4th IAASS Conference - Making Safety Matter

Nondestructive Evaluation and Monitoring Results from COPV Accelerated Stress Rupture Testing, NASA White Sands Test Facility (WSTF)
(No. 1876627)

POCs:
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NASA JSC: Scott Forth
NASA MSFC: Curtis Banks
NASA/KSC: Richard Russell
Cornell University: Leigh Phoenix

Overview

• Background

• Test Programs of Focus

• NASA Nondestructive Evaluation (NDE) Working Group (NNWG) Testing

• Orbiter Testing – NNWG Piggyback Efforts
Background and Issues

- Safe applications of Composite Pressure Vessels (CPVs) is major concern
  - The NASA Engineering and Safety Center (NESC) conducted two major Composite Overwrapped Pressure Vessel (COPV) Technical Assessments (concerns were passed on to associated programs)
    - NDE was not adequately implemented during Shuttle and ISS COPV manufacturing, and provisions were not made for on-going COPV structural integrity or health checks
    - "Stress rupture" of Orbiter (Kevlar®) and ISS (carbon) COPVs is a major concern
    - Stress rupture failure of gas pressurized COPVs on the ground or in flight presents a catastrophic hazard
  - Findings and recommendations issued in the carbon and Kevlar reports:
    - F: No NDE technique is currently known to be directly applicable to prediction of stress-rupture and other life-limiting damage mechanisms in COPVs
    - R: The NDE, Materials, and Structures technical communities should join forces to plan and undertake a feasibility study of various potential NDE techniques that may be capable of detecting degradation leading to stress rupture in carbon COPVs. This includes:
      - Identification of physical and chemical changes to target appropriate NDE
      - Identification of any NDE response that correlates to progression toward stress rupture

Objective

- Develop and demonstrate NDE techniques for real-time characterization of CPVs and, where possible, identification of NDE capable of assessing stress rupture related strength degradation and/or making vessel life predictions (structural health monitoring or periodic inspection modes)
  - Secondary: Provide the COPV user and materials community with quality carbon/epoxy (C/Ep) COPV stress rupture progression rate data
  - Aid in modeling, manufacturing, and application of COPVs for NASA spacecraft
Technical Methodology/Approach

- The recent carbon stress rupture testing builds on previous Kevlar® composite projects
  - NNWG Kevlar Stress Rupture 2006-2008
  - Orbiter Kevlar testing 2006-2009
  - Carbon stress rupture project 2008-2012
  - On-going NESC Composite Pressure Vessel Working Group testing and analysis
- To support the effort, a team of NDE experts was selected from the NNWG membership, the NASA Engineering and Safety Center (NESC), academia, and industry, with the goal of accomplishing this project in a highly collaborative manner.

Expanded Composite Stress Rupture NDE Team

- **WSTF:**
  - Regor Saulsbury - PM/project oversight, piggyback campaign
  - Jess Waller - scheduling and project tracking assistance
  - Mark Leifheit - laboratory analysis
  - Tony Carden, eddy Andrade/Charles Nichols
  - Daren Cone - eddy current
- **JSC:**
  - Ajay Kohli - NDE liaison to CEV, Bud Castner Standards, Scott Forth - M&P/Analysis
  - Tom Yolken (MD) - technical oversight and project administration
  - Scott Thompson (TX) - CPV aging and real-time NDI and stress testing
  - George Matzkanin - ASTM Aerospace Composites Chair
- **LaRC:**
  - Eric Macdonald - NDE technical oversight, AE, extensive other NDE
  - Buoz Wincheski - NDE technical oversight
  - Philip Williams
  - Elliot Cramer - thermography
- **MSFC:**
  - Tom Yolken (MD) - technical oversight and project administration
  - Scott Thomson (TX) - CPV aging and real-time NDI and stress testing
- **C:**
  - Rick Russell - liaison to Shuttle Orbiter Project Office, NDE/materials
- **DFRC:**
  - Lance Richards - FOBG consulting
- **GRC:**
  - Don Roth - NDE (e.g., guided waves)
  - Frank Person - extensive destructive analysis (Jeffrey L. Fristogi - Raman)
  - Rick Russell - liaison to Shuttle Orbiter Project Office, NDE/materials
  - John Theisen - analysis
- **UoM-C:**
  - Glenn Washburn - Raman spectroscopy, technical recommendations
  - Cornell University
  - Leigh Phoenix - Stress rupture consulting and laboratory testing
Technical Methodology/Approach

