Reinforced Carbon-Carbon Subcomponent Flat Plate Impact Testing for Space Shuttle Orbiter Return to Flight

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Abstract

Following the tragedy of the Space Shuttle *Columbia* on February 1, 2003, a major effort commenced to develop a better understanding of debris impacts and their effect on the Space Shuttle subsystems. An initiative to develop and validate physics-based computer models to predict damage from such impacts was a fundamental component of this effort. To develop the models it was necessary to physically characterize Reinforced Carbon-Carbon (RCC) and various debris materials which could potentially shed on ascent and impact the Orbiter RCC leading edges. The validated models enabled the launch system community to use the impact analysis software LS DYNA to predict damage by potential and actual impact events on the Orbiter leading edge and nose cap thermal protection systems.

Validation of the material models was done through a three-level approach: fundamental tests to obtain independent static and dynamic material model properties of materials of interest, sub-component impact tests to provide highly controlled impact test data for the correlation and validation of the models, and full-scale impact tests to establish the final level of confidence for the analysis methodology. This paper discusses the second level subcomponent test program in detail and its application to the LS DYNA model validation process.

The level two testing consisted of over one hundred impact tests in the NASA Glenn Research Center Ballistic Impact Lab on 6 by 6 in. and 6 by 12 in. flat plates of RCC and evaluated three types of debris projectiles: BX–265 External Tank foam, ice, and PDL–1034 External Tank foam. These impact tests helped determine the level of damage generated in the RCC flat plates by each projectile.

The information obtained from this testing validated the LS DYNA damage prediction models and provided a certain level of confidence to begin performing analysis for full-size RCC test articles for returning NASA to flight with STS–114 and beyond.

Background

On January 16, 2003, at 10:39 a.m. Eastern Standard Time, the Space Shuttle *Columbia* lifted off from Launch Complex 39–A at Kennedy Space Center in Florida. At approximately 82 sec into launch, *Columbia* was traveling at Mach 2.46 (1,650 mph) at an altitude of nearly 66,000 ft when it was struck by a large piece of foam that had separated from the shuttle's external fuel tank. The foam, decelerated by the air flow past the Orbiter, struck the left wing leading edge of *Columbia*, at a relative speed of 416 to 573 mph, causing the breach in the leading edge thermal protection system (TPS) that ultimately led to the tragedy. Two ground movie cameras captured the event. Figure 1(a) is an image taken from one of the movies just before the event
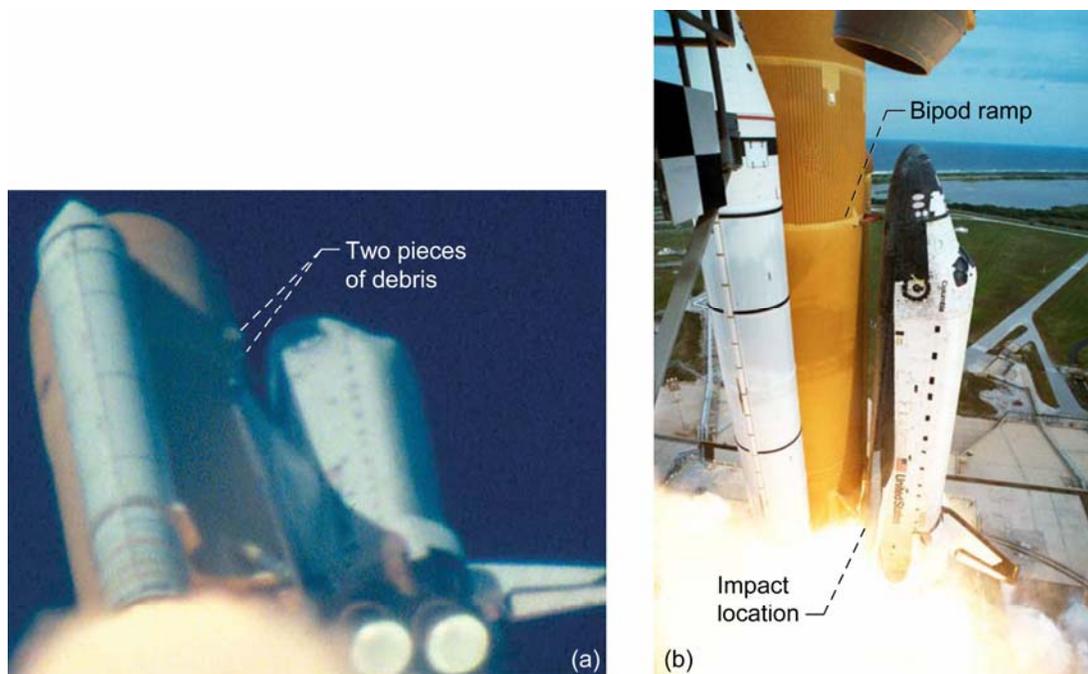
Figure 1.—Two pieces of foam debris separating from bipod ramp (left) and Shuttle Columbia just after liftoff showing the bipod attachment, the bipod ramp, and the location of impact (right).

and depicts two foam pieces separating from the bipod ramp. Figure 1(b) identifies the bipod ramp location from where the foam separated on the Shuttle and the impact location on the left wing leading edge of the Orbiter. For the next several months an extensive investigation of the accident ensued involving a nationwide team of experts from NASA, industry, and academia, spanning dozens of technical disciplines. This team was identified as the *Columbia* Accident Investigation Board or CAIB.

The CAIB, concluded its investigation in August, 2003 and determined that the cause of the loss of *Columbia* and its crew was a breach in the left wing leading edge Reinforced Carbon-Carbon (RCC) TPS initiated by the impact of thermal insulating foam that had separated from the Orbiter external fuel tank 81 sec into the mission's launch. During reentry, this breach allowed superheated air to penetrate behind the leading edge and erode the aluminum structure of the left wing which ultimately led to the breakup of the orbiter.

During reentry, the wing leading edges of the Orbiter see temperatures up to nearly 3000 °F and are thermally protected through the use of the brittle composite RCC. Each orbiter wing has 22 unique panels (numbered 1 to 22 from front to back) made by hand to conform to specific locations on the wing. The gaps between these panels are sealed with a structure, also made of RCC called a T-Seal. Figure 2 shows a graphic of several panels on an orbiter wing leading edge spar with a close-up rear view of a single leading edge panel with a T-Seal.

