Proof of life requirements for deep-ocean autonomous underwater vehicle (AUV) component

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Hannah Budinoff
Audrey Ford
Maxwell Micali

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Introduction

The Monterey Bay Aquarium Research Institute (MBARI) was founded in 1987 by David Packard, of Hewlett Packard, as a private, non-profit research institute located in Moss Landing, CA. The dual mission of is to advance marine science, as well as advance the state of engineering required to push the limits of what is capable in marine science. In the vein of the latter, much of their research focuses on remotely operated vehicles (ROVs) to explore and house experiments in the deep sea trench extending from Moss Landing into the Monterey Bay. While ROVs enable research that could not be performed by manned vessels, ROVs do still require a tether to a staffed boat on the surface, as well as a team to operate the ROV. These requirements limit the frequency and duration of expeditions due to cost and surface weather conditions.

To address the issues with ROVs, MBARI is in the process of transitioning some projects and experimental platforms to Autonomous Underwater Vehicles (AUVs), which require neither a tethered boat nor a team to control them in real time. Given that the AUVs are not actively piloted, they are currently best suited for long-continuous data collection missions where they passively collect data about whatever the AUVs may encounter over the course of a multi-day pre-planned route at a given depth. One example is outfitting a torpedo-shaped AUV with a high resolution camera in its nose, and passively recording footage of any sealife or geographic features that may enter the field of view during its journey. The camera requires that one end is transparent, optically precise, and capable of withstanding up to 1500m of water pressure, which drove the MBARI engineers to manufacture dome-shaped housings out of H-K9L glass. Since data do not readily exist for the mechanical properties of H-K9L glass, MBARI is assuming it is similar to the BK-7 glass used in Space Shuttle windows, and this report will carry forward with that assumption. The design for the glass dome is a spherical cap with a 250mm edge diameter, 162.4mm spherical radius to the outer surface, and 22 mm wall thickness. A model of the dome and housing assembly is shown in Figure 1.

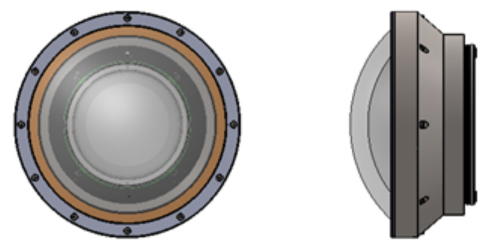

Figure 1. Model of dome and housing system.

MBARI has been through three design revisions of the dome and housing system, with most of the changes taking place in the design of the housing. The first and second designs were pressure tested in a thermally-controlled pressure vessel at 4˚C in water. Both had unsatisfactory performance, causing the glass dome to fracture at pressures lower than the required service pressure. After consulting an external fractographer, the MBARI engineers are confident about the third design revision and have finalized that design. Their current challenge, which this report addresses, is to determine a proof testing strategy by which to inspect the glass domes upon receipt from the manufacturer and guarantee a minimum service life of 60 autonomous missions at depths up to 1500m of seawater.

Analysis

Proof testing of ceramics determines if flaws are present in the material that could cause failure during the part's expected lifetime of use. Proof testing is based on observations of crack growth speeds at different loads and used to predict time dependent crack growth and the time to failure at a given load. The proof test is a single overload event at a magnitude that ensures that any flaws are below a critical size. The critical size is determined by the size that could cause failure due to crack growth over the desired service life and service loading conditions. A part with flaws large enough to cause failure in the service lifetime is expected to fail under the destructive proof test. The proof test is therefore a method of inspection for flaws that are below a reasonable size for inspection. Additionally proof testing ensures that any damage that was incurred during the proof test does not invalidate the results of the test.

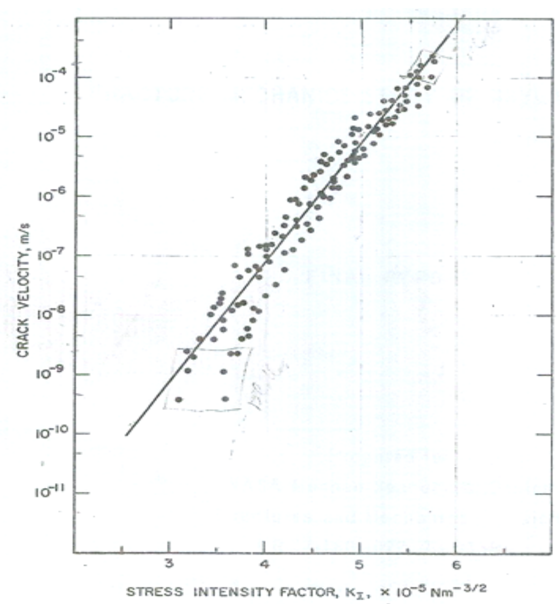

Figure 2. Crack velocity (V) versus stress intensity factor (K_I) for BK-7 glass (*National Bureau of Standards Report, 1972).*

This report outlines the application of proof testing to the glass UAV dome. The approach is based on a fracture mechanics defect tolerant life prediction approach. Fracture mechanics defines the stress intensity (K_I) as a measure of the combination of applied stress, crack size, and crack geometry (Equation 1). Fracture occurs at a critical value of stress intensity, known as the fracture toughness, K_{Ic}, when the crack length, a, reaches a large enough length to cause unstable fracture. When measured in a state of plane strain, K_{Ic} is a material property independent of geometry and stress state.