• First, complete the NNWG Kevlar efforts and Orbiter Kevlar Stress rupture testing
• Build a state-of-the-art 20 station stress rupture NDE and monitoring test bed
  • Allow inspection and monitoring at pressure
• Evaluate numerous (80-100) carbon bottles during stress rupture progression in lots of 20
  • Fiber types are to represent ISS, current, and potential future vessels

Technical Methodology/Approach (cont'd)

• Correlate real-time NDE and instrumentation with stress rupture progression:
  – Include conventional and fiber-based acoustic emission (AE), and distributive impact detection systems (DIDS) sensors
  – Include GRC capacitance sensors, Métis sensors, AE arrays, Agilent passive wireless sensors (strain and temperature), and others developed by Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) to be added as available
  • Other structural health monitoring (SHM) collaborations are openly invited
  – Add in situ portable Raman if feasible
  – Evaluate feasibility of ISS vessel monitoring with AE sensors on interface lines
Progress - Kevlar

• Completed the second Kevlar® campaign
• ~18-month Orbiter Kevlar stress rupture test concluded with vessel failure
  – Excellent AE data from start to vessel failure
  – Eddy current used to monitor liner and composite thickness variations
  – Portable WSTF/LaRC Raman developed and applied in situ to the Orbiter 40-in. vessel
  – Also good progress made with Raman scanning of NNWG Kevlar vessels at LaRC

WSTF Orbiter COPV Instrumentation and NDE During Rupture and Stress Testing

<table>
<thead>
<tr>
<th>Method</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Inspection (Pretest)</td>
<td>External inspection of overwrap. Indication of gross damage</td>
</tr>
<tr>
<td>Both Flash and Heat Soak</td>
<td>Heat Signature Decay Sub-surface Ply Delamination. Heat soak or thru transmission works better with thicker composites.</td>
</tr>
<tr>
<td>Thermography (Pretest)</td>
<td></td>
</tr>
<tr>
<td>Videoscope Inspection (Pretest)</td>
<td>Internal inspection of liner. Indication of damage or buckling</td>
</tr>
<tr>
<td>Laser Profilometry</td>
<td>Internal surface mapping and measurement. Evaluate ripples, potential buckling, and crossover imprinting on spherical tanks</td>
</tr>
<tr>
<td>Laser Shearography</td>
<td>Differential strain resulting from any cause (e.g., impacts, delaminations, broken fiber, etc.)</td>
</tr>
<tr>
<td>Cabled Girth and Boss LVDT</td>
<td>Circumferential and axial displacement</td>
</tr>
<tr>
<td>Strain Gauge (Test)</td>
<td>Change in length. Average fiber strain under the sensor.</td>
</tr>
<tr>
<td>Fiber Bragg Grating (Test)</td>
<td>Change in length. More localized strain</td>
</tr>
<tr>
<td>Acoustic Emission (Test)</td>
<td>Acoustic noise. Fiber breakage or delamination.</td>
</tr>
<tr>
<td>Full Field Digital Image Correlation</td>
<td>Global or localized strain</td>
</tr>
<tr>
<td>Eddy Current Probes</td>
<td>Composite thickness change</td>
</tr>
<tr>
<td>Portable Raman Spectroscopy</td>
<td>Residual stress/identification of stress gradients. May have potential to indicate stress rupture progression (SN.007)</td>
</tr>
</tbody>
</table>
Laser Profilometry Accurately Quantifies Liner Buckling and Other Surface Features

Calibration traceable to National Standard and demonstrated 0.001 in. accuracy/repeatability on 30-in. and better than 0.002 in. accuracy/repeatability on 48-in.
Shearography Data at the Equator Correlated Well with COPV Liner Profilometry Scan

- Profilometer scan of the inside surface of the liner at the equator shows 0.020 to 0.040 in. liner deformations (large ripples) at these same locations.

Pressure Shearography Data @ Equator

Interior Profilometry Scan of the Equator

Profile of COPV Liner ID
The large ripples around the girth weld raised a question, but other no observed indications were an issue with planned stress rupture testing.