The CAIB report (ref. 1) made over two dozen recommendations to increase the overall safety of the Shuttle for future launches. Prior to the *Columbia* accident, there were no sophisticated analysis tools in existence to reliably quantify the debris impact damage threat to the Shuttle system. As a consequence, CAIB recommendation R3.8–2 directed NASA to "*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.*" In response to R3.8–2, an agency team, named the DYNA team, consisting of members from NASA Glenn Research Center, NASA Langley Research Center, NASA Johnson Space Center, and Boeing, was assembled to develop such a tool using LS DYNA (ref. 2). LS DYNA is a commercial finite element code which utilizes an explicit (as opposed to the more common implicit formulations) formulation to predict a wide range of transient dynamic phenomena.
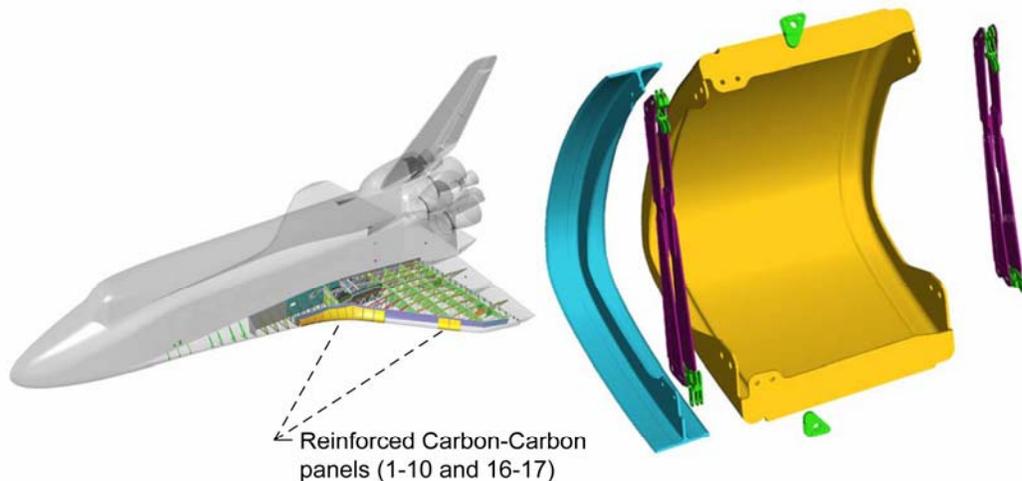
Figure 2.—Reinforced Carbon-Carbon panels (in yellow) are attached on the Orbiter leading edges spar with rear view of Reinforced Carbon-Carbon composite panel (in yellow) shown with T-Seal (in blue) at right.

Approach

As a critical path element of NASA's return to flight program, the primary objectives set for the DYNA team were to develop analysis models for potential debris and RCC materials. RCC is used as the TPS on the Orbiter Leading edge and nose cap. The debris materials under consideration were ice, which might potentially shed off of the external tank, and three External Tank foams; BX–265, PDL, and NCFI. To address these objectives, the team established a three level approach: 1) fundamental tests to obtain independent static and dynamic material property data for materials of interest, 2) sub-component impact tests to provide highly controlled impact test data for the correlation and validation of the models, and 3) full-scale impact tests to establish the final level of confidence for the analysis methodology. The intent of this paper is to present details of the Level 2 RCC flat panel impact tests, however, Levels 1 and 3 are briefly discussed below and several references provided for details on those topics.

Level 1 Fundamental Materials Tests

As with any structural analysis, obtaining appropriate, high-fidelity material properties is critical to making reliable engineering predictions. Performing impact analysis adds another level of complexity as materials data at various strain rates is usually required for the materials under consideration as was the case in this program. With a few exceptions, virtually all of the materials data required for this effort had to be generated. For RCC, some static data was useful from previous literature (ref. 3) however high strain-rate data was generated from a series of Split Hopkinson Bar tests at Ohio State University using techniques similar to those described in reference 4. Extensive static and dynamic testing was preformed on External tank foams and ice to acquire the model dependant data. Hopkinson Bar testing of ice was conducted at Case Western Reserve University to establish the stress-strain response at various strain rates (ref. 5). A drop facility at Langley Research Center was used to establish similar properties for foam (ref. 6).

As the material properties for the foams and ice were collected, the respective models in LS DYNA were developed and validated against fundamental impact tests performed at the NASA Glenn Ballistic Impact Lab. These tests were conducted on load cells at various angles, speeds, and environmental pressures to establish that LS DYNA was accurately predicting the same force-time response of the ice and foams as observed in tests. Figure 3 shows typical digital high-speed images of BX–250 foam impacting a load cell at 90° under vacuum and non-vacuum conditions. In addition, this figure depicts a typical LS DYNA analysis of the experiment performed in the validation process. Load cell force-time histories from these experiments (fig. 3(a)) were correlated with the LS DYNA predictions (fig. 3(b)) as well as the deformation and failure
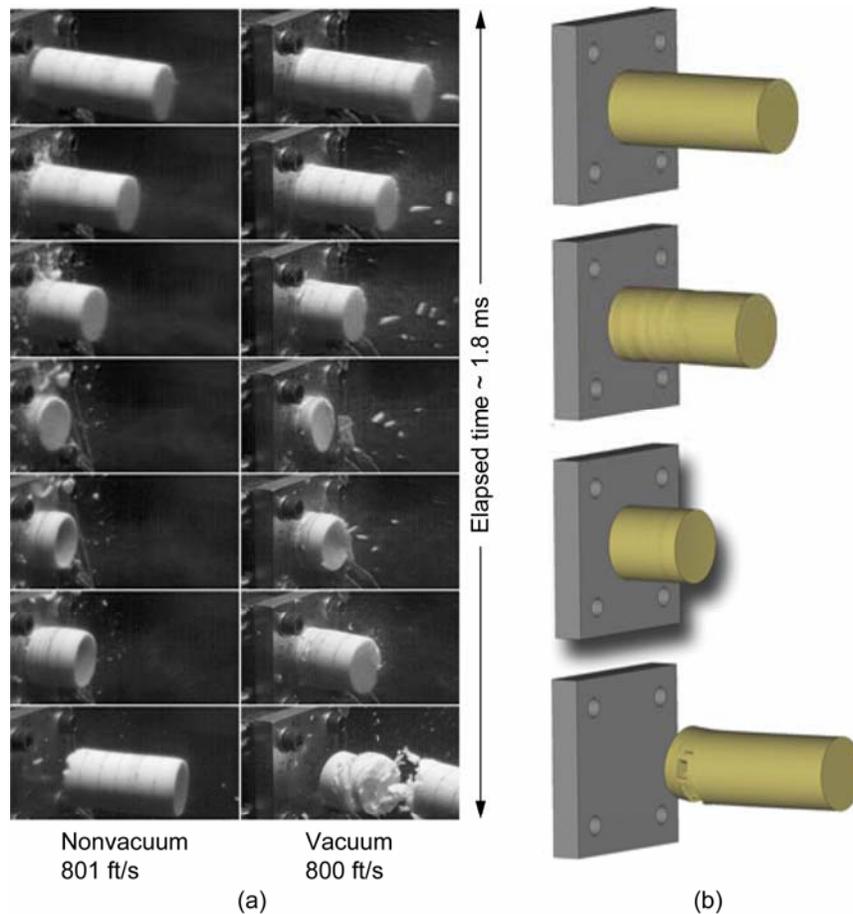
Figure 3.—High-speed imagery compares BX-250 foam undergoing impact on a load cell at vacuum and nonvacuum conditions (left) with correlation to LS-DYNA load, deformation, and damage predictions (right).

behavior of the foam. Figure 4 shows NCFI foam and ice respectively impacting load cells at 90°. These two materials exhibit interesting impact behavior as both undergo a structural or phase change and become fluid in nature during the impact event which in turn significantly complicates the modeling process.

