An Investigation of the Impact Damage Threshold of Space Shuttle Leading Edge Wing Panels

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Charles Camarda, NASA astronaut

Columbia Accident Investigation Board, Report, Aug 2003

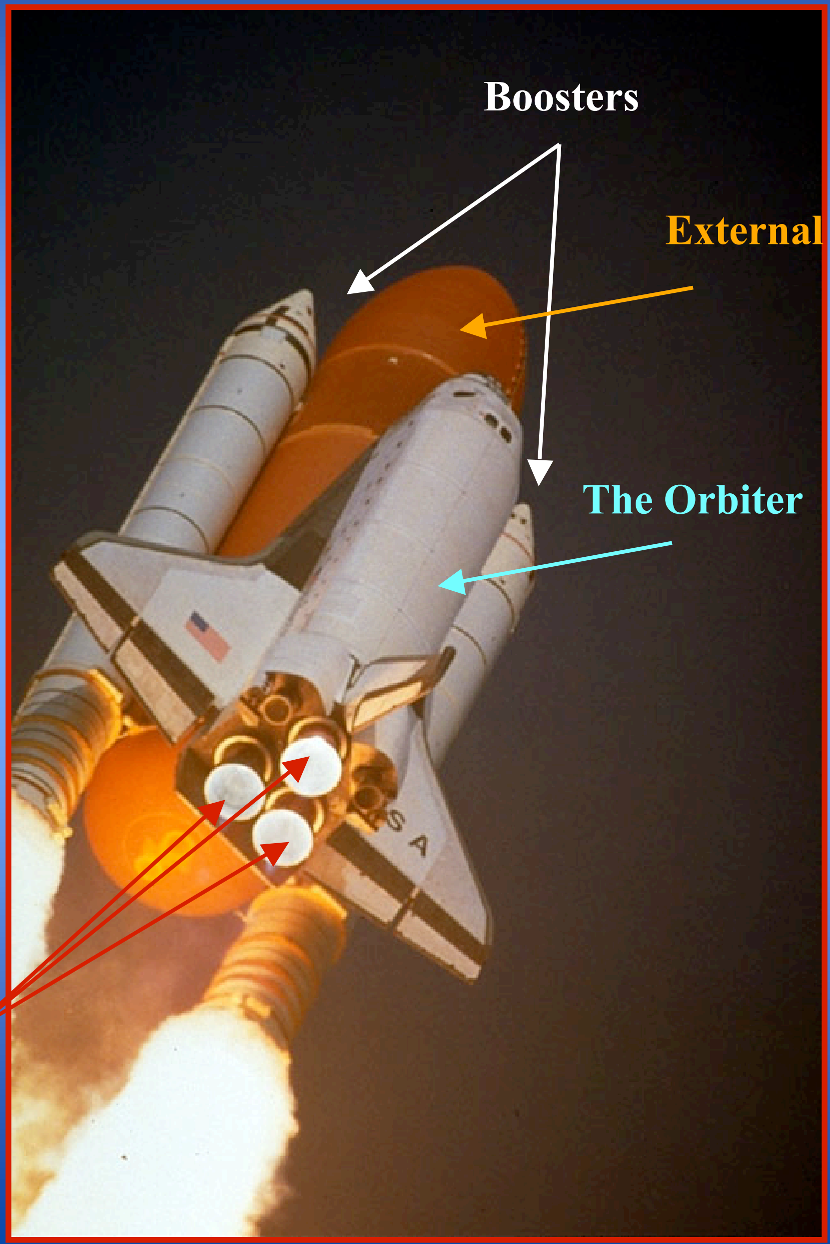
(special thanks to Matt Melis of NASA GRC for allowing use of his slides of the shuttle components and of the GRC Ballistic Lab tests)

Outline

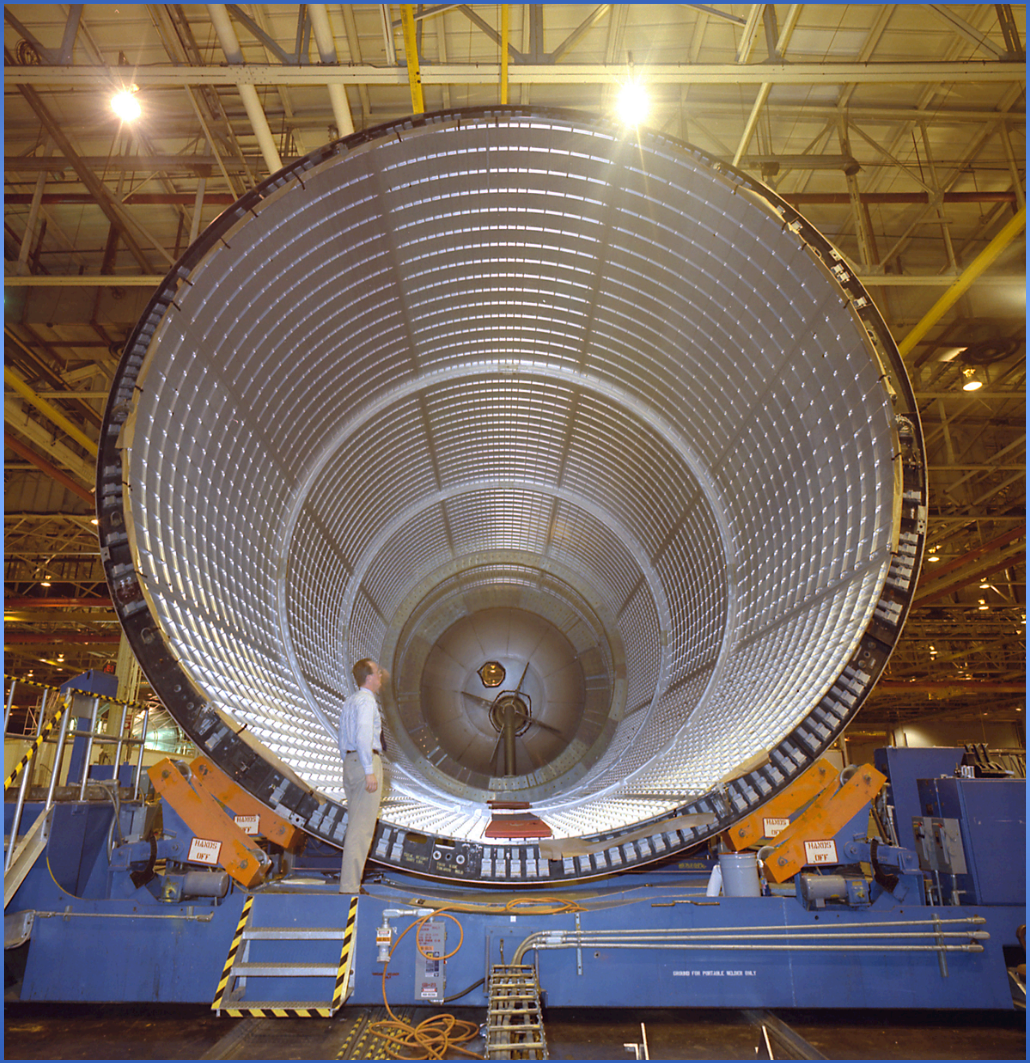
- Space Shuttle Launch System Overview
- Foam Impacts Columbia Wing During Launch
- Columbia Accident Investigation
- Test and Analysis Teams Created
- Leading Edge Reinforced Carbon-Carbon (RCC) Panels
- Reconstructing Columbia from the Debris
- Generating Foam Material Models for LS-DYNA
- Full-Scale Foam Impact Test of Foam onto RCC Panels
- Full-Scale Impact Analysis with LS-DYNA
- Test/Analysis Correlation
- Parametric Studies
- Return-to-Flight Production Runs
- Concluding Remarks


BROWN
CLARK
CHAWLA
ANDERSON
RAMON
HUSBAND
MCCOOL
STS 107

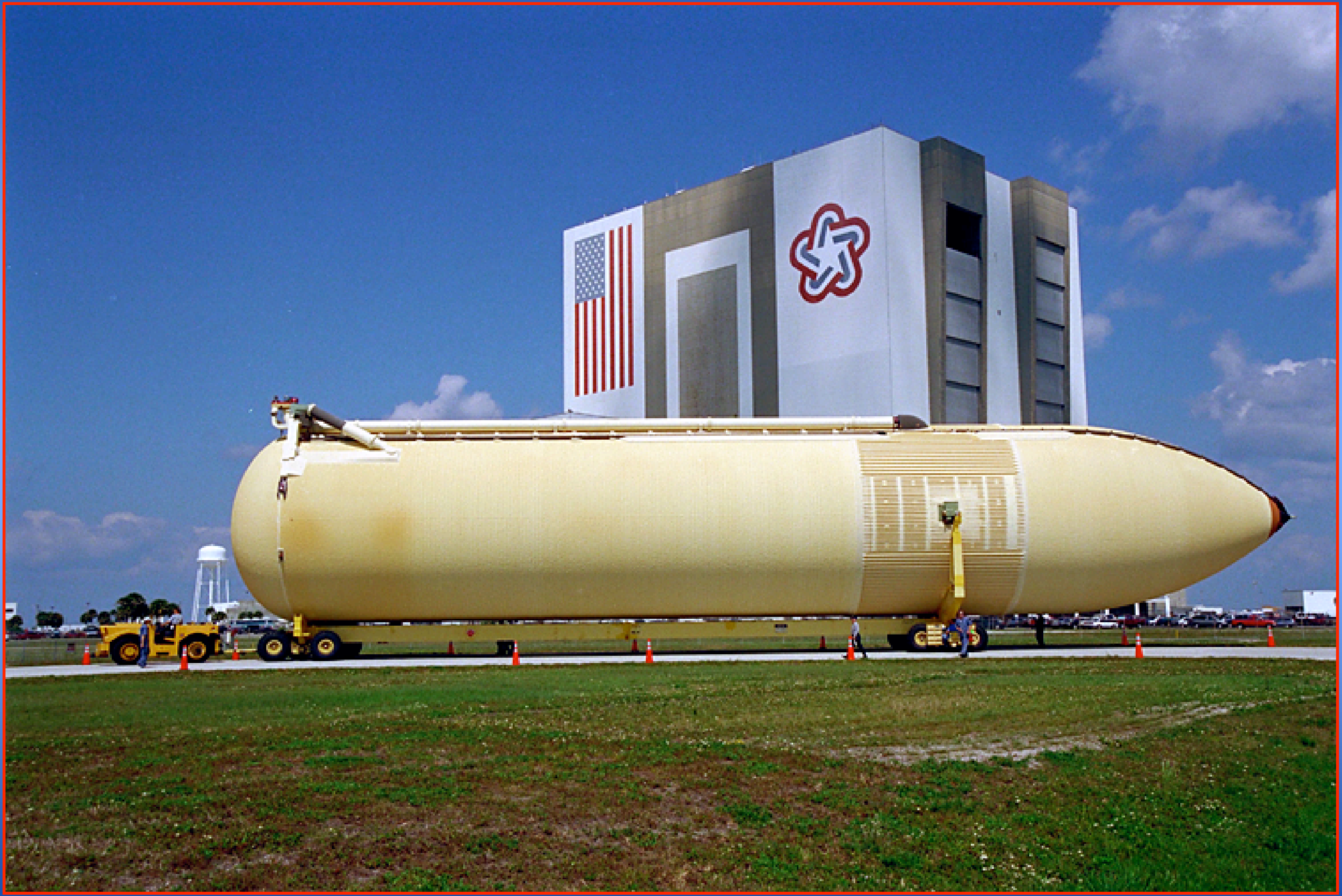
A Brief Overview of the Shuttle Launch System



The External Tank is manufactured at NASA's Michoud Assembly Facility in New Orleans LA by Lockheed Martin Corporation



