NDE of Fiber Reinforced Foam Composite Structures for Future Aerospace Vehicles

American Society for Nondestructive Testing Fall Conference

James Walker (NASA MSFC)
Don Roth (NASA GRC)
Dale Hopkins (NASA GRC)

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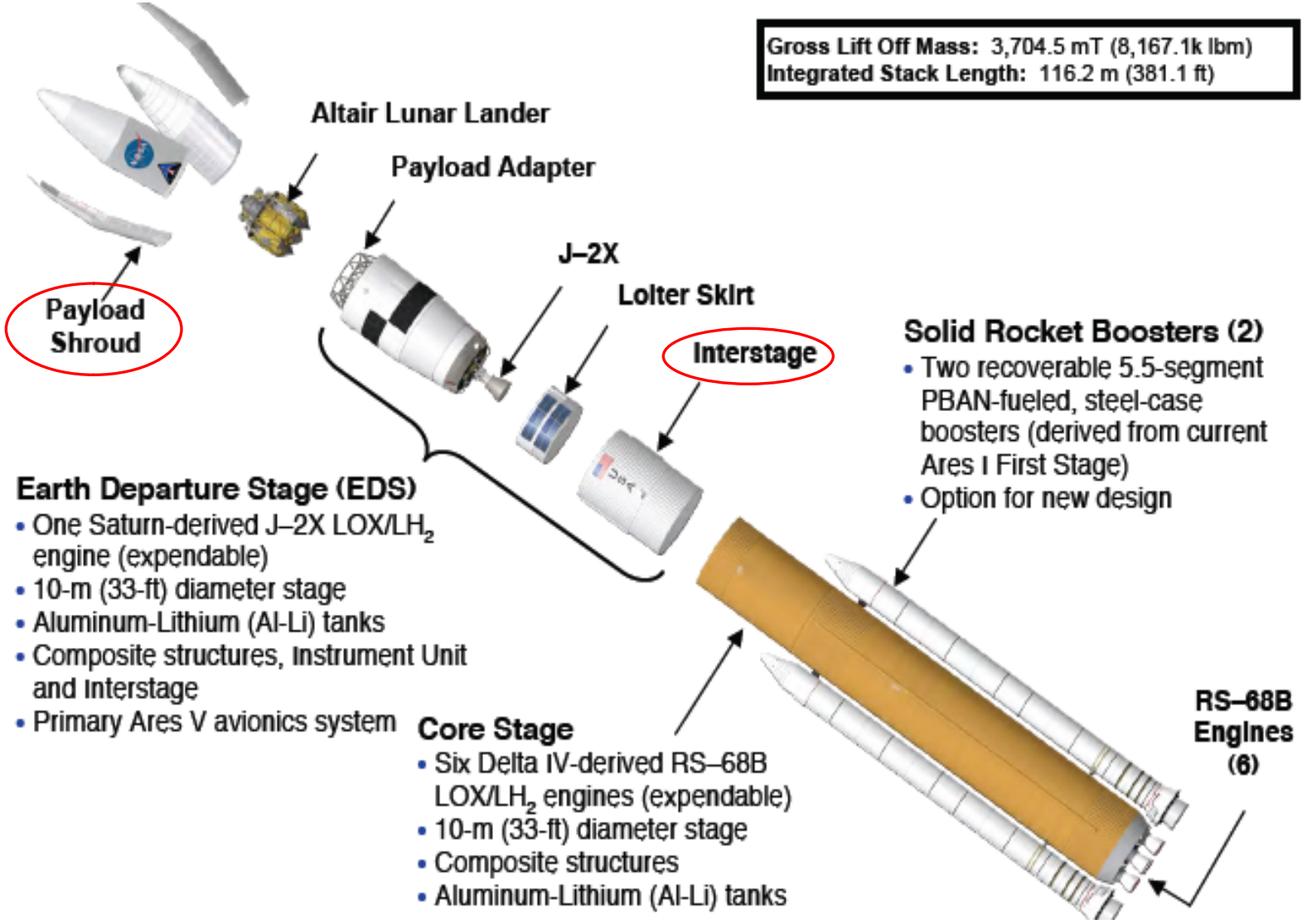
Outline

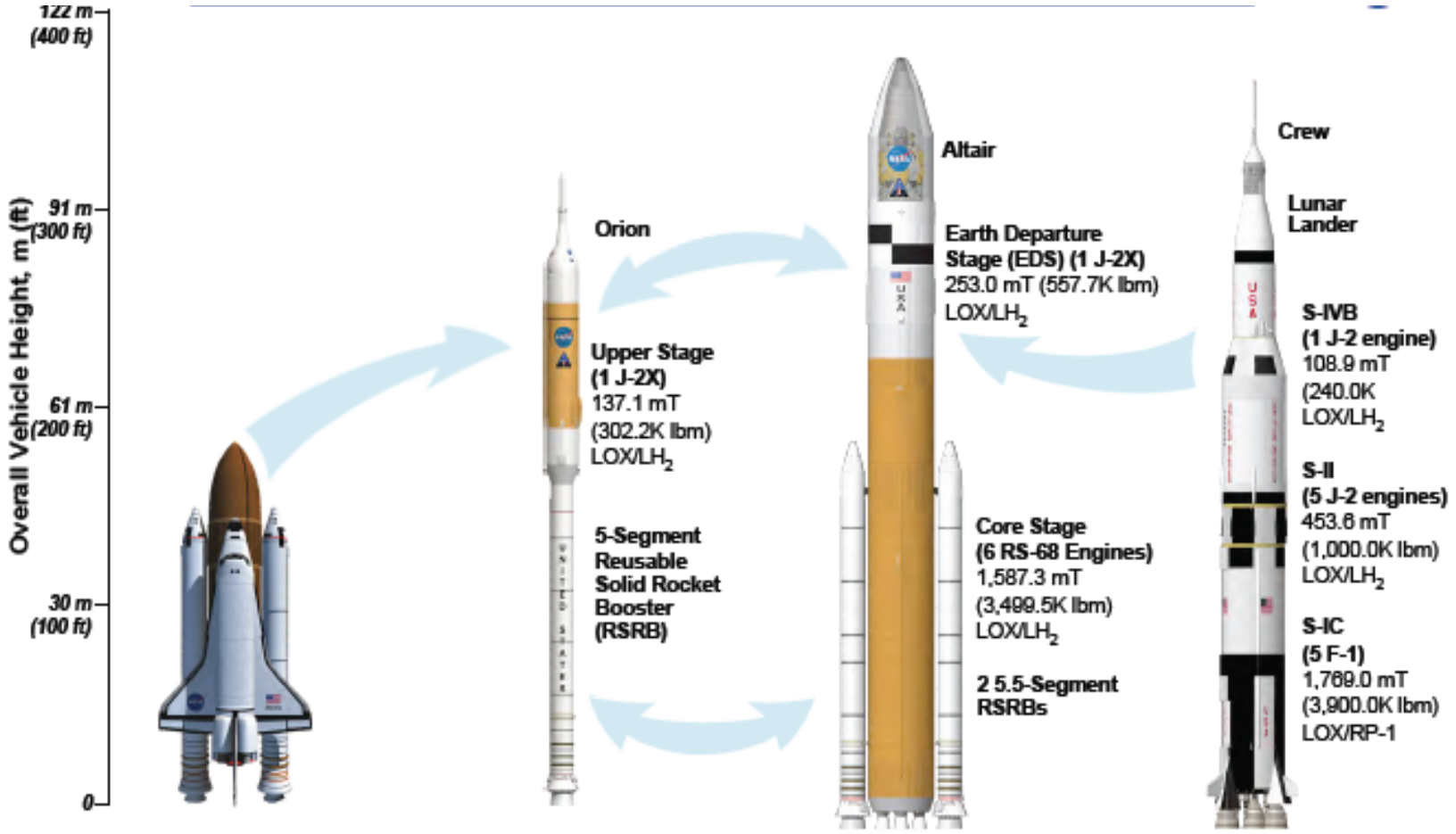
- Vehicle Overview (Ares V type)
- Fiber Reinforced Foam Materials System
- NDE Methods Investigated
  - Micro-computed X-Ray Tomography
  - Shearography
  - Thermography
  - Phased Array Ultrasonics
- Conclusions