- Eddy current sensors were placed over the peak of each girth ripple and monitored during pressurization to verify the liner did not flex causing a metallic fatigue concern.
- Decrease of stand-off between the fixed composite surface and liner ripple would indicate a liner buckle and associated air pocket.
- Stand-off remained fixed during pressure cycles, indicating that the indications were not a concern.
Testing: 3/18/09-10/23/09: Final Week

Energetic Event No. vs. Time: Final Week

Energetic Signal Levels vs. Time: Final Week
Testing: 10/13/09-10/23/09:
Final High Energy Burst (Final 24 h)

Locations of Energetic Events
- Red lines are the location of the larger events
- The dark red line is the location at depressurization (which was the largest)

AE Summary

- There were two AE event rate increase periods that occurred during the last 7 days. The last rate increase ended in failure.
  - There were over 3000 recorded events during the last 10 days.
  - There were more than 300 very energetic events recorded during the last week.
  - The rate increases were coincidental with trains of very large energy signal events.
  - The first rate increase for large energy, signal events (24 to 96 hours before the end) was approximately 2/hour.
  - The second and final rate increase for large energy signal events (last 24 hours) was approximately 6/hour.
- Event energies rose to very elevated levels during the last 96 hours.
  - High energy events were >25 times greater than energetic events in the past.
  - The loudest events occurred at the end (last 24 hours).
  - The final event, which was the loudest, was located ~45° below the equator and near the azimuth angle of 45°.
Comparison of AE Events to Strain During Final Week

- AE event numbers show increasing at ~6070 hours
- Strain near failure location increases rapidly near the end

Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing

- Portable WSTF/LaRC Raman developed and applied in situ to Orbiter 40 in. vessel in stress rupture test
- Tim Gallus performing bench top testing of a Raman spectography system prior to installation in the test cell
Typical Raman Spectrum of Kevlar

<table>
<thead>
<tr>
<th>Wavenumber (cm⁻¹)</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3250</td>
<td>Ring vibration</td>
</tr>
<tr>
<td>3450</td>
<td>C-H out-of-plane bending</td>
</tr>
<tr>
<td>3500</td>
<td>C-H in-plane bending</td>
</tr>
<tr>
<td>3550</td>
<td>C=C ring stretching</td>
</tr>
<tr>
<td>3570</td>
<td>C-H in-plane bending</td>
</tr>
<tr>
<td>3590</td>
<td>Amide I, II, III, IV, V bands</td>
</tr>
<tr>
<td>1610</td>
<td>C=C, C-N stretching</td>
</tr>
</tbody>
</table>

Raman Data by LaRC-Buzz Wincheski and Philip Williams

strain-induced Raman Shift in Kevlar 49 fiber

Real-time Raman During COPV SN007 Stress Rupture Testing - 8/15-10/22/09

1610 cm⁻¹ Peak FWHM Normalized by 1325 cm⁻¹ Peak FWHM

Aging induced peak broadening

Note: FWHM = Full Width at Half Maximum
Slide 27

Remote Scanning Raman Configuration

LaRC Experimental Setup for Measurements on 6.25 in. NNWG Kevlar® and Carbon CPVs

Slide 28

360 Degree Raman Scan of COPV S/N 009

Position of 1610 cm⁻¹ peak  Amplitude of 1610 cm⁻¹ peak  FWHM of 1610 cm⁻¹ peak
Progress – Carbon Stress Rupture Project

- 100 carbon COPVs designed and fabricated
  - 50 ea IM7 carbon vessels to represent ISS
  - 50 ea from T1000 to represent Orion and potential future NASA spacecraft
  - 6.3 in. dia., 6061 T6 aluminum liners, nominal 7500 psi burst to provide adequate carbon thickness
  - Same lots of fiber used and many strand tests made to ensure quality
  - Plant trips to observe winding process and witness burst tests
- NESC assisted with comprehensive modeling of vessels in Abacus® to identify the mechanical response
  - WSTF modeled in Genoa™ and got similar results
  - Separate autofrettage tests done on identical bottles on NESC funding to evaluate response as compared to the model

Progress – Carbon Stress Rupture Project (cont'd)

- T1000 and IM7 strand tensile tests and stress rupture completed at Cornell University and WSTF to ensure lot consistency and help set test pressures
- State-of-the-art 20 station test system brought on-line
  - Maintains pressure at approximately 30 ± 2 psi regardless of temperature swings (appears to be a first for the Stress Rupture test industry)
  - Rapidly auto-isolates bottles as they rupture
  - Protective enclosures allow inspection of vessels up to rupture pressure
  - Extensive data acquisition and real-time NDE capability to validate sensors and NDE
Progress – Carbon Stress Rupture Project (cont'd)

20 carbon vessels and real-time NDE in WSTF. Lexan protective enclosure allows inspection while at test pressure.