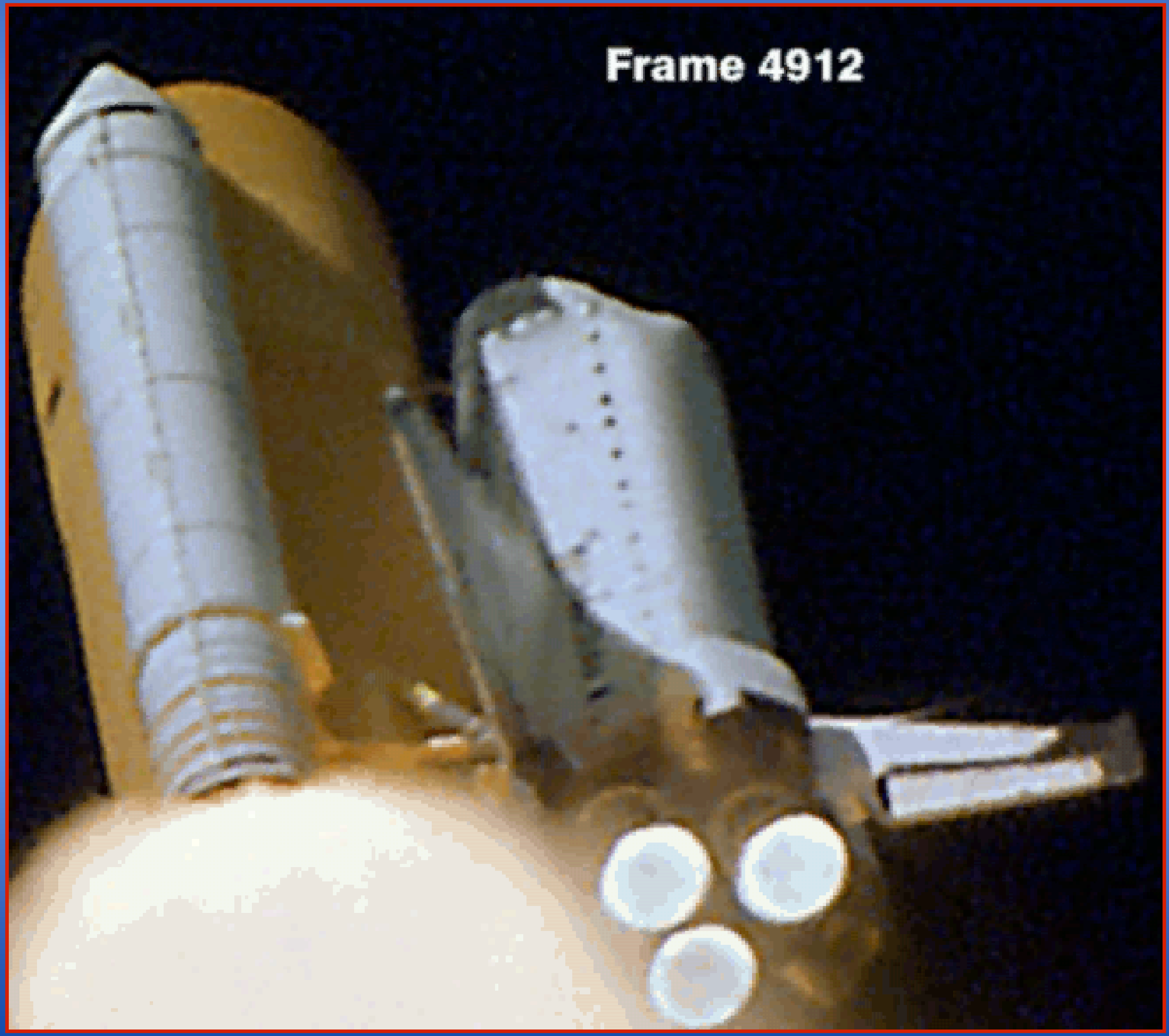
External Tank on its way to the VAB

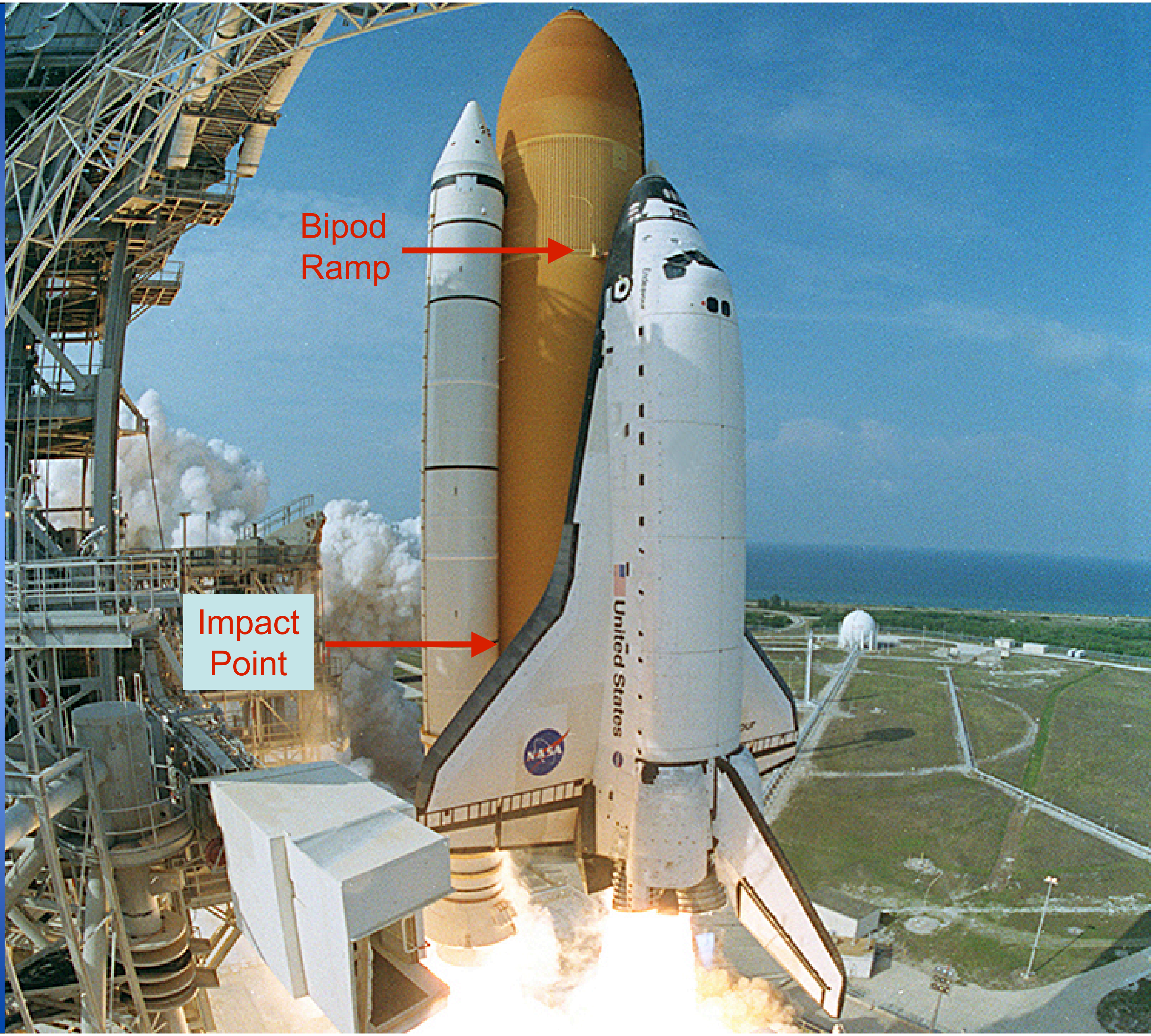


On January 16 2003, Columbia’s leading edge was impacted by a piece of foam suspected to have separated from the external tank bipod ramp at 81 seconds into its launch.

Columbia was traveling at Mach 2.46, at an altitude of 65,860 feet. The foam was calculated to have hit the orbiter at 700 – 800 feet per second (over 500 mph).

Insulating Foam Separates from Bipod Ramp and Impacts Left Wing of Columbia




Bipod
Ramp
Impact
Point
United States
NASA

The Bipod Ramp

The Analysis Team

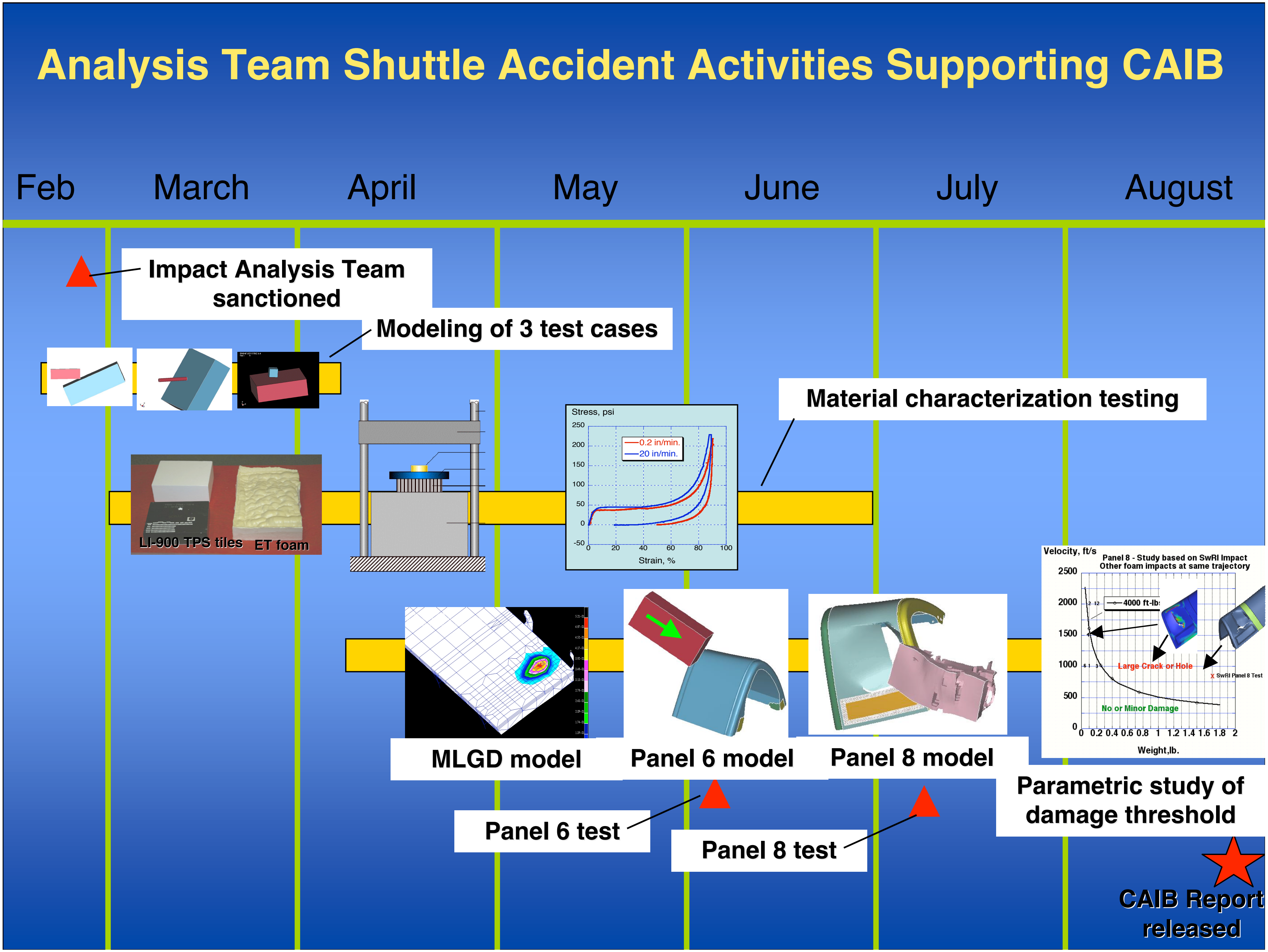
Shortly after the Columbia accident on February 1, 2003, a team was assembled to use dynamic finite element codes, often called physics-based codes to separate them from semi-empirical codes, to simulate foam impact onto TPS tile and the RCC wing leading edge. Astronaut Dr. Charles Camarda, a former LaRC structures Branch Head was an advocate for the formation of this team.

The original team was composed of impact modeling specialists from three NASA centers, industry, a DOE government lab, and academia.
In less than three months, the team had developed models to simulate foam impacts onto TPS tile and the RCC wing leading edge.

The LS-DYNA analysis team was reduced to three primary players in June 2004: Boeing, GRC, and LaRC. That team continues to improve the models to determine the threshold of damage for various external tank or solid rocket booster debris that might impact orbiter TPS.

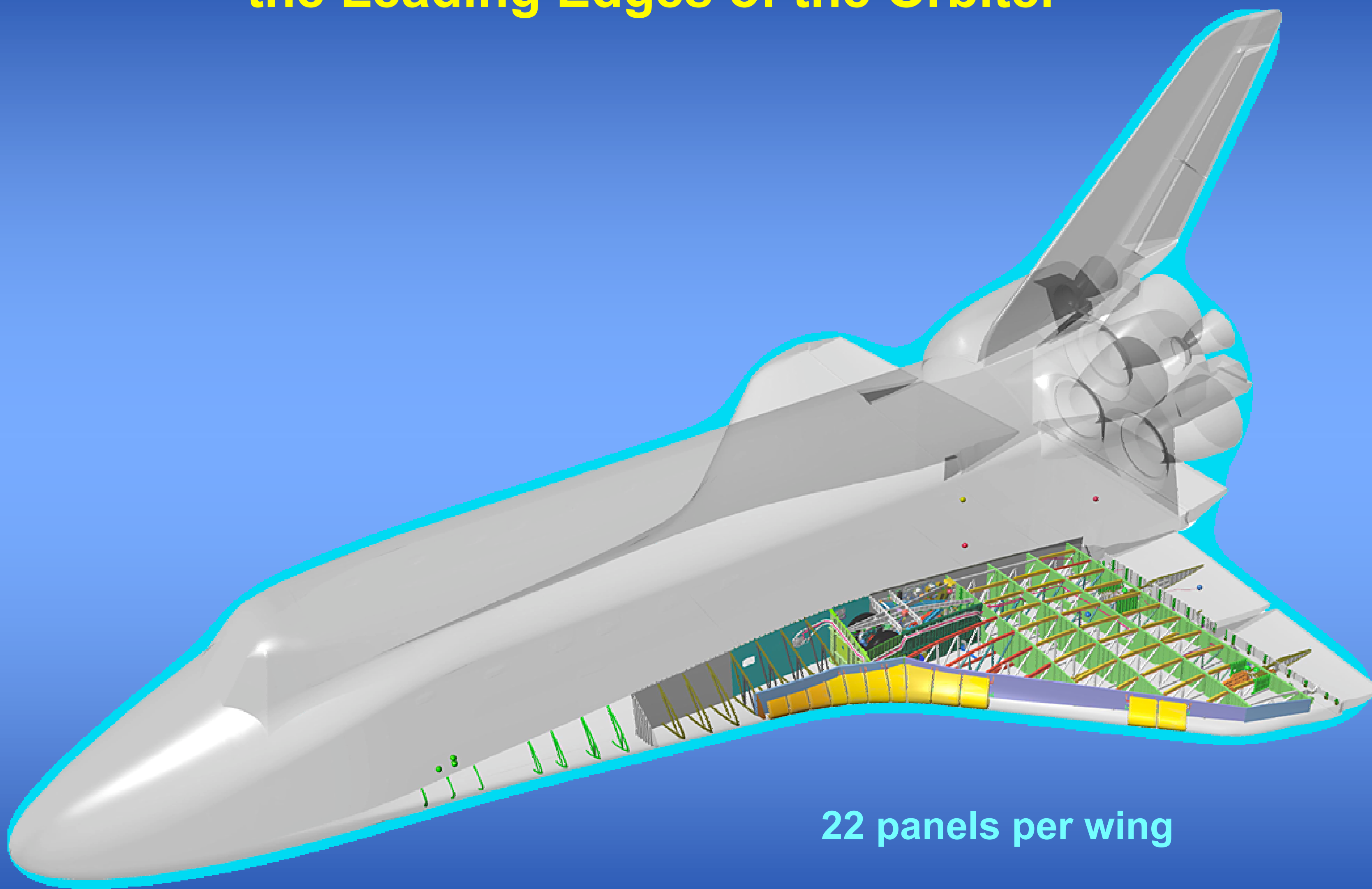
Original Team Members Using Physics-based Codes to Simulate the Foam Impact onto shuttle Thermal Protection System (TPS) During the Columbia Accident Investigation

Analysis Team Members at the Orbiter Processing Facility at KSC in April 2003. Shuttle in background.


Analysis Team Shuttle Accident Activities Supporting CAIB
Feb
March
April
May
June
July
August
Impact Analysis Team sanctioned
Modeling of 3 test cases
Material characterization testing
LI-900 TPS tiles
ET foam
Stress, psi
0.2 in/min.
20 in/min.
Strain, %
Velocity, ft/s
Panel 8 - Study based on SwRI Impact
Other foam impacts at same trajectory
Large Crack or Hole
No or Minor Damage
SwRI Panel 8 Test
Weight,lb.
MLGD model
Panel 6 model
Panel 8 model
Parametric study of damage threshold
Panel 6 test
Panel 8 test
CAIB Report released

The Orbiter Leading Edges

Reinforced Carbon-Carbon (RCC) Panels Protect the Leading Edges of the Orbiter



Leading Edge Panel Used for Full Scale Tests With Photogrammetry Targets

(Matt Melis of GRC)

