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Proof Test Screening as a Mitigation Against Stress Rupture Failure of Carbon Fiber Composite Overwrapped Pressure Vessels (COPVs)

Peter A. Parker and William H. Prosser
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Nomenclature

AE	Acoustic Emission
COPV	Composite Overwrapped Pressure Vessel
FEM	Finite Element Model
MEOP	Maximum Expected Operating Pressure
PoF	Probability of Failure
SF	Safety Factor

Abstract

Proof testing of composite overwrapped pressure vessels (COPVs) is performed to screen vessels with low burst strength to mitigate the potential for failure at lower than operational pressures. It has also been proposed that the proof test provides a similar benefit against the likelihood of stress rupture failure while vessels are held at constant pressure for long operational periods. However, this has not been accepted because of a theoretical concern that damage accumulated in the COPV during proof pressurization may result in the vessel having a lower strength than if it were pressurized to failure without first being proof tested. Data and analysis presented in the following for two types of carbon fiber specimens (strands and small scale COPVs) demonstrate that previous load cycles to higher pressures (at stress rupture pressures that exceed proof test pressures in magnitude and time duration) do not result in changes to strength. That is, there was no detectable change in the strength distribution between specimens exposed to a higher proof type stress versus those that did not. As a result, a strain-based methodology is proposed to demonstrate that proof test mitigates the likelihood of stress rupture failure for a desired COPV lifetime. The proposed approach can be directly applied on flight COPVs as opposed to surrogate specimens such as strands or subscale vessels used for previous proposed approaches to estimate a safe lifetime against stress rupture failure as a result of proof testing.

1.0 Introduction

Stress rupture, also known perhaps more appropriately as creep rupture, is a failure mode exhibited in structures comprised of viscoelastic materials. Stress rupture failures occur at periods of time after a structure has been held under a condition of constant load/stress. As such, the structure fails at stresses that are lower than the nominal expected quasistatic strength of the structure. Additionally, a specimen fails in stress rupture at a stress below the strength that would have been achieved under conditions of quasistatic loading until failure (i.e., in a strength or burst type test). In addition to resulting in failures at lower-than-expected stresses, stress rupture failures are stochastic. When testing multiple nominally identical test articles in conditions designed to induce stress rupture failures, some test articles fail at short times, while others fail at later times, and some test articles do not fail at all. Stress rupture has been of particular concern for composite overwrapped pressure vessels (COPVs) because these vessels are used at extremely high pressures. As a result, COPVs have stored potential energy that is equivalent to pounds of explosive materials. COPVs are widely used in aerospace launch vehicles and spacecraft and burst failures of these vessels will result in catastrophic loss of the vehicle. While there have been COPV failures in operational space vehicles with catastrophic consequences, none have been documented to be a result of stress rupture failure.

Because of a lack of understanding of the stress rupture phenomenon along with the stochastic nature, a margin-based design methodology to mitigate against this type of failure does not exist. Instead, a probabilistic-based reliability assessment approach has been used [1]. Accelerated life testing is performed at higher loads or pressures to induce stress rupture failures for statistical analysis in reasonable test times, on the order of months instead of years. The results of these tests are used to estimate the probability of failure (PoF), which is commonly expressed as the vessel reliability (1 – PoF), as a function of pressure and time-on-hold under the accelerated test conditions. The statistical model developed at accelerated life conditions is extrapolated down to the expected use conditions (i.e., lower pressures) as well as extrapolated in time to the usage life conditions beyond the test times.

Recently, a number of issues were identified with this accelerated life testing approach when applied to carbon fiber COPVs [2]. The degree of acceleration required to produce failures for carbon fiber COPVs is extremely high, far beyond accelerated testing levels in other engineering/industrial applications. This excessive degree of acceleration raises concerns that the failure processes are altered, and the resulting statistical models are not relevant to the actual operational conditions and failure modes. Another concern is that large numbers of specimens are required to ensure adequate numbers of failures to support statistical modeling. This is an economic burden for the cost of testing, but more significantly causes the testing to be done with surrogate specimens as it is not affordable to be done using full scale structural articles. In the case of COPVs, extremely simple specimens such as fiber strands have been tested, as well as subscale COPVs. It is infeasible to verify that the results from these surrogate specimens are transferrable to the actual structural articles due to validation cost with full-scale vessels. Moreover, recent research has shown in one case that results from fiber strand testing were not representative of subscale carbon vessels made from the same fiber/epoxy system [2]. Furthermore, an improved understanding of the physical process and modeling of stress rupture phenomena has shown that it should not be expected that different structural configurations, even when they are constructed of the same materials, should produce the same stress rupture behavior [2]. Lastly, as most structural design practices use deterministic, margin-based, methodology, defined reliability-based acceptance criteria do not exist. Thus, assuming that the estimated reliability from such accelerated life tests is valid (which is subject to considerable debate), it is not clear how to apply the results to determine if a particular component is acceptable for operational use.

