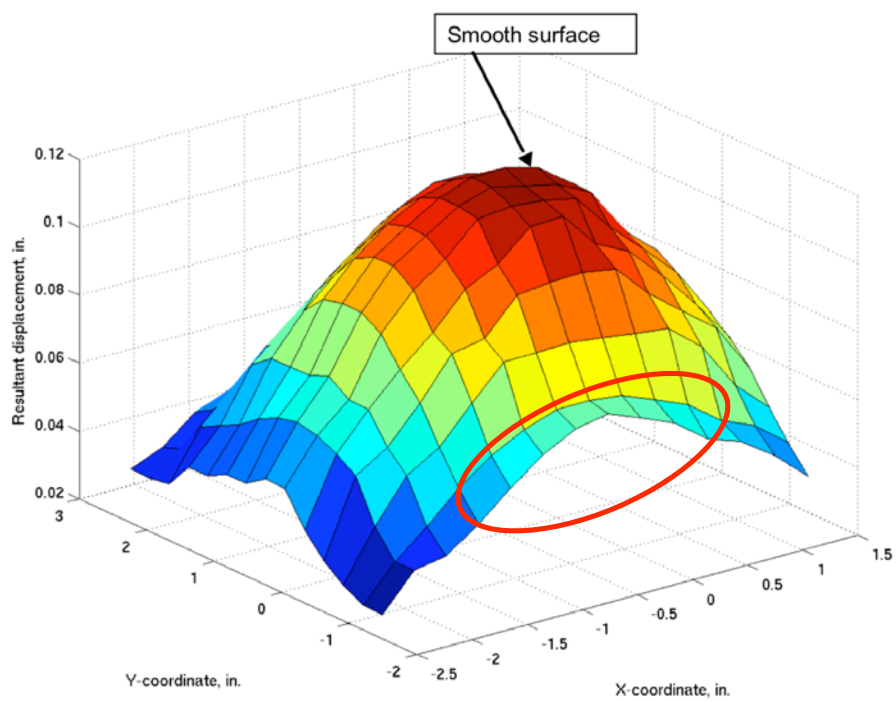

Figure 11. Resultant displacement deformation after spatial smoothing performed.

IV. Finite Element Model

The finite element model was generated for execution in LS-Dyna, Ref. [19]. LS-Dyna is a commercial, nonlinear, transient dynamic, finite element code derived from the public domain code DYNA3D, which was developed at Lawrence Livermore National Laboratories in the 1970's. Figure 12 contains a schematic of the finite element model. The RCC plate model was 6 x 6 in., with the element edge length of 0.1 in. Idealized boundary conditions were applied at the locations matching the test. Specifically, the out-of-plane displacements were constrained along three edges as represented by the dashed lines. Along the solid Line A-A, the displacements, both out-of-plane and in-plane perpendicular to Line A-A, were constrained. No rotations were constrained at the boundaries. This modeling assumption validated through comparisons of test and analysis free vibrations. The foam projectile was modeled foam using 5250 solid elements. The foam dimensions were 1.5 inches in diameter and 3.0 inches long.

Both the foam projectile and target RCC plates exhibit complex behavior during the impact. The RCC material failure properties and plate thickness were adjusted for each impact simulation based on material characterization data. No material modeling parameters were changed to improve upon the test and analysis correlations (i.e., no post-correlation tweaking to improve correlations). The RCC material behavior was modeled using MAT_LAMINATED_FABRIC (LS-Dyna Mat #58). The foam projectile material behavior was modeled using MAT_FU_CHANG_FOAM (LS-Dyna Mat #83). The crush-stress curves, based on the test data shown in Figure 4, represented room-temperature BX265 foam. Additional details about the material modeling approach are provided in Reference 5.

