INTERRELATIONSHIP OF NONDESTRUCTIVE EVALUATION METHODOLOLOGIES APPLIED TO TESTING OF COMPOSITE OVERWRAPPED PRESSURE VESSELS

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ABSTRACT

Composite Overwrapped Pressure Vessels (COPVs) are commonly used in spacecraft for containment of pressurized gasses and fluids, incorporating strength and weight savings. The energy stored is capable of extensive spacecraft damage and personal injury in the event of sudden failure. These apparently simple structures, composed of a metallic media impermeable liner and fiber/resin composite overwrap are really complex structures with numerous material and structural phenomena interacting during pressurized use which requires multiple, interrelated monitoring methodologies to monitor and understand subtle changes critical to safe use.

Testing of COPVs at NASA Johnson Space Center White Sands Test Facility (WSTF) has employed multiple in-situ, real-time nondestructive evaluation (NDE) methodologies as well as pre- and post-test comparative techniques to monitor changes in material and structural parameters during advanced pressurized testing. The use of NDE methodologies and their relationship to monitoring changes is discussed based on testing of real-world spacecraft COPVs. Lessons learned are used to present recommendations for use in testing, as well as a discussion of potential applications to vessel health monitoring in future applications.

1. OVERVIEW OF COPV CONSTRUCTION AND MATERIALS

The COPVs addressed in this paper utilize a media impermeable metallic liner and a composite overwrapped structure for strength and weight savings. The selection of liner material is based on media compatibility and vessel design; specifically whether the liner is itself intended to carry a significant portion of the load when pressurized or whether a majority of load is to be effectively carried by the composite overwrap. The selection of composite overwrap construction is based on design stress level and long-term reliability. Together, vessel life and performance should be optimized for the design application.

Metallic liners share some portion of the load with the composite. The amount of load sharing is dependent on the liner material and thickness. Many COPVs have been identified as having non-load sharing liners indicating that the amount of load carried by the liner is insignificant. The reality is that the load carrying amount should be included in the assessment of the COPV operating stress. The investigation of the database of non-load sharing aluminum lined Lawrence Livermore National Laboratories (LLNL) test vessels found that the load carrying amount was significant in predicting stress rupture performance [1].

Liner material selection includes consideration of the following:

- Compatibility with the pressurizing fluid
- Corrosion resistance to the operating environment
- Ability of the liner to share load with the composite
- Response to fatigue cycling to meet leak before burst requirements [2]
- Safe life considerations [3]

Perhaps the most insidious failure mechanism in COPVs is stress-rupture, failure process in which the load carrying capability of the composite overwrap fiber is reduced over time until incapable of sustaining the load. Failure is sudden and energetic and comes typically without warning. Several models [4] have been developed to predict failure with the intent of improving the safe use of vessels; however actual statistical data to validate these models is still being gathered.

At this time there is no validated monitoring or inspection method which allows for anticipation of impending stress rupture failure. The NASA White Sands Test Facility has several projects investigating the ability of several NDE techniques that show promise of indicating the state of health of the composite of a COPV. Phase I efforts have identified indicators of failure significantly prior to burst via AE, temperature, audio and visual indication. Significant work is needed to develop a quantitative relationship between NDE and composite heath in stress rupture.

2. NDE/MEASUREMENT METHODOLOGIES

There are numerous NDE or measurement methodologies available for examining the liner and composite overwrap, all of which have varying degrees of value and applicability to COPVs. The ability to inspect and identify defects before use is important to avoid putting compromised vessels into service; however the need to monitor vessels during service is critical as well. It is here that failure could have catastrophic results due to sudden release of stored energy. Because the liner does not carry the bulk of the pressurized load, most inspection techniques concentrate on the composite overwrap. Detection of impending failure will allow removal of pressure before sudden vessel rupture. Measurements that have been used to examine composite health in recent testing include acoustic emission, eddy current, shearography, thermography, linear variable differential transducers (LVDTs), strain gauges, digital image correlation, fiber Bragg gratings, high speed video and audio. Tab. 1 summarizes NDE methods with the pros and cons of each method.