A different approach to mitigating against stress rupture failure that was considered previously is based on a benefit associated with proof testing [3]. Proof testing is required for COPVs to provide mitigation against burst failures during static pressure loading to operational pressures. By exposing vessels to a pressure that is higher than operational pressures (i.e., a proof test pressure), vessels with a burst strength lower than the proof test pressure should fail and be eliminated from the population available for flight operations. Thus, the proof test serves as a screen against vessels that have a low burst strength from either random statistical variation in strength or processing anomalies that led to low strength. This screening has also been suggested as providing benefit against stress rupture. The premise is that the likelihood of stress rupture failure would be reduced or eliminated with the low burst strength vessels eliminated from the population. The proposed method of implementation of this approach is through the estimation of a “safe time”. That is, a time following the proof test load when the vessel is held at the operational pressure during which a stress rupture failure is not expected to occur. This time is estimated based on statistical model parameters obtained from accelerated stress rupture testing and the ratio of the proof test pressure to the operational pressure. If the safe time exceeds the planned operational time, then no stress rupture failure would be expected. The main argument against this approach, which has prevented it from being used in practice, is that there may be an accumulation of damage in the proof test such that the vessel might fail at a lower strength (and have a reduced stress rupture lifetime) than if the vessel had not been proof tested.

In the following, data are presented that demonstrate proof testing (or more accurately, exposure to pressure cycles exceeding nominal proof pressures and durations) does not lead to changes in the inherent strength of a particular specimen, which would alter the stress rupture performance. Of course, the same vessel cannot be tested to burst failure twice (i.e., with and without being exposed to a higher proof pressure). Thus, this cannot be demonstrated directly and relies on inference that the vessels tested are representative of the population of vessels under consideration. However, it was shown by evaluating the strength distribution comprised of two different populations of otherwise identical vessel design and fabrication. One population experienced higher pressure loading (simulating a proof test) before burst testing, while the other did not and was loaded directly to failure. The strength distribution of the combined populations was evaluated. The results showed that all of the strength values are indistinguishable whether the vessels were or were not exposed to a simulated proof test type loading. This suggests that the proof loading does not result in changes to the burst strength. This behavior was observed for both fiber strand type specimens and for subscale COPVs. It is noted that should a reduction in strength be observed as a result of proof testing, it would not only provide rationale against using proof testing to screen against stress rupture failure, but against burst failure as well. If the burst strength is changing as a function of pressure cycling as suggested, then there could be no assurance against failure at subsequent pressurizations, therefore eliminating the original rationale for proof testing. Fortunately, again, this behavior has not been observed.

While the concern of whether proof test damage accumulation reduces the strength of COPVs has been addressed, there still remain the concerns previously discussed about the accelerated life test methods and statistical models required to estimate proof test safe times. As such, an alternate methodology is provided to assess the proof test benefit relative to the planned operational life conditions of carbon fiber COPVs. The proposed strain-based methodology uses measurements acquired both during the proof test cycle and as a function of time while vessels are held at the operational pressure. This methodology provides an approach (with a margin factor) for accepting vessels for flight that is similar to approaches currently used for mitigating against burst strength failures. This approach addresses the identified limitations of the current accelerated stress rupture testing required to estimate proof test safe time.

2.0 Burst/Strength Distribution Results of Specimens with and without Proof Type Loading

Two types of specimens were included in a previous study [2] to assess stress rupture reliability of carbon-fiber COPVs. The first was a fiber composite strand and the second was a subscale COPV. The subscale COPVs were all exposed to an autofrettage and proof cycle prior to any additional strength or stress rupture testing. The strand specimens were not exposed to any load cycles (i.e., autofrettage or proof) prior to strength or stress rupture testing. In both cases, a large number of the specimens were subjected to quasistatic increasing load until failure (i.e., strength or burst tests) to characterize the average or nominal strength. For both strands and vessels, the specimens that were not failed during strength or burst tests were subjected to accelerated stress rupture testing where they were loaded or pressurized to stresses exceeding that of typical proof tests and held until they either failed or reached a predetermined test time. A number of the specimens that survived accelerated stress rupture tests were also tested to failure in quasistatic strength or burst tests. Due to the large degree of acceleration required for the stress rupture testing, the loads and pressures experienced in the stress rupture tests exceeded that of a typical proof test

(1.25 to 1.5 times the Maximum Expected Operating Pressure or MEOP [4]). Additionally, the loads were applied for long time periods (ranging from days to years) in the stress rupture testing as compared to a proof test where the loads are not held for any appreciable time. Thus, relative to assessing whether proof testing leads to strength degradation, the testing in this program was more severe than proof testing both in magnitude and duration of loading. The strength values measured for both types of specimens that saw no previous loading and those that experienced stress rupture testing (i.e., a proof test type load) were statistically analyzed to evaluate whether the proof test type loading resulted in detectable changes in the strength distribution. Changes in the strength distribution would indicate whether the proof testing resulted in a detrimental effect on strength.