Ares V Vehicle



Targeting dry structures including the payload shroud and interstage

Launch Vehicle Comparison



Space Shuttle

Height: 56.1 m (184.2 ft)
Gross Liftoff Mass:
2,041.1 mT (4,500.0K lbm)
Payload Capability:
25.0 mT (55.1K lbm) to
Low Earth Orbit (LEO)

Ares I

Height: 99.1 m (325.0 ft)
Gross Liftoff Mass:
927.1 mT (2,044.0K lbm)
Payload Capability:
25.5 mT (56.2K lbm)
to LEO

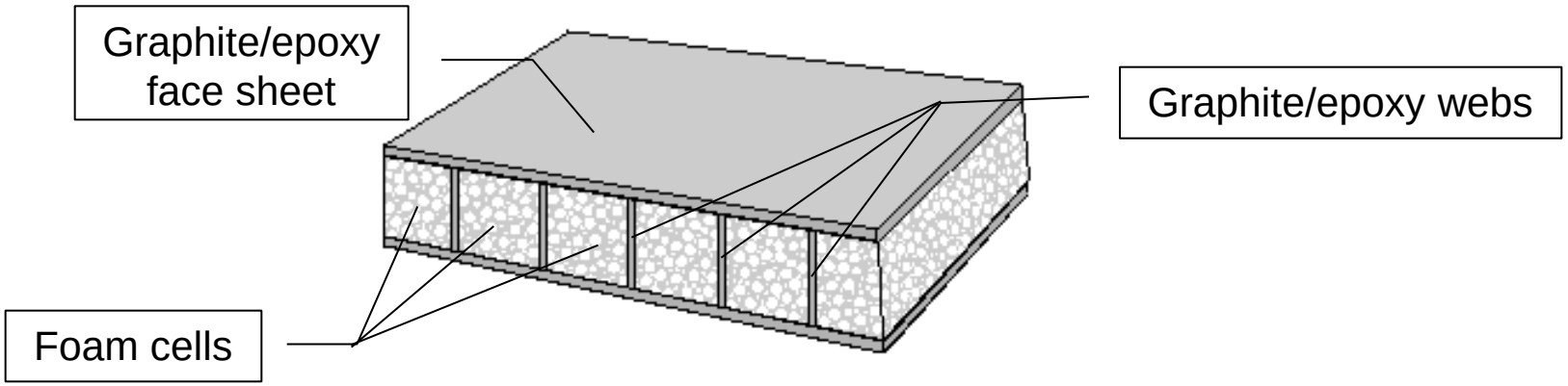
Ares V

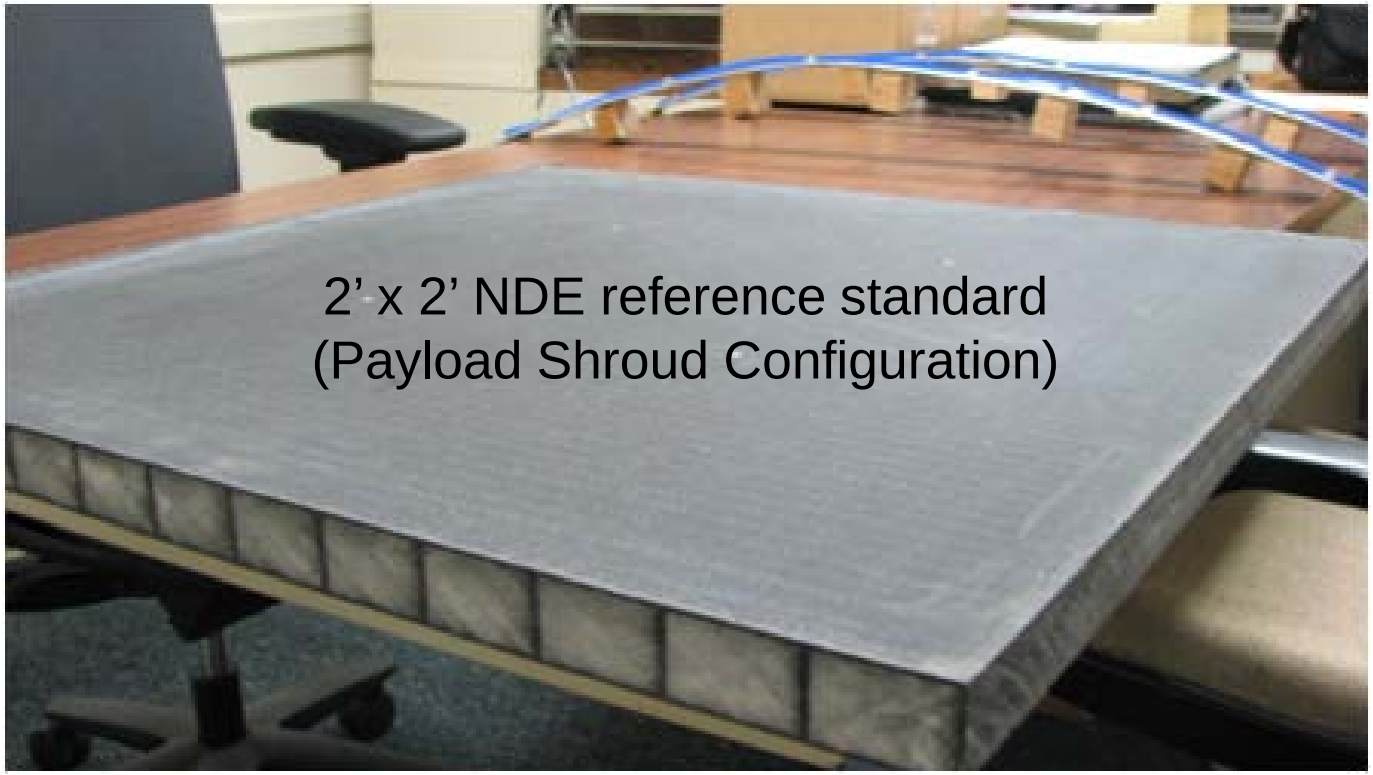
Height: 116.2 m (381.1 ft)
Gross Liftoff Mass:
3,704.5 mT (8,167.1K lbm)
Payload Capability:
71.1 mT (156.7K lbm) to TLI (with Ares I)
62.8 mT (138.5K lbm) to Direct TLI
~187.7 mT (413.8K lbm) to LEO

Saturn V

Height: 110.9 m (364 ft)
Gross Liftoff Mass:
2,948.4 mT (6,500K lbm)
Payload Capability:
44.9 mT (99K kbm) to TLI
118.8 mT (262K lbm) to LEO

Fiber Reinforced Foam Material System





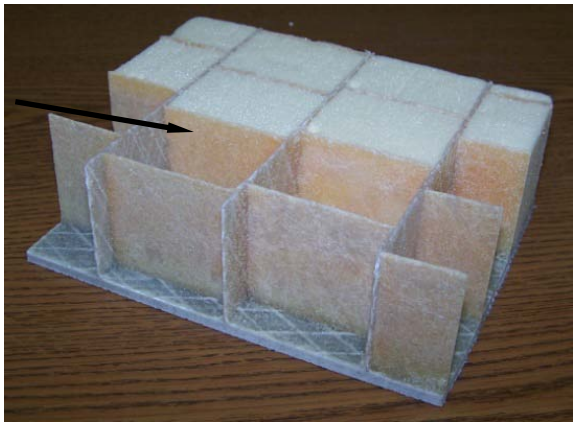
Fiber Reinforced Foam Material System

TYCOR® Fiber Reinforced Foam (FRF)