Proof testing predictions utilize the empirical relationship between stress intensity and crack speed (crack extension per unit time) to predict the service life of the part. Wiederhorn's paper presents data for K_I vs. Crack Velocity (Figure 2) that can be fit to a power law (Equation 2, Wiederhorn, 1974). A power law fit yields coefficients A and n, 21.8 and 20.95, respectively. In order to relate stresses to time to failure a relationship between strength (σ) and stress rate ($d\sigma/dt$) was developed by Charles and Evans. This is based on a relationship between constant loading rate data and crack growth data (Equation 3; Wiederhorn, 1974). In this relationship Y is a geometric parameter, approximately equal to $\sqrt{\pi}$ and K_{Ii} is the initial stress intensity factor.

For proof testing the initial stress intensity, K_{Ii} (calculated from the local service stresses and flaw sizes at the applied service load), must be less than some fraction of the critical stress intensity factor K_{Ic} (Equation 4; Wiederhorn, 1974). This fraction is set at the local service stress divided by the local proof stress. Combining Equations 3 and 4 gives a minimum time to failure (Equation 5), where:

$$K_I = Y\sigma\sqrt{\pi a} \quad [1]$$

$$V = A(K_I)^n \quad [2]$$

$$t = \frac{2K_{Ii}^{2-n}}{A\sigma_a^2 Y^2 (n-2)} \quad [3]$$

$$K_{Ii} \leq \left(\frac{1}{R}\right) K_{IC} \quad [4]$$

$$t = \frac{2\left(K_{IC}\frac{1}{R}\right)^{2-n}}{A\sigma_a^2 Y^2 (n-2)} \quad [5]$$

$K_{IC} = 0.82$ MPa$\sqrt{m}$
n = 46
A = 2.02 x 10^{12}
$Y = \sqrt{\pi}$
R = Proof Ratio - Local proof stress/ service stress (MPa)
σ_a = Local service stress (MPa)

In order to solve for the time to failure, a better understanding of the stress state in the dome was needed. A finite element analysis (FEA) of the final design of the dome assembly was performed in ANSYS Workbench. The model was set up to be 2D axisymmetric. The pressure from the water was applied to the outer surface of the dome. The back face of the titanium housing was fixed in all directions. The dome in the design is fixed on the edges with epoxy and seated against kapton tape. The glass, kapton tape, epoxy, and all metal components were modeled as linear elastic with Young's modulus and Poisson's ratios as given in literature. The contact between the glass dome and the epoxy was modeled as bonded, while the contact between the glass and the kapton tape was modeled as a frictional contact with a coefficient of 0.2. The environment was modeled at 5°C to capture the effects of thermal strains when the assembly is taken into the ocean after being assembled at room temperature.

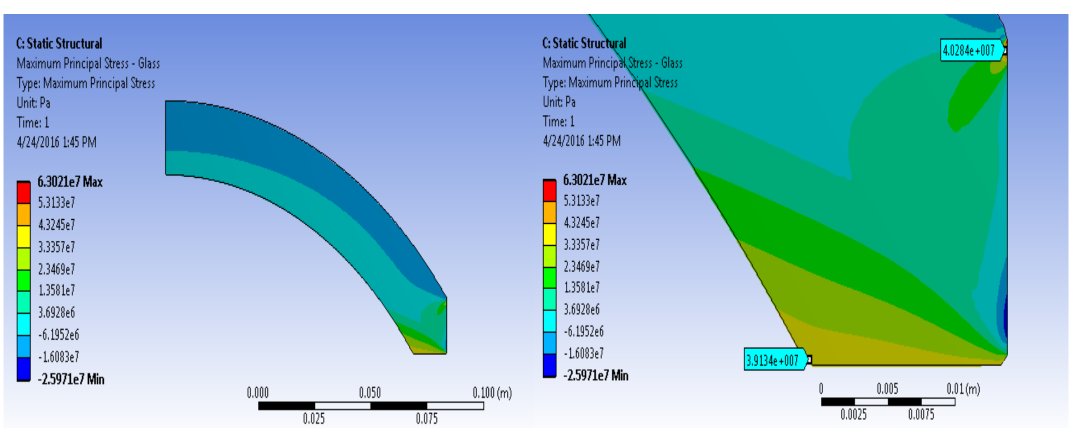

Figure 3. ANSYS simulation results showing predicted maximum principal stress in the glass dome.The right image focuses on the edge of the dome which is seated in the housing, where stresses are highest.