One objective during test is to maximize the capture of salient, complimentary physical state information without undue duplication or redundancy. This provides for a cost-effective test effort with maximal information gain. To achieve this, inspection/monitoring techniques should be chosen for their independence and ability to measure physical changes on a continuous basis with specific relevance to a parameter of interest.

3. WSTF TESTING EXPERIENCE

3.1 WSTF-JPL Vessels Subscale COPVs

In 1998, WSTF began a long-term stress rupture test effort utilizing graphite/epoxy COPVs originally fabricated for use by NASA Jet Propulsion Laboratory (JPL). This early test effort concentrated on evaluating the stress rupture life of artificially damaged (impact) vessels held under controlled temperature conditions. Monitoring consisted of periodic examination and maintenance of pressure conditions. No instrumented monitoring techniques were utilized. This testing, which continues today, includes only examination of vessels following rupture. The construction of these vessels does not mirror that of flight vessels and was found to lead to different failure mechanisms. The knowledge gained through this early test program led to refinements in pressurized testing at WSTF. Among those identified is the need for specific vessel/test article design and control of pressurization rates in order to reduce variability in test results. Additionally, placing the test articles in a single pressurized bank of vessels meant failure of a single vessel resulted in depressurization of the remaining vessels. Restoration of the test pressure in those vessels contributes to variation in the stress rupture behavior, introducing new variables into the analysis of the results.

22-in. Kevlar COPV Testing

40-in. Kevlar COPV Testing

4. UTILIZING A 40-IN. KEVLAR COPV AS A CASE STUDY

Pressurization and burst testing of a 40-in. Kevlar vessel utilized the broadest range of simultaneous NDE methodologies known to have been attempted. The type and number of techniques and sensors is illustrated in Tab. 2.

The vessel tested was a titanium lined Kevlar/epoxy overwrapped COPV.
Testing consisted of pressurization cycles at both slow (5 psi/sec) and rapid (50 psi/sec) rates and culminated in conducting a burst test. Collection of data was focused on understanding vessel behavior and potential identification of failure precursors which could serve as predictors of failure in in-situ health monitoring applications.

The test team included a primary test conductor with overall responsibility for the test activities. Each instrumentation system had a dedicated monitor technically familiar with the acquisition and interpretation of the output data who reported directly to the primary test conductor regarding instrumentation performance and could call a stop at any point, if necessary. Each actual test run was preceded by a system and instrumentation validation run to 1000 psig which validated readiness of all systems for the actual test.

Final burst testing was conducted at a pressurization rate of 50 psi/sec using water as the pressurant.

Table 1. NDE Methods for Composite Overwrapped Pressure Vessels

NDE Method	Parameter Evaluated	Pros	Cons
Acoustic Emission	Audio signals associated with mechanical and micro-mechanical events within the material or on the vessel surface	Useful for real-time monitoring and applicable to a broad range of materials and structures. Can be used in-situ in most applications. Very sensitive	Active only during stress, does not give cumulative or predictive information except for *immediate* future.
Shearography	Composite internal discontinuities (such as delaminations) which affect material dimensional changes under pressure	Sensitivity and ability to see below the surface of composite materials	Difficult for in-situ use or continuous monitoring. Current practical use is limited to pre- and post-test inspection.
Eddy Current	Material thickness, based on time-based reflection of sound waves	Applicable to real-time monitoring. Can monitor thickness of both liner and overwrap independently. Very sensitive to changes	Potential interferences from other devices if sufficient spacing not allowed.
Thermography	Composite material discontinuities (e.g. delaminations) which affect material thermal conduction	Ability to locate subsurface discontinuities in composite materials	Difficult for in-situ use or continuous monitoring. Current practical use is limited to pre- and post-test inspection
Fiber Bragg grating	Can measure material strain or temperature, depending upon configuration	Can be embedded in material under test	Very delicate and prone to failure
High Speed Video	Visual events which may be precursor to failure	Useful for examining easily missed and possibly important details of failure events.	Not practical for long-term monitoring. Limited to externally visible phenomena. Negligible applicability to prediction, except for imminent events
Strain Gauges	Material strain	Relatively inexpensive and capable of long-term monitoring effectiveness. Proven technology and low cost means they can be used extensively on any given test article	Must be bonded to test material surface – some areas may be difficult to access directly. Provides differential measurement, not absolute.
Digital Image Correlation	Surface visual effects which may be very subtle	Very sensitive to subtle surface changes	Requires significant set-up
Raman Spectroscopy	Composite fiber surface strain	Non-contact method; sensitive to differential strain condition in material under test	Absolute stress measurements are uncertain. Measures at exposed surface only
Physical Displacement (e.g. LVDT)	Dimension changes in one axis	Simple technology	May be difficult to locate precisely

