Stress Rupture Nondestructive Evaluation of Composite Overwrapped Pressure Vessels

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A team of nondestructive evaluation (NDE) experts was assembled to develop and demonstrate NDE techniques capable of assessing stress rupture-related strength degradation for carbon composite overwrapped pressure vessels (COPVs), either in a structural health monitoring (SHM) or periodic inspection mode. The team was composed of individuals from the NASA NDE Working Group (NNWG), the NASA Engineering and Safety Center, academia, and industry.

The team approach was to build a versatile NDE test bed for real-time monitoring of the carbon composite vessels as they progressed under stress toward failure. To accomplish this, a 20-station test system, referred to as the NNWG Carbon Stress Rupture Test System (CSRTS), was fabricated at NASA Johnson Space Center's White Sands Test Facility (WSTF) (figure 1). 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 management," which uses computer control to maintain the bottle pressure within ±2 pounds per square inch (psi) regardless of temperature variation without the use of accumulators. The COPVs are housed in a protective polycarbonate enclosure so that visual inspection can be performed while vessels maintain full test pressure. In addition, pressure vessels are automatically isolated as they rupture, so adjacent vessels remain in test. The state-of-the-art facility offers extensive data acquisition and real-time NDE capability to validate sensors and NDE for spacecraft applications.

Fig. 1. *Reviewing data from carbon vessels and real-time nondestructive evaluation in test bed.*

T1000 and IM7 carbon fiber bottles were wrapped and stress rupture aged in lots of 20. The team selected these two fiber types to represent current and future carbon COPV designs. During stress rupture progression testing that started in 2008, NDE and SHM data were correlated with real-time instrumentation (pressure, strain gauges and belly bands, and temperature) to evaluate and demonstrate potentially effective spacecraft applications. Creep was monitored during progression to failure for the accelerated 6- to 8-week tests. Data from fiber Bragg grating sensors (surface mount and embedded) (figure 2), conventional and fiber-based acoustic emission sensors, wireless distributive impact detection systems, and phased array acoustic emission were collected for comparison. A new felicity ratio method for COPVs developed by WSTF has shown promise, and in limited testing has predicted failure within 2%. WSTF personnel are creating real-time analysis software to further refine predictions and modularize the system for flight applications.

The test system is offered as a test bed to evaluate other SHM systems being developed by Small Business Innovation Research and Small Business Technology Transfer programs. As long as NNWG testing continues,

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continued

these SHM systems can be added to COPVs as they become available. Without testing of these SHM systems on COPVs, their performance is subjective and not well evaluated. Current plans call for application of various in-situ fiber-based methods, the WSTF-developed felicity ratio acoustic emission method, as well as passive wireless (strain and temperature measurement) and eddy current strain sensors orientated to measure strain in specific wrap angles. These new methods are to be added during testing planned from 2012 through 2014 as a close simulation of future flight applications. In testing to date, pretest NDE (shearography, thermography, and internal profilometry) has been performed on vessels prior to installation in the test system. The NDE response has been compared to physical standards to better quantify results and evaluate manufacturing consistency. After pretest NDE, the vessels have been instrumented in lots of 20 and installed in the test system. Once the test is started, the vessels are initially pressurized to approximately 90% of their design burst pressure. If no failure occurs after 2 weeks, the pressure is increased by approximately 100 psi and held at this pressure for another 2 weeks before implementing the next pressure step. The process continues until four or five of the vessels fail, then the system pressure is dropped to ambient and the remaining vessels are removed for NDE evaluation. Correlations are made between pretest, real-time, and posttest data. Posttest NDE is being performed at NASA centers (Marshall Space Flight Center, Langley Research Center, and Glenn Research Center [GRC]), in academia, and at industry sites best suited to apply the various techniques.

Once posttest evaluation is complete, vessels are returned to WSTF for further stress rupture aging and monitoring. The posttest NDE is then repeated to provide at least two levels of stress rupture aging data for NDE response comparison. Posttest NDE methods have included Raman spectroscopy scanning, phased array ultrasonic testing (UT), immersion UT scanning, other UT-guided wave techniques to evaluate modulus change and distributed damage, and profilometry to map and measure bulging, distortions, and growth that have occurred. Deformation is evaluated by internal laser profilometry and other techniques such as shearography, UT, and line scan thermography, which is used 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.

Fig. 2. *Conventional strain gauges installed near fiber Bragg gratings, relative to laser profilometry map.*

In addition to evaluating the progression toward stress rupture failure by NDE, WSTF has partnered with GRC for performing destructive analysis of failed and virgin vessels to further evaluate physical property and microstructural changes. Data from this analysis may be useful in selecting additional NDE techniques to measure these changes.

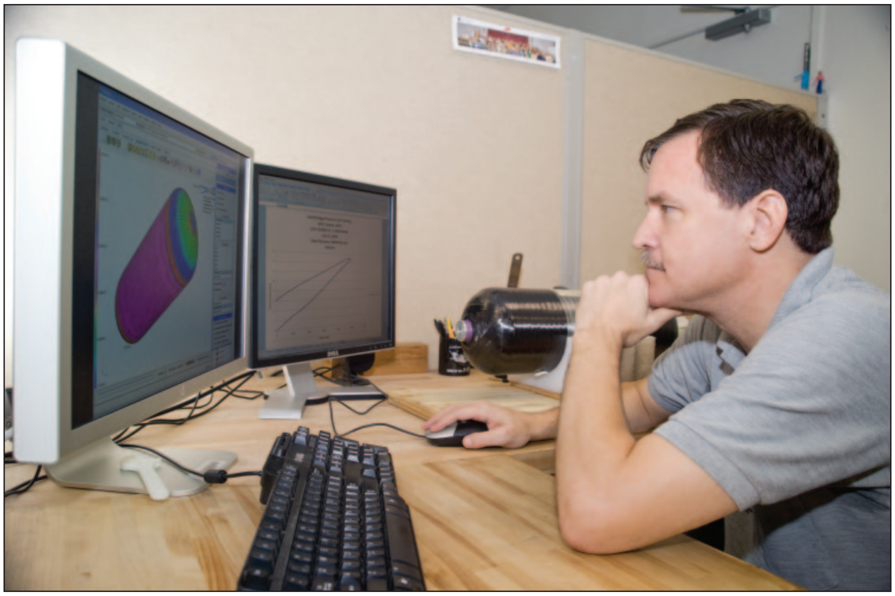

Fig. 3. *Comparing vessel test data to a composite overwrapped pressure vessel model.*

Understanding the physical and chemical property changes associated with stress rupture progression, and development of fundamental methods for stress rupture aging evaluation and vessel health monitoring can help ensure mission success and safe COPV use. This will benefit NASA spaceflight programs, Department of Defense, Department of Transportation, Department of Energy, and commercial aerospace companies that are developing NDE and SHM technology. Data from the program also serve to enhance the carbon stress rupture database, housed at WSTF, as well as increase the technical communities' understanding of vessel mechanical response as compared to modeling effort results (figure 3) being worked at WSTF and GRC and supported by the NASA Engineering and Safety Center Composite Pressure Vessel Working Group.