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Test and Analysis of Foam Impacting a 6x6 Inch RCC Flat Panel

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Abstract

This report presents the testing and analyses of a foam projectile impacting onto thirteen 6x6 inch flat panels at a 90° incidence angle. The panels tested in this investigation were fabricated of Reinforced-Carbon-Carbon material and were used to aid in the validation of an existing material model, MAT58. The computational analyses were performed using LS-DYNA®*, which is a physics-based, nonlinear, transient, finite element code used for analyzing material responses subjected to high impact forces and other dynamic conditions. The test results were used to validate LS-DYNA® predictions and to determine the threshold of damage generated by the MAT58 cumulative damage material model. The threshold of damage parameter represents any external or internal visible RCC damage detectable by nondestructive evaluation techniques.

Introduction

Compelling evidence obtained from still photographs and video of the STS-107 Columbia launch clearly showed that a piece of external tank insulating foam separated from the left bipod ramp and struck the bottom part of wing panel 8 (Figure 1). Immediately following the accident, the Columbia Accident Investigation Board (CAIB) was quickly formed to identify the root cause of the accident and recommend corrective action to return the Shuttle fleet to flight. The CAIB identified that the technical failure was due to the foam impact that caused a breach to form, thereby exposing the aluminum sub-structure to the surrounding superheated gases. Once breached, the wing's inner structure began to melt, rendering the Shuttle unable to withstand the high temperatures or loads, which led to its eventual breakup.

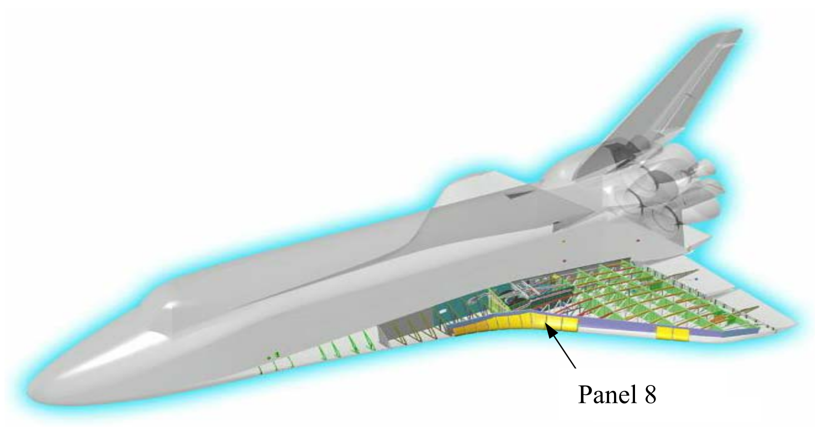

Figure 1. Location of panel 8 on the left wing of the Shuttle Orbiter

*® LS-DYNA is a registered trademark of Livermore Software Technology Corporation

One of the corrective actions (R3.3-2) suggested by the CAIB was to “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 also to “determine the effect of likely debris strikes.” A second corrective action (R3.8-2) from the CAIB report recommended that “a team should develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts” and that “these tools provide realistic and timely estimates of any impact damage from possible debris” as well as “establish impact damage thresholds that trigger responsive corrective action …..” [1].

After the CAIB report was released, NASA formed a team consisting of NASA Glenn Research Center (GRC), NASA Langley Research Center (LaRC), and Boeing Philadelphia to address the above recommendations. The purpose of this team was to develop analytical tools that could be used to study the effect of foam impacting the RCC leading-edge panels and to accurately predict the onset threshold of damage from debris impacting the wing leading-edge panels for a variety of conditions. The definition of “threshold” used by the team was any internal RCC damage detectable by nondestructive evaluation (NDE) methods.

Overall RCC Damage Threshold Analysis Approach

The team conducted a series of analyses to simulate the RCC impact material response for the full-scale leading edge panels on the Shuttle Orbiter using LS-DYNA® [2], a three-dimensional nonlinear transient finite element code, using the MAT58 [3] material model, MAT_LAMINATED_COMPOSITE_FABRIC. The MAT58 composite laminate material model in LS-DYNA® allowed for degradation and failure using a cumulative damage material model. Modeling the RCC composite laminate material was quite challenging. First, the variability that exists during the lengthy casting and heating manufacturing process for the panels can cause various degrees of anomalies and inconsistencies in the panels. The normalized compression and tension parameters for the RCC material were obtained from the Loral Report [4] and compared to measured RCC test parameters obtained from the 6x6 inch panel tests performed by GRC. This comparison is depicted in Figure 2, which clearly shows that the RCC material properties can vary considerably. Secondly, the accurate modeling of the RCC full scale leading edge panels was further complicated by the fact that the panels used for testing had been exposed to many launches and debris strikes.

Since the variability of the RCC material was of concern to the team, a flat panel study that included both testing and finite element analyses was undertaken specifically for RCC material characterization. A major advantage of the flat panel study from an analytical point of view was that the panels were simple to model and provided timely solutions. GRC conducted a series of tests in which a cylindrical foam projectile was impacted onto thirteen 6x6 inch RCC flat panels at 45° and 90° angles of incidence. LaRC then modeled these RCC flat panel tests using LS-DYNA®. Some effort was geared to investigating the effect of varying several of the MAT58 material parameters; however, these changes either had little effect on the solution or resulted in unrealistic (non-physical) results. Therefore, no updates were made to the initial material model; however, the team had the opportunity to gain some useful experience and insight into the applicability and limitations of the LS-DYNA® code for this type of high velocity impact. The team was also able to define and interpret the damage parameter, which was used to identify the maximum analytical damage threshold that a panel could experience before coating cracks and/or internal damage would be expected to occur.

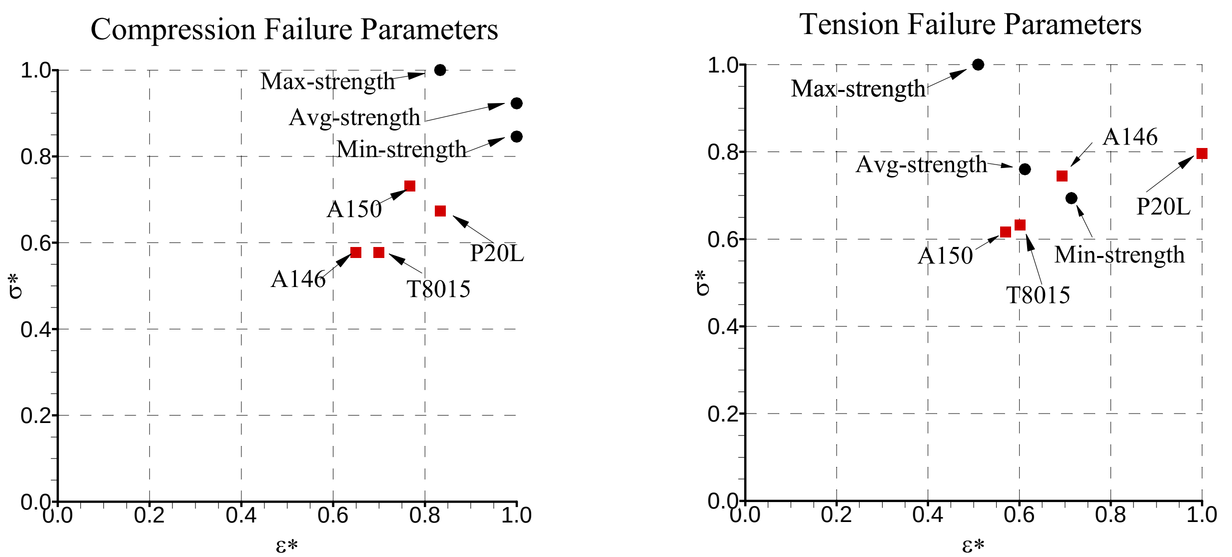

Figure 2. Normalized compression and tension parameters for the RCC material obtained from the Loral Report (black data points) and the 6x6 flat panel test (red data points).