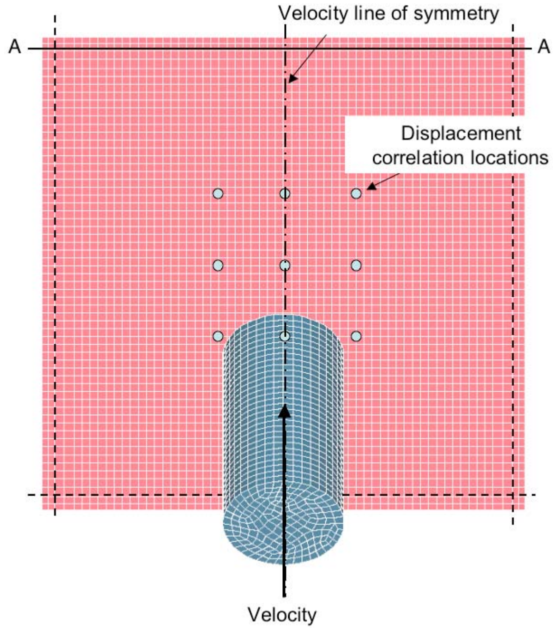

Figure 12. Schematic of finite element model.

V. Discussion of Results

A comprehensive and systematic approach was used for correlating the analytical results with the test data. A detailed review of the test results was performed to determine suitability of the test results for assessing the simulation accuracy. The evaluations included looking for symmetry, repeatability, and post-processing effects. The evaluations indicate that high-quality data were acquired. The quantitative correlations were based on a comparison of displacements at nine locations on the panel, see Figure 12. These locations form a grid with coordinates at x,y = 0, ±0.9 inches from the center. Only displacement results for impact velocities at or below the NDE detectable damage limit are included in this section. In addition to the quantitative correlations, qualitative comparisons of end-state damage are provided. The experimental damage is based on post-test photographs and NDE results. Analytically, the damage is presented as history variables generated by LS-DYNA for the RCC material model implementation.

Detailed correlations were performed for each test. An example of the resultant displacement time history correlations is shown in Figure 13. With an impact velocity of 1837 ft/s, this case was selected because the damage is very close to the NDE detectable limit. Symmetric locations are shown in a series of plots on the left. The difference in the experimental results for symmetric locations is small indicating that a nearly symmetric response was measured. The simulation results showed no discernable difference between the left and right locations. The series of figures on the right show comparisons for the middle locations. The comparison of analytical and experimental displacement time histories is very close for all locations.

A comparison of maximum displacements for the indicated correlation locations as a function of impact velocity is shown in Figure 14. These five tests were performed at impact velocities less than 2000 ft/s, where no or minimal NDE detectable damage resulted from the impact. The experimental values are based on averaging the experimental data for symmetric locations. The error in maximum displacements for these locations ranges from 1-19% with 3/4 of the comparisons having an error less than 15%. The comparison of maximum displacements anywhere on the plate as a function of impact velocity is shown in Figure 15. Note that as the velocity increases, the maximum predicted displacement increases. For the experimental data, as the velocity increases from 1800 to 2000 ft/s (an increase of 23% in the kinetic energy), the maximum displacement is nearly the same. This variation in results is indicative of the variability of the material response near the damage threshol. In addition to producing confidence at the component level, these types of data comparisons enhanced the understanding of and expectations for correlations for the full-scale panels.

The qualitative comparison of measured and predicted damage is shown in Figures 16 and 17. For each test, represented as a row in the figures, experimental and analytical results are given. The first column provides the impact velocity and a description of the damage. Post-test ultrasound (NDE) results are provided in the 2nd column where dark indicates internal damage. Back and front side post-test photographs are shown in the 3rd column. Only the back-side was speckled with paint to enhance the photogrammetry results. The final column contained the color fringe plots representing the analytical damage parameter. Blue reflects little or no potential of damage while red indicates a high potential for damage. These correlations of analytical and experimental damage provided insights as to analytical damage threshold value. The results shown in Figure 16 represent the cases where the quantitative comparisons of displacements have been evaluated. The cases shown in Figure 17 represent impact velocities significantly above the NDE-detectable damage limit. A review of these 8 impacts indicates that the general trends for damage are well predicted. Both test and analysis indicate a similar amount of minimal damage for impacts ranging from 1837 to 1940 ft/s. This could be considered as representative of the range in velocities possible for NDE-detectable damage. At the higher velocities, both the test and analyses show significant damage to panels emanating from the center and progressing to the corners downstream from the impact site. A comparison of the impact data also highlights the variability of damage possible for two nearly identical impacts. Tests at similar velocities 2230 ft/s (R284-20) and 2241 ft/s (R285-12) produced significant internal damage. However, only the 2241 ft/s (R285-12) impact resulted in significant front side damage.