- WebCore creates value-add FRF preforms (TYCOR materials)
- TYCOR is comprised of composite vertical webs (walls) inside foam
  - Fiber reinforced composite webs provide strength
  - Low-density foam used as tooling for fiber placement – secondary structural benefits such as local buckling suppression and other multifunctional benefits e.g. thermal management, acoustics and fire.
  - Reinforcements can be fiberglass, carbon, or other structural fiber
- Unidirectional or Bi-directional Web Orientation
- High strength, stiffness, durability and damage tolerance
- Unique patented technology

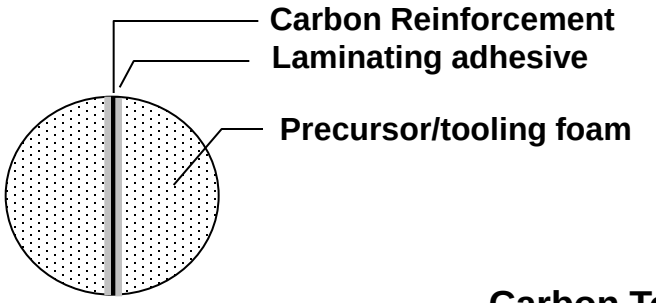
TYCOR Panel with Unidirectional FRF

Foam removed to display webs



TYCOR Panel Interior with Bi-Directional FRF

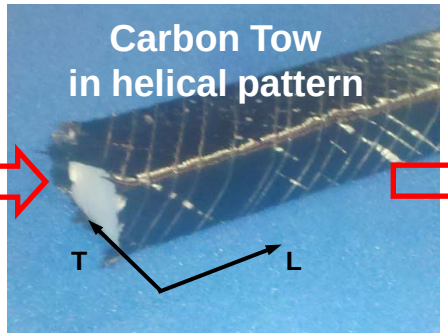
Fiber Reinforced Foam Material System

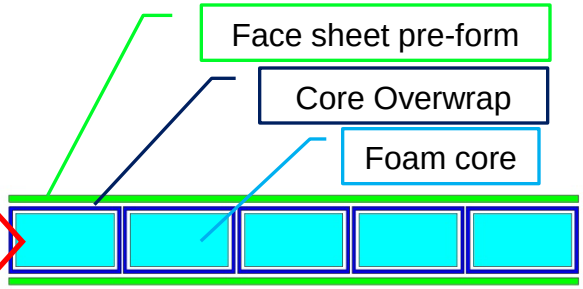


Engineered Core: Orthotropic stiffness and strength properties can be tailored independently in *L* and *T* directions, or only in a single direction (uni-directional)

Carbon Tow

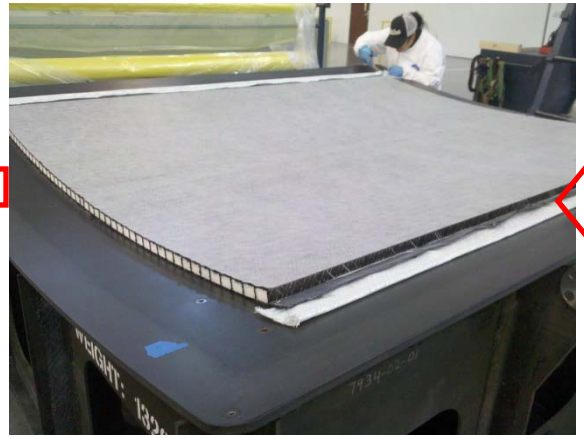
High-Speed Winding Process

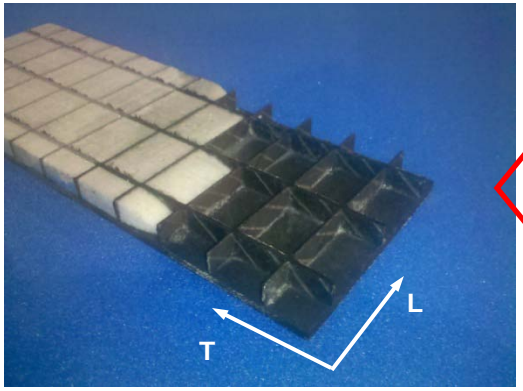




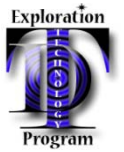
Fabric/Core/Fabric Lay-up

Resin infusion and sheet consolidation process



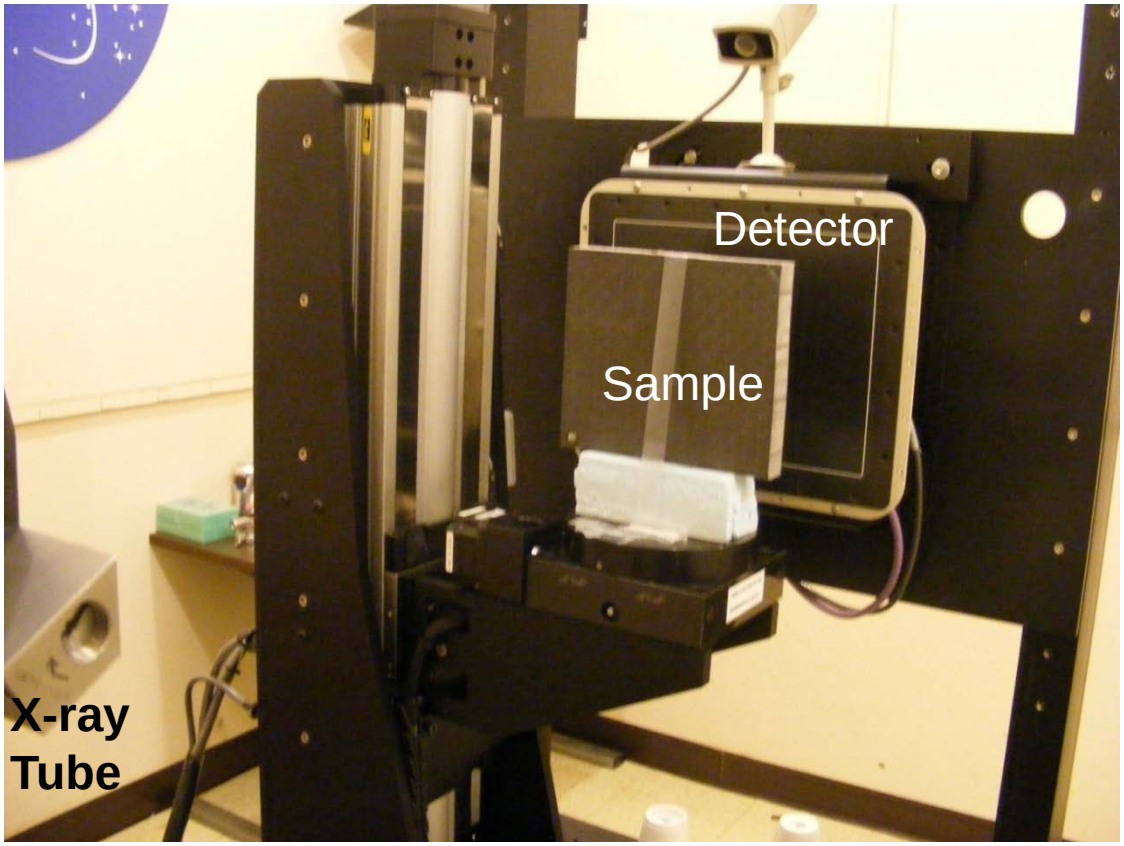


Bi-directional composite web architecture



NDE Methods Explored

Micro-computed X-Ray Tomography



CT Test Setup

- Feinfocus FXE200 X-ray tube
- Voltage 80KV at 90 micro amps
- Microfocus spot source
- Aluminum filter
- Sampled in 2x2 mode
- Frame rate 5 fps in 2x2
- Frames averaged=5
- Air and dark shots average = 128 frames each
- 1.2X magnification
- Source to object dist. = 615mm, Source to detector dist. = 746mm
- Geometric limitation was met @ 615 mm source to object distance
- DX2 GPU processor used to process data
- Geometry calibration done before and after each test