Panel Test Description

The results from GRC's 6x6 inch RCC panel tests at a 90° angle of incidence are summarized in this paper; details of these tests and the results can be found in references 5 and 6. Thirteen tests were performed on four different RCC plates, which were left over from a previous Shuttle configuration. The panels were composed of a 19-layered RCC substrate which had a laminate coating and a nominal thickness of 0.233 inches. Each of the four plates were cut into smaller plates and labeled with a different prefix, which was used to identify what larger plate it was cut from. Although the plates were all made of the RCC material, the variability of material properties among the panels required that each panel be identified; hence, each panel group was identified via prefix labeling. The panel prefixes were designated as T8015, A146, P20L, and A150 (see Table 1). The BX-265 (named to represent the material model used in LS-DYNA®) foam projectile was shot from an air gun at various speeds into a vacuum box containing a panel that was restrained by the framed fixture as shown in Figure 3. The diameter and length of the projectile was 1.25 in. and 3.0 in., respectively, and had a nominal mass of 2.0 grams. Each panel was restrained approximately 0.16 in. from the outer sides by half-round aluminum rods to uniformly clamp the outer edges of the panel firmly in place. Table 1 lists the 13 tests along with their normalized material descriptions, physical property characteristics, and test conditions. Note that all the panels in each prefixed group had the same thicknesses and material properties. Pre- and post-test still photographs, NDE such as ultrasound and thermography, and Aramis displacement data were obtained for each panel, which was impacted by a foam projectile at different velocities.

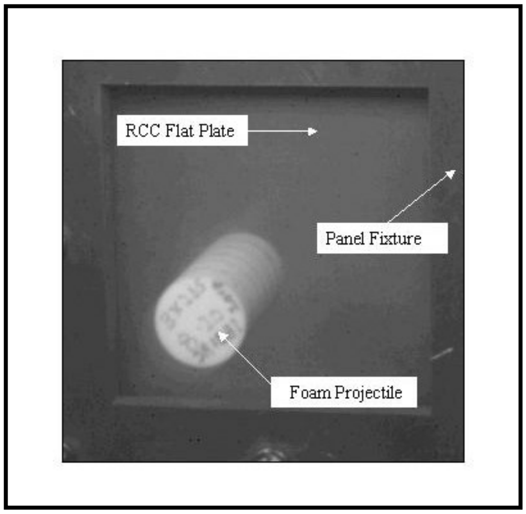

Figure 3. Test set-up showing the BX-265 foam projectile impacting the RCC panel.

Table 1: 90° Panel Test Properties & Conditions

Panel	Panel Thickness in.	Density ρ^*	E^*, Comp	E^*, Tension	Ult ε_c^*	Ult σ_c^*	Ult ε_t^*	Ult σ_t^*	Velocity Foam in./sec
T8015_1	0.243	1.000	1.000	1.000	0.880	0.620	0.602	0.660	24648
T8015_2	0.243	1.000	1.000	1.000	0.880	0.620	0.602	0.660	16656
T8015_3	0.243	1.000	1.000	1.000	0.880	0.620	0.602	0.660	20604
T8015_4	0.243	1.000	1.000	1.000	0.880	0.620	0.602	0.660	22884
A146_1	0.210	1.028	0.935	1.125	0.760	0.619	0.694	0.741	24180
A146_2	0.210	1.028	0.935	1.125	0.760	0.619	0.694	0.741	24024
A146_3	0.210	1.028	0.935	1.125	0.760	0.619	0.694	0.741	22140
A146_4	0.210	1.028	0.935	1.125	0.760	0.619	0.694	0.741	20892
P20L_23	0.248	1.035	0.814	0.464	1.000	0.669	1.000	0.782	24924
P20L_24	0.248	1.035	0.814	0.464	1.000	0.669	1.000	0.782	25308
A150_17	0.211	1.056	0.928	0.679	0.940	0.733	0.551	0.627	24000
A150_18	0.211	1.056	0.928	0.679	0.940	0.733	0.551	0.627	23424
A150_19	0.211	1.056	0.928	0.679	0.940	0.733	0.551	0.627	23736

* Denotes non-dimensional values.

Finite Element Simulations

The impact tests performed by GRC were simulated by LaRC using LS-DYNA®. The finite-element model, depicted in Figure 4, was composed of a 6x6 inch flat panel containing 3600 quadrilateral shells (with element edge length of 0.1) and a foam projectile, which consisted of 5250 solid elements. The foam, which impacted the center of the plate at 90° (normal to the plate), was 1.25 inches in diameter and 3.0 inches long. The analytic dynamic response of the panel was symmetric; hence, all corner and edge displacements produced the same dynamic behavior. Each edge and corner point was approximately 0.9 inches in the x and y direction from the center point of the panel (shown notionally in Figure 4b). The simulated displacement values were extracted from the four corner points, four edge points, and one center point and compared to test data. This basic model was replicated to create a series of models to capture the exact RCC panel thickness and the proper mass of each foam projectile for each of the GRC tests (see Table 1).

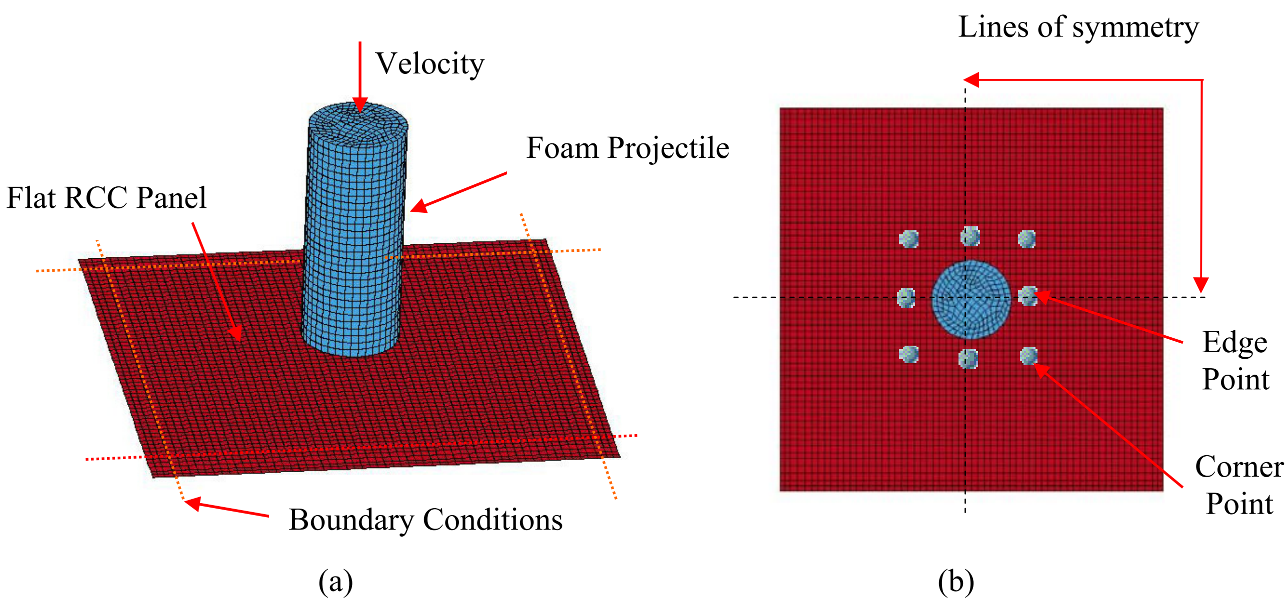

Figure 4. Finite element model of flat RCC panel with the BX-265 cylindrical foam set up to impact normal onto the panel is shown in Figure 4a. Measurements are taken at nine correlation points shown in Figure 4b.