3.0 Carbon Fiber Strand Strength Test Results

Composite strand test specimens were fabricated by resin-impregnating 12K tows of T1000GB carbon fibers with Epon 828 resin with Epikure curing agent W. Details of the strand fabrication process including the installation of specialized grips to minimize stress concentrations and slippage are provided in [2]. The strand specimens were not previously loaded prior to strength or stress rupture testing to simulate an autofrettage and/or proof cycle. Tensile loads were applied to each strand by a precision electromechanical drive system.

Strength testing was performed on two batches of specimens. The first group (63 specimens) received no previous loading and were simply loaded to failure at a rate of 5 lbs/sec. A second group (730 specimens) was subjected to stress rupture testing at loads of either 330, 351, or 372 pounds-force (lbf) and held at this load for a period of 168 hours (about 1 week). Relative to the strength testing performed, these stress rupture load cycles were considered to be “effective” proof test load cycles. In the stress rupture testing, a number (22) of samples failed during the loading before reaching the prescribed hold loads. These were treated as strength failures (without proof test type loads) since they failed after testing in the same manner as the initial group of 63 specimens tested (i.e., as a result of quasistatic increasing loads) without having experienced any prior (i.e., effective proof) loading. Thus, the results from those 22 specimens were combined with the original 63 strength tests to provide a total of 85 strength failure specimens without any prior loading.

There were 660 specimens out of 708 that survived the stress rupture hold periods at one of the three load values without failure. From these 660, 155 were then tested to failure to determine the strength of the specimens after being subjected to stress rupture test load/holds. The resulting strength values were statistically analyzed.

A Weibull distributional model is typically assumed for strength and stress rupture failure distributions of fiber composite materials; however, alternative distributions were also considered. For this strand dataset, the Weibull distribution provided the best fit, and it is shown as a probability plot [1] in Figure 1. The x-axis of the plot is the load level at failure, and the y-axis is the cumulative probability of failure. The y-axis is transformed to display the fitted Weibull cumulative probability of failure as a function of load as a straight line. Employing this y-axis transformation of the Weibull cumulative distribution function is conceptually similar to using a logarithmic scale to linearize a plot of data with a logarithmic relationship. The markers are nonparametric probability of failure estimates of the observed strand failure loads based solely on the data, not the fitted Weibull parameters. Agreement between the markers and the line indicates that the fitted distribution characterizes the observed data. The plot symbols differentiate data values for strength tests that occurred with or without prior stress rupture hold loading (i.e., simulated proof testing). Stress rupture hold survivors that were not subjected to post-hold strength testing are shown in the top panel of Figure 1 and are included in the statistical modeling as right-censored.

In Figure 1, there is no significant distinction between observed results from strength tests with and without the additional stress rupture load cycles. Thus, these results indicate that the application of conservative (i.e., higher than typical) proof loading does not result in changes to the strength of these fiber strand specimens. If there was an indication of a difference between the average strength and/or variability with and without proof loading, then the observed failures after proof would follow a different line. As an example, if the average strength of the strands were reduced after proof, then the distribution of with-proof points would appear to the left of the distribution of without-proof points at 0.50 probability of failure.