Several other modeling concerns were postulated as influencing the results including: the absence of strain-rate effects in the RCC model; the absence of RCC material damping; the idealization of the plate boundaries conditions; the appropriate incorporation of friction; and the use of a smeared properties RCC material model. These topics have been identified for future investigations to enable modeling refinements.

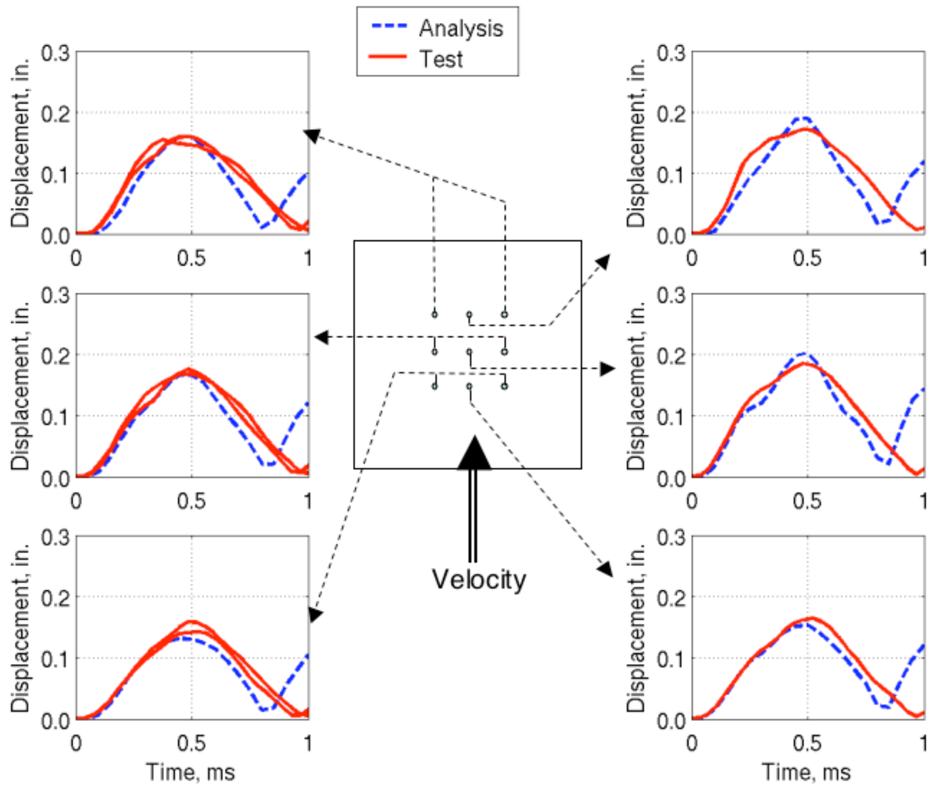

Figure 13. Sample displacement comparison of experimental data and analytical results for test R285-10 @ 1837 ft/s.

