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Proof Test Levels for Advanced LIGO Viewports

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1 Introduction

The “LIGO Generic Requirements & Standards for Detector Subsystems”[1] calls for inert environment, proof testing for all brittle, non-metallic materials on the vacuum envelope. The minimum proof test factor for pressurized brittle, non-metallic materials is 2.0. Better than proof testing at the minimum test factor is to proof test at a stress which guarantees the desired minimum lifetime[2,3]. In this memo the appropriate proof test levels, based on fracture mechanics, are calculated for each of the Advanced LIGO (aLIGO) viewports.

2 Fracture Mechanics for Glasses

2.1 Formulation

It is well established that subcritical crack growth, or slow crack growth (SCG), in glasses and ceramics, in environments containing water vapor, is caused by a tensile stress enhanced, chemical corrosion at the tip of pre-existing surface flaws[4]. This phenomenon is known as “delayed failure” or “static fatigue”.

Weiderhorn et. al. found that some glasses exhibited subcritical crack growth in vacuum, whereas some other glasses did not (including two that had anomalous elastic behavior and an Ultra-Low Expansion (ULE) glass). I am unaware of any studies on subcritical crack growth for the optical materials that we use in our vacuum viewports. It is possible (even likely) that these materials do not exhibit subcritical crack growth (static fatigue) while under vacuum. However, it is important to consider the lifetime and strength due to static fatigue in this application, because (a) the viewports are cycled up to air multiple times and for significant durations during their lifetime and (b) there can be tensile stresses on the air side of the viewport windows (associated with the compressive loading of the seal or due to slight overpressure when venting).

Pre-existing flaws grow in size under the service load (stress) to a critical size at which a crack propagates quickly. The subcritical growth can be expressed as a power function of the stress intensity factor, K_I:

$$V = AK_I^N$$

where V is the crack velocity, A and N are constants that depend on the environment and material composition. From this equation it can be derived that the time to failure, t_f, under a constant tensile stress, σ_a, is:

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[1] D. Coyne, “LIGO Generic Requirements & Standards for Detector Subsystems”, E010613, section 3.4.4.1.1. This section is based upon: “Structural Design and Test Factors of Safety for Spaceflight Hardware”, NASA-STD-5001, 21 June 1996. *N.B.: The current version of the requirements document (E010613-v1), requires a minimum proof test load of 1.2 times the maximum in-service load with a minimum design factor of safety of 3. However, this is really only appropriate for non-pressurized applications. The document will be revised to call for a proof test factor of 2.0 for pressurized applications, such as viewports.*

[2] J. Ritter, D. Coyne, K. Jakus, “Failure Probability at the Predicted Minimum Lifetime After Proof Testing”, Journal of the American Ceramic Society, Vol. 61, No.5-6, pp. 213-216

[3] K. Jakus, D. Coyne, J. Ritter, Analysis of fatigue data for lifetime predictions for ceramic materials, J. Materials Science, 13 (1978) 2071-2080.

[4] .

$$t_f = B S_i^{N-2} \sigma_a^{-N}$$

where $B = 2/(AY^2(N-2)K_{IC}^{N-2})$, Y is a geometric constant ($\sqrt{\pi}$ for surface flaws), K_{IC} is the critical stress intensity factor and S_i is the fracture strength in an inert environment.

The probability distribution function for the inherent fracture strength is often well modeled by a Weibull function:

$$\ln\left(\ln(\frac{1}{1-F})\right) = m \ln\left(\frac{S_i}{S_0}\right)$$

where F is the cumulative failure probability and m, S_0 are constants.

2.2 Material Properties

2.2.1 Fused Silica (SiO_2)

The strength and delayed failure properties of fused silica are discussed in the report[5] on the design, and stress analysis, of the elastomer sealed viewports for aLIGO. Here only a summary of the relevant parameters are restated for convenience.