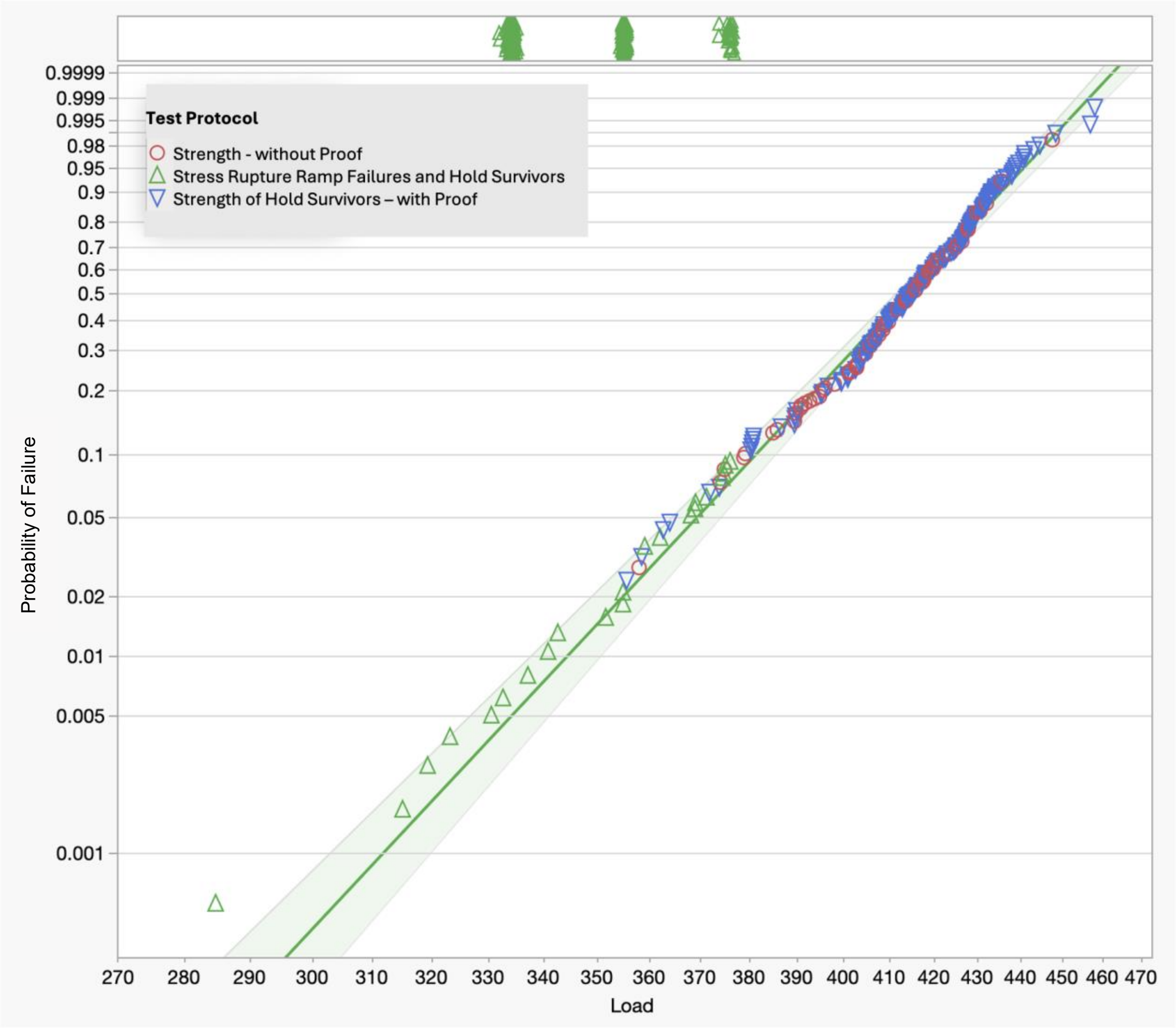

Figure 1. Weibull Probability Plot of Strand Specimen Burst Strength Data with Weibull Model (green). Plot symbols indicate data points from specimens that received or did not receive additional stress rupture (i.e., effective proof) loading.

A strand fiber load of 210 lbs was approximated to represent the MEOP load for the vessels. However, this approximation was not based on a validated finite element model (FEM) or experimental testing that considers the complex load distribution in the vessel overwrap. Based on 210-lb equivalent MEOP, 125% proof is 262 lbs, and 150% proof is 315 lbs. Thus, all of the stress rupture test loads (i.e., 330, 351, and 370 lbs), exceed what would be expected to be proof test loads, and were applied for much longer duration times. As such, any damage that could accumulate and result in a "change in strength" in the strand specimen would expect to be increased (i.e., these test conditions are conservative relative to typical COPV proof testing).

These data and models suggest that the post-hold strength testing is consistent with pristine strength testing and there is no distinguishable degradation in strength due to holding the load above proof.

4.0 Subscale COPV Burst Test Results

Subscale carbon fiber COPVs were also tested [2]. The vessels were procured from General Dynamics and were fabricated from 7.5-liter (L) 6061-T6 aluminum liners manufactured by Samtech. The liners were seamless, spun-formed aluminum with a large boss/dome taper that extended about 2 inches into the cylinder. Beyond the taper, the cylinder wall thickness was 0.06 inch. The liners were overwrapped with T1000GB/LRF092 resin towpreg tape and the overwrap was bonded to the liner using FM-73 film adhesive. The vessel design burst pressure was 6,450 psig and designed for a MEOP of 4,300 psig. Unlike the strand specimens, all of these vessels experienced an autofrettage cycle at a pressure of 5,475 psig as well as an additional proof pressure of 5,425 psig. The design criteria of these vessels are consistent with [4] having a 1.5x burst factor and 1.25x proof pressure. Approximately 200 vessels were fabricated for the stress rupture study.