Level 2 Sub-Component Impact Tests

Facilities

All of the level two tests were conducted at the Ballistic Impact Laboratory which resides in the Materials and Structures Division at NASA Glenn Research Center in Cleveland, Ohio. Aeronautics and Space programs are both supported at this lab. The facility incorporates a number of light gas guns ranging in size from a 16 in. diameter, 40 ft long gas gun to a small gun with a diameter of approximately 0.056 in. In general, helium is used as the propellant. Vacuum chambers are used for much of the testing to control the test environment, decrease the pressure required to achieve the desired impact velocity, and in some cases to limit the pressure pulse impacting the target prior to projectile impact. Figure 5 shows the small, particle, and large vacuum chamber setups and figure 6 shows the 8 in. gas gun typically used to conduct turbine engine fan containment testing for aeronautics programs. All of the level 2 flat panel testing was conducted in the large vacuum chamber.

(a)   (b)
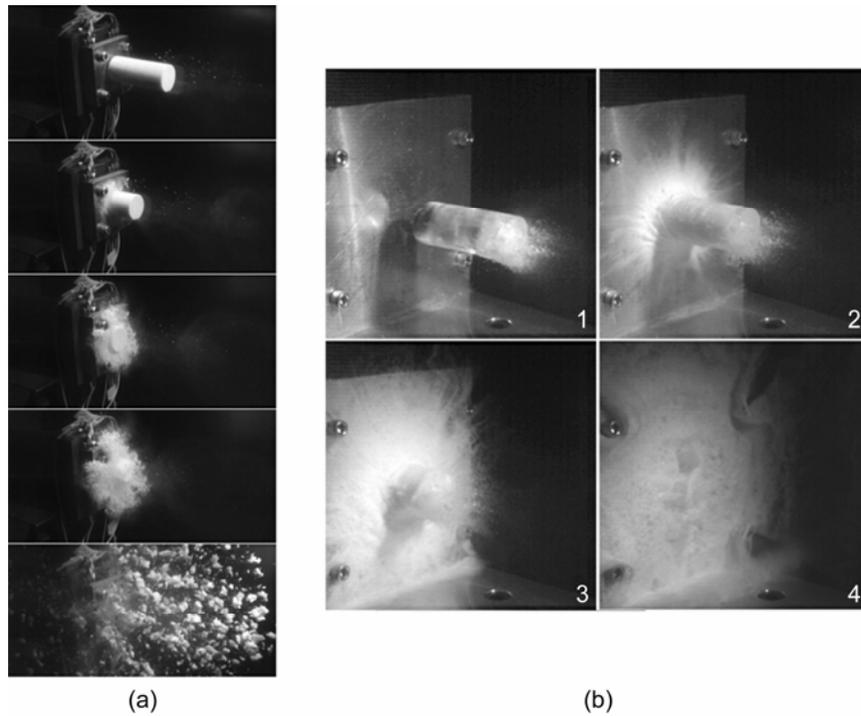
Figure 4.—NCFI External Tank foam undergoing impact at 800 ft/s at 1 psi
    environment (left) and the impact of 1.25 in. diameter by 3 in. long ice cylinder
    on load cells at approximately 800 ft/s (right).

Figure 5.—From left to right; small vacuum chamber, particle gun chamber, and large vacuum chamber guns at the
    NASA Glenn Ballistic Impact Facility.

Figure 6.—Eight inch gun at the NASA Glenn Ballistic Impact Facility.

The large vacuum chamber has an inside dimension of 5 by 4 by 4 in. (LWH). It currently has provisions for 16 instrumentation feed-throughs (with the ability to easily add additional ones). Viewing access ports on the front, side, top, and back allow for photo instrumentation with high-speed digital cameras. Generally speaking, any size barrel up to 8 in. inner diameter (ID) can be mated to the chamber; however, for these tests, a 2 in. ID barrel was used for 90° impact tests to accommodate a 2 in. sabot, and a 1.5 in. ID barrel was used for the 45° tests which were shot without sabots to obtain higher projectile speeds. Four 120 V feed-throughs provide power for high intensity lighting inside the chamber required for the high-speed digital imagery. This test program employed a Mylar (DuPont) burst disk and nichrome wire system to release the propellant gas, however, pneumatic and fast-valves are used as necessary for other specific testing.

Level 2 objectives

The level two test program consisted of over 100 impact tests of ice and External Tank foams on 6 by 6 in. and 6 by 12 in. simply supported flat panels of as delivered RCC. The RCC panels tested in this program were manufactured at Lockheed Martin Missiles and Fire Control in Dallas, Texas. Initially the RCC panels were fabricated to the dimensions of 12 by 12 in. and cut into half or quarters accordingly. Each panel was 19-ply RCC in an "as-fabricated" condition with the silicon carbide coating on both sides. The objectives of these tests were to establish deformation and damage characteristics of the material subjected to impacts from BX–265 and PDL foams, as well as high and low density or "soft" ice projectiles at 90° and 45° impact angles. High density ice was established to be the worst case ice type formed on the External Tank and soft ice was used to evaluate the damage threat to RCC from lower density "frost" formations. Two different angles were chosen for testing to insure validity of LS DYNA predictions at different impact angles. Results from these tests provided the necessary validation of material models developed and implemented in LS DYNA which would ultimately be used for debris impact assessment on the Orbiter RCC TPS. Quality oversight and configuration control was maintained on all aspects of this test series.