For the GRC experiments, the RCC flat panel specimens were constrained on all four sides by a frame composed of aluminum half-rounds. For the simulation, the RCC panels were constrained along the outer boundary shell edges 0.16 inches from the outer panel (shown notionally in Figure 4a). The edges were constrained in the normal out-of-plane (z-direction), and were free to rotate in all directions. The modeling of the frame's boundary constraints significantly influenced the panel's impact response. This was partly due to the small size of the panels. The effects of the boundary conditions would have been minimized if the panels had been larger.

Results

The computational and test results for the 6x6 inch RCC flat panels are presented and analyzed in this section of the paper. The deflection versus time of a representative panel simulation were compared to test, and colored contours of the first principal stresses at different time intervals for each panel are presented and discussed. In addition, NDE (ultrasound and still photographs) and computational impact damage thresholds are shown and discussed. As previously mentioned, each of the 13 panels was cut from four different pieces of RCC material. Because these panels were left over from a previous Shuttle configuration and had been in storage for some time, obtaining exact material properties for each panel was challenging and some of the smaller 6x6 inch panels revealed anomalies when the post-impact NDE results were processed.

The predicted displacement time history curves for the T8015 panels at the corner, center and edge locations are shown in Figure 5 (analytical curves are dotted). The deflection results shown are representative of the time displacement curves obtained for the other panels. Due to the horizontal and vertical planes of symmetry in the LS-DYNA® models, only one analytic curve is needed per test to represent all the corner and edge response behavior while all four experimental curves are plotted. Predicted time histories for T8015-2 and T8015-3 compared reasonably well with the test data, and the predicted peak deflections are within 20% of the measured values, as shown in Figure 6. There is a 26% error between test and analysis at the maximum peak displacement for the center point of the T8015-4 panel. This test case had the highest impact velocity (22,884 in/sec) for that particular panel type. Factors which may have contributed to the displacement discrepancies are: 1) the post-processing of the Aramis displacement test data, 2) the small size of the panels, 3) pre-test RCC plate and coupon anomalies, which were evident in the A146 panel, 4) incorrect simulation of the panel stiffness at its center, and 5) no damping parameters were used in LS-DYNA®.

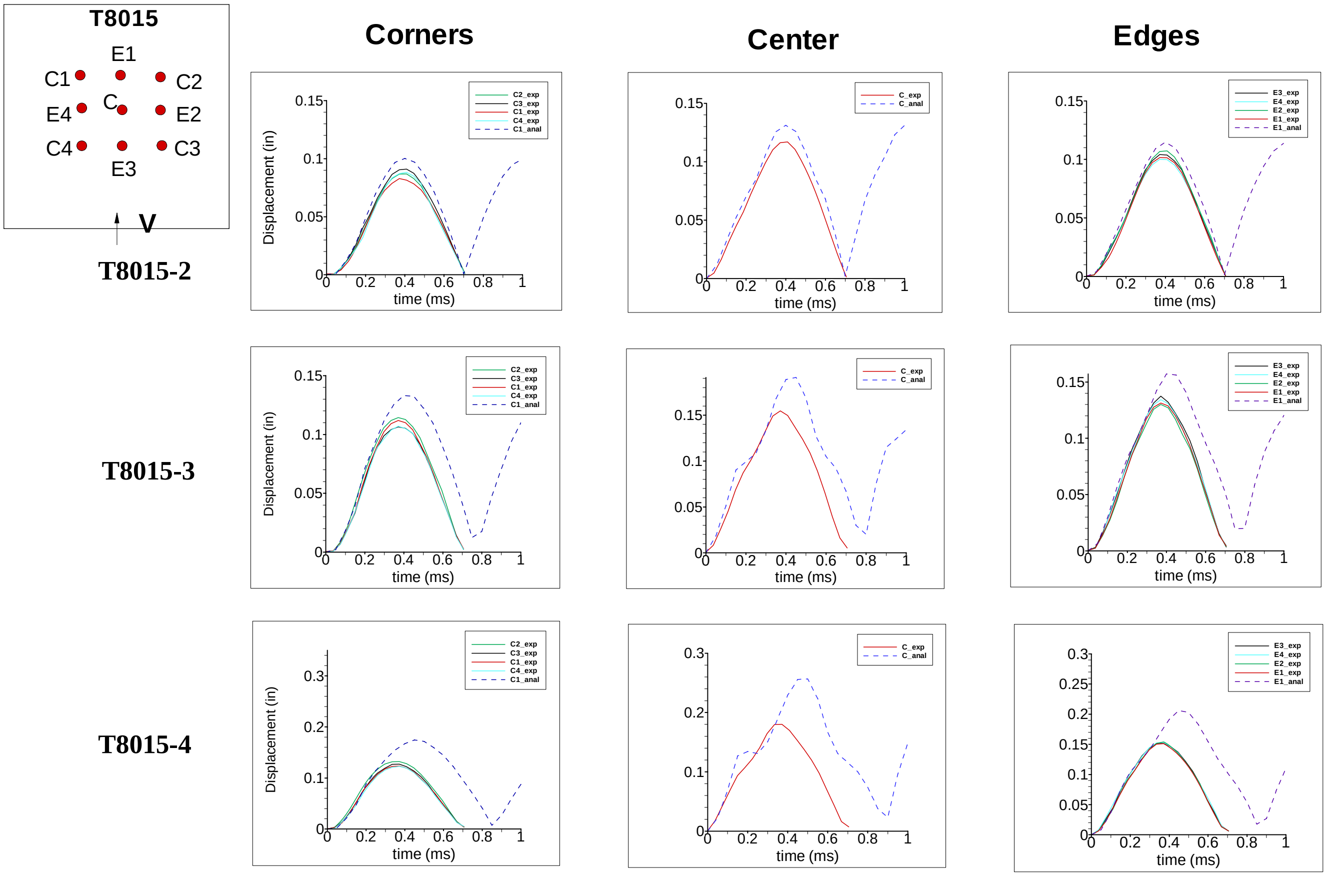

Figure 5. Predicted displacement time histories compared to the flat panel test results.

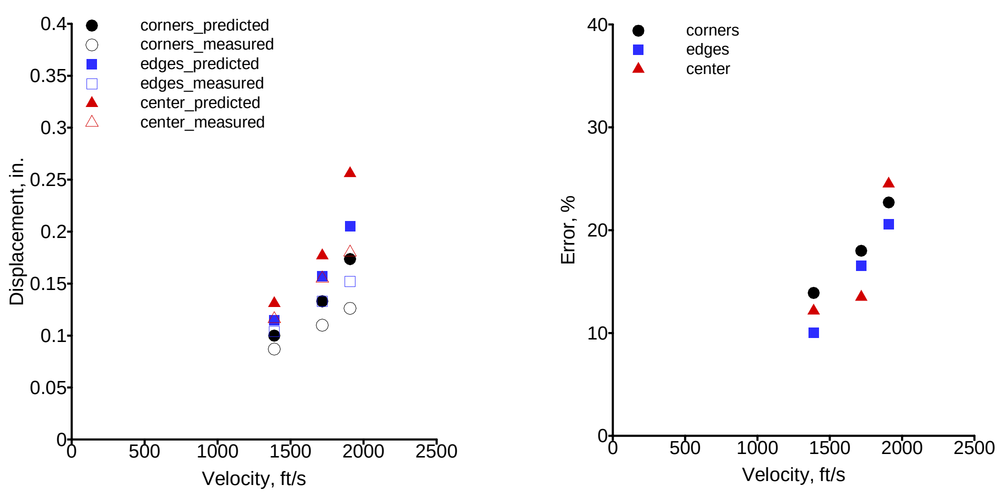

Figure 6. The maximum displacements and percent error of all the correlated data points.