All of the vessels experienced autofrettage and proof. Relative to assessing the effect of "damage accumulation" during proof, the comparison of burst strength results was made for vessels that did not see any additional loading as compared to those that experienced a higher pressurization cycle and hold during stress rupture testing. Thus, similar to the fiber strands, the stress rupture pressure cycle was considered as an "effective proof" cycle. As with the fiber strands, the effective proof pressures were considerably higher than those for the actual proof following manufacture. The stress rupture holds occurred at pressures of 5700, 6040, 6388, 6750, and 6874 psig, corresponding to 1.33, 1.40, 1.49, 1.57, and 1.6 times the MEOP of 4300 psig, respectively. The duration of time that the vessels were held at pressure varied depending on the pressure level. The lower pressures (i.e., 5700, 6040, and 6388 psig) were held for approximately 4.5 years. The two higher pressures were intended to be held for approximately 53 days. However, a facility mishap led to the depressurization of 65 of the 74 of vessels tested at the highest pressure (6874) such that they were only held at pressure for 15 hours.

Similar to the strand testing, a statistical analysis of the vessel burst pressures was performed for vessels that were not subjected to stress rupture testing (i.e., an additional effective proof cycle) as well as vessels that failed on ramp to the hold pressure in stress rupture testing. The analysis also included vessels that survived the hold pressure during stress rupture testing that had been exposed to an effective proof cycle (higher than nominal proof) and held for excessive times (from 15 hours to approximately 4.5 years). The total number of vessels that did not see the effective proof was

66 and the number of survivor vessels that were subjected to the effective proof was 44. There were 75 additional vessels that were subjected to stress rupture testing and survived but were not subsequently burst tested. These 75 vessels were treated as right-censored values in the statistical analysis.

A Lognormal distribution provided the best fit to the vessel burst data [2] instead of a Weibull distribution that provided the best fit to the strand specimen data. The two datasets highlight the significant differences in PoF and reliability estimates between strands and vessels. Figure 2 is a probability plot of the fitted Lognormal distribution and observed burst pressures. The data from vessels that experienced an effective proof fall along the same Lognormal distribution (red line) as those that did not see an additional effective proof cycle. The four clusters of failures on the top panel of Figure 2 represent right-censored stress rupture hold-survivors. Thus, the conclusion from the vessel tests is the same as the strand test: Excessive load/pressure cycles such as provided by proof testing, do not change the strength of a given specimen than if the specimen had not experienced the additional higher loading. This is the case for not only when a proof cycle is executed with minimal hold time such as in typical proof testing of COPVs, but even when the excessive load cycle is held for substantial times (up to approximately 4.5 years).

