CURRENT TASKS

White Sands Test Facility

Task

Smart Composite Overwrapped Pressure Vessel - Integrated Structural Health Monitoring System to Meet Space Exploration and International Space Station Mission Assurance Needs
(FY12 New Start)

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Background

Currently there are no integrated NDE methods for baselining and monitoring defect levels in fleet for Composite Overwrapped Pressure Vessels (COPVs) or related fracture critical composites, or for performing life-cycle maintenance inspections either in a traditional remove-and-inspect mode or in a more modern *in situ* inspection structural health monitoring (SHM) mode. Implicit in SHM and autonomous inspection is the existence of quantitative accept-reject criteria. To be effective, these criteria must correlate with levels of damage known to cause composite failure. Furthermore, implicit in SHM is the existence of effective remote sensing hardware and automated techniques and algorithms for interpretation of SHM data.

SHM of facture critical composite structures, especially high pressure COPVs, is critical to the success of nearly every future NASA space exploration program as well as life extension of the International Space Station. It has been clearly stated that future NASA missions may not be successful without SHM [1]. Otherwise, crews will be busy addressing subsystem health issues and not focusing on the real NASA mission.

Objectives

NDE sensors will be applied to COPVs during and after manufacturing. The higher technical readiness level (TRL) NDE methods under consideration in this project are acoustic emission (AE), surface fiber Bragg grating (FBG) strain measurement, eddy current stress measurement, and temperature. The lower TRL NDE methods are embedded FBG strain measurement and fiber optic acoustic emission (FOAE). In each case, the TRL will be raised so that an integrated end-to-end 'smart' COPV demonstration can be accomplished by the end of the third year. This demonstration will in turn provide additional proof-of-concept and direction towards developing an autonomous, real-time warning system that can be used during missions to alert crew members about COPV-related hazards.

Concurrent with the above objective will be development of NDE hardware and software. More specifically, commercially available and custom hardware will be evaluated during this project. The hardware evaluated will include data acquisition systems and various types of sensors, with an emphasis on remote (wireless) sensing. Automated software techniques and algorithms for real time data collection, reduction, and interpretation will be further refined and applied. Both vendor and in-house NASA software will be evaluated and, if necessary, combined.

As a whole, this project develops enabling technologies for NDE of space exploration systems containing composite materials, in particular, COPVs. Upon further refinement these enabling technologies can served as the basis for engineering systems and controls that can in turn mitigate or eliminate the catastrophic hazards associated with load bearing composite materials and components such as COPVs that pose a risk to existing and future exploration spacecraft and crews. This is especially important for the COPVs now used on the International Space Station, some of which have unfavorable long term reliability risk factors. Safety is also improved for COPVs that have been compromised due to impact, thermal cycling, or radiation damage, or whose safety margins have otherwise been reduced by increased performance or weight saving demands, for example, the push to thin-walled metal liners. The impetus will be the pull of the best suited NDE methods to a TRL 6 demonstration level, ultimately opening up the possibility of autonomous inspection during service.

Approach

The 'smart' COPV project is guided by technical experts and applies down-selected NDE methods which have been fully demonstrated or shown to be highly promising in previous NASA projects. Successful projects contributing to this effort include:

- NDE of Kevlar®-epoxy (K/Ep) and carbon epoxy (C/Ep) COPV Stress Rupture projects
- *In-Situ* Nondestructive Evaluation of Kevlar® and Carbon Fiber Reinforced Composite Micromechanics for Improved COPV Health Monitoring [2]
- Acousto Optic Measurement with Fiber Bragg Gratings
- Multiaxial Fiber Brag Grating Systems for Real-time Inspection
- LaRC International Space Station Leak Detection project

This project also includes advancements made through NASA's Lightweight Spacecraft Structures & Materials and precursor programs.

A building block approach will be used to establish necessary proof-of-concept before embarking on more complex and costly COPV-level testing. In other words, if insufficient prior precedent exists for a given NDE method vis-à-vis COPVs, the NDE will be applied to simpler composite materials; namely, composite tow or laminate.

As for software development, both vendor and in-house NASA software will be evaluated. In some cases, this may require NASA to work with NDE equipment manufacturers to ensure the best combination of software features is obtained.

As for hardware development, commercially available, off-the-shelf NDE hardware will be used whenever possible. Only when it becomes apparent the needed features in available hardware do not exist, will custom hardware be developed.

None of the NDE techniques under consideration is locked in. That is to say, NDE methods will be eliminated unless feasibility is demonstrated for that method as an autonomous SHM technique. Similarly, methods not presently under consideration may emerge and replace the candidate NDE techniques mentioned here. To be feasible, a method must be portable, have remote sensing capability, be sensitive to meaningful composite (or liner) damage, be durable, and be amenable to ruggedization.