Table 2. WSTF Example COPV Test Instrumentation List

Technique	Sensors	Locations	Rationale	Remarks	Results
Acoustic Emission	12	Six equispaced about equator plus three equispaced below each boss.	Allow for broad coverage and triangulation of signals for AE event mapping	Threshold settings critical to avoid loss of relevant data	Increase in hits prior to rupture overwhelmed system 20 sec. prior to burst
Belly Bands	3	Equator, 45 degrees, near boss to boss	Measure radial displacement in three orientations as vessel distends	Global strain measurements, not localized information	Good agreement with other sensors and reproducibility
Strain Gauges	30	120 degrees apart radially in both upper and lower hemispheres	Relatively low cost, allowing for instrumenting numerous locations	Durable and reproducible. Excellent localized strain data.	Many gauges provided quality data, even after rupture
Eddy Current	5	Four upper hemisphere on one side and one in lower hemisphere	Thickness monitoring of composite overwrap	Sensitive to changes in both the composite and metallic liner	Excellent correlation of thickness changes in both liner and Overwrap with bonus performance as acoustic event sensor.
Mass change	1	At boss	Measurement of volume change based on density of water pumped into the vessel during pressurization		
Digital Image Correlation	2	External to blast enclosure; oriented to one view through the Lexan “window”	Location dictated by orientation; random with respect to the vessel itself	Optical techniques constrained to the side of the enclosure having Lexan “window”	Identified local strain field changes, allowing correlation to observed surface events and final rupture location
Video	1	External to blast enclosure; oriented to one view through the Lexan “window”	Location dictated by orientation; random with respect to the vessel itself	Optical techniques constrained to the side of the enclosure having Lexan “window”	Captured surfaced fiber tow delaminations correlated to audio events
Fiber Optic Bragg Gratings					
Pressurization Shearography	N/A	360 degrees around vessel	Baseline inspection done prior to pressurization events	Only done prior to pressurization tests. Inspection only – no monitoring capability for this test	Easily realized stress concentrations at the equatorial weld. Noted localized delaminations prior to test

4.1 Lessons Learned

Ensure sensor methodologies are complimentary to maximize opportunities for collection of important data.

Data in tests such as these may be difficult to interpret alone. Using different methodologies or techniques which view developing events through different phenomena or parameters significantly reduces the potential of missing a developing, significant event. Similarly, it reduces the potential of viewing a spurious observation for the analysis.

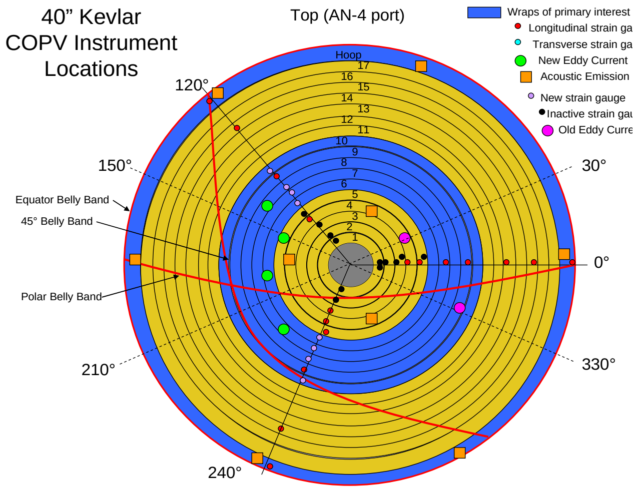


Figure 1. Schematic illustration of the vessel monitoring sensor types and locations in the upper hemisphere of the vessel