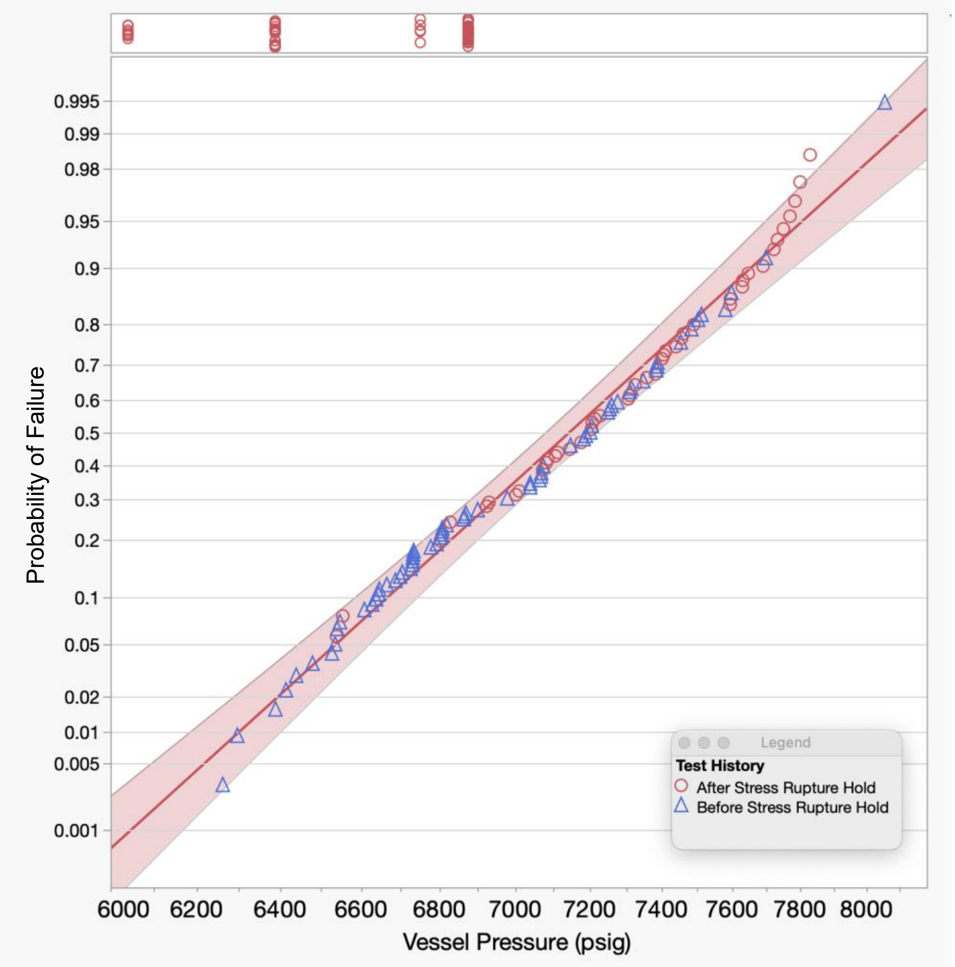

Figure 2. Lognormal Probability Plot (y-axis scaling) of Burst Strength Data with Lognormal (red). Plot symbols indicate data points from specimens that received or did not receive additional stress rupture (i.e., effective proof) loading.

5.0 Discussion of Strength Testing Results

These data do not support the assertion that damage that occurs during a proof test results in a reduced strength upon reloading. While any loading of a composite can result in damage accumulation, the damage that accumulates in a proof test will be the same damage that results as a specimen reaches the same pressure as the proof test when being strength or burst tested. This is consistent with previous acoustic emission (AE) testing in composites and COPVs that indicates that no additional damage is detected in composites upon repeated loading until the specimen nearly reaches the previous maximum load or pressure [5]. Thus, no difference in ultimate strength should be expected, nor was observed, between specimens subjected to proof type loads and those that were not prior to burst testing. As such, the rationale that proof test should not be considered as a mitigation against stress rupture failure because of the possibility of damage accumulation during proof testing is not substantiated.

6.0 Alternate Methodology to Implement Proof Test Benefit for Stress Rupture Mitigation

The postulated detrimental effect of proof loading on strength of COPVs is not supported by the data and analysis presented in the previous section. However, as discussed, there remain many concerns with accelerated life stress rupture testing especially for carbon fiber COPVs. As such, the use of accelerated life testing results to estimate a safe time as a result of proof testing is not recommended and the extreme acceleration required to observe vessel burst in a reasonable amount of time makes the applicability and utility of models built on these data questionable. An alternate approach is proposed that is based on simple strain monitoring. In this approach, strain is first measured during the proof test of a COPV. Then strain is also monitored during a pressurization to MEOP and during hold period while the pressure is maintained at the MEOP. Because of viscoelastic effects in the composite, the strain will continue to increase during the hold at MEOP as illustrated in Figure 3. Based on the measured strain during this hold period and using existing model forms for viscoelastic strain in composites [6], the viscoelastic strain can be extrapolated beyond the measured time to estimate the maximum strain that will occur if the vessel is held at MEOP for the lifetime, as shown in Figure 3. Note that the strain in Figure 3 during hold and extrapolated to lifetime is exaggerated relative to the magnitude of strain to reach MEOP in a typical COPV test for illustration purposes. The increase in strain due to viscoelastic effects is typically only a small percentage (< 10%) of the strain reached at MEOP. Additionally, it is recommended that these strain measurements be made in the direction of the fibers in the outer wrap of the COPV. This is to avoid deleterious effects of matrix microcracking on strain gauges and measurements that are often observed when making strain measurements transverse to the fibers in COPVs. Also, it is recommended that the strain measurements be obtained from regions of the vessel where there are not expected to be significant strain gradients (e.g., in the cylindrical region versus the dome and/or transition). This will minimize any variability due to spatial positioning of the strain gauges when comparing data across multiple vessels.

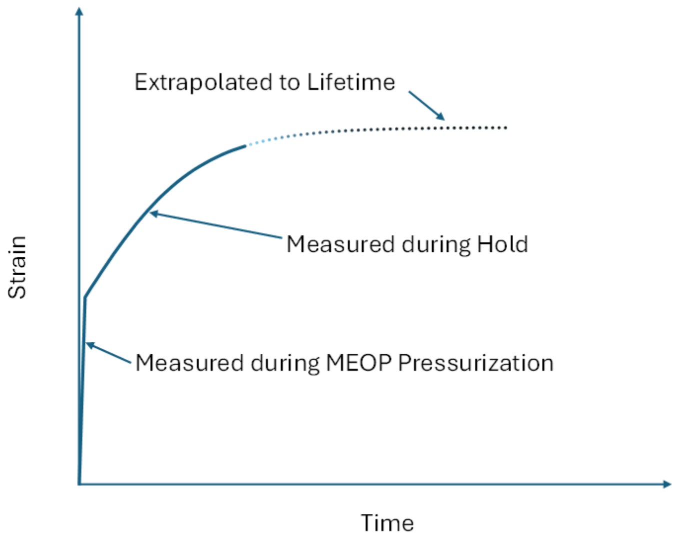

Figure 3. Illustration of Measured and Extrapolated Strain in a COPV when Exposed to a Ramp Pressurization to MEOP and then Held at that Pressure

