NDE of Fiber Reinforced Foam Composite Structures for Future Aerospace Vehicles

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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

**Earth Departure Stage (EDS)**
- One Saturn-derived J-2X LOX/LH₂ engine (expendable)
- 10-m (33-ft) diameter stage
- Aluminum-Lithium (Al-Li) tanks
- Composite structures, Instrument Unit and Interstage
- Primary Ares V avionics system

**Core Stage**
- Six Delta IV-derived RS-68B LOX/LH₂ engines (expendable)
- 10-m (33-ft) diameter stage
- Composite structures
- Aluminum-Lithium (Al-Li) tanks

**Solid Rocket Boosters (2)**
- Two recoverable 5.5-segment PBAN-fueled, steel-case boosters (derived from current Ares I First Stage)
- Option for new design

**Payload Shroud**

**Payload Adapter**

**Altair Lunar Lander**

**Loiter Skirt**

**Interstage**

**Gross Lift Off Mass**: 3,704.5 mT (8,167.1k lbm)
**Integrated Stack Length**: 116.2 m (381.1 ft)

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 lbm) to TLI
- 118.8 mT (262K lbm) to LEO
Fiber Reinforced Foam Material System

Graphite/epoxy face sheet

Graphite/epoxy webs

Foam cells

2’ x 2’ NDE reference standard (Payload Shroud Configuration)
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
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 in helical pattern

Fabric/Core/Fabric Lay-up

Face sheet pre-form
Core Overwrap
Foam core

Precursor Foam strip with transverse webs

High-Speed Winding Process

Carbon Tow

Precursor/tooling foam

Resin infusion and sheet consolidation process

Bi-directional composite web architecture

Low-Cost TYCOR® Core

Preform Sheets Shipped to Customer

High-Speed Winding Process

Resin infusion and sheet consolidation process
NDE Methods Explored
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

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

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

Boom inspection of 1/16th scale FRF barrel segment
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.

Defect (delamination) remains warmer than surroundings.
Typical IRT Results

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<th>Impact 5</th>
<th>Impact 4</th>
<th>Impact 3</th>
<th>Impact 2</th>
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<td>0.58”</td>
<td>0.58”</td>
<td>0.48”</td>
<td>0.44”</td>
<td>0.41”</td>
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</table>

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
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

(Test Setup at MSFC)
How Shearography Works

- 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 (λ/10).
- Real-Time imaging of subsurface defects.
- Non-Contact.
- Non-contaminating.

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

Shear vector

Contour map of slope changes

Displacement profile
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)
Typical Shearography Results

Shearogram

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<th>Impact 4</th>
<th>Impact 3</th>
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<td>0.30”</td>
<td>0.27”</td>
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</table>

Live (Sheared) Image

<table>
<thead>
<tr>
<th>Impact 12</th>
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<th>Impact 10</th>
<th>Impact 9</th>
<th>Impact 8</th>
<th>Impact 7</th>
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<td>Width</td>
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<td>0.43”</td>
<td>0.35”</td>
<td>0.32”</td>
<td>0.29”</td>
</tr>
</tbody>
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Structural Health Monitoring Test Panel
Phased Array Ultrasonics (PAUT)

- 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.

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
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