AE: method development will focus on application of modal (wideband) sensors, resonant sensor parameter (RSP) (narrow band) sensors, and wireless distributive impact detection systems (DIDS). The use of quantitative accept-reject criteria such as Felicity ratio (*FR*), cumulative fiber breakage, event rate, event energy relative to actual in-service pressure profiles will be thoroughly investigated. Software Optimized real-time data reduction using customized software algorithms will be demonstrated. Statistically-based prediction methods based on out-of-family behavior will be applied and vetted. Lessons learned from on-orbit application of DIDS will be applied to general AE SHM development.

FBG: method development will focus on using surface mounted and embedded single mode multiaxial grids. Both the accuracy and durability of the grids as a function of thermal and mechanical loads in the composite material will be investigated. Finite element analysis and mechanical testing of laminates will be used to garner more information about FBG accuracy and durability. Ingress/egress issues will be also examined.

FOAE: method development will be performed by NASA MSFC in collaboration with Los Gatos Research, Inc. Testing, much of it at the laminate level, will consist of comparing FOAE and AE response to piezoelectric transducer (PZT) excitation in a laboratory pitch-catch mode test. Different FOAE sensors with be tested as well as different composite materials. The ability of the FOAE method to measure *FR* will be further developed and refined.

Eddy current: a novel health monitoring technique will be investigated by NASA KSC that is synergistic with AE measurements. More specifically, eddy current sensors will be used as magnetic stress gages (MSGs) to measure stress in internal COPV plies as a function of applied pressure.

NDE Wave Image Processor (NDEWIP): NDE data handling and reduction will be performed in collaboration of NASA GRC, and the overlaps evaluated between NDEWIP, custom WSTF AE data analysis software, and proprietary vendor software (Mistras Group, Inc. and Digital Wave Corp.). The use of NDEWIP to batch process the fast Fourier transforms (FFTs) of individual AE events so that cumulative fiber breakage can be measured will also be developed.

Temperature: Due to the unknown effect of diurnal temperature cycling of ISS COPVs on-orbit temperature sensors will be applied to assess the effect of thermal cycling on AE, FBG (strain), FOAE and/or eddy current response.

Co-Funding

The plan is to leverage extended agency involvement to attract extended agency interest and synergistic co-funding and involvement. Direct benefit is derived from the following funded efforts:

- JSC/WSTF FY11/12 Innovations project on AE of COPVs to predict COPV burst pressure by estimating unknown COPV response relative to the known response of an alike population
- JSC/WSTF ISS COPV Stress Rupture project on long-term stress rupture tests on 80 flight-like C/Ep COPVs (these COPVs are configured with AE sensors and AE data is being monitored to detect trends indicative of impending failure using improved noise reduction and optimized data acquisition techniques)
- WSTF: Anticipated NASA USRP support
- DFRC: Loan of a compact flight certified FBG system
- MSFC: Laminate coupon fabrication, testing and support
- LaRC: Collaboration stemming from synergistic funding received for integrated vehicle health monitoring (IVHM) developments

Customers

This project directly targets the Reliability/Life Assessment/Health Monitoring in the NASA Office of the Chief Technologist Roadmap TA12, Materials, Structures, Mechanical Systems and Manufacturing Materials, Structures, Mechanical Systems and Manufacturing and is crosscutting to other discipline road maps. This project is the first step in promulgating and developing the necessary real time NDE methods that will be used in these integrated health management systems. The International Space Station program, all future manned and unmanned NASA space exploration programs, the Office of the Chief Technologist; plus commercial, and Department of Defense concerns utilizing COPVs will benefit from this work. Incidental but direct benefits also exist for COPVs used in Department of Transportation liquid natural gas and hydrogen storage applications. Other NASA partners include the Lightweight Spacecraft Structures & Materials, the NESC, and the Composite Pressure Vessel Working Group. Applicable NASA COPVs include carbon-epoxy vessels as used on the International Space Station (ISS), ISS Nitrogen-Oxygen Recharge System, the Orion Crew and Service Modules and all anticipated future NASA spacecraft.