The approach to determine whether the proof test adequately mitigates against stress rupture failure is to determine if the estimated strain at lifetime at MEOP remains less than the strain reached during proof testing. This is illustrated in Figure 4 which shows the strain when the vessel is subjected to a proof test (ε_P) as well as the strain when the vessel is subjected to pressurization to MEOP (ε_M) followed by a hold with the measured strain during the hold used to extrapolate and estimate the strain after the planned lifetime (ε_L). If the estimated strain after the lifetime pressurization at MEOP remains less than the strain at proof (i.e., $\varepsilon_L < \varepsilon_P$), then the vessel is not expected to fail in stress rupture. This proposed methodology is supported by studies in which AE was used to monitor COPVs during repeat pressurization such as in [5]. AE provides a method to determine the onset of damage in COPVs as a function of increasing pressure. In these studies, it has been shown that when a vessel is loaded to a higher pressure, and then unloaded and repressurized, that new damage is not detected until the vessel almost reaches the previous maximum pressure and corresponding strain. If the maximum pressure is low relative to the burst pressure, no damage is detected until the previous maximum pressure/strain is reached. However, as the previous maximum pressure gets closer to the burst pressure, some new damage will begin to be detected but only as the pressure nearly reaches the previous maximum pressure (e.g., above 95+% of the previous maximum). In either situation, no new damage and thus no likelihood of failure is expected when the pressure and strain remain well below the previous maximum and thus there is no expected PoF. This approach is also supported by an improved understanding of the stress rupture phenomenon and associated micromechanics [2] in which the increased viscoelastic composite strain is shown to be equal to a resultant increase in fiber stress. Therefore, if the fiber stress while the vessel is held at MEOP does not exceed the stress reached during proof pressurization (during which all vessels that had lower strength would have failed), there should be no expectation of failure as a result of stress rupture. (Note that this is only applicable to the conditions under which the vessels were proof tested. Operation of the vessels under different conditions such as extreme higher temperatures or radiation environments that may degrade the material strength are not considered.) This is assuming that the proof pressurization did not result in any decrease in strength, which is supported by the data and analysis presented in the previous section.

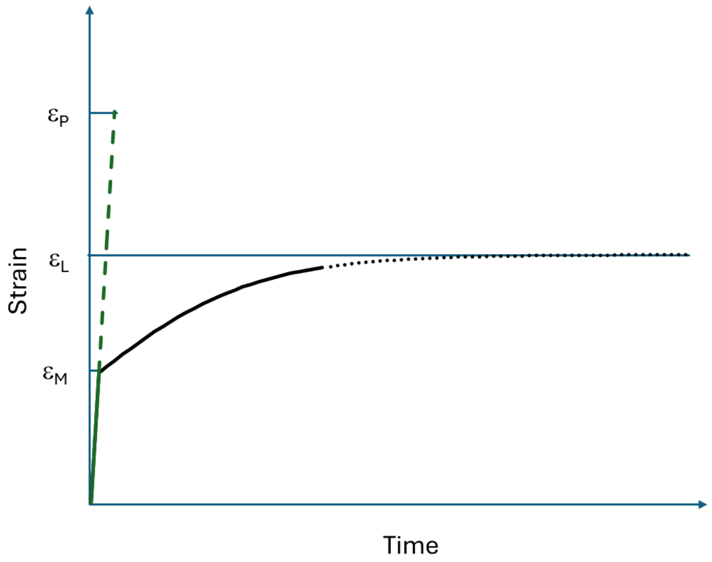

Figure 4. Illustration of Proof Strain (ε_P) Resulting from a Proof Test Pressurization as well as the Strain to Reach MEOP (ε_M) and the Resulting Viscoelastic Strain Measured and Extrapolated to the Planned Lifetime of a COPV (ε_L)