X-ray CT Results

Side View (YZ)

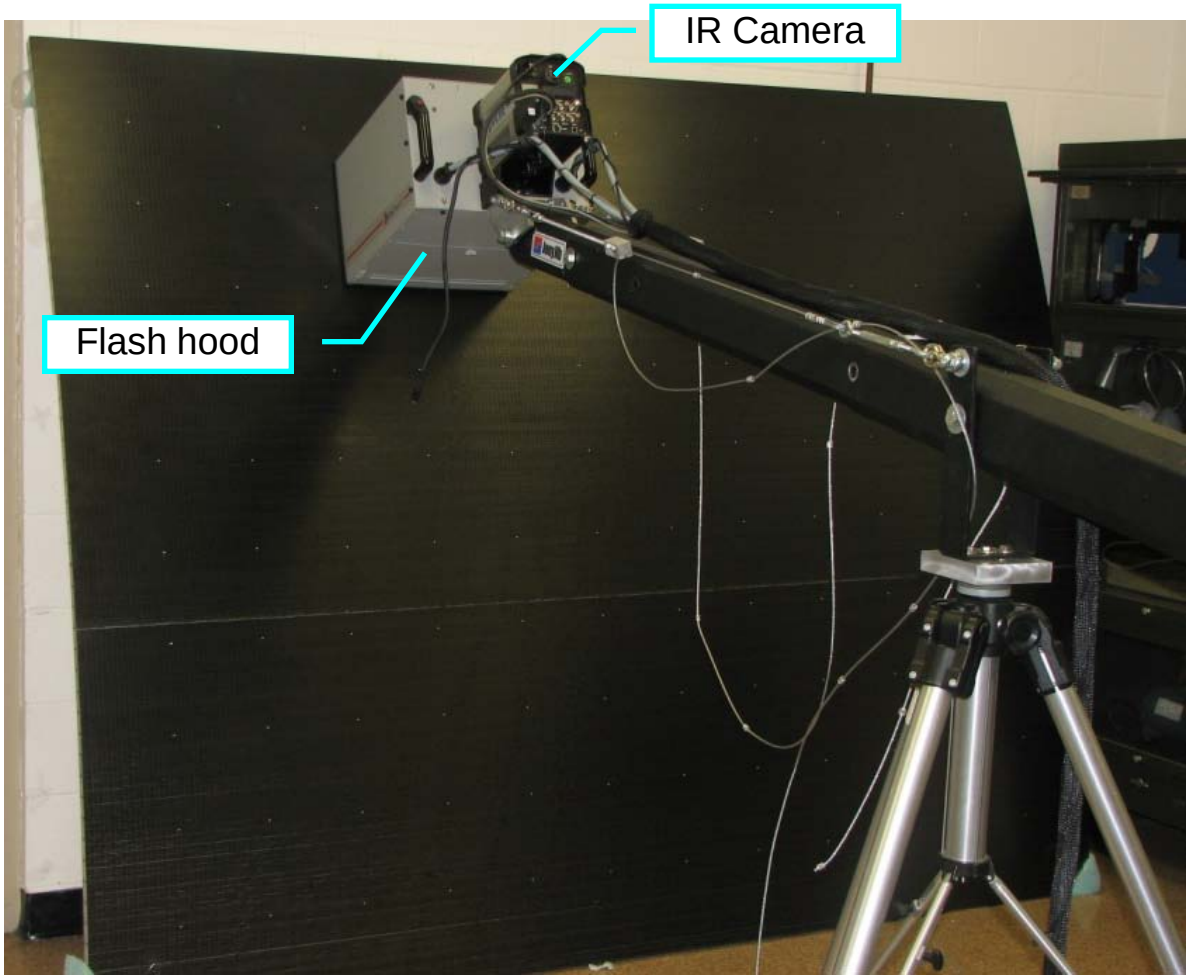
Crack in foam

The side view section is at the position thru the sample denoted by the vertical cursor on the top view.

Animations (AVI) of the slices can be made all the way thru the sample as this cursor is moved over the top view.

As the vertical cursor Is slide along the width, the crack is seen to extend well into the foam.

Thermography System



Boom inspection of 1/16th scale FRF barrel segment

General Notes

Thermal Wave Imaging Flash IRT system using Echotherm and Mosaic Software

Pulsed thermal excitation

Inspecting from both sides

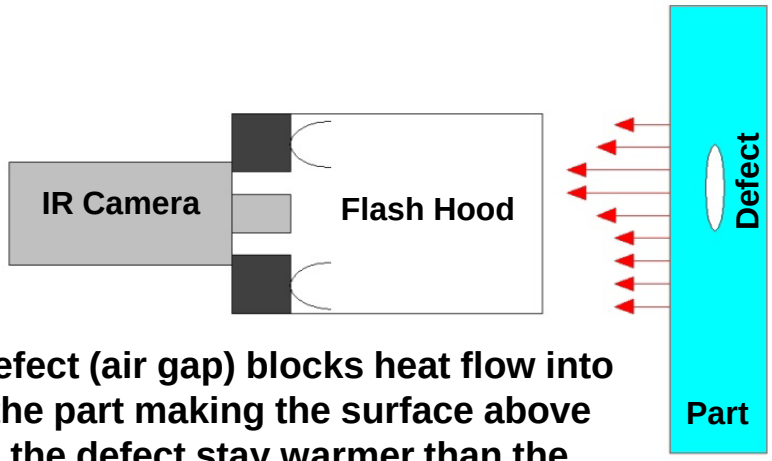
Hood held close to part (≈ 2”)

Non-contact

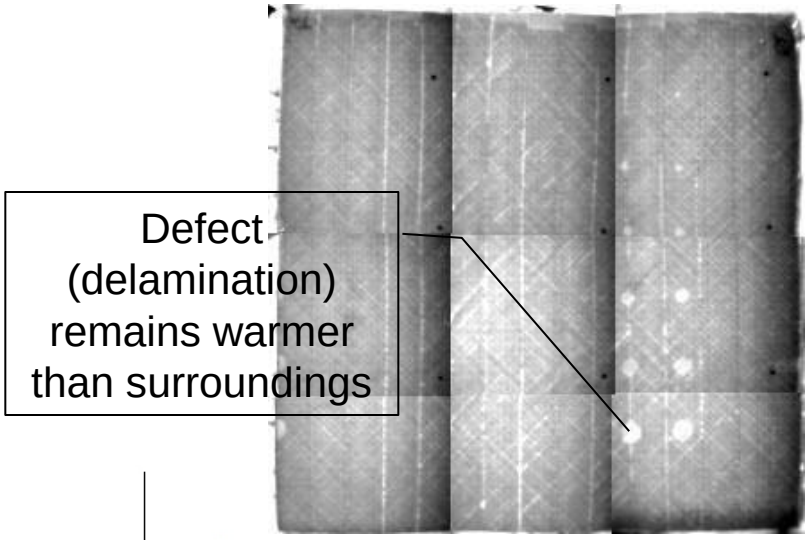
Requires dull surface; emissivity > 0.7 and dark