$E = 10.7\ 10^6$ psi (73.6 GPa)

$\nu = 0.17$

$m = 4.4$

$S_0 = 156.5$ MPa

$N = 40.5$

$B = 5.1 \times 10^{-4}\ \mathrm{MPa}^2\ \mathrm{s}$

$A = 7.49 \times 10^6\ \mathrm{m/s}\ (\mathrm{MPa}\ \sqrt{m})^{-N}$

$K_{Ic} = 0.722\ \mathrm{MPa}\ \sqrt{m}$

2.2.2 Corning 7056 Alkali Borosilicate Glass

The elastic properties of Corning 7056[6] (a glass designed to have a coefficient of expansion matched to Kovar for sealing to glass) are:

$E = 62.8$ GPa

$\nu = 0.21$

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[5] D. Coyne, "Design of the Elastomeric Sealed, High Quality, Viewports", T1100346-v2, section 4.1. The KIc and A values are not reported in T1100346 but available from the principal source for fused silica delayed failure parameters: L. Braun et. al., "Fracture Mechanics and Mechanical Reliability Study: Comparison of Corning Code 7980 and 7940 Fused Silica", NIST, Nov 1998.

[6] MatWeb, Corning 7056 Alkali Borosilicate Crushed/Powdered Glass

I have been unable to find any delayed failure (static fatigue) data in the literature[7] for Corning 7056 glass, or more generally for borosilicate glass. As a consequence, the proof test factor for this glass will default to 2.0.

2.2.3 Zinc Selenide (ZnSe)

The elastic properties of chemical-vapor-deposited (CVD) ZnSe windows are[8]:

$E = 74.3$ GPa

$\nu = 0.31$

and the Weibull distribution parameters for the equibiaxial fracture strength (determined by the maximum likelihood estimator) are:

$m = 9.6$

$S_0 = 60.6$ MPa

With a failure probability of $F = 10^{-5}$ and a lifetime, $t_f = 20$ years:

$S_i = 18.3$ MPa

$\sigma_f = 7.86$ MPa

A NASA report[9] on slow crack growth properties of CVD ZnSe windows showed a remarkably large variation in slow crack growth properties from (or derived from) data in the literature. In my opinion[10] the most appropriate slow crack growth parameters are:

$N = 39.6$

$B = 6.74 \times 10^{-4}$ MPa^2-s

$A = 1.09 \times 10^{3}$ m/s (MPa $\sqrt{m}$)$^{-N}$

$K_{Ic} = 0.9$ MPa $\sqrt{m}$

However it should be noted that there is a great deal of uncertainty in these values (despite reporting 3 significant digits). The interested reader should consult the source references.

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[7] albeit with a very limited search.

[8] J. A. Salem, "Mechanical Characterization of ZnSe Windows for Use With the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) Module", NASA/TM-2006-214100, Feb 2006

[9] J. A. Salem, "Estimation of ZnSe Slow-Crack-Growth Properties for Design of the Flow Enclosure Accommodating Novel Investigations in Combustion of Solids (FEANICS) Windows", NASA/TM-2005-213359, Apr 2005

[10] The SCG properties reported in Ref. 9 are derived principally from two other references, which are referred to in Ref. 9 as Ref. 1 and Ref. 2. The Ref. 2 data has large scatter, or was fitted after truncating some of the data for a better fit. For these reasons the Ref. 2 data is suspect in my opinion. The Ref. 1 data set which has the least scatter and has an N value which is consistent with most other data cited in Ref. 9, including Ref. 2, seems the best choice for N and A values. In order to derive a B value, one must use an appropriate K_{Ic} value. In Ref. 9 the K_{Ic} value for small cracks of intergranular or transgranular nature is recommended as conservative. However this value is so conservative that the aLIGO ZnSe viewport would not be predicted to sustain even 1 atm. Consequently, the less conservative, but more realistic K_{Ic} value reported for a dry nitrogen environment is used in my recommended SCG property set.