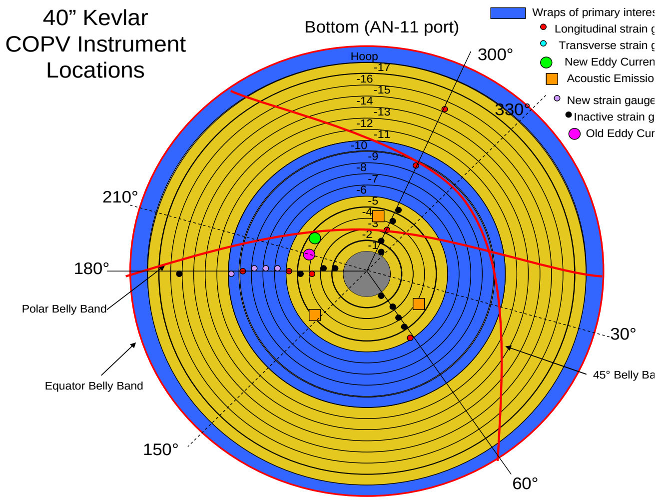


Figure 2. Schematic illustration of the vessel monitoring sensor types and locations in the lower hemisphere of the vessel

Cover the entire vessel to the maximum extent possible; the event you're looking for will always occur on the unmonitored area if you don't.

Testing of the 40-in. Kevlar vessels is a good example of this premise. Safety concerns required use of a blast enclosure. Post-burst analysis of the vessel and the gathered data located the point of vessel failure just out of the field of view, limiting the usefulness of techniques such as digital image correlation (DIC) and high speed video. The belly bands and strain gauges provided some compensation for this; however high-speed imaging would have been highly valuable in the post-burst analysis. While some sensors may be relatively expensive to apply extensively, others such as strain gauges are not. Changes are often very subtle and the onset of catastrophic damage typically occurs at discrete localities. The ability to identify these local changes early-on in the development of damage can significantly improve the failure analysis process and understanding of vessel behavior under stress.

Key instrument/sensor thresholds to the anticipated time behavior to be examined and set levels accordingly. The number of monitored events, frequency and magnitude will vary as the test continues. Utilize experience gained to fine tune experiments.

While following the lessons learned and guidance provided will increase the likelihood of gathering the best possible useful data, it is imperative to review what worked and what did not work in order to refine the data gathering protocols for future tests. Some measurement techniques (e.g. high speed video) are capable of capturing extremely large amounts of data, much of which will be of little or no interest in understanding the behavior of the vessel under test. In order to concentrate on events of interest, use of past experience and data from other measurements may be used to trigger such monitoring techniques at the appropriate time. This provides for cost savings and time savings in data analysis.

Use a mix of real-time monitoring and pre/post evaluation; both yield key information and tend to be complimentary.

Some methodologies are readily applicable to continuous, real-time monitoring and others are not, yet each has points of merit which should not be overlooked or minimized. Cost constraints may force limitation of the extent of testing and monitoring, making evaluation of complimentary methodologies even more important (see

Lesson Learned No. 1). In general, inspection methodologies which tend to have more sensitivity for identifying sub-surface discontinuities require more control (e.g. elimination of vibration during measurement) and are less amenable to use during pressurization events. Methodologies which monitor physical phenomena which change during pressurization should be exploited for real-time monitoring. A key to remember is that sensitive inspection methods (e.g. shearography) which may not lend themselves to real-time monitoring may be very useful tools for identifying areas of interest. These areas of interest may warrant specific location of real-time monitoring sensors during pressurization testing.

Assembly of data by time and result is the best way to reconstruct the on-set and development of important events.