3 minutes / square foot

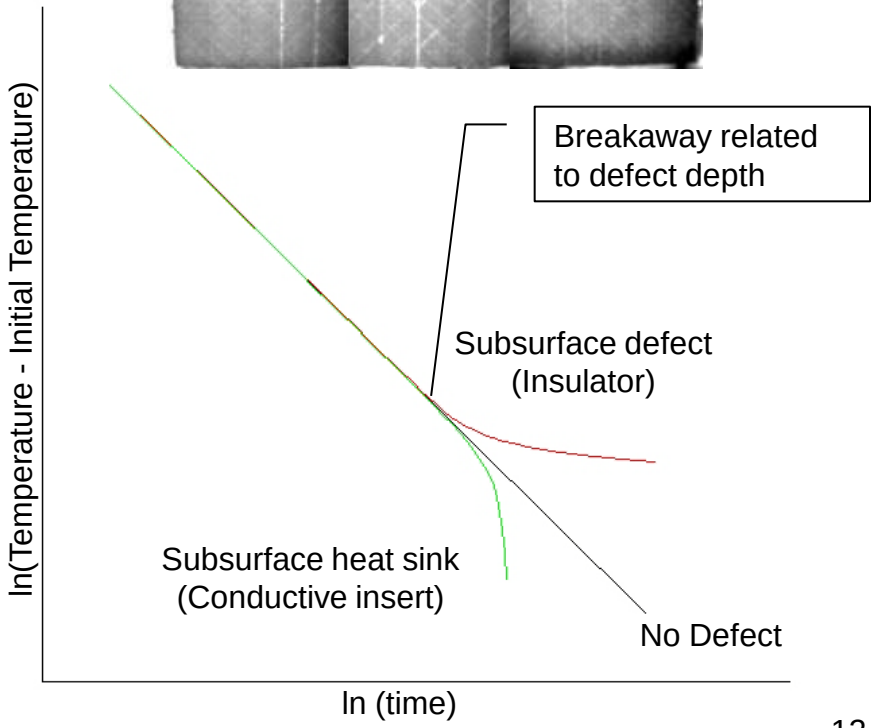
Thermography Method



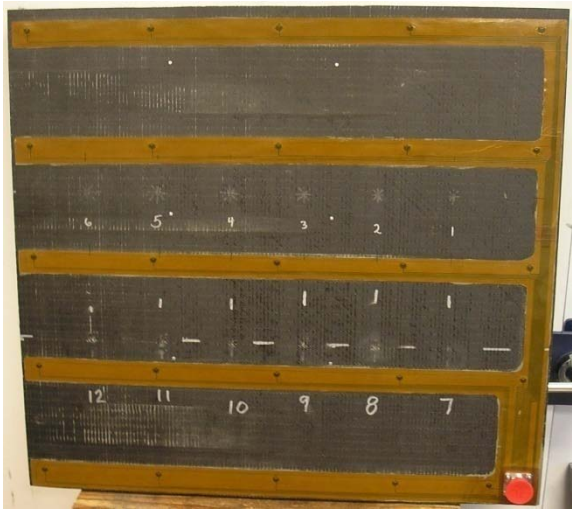
Defect (air gap) blocks heat flow into the part making the surface above the defect stay warmer than the surrounding area



- Image subtraction (T-T0) can enhance the thermal contrast but only to a small degree
- The first and second derivatives of the ln(T-T0) - ln(t) curve enhances any deviation of the curve from the “no-defect” line



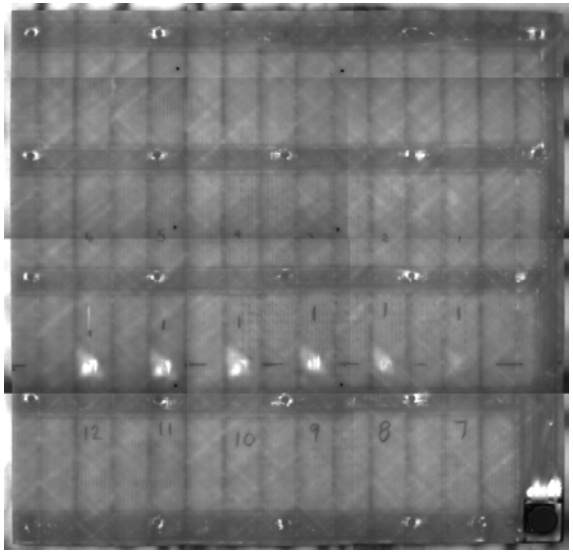
Typical IRT Results



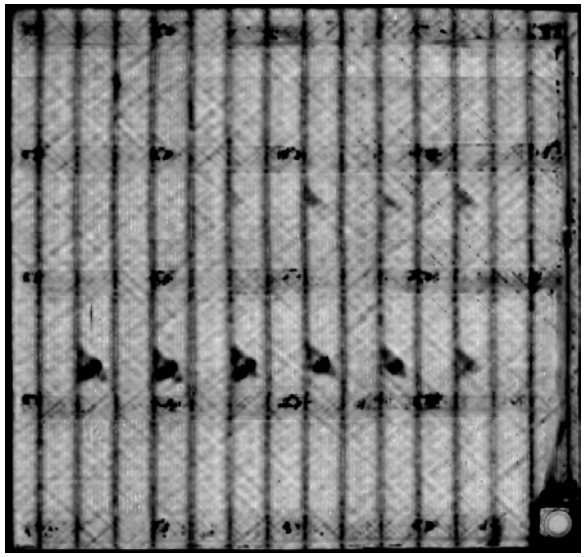
	Impact 6	Impact 5	Impact 4	Impact 3	Impact 2	Impact 1
Height	Not detected	Not detected	0.45”	0.60”	0.43”	0.85”
Width			0.60”	1.20”	0.88”	0.90”

	Impact 12	Impact 11	Impact 10	Impact 9	Impact 8	Impact 7
Height	0.68	0.68”	0.62”	0.58”	0.44”	0.34”
Width	0.58”	0.58”	0.58”	0.48”	0.44”	0.41”

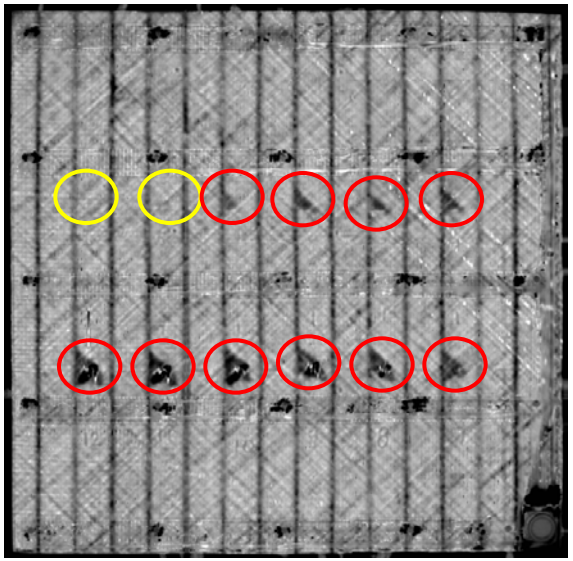
Surface delaminations measured diagonally along major axis



