RELIABILITY CONSIDERATIONS FOR COMPOSITE OVERWRAPPED PRESSURE VESSELS ON SPACECRAFT

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Introduction
Composite Overwrapped Pressure Vessels (COPVs) are used to store gasses under high pressure onboard spacecraft. These are used for a variety of purposes such as propelling liquid fuel etc. Kevlar, glass, Carbon and other more recent fibers have all been in use to overwrap the vessels. COPVs usually have a thin metallic liner with the primary purpose of containing the gasses and prevent any leakage. The liner is overwrapped with filament wound composite such as Kevlar, Carbon or Glass fiber. Although the liner is required to perform in the leak before break mode making the failure a relatively benign mode, the overwrap can fail catastrophically under sustained load due to stress rupture. It is this failure mode that is of major concern as the stored energy of such vessels is often great enough to cause loss of crew and vehicle. The present paper addresses some of the reliability concerns associated specifically with Kevlar Composite Overwrapped Pressure Vessels. The primary focus of the paper is on how reliability of COPV's are established for the purpose of deciding in general their flight worthiness and continued use. Analytical models based on existing design data will be presented showing how to achieve the required reliability metric to the end of a specific period of performance. Uncertainties in the design parameters and how they affect reliability and confidence intervals will be addressed as well. Some trade studies showing how reliability changes with time during a program period will be presented.

Design data
COPVs are susceptible to many of the same failure modes as metallic pressure vessels, but additional considerations are required to ensure that the vessel has a reliable composite overwrap. One of the failure modes these overwraps can experience under sustained loading is the so called "stress rupture" failure. A COPV that fails due to the stress rupture failure mode will burst suddenly leading to catastrophic consequences such as loss of a vehicle and the crew.

Stress rupture life testing for Kevlar has been performed primarily by Lawrence Livermore National Laboratory (LLNL) and Cornell University with Kevlar material characterization contributions from the Y12 Plant at Oak Ridge National Laboratory and Sandia National Laboratories. These tests have consisted of single-fiber, fiber-bundle, resin impregnated strand (or tow tests), and COPV testing at a single constant stress level (1-4)

Although models based on data from LLNL, Cornell, and DOE are available in the literature, they are not directly comparable nor applicable to any other COPV designs that are used on spacecraft. Changes have to be made to account for the load carrying effects of the liner, the effects of strength variations between different spools used to overwrap the COPVs, and compensation for differences in ultimate burst strength of the composite due to differences in pressurization rate between the spacecraft COPVs and LLNL test COPVs. In addition correction to account for Kevlar creep relaxation needs to be made.

Phoenix Model
The Phoenix model has been developed over the past 27 years and is well documented in the literature. It is based on a Weibull distribution framework for strength and lifetime with the embodiment of a power law to describe damage in a composite versus stress level. Derivation of the model is available in references where the power-law in stress level (with temperature dependence) is derived from thermally activated chain scission using a Morse potential as a model. The model parameters are based on the LLNL pressure vessel data. In the simplest setting of constant stress applied quickly and maintained over a long time period, the basic equation for the model is below.

$$P(t,\sigma) = 1 - \exp\left[-\left\{ \left(\frac{t}{t_{c,ref}} \right) \left(\frac{\sigma_{op}}{\sigma_{burst}} \right)^{\rho} \right\}^{\beta} \right] \quad (1)$$

In the above equation the quantity ($\sigma_{op}/\sigma_{burst}$) is the ratio of fiber stress at operating pressure to fiber stress at burst pressure (stress ratio), t is time, $t_{c,ref}$ is a reference time, ρ is the power law exponent, and β is the Weibull shape parameter for lifetime. The value for σ_{burst} is determined from the flight COPV burst test accounting for pressurization rate differences between flight COPVs and the LLNL test COPVs. The model is shown for a single stress level over time, but for more general time histories a memory integral is used to accumulate damage (similar to Miner's rule for fatigue) at different stress levels. Also, at very high stress levels a second quantity within square brackets and of similar structure to the first must also be included with a leading minus sign as well (i.e., in a weakest damage mechanism framework). This second quantity has different parameter values, especially a much higher ρ value.

In the Phoenix model, values for the parameters $t_{c,ref}$, ρ, and β are determined based on the LLNL vessel data and are influenced by observations of stress rupture behavior of strands and single fibers. Values for these parameters determined by Phoenix for the LLNL vessel data are shown in Table 1. The power law exponent, ρ, is the inverse of the slope of the logs of the scale parameter of the stress rupture data and the stress ratio. The parameter $t_{c,ref}$ is an anchor point determined from this slope and an instantaneous reference strength. In the Phoenix model, both ρ and β are based primarily on the LLNL vessel data but were chosen such that all data available (which includes data from other Kevlar COPVs and strands) are considered. In this way the parameters are determined from broader observations of stress rupture data as a whole, making the resulting reliability estimations consistent with all stress rupture data. This "big picture" approach is a unique feature of the Phoenix model.

Table 1. Parameter values for the Phoenix model.

Parameter	Value
ρ	24
β	1.2
$t_{c,ref}$	0.5456

Based on the Phoenix model, a series of reliability quantile curves can be developed for use in design that allow estimation of the lifetime for a chosen quantile (Figure 2). Analysis based on this approach is employed currently by COPV manufacturers.

For recertification purposes of spacecraft which endured a long successful history, a conditional probability approach needs to be used. In this approach, because the vessels successfully "survived" up to now, this successful past history is credited in the analysis. The conditional reliability equation for the Phoenix model can be derived from equation (1) using the simple probability principles. This conditional reliability was used in all Phoenix calculations for Orbiter reliability estimates for future flights.

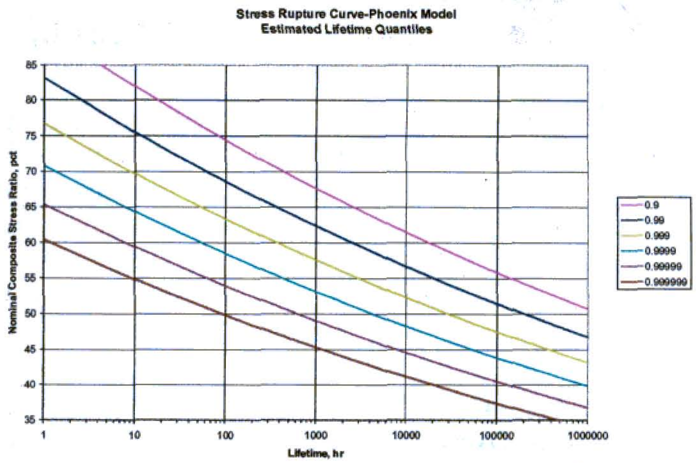

Figure 2. Phoenix Stress Rupture Curve. Quantiles are for probability of survival.

Results and Discussion

Based upon the above expression the reliability of a system of COPVs on board the spacecraft is established and projections are made for the number of possible missions with a specified reliability. Several trade studies are conducted to establish the sensitivity of the model parameters on probability of survival. Furthermore, uncertainties in parameters are considered and Monte Carlo based simulations are run to establish the confidence bounds on the reliability predictions. These results and further details of the model will be presented at the conference.

References

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