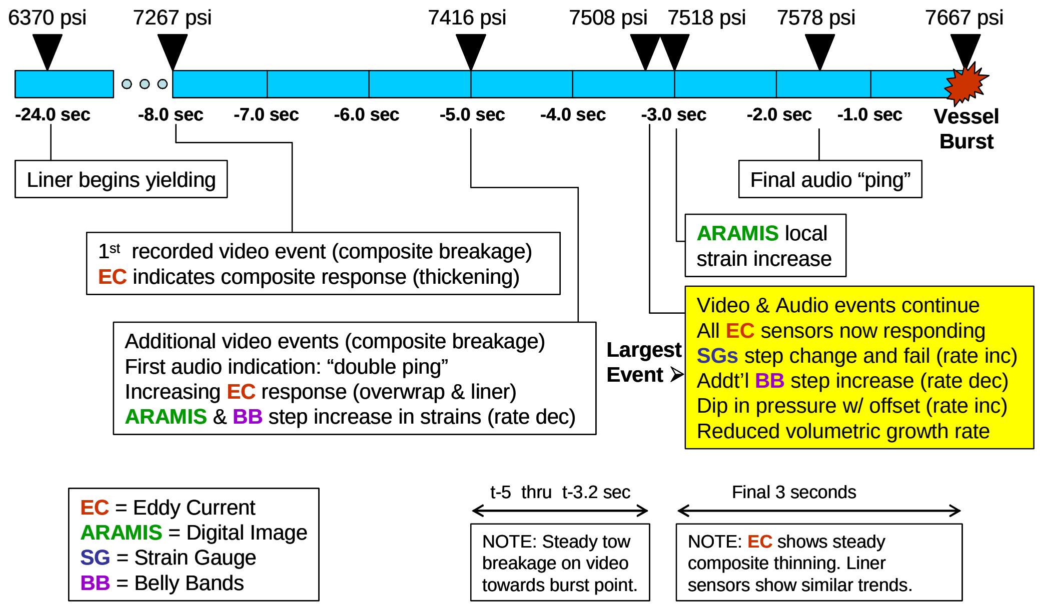
Particularly when multiple monitoring or inspection techniques are used a very valuable method for determining what observed events are significant is construction of an event timeline. As shown in Fig. 3, the events observed in the burst event of the 40-in. Kevlar COPV illustrate a sequence of developing damage prior to the rupture. Evaluation of this sequence of events allows for reconstruction of the physical phenomena leading to failure. This timeline analysis proved invaluable during the post-burst analysis of the WSTF test to resolve the timing of liner failure versus overwrap failure, enhancing the knowledge of the failure process.

Establish principal monitors for each detection system for maximal effectiveness of data understanding and sensor performance during test.

As the monitoring and data collection methodologies used increase, the ability of the test conductor to monitor them diminishes. The approach taken during the orbital maneuvering system (OMS) vessel testing at WSTF was to assign a principal monitor for each technique or data acquisition method who reported to the test conductor. This allowed for identification of data acquisition or monitoring anomalies or significant events which could impact the overall collection of data or real-time changes that might be needed.

Be sure to develop an indexing system for location of sensors.

This is important not only for systems which allow triangulation of events, but in the eventual analysis of the post-burst fragments and linking that material physical evidence back to the observation data.



Liner begins yielding

1st recorded video event (composite breakage)
EC indicates composite response (thickening)

Additional video events (composite breakage)
First audio indication: “double ping”
Increasing **EC** response (overwrap & liner)
ARAMIS & **BB** step increase in strains (rate dec)

Final audio “ping”

ARAMIS local strain increase

Video & Audio events continue
All **EC** sensors now responding
SGs step change and fail (rate inc)
Addt’l **BB** step increase (rate dec)
Dip in pressure w/ offset (rate inc)
Reduced volumetric growth rate

EC = Eddy Current
ARAMIS = Digital Image
SG = Strain Gauge
BB = Belly Bands

t-5 thru t-3.2 sec

NOTE: Steady tow breakage on video towards burst point.

Final 3 seconds

NOTE: **EC** shows steady composite thinning. Liner sensors show similar trends.

Figure 3. Observed event timeline with overlay of vessel pressure.

5. REFERENCES

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