Raw: 2.6 seconds after flash



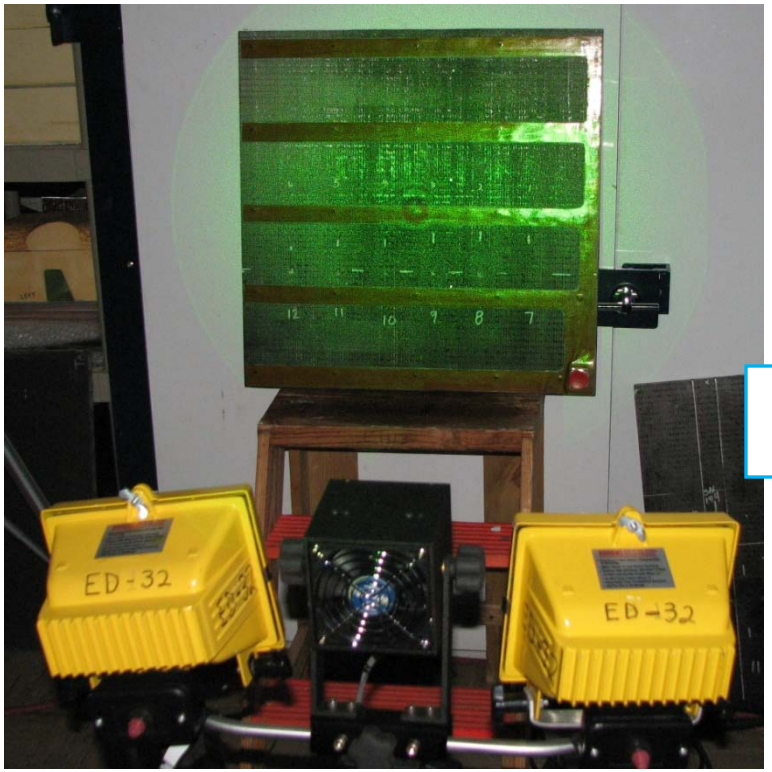
1st Derivative: 4.6 seconds after flash



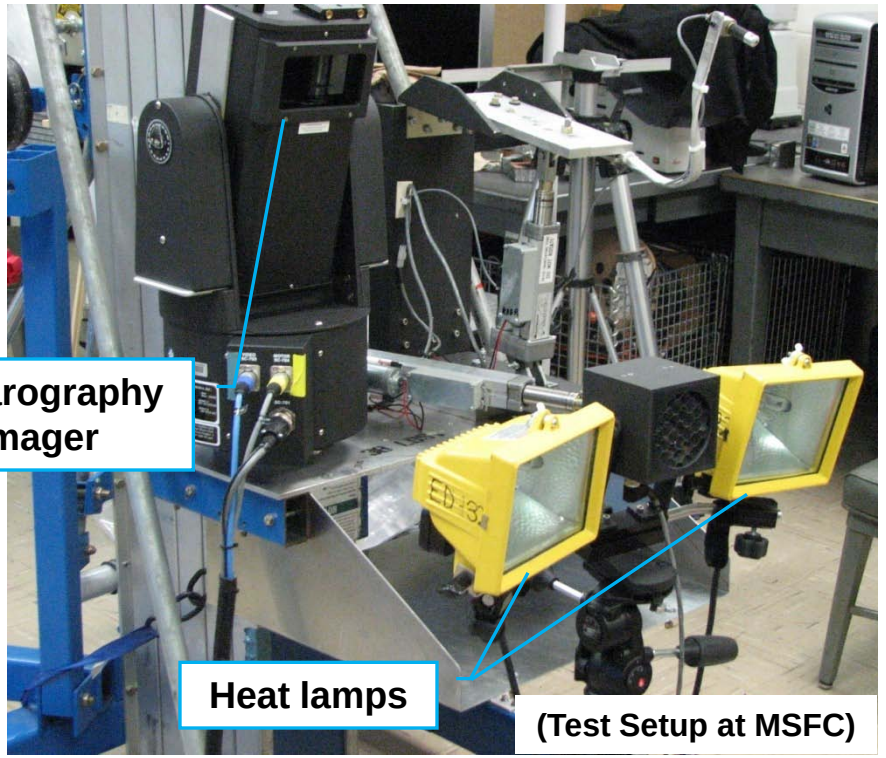
2nd Derivative: 1.6 seconds after flash

Structural Health Monitoring Test Panel

Shearography System



Shearography Imager



Heat lamps

(Test Setup at MSFC)

General Notes

Shearography Camera: LTI-5100HD

Thermal stressing

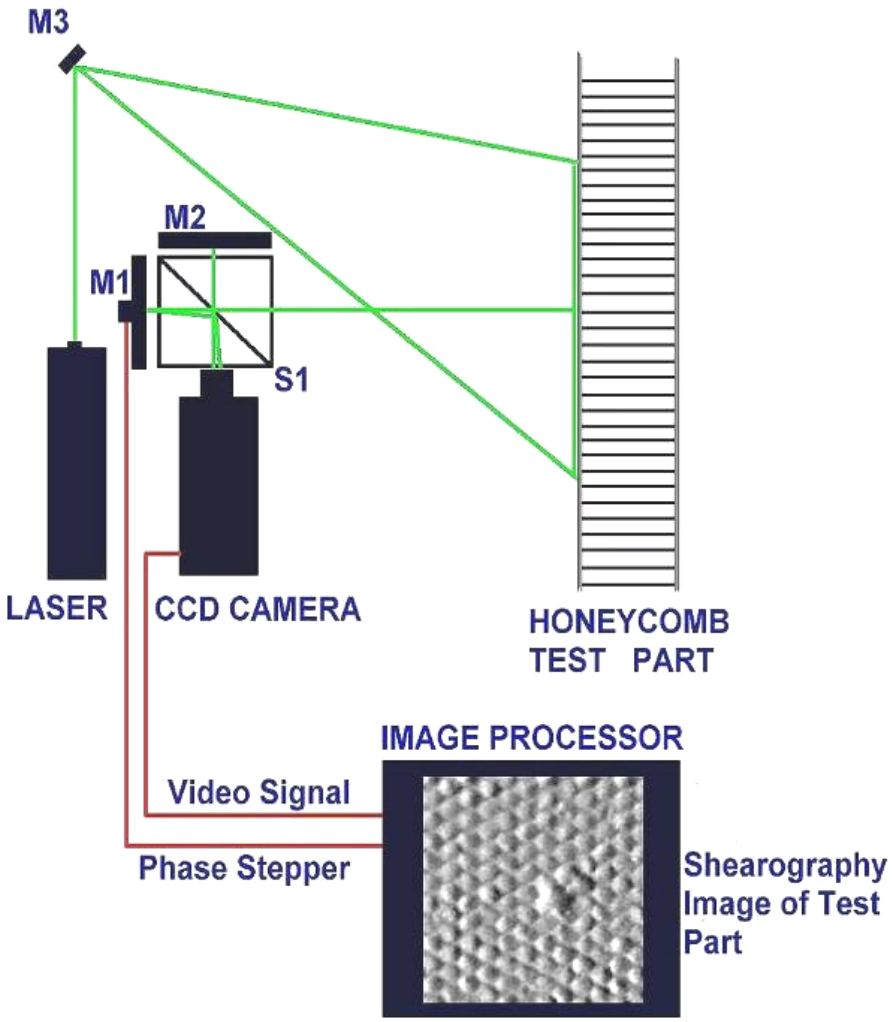
Field of view: 24” x 24”

Surface Prep: None

Non-contact (Works on bare composite surface if not overly reflective or dull, flat white is ideal)

3 minutes / square foot

How Shearography Works



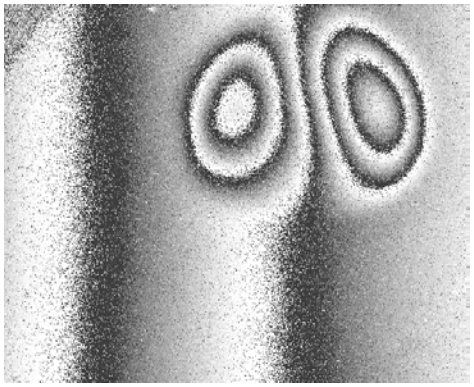
532 nm laser => Frequency doubled Nd:YAG
(Neodymium-doped Yttrium Aluminium Garnet)

- Uses a “laterally sheared” laser interferometer to compare the positions of adjacent points on the surface of a test article
- Provides a “map” of “relative” out-of-plane displacements between adjacent points on the test article
- Directly related to the first derivative of changes in target surface profile when a change in stress is applied
- The “shear vector” controls the direction and magnitude of maximum sensitivity
- Sensitive to changes in target surface profile to about 50 nm ($\lambda/10$)

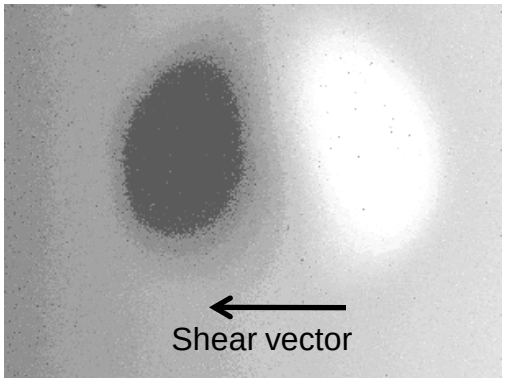
- Real-Time imaging of subsurface defects
- Non-Contact
- Non-contaminating