3 Stress

3.1 Stress due to the Pressure Load

The response (deflection and stress) of the window/optic due to one atmosphere of load can be estimated by the response of a circular flat plate of constant thickness loaded with a uniform pressure on one side and simply supported at its perimeter[11]:

$$y_c = \frac{-qa^4(5+\nu)}{64D(1+\nu)}$$, the deflection of the plate (window) at the center

$$\sigma_c = \frac{3qa^2(3+\nu)}{8t^2}$$, the stress at the face of the plate (window) at the center

where

a = radius to the simple support (taken as the compressed o-ring I.D.)
q = applied pressure load
t = window thickness
$D = \frac{Et^3}{12(1-\nu^2)}$ is the "plate constant", or stiffness
E = modulus of elasticity
ν = Poisson's ratio

This approximate calculation is reasonably close to finite element results, indicating that the response is primarily plate-like bending[12]. The finite element analysis for the non-wedged, 6 inch, high quality viewport windows[13] is documented in T1100346. The finite element analysis for the TCS viewport ZnSe window[14] is documented in E1100379. In both of these cases the approximate plate bending formulation given above yields a higher (conservative) stress. The approximate plate bending formulae is used for all other viewport designs in section 4.

3.2 Thermal Stress

The only viewports which have some thermal loading are the following:

- PSL injection viewports
- TCS injection viewports

As shown in E1100379, with nominal (low) surface and bulk absorption, the small amount of absorption in the TCS viewport window causes very little temperature increase and insignificant stress. Both of these high power injection viewports (PSL and TCS) have an outer, secondary,

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[11] W.C. Young, Roark's Formulas for Stress & Strain, 6th ed., Mc-Graw-Hill, 1989, Table 24, case 10a with r_0=0

[12] Even though the window is quite thick, its response is dominated by the plate stiffness, D (i.e. the elastic modulus, E, and Poisson's ratio, ν), as opposed to the bulk modulus, K.

[13] D. Coyne, "Design of the Elastomeric Sealed, High Quality, Viewports", T1100346-v2.

[14] M. Jacobson, "Analysis Report of ZnSe Viewports for aLIGO TCS", E1100379-v3. *N.B.: The –v3 version has an error in the finite element analysis under pressure load and will be corrected.*

window which does not have a differential pressure across it. This window prevents significant surface contaminants (e.g. bugs) from causing increased absorption on the pressurized window.

4 Proof Test

The proof test should have the same stress field as the service stress, except amplified. Since the in-service stress is principally due to differential pressure, the proof stress can be accomplished by simply applying a higher differential pressure.

The minimum lifetime after proof testing is given by:

$$t_{min} = B\sigma_p^{N-2}\sigma_a^{-N}$$

where σ_p is the proof stress, σ_a is the applied, or service, stress and N and B are fracture mechanics material parameters defined above. The applied/service stress is the result of 1 atmosphere of differential pressure load. A proof test would impose a higher differential pressure in order to get the same stress field response except at higher amplitude. Due to the linear elastic response of the window, the proof stress can be expressed as a multiple of the applied/service stress:

$$\sigma_p = x\sigma_a$$

where x is the number of atmospheres of load to be used in the proof test and σ_a is the applied stress in service.

However the proof test load can be high enough to cause unintended damage if not careful. The viewport is either sealed with an o-ring or a glass-to-metal fused bellows/flexure seal. In the case of the o-ring seal, the proof pressure is generally high enough that the gap between the glass and the viewport flange will close and cause contact between the glass and metal, which can initiate surface flaws that lead to failure, i.e. without proper precaution the proof test can lead to premature failure. As a consequence either (a) a protective thin shim of soft material is placed between the glass and the metal (e.g. kapton), or (b) the window is proof tested separately from the viewport assembly and care is taken not to compromise the glass surface is subsequent handling and assembly. We have chosen the former approach.

In the case of a glass-to-metal fused seal, the proof test load is high enough to cause permanent deflection of the bellows/flexure. In this case the proof test apparatus must provide a soft landing to support the edge of the glass before the bellows/flexure exceeds the elastic limit. In the aLIGO viewport proof tester (D1101939) this is accomplished with a PEEK ring which contacts the outer radius of the face of the window, just inside the o-ring gland, which approximates the boundary condition afforded by the bellows/flexure reasonably well (though of course not exactly).

The proof test values, as well as other relevant parameters, for each of the aLIGO viewport windows is given in Table 1. The proof test levels are based on a 20 year lifetime.

Note that the TCS viewport includes two windows, one comprised of fused silica and the other comprised of zinc selenide. Both of the windows are exposed to the same proof pressure at the same time. Consequently the larger of the two proof pressures should be used (to ensure a 20 year minimum lifetime). This is possible only because the proof test levels for both windows are so similar.

For the commercial viewports which have a metal-to-glass, fused seal, the outer radius of the glass window is assumed to be .25" larger than the clear aperture, based on measurements for one design.

Note that for the large aperture (7.8” diameter) commercial viewports, the Factor of Safety (FS) is only 1.5 with a failure probability, F, of 10^{-2}, whereas for all other windows FS = 3.0 and F = 10^{-5}.

Table 1: Proof Test Levels

								Weibull Parameters												
Type	**Supplier**	**Model Number**	**Flange OD (in)**	**Optic material**	**View Dia (in)**	**window Radius (in)**	**Optic thick. (in)**	**S0 (Mpa)**	**m**	**F**	**Inert Strength Si (Mpa)**	**Limit Stress sf (Mpa)**	**bending stress (MPa)**	**FEA stress (Mpa)**	**Factor of Safety**	**Margin of Safety**	**N (--)**	**B (Mpa^2-s)**	**proof pressure (atm)**	**GN2 pressure (psig)**
AOS Commercial 6"	Norcal	ZV800	9.97	7056 glass	5.600	3.050	0.375						8.07		3.00		NA	NA	2.00	14.7
AOS Commercial 7.8"	MDC	9722012/450027	9.97	Quartz/Fused Silica	7.780	4.140	0.375	156.60	4.40	1.E-02	55.05	22.71	14.68		1.50	0.03	40.5	5.10E-04	2.37	20.1
AOS Commercial 4.5"	MDC	450004	4.47	7056 glass	2.690	1.595	0.17						10.74		3.00		NA	NA	2.00	14.7
AOS High Quality 6"	LIGO	D1100999	9.97	Fused Silica	5.240	2.669	0.75	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.00	0.16	40.5	5.10E-04	2.10	16.2
AOS High Quality 6", wedged	LIGO	D1101000	9.97	Fused Silica	5.240	2.669	0.87	156.60	4.40	1.E-05	11.44	5.10	1.13		3.00	0.50	40.5	5.10E-04	2.07	15.8
AOS High Quality 6", septum	LIGO	D1101535	9.97	Fused Silica	5.240	2.669	0.75	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.00	0.16	40.5	5.10E-04	2.10	16.2
AOS High Quality 6", septum, wedged	LIGO	D1101092	9.97	Fused Silica	5.240	2.669	0.87	156.60	4.40	1.E-05	11.44	5.10	1.13		3.00	0.50	40.5	5.10E-04	2.07	15.8
TCS Dual 3"	LIGO	D1003194	9.97	Fused Silica	2.250	1.306	0.5	156.60	4.40	1.E-05	11.44	5.10	0.82		3.00	1.07	40.5	5.10E-04	2.04	15.3
				ZnSe	2.250	1.306	0.5	60.60	9.60	1.E-05	18.27	7.86	0.86	0.76	3.00	2.44	39.6	6.74E-04	2.05	15.5
PSL High Power, 6" (non-wedged)	LIGO	D1101670	9.97	Fused Silica	5.240	2.669	0.75	156.60	4.40	1.E-05	11.44	5.10	1.53	1.47	3.00	0.16	40.5	5.10E-04	2.10	16.2
PSL High Power, 6", wedged	LIGO	D1101714	9.97	Fused Silica	5.240	2.669	0.87	156.60	4.40	1.E-05	11.44	5.10	1.13		3.00	0.50	40.5	5.10E-04	2.07	15.8