Metrics

- The key metric will be successful development of a fully automated, real-time AE system that will gather real-time data that can be used to monitor the health and instantaneously predict impending failure of COPVs, with potential application to more generic fracture critical composites.
- Documentation of progress and findings in annual reports with well documented steady progress to the key metric.
- Progress in industry-first Smart COPV development shall be reported on an annual basis and peer reviewed by *NASA Nondestructive Evaluation Working Group (NNWG)* members.
- Progress was reported on an annual basis and peer reviewed by the NNWG members. Comparisons were made to the original project plan and schedule, providing a measure of project progress.
- External peer review was considered to be essential and was obtained by communicating findings to E. Madaras of NASA LaRC. Non-NASA peer review was also obtained from the American Society of Testing and Materials Committee (ASTM) E07 on Nondestructive Testing, the American Society of Nondestructive Testing (ASNT), and the Acoustic Emission Working Group (AEWG).

Products-to-date

Synergistic projects predating this project have produced quantitative AE methods that can be used to monitor progressive damage accumulation in K/Ep and C/Ep tows and C/Ep COPVs [3, 4, 5]. AE data acquisition parameters have been optimized, and sensor spacings determined for common COPV geometries. Products also include a more reliable tabbing method for K/Ep and C/Ep uniaxial tow specimens (valid for tows with breaking forces up to 1800 N (400 lb_f)). Prior work has led to modification of the NDEWIP program developed by NASA GRC, so that it can better accommodate large AE data files. To reduce the labor needed for AE data reduction, thus increasing analysis throughput, and to eliminate operator subjectivity, an in-house AE data reduction software that has utility for both tow and COPVs has been developed by WSTF (see Figure 9 in ref.[6]). Features of the software include the ability to:

1) calculate the Felicity ratio (*FR*) automatically as a function of load (pressure), representing a vast improvement in labor savings
2) optimize the *FR* using various consensus methods for determining the onset of significant AE
3) calculate pressure breakpoints from noisier COPV pressure schedule data, overcoming errors caused by pressure spikes and overshooting of pressure set points
4) discard *FR* outliers using a robust fitting method

At this time, three preliminary generations of 'smart' COPVs have been produced. The first generation 'smart' COPV was instrumented with FBGs at DFRC using various orientations (0°, ±45°) in the cylindrical section of a flight-like COPV similar to vessels used aboard the ISS (Figure 1).

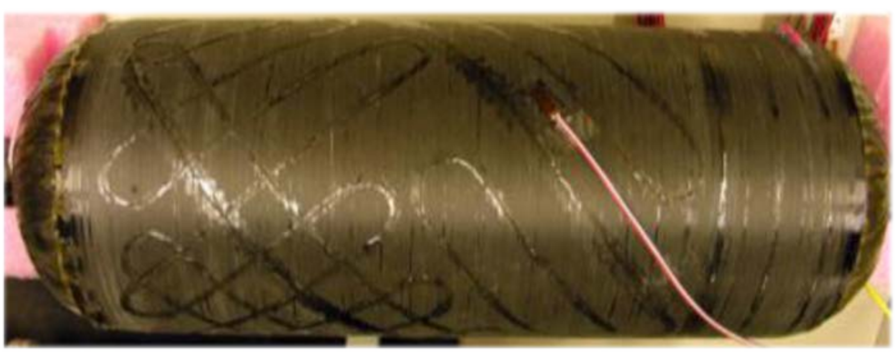

Figure 1. First generation 'smart' composite overwrapped pressure vessel with a surface-mounted multiaxial fiber Bragg grating grid for structural health monitoring.

The second generation 'smart' COPV was instrumented with a) circumferential (0°) FBG arrays on the top, center, and bottom of the cylindrical section, b) foil-type strain gages, and c) wideband AE sensors (Figure 2).

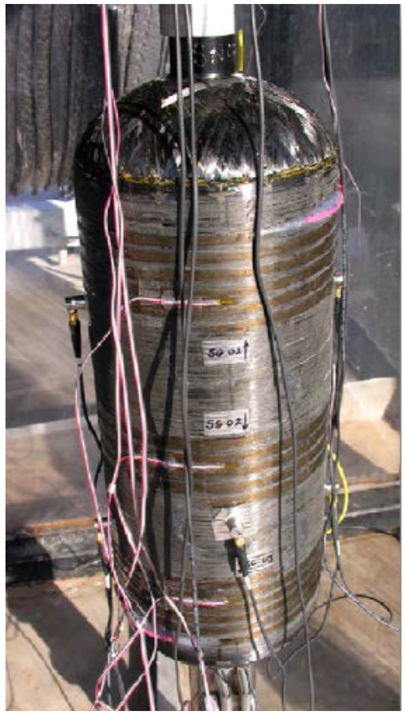

Figure 2. Second generation ‘smart’ composite overwrapped pressure vessel with circumferential fiber Bragg grating arrays on the top, center, and bottom of the cylindrical section, strain gages, and wideband acoustic emission sensors.