How Shearography Works

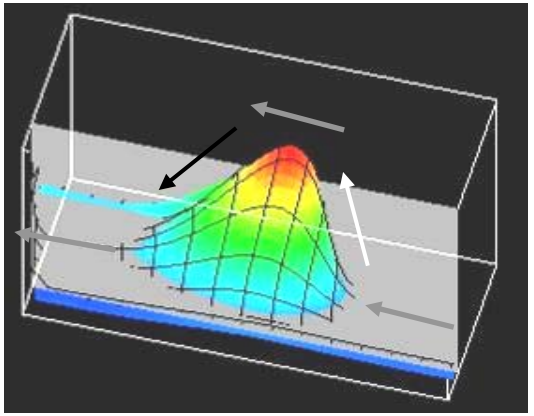
- Image of a indication yields a two lobed, light-dark, pattern
- Wrapped phase map image shows individual fringes corresponding to integer amounts of motion related to the wavelength of the laser illumination
- Unwrapped phase map stacks those integer amounts of motion on one another to give a summation of motion for each lobe
- The lobes are the result of the surface slope changing from zero (no fringe), to positive (white to black fringes or white summation), to zero at the peak of the defect deflection, to negative (black to white or black summation, and then back to zero as you step off the defect



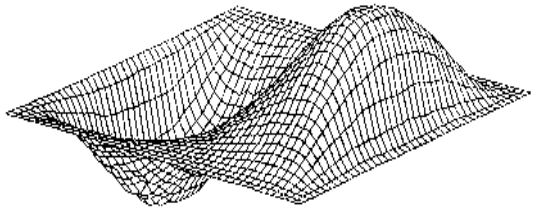
Wrapped Phase Map



Unwrapped Phase Map



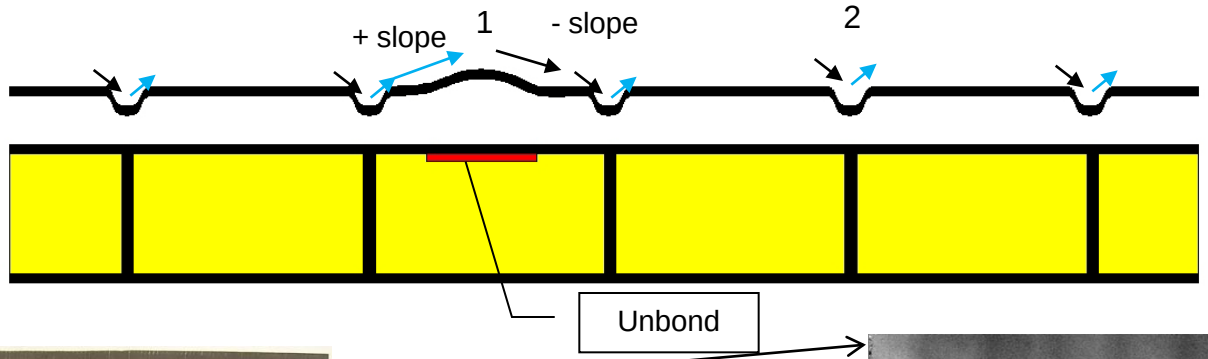
Displacement profile

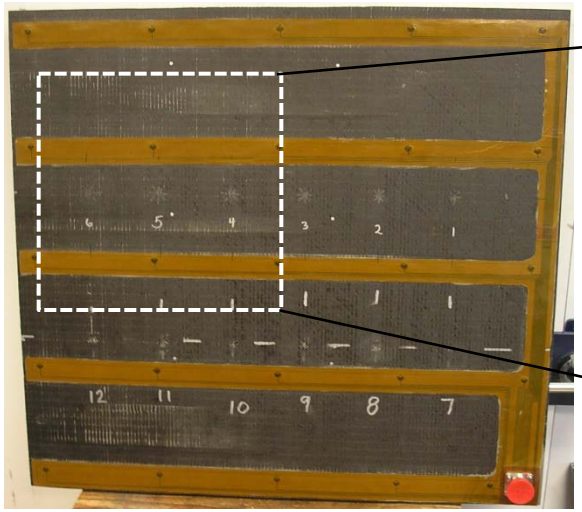


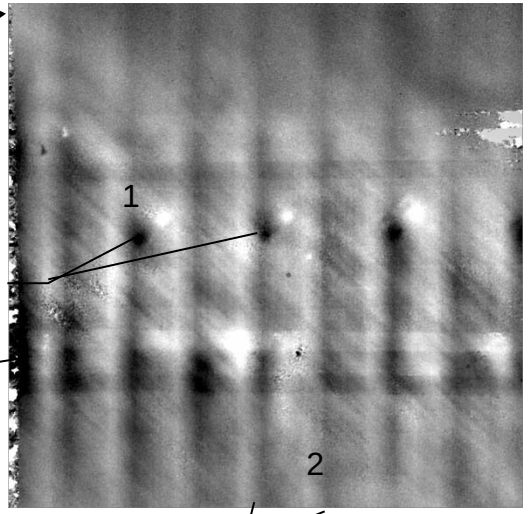
Contour map of slope changes

How to Interpret the Shearography Images

- **Stressing => Thermal**
- **Moving in the direction of shear**
  - **(1) Black to white indication => Indication moving outward relative to its surrounding (Less stiff, indicating weak bond, unbond or core defect)**
  - **(2) White to black signature => Indication moving inward relative to its surrounding (added stiffness, the webs add stiffness to the core)**