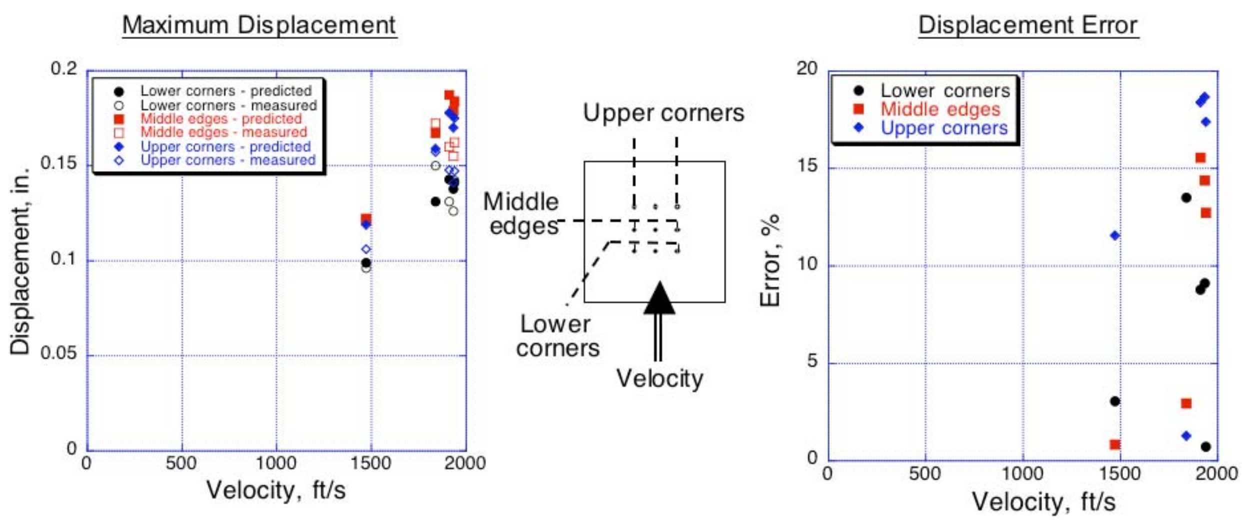

Figure 14. Comparison of maximum displacements at correlation locations.

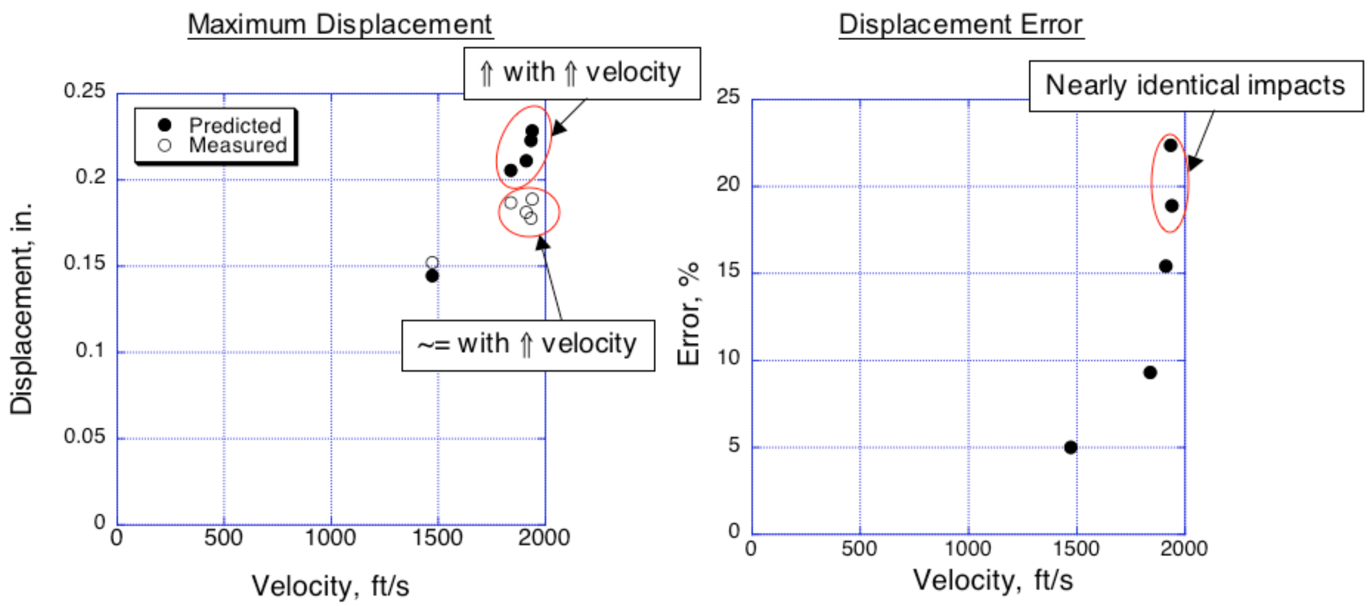

Figure 15. Comparison of maximum displacements.

