Correlating Composite Vessel Shearography Nondestructive Evaluation Response to Impact Damage and Associated Burst Pressure Reductions

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The NASA Johnson Space Center White Sands Test Facility (WSTF) has used laser shearography (LS) for several years to inspect and test composite overwrapped pressure vessels (COPVs). Shearography provides full-field, non-contact nondestructive testing for rapid wide-field inspection of composites, bonded structures, and other advanced materials. Shearography is an optical video strain gauge that uses appropriately applied stress to locate strain concentrations caused by internal defects. WSTF has worked closely with Laser Technology Inc. (Centennial, Colorado) to refine the LS inspection methods used for quality control by NASA and COPV manufacturers. Various types of COPVs were custom wrapped with carefully placed defects to provide reference standards (figure 1) and accomplish blind tests in which LS was compared against thermographic, ultrasonic, and other nondestructive evaluation (NDE) methods. A series of tests correlated the response of the different methods to varying amounts of impact damage and evaluated the resulting reduction in burst pressure. Shearography was identified as the most effective method of locating and quantifying defects within the carbon overwrap of COPVs. WSTF acquired a new high-definition LS system with thermal excitation to achieve greater scan versatility.

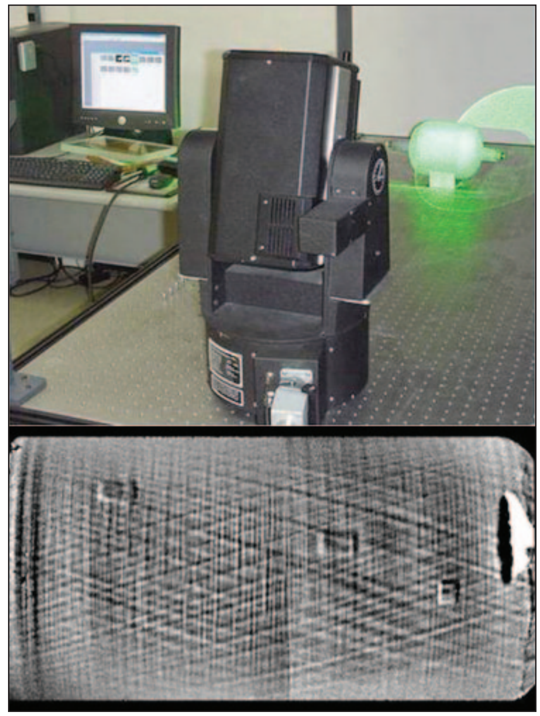

Fig. 1. *Composite overwrapped pressure vessel inspection (top) and thermal shearograph of a vessel with delaminations and a void (bottom).*

Shearography uses a laser-based imaging interferometer to detect, measure, and analyze surface and subsurface anomalies in structures. This is achieved by imaging slightly out-of-plane changes to a test article surface when an appropriate stress is applied or removed. The stress can result from excitation of pressure/vacuum, thermal, and/or acoustic sources, for example. Similar shearography systems are used by NASA and the aerospace industry for rapid, near-real-time evaluation of critical structures. Inspections of composite structures such as the space shuttle external tank, solid rocket booster heater cable and joint ablators, aircraft control surfaces, flight leading edges, carbon nozzle exit cones, helicopter blades, concrete bridges, radomes (radar dome), and many other components also rely heavily on laser shearography for quality control inspections and structural health monitoring.

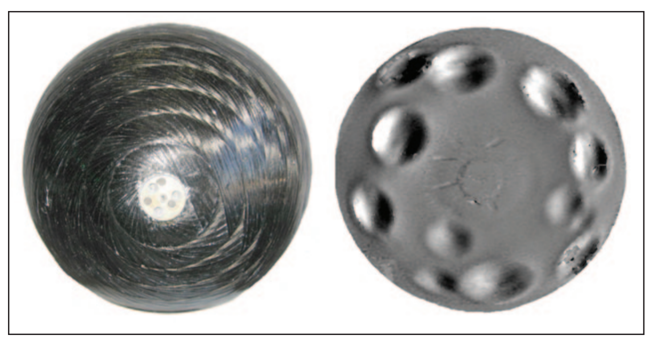

Fig. 2. *Spherical composite overwrapped pressure vessel with visible 0.15-in.-dia. dent and shearograph showing 0.75- to 2.3-in.-dia. damage.*

As an NDE technique widely used as a component screening tool, LS is capable of detecting defects on composite structures such as mechanical damage (figure 2), disbonds, delaminations, near-surface porosity, wrinkled fibers, fiber bridging, foreign objects, and cracks. Thermal, mechanical, and a combination of the two methods provided optimized results depending on the indication.

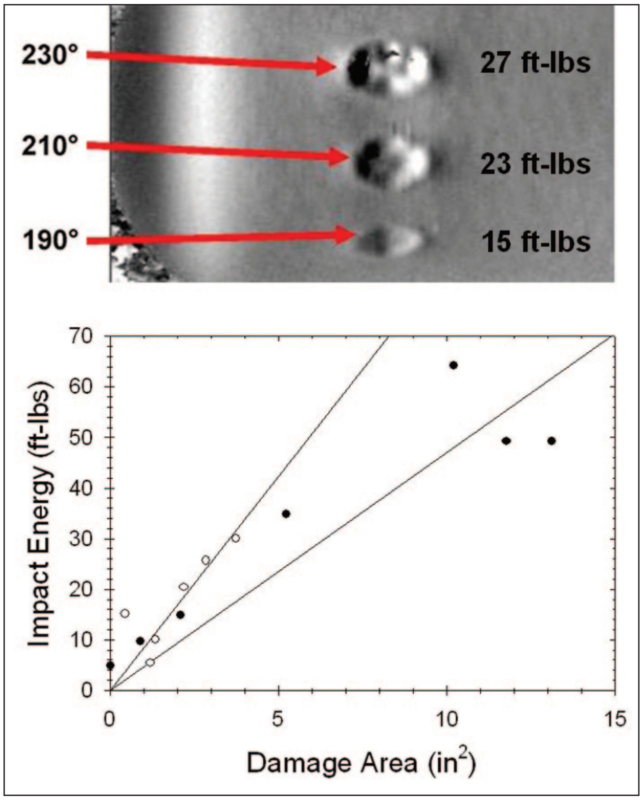

Fig. 3. *Damage area increases in composite overwrapped pressure vessels with impact energy.*

WSTF's LTI-5100HD Advanced Shearography System, equipped with a TES-200 thermal excitation unit, has greatly improved the ability to baseline the received stress state and monitor and identify visually undetectable subsurface impact damage. This capability provides support for inspection standard development efforts within NASA, manufacturing partners, and the American Society for Testing and Materials (ASTM). In fact, WSTF worked with ASTM to produce an NDE standard: ASTM E 258107, *Standard Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials, and Filament-Wound Pressure Vessels in Aerospace Applications*. Testing confirmed that the subsurface damage area, which was frequently below the visual detection threshold, increased with impact energy (figure 3) and was much more extensive than was visually evident.

Visual indications of composite damage range from severe fracturing at the impact site to a small crack or dimple, but shearography uncovers the visually undetectable damage.

Impact energy tests were performed on 43 426-cm^3 (2650-in^3), 17-cm × 56-cm (6.6-in. × 22-in.) cylindrical and 8194-cm^3 (500-in^3), 26-cm (10.25-in.) spherical COPVs to determine the reduction in residual strength as a consequence of impact energy (figure 3). Test results suggest impact energy greater than 13.6 Newton-meters (10 ft-lbs) (a 13-cm^2 [2-in^2] damage area) causes significant burst after impact pressure decreases for composite pressure vessels. An impact damage threshold was suggested to define the acceptable level of damage for a given impact subsequently. These findings can be directly applied to present and future aerospace systems of similar graphite composite construction, including commercial and military applications. Commercial applications can also be realized for compressed-gas storage systems including natural and hydrogen gas-powered vehicles.

Shearography inspection of COPVs for impact damage and other anomalies has been demonstrated to have a lower detection limit than most other NDE methods, but the technology still requires more work to develop the capability of directly correlating burst pressure reductions to impact energy. Future work will add more data and complete this analysis for a more effective impact standard. Since the sensors used for acoustic emission NDE respond to fluctuations in out-of-plane strain measurements, it is suspected that, after factoring in acoustic emission attenuation effects, a relationship would exist between impact damage energy and acoustic emission event energy. Furthermore, acoustic emission may be capable of locating and tracking the formation and growth of micromechanical flaws detected using LS. Additional instrumentation and high-pressure testing are planned to investigate the link between these measurements and impact damage.