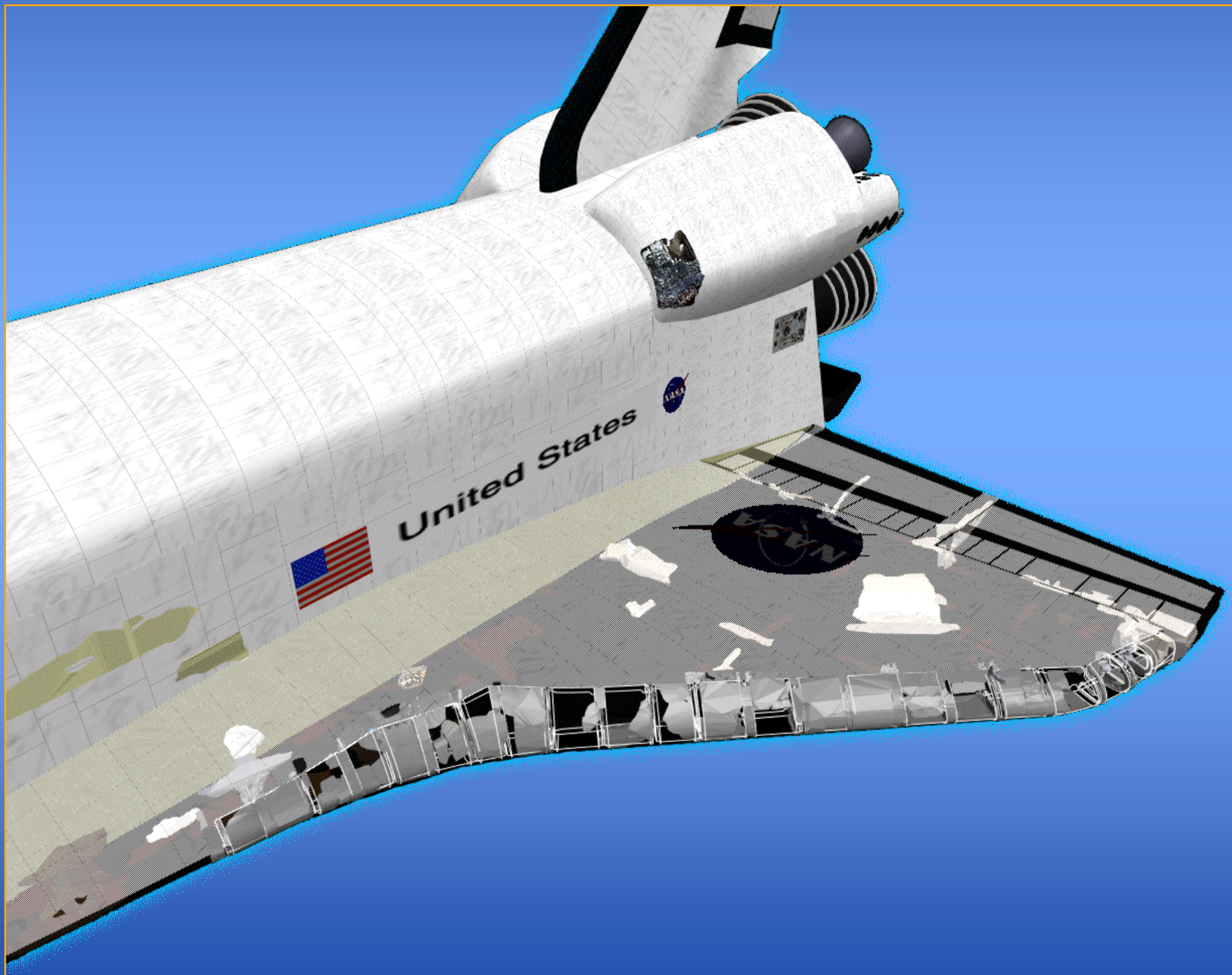
The Reconstruction Effort

The Debris Hanger at KSC

The Debris Hanger

Reconstructing the Left Wing Leading Edges

Reconstructing the Left Wing Leading Edges



Impact Research Efforts During the Accident Investigation

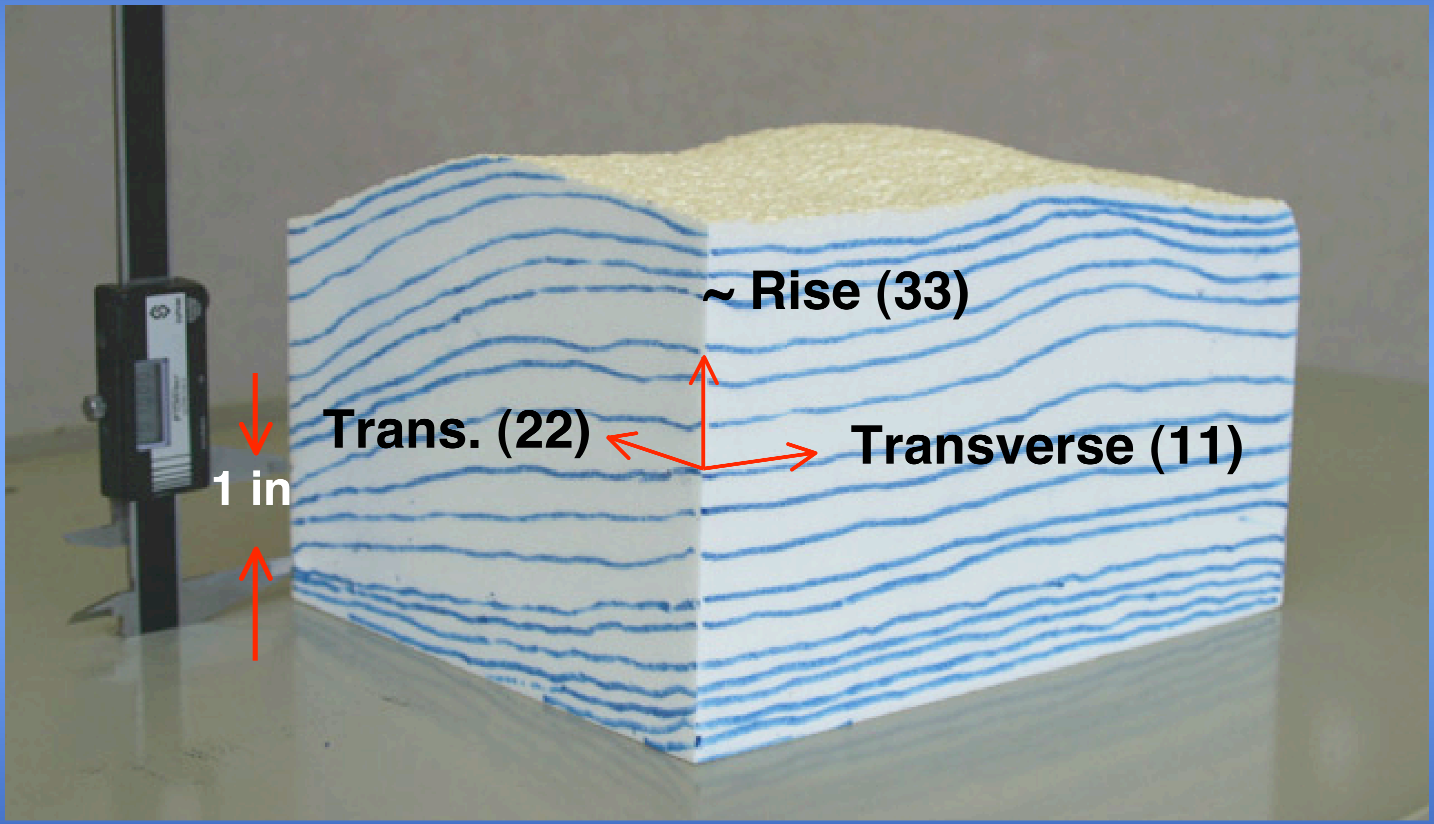
- Impact testing to characterize External Tank foam and reinforced carbon-carbon leading edge material
- Develop impact analysis capability to predict such impact events
- Support Full Scale Impact Test in San Antonio Texas by developing pre-test models and by instrumentation and camera support

Dynamic Material Characterization

LS-DYNA Requires Detailed Material Characterization

- Physics-based modeling requires physics-based inputs.
- Material model requires complete dynamic stress-strain behavior & damage mechanisms, including strain-rate effects.
- Materials characterization efforts have concentrated on foam, ablators, and RCC. In particular, dynamic material testing is being performed at high velocity to capture dynamic (strain-rate) behavior at impact. Both ballistic (Glenn) and specialized drop tower tests (Langley) are being performed.
- There are few applicable standards for dynamic rate testing of complex materials. Even “simple” crush tests may have hidden inaccuracies due to boundary conditions and unknown experimental errors.

Sprayed ET Foam with “Knit” Planes Outlined in Blue

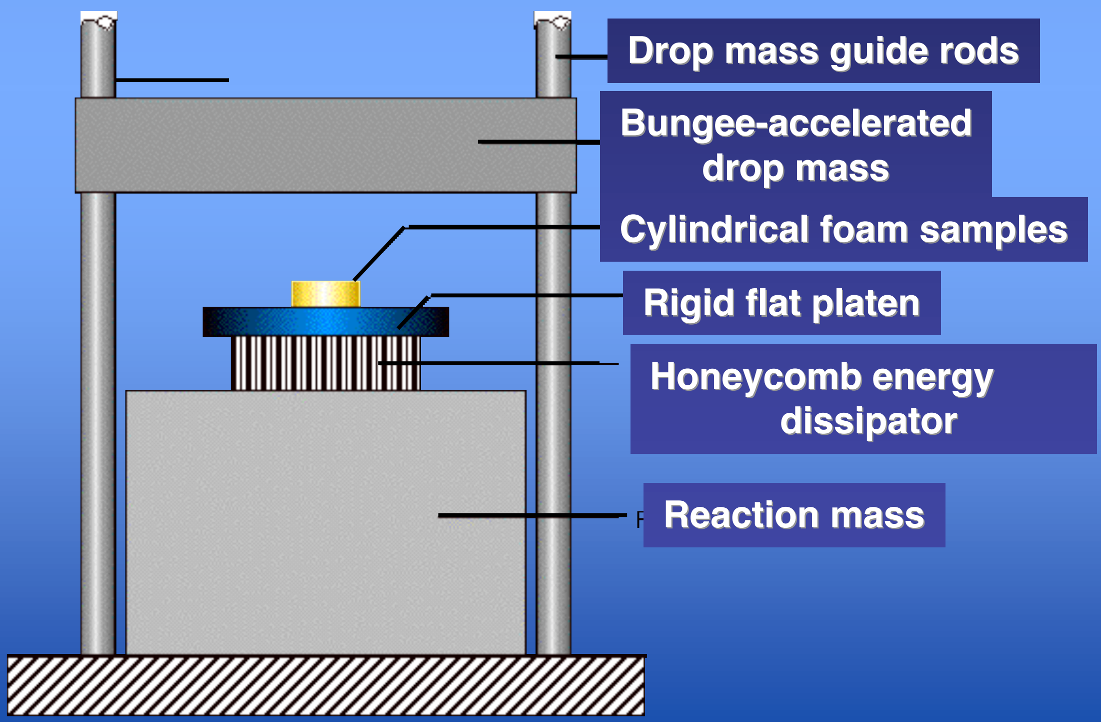


Block of External Tank Foam from which test specimens can be cut along different directions

Dynamic material characterization at high strain rates

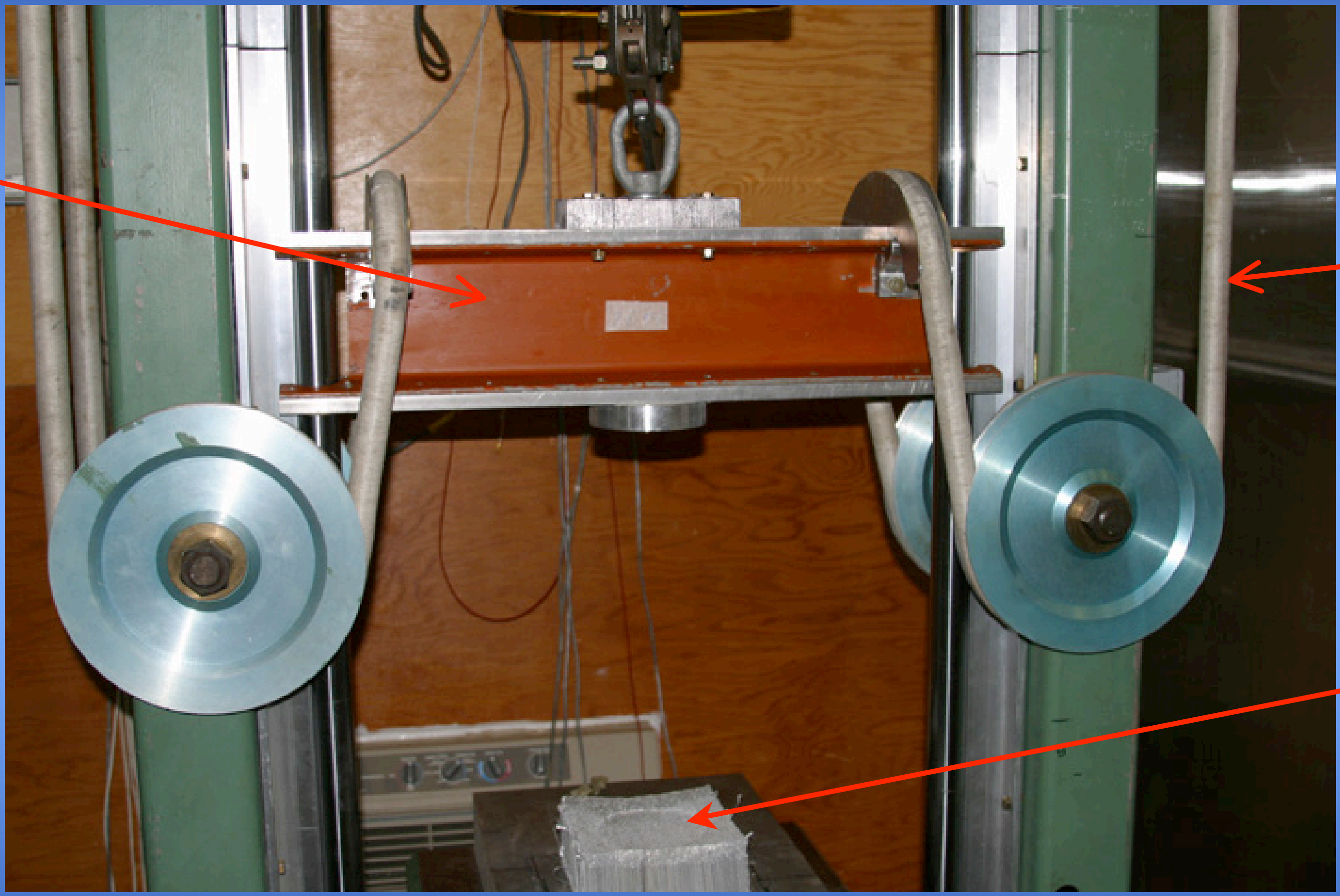
- Debris characterization tests were performed at LaRC using a bungee-assisted drop tower
- Velocities up to 70 mph were achieved with the drop tower

Schematic of LaRC drop tower test set-up



Bungee Assisted Drop Tower

Drop Head

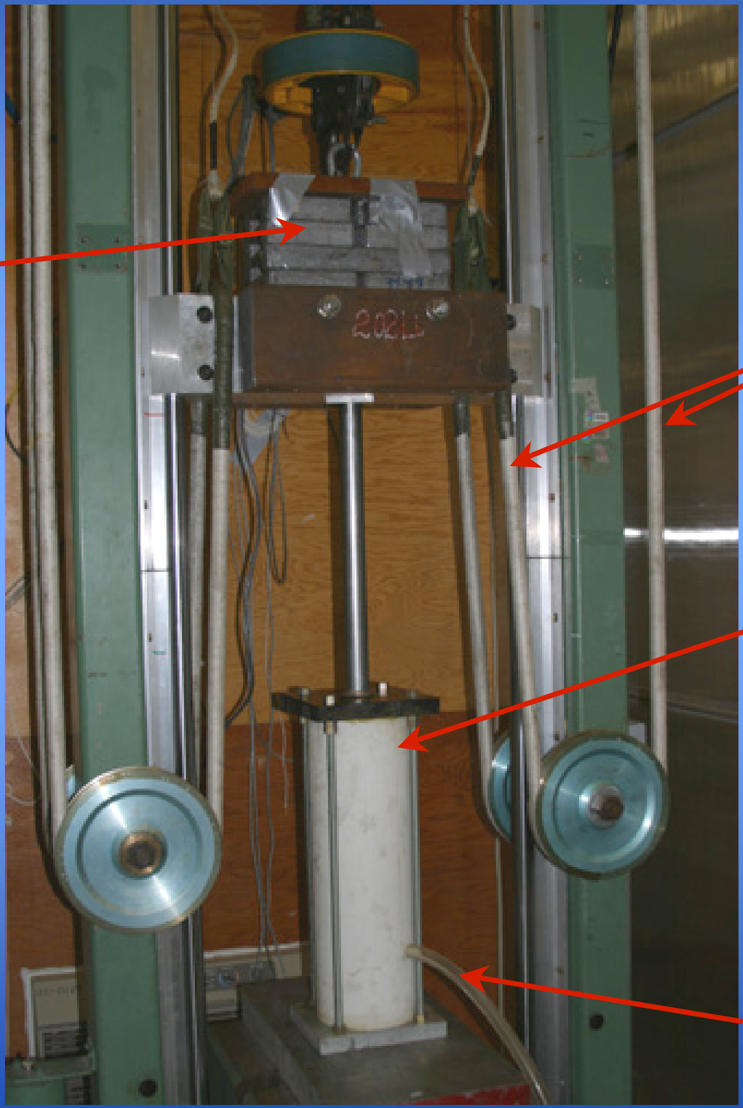


Bungee

Honeycomb

Multiple drop heads & auxiliary equipment are available for specific setups
Impact velocities up to 70 mph, quasi-constant strain-rates up to 500/s.