Colored contour plots of the analytical predictions for the first principal stresses at different impact time intervals for the 12 RCC panel tests (there was no test data available for T8015-1) are shown in Figures 7–18. Each figure depicts 6 different "snap-shots" in time. The stress predictions for panels T8015-2, T8015-3, and T8015-4 are shown in Figures 7, 8 and 9, respectively. The highest analytical stress contours among the T8015 group occurs for the T8015-4 panel at t = 0.2 ms (Figure 9). This finding is consistent with the displacement trends in Figure 5, which show that the T8015-4 panel has the highest test and analysis displacement values for the corner, edge and center locations. A small bump in the displacement curve at the center point appears at t ~ 0.18 ms for all the T8015 cases shown in Figure 5. The magnitude of the bump increases with velocity. The LS-DYNA® code appears to treat the center of the plate different from the corners and edges and produces a softer dynamic response in the panel center, while the tests show this region to be much stiffer. Stresses depicted as colored contours are shown for panels A146 (Figures 10–13), P20L (Figures 14 and 15), and A150 (Figures 16–18). For the most part, the stress color contours are symmetrical; however, there are some asymmetries that occur after the foam has fully impacted the panel ($t \geq 2.0$ ms).

The predicted maximum damage parameter and principal strain are plotted as colored contours and compared to post-impact photographs of the top and bottom surfaces (Figure 19). Overall, the breaches and coating cracks, which resulted after impact, proved to be a good indicator of the NDE images, except for the A146 panel, which had anomalies. Usually, as more damage was inflicted to the panel surface after impact, more internal damage was noted. This was not the case for the A146 panel group, which showed massive internal damage without any significant external cracks or ablations. Both the test and analyses indicated through cracks for the following panels: T8015_1, P20L-23, P20L-24, A150-17, A150-18, A150-19 (Figure 19). It appears that the greatest internal damage (detected by ultrasound) occurred in the T8015_1 panel, the A150 panels, and the P20L panels. Again panel A146 is not included due its probable pre-test anomalies.

The threshold of damage parameter represents any external or internal visible RCC damage detectable by NDE techniques. According to the computational damage parameter shown in Figure 19, the threshold of damage is between 0.92 and 0.98. Therefore, thresholds below 0.92 should not result in any internal or external damage. As the threshold damage increases from 0.92 to 0.98, (at 1.0, the panel is completely damaged), the amount of internal and external damage increases.

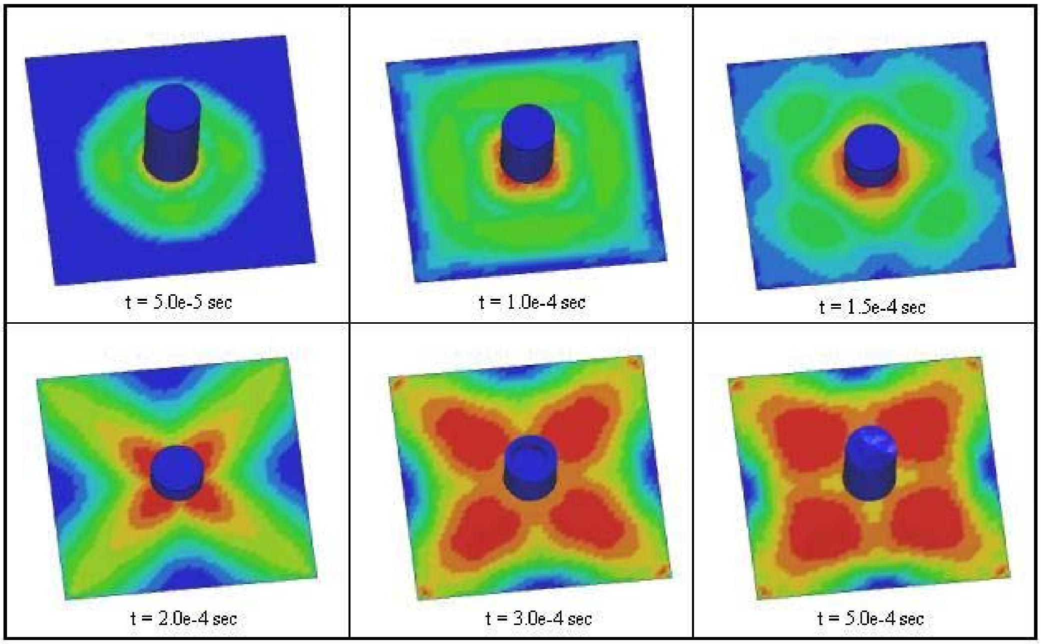

Figure 7. Colored contours of the first-principal stresses at different time intervals for the T8015-2 flat panel. The impact velocity of the foam is 16,656 in/sec.

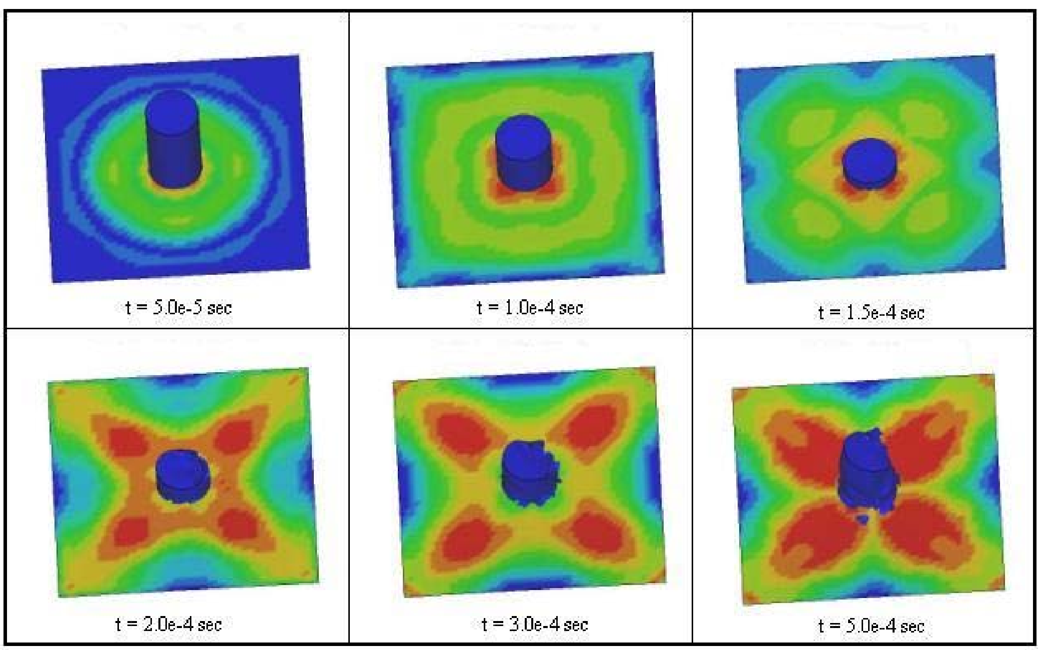

Figure 8. Colored contours of the first-principal stresses at different time intervals for the T8015-3 flat panel. The impact velocity of the foam is 20,604 in/sec.