Results from the ANSYS simulation, as shown in Figure 3, show local stresses of approximately 40 MPa at the corners of the glass under an applied service stress of ~14.7 MPa (1500 m of sea water). This provides an estimated stress concentration factor of 2.7 (the local proof and service stresses were assumed to be 2.7 times that of the applied load from external pressure.) These values were used to predict the local proof stress required to ensure a given design life based on dive duration and frequency. The predicted life is a function of the desired local service stress and the proof ratio (local proof stress/local service stress), as plotted in Figure 4 for a range of proof ratio. This plot enables the engineers at MBARI to select a suitable proof stress to guarantee a certain life for different scenarios. For example, if the desired life of the dome is 1 hour, and the estimated local service stress is assumed to be equal to the maximum principle stress predicted by FEA, ~40 MPa, the necessary proof ratio would need to be between 2 and 3. The desired local proof stress would be between 80 and 120 MPa. Based on the stress concentration factor of 2.7, the applied proof stress would need to be between 30 and 44 MPa.

The proof testing predictions are limited by the assumptions made throughout. The first assumption is that the H-K9L glass that the dome is made out of is mechanically equivalent to BK-7 glass. This assumes that the A and n values for the power law fit and strength to stress rate relationship for BK-7 applies to the dome glass. There is further uncertainty in the interpolation and these values from data. The second assumption is that no additional flaws are introduced during the process of proof testing. For example, no additional flaws are created when reassembling the part, transporting, etc. The third assumption that was made is that the critical stress intensity for the H-K9L glass is also equivalent to BK-7. The value was assumed to be 0.82 MPa√m based on values found in the literature (Lv, 2013). A fourth assumption is in the constant geometry factor Y. In reality this factor is a function of the location and shape of the critical flaw. The final assumptions are made in the FEA prediction of the service stress. FEA enables a connection to be made between the applied external water pressure on the local stresses that will be relevant to flaw growth and failure. To account for the uncertainty caused by these assumptions a design life factor of safety should be applied to the predicted life of the dome. This factor of safety would be multiplied by the actual desired service life of the part before determining the appropriate proof ratio as shown in Figure 4.

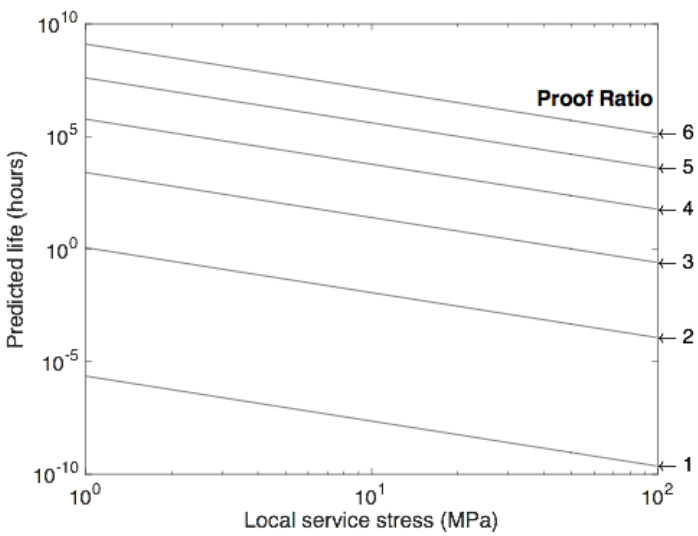

Figure 4. The predicted life of the part decreases with increasing service stress. Increasing proof stress to service stress ratio increases the predicted life of the part for a given service stress. Service and proof stress refers to the local maximum stress in the part. From the stress analysis, this is approximately 2.7 times greater than the applied external pressure.

Conclusion

MBARI is not well equipped to perform precision inspection of manufacturing defects in the glass domes upon receipt, since the critical crack sizes are relatively small and unreasonable to measure without specialized equipment. Due to the fact that BK-7 is a brittle material, proof testing may serve as a functional substitute for defect inspection, since any critical cracks present will cause the dome to fail during the proof test. The stress analysis performed with ANSYS shows that maximum predicted principle stress does not exceed the ultimate tensile strength of the material, meaning that a flawless dome should survive the service depth of 1500m of seawater. However, the presence of flaws is realistically unavoidable, which is why the proof testing is necessary. If the components survive the proof test, it shows that there are not critical flaws in the glass, and that the dome should survive in operation for a selected minimum guaranteed life. As with any model, these proof test calculations and stress analyses use simplifying assumptions, and these results must be validated through pressure testing. The primary output of this work is the plot in Figure 4, yielding a graphical tool for the engineers at MBARI to select a proof ratio for given use conditions.

References

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