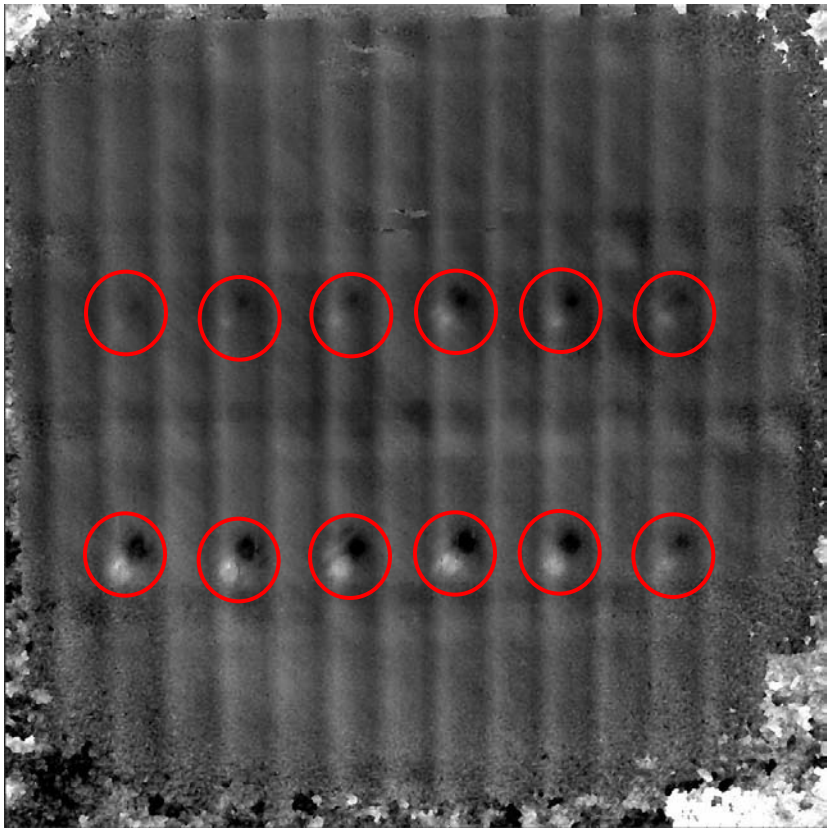
Impact damage

Sensor Strip

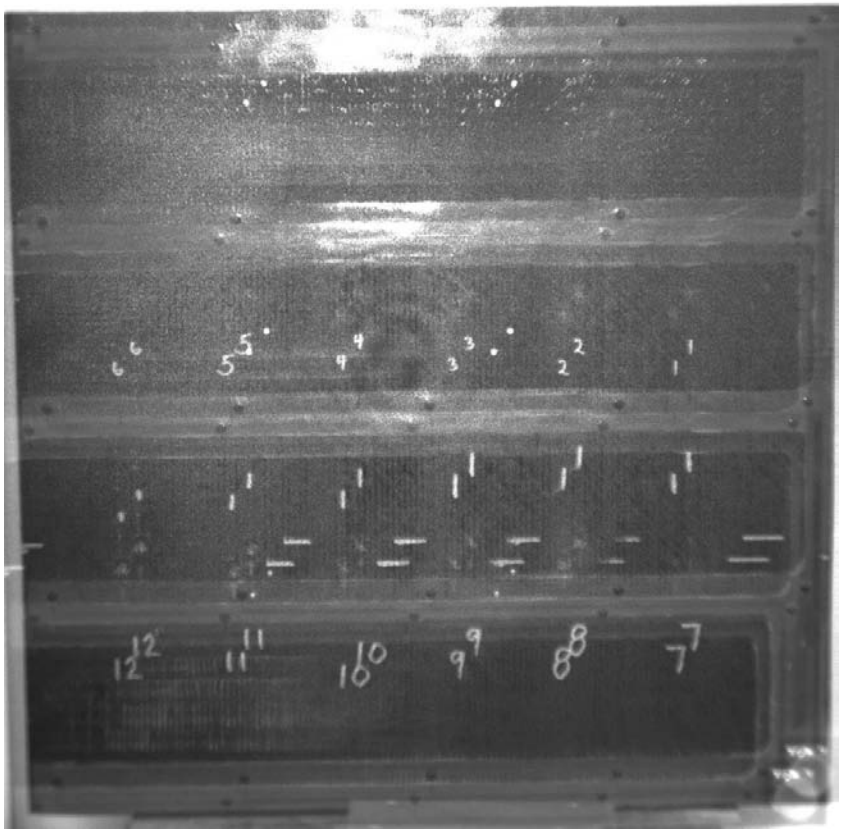
Webs

Shear vector

Typical Shearography Results



Shearogram



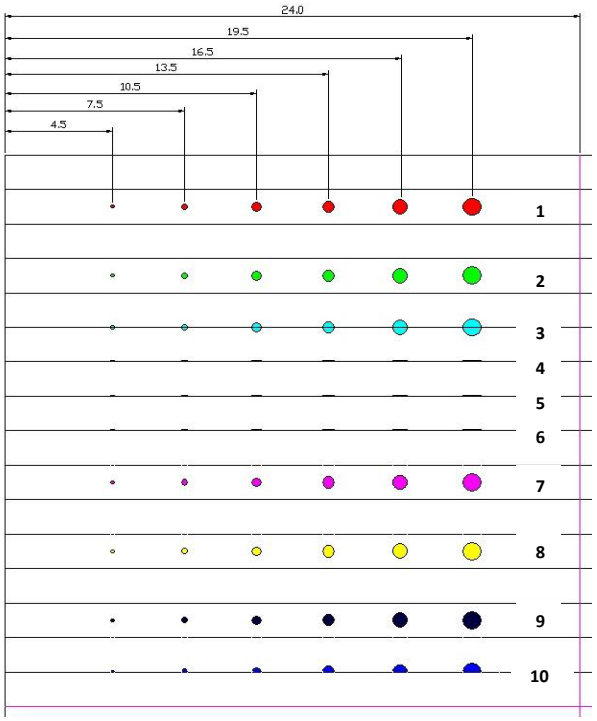
Live (Sheared) Image

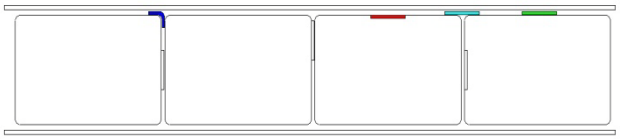
	Impact 6	Impact 5	Impact 4	Impact 3	Impact 2	Impact 1
Height	0.18”	0.33”	0.34”	0.61”	0.32”	0.21”
Width	0.10”	0.16”	0.17”	0.30”	0.27”	0.13”

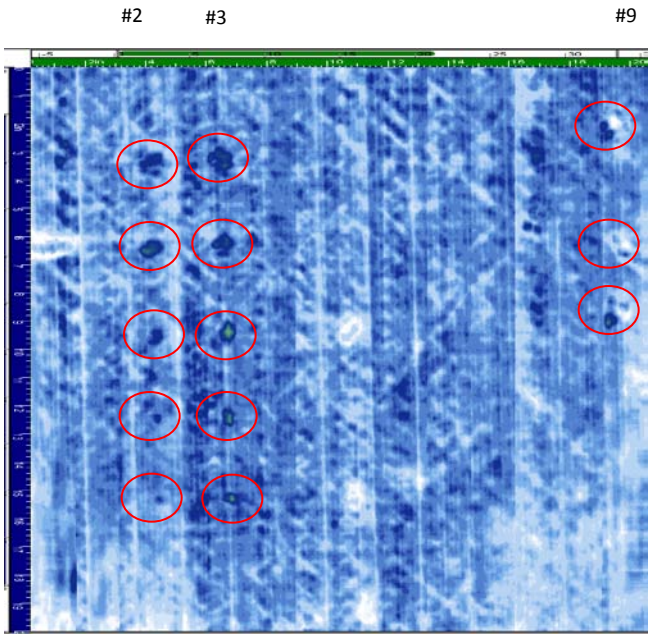
	Impact 12	Impact 11	Impact 10	Impact 9	Impact 8	Impact 7
Height	1.03”	0.82”	0.74”	0.69”	0.66”	0.57”
Width	0.53”	0.43”	0.35”	0.32”	0.29”	0.22”

Structural Health Monitoring Test Panel

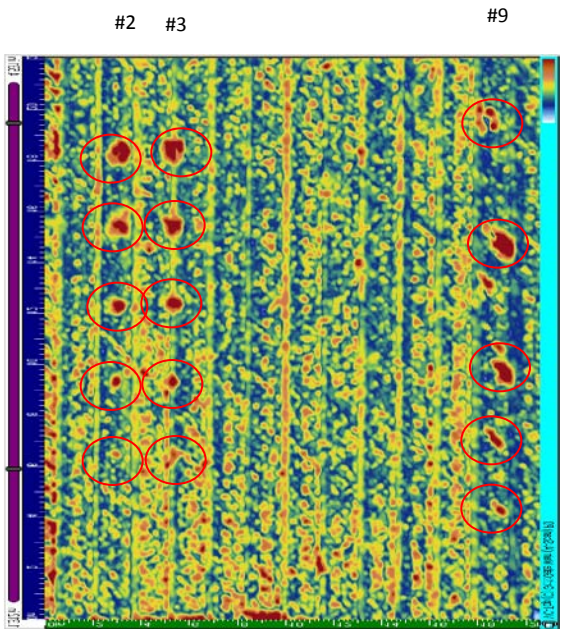
Phased Array Ultrasonics (PAUT)







Contact PAUT(2.25MHz)



Immersion UT (1 MHz)

Defects found
2. Between foam core overwrap and face sheet, centered between webs
3. Between foam core overwrap and face sheet, centered over web
9. 6 levels of impact damage

- Very noisy data due to high porosity, low consolidation of panel
- Contact PAUT was not as sensitive to impact damage or simulated delaminations (Teflon Inserts) as immersion UT
- Will be continuing to work method to see if UT results can be improved.

Conclusions

- **Fiber reinforced foam has proven to be a challenge for NDE**
- **Need a better understanding of damage tolerance and critical defect types/sizes**
- **Conventional methods for composites including shearography and thermography appear to work well on the face sheet and face sheet to core bond but do not provide adequate coverage for the webs**
- **Additional methods will need to be developed for the webs and web to foam core bond if it turns out that critical defects in these regions can't be controlled during manufacture**