Test setup and data acquisition

It was the intent of the level 2 tests to provide controlled well understood boundary conditions on the panels to enable the highest level of confidence in the analysis model validation process. To accomplish this, a fixture was fabricated (shown in an exploded view with a 6 by 6 in. panel in fig. 7) that clamps the panels between round aluminum bar stock resulting in a simply supported panel. The simple support condition is easily modeled using the finite element method. For testing, the panel fixture was mounted in the large vacuum chamber at either 90° or 45° to the gun barrel.
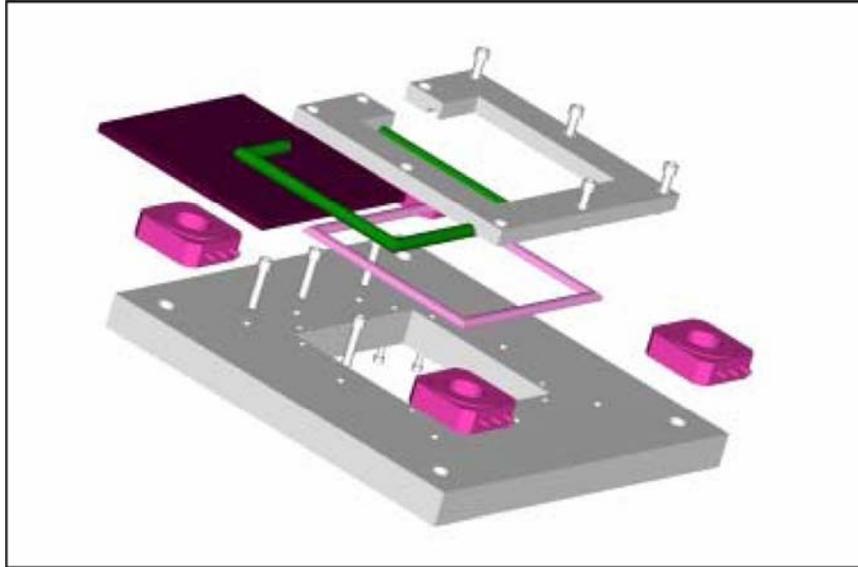
Figure 7.—Exploded view of RCC flat panel holder.

Impact loads were measured for each test using four piezo-electric load cells mounted in the fixture used to hold the flat panels for testing. The fixture, shown in figure 7, depicts the load cells (in deep magenta) mounted at each corner of the target panels. Measurements taken from the load cells are averaged and filtered to obtain force time histories of each impact event. The load cells are Kistler Model 9067 piezo-electric three-axis load washers.

To record data output from the load cells, two data acquisition systems were used for this test program: The first is a Spectral Dynamics model VX2805D 8 channel, 16 bit, 5 Msample/sec/channel system with signal conditioning capabilities. The second is a Iotech Wavebook 516E, 16 bit, 1Msample/sec system with 8 analog input channels, 8 strain gage conditioning channels, and 8 ICP sensor channels. Dual-mode Kistler model 5010B charge amps, powered the load cells.

High-speed digital Phantom cameras from Vision Research were used to document each impact test. Two Phantom v5.0 and three Phantom v7.0 cameras were used to measure projectile velocity, observe the impact event, and measure strain and deformation (using the Aramis system discussed below) for each test. The frame rates of these cameras are directly dependant on the desired output resolution which varied depending on the reason for which the camera was being utilized. Typically 256 by 256 pixel images were recorded at ~27,000 frames per second for Aramis and impact observation.

The Phantom cameras record a continuous 1 to 2 sec loop until stopped and do not require a trigger system to start recording. They are triggered manually to stop data acquisition at the sound of the gun blast, thus capturing the impact event in its entirety and making the triggering aspect of the testing highly reliable.

Strain gages were not added to the RCC test articles due to the low quality of data provided by this instrumentation method on RCC. Laboratory level tests indicate that strain gages produce erratic data due to the craze cracking of the SiC coating. As an alternative, strains were measured using the Aramis system, shown in figure 8 from Trilion Optical Test Systems. Aramis is a 3D image correlation photogrammetry system that captures full field deformation and stress-strain measurements under static, quasi-static, and ballistic impact loading (refs. 7 and 8). This system measures the deformation and stress-strain response of the rear side of the RCC flat panels as they undergo impact.

For Ballistic Testing two Phantom v7.0 cameras were used to acquire the photographic images Aramis needs to make its measurements. Using photogrammetric principals, the 3D coordinates of the surface of the specimen, which are related to the facets at each stage of load, can be calculated precisely. On the basis of the 3D coordinates of the 3D displacements, the strains and shape of the specimen can be calculated with a high degree of accuracy and resolution. The results were rapidly post-processed after each test and visualized in similar fashion to finite element results.

Figure 8.—Aramis 3D deformation/strain measurement system shown with static
camera assembly.

In order for the Aramis system to make its measurements, a painted irregular dot pattern must be applied to the field area of interest. The backside of each panel was painted before the impact testing was performed. Using Aramis to obtain ballistic impact deformation data for the flat panel tests was very successful, and the results were invaluable to the LS DYNA model validation process. This success established the motivation to utilize Aramis for full-scale Orbiter leading edge and nose cap impact testing at Southwest Research Center in San Antonio, Texas and on Orbiter composite pressure vessel testing to obtain full field 3D deformation data.

Non-destructive evaluation

In order to quantify and better understand damage and material irregularities in the RCC flat panels not visible to the naked eye, non-destructive evaluation (NDE) was performed on each RCC panel before and after testing. NASA Glenn has two NDE methods that were utilized for this program: Pulse, or flash, thermography and through transmission ultrasound. Both of these methods were employed for this test program to gain a better understanding of the advantages and disadvantages of each as applied to the RCC material. At the end of the program, it was determined that Ultrasound provided adequate damage assessment of the RCC panels which was not significantly complemented by the thermography.

Pulsed, or flash, thermography involves the heating of a specimen with a short duration pulse of energy and monitoring the transient thermal response of the surface of the specimen with an infrared camera. The thermal energy on the surface conducts into the cooler interior of the sample. In turn, there is a reduction of the surface temperature over time. This surface cooling will occur in a uniform manner as long as the material properties are consistent throughout the specimen. Subsurface defects that possess different material properties (e.g., thermal conductivity, density, or heat capacity) will affect the flow of heat in that particular region. This resistance in the conductive path causes a different cooling rate at the surface directly above the defect, when compared to the surrounding, defect-free material. The change in the subsurface conduction is seen as a non-uniform surface temperature profile as a function of time. Since the method depends on the interaction of the defect with the advancing thermal front, defects that are located at greater depths will show up later in time. Due to lateral diffusion, deeper defects will tend to have less contrast than near-surface flaws. Therefore, the critical flaw size capability of a thermographic inspection system is a function of the defect size, depth, and the material properties of the component being tested. Analysis of thermographic data involves examination of images based on the temperature-time data or derivatives calculated from the original data sets. Anomalous areas can then be identified based on deviations in the cooling behavior.