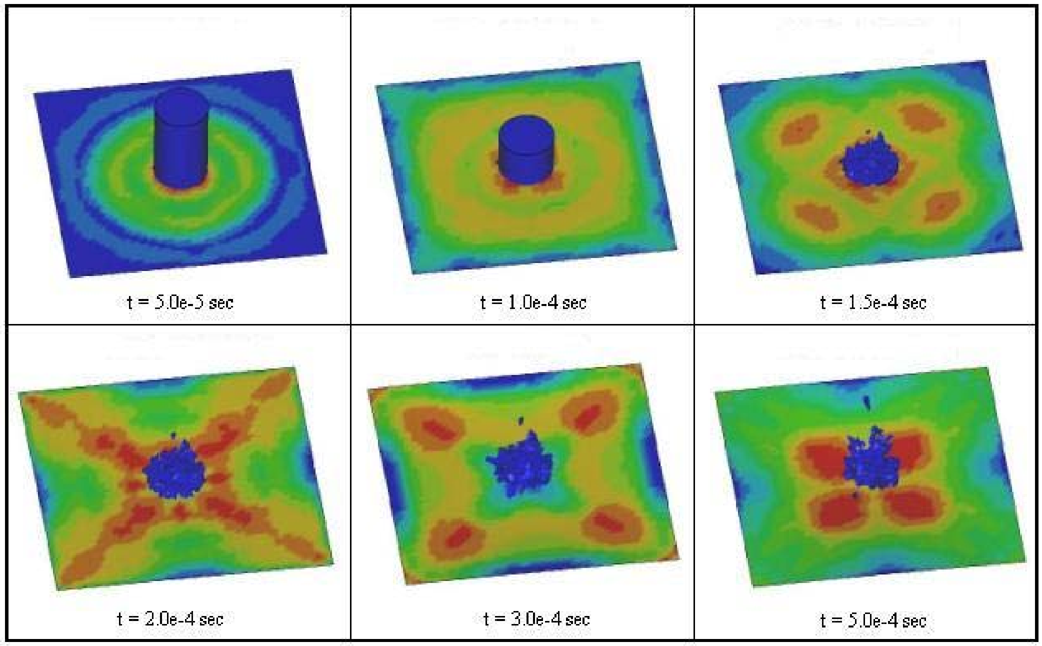

Figure 9. Colored contours of the first-principal stresses at different time intervals for the T8015-4 flat panel. The impact velocity of the foam is 22,884 in/sec.

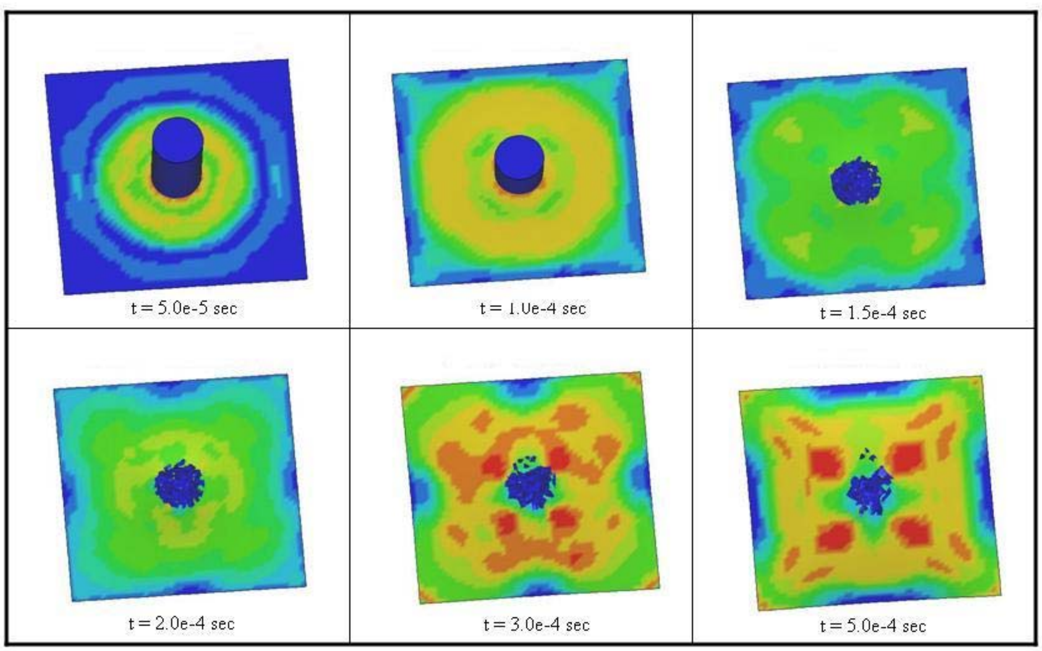

Figure 10. Colored contours of the first-principal stresses at different time intervals for the A146-1 flat panel. The impact velocity of the foam is 24,180 in/sec.

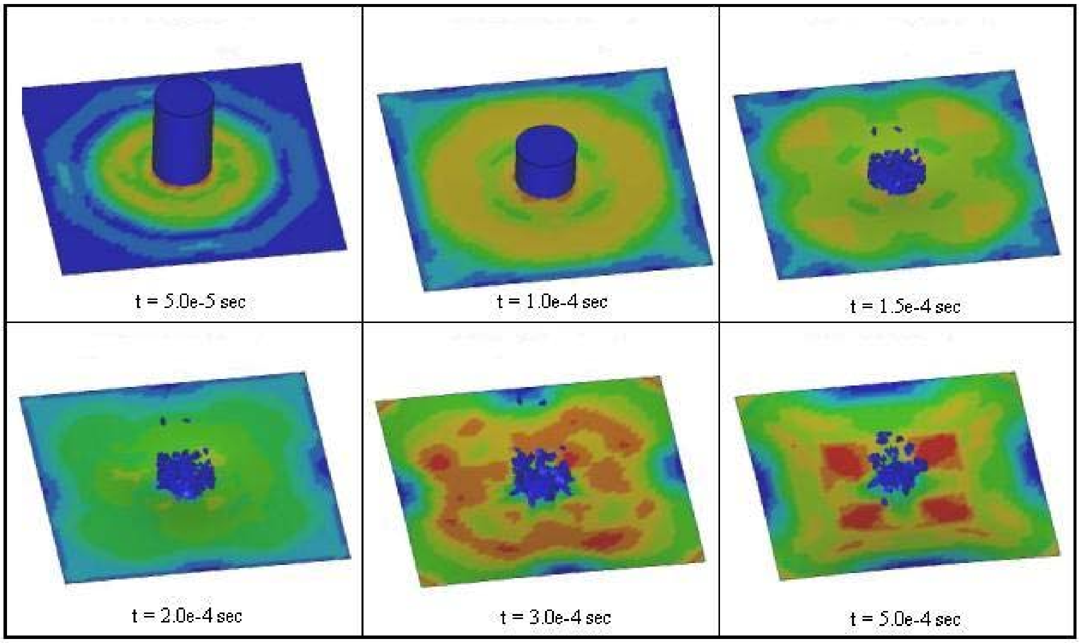

Figure 11. Colored contours of the first-principal stresses at different time intervals for the A146-2 flat panel. The impact velocity of the foam is 24,024 in/sec.