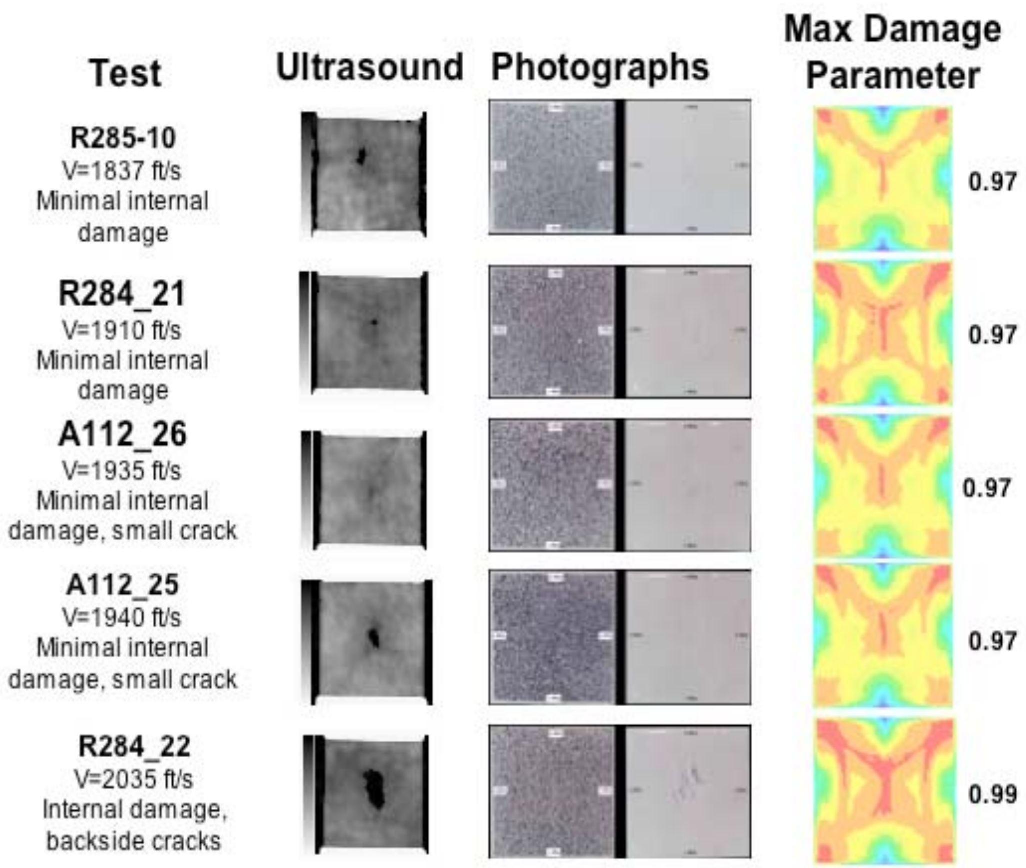

Figure 16. Comparisons of measured and predicted damage for lower velocity impacts.

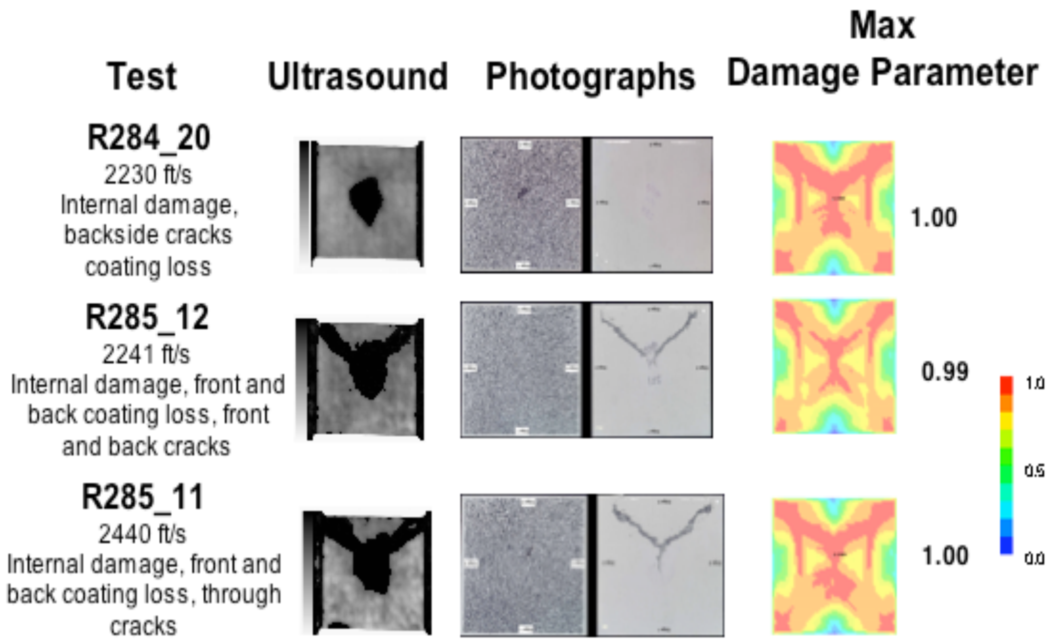

Figure 17. Comparisons of measured and predicted damage for higher velocity impacts.