Figure 9.—Non-destructive evaluation facilities at NASA Glenn: through transmission ultrasonic immersion tank with RCC panel undergoing scanning (left) and thermal imaging setup to perform pulse thermography (right).
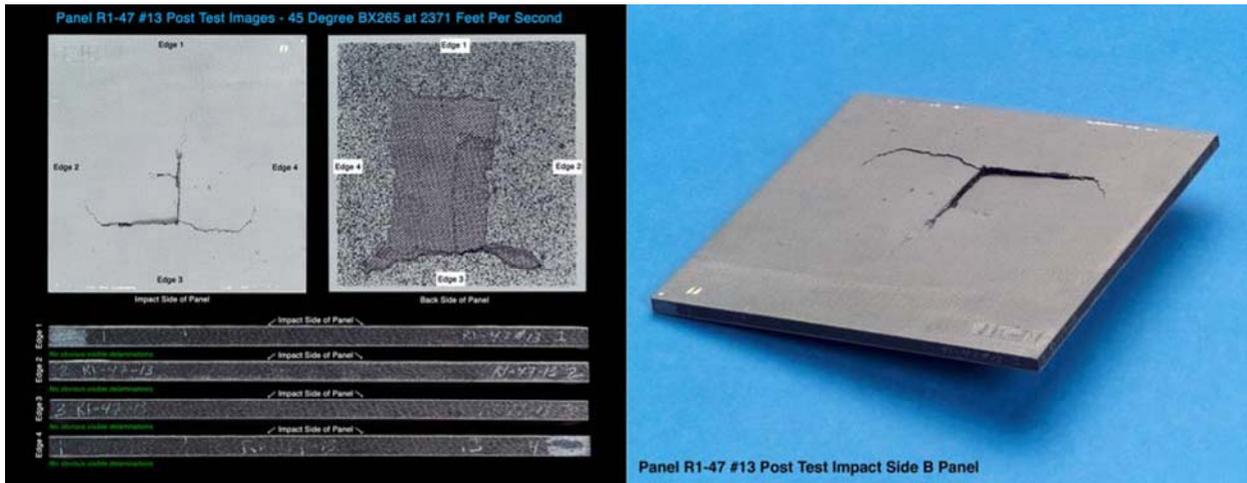
Figure 10.—Typical post test digital photographs taken of RCC panels to document visual damage observations.

Through transmission ultrasonic inspection utilizes two transducers, placed on opposite sides of a material for interrogation. One transducer sends an ultrasonic pulse through the material where it is received by the second. In scanning mode, the transducer pair is moved across the area of interest and an image based on the amplitude of the received waveform is generated. Defects and other significant variations will result in the additional attenuation and scattering of the ultrasonic signal as it passes through the material, thus reducing the signal amplitude. Flaws are located in the image based on this decrease in signal amplitude. Minimum flaw resolution is a function of the wavelength of the ultrasonic signal flaw orientation. Resolution, in general, increases with increasing frequency. Figure 9 shows both the immersion ultrasonic tank with relevant hardware to perform the through transmission ultrasonic inspection and thermal imaging setup used to conduct pulse thermography.

In addition to the above NDE, all panels were digitally photographed prior to and after testing. Both fronts and backs of the panel were photographed as well as all four edges on each panel. These images were assembled in composite photographs and archived at NASA Glenn to document any damage incurred. Two images are seen in figure 10 are representative examples from this archive of images.
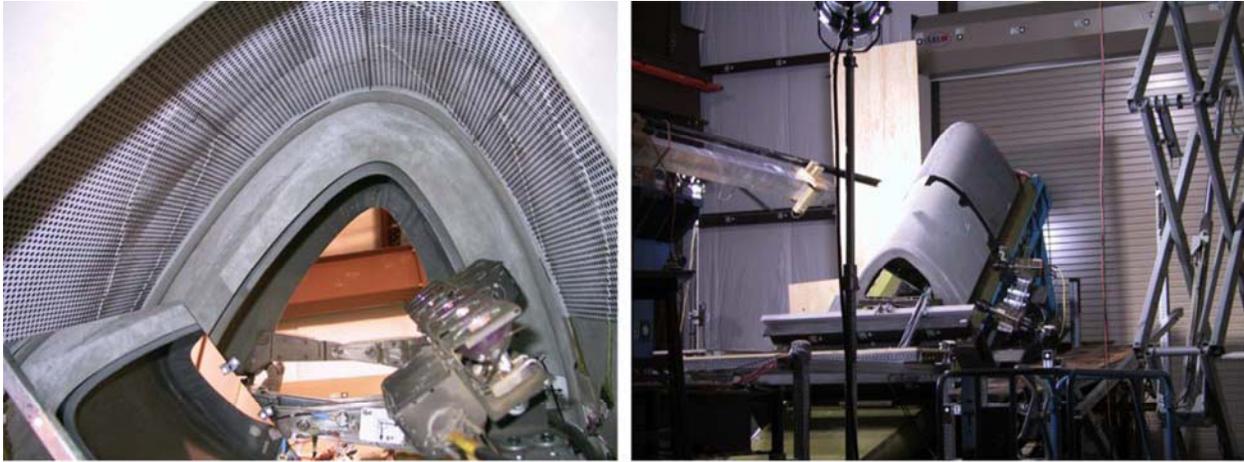
Figure 11.—Full-scale Orbiter leading edge test setup at SwRI. View inside leading edge test articles showing Aramis dot pattern on inside surface (left) and external view showing gun barrel in foreground (right).

Level 3 Full Scale Orbiter Leading Edge and Nosecap tests

Level three impact testing on full-scale Orbiter leading edges and nose caps were performed as the final support element in validating the LS DYNA analysis capability. This entire series of system-level tests was performed at Southwest Research Institute (SwRI) in San Antonio, Texas. Figure 11 shows two views of the full-scale Orbiter Leading Edge Panel testing setup at SwRI.

Two RCC leading edge panels (designated 9L—ninth panel from front of Orbiter with L indicating left wing) and one nose cap was used for the official DYNA impact testing. Two gap T-Seals, shown in figure 2, were also included in the series. A total of 15 shots were taken for the two Panel 9L test articles, 6 shots for the T-seals and 8 shots for the Nose cap. BX–265 foam, PDL foam, and ice were used as projectiles. The Aramis system was used to obtain the panel and nose cap deflection data which was directly correlated with LS DYNA predictions for the model validation process.

In total, more than nine full-scale Orbiter RCC full-scale assets were taken from spares and were used as test articles at SwRI. Additional testing of RCC panels 16R (right wing), 6L, 8L, and 9L (see Background section for discussion on panels) was performed by teams other than the DYNA Team, but the information from those tests was also used for validating the LS DYNA models.