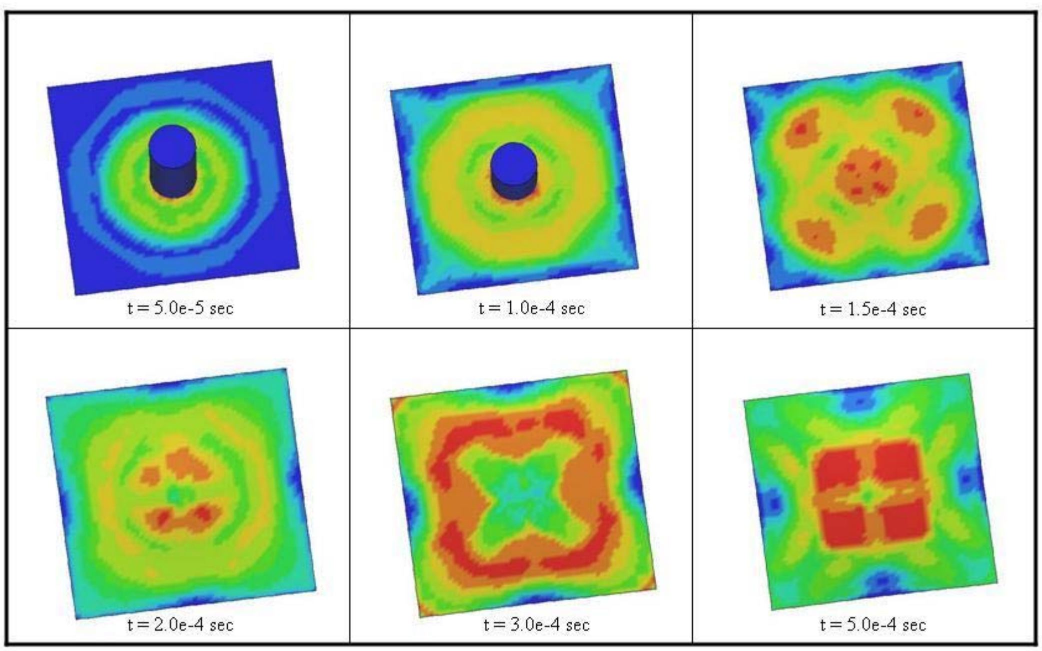

Figure 12. Colored contours of the first-principal stressess at different time intervals for the A146-3 panel. Then impact velocity of the foam is 22,140 in/sec.

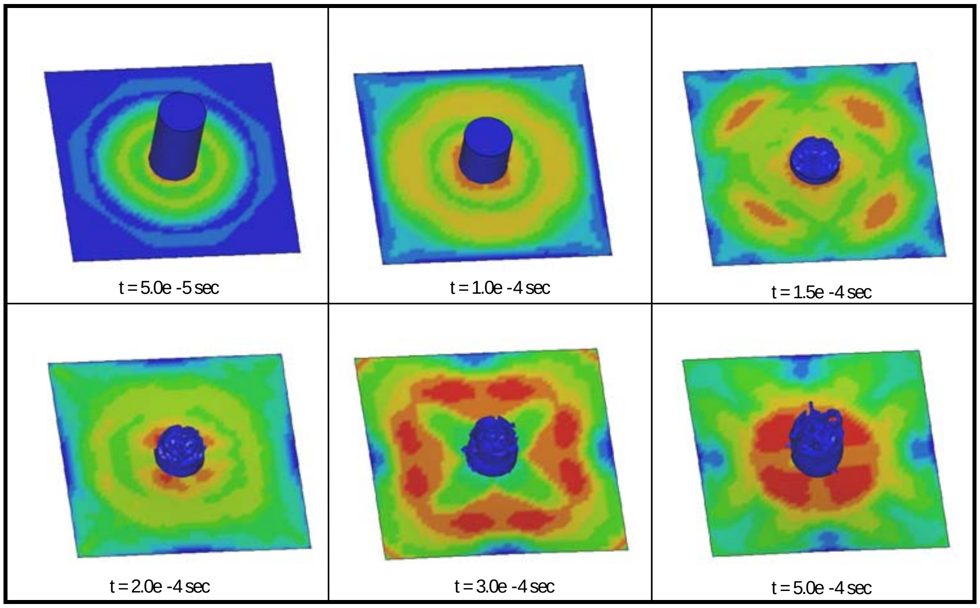

Figure 13. Colored contours of the first-principal stresses at different time intervals for the A146-4 flat panel. The impact velocity of the foam is 20,892 in/sec.

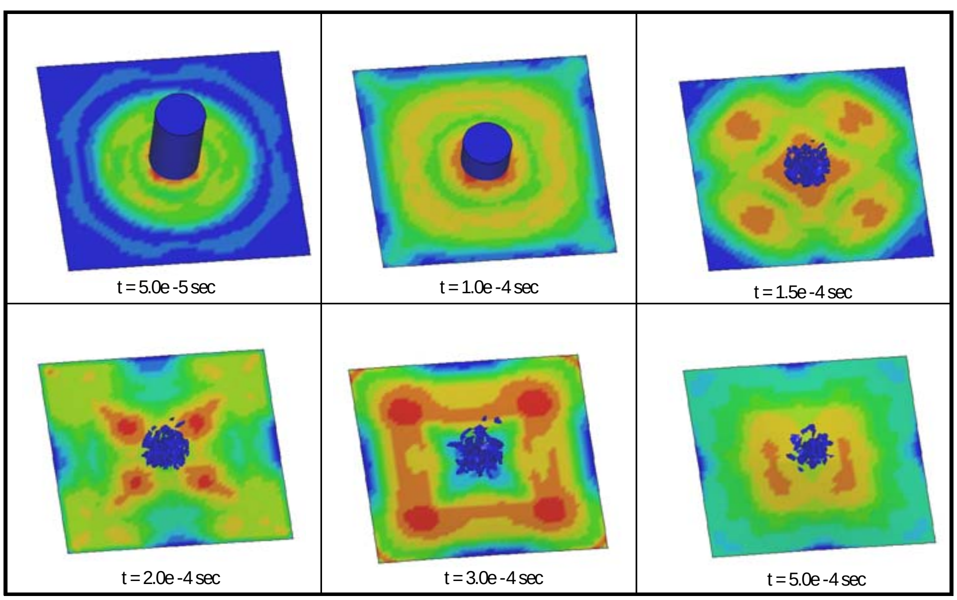

Figure 14. Colored contours of the first-principal stresses at different impact time intervals for the P20L-23 flat panel. The impact velocity of the foam is 24,924 in/s

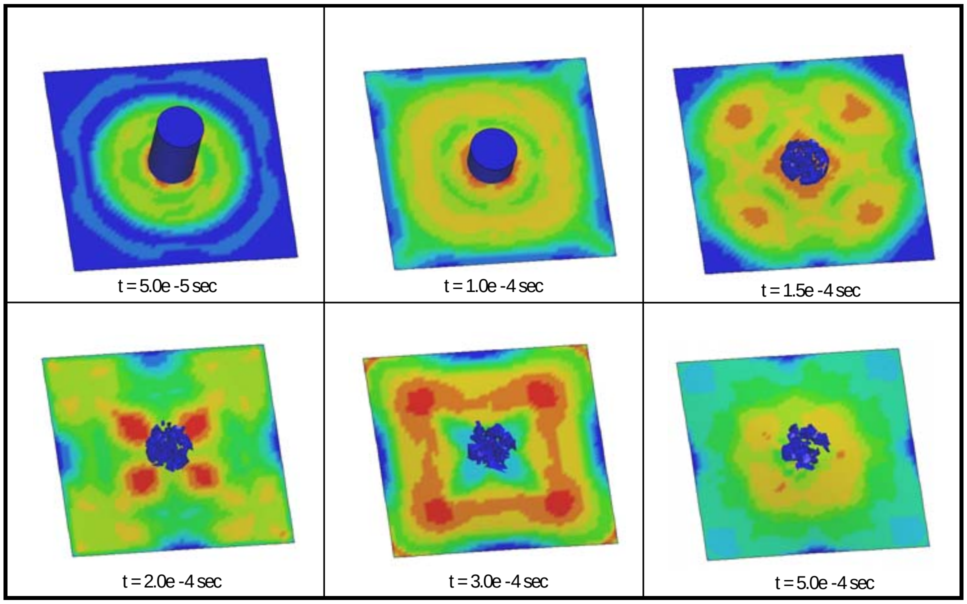

Figure 15. Colored contours of first-principal stresses at different time intervals for the P20L-24 flat panel. The impact velocity of the foam is 25,308 in/sec.