Bungee-assisted Drop Tower Modified for High Strain-rate Testing in Vacuum



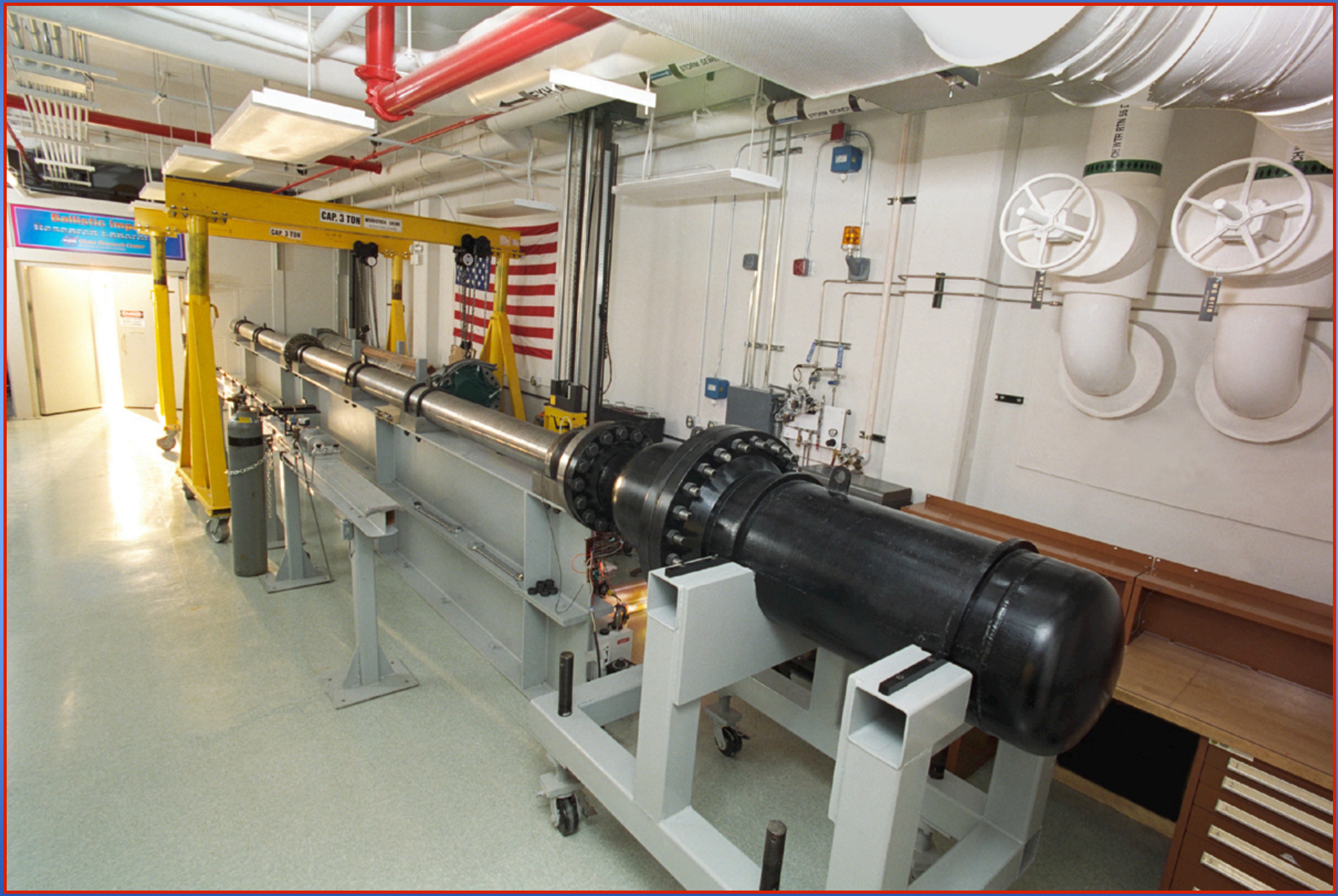
Added drop mass

Bungee cords

Vacuum chamber with plunger and foam specimen

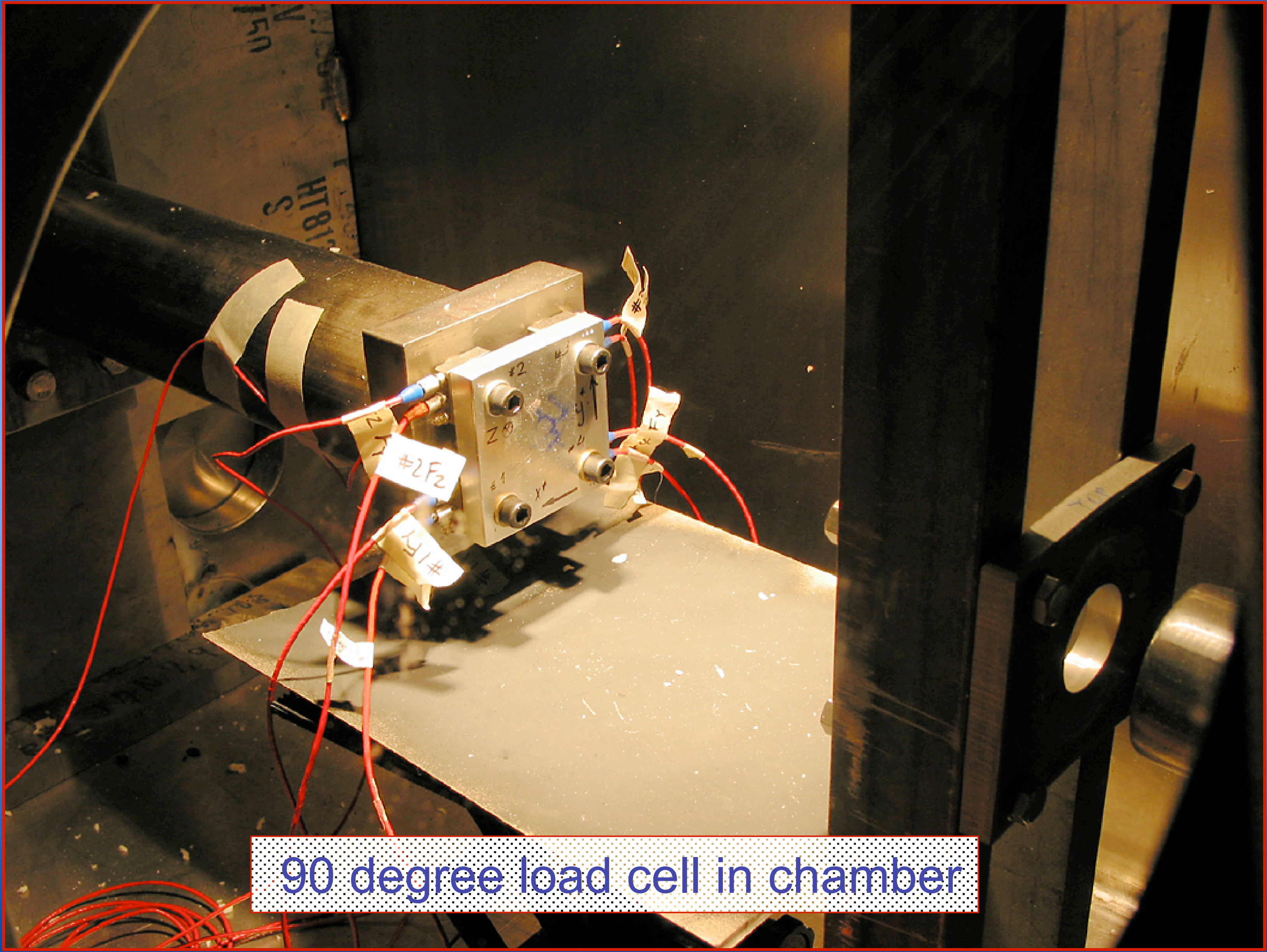
Vacuum hose

The NASA Glenn Ballistic Impact Lab Assisted in the Columbia Accident Investigation



Ballistic Research Supporting the Accident Investigation

BX-250 External Tank Foam Characterization at Glenn Research Center



90 degree load cell in chamber

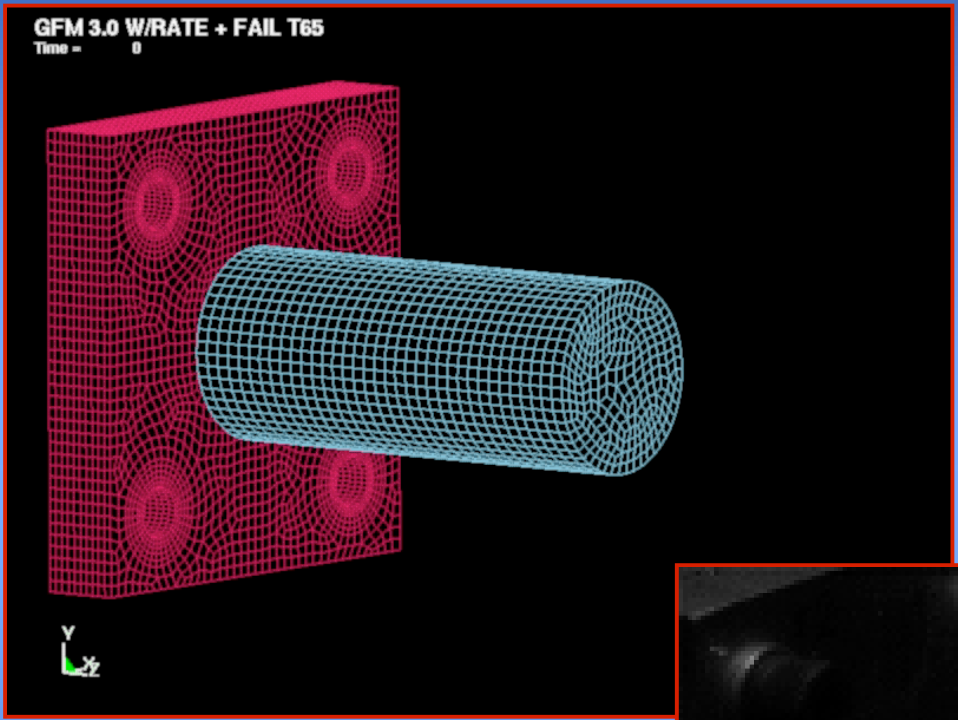
Ballistic Research Supporting the Accident Investigation

BX-250 External Tank Foam Characterization

Sabot Stopped before exiting barrel to contain gun pressure

Ballistic Research Supporting the Accident Investigation

LS-DYNA - explicit finite element impact analysis



LS-DYNA Predicts 90 Degree

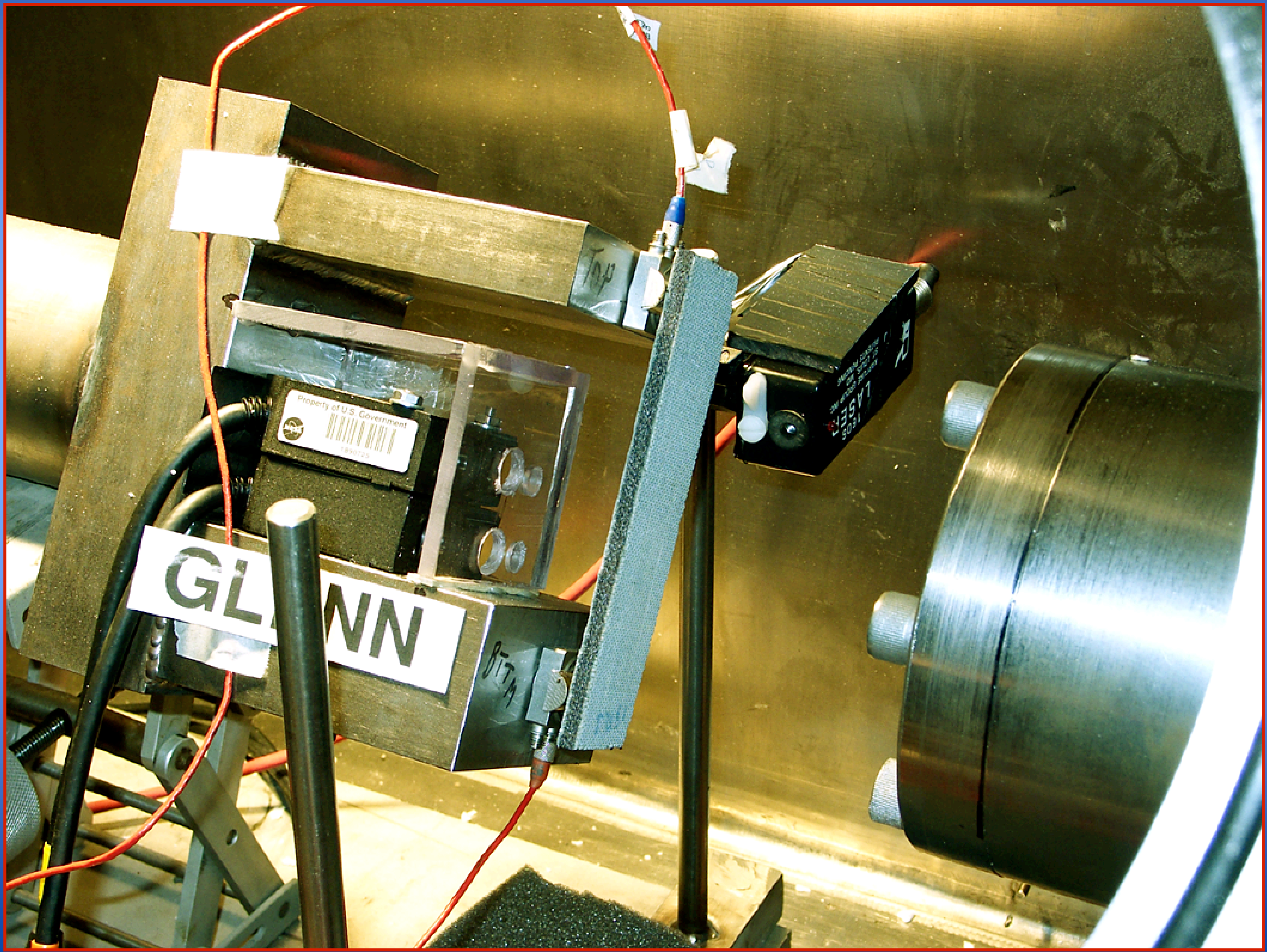
Foam Impact on Load Cell

Actual ballistic impact
Of foam projectile 1.25-in
By 3-in. long conducted at
Glenn Research Denter

Reinforced Carbon-Carbon Characterization

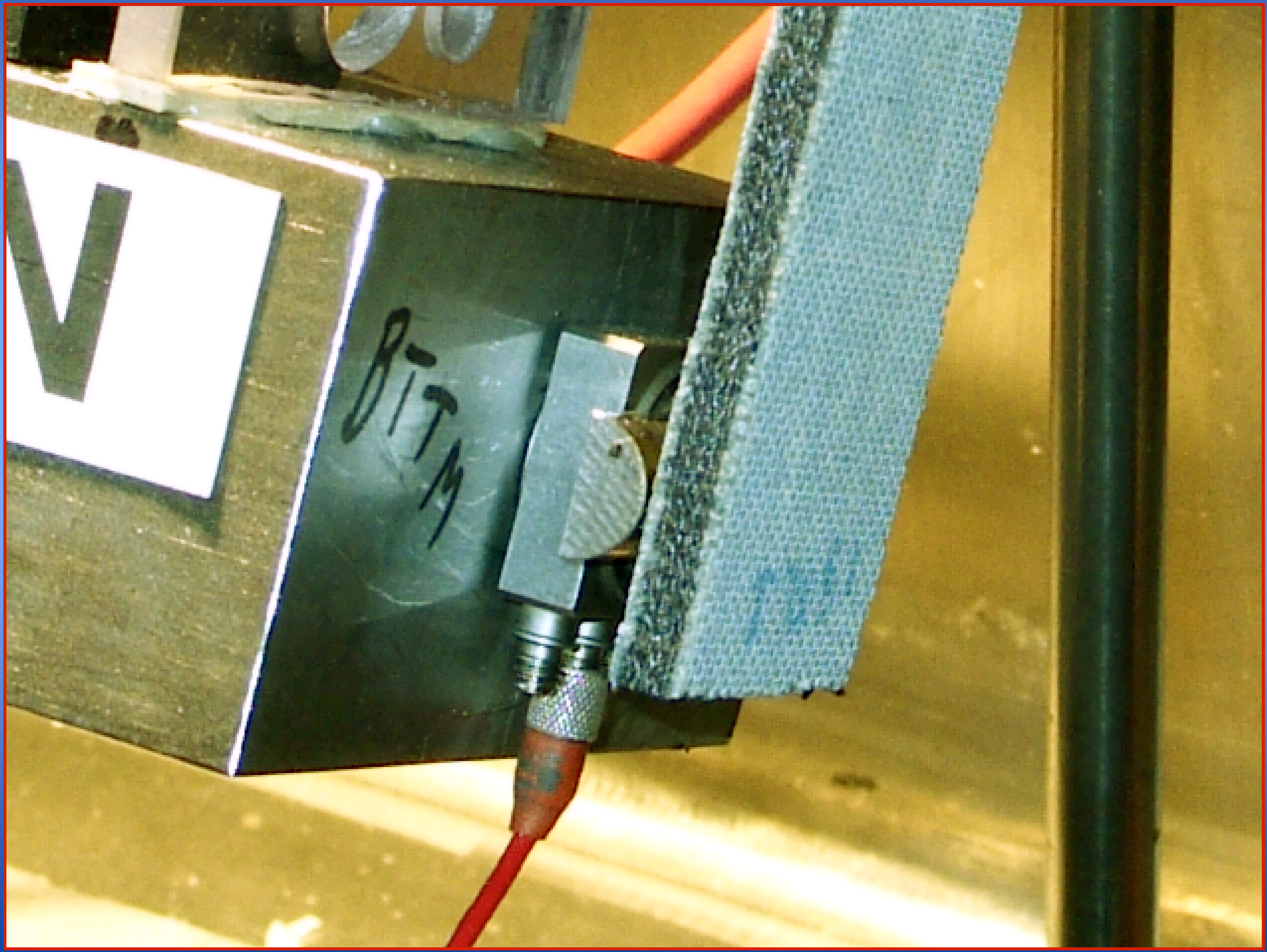
Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