V. Concluding Remarks

Based on the Space Shuttle Columbia Accident Investigation Board recommendations, NASA needed a modeling tool capable of predicting the damage threshold for debris impacts on the Space Shuttle Reinforced Carbon-Carbon (RCC) wing leading edge and nosecap assembly. The results presented in this paper are one part of a multi-level approach that supported the development of a predictive tool used to recertify the shuttle for flight following the Columbia Accident.

A comparison of the test data with finite element simulation results for external tank foam debris impacts onto 6-in. square RCC flat panels has been summarized. The simulations incorporated measured foam mass, RCC plate thickness, material strength and failure data. As input for LS-Dyna simulations, issues about the validity of using the post-impact coupon material properties were considered. However, because of the scarcity of RCC resources, this approach was selected as the best compromise.

Detailed reviews of the impact test results indicate that high-quality data were acquired. The wealth of full-field photogrammetry data proved to be valuable for correlations. In addition, the importance of the NDE data increased once the damage threshold was reduced to the NDE-detectable damage limit. No model changes were required to accommodate the change in damage threshold definition. Good agreement between predicted and measured results was found. The error in maximum displacement was less than 15% for three-fourths of the locations. All of the errors were less than 22%. The qualitative comparisons of damage were also good.

Good comparisons between experimental and analytical results were shown. This level of agreement provided the Space Shuttle Program with confidence in the predictive tool, which led to certification of the space shuttle for flight.

Acknowledgements:

The author would like to acknowledge the assistance of several researchers who contributed experimental results – Matthew Melis and Duane Revilock (NASA Glenn Research Center), Timothy Schmidt (Trilion Quality Systems), and John Koenig (Southern Research Institute).

References

1. Gehman, Harold W., et al, “Columbia Accident Investigation Board Final Report”, Volume I, August 2003.
2. Lyle, K., Fasanella, E., Melis, M., Carney, K., and Gabrys, J.: "Probabilistic Studies of RCC Beam Coupons Using LS-DYNA." Eighth International LS-DYNA Users Conference, Dearborn, Michigan, May 2 - 4, 2004.
3. Fasanella, E. L., Lyle, K. H., Gabrys, J., Melis, M., and Carney, K.:"Test and Analysis Correlation of Foam Impact onto Space Shuttle Wing Leading Edge RCC Panel 8," Eighth International LS-DYNA Users Conference, Dearborn, Michigan, May 2 - 4, 2004.
4. Melis, M., Carney, K., Gabrys, Jon, Fasanella, E., and Lyle, K.: "A Summary of the Space Shuttle Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts." Eighth International LS-DYNA Users Conference, Dearborn, Michigan, May 2 - 4, 2004.
5. Carney, K., Melis, M., Fasanella, E., Lyle, K, and Gabrys, J.: "Material Modeling of the Space Shuttle Leading Edge and External Tank Materials for Use in the Columbia Accident Investigations." Eighth International LS-DYNA Users Conference, Dearborn, Michigan, May 2 - 4, 2004.
6. Gabrys, J., Schatz, J., Carney, K., Melis, M., Fasanella, E., and Lyle, K.: "The Use of LS-DYNA in the Columbia Accident Investigation and Return to Flight Activities." Eighth International LS-DYNA Users Conference, Dearborn, Michigan, May 2 - 4, 2004.
7. Jackson, Karen E., Fasanella, E. L., Lyle, K. H., Spellman, R. L., "The Influence of Mesh Density on the Impact Response of a Shuttle Leading Edge Panel Finite Element Simulation," NASA Technical Memorandum (TM) NASA/TM-2004-213501, ARL-TR-3337, November 2004.
8. Jackson, Karen E., Fasanella, E. L., Lyle, K. H., Spellman, R. L., "The Influence of Clocking Angle of the Projectile on the Simulated Impact Response of the Shuttle Leading Edge Wing Panel," NASA/TM-2005-213538, ARL-TR-3447, March 2005.
9. Stockwell, Alan E., "The Influence of Model Complexity on the Impact Response of a Shuttle Leading-Edge Panel Finite Element Simulation," NASA/CR-2005-213535, March 2005.
10. Spellman, Regina L. Jones, Lisa E., Lyle, Karen H., Jackson, Karen E., and Fasanella, Edwin L., "The Influence of Projectile Trajectory Angle on the Simulated Impact Response of a Shuttle Leading Edge Wing Panel," NASA/TM-2005-213546, ARL-TR-3448, April 2005.
11. Fasanella, Edwin L., Jackson, Karen E, Lyle, Karen H., Jones, Lisa E., Hardy, Robin C., Spellman, Regina, Carney, Kelly S, Melis, Matthew E., and Stockwell, Alan E. "Dynamic Impact Tolerance of Shuttle RCC Leading Edge Panels Using LS-DYNA." AIAA Joint Propulsion Conference, Tucson, AZ, paper #AIAA-2005-3631, July 2005.
12. Lyle, Karen L., Spellman, Regina, L., Hardy, Robin, H., Fasanella, Edwin L., and Jackson, Karen E., "Effect of Impact Location on the Response of Shuttle Wing Leading Edge Panel 9," NASA/TM-2005-213544, ARL-TR-3426, July 2005