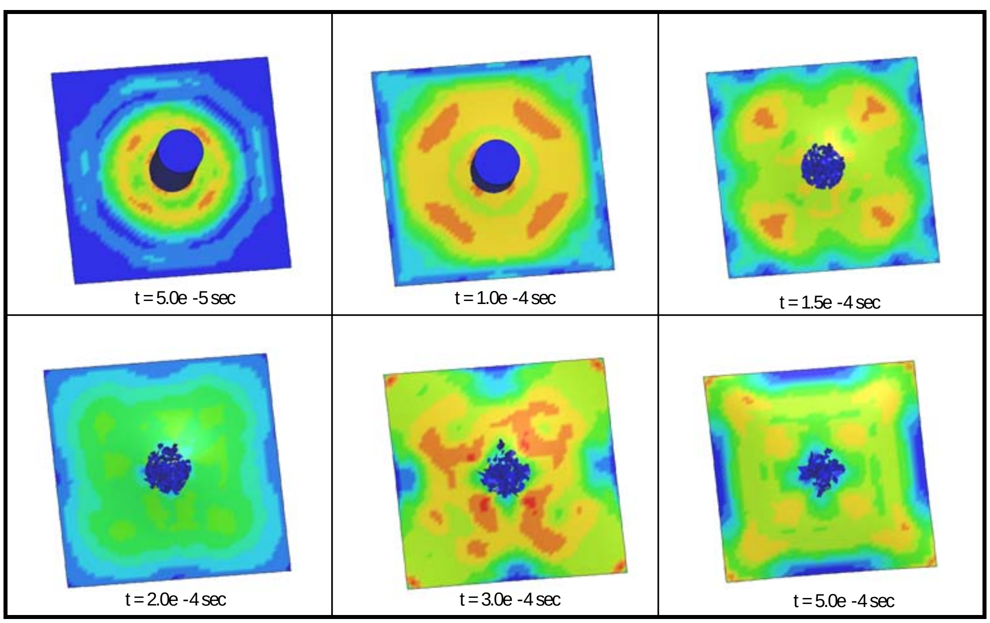

Figure 16. Colored contours of first-principal stresses at different time intervals for the A150-17 flat panel. The impact velocity of the foam is 24,000 in/sec.

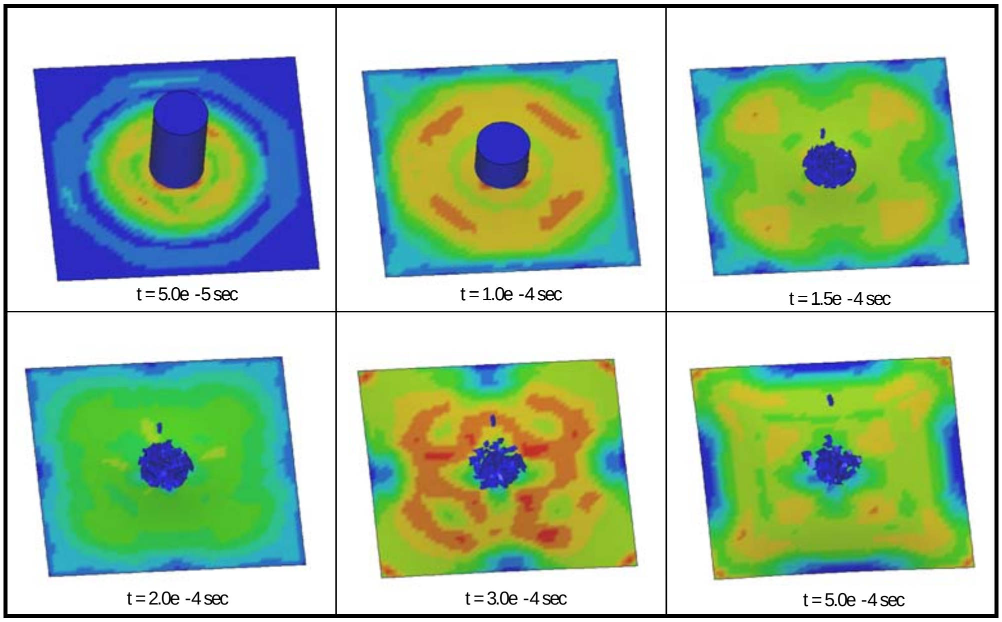

Figure 17. Colored contours of first-principal stresses at different time intervals for the A150-18 flat panel. The impact velocity of the foam is 23,424 in/sec.

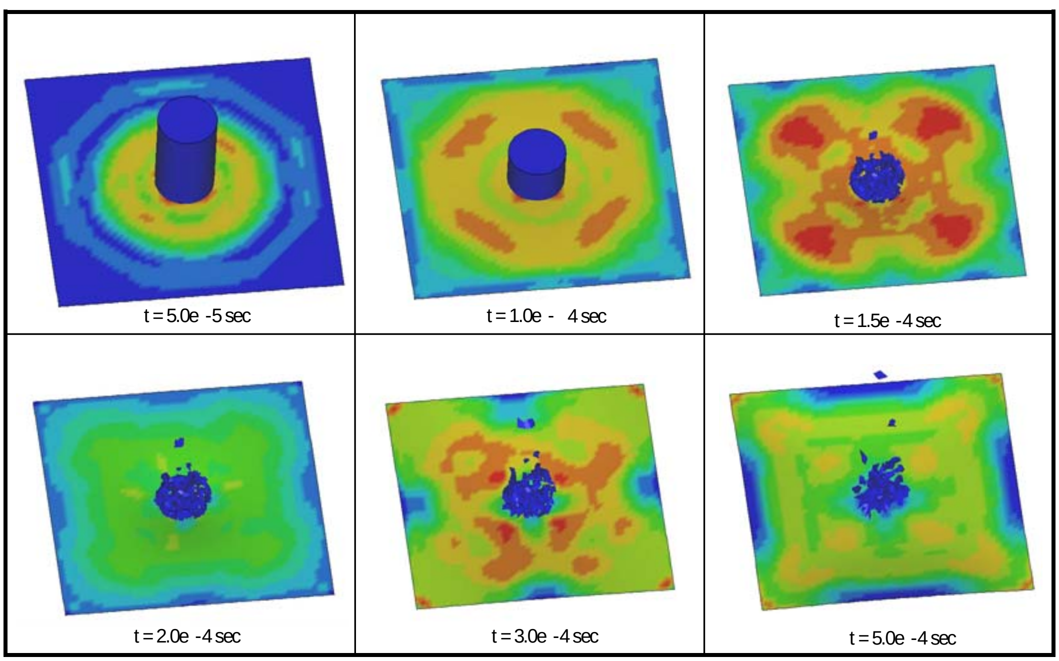

Figure 18. Colored contours of first-principal stresses at different time intervals for the A150-19 panel. The foam impact velocity is 23,736 in/sec.