Level 2 Test Results

For this series of panel tests four projectile materials were selected: BX–265 foam, PDL foam, High density ice (no entrained air bubbles), and "soft ice" (ice projectiles manufactured from ice shavings). For each projectile material, a spectrum of tests was conducted at 90° and 45° impact angles to establish both a maximum velocity at which no damage, detectable by ultrasound, thermography, or visual inspection would occur, as well as the minimum velocity resulting in severe damage to both the front and backside of the panel. Figures 12 through 15 show still images taken from the high-speed digital camera movies captured for each test from both front and back views. Note painted speckle pattern on the back views (on the lower rows) of these figures used for the Aramis system. Projectile velocities were obtained for each test through the use of one high-speed camera capturing the projectile flight path and measuring the distance traveled within the known time increment between frames.

Images from the above four figures depict the most severe failure cases of the RCC panels. The majority of tests only yielded small cracking or coating loss or no visible damage at all, hence the need for NDE post inspection. In addition, it can be noted that a bending type failure occurs with foam impacts and a shearing type failure occurs with ice.
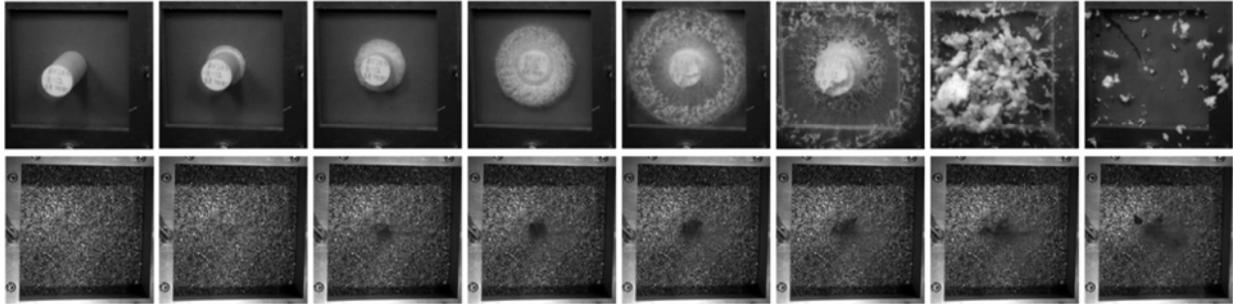
Figure 12.—Front and back views of 2.2 g BX-265 External Tank foam projectile impacting at 90° angle on 6 by 6 in. 19-ply RCC panel at 2054 ft/s (front and back views not time synchronized).
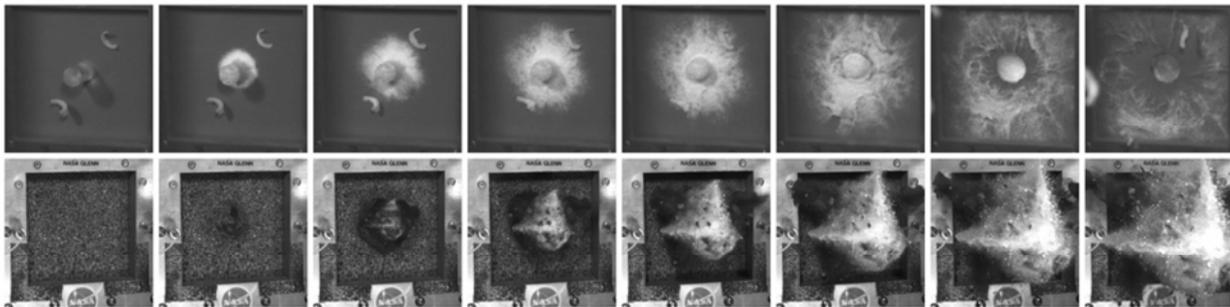
Figure 13.—Front and back views of 9 g high density ice projectile impacting at 90° angle on 6 by 6 in. 19-ply RCC panel at 641 ft/s (front and back views not time synchronized).
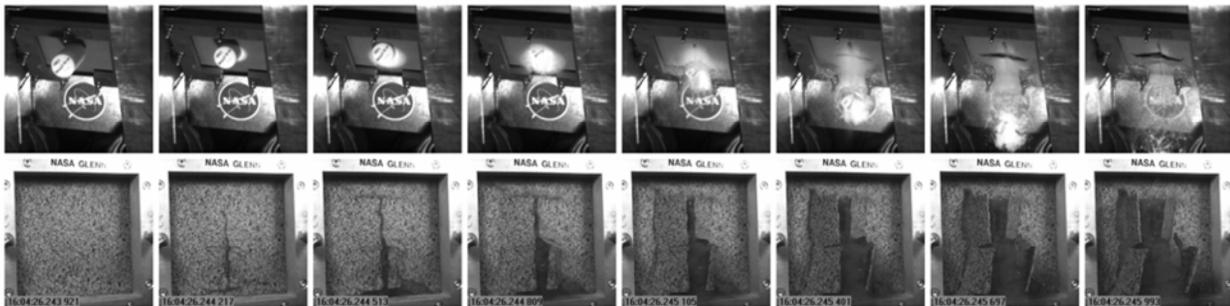
Figure 14.—Front and back views of 3 g BX-265 External Tank foam projectile impacting at 45° angle on 6 by 6 in. 19-ply RCC panel at 2371 ft/s (front and back views not time synchronized).

Figure 15.—Front and back views of 8.6 g high density ice projectile impacting at 90° angle on 6 by 6 in.19-ply RCC panel at 858 ft/s (front and back views not time synchronized).
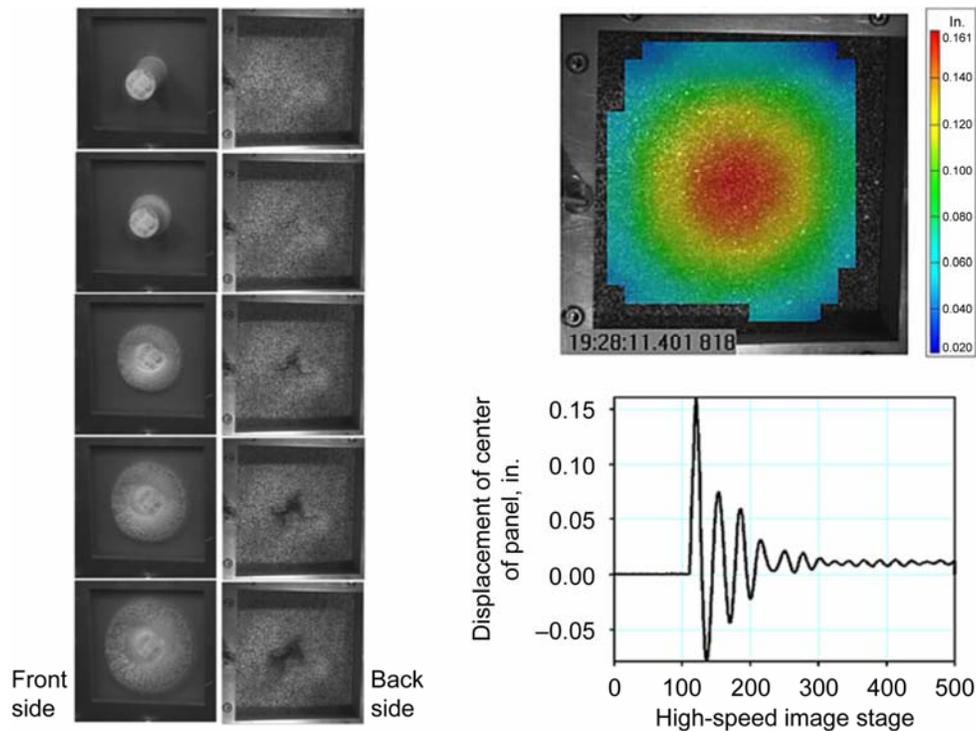
Figure 16.—High-speed images of RCC flat panel impact with BX-265 foam from front and back sides of panels (left) with sample output from Aramis system depicting out-of-plane RCC panel displacement as it undergoes impact (right).

