White Sands Test Facility

Task: Composite Stress Rupture NDE Research and Development Project (Kevlar® and Carbon)

Figure 1
Regor Saulsberry and Luis Hernandez review data from carbon vessels and real-time NDE in test. These vessels are in a WSTF Lexan® protective enclosure that allows inspection while at test pressure. Shown to the right is a solid model of the enclosure.

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Materials and Sensors Technologies (MAST Inc.): UT scanning support

Objective
To develop and demonstrate nondestructive evaluation (NDE) techniques capable of assessing stress rupture related strength degradation for carbon composite pressure vessels, either in a structural health monitoring (SHM) or periodic inspection mode.

Approach
A team of NDE experts was selected from the NASA NDE Working Group (NNWG) membership, the NASA Engineering and Safety Center (NESC), academia, and industry to accomplish this project in a highly collaborative effort. The team approach is to build a versatile NDE test bed for real-time

monitoring of pressure vessels as they progress under stress toward failure. The majority of the vessels will be removed prior to failure for post-test NDE applications to develop a correlation between various types of NDE response and damage accumulation.

To accomplish this, a 20-station test system, referred to as the NNWG Carbon Stress Rupture Test System (CSRTS), was fabricated at NASA White Sands Test Facility (WSTF). The CSRTS provides a test bed for NDE and SHM development and verifications. The system design is unique because it uses a technique called "active pressure," which uses computer control to maintain the bottle pressure within ± 2 °F regardless of temperature variation, without the use of accumulators. The CSRTS is housed in a protective polycarbonate enclosure so viewing and visual inspection can be performed while vessels maintain full test pressure, although personnel working around the system receive a safety briefing and are required to wear eye and ear protection. In addition, pressure vessels are automatically isolated as they rupture, reducing pressure variations on adjacent vessels. The state-of-the-art facility offers extensive data acquisition and real-time NDE capability to validate sensors and NDE for spacecraft applications.

Fifty T1000 and fifty IM7 carbon fiber bottles were wrapped and are being stress rupture tested and aged in lots of 20. These two fiber types were selected to represent current and potential future carbon composite overwrapped pressure vessel (COPV) designs. During stress rupture progression, NDE is being correlated with real-time instrumentation (pressure, strain gauges and belly bands, and temperature) to evaluate and demonstrate potentially effective spacecraft applications (Fig.1). Creep is monitored during progression to failure (~ 6 to 8 weeks). Data from conventional and fiber based acoustic emission (AE), wireless distributive impact detection systems (DIDS), and phased array AE are collected for comparison. Other SHM systems being developed by Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs are added as they become available. Passive wireless strain and temperature measurement sensors will be added on the COPV exterior and interior surfaces to evaluate potential application of these passive instrumentation tags. Portable Raman spectroscopy is also to be further developed and added.

Pre-test NDE (shearography and thermography) is performed on vessels prior to installation in the test system. The NDE response is compared to physical standards to better quantify results and ensure manufacturing consistency. After pre-test NDE, the vessels are instrumented in lots of 20 and installed in the test system. Once in test, the vessels are pressurized to approximately 90 % of their design burst pressure. If no failure occurs after two weeks, the pressure is increased ~ 100 psi and held for another two weeks before implementing the next pressure step. This process is continued until 4 or 5 of the vessels have failed, at which time the system pressure is dropped to ambient and the remaining vessels are removed for evaluation by NDE. Correlations are made between pre-, real-time, and post-test data. The post-test NDE is being performed at the NASA Centers and industry sites best suited to apply the various techniques. Once this post-test evaluation is completed, vessels are returned to WSTF for further stress rupture aging and monitoring. The post-test NDE is then repeated at the Centers to provide two levels of aging data for NDE response comparison. Post-test NDC methods include Raman spectroscopy scanning, phased array ultrasonic testing (UT), immersion UT scanning, and other UT guided waves techniques to evaluate modulus change and evaluate distributed damage. Deformation is also evaluated by internal laser profilometry and shearography, and line scan thermography is applied to evaluate distributed damage accumulation. The UT techniques have shown the greatest promise for physical property evaluation, such as modulus, which may be correlated to loss of integrity.

In addition to evaluating the progression toward stress rupture failure by NDE, Glenn Research Center will perform destructive analysis (DE) of failed and virgin vessels with various laboratory equipment to further evaluate physical property and microstructural changes. Data from this analysis can be useful in selection of additional NDE techniques to target these changes.

Customers
The direct customers for this task are the Space Transportation System, International Space Station (ISS), Constellation or "Flexible Path" vehicles, "Flagship" mission vehicles, "In-Space Propulsion"/Planetary programs, and others related to NASA's Space Exploration Initiatives. Indirect customers are all other space flight systems employing COPV technology. The results developed could be used across the Agency, DOD, and in commercial aerospace applications.

Metrics
Progress toward understanding the physical and chemical property changes associated with stress rupture, and development of fundamental methods for evaluation of stress rupture, shall be detailed in annual status presentations made to the NNWG, with metrics provided for comparison to the original project plan. The final report shall describe overall project progress and accomplishments and make recommendations for future efforts.

Products
- Stress rupture data, SHM, NDE, and DE techniques available to NASA and Government programs to help ensure safer COPV utilization and mission success
- Advancement in accelerated aging methodologies and systems
- Annual status reports
- Final report
- Open literature publications

Progress
Year 1 (2008)
- A portable Raman spectroscopy system was developed. This system was applied in situ to a 40-in. Orbiter vessel being put into stress rupture testing (Figure 2).
- The Orbiter Kevlar® stress rupture test was begun. NNWG members closely monitored AE, eddy current, and Raman data and oversaw system development of real-time NDE.
- A formal WSTF carbon vessel testing plan was developed, and the test schedule was based on lessons learned from previous Kevlar® testing.
- 100 carbon COPVs (50 T1000 and 50 IM7) were designed and fabricated to represent current and anticipated future applications. Thicker composites were used to reduce liner influence on NDE results. The manufacturing process was closely documented, and NNWG members made site trips to the fabrication plant to observe the winding process and witness burst tests. Vessels were made from the same lot of fiber to reduce variability, and many strand tests were performed to ensure consistent tensile strength. Stress rupture testing was also done at the strand level to better target vessel-level test pressures.
- Five highly protective hard-shell shipping containers were built for vessel shipping (12 vessels per container), and the first 12 vessels were shipped to MSFC for a baseline UT scan.
- Vessel "as received" NDE was accomplished. Results indicated that autofrettage (pressurization to the point of plastic liner deformation) was necessary prior to baseline testing.
- All facilities were designed and hardware procured, and the CSRTS build-up was started.

Year 2 (2009)
- NESC assisted with comprehensive modeling of vessels in Abacus® finite element analysis software to identify the mechanical response. Similar results were obtained at WSTF using Genoa™ software.
- Autofrettage tests were performed by NESC on NNWG bottles to evaluate response as compared to the Abacus® models.
- The 18-month Orbiter Kevlar® stress rupture test concluded with vessel failure. Extensive data reduction is still in progress for the AE, eddy current, and Raman data gathered.

- Excellent progress was made with Raman scanning at LaRC.
- Virgin bottles were autofrettaged and sent to NASA Centers and to MAST Inc. for NDE.
- T1000 and IM7 strand tensile tests were completed at Cornell University, and strand stress rupture tests were started. Separate Cornell/TRI (Texas Research International, Inc.) stress rupture plans were completed.
- The completed CSRTS facility was brought on-line.
- Testing of the first 20 T1000 vessels commenced.

Year 3 (2010)

- Stress rupture testing was completed on the first and second lots of 20 (each) T1000 vessels. Six vessels from the first lot failed, and 4 failed from the second lot. Data reduction for the T1000 vessels is in progress. Post-test NDE is in progress at the appropriate NASA Centers and industry locations.
- Instrumentation of the first 20 IM7 vessels has begun.
- Lessons learned from first round testing are being implemented (e.g., autofrettage should be accomplished first to enhance AE, DIDS improvements).
- Laser UT and low noise water jet UT now looks promising. Laser UT is especially effective in evaluation of modulus changes.
- Stress rupture rate analysis has started within NESC to enhance the database.
- Profilometry is being performed to evaluate deformation and growth (direct strain measurement) over the stress rupture period.
- Overall, this NDE test project is considered one of the most comprehensive, well controlled, and informative carbon COPV stress rupture testing programs done to date.

Future Milestones

FY 2010

- Complete stress rupture aging of the first lot of 20 IM7 vessels by June 15, 2010
- Complete stress rupture aging of the second lot of 20 IM7 vessels by August 12, 2010

FY 2011

- Complete the second stress rupture aging of T1000 vessels by November 3, 2010
- Complete the second stress rupture aging of IM7 Vessels by January 24, 2011
- Perform SHM sensor and system data evaluation/validation during stress rupture testing, including impedance sensors at GSC; Acellent Technologies, Inc. sensors at MSFC; DIDS at JSC, portable Raman at WSTF

FY2012

- Complete post-test NDE at NASA Centers by April 8, 2012
- Compile data and complete final report by July 15, 2012

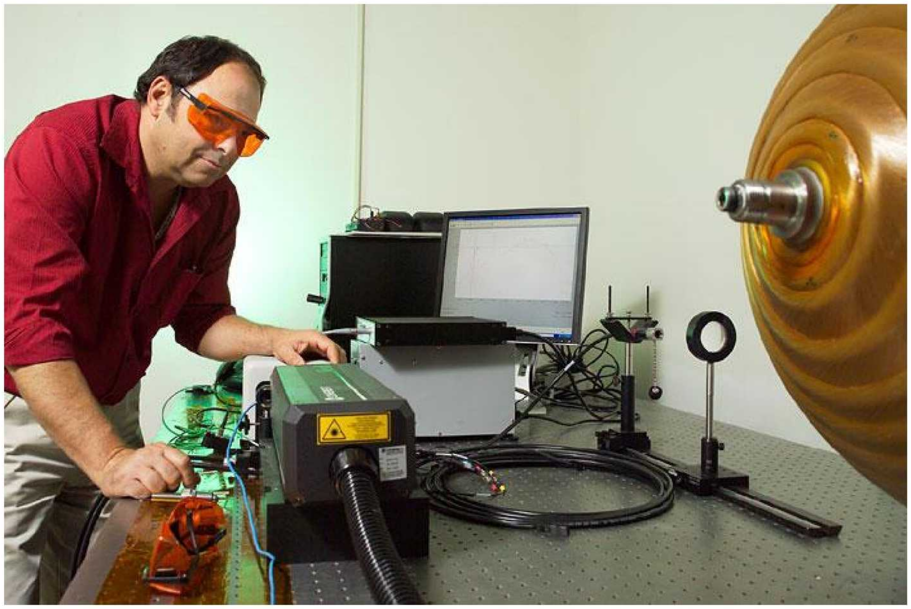

Figure 2
Tim Gallus (WSTF) sets up the portable Raman spectroscopy system.

Figure 3
Robert Browning (left) from WSTF and Curtis Banks from MSFC install conventional strain gauges next to fiber Bragg gratings, relative to a laser profilometry map.

Figure 4
WSTF analyst Chris Keddy compares NNWG and NESC vessel test data to a COPV model to better understand vessel behavior.