13. Fasanella, Edwin L., Lyle, Karen H., Hardy, Robin C., and Stockwell, Alan H., "Test and Analysis Correlation of Foam Impact onto Space Shuttle Wing Leading Edge RCC Panel 8." NASA/TM-2005-213774, ARL-TR-3490, July 2005.
14. Melis, M., Brand, J., Pereira, J. M., and Revilock, D., Lyle, K. H.: Impact Testing on Reinforced Carbon-Carbon Flat Panels with BX265 and PDL-1034 External Tank Foam supporting the Space Shuttle Return to Flight Program - Final Test Report. NASA TM-213642, April 2007.
15. Schmidt, T.; Tyson, J.; Revilock, D. M.; Padula, S.; Pereira, J. M.; Melis, M.; **Lyle, K.**: Performance Verification of 3D Image Correlation Using Digital High-Speed Cameras. Proceedings of the 2005 Society for Experimental Mechanics Annual Conference and Exposition, Portland OR, June 7-9, 2005.
16. Fasanella, Edwin L., Boitnott, Richard L, and Kellas, Sotiris, "Dynamic Crush Characterization of Ice," NASA TM-2006-214278, February 2006.
17. Kellas, Sotiris, "Quasi-Uniform High Speed Foam Crush Testing Using a Guided Drop Mass Impact," NASA CR-2004-213009, April 2004.
18. Smith, T. W.: Leading Edge Structural Subsystem Mechanic Design Allowables For Material With Improved Coating System, Loral Vought Systems, Report No. 221RP00614, July 15, 1977.
19. Anonymous: LS-Dyna Keyword User's Manual, Livermore Software Technology Corporation, Version 971, August 2006.

REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01- 03 - 2008

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Test-Analysis Correlation for Space Shuttle External Tank Foam Impacting RCC Wing Leading Edge Component Panels

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lyle, Karen H.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
644423.04.31.04.40.43.20

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-19437

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2008-215115

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://ntrs.nasa.gov

14. ABSTRACT
The Space Shuttle Columbia Accident Investigation Board recommended that NASA develop, validate, and maintain a modeling tool capable of predicting the damage threshold for debris impacts on the Space Shuttle Reinforced Carbon-Carbon (RCC) wing leading edge and nosecap assembly. The results presented in this paper are one part of a multi-level approach that supported the development of the predictive tool used to recertify the shuttle for flight following the Columbia Accident. The assessment of predictive capability was largely based on test-analysis comparisons for simpler component structures. This paper provides comparisons of finite element simulations with test data for external tank foam debris impacts onto 6-in. square RCC flat panels. Both quantitative displacement and qualitative damage assessment correlations are provided. The comparisons show good agreement and provided the Space Shuttle Program with confidence in the predictive tool.

15. SUBJECT TERMS
Debris Damage; LS-Dyna; Reinforced Carbon-Carbon; Space Shuttle; Wing Leading Edge

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	23	STI Help Desk (email: help@sti.nasa.gov)	(301) 621-0390