After each test, image data from the Aramis system cameras was downloaded and reduced for rapid assessment. Aramis has extensive post processing capabilities for evaluating deformation, stress, and strain for any given test, however, for the purposes of validating the analysis methodology, we focused our attention on three types of deformation plots from Aramis: The full-field displacements normal to the RCC panel, center point displacement versus time plot seen in figure 16, and deformation profiles across the center line of panels shown in the right column of in figure 17. Immediately after each panel was tested, it was subjected to visual, thermography and ultrasound inspections followed by photographic documentation (Typical examples of the digital photos were discussed above and shown in figure 10. The left columns in figure 17 are representative NDE images organized by increasing impact velocity. Subtle increases in damage versus impact velocities can be observed in both thermography and ultrasound results at the 1716 ft/sec and 1907 ft/sec tests. This can be seen by comparing the baseline ultrasound images to the post test images. Thermography NDE.

Figure 16 High-Speed Images of RCC Flat Panel Impact with BX–265 Foam from front and back sides of panels (left) with sample output from Aramis system depicting out of plane RCC panel displacement as it undergoes impact (right) is plotted for comparison to the ultrasound. From these images, the internal damage/delaminations in the panels is seen to develop at the lower test velocities before any visual damage was evident underscoring the importance of the NDE inspection. The "onset of NDE damage threshold" for each debris type would ultimately be correlated with the LS DYNA analysis models to establish impact damage threshold limits for the Orbiter leading edges and nose caps.

As a result of the enormous amount of imagery data generated by this test program, a concerted effort to organize and archive it in an easily accessible form was made. As a consequence, the data now resides on storage servers at the NASA Glenn and NASA JSC for efficient access by technical staff. In addition, image data organized by projectile type and impact angle was comprehensively organized on large format composite prints for quick visual assessment of each test group. In composite form, the viewer can quickly compare all data (NDE, Aramis, and photography) in a one snapshot to gain intuition of the progression of RCC damage as a function of debris type, impact angle, and velocity. These prints were used extensively by the LS DYNA
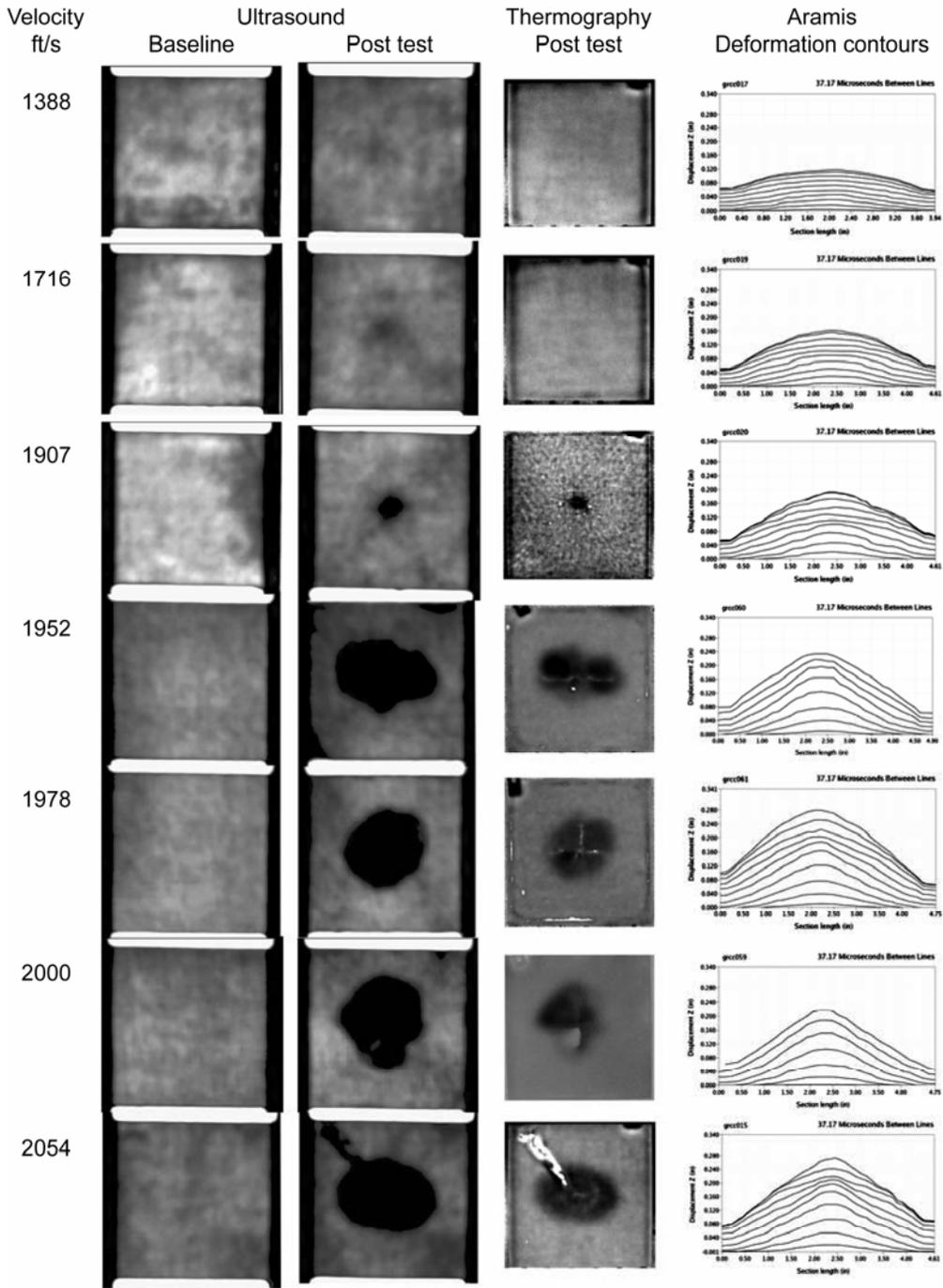
Figure 17.—Representative baseline and post test NDE scans presented in ascending order of impact velocity. Right column depicts Aramis deformation profiles across centerline of RCC panel in 37 µs increments.