To address uncertainty factors such as strain measurement error, vessel-to-vessel variability, etc., a safety factor (SF) can be included similar to the approach used for stress-based margin approaches, e.g., structural factor of safety. Additionally, instead of comparing the absolute strain values, one could also compare the percent increase in strain to reach proof from MEOP (Δ_{PM}) to the percent increase in strain after extrapolating to the lifetime at MEOP (Δ_{LM}), where

$$\Delta_{PM} = ((\varepsilon_P - \varepsilon_M)/\ \varepsilon_M)*100$$

and

$$\Delta_{LM} = ((\varepsilon_L - \varepsilon_M)/\ \varepsilon_M)*100$$

The criteria for accepting a proof test as mitigation against stress rupture is then given by

$$\Delta_{LM} * SF < \Delta_{PM}$$

Further conservatism can be introduced by making these measurements on multiple vessels and then using a statistically estimated lower bound for the increase in proof test strain and an estimated upper bound for the increased strain at lifetime. Such an approach would be consistent with stress-based margin structural analysis approaches where upper bounds on loads are compared against lower bound material properties with the inclusion of a SF. Since all COPVs are proof tested, it would be relatively straightforward to instrument all vessels with strain gauges to measure their respective proof strains. Then, a number of vessels could be monitored with strain gauges during the application of MEOP pressures for a designated hold period. It is important to note that these data can be obtained from actual (i.e., flight) vessels instead of surrogate specimens, whose behavior has not been demonstrated to be relevant to actual flight vessels. Even the strain monitoring during a hold at MEOP can be carried out on flight vessels as the hold period would only be required to be a short portion of the desired lifetime, and so the vessels used to gather that data could subsequently be used for flight applications.

For vessels designed per AIAA S-081B [4], Δ_{PM} is specified to be between 25 and 50 because of the requirements to proof at between 1.25 and 1.5 X MEOP. Although data for strain monitoring during a MEOP cycle was not available, strain data during extended holds at elevated pressures during previous stress rupture testing of subscale vessels [7] was obtained and evaluated [2]. The vessels were pressurized and held at higher pressures than MEOP and so the measured (and extrapolated) strain increase would be expected to be conservative relative to a similar hold at MEOP. The average estimated percent increase in strain over a 10-year lifetime was 3.3 and the estimated upper bound was 5.4 for the vessels in this study. Thus, using the upper bound, they would still satisfy the criteria for accepting the proof test as adequate mitigation against stress rupture with a SF exceeding 4 for the lower proof test value of 25, calculated as 25/5.4 = 4.6. These data suggest that such an approach would be successful for carbon fiber COPVs, although data for specific flight vessels of interest would be needed for verification for a particular design.

Although the proposed approach still requires extrapolation as a function of time, it no longer requires hyper acceleration to produce vessel failures and extrapolation down in pressure. Additionally, it does not require large numbers of samples to produce adequate numbers of failed vessels for statistical analysis, because continuous strain measurements are acquired and modeled rather than discrete pass/fail in traditional rupture testing. Moreover, since the vessels are not tested to failure it can be performed on actual flight vessels, as opposed to surrogate specimens that may not have the same stress rupture behavior. Thus, the approach eliminates the concerns recently identified with accelerated life testing necessary for estimating proof test based safe time.

7.0 Conclusions

Proof testing is required for COPVs to mitigate risk against burst failure during normal pressurization of vessels with low strength that may be due to normal statistical variability or poor workmanship. Proof testing has been proposed for mitigation against stress rupture failure. However, the primary reason for the lack of acceptance for its mitigation against stress rupture failure has been the concern that damage accumulated during proof testing might result in a lower burst strength during subsequent pressurization. Data and analysis provided in this research show that a reduction in strength due to proof type pressurization was not observed for carbon fiber strands or COPVs. However, there are additional concerns with the previously identified approach of estimating a safe time as a result of proof pressurization that a vessel can be held at MEOP without risk of stress rupture failure. These concerns include the extreme acceleration required in testing to develop model parameters based on observed failures on-hold required to estimate safe time as well as the fact that surrogate specimens are needed to perform this accelerated testing. Therefore, an alternate strain-based measurement approach was developed to provide a method for demonstrating that proof test has mitigated the likelihood of stress rupture for a desired lifetime. If the strain reached during proof testing exceeds the estimated strain that would accumulate during a hold to the desired lifetime at MEOP, then failure due to stress rupture is not expected to occur (under operating conditions consistent with those in which the proof testing occurred). This approach is supported by previous AE testing as well as more recent improvements in the understanding of the stress rupture failure phenomena. The proposed implementation of this approach is to compare the percent increase in strain to reach proof above MEOP to the percent increase in strain that results from viscoelasticity during the hold at MEOP extrapolated to the lifetime to include a SF to address vessel-to-vessel variability or measurement uncertainties. Additionally, measurements across multiple vessels can be used to provide upper and lower bound strains in this evaluation for additional conservatisms. Since the required strain measurements can be obtained on actual flight COPVs rather than surrogate specimens and the testing performed at MEOP and proof rather than at extreme accelerated conditions, this approach addresses the concerns with the previously identified approach. Further, data from previous testing of carbon fiber COPVs show that for the 10-year lifetime considered, the vessels would be protected against stress rupture failure with a SF exceeding 4. The proposed approach is consistent with margin-based approaches with SFs used for protection against burst failure.

8.0 References

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