Preparing the Stress Rupture Test System

Team of WSTF (using Digital Wave 32 channel) and Physical Acoustics AE experts evaluate response of different AE systems during system checkout.
<table>
<thead>
<tr>
<th>Method</th>
<th>Measurement Results</th>
<th>Location/Responsible Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guided Wave</td>
<td>Defects in the wave path and modulus change</td>
<td>GRC/GFC (others as available)</td>
</tr>
<tr>
<td>Laser-induced UT</td>
<td>Defects in the path of wave path and modulus change</td>
<td>Materials and Sensors Technologies, Inc. (MSFC if available)</td>
</tr>
<tr>
<td>Laser Profilometry</td>
<td>Inspection of the liner for dimension changes and for buckling</td>
<td>WSTF/LTC</td>
</tr>
<tr>
<td>Pressure, Temperature</td>
<td>Pressure and temperature for given duration</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Cabled Girth LVDT</td>
<td>Circumferential displacement measured at the middle of the barrel section</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Strain Gauge</td>
<td>Change in length, Fiber strain</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Fiber Bragg Grating</td>
<td>Change in length, High resolution low fiber strain information</td>
<td>WSTF/MSFC</td>
</tr>
<tr>
<td>Acoustic Emission</td>
<td>Acoustic noise, Fiber breakage or delamination</td>
<td>WSTF/LaRC</td>
</tr>
<tr>
<td>Visual Inspection (interior)</td>
<td>Internal inspection of liner Indication of damage or buckling of the liner</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Shearography (Barrel)</td>
<td>Forced out-of-plane deflection Sub-surface mechanical damage or ply delamination</td>
<td>WSTF/WSTF, MSFC/MSFC</td>
</tr>
<tr>
<td>Flash Thermography (Domes)</td>
<td>Heat signature decay Sub-surface ply delamination</td>
<td>WSTF/WSTF</td>
</tr>
<tr>
<td>Ultrasonic Inspection</td>
<td>Acoustic time of flight measurement to determine composite ply delamination and modulus</td>
<td>MSFC/MSFC</td>
</tr>
<tr>
<td>Specialized Thermography</td>
<td>Fine distributed damage from fiber breakage/matrix cracking</td>
<td>LaRC/LaRC</td>
</tr>
<tr>
<td>Raman Spectroscopy</td>
<td>Strain mapping and FWI/M wave form changes</td>
<td>LaRC/LaRC</td>
</tr>
<tr>
<td>Real-time Raman Spectroscopy</td>
<td>Real-time strain mapping and FWI/M wave form changes</td>
<td>WSTF/LaRC</td>
</tr>
<tr>
<td>Structural Health Monitoring Sensor</td>
<td>Multiple structural health monitoring (SHM) sensors are planned to be applied as made available from SBIR/STTR Phase I/II and by participating Centers</td>
<td>WSTF/MSFC, MSC, &amp; GRC</td>
</tr>
</tbody>
</table>
Progress – Carbon Stress Rupture Project (cont’d)

• Completed stress rupture testing on the 1st and 2nd lot of 20 (each) T1000 vessels
  – Failed 6 vessels on first lot and 4 on the second lot
  – First 20 IM7 lot installed
  – NDE of aged and virgin vessels in progress at NASA Centers and at Materials and Sensors Technology (MAST Inc.)
  – Lessons learned from first round being implemented
    • e.g., autofrettage first to enhance AE, DIDS improvements
• Laser UT and low noise water jet UT looks promising at MAST Inc.
  – Laser UT especially effective in evaluation of modulus changes

Progress – Carbon Stress Rupture Project (cont’d)

• NESC correlating stress rupture progression rate data with existing community database
  – Carefully controlled data should improve database
  – Profilometry also being done to directly evaluate residual deformation and growth (strain measurement) over the stress rupture period
Lot #1, Vessels 1-10, Full Time History, Hoop

Lot #1, Vessel 14, Ramp and Failure, Hoop

Note: ~100 times faster strain creep to failure when progressive failure starts.
Slide 39

**NNWG IM7 C/Ep COPV AE Energy**

**Events vs. Time**

- Channel 2
- Channel 3
- Channel 4
- Channel 5
- Channel 6
- Channel 7

Slide 40

**Felicity Ratio**

Felicity ratio (FR) given by:

\[ FR = \frac{\text{stress at onset of significant acoustic emission during loading}}{\text{maximum previous stress plateau}} \]

Example using an intermittent load hold (ILH) profile:

\[ FR = \frac{121.2}{120} = 1.01 \]
C/Ep Results & Discussion

Regions of high AE activity correspond to events occurring early in COPV life cycle up to catastrophic failure.

Correlation coefficients for ILH method good to excellent agreement ($R^2 \geq 0.90$).