analysis team as they progressed in the development and validation process. Figure 18 is a low resolution image of one such print. It is only intended to provide the reader an idea of the overall organization and not provide any significant information. The composites are archived and NASA Glenn and are available in both print and digital format.
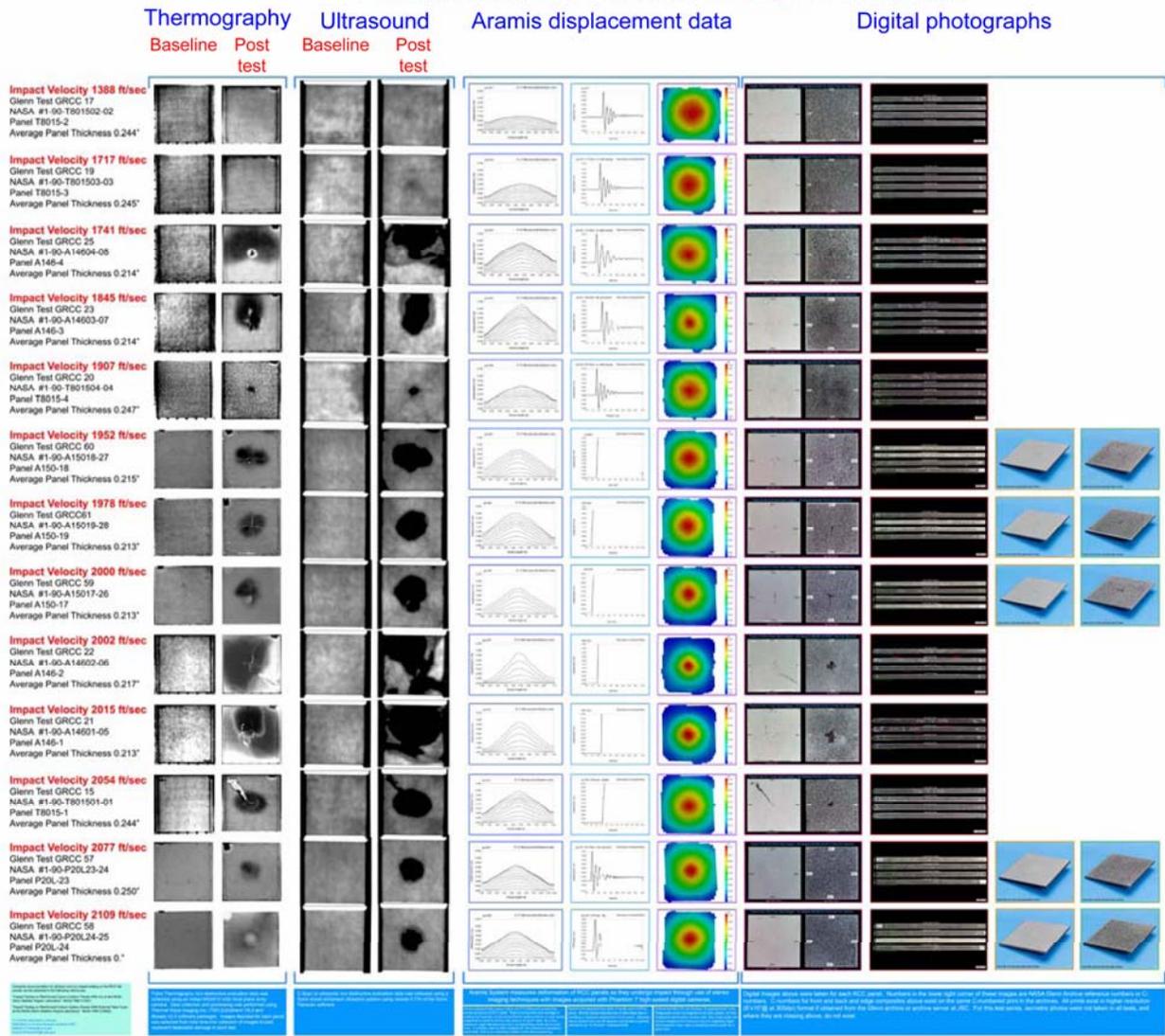
Figure 18.—Low resolution image illustrates large format data composite of a RCC flat panel impact test series.

Summary

The level two RCC flat panel impact test program at the NASA Glenn Ballistic Impact Laboratory was successfully completed on time supporting NASA's Return to Flight with the STS–114 mission. Results from these tests were used to demonstrate the validity of BX–265, PDL, ice and RCC models developed and implemented in the LS-DYNA impact analysis program. Results form the system level full-scale Orbiter wing leading edge and nose cap tests provided a final demonstration and complement to the validation process. Prior to STS–114, virtually hundreds of analyses with LS DYNA were performed to establish certified impact damage thresholds for Reinforced Carbon Carbon thermal protection systems on the Orbiter helping to recertify the Shuttle system for flight. For the interested reader, references 9 through 20 provide comprehensive details on much of the analysis development process, and references 21 through 25 provide a similar level of detail on the testing programs associated with this effort.

In the current timeframe, existing LS DYNA models are currently being refined to provide a higher level of fidelity in predictive capability and new debris material models including gap filler and ablators are under development.

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14. ABSTRACT
Following the tragedy of the Space Shuttle Columbia, a major effort commenced to develop a better understanding of debris impacts and their effect on the Space Shuttle subsystems. An initiative to develop and validate physics-based computer models to predict damage from such impacts was a major component of this effort. To develop the models it was necessary to physically characterize Reinforced Carbon-Carbon (RCC) and various debris materials which could potentially shed on ascent and impact the Orbiter RCC leading edges. Validation of the material models was done through a three-level approach: fundamental tests to obtain independent static and dynamic material model properties of materials of interest, sub-component impact tests to provide highly controlled impact test data for the correlation and validation of the models, and full-scale impact tests to establish the final level of confidence for the analysis methodology. The second level of testing consisted of over one hundred impact tests in the NASA Glenn Ballistic Impact Lab on flat plates of RCC and evaluated several types of debris projectiles: BX-265 and PDL-1034 external tank foams, and ice. This paper discusses the level 2 subcomponent test program in detail and its application to the LS DYNA model validation process.

15. SUBJECT TERMS
Reinforced carbon-carbon; Impact testing; Ballistic; Ice; BX-265; External tank; Shuttle; Orbiter

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