Structural Design of Glass and Ceramic Components for Space System Safety

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1.1 Introduction

Manned space flight programs will always have windows as part of the structural shell of the crew compartment. Astronauts and cosmonauts need to and enjoy looking out of the spacecraft windows at Earth, at approaching vehicles, at scientific objectives and at the stars. With few exceptions spacecraft windows have been made of glass, and the lessons learned over forty years of manned space flight have resulted in a well-defined approach for using this brittle, unforgiving material in NASA's vehicles, in windows and other structural applications. This chapter will outline the best practices that have developed at NASA for designing, verifying and accepting glass (and ceramic) windows and other components for safe and reliable use in any space system.

1.2 Strength Characteristics of Glass and Ceramics

Glass is a brittle material. Structural design with glass is governed by fracture mechanics and static fatigue analysis. Every glass material has characteristic properties associated with fracture and static fatigue that must be known by the designer and analyst in order to meet the strength, life and safety requirements specified by the spacecraft or payload developer. The following sections are a brief summary of fracture and static fatigue. For more detailed information about these topics, the reader is directed to any textbook about fracture of brittle materials.

1.2.1 Fracture of Glass

As originally described by A. A. Griffith in his 1920 paper, brittle materials like glass fail in tension as a result of tiny flaws in the surfaces of the part created during manufacturing or handling. When these cracks are placed in a tensile stress field they grow, and when a crack reaches the critical stage, the glass fails. The fracture strength of a piece of glass is inversely related to the size of the surface flaw:

$$\sigma_F = \frac{YK_C}{\sqrt{\pi a}} \tag{1.1}$$

where Y is a factor related to crack and part geometry, a is the crack depth from the surface and K_C is the critical stress intensity, discussed later. The critical stress intensity is also called the material's fracture toughness.

Since most of these initial flaws are too tiny to see, failure of the glass can come without any forewarning. It is important to note that surface flaws are the controlling feature of the strength of any glass product. There are four reasons why glass parts fail from surface flaws. Manufactured glass has few internal flaws, and those that do exist are usually smooth in nature, like bubbles, and won't concentrate stresses. For most loading conditions, the maximum tensile stress is on the surface. The surface is also subject to flaws induced by the manufacturing process (polishing) and other contact events, both intentional and accidental. Finally, surface cracks are exposed to the environment and are subject to subcritical crack growth, or static fatigue, which is discussed in the next section (Varner 1996).

To determine the design strength of a glass part, it is necessary to know K_{IC}, the critical stress intensity, and the size of the flaws present in the final part.

1.2.2 Static Fatigue of Glass

Unlike metals, glass and ceramics will experience static fatigue, something similar to stress corrosion, where the strength of any part will decrease over time at load when water

molecules are present in the operational environment. Cyclic loading is not normally detrimental to glass parts, but the total time at load and the humidity of the operating environment is critical. The rate of static fatigue, or subcritical crack growth, in glass is described by special crack growth parameters determined by test.

Some compositions of glass, like soda-lime, will only experience subcritical crack growth when the tensile stress exceeds a certain threshold amount. In the space program, the glass most commonly used is fused silica, for which no threshold stress has ever been determined. Therefore, even at the lowest operating stresses, subcritical crack growth can be expected in fused silica parts. A good understanding of the crack growth properties, the flaw population and the operating stresses is extremely important for accurately predicting the structural life of this kind of hardware.

1.2.3 Fatigue and Fracture Parameters

Both fracture toughness and the crack growth parameters are determined with test programs involving many samples. ASTM International and other standards agencies have published several test standards in recent years that describe programs to determine these parameters for glass and ceramics. The following table lists some of the relevant standards and which properties are determined.

Table 1.1 Test Standards for Fracture and Fatigue Properties

Standard Title	Standard Number	Parameters Tested
Standard Test Methods for Strength of Glass by Flexure (Determination of Modulus of Rupture)	ASTM C 158-02	Modulus of rupture

Testing of Glass and Ceramics: Determination of Bending Strength	DIN 52-292 part 1	Modulus of rupture
Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress-Rate Flexural Testing at Ambient Temperature	ASTM C 1368-06	Slow crack growth parameters ***n*** and ***A***, for a model of crack growth velocity represented by the power-law form shown in equation 1.2.
Standard Test Method for Determination of Slow Crack Growth Parameters of Advanced Ceramics by Constant Stress Flexural Testing (Stress Rupture) at Ambient Temperature	ASTM C 1576 – 05	
Standard Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature	ASTM C 1421-01b	K_{IC}

1.2.4 Notes about Modeling Static Fatigue

The model of crack growth noted in this table, a power-law relationship between the crack velocity and the crack tip stress, is the most common approach to modelling subcritical crack growth. This model is often called the Paris equation.

$$v = A\left(K_I / K_{IC} \right)^n \tag{1.2}$$

It is empirically based and relatively simple to apply. However, an exponential relationship has also been used, and this has more basis in the physics of crack growth.

$$v = V_0 e^{n\left(K_I / K_{IC}\right)} \tag{1.3}$$

The parameters in the exponential form can be developed with a curve-fit process, somewhat more complicated than for the power law. There are no published standards for this numerical analysis. Some versions of the exponential formulation account for variations in humidity and temperature, which is not typically done with the power formulation. Some versions of the power law model account for different regions of crack growth, which is not done in the exponential model.

For low stresses or long times to failure, the two formulations diverge. Figure 1.1 illustrates static fatigue data for borosilicate glass and the two fatigue models fit to the data. Figure 1.2 shows the divergence of the time-to-failure predictions for each model. At a proof test ratio of 3.0, which is typical for human rated space flight hardware, the time to failure for soda-lime silicate glass modelled with the power law formulation is almost 60 times longer than the predicted life using the exponential form.

[figure 1.1](NASGRO reference manual 2005)

[figure 1.2] (Wiederhorn 1977)

For most applications in the payload community, the power-law relationship is appropriate. For long-life parts like Space Station windows the exponential relationship was specified because it gives a more conservative result. Industrial users of glass, like optical fiber manufacturing and cabling, implement modifications of the power law with good results (Baker 2001). Other researchers also prefer the power-law formulation and show that results are more accurate for both long and intermediate life parts (NASGRO reference manual 2005). NASGRO, a widely used numerical analysis tool for predicting fatigue life, offers both models.

1.2.5 Alternative Approaches to Assessing Strength and Reliability

For some applications of glass in space hardware, the operating stresses are very low compared to the advertised strength of the material. NASA permits an alternative verification path which requires the hardware provider to demonstrate that the part is at least five times stronger than the applied load. This approach derives from the fact that at such low stresses, the critical crack size likely exceeds the nominal dimensions of the part, and the fracture analysis becomes invalid.

To pursue this path, the hardware provider must show a glass rupture strength value developed from controlled test