The third generation ‘smart’ COPV (not shown) was wrapped with C/Ep hoop plies at MSFC, thus embedding the circumferential FBG arrays shown in Figure 2, and then instrumented with a) circumferential FBG arrays on the top, center, and bottom of the cylindrical section (mirroring the embedded FBGs), followed by b) foil-type strain gages, c) circumferential FOAE sensors, and d) wideband AE sensors.

It is interested to note that DFRC has produced a ruggedized FBG sensing system that provides high spatial resolution in real time approaching the spatial resolution of finite element models. In the COPV that had embedded and surface FBGs (third generation), the strain response of 1600 FBG nodes could be monitored (Figure 3).

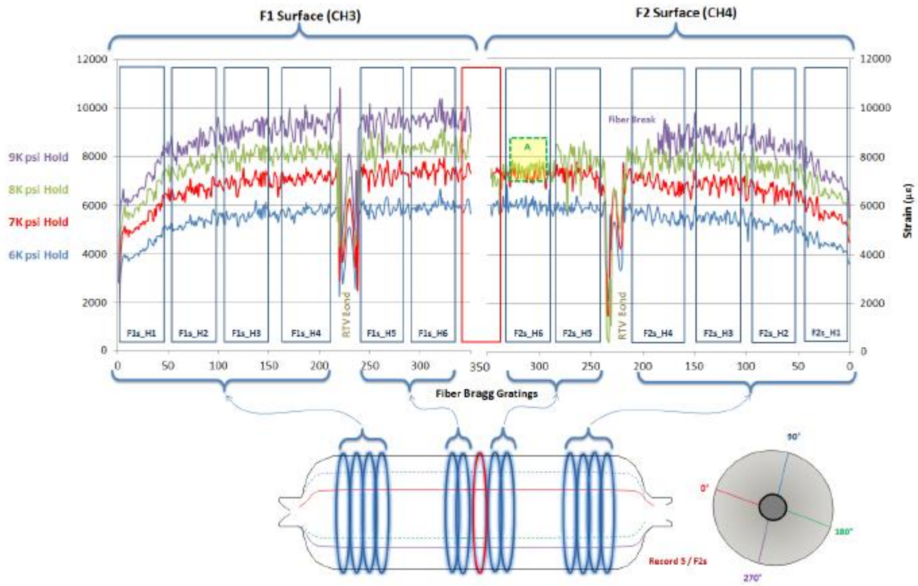

Figure 3. Response of circumferential fiber Bragg grating strain sensors on the surface of an IM7 carbon-epoxy composite overwrapped pressure vessel (COPV) subjected to pressures up to 9000 psi showing locus of locus of failure: third generation 'smart' COPV.

AE data analysis of the third generation 'smart' COPV gave distinct evidence of frequency clustering, indicative of certain types of composite damage, and when frequency and events were plotted versus a temporal time or pressure scale, revealed the real-time damage evolution in the COPV composite overwrap (Figure 4).

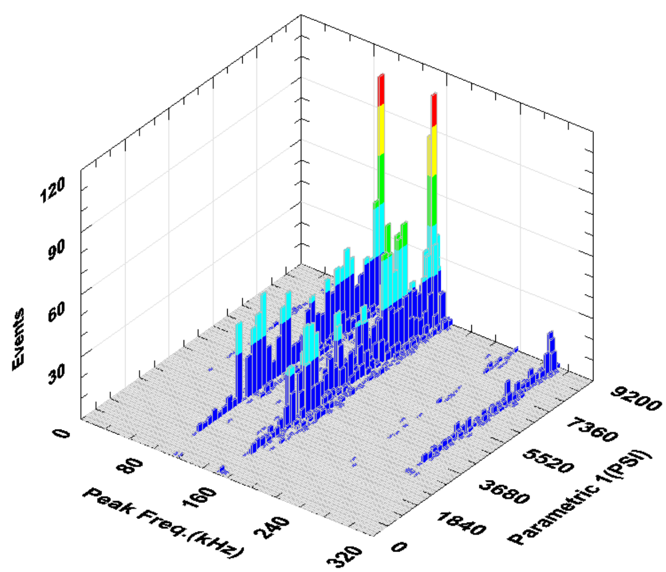

Figure 4. Damage evolution as a function of pressure (psi) for an IM7 carbon-epoxy composite overwrapped pressure vessel (COPV): third generation 'smart' COPV.

WSTF has developed a new method for determining the onset of significant AE used to calculate the *FR* using an exponentially weighted moving average (EWMA) approach [7]. During tow tensile tests, the EWMA method demonstrates good to excellent linearity and greater consistency compared to other *FR* onset determination methods tested to date (Figure 5). This suggests more accurate failure predictions may now be obtained than was previously possible.