Correlation of IM7 C/Ep COPV AE Felicity Ratio to Strand Data

Proof-of-concept Felicity ratio analysis of an IM-7 reinforced C/Ep COPV (blue data) superimposed on Kevlar® 49 (green line), T1000 (red line), and IM7 (blue line) single tow data.
Future Milestones

FY 2010
- Complete stress rupture aging of the 1st lot of 20 IM7 vessels by June 15, 2010
- Complete stress rupture aging of the 2nd lot of 20 IM7 vessels by August 12, 2010

FY 2011
- Complete the 2nd stress rupture aging campaign of T1000 vessels by November 3, 2010
- Complete the 2nd stress rupture aging campaign of IM7 Vessels by January 24, 2011

FY 2012
- Complete post-test NDE at NASA Centers by April 8, 2012
- Complete final report by August 30, 2012

Conclusion
- NDE has proven highly effective in real-time characterization of COPVs during testing
- NDE is reasonably effective in evaluating the health of COPVs, but still more work is needed to make it more quantitative and predictive
- Overall, a well controlled and informative Carbon COPV Stress Rupture test is being accomplished
  - Collaboration on SHM sensor evaluation is invited
Backup

Slide 46

Composite Vessel Test Programs – Multi-Center
(NDE in red)

- Kevlar® and PBO COPV Stress Rupture/Burst
- COPV Cryogenic Carbon Composite Testing
- Carbon COPV Stress Rupture/Burst (Pretest & real-time NDE)
- Hypergolic Propellant Compatibility Study
- COPV Stress Rupture Testing
- Advanced COPV Feasibility Studies
- COPV Stress Rupture Studies
- Vacuum, Humidity and Shear Life Stress Rupture Testing
- Carbon Fiber COPV Impact Damage Studies
- Composite COPV Liner NDE Standards FY05-10
- Stress Rupture NDE Kevlar® 05-07 and Carbon 08-10
- Composite NESC Regions & Burst Reductions FY08-10
- Characterization of Composite Microstructure, e.g. Acousto-Optics - 08-10
- Vacuums, Humidity and Shear Life Testing
- COPV Stress Rupture Testing
- Advanced COPV Feasibility Studies
- Composite COPV Liner NDE Standards FY05-10
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- Composite COPV Liner NDE Standards FY05-10
**Summary/Status of NDE Methods**

(Full table in the Final Report)

### Acoustic
- **Acoustic Emission**: Promising recommend for Phase II (indirect/monitoring)
- **Conventional Pulse Echo Ultrasonics**: Delayed
- **Acousto-ultrasonics**: Exploring Lamb Waves/Plate Waves instead
- **Lamb Waves/Plate Waves**: GRC found delams, but further work currently in progress to evaluate stress rupture
- **Laser Induced Acoustic Waves**: Promising recommend for Phase II, modulus (Boro Djordjevic)

### Electromagnetic
- **Eddy Current**: Provides indirect data for characterization
- **Microwave/millimeter Wave**: Promising recommend for Phase II
- **Terahertz**: Under further evaluation
- **One-sided NMR**: Delayed recommend under Phase II
- **Raman Spectroscopy**: Promising recommend for Phase II
- **IR Thermography**: Finds conventional damage, but no SR correlation

### Strain Measurement
- **Distributed Strain Sensing (FBG)**: Promising recommend for Phase II
- **Berea Mechanical Strain Gauges**: Promising recommend for Phase II
- **Belly Band LVDT**: Being applied further by manufacturing NDE Project
- **Image Correlation**: Being applied further by manufacturing NDE Project
- **Shearography**: Being applied further by manufacturing NDE Project

### Penetrating Radiation
- **X-ray Radiography & CT**: Deemed Low chance of success, delay/delete?

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**Summary/Status of DE Methods**

(Full table in the Final Report) (cont’d)

### Optical Microscopy
- Successful for supporting data (fiber splitting, kink bands, ply lay-up, fiber/resin volume ratios)

### Scanning Electron Microscopy
- Successful for supporting data (fiber splitting, kink sheath peeling in fracture, fiber ends taper on fracture)

### Scanning Electron Microscopy/ Micro-load frame/AE
- Promising for visualization of stress rupture failure propagation events and associated AE

### X-ray Diffraction
- Initial work appears promising, indicates difference in intensities of major Bragg peaks between intact fibers, frayed fibers, fast fracture fibers, and stress-ruptured fibers. Also showed possible difference between bottles aged at elevated temperature and elevated stress.

### Energy dispersive x-ray spectroscopy
- Carbon only element identified; not useful in differentiating among test bottles and rupture conditions