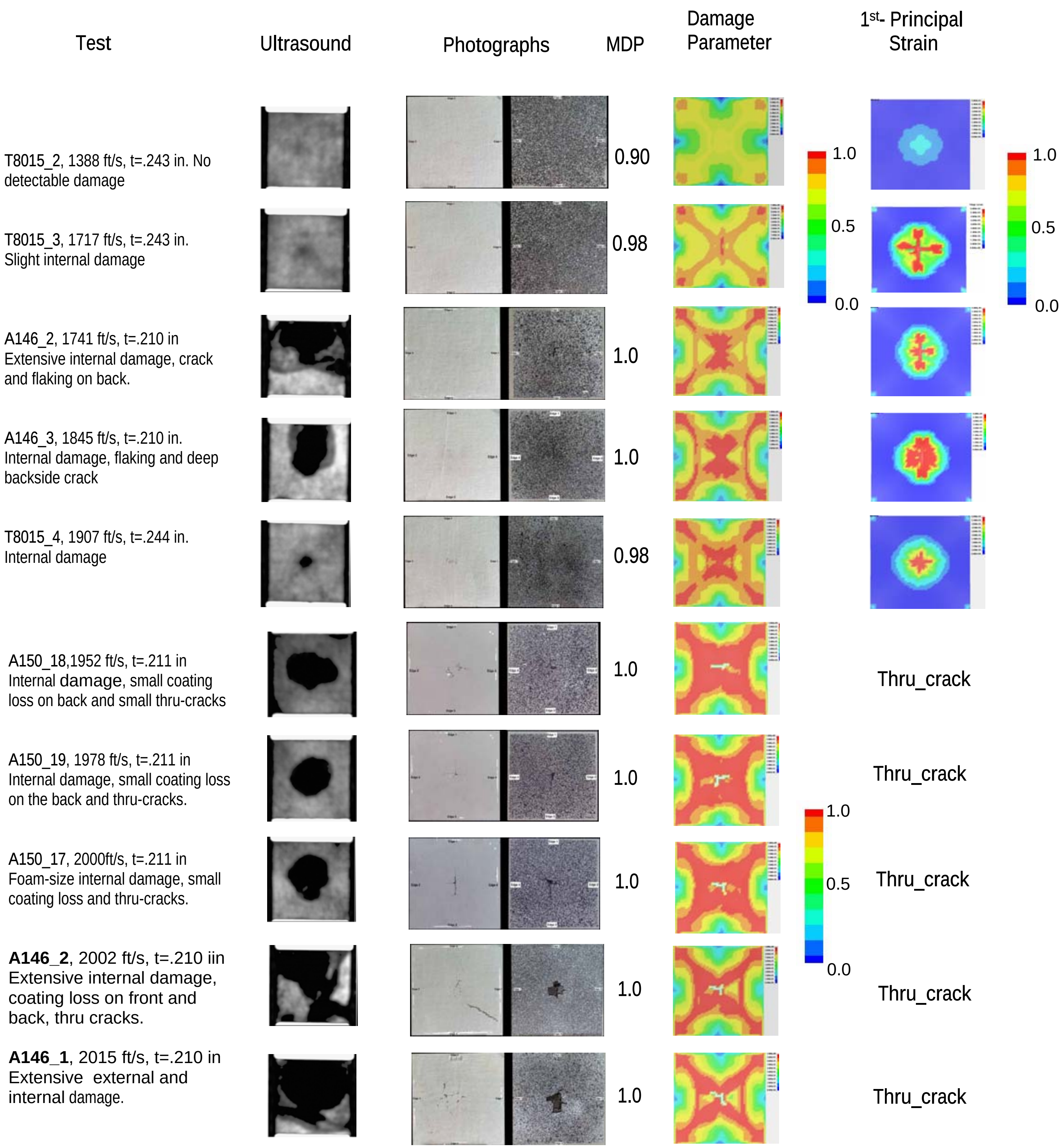

Figure 19. Post-impact test and computational qualitative results. MDP is the maximum damage parameter.

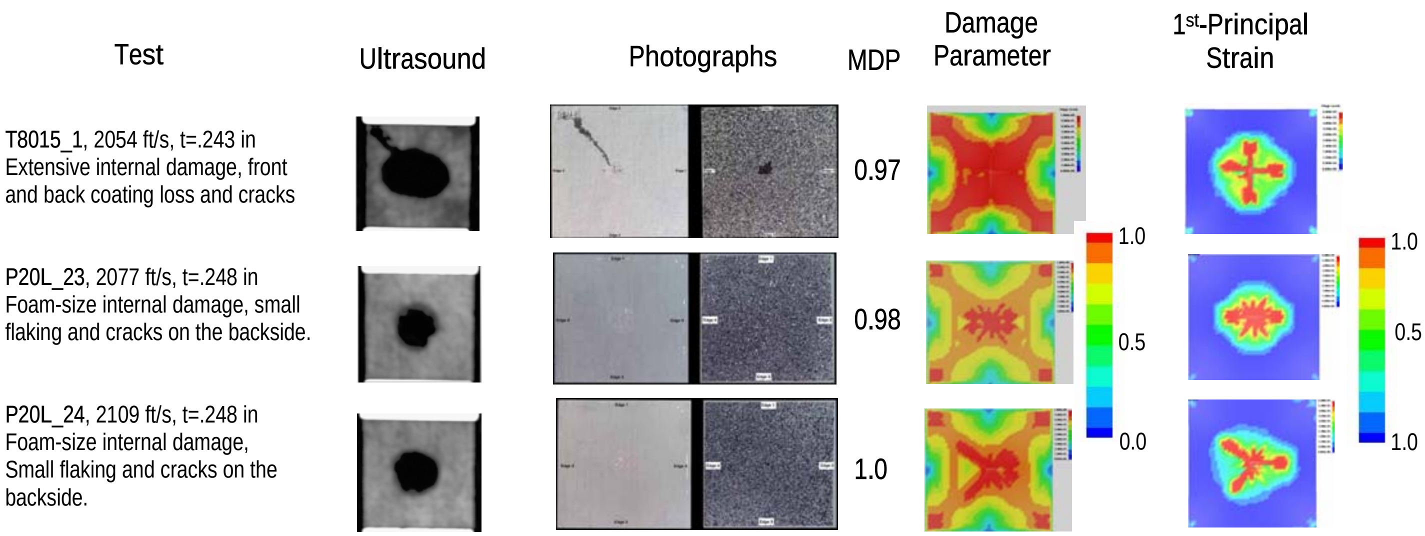

Figure 19. Continued

Conclusions

A flat panel study that included tests and LS-DYNA® analytical predictions for thirteen 6x6 inch RCC flat panels was performed to validate full scale Orbiter panel impact simulations. The RCC panels tested in this study were very challenging to simulate because of the inherent variability of the material due to its complex make-up and manufacturing process. The material model parameters were varied in an attempt to obtain better comparison with test data; however, no specific model improvements could be developed for the RCC due to material variability. A more realistic simulation would have required modification of the material model for each individual panel on a case-by-case basis. For each panel, this would require that the pre-test material properties be accurately quantified and the panel be certified as anomaly free before impact testing. In any case, the single MAT58 material model that was used appeared to provide a good representation of the impact response for the 6x6 inch panels. For the high velocity impacts that resulted in moderate damage to the flat RCC panels, it was shown that the computed deflection-time response compared well with the experimental response up to the time of significant damage, and the deflection-time history comparisons deviated as the damage became more substantial. The colored contour plots of the panel stresses show a symmetrical pressure footprint; however, there was some asymmetry seen as the plate was subjected to greater deformations. A criterion for failure based on the threshold of an analytical damage parameter was established. The observed damage correlated well with the maximum damage parameter generated by the MAT58 cumulative damage material model used in the LS-DYNA® code, and it was determined that a damage threshold parameter of approximately 0.92 or greater would have to exist to cause any NDE-detectable damage.

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14. ABSTRACT
This report presents the testing and analyses of a foam projectile impacting onto thirteen 6x6 inch flat panels at a 90° incidence angle. The panels tested in this investigation were fabricated of Reinforced-Carbon-Carbon material and were used to aid in the validation of an existing material model, MAT58. The computational analyses were performed using LS-DYNA®, which is a physics-based, nonlinear, transient, finite element code used for analyzing material responses subjected to high impact forces and other dynamic conditions. The test results were used to validate LS-DYNA® predictions and to determine the threshold of damage generated by the MAT58 cumulative damage material model. The threshold of damage parameter represents any external or internal visible RCC damage detectable by nondestructive evaluation techniques.

15. SUBJECT TERMS
Space shuttle; Damage parameter; Foam impact; Nondestructive test; Reinforced-Carbon-Carbon (RCC); Wing leading edge panels

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