Ballistic Research Supporting the Accident Investigation

Ballistic Impact Tests on RCC Coupons



Full-Scale Impact Tests Conducted in 2003

During the Columbia Accident Investigation

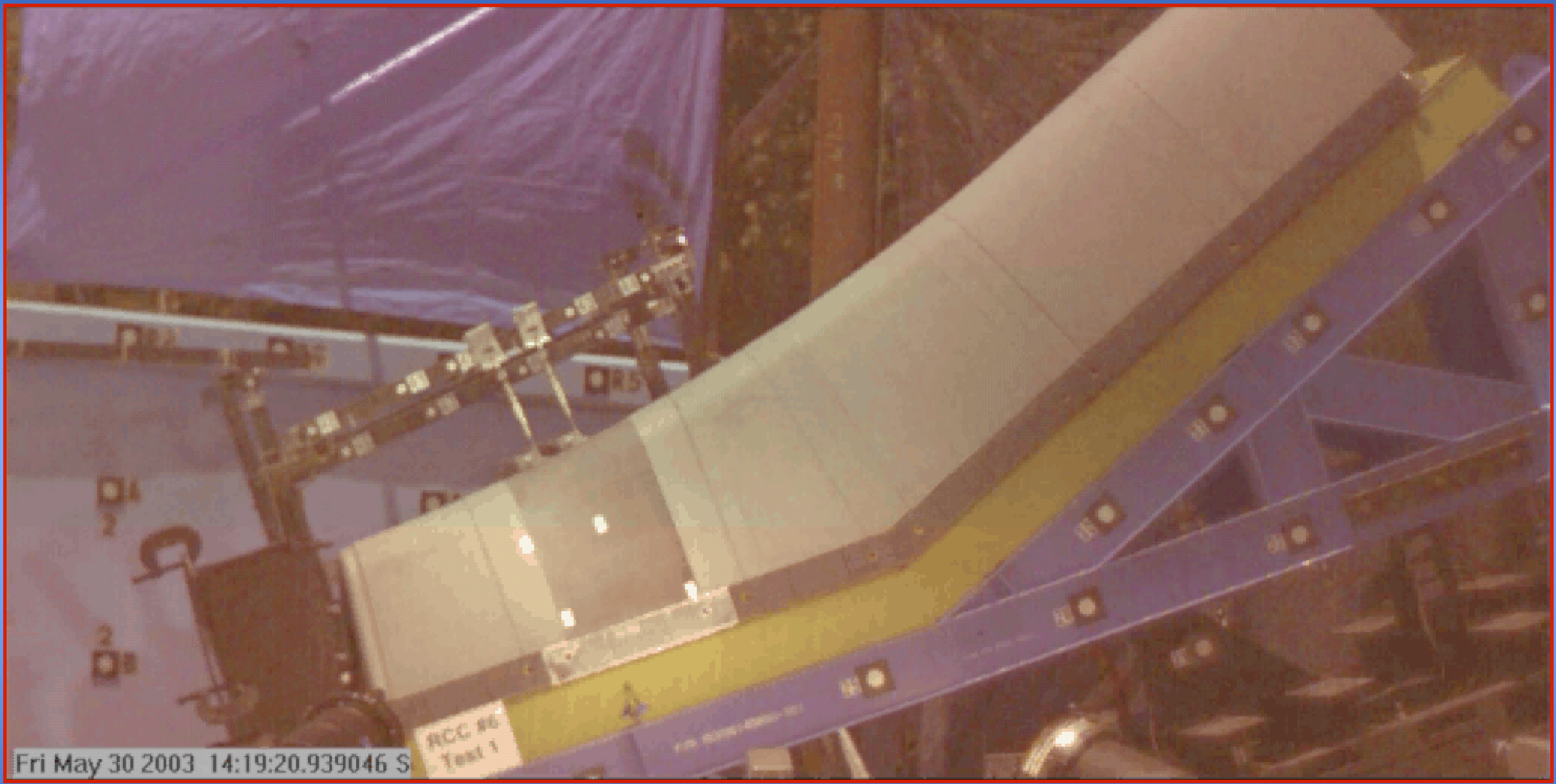
Orbiter Leading Edge Full Scale Tests

Tests conducted at Southwest Research Institute, San Antonio, TX

Orbiter Technicians Install T-Seal

Orbiter Leading Edge Full Scale Tests

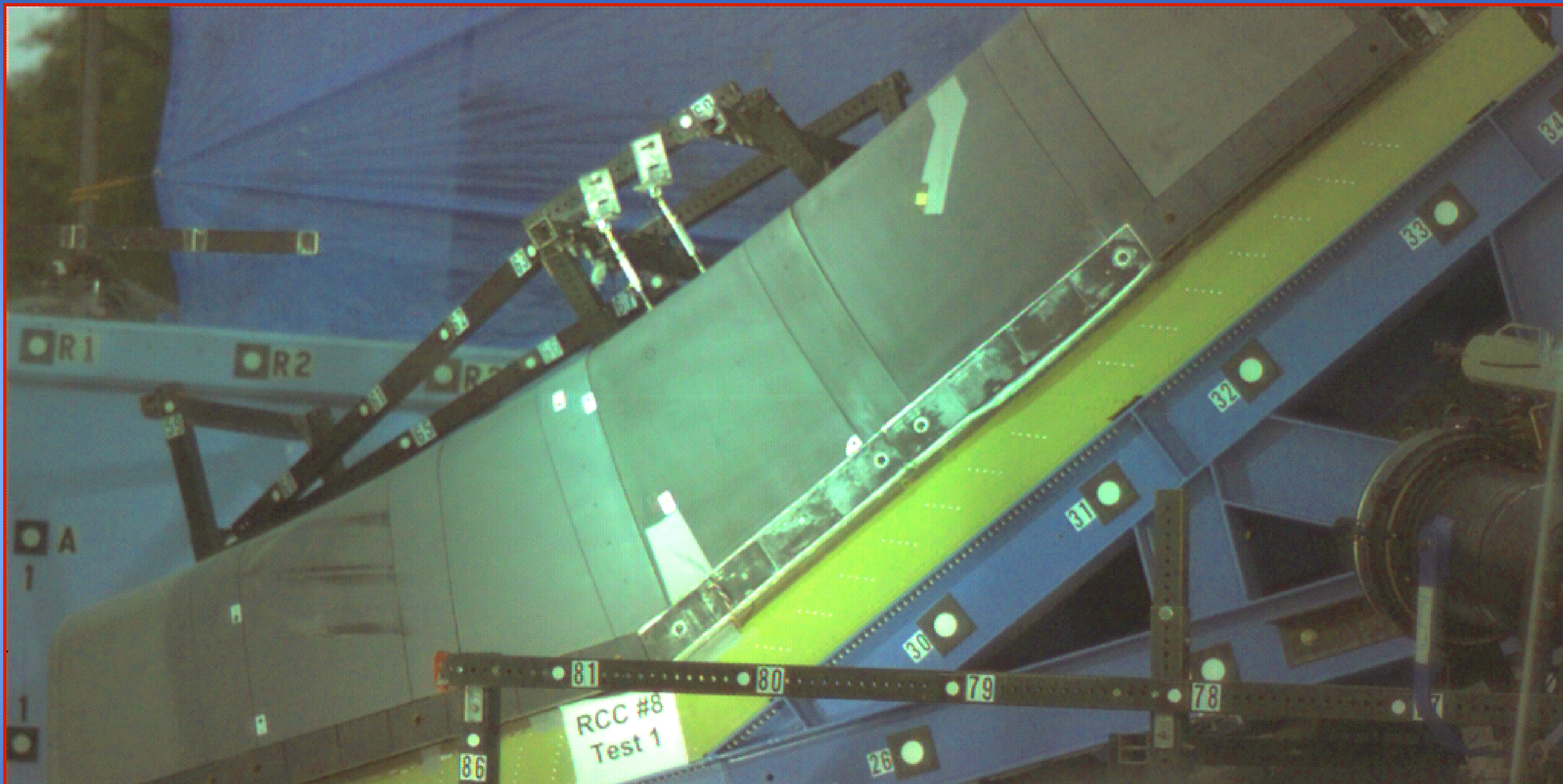
Incidence angle 22 degrees



External View of RCC Panel 6 Test (June 2003)

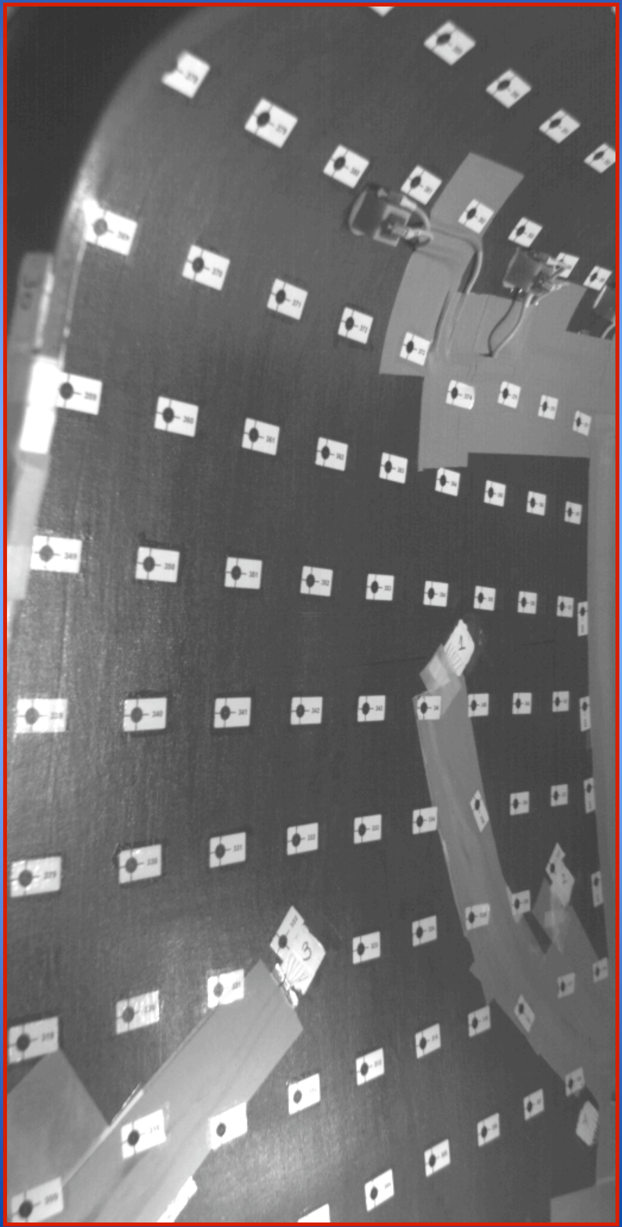
Orbiter Leading Edge Full Scale Tests

Incident angle 25.1 degrees, full edge impact



External View of RCC Panel 8 Test (July 2004)

Orbiter Leading Edge Full Scale Tests



Internal View of

RCC Panel 8 Test

Orbiter Leading Edge Full Scale Tests

Post Impact of Panel 8

Full Scale Impact Analysis with LS-DYNA

LS-DYNA Panel 8 Model

PARTS

25 including:

main panel, ribs, spars, doublers, rigid bolt hole fillers,

PANEL 8 (RCC)

59,360 shell elements

Mat58 (Mat Laminated Composite Fabric) with cumulative damage material model

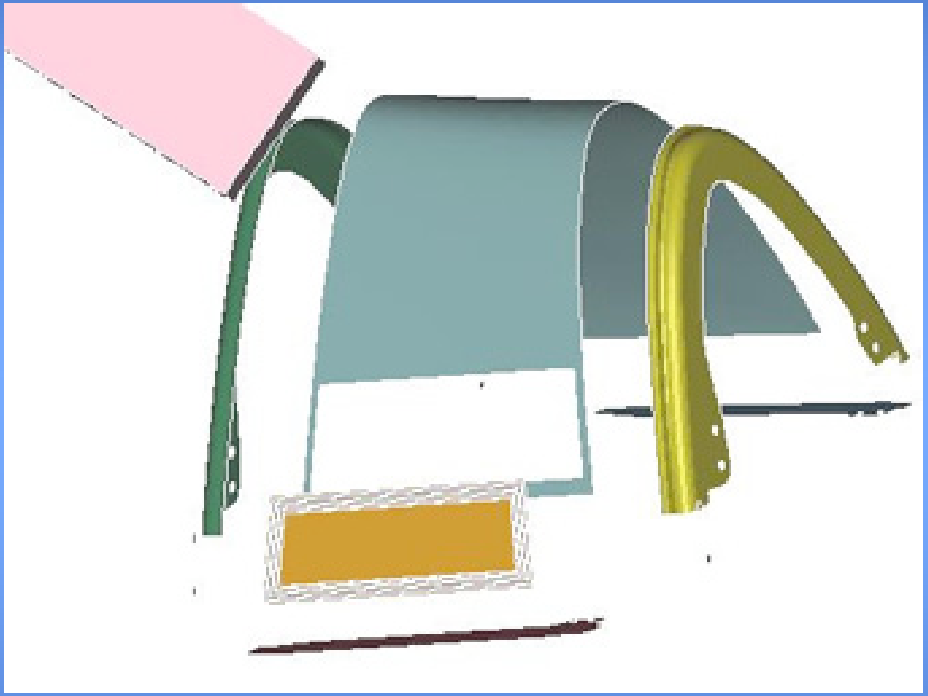
Minimum of 19-plies

Nominal edge length of 0.2 inch

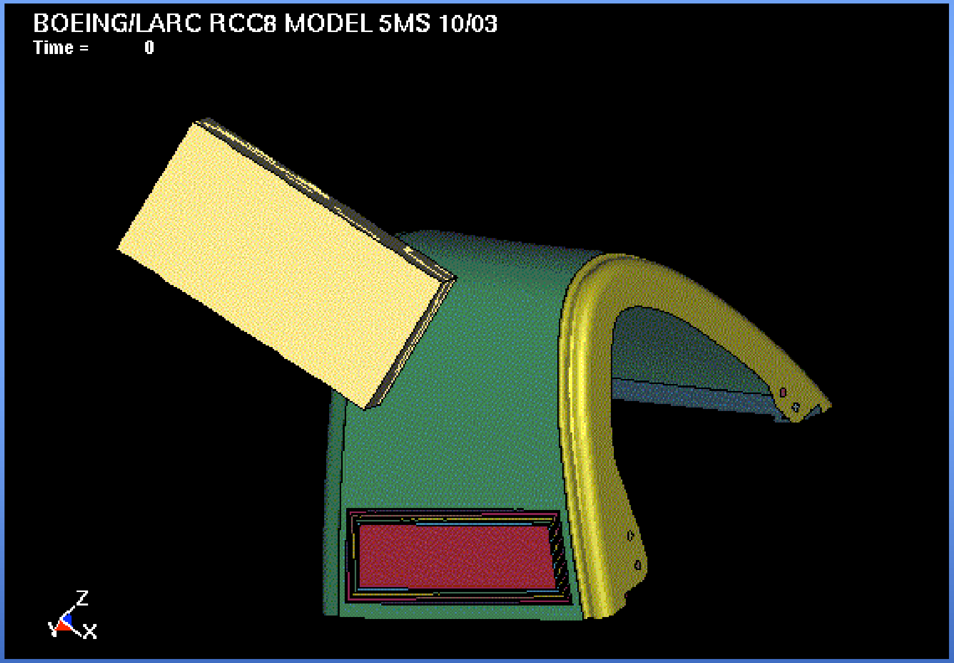
FOAM

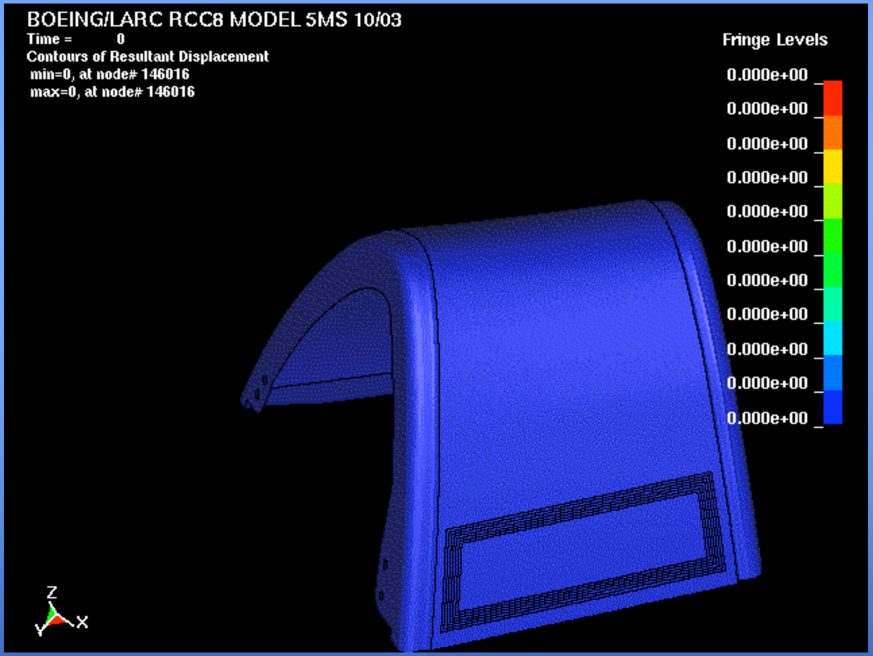
11,636 solid elements

Fu-Change foam material model with strain-rate effects included

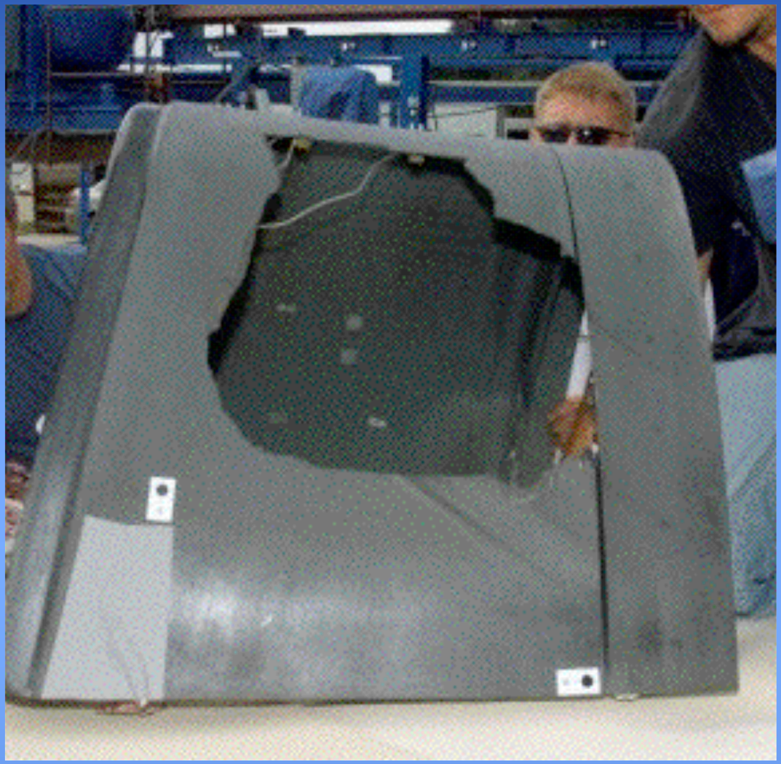


Full Scale Impact Analysis of Panel 8 Test with LS-DYNA

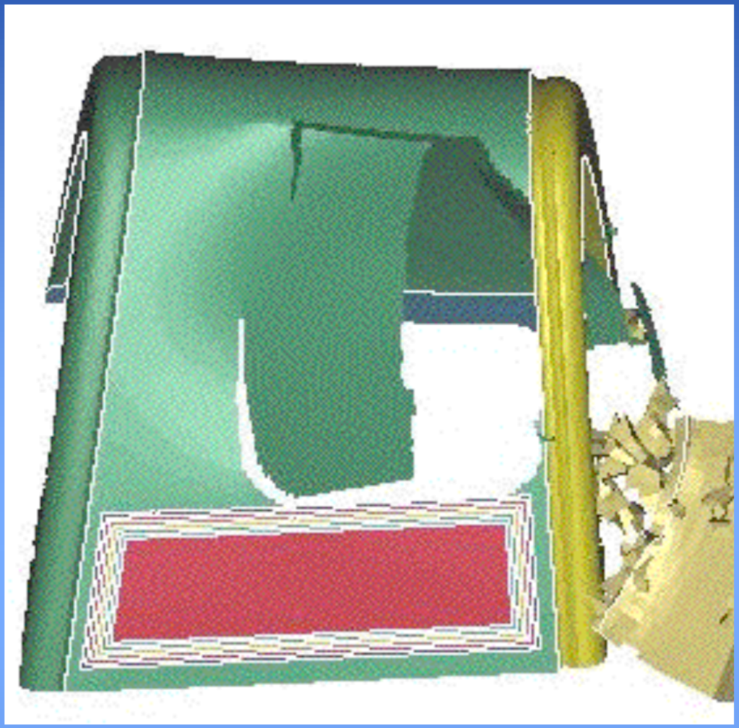




LS-DYNA Panel 8 Qualitative Correlation

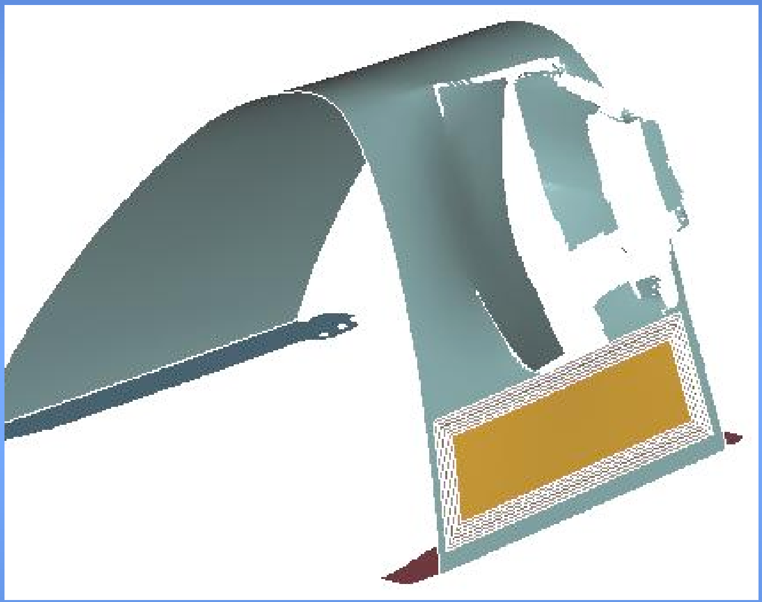


Panel 8 - showing gaping hole after SwRI impact test conducted on July 7, 2003.



LaRC LS-DYNA simulation. The RCC material model (Mat58) used a cumulative damage model

Major RCC Fragments from the Panel 8 Foam Impact



Panel 8 panel without ribs showing fragments created by foam impact.

Major fragments created by foam impact. The ruler at the right is 12 inches long.

RTF Program Objectives

- Determine the threshold of impact damage to shuttle wing leading edge RCC panels for foam, ablators, ice, and other debris.

  - Characterize foam and other debris materials by dynamic testing at high velocity for input into the LS-DYNA computer models.

  - Test-analysis correlation to be applied to a battery of impact tests Validate finite element models through test-analysis correlations. from small flat panels to full-scale shuttle wing leading edge panels.

  - Complete LS-DYNA production runs for multiple debris impacts to establish damage thresholds for representative RCC panels.

Efforts Supporting the Return to Flight

- Impact testing to characterize additional materials that may shed during ascent such as solid rocket booster ablators.
- Additional impact testing of RCC panels to validate models
- Impact analysis of each material threat to Orbiter leading edges
- Impact testing to assess threats to External Tank foam insulation
- Parametric studies using LS-DYNA of impacts in preparation for production runs

Test-Analysis Correlation

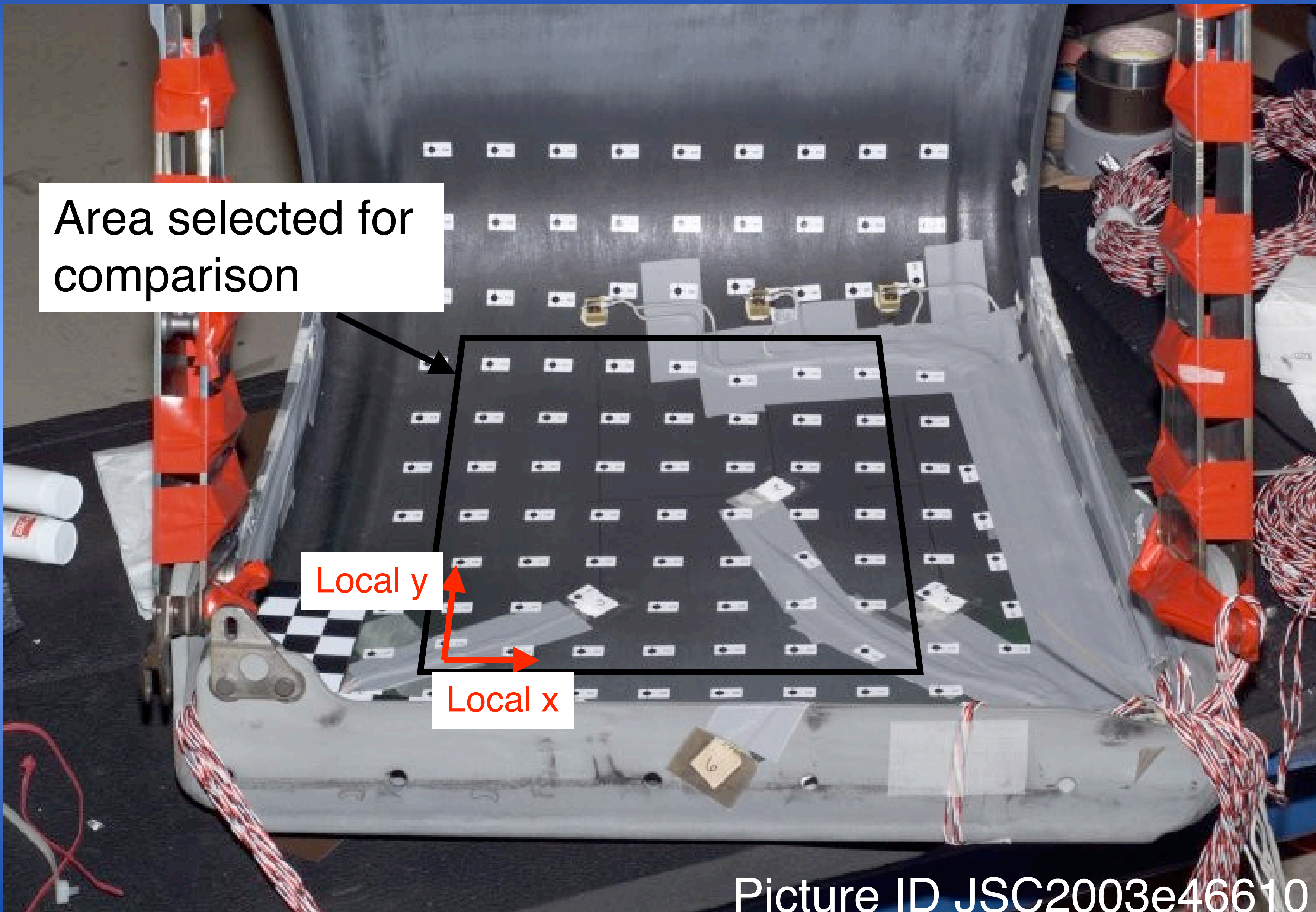
The LS-DYNA models generated to simulate the impact tests onto RCC Panels 6 and 8 at Southwest Research Institute (SwRI) during the CAIB phase were only qualitatively compared with the test.

During Return-to-Flight (RTF) program, quantitative test-analysis correlations were generated for both panel impact tests.

Instrumentation used on the SwRI full-scale tests included displacement gages, accelerometers, strain gages, high-speed video, and load cells. Photogrammetry was also used to measure displacements.

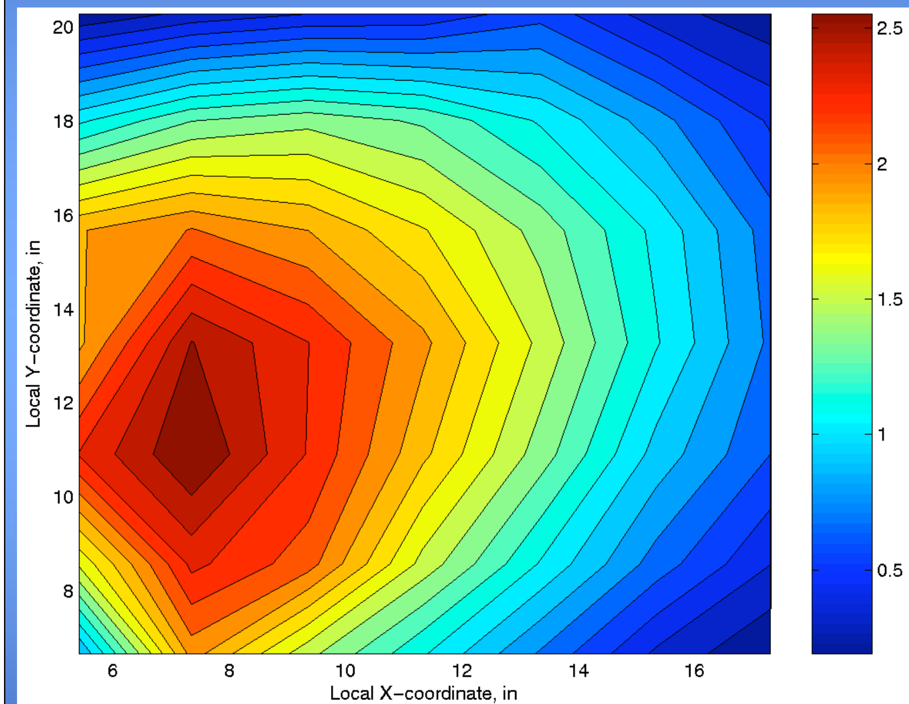
For this presentation, selected test-analysis correlation comparisons will be shown for the SwRI RCC Panel 8 test.

RCC Panel 8 Photogrammetric Targets



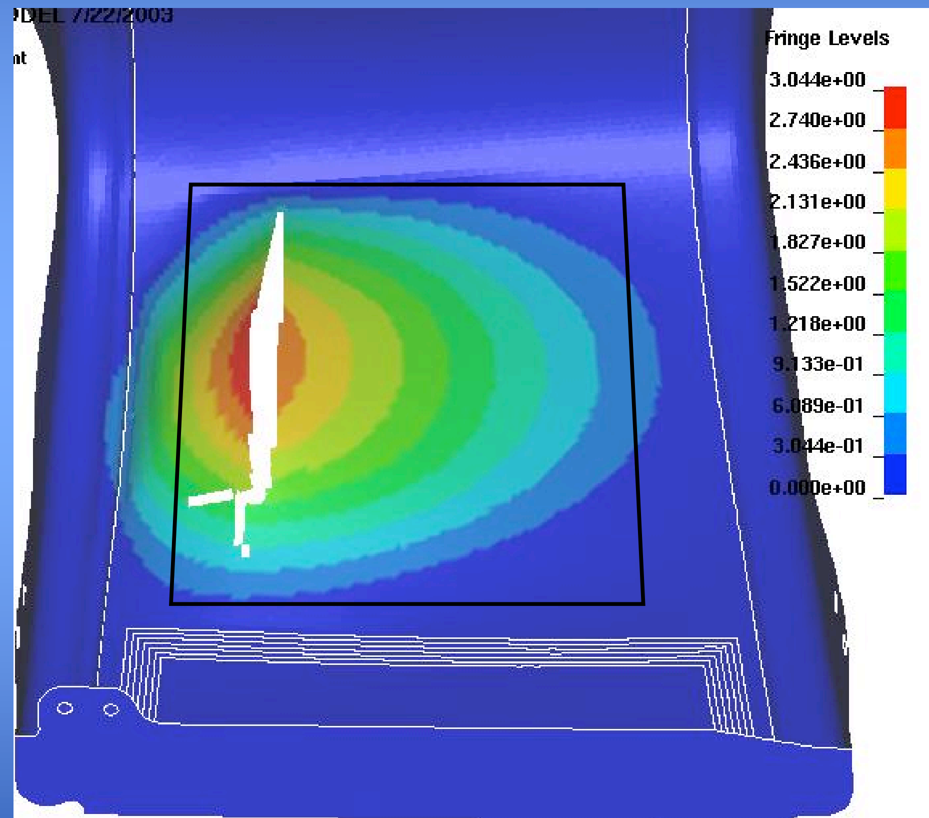
Comparison of Test and Analysis Displacement for Panel 8 Test at ~ 2.8 ms after Impact

Measured



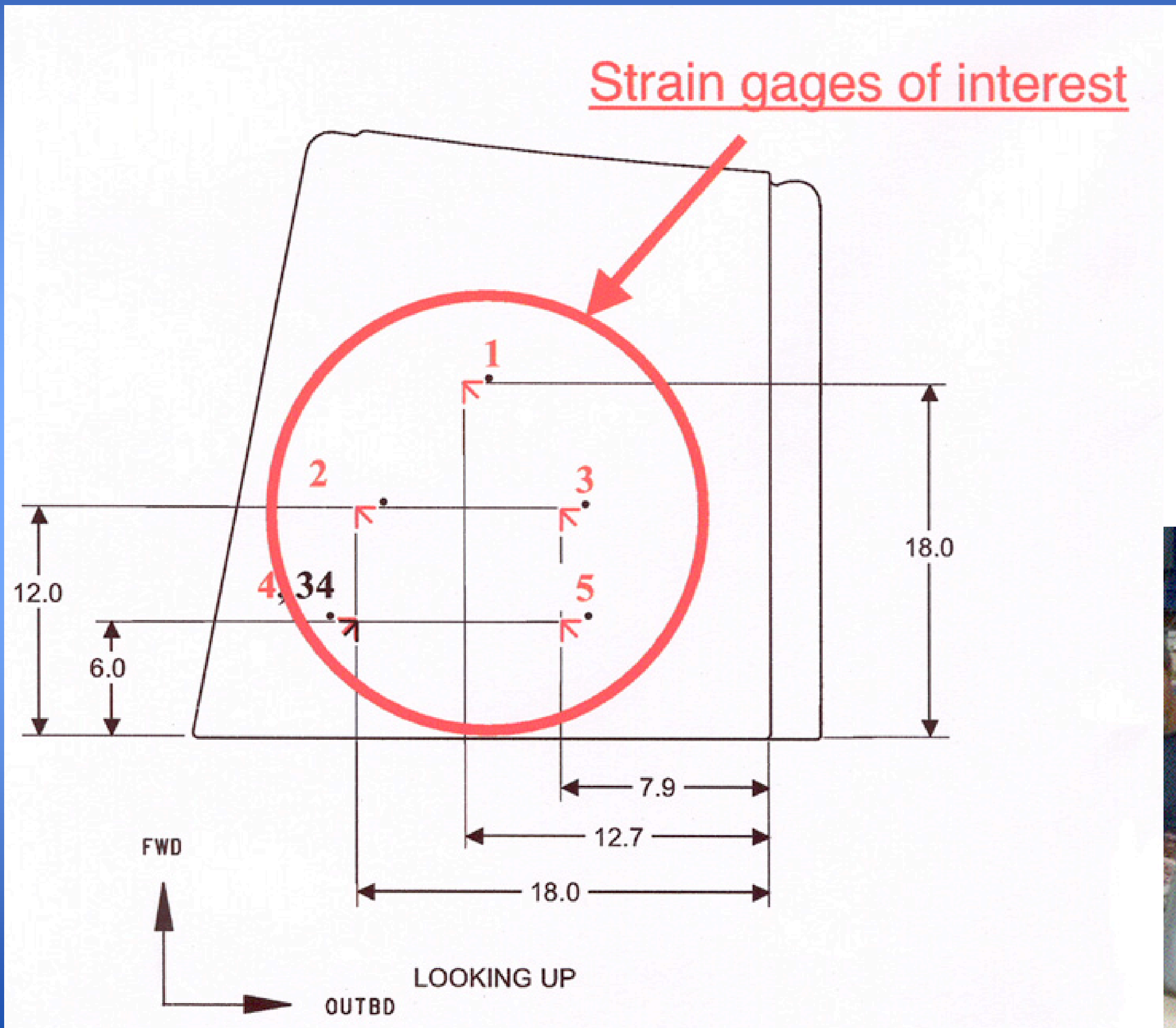
Resultant displacement (inches)
From photogrammetry
(not-to-scale, see white square on right)

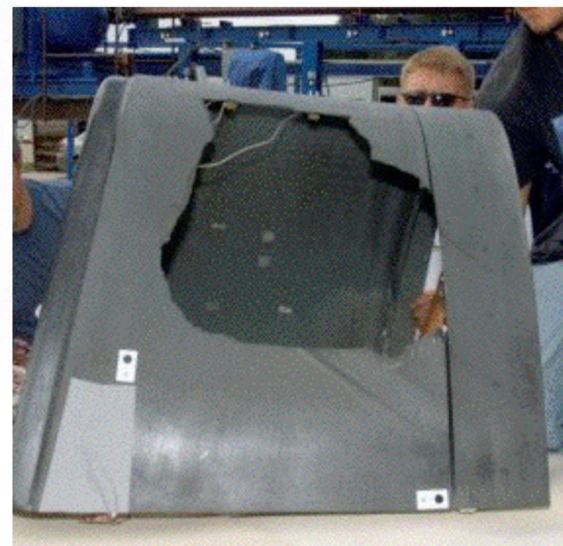
Predicted



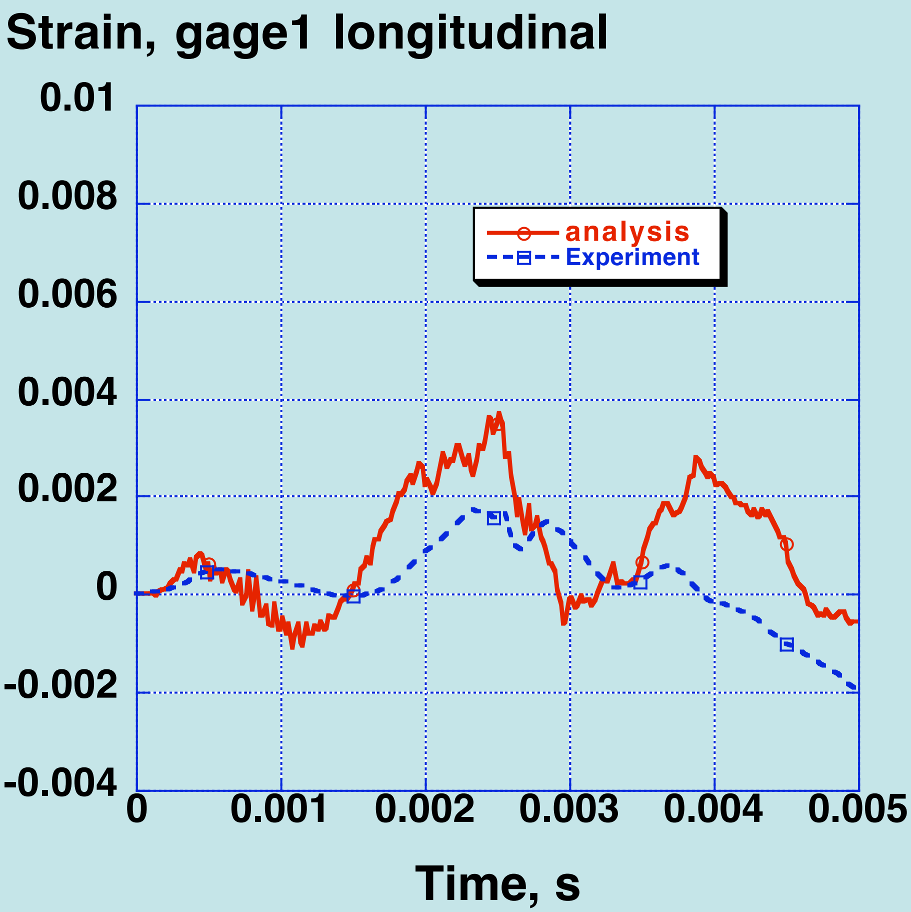
LS-DYNA model
(rear inside view)

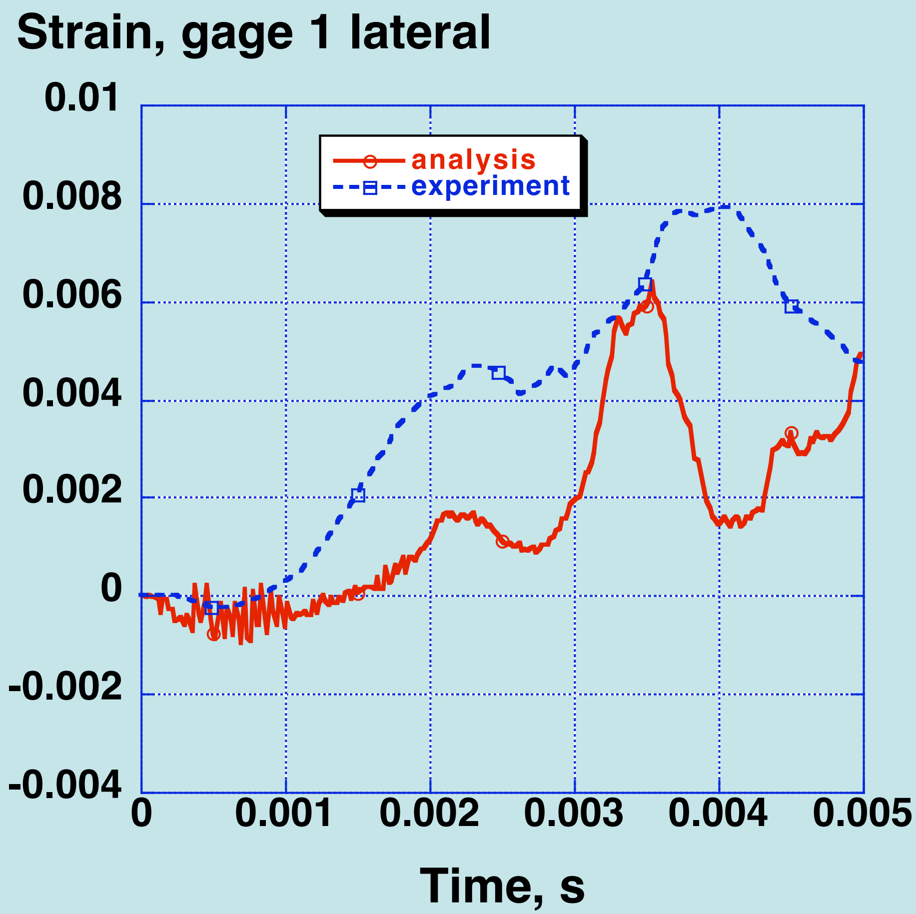
Strain Gages of Interest on Front of Panel



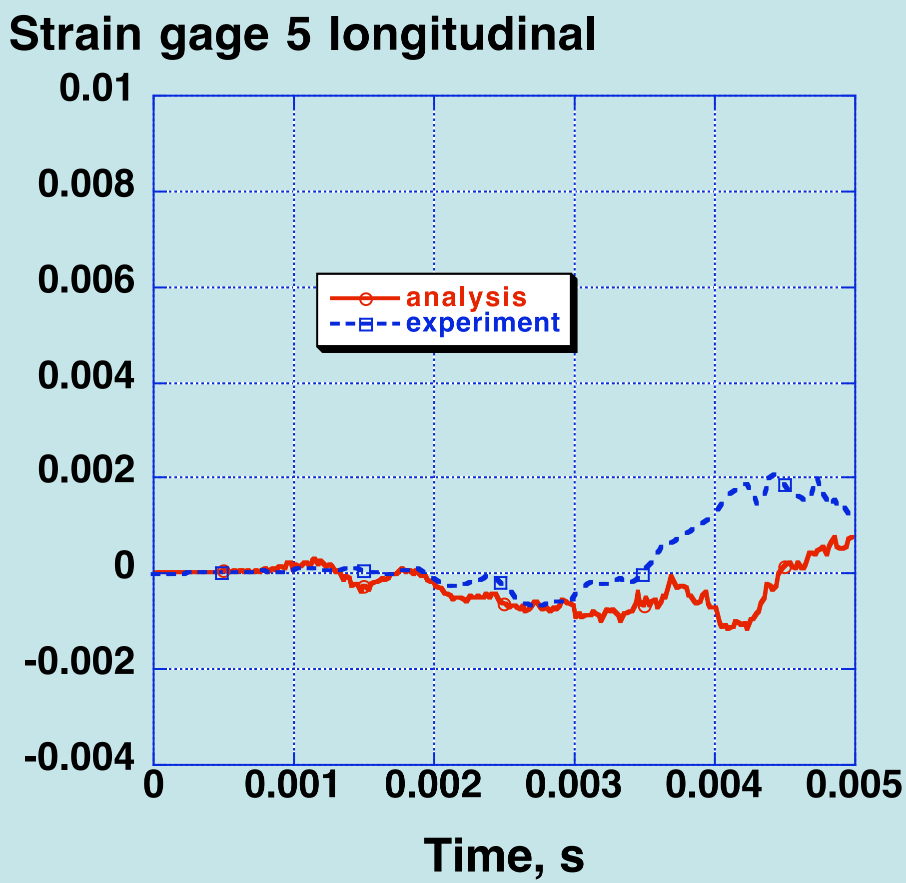


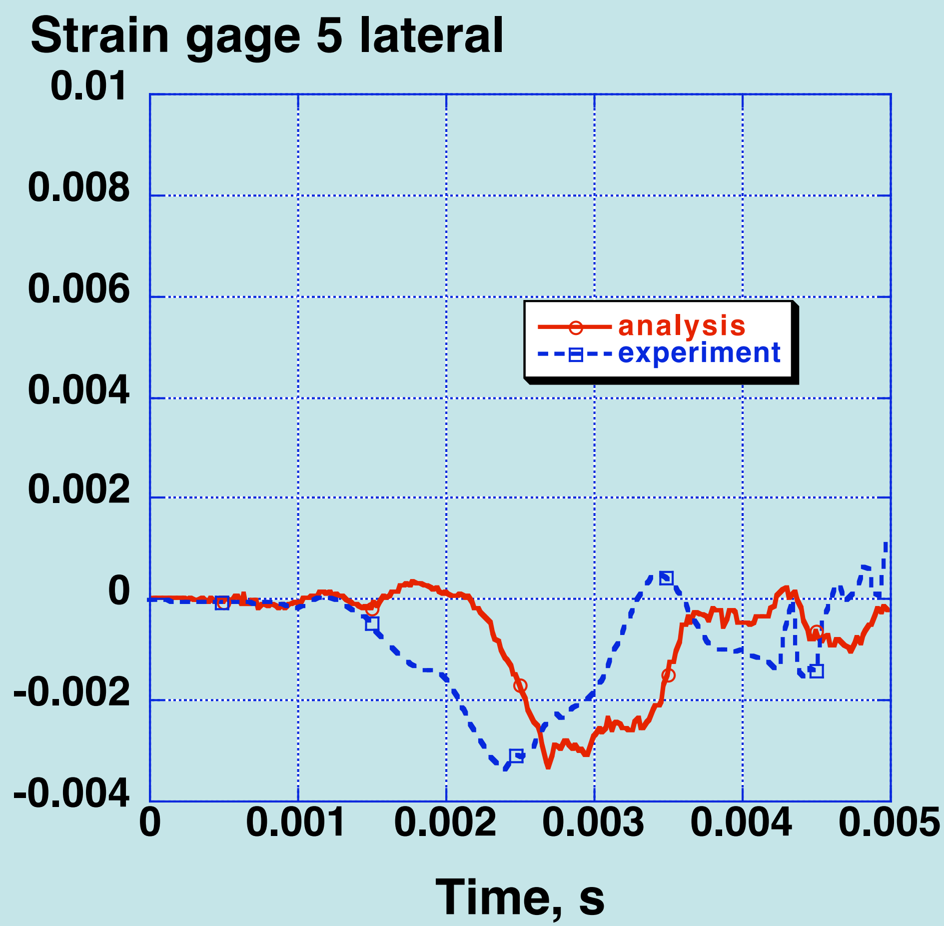
Strain Gages of Interest on Front of Panel





Strain Gages of Interest on Front of Panel





Parametric LS-DYNA Studies

- Perform parametric studies of debris impacts:

  to find worse cases
  to focus the scope of the production runs
  to gain insight

Panel 9 location sensitivity study

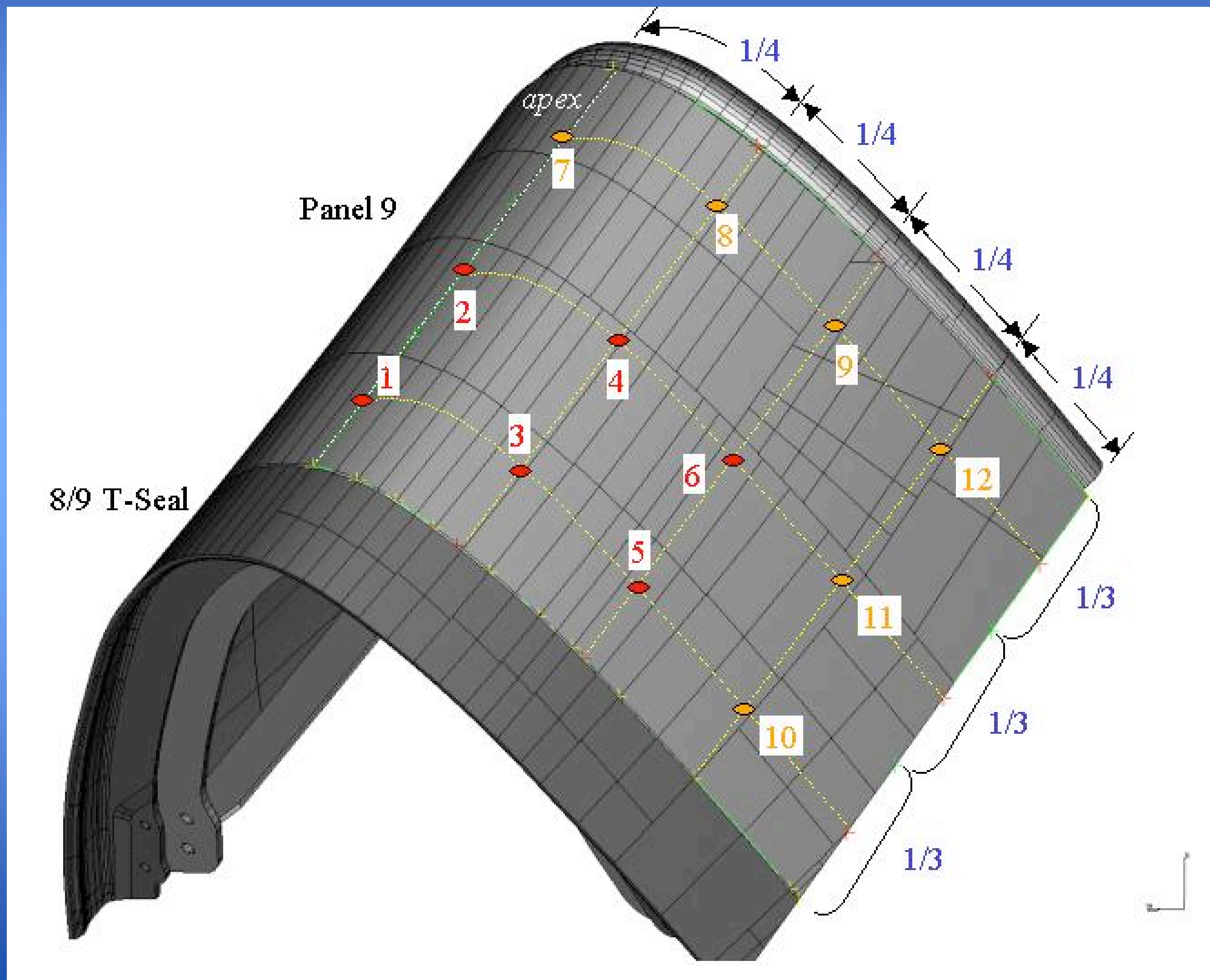
A sensitivity study for foam debris onto panel 9 was initiated before the SwRI Panel 9 test to determine the weakest area on the lower face. Originally, a 5.5-in cube of foam was assumed with a velocity of 1000 ft/s along the X-axis of the orbiter (nose to tail direction).

Since the panel is curved, the incident angle for foam traveling along the X-axis varies from 45 degrees at the apex to around 10 degrees at the lower edge of the lower surface.

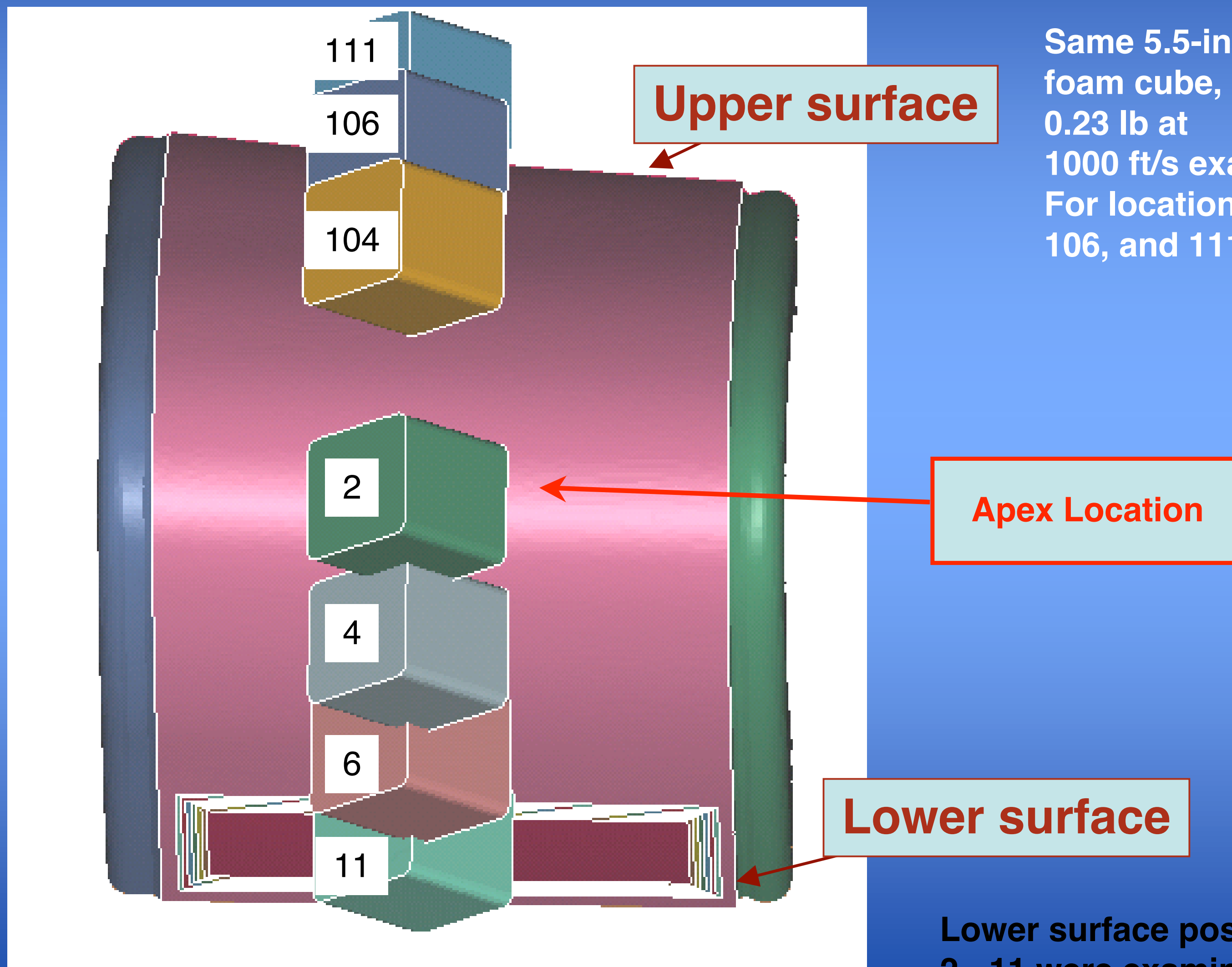
The impulse is expected to be approximately proportional to the sine of the incident angle. However, the stiffness of the structure at each impact location must also be considered

The original study only looked at lower surface impacts. Recently, the upper surface was Included in the parametric study. Also, the shape of the impactor has been modified from a cube to a rectangular solid, and orientation, and pitch and yaw of the velocity vector are considered.

Lower surface impact location study pre-Panel 9 shot for 5.5 in, 0.23 lb. foam cube 1000 ft/s



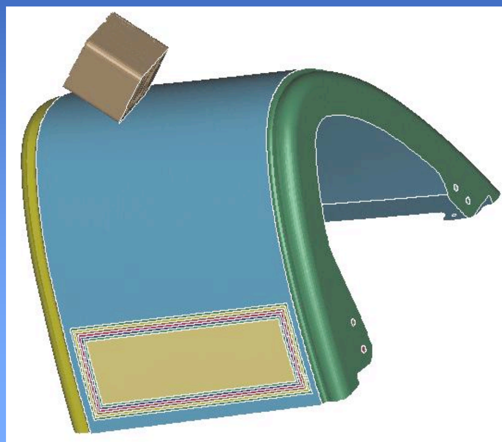
Impact location study: top view of Panel 9 corner impact 5.5-in cube, 1000 ft/s



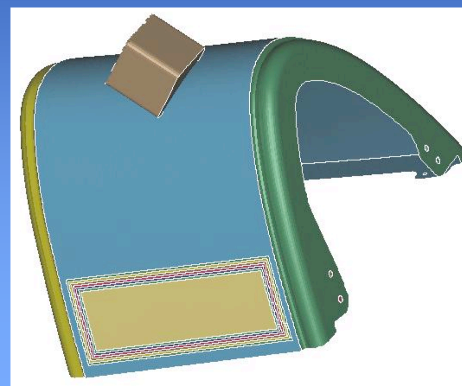
Same 5.5-inch foam cube, 0.23 lb at 1000 ft/s examined For location 104, 106, and 111

Lower surface positions 2 - 11 were examined before the Panel 9 shot at SwRI.

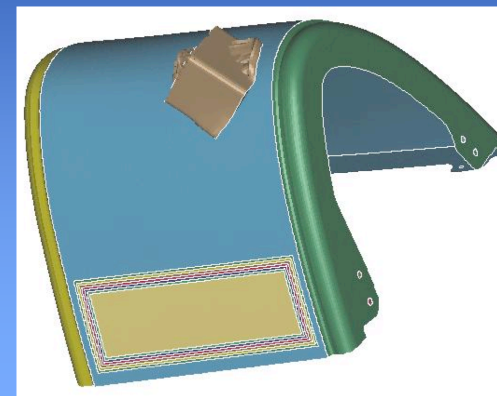
Apex Impact (location 2) 0.23lb 5.5-in cube on Panel 9
Corner impact, velocity 1000 ft/s. (NO DAMAGE)



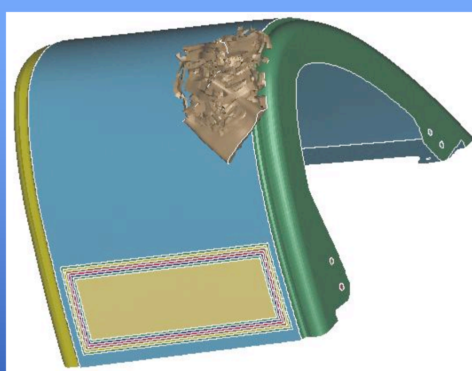
time = 0.0 msec



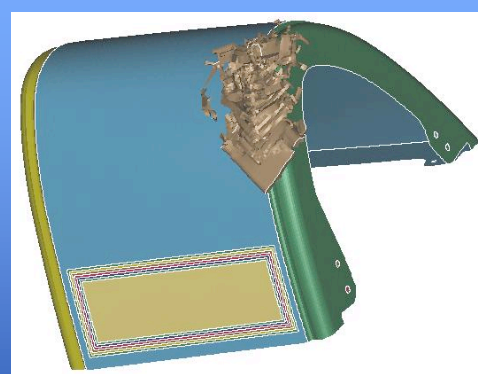
time = 0.4 msec



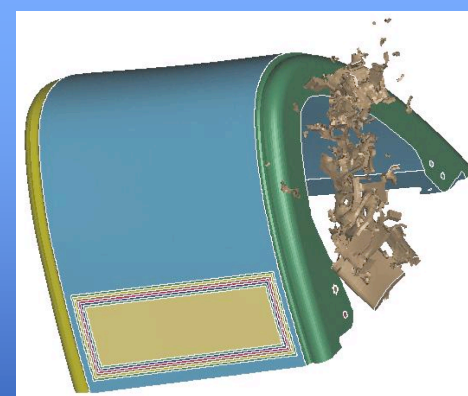
time = 0.8 msec



time = 1.2 msec



time = 1.6 msec



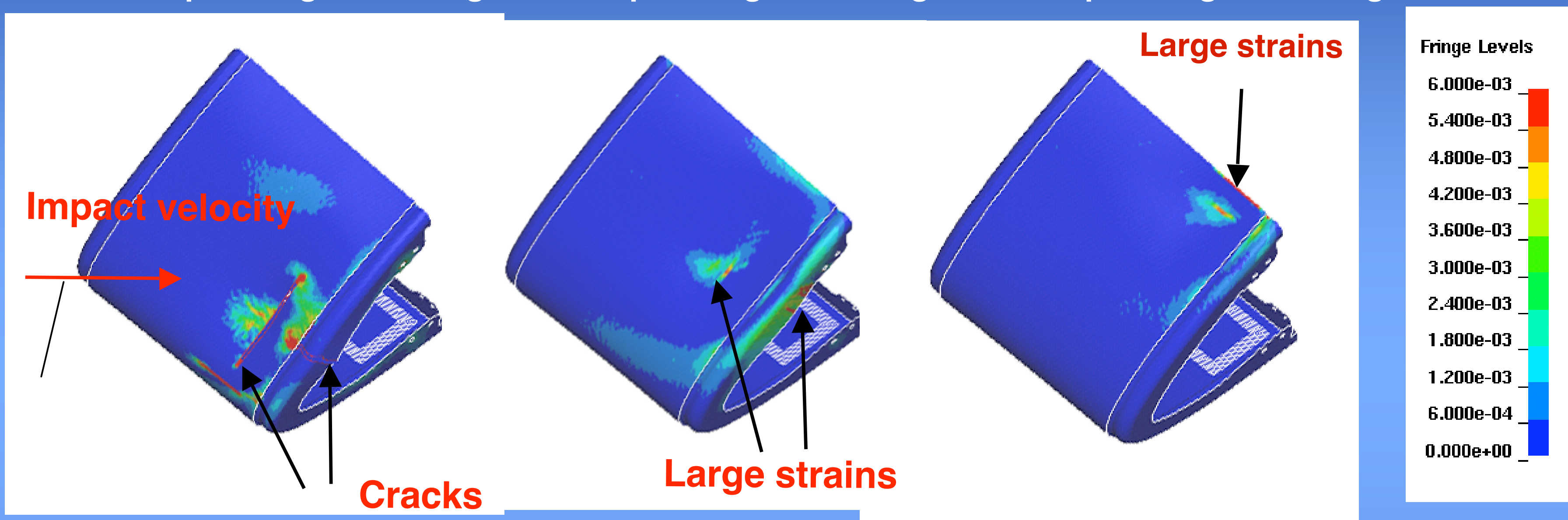
time = 3.0 msec

Damage on top surface of Panel 9 - corner impact for same 0.23 lb, 5.5-in cube, 1000 ft/s

Location 104: Impact angle = 35 deg.

Location 106: Impact angle = 26 deg.

Location 111: Impact angle = 21 deg.



4.0 ms

3.2 ms

1.6 ms

Concluding Remarks

Ongoing Shuttle RTF Impact Testing and Analysis

- Due to the complexity and variability of the RCC failure, additional RCC coupon testing under dynamic loading is planned. The GRC gas gun and the high-speed drop tower at LaRC will be used for additional testing once sufficient RCC material is obtained.

- Return-to-Flight (RTF) requires characterization of debris besides foam. Various External Tank and Solid Rocket Booster ablators plus ice will need to be characterized for high strain-rate behavior.

- LS-DYNA modeling has been determined to be a critical path in the RTF activities. Upcoming production runs will determine the threshold of damage for various RCC panels for a matrix of debris materials, debris geometries, trajectories, sizes, orientations, etc.