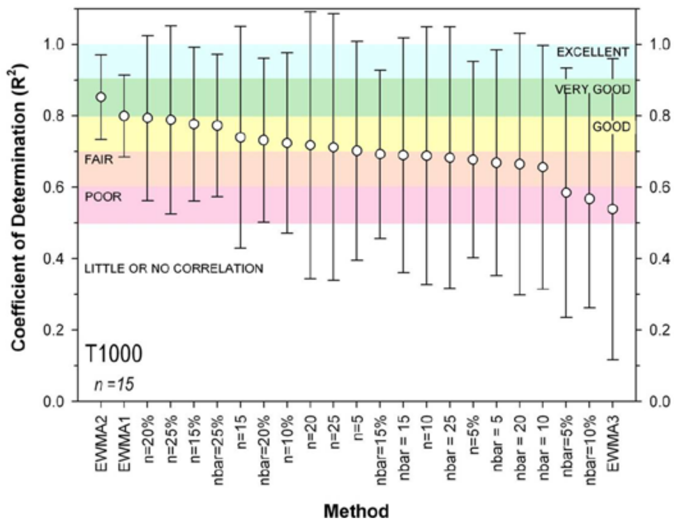

Figure 5. Acoustic emission Felicity ratio onset method comparison for T1000 12k composite tow (average of fifteen T1000 specimens, standard deviation bars shown)

<u>Future Products</u>

- A comprehensive test report following completion of the project. The report will contain ‘smart’ COPV response to stress rupture progression, and results for the candidate NDE-SHM methods evaluated.
- Real-time AE automated software incorporated with NDEWIP and/or vendor software packages with the following features:
    - 3-dimensional AE event source location
    - FFT-batch processing, showing cumulative energy release due to fiber breakage
    - *FR*–based predictions of COPV burst pressure, if applicable, depends on pressure profile(s) used
    - a hardware platform on which the above software is incorporated for “black-box” diagnostic and predictive capabilities (minimum breadboard level)
    - this system will be used to accomplish an end-to-end demonstration of the real-time AE SHM system as noted above
- An end-to-end demonstration of the real-time wireless AE SHM system developed
- An end-to-end demonstration of the real-time embedded and surface FBG SHM System

<u>Technical Considerations for AE</u>

Further work is needed to improve the use of *FR* as an analytical damage parameter. The effect of the activation time (the time a composite as allowed to rest unloaded, prior to re-application of load) on the *FR* must be better understood. The dependence of cumulative fiber breakage on applied load must be understood, which will require batch processing of FFTs using, for example, the NDEWIP software developed at NASA-GRC. Specimen-to-specimen reproducibility and damage progression within a given material or design class must be better understood, which could be facilitated by using commercially available pattern recognition software that differentiates individual acoustic emission events on the basis of energy, duration, and rise time. More work is needed to show whether *FR* trends consistently predict the burst pressure and out-of-family behavior (JSC/WSTF FY11/12 Innovations project).

<u>Schedule/Milestones</u>

Meetings are currently being held with the NNWG Core Team, to determine a detailed schedule and associated milestones. Once concurrence is achieved withing the NNWG Core Group on a draft plan, the draft plan will be sent out for review to an extended Agency Team to receive broader input.

Year	Qtr	DFRC	GRC	MSFC	KSC / LaRC	WSTF
FY12	Q1	Development of FBG sensors/methods for embedment in COPVs	Outline AE updates to NDEWIP software	Acousto-optic method and sensor development	Eddy current sensor and method development	Down select Felicity ratio algorithms; AE method development
	Q2	Feb. 27, 2012: Hydrostatic test of DFRC Bottle 2, Phase 2 instrumented with 800 FBG, 6 SG, and 6 PZ AE sensors				
	Q2 - Q3	COPV-level test of selected FBG arrays	Add WSTF AE algorithms to NDEWIP	Test selected AO sensors and systems	COPV-level test of EC sensors	Assist GRC with algorithms; global JFT algorithm dev.
	Q4	Reporting to NNWG. Assess successes and faults for each method. Team vote to decide development continuation.				
FY13		Model validation of COPV FBG strain results	Validation of new NDEWIP AE modules	Comparative validation of AO AE to PZT AE sensors	Validation of EC and new NDEWIP AE modules	NDEWIP AE mods. software validation
FY14		Structural health monitoring integration efforts for each technique as capabilities allow				
FY15		System level Testing with Team-Selected Sensor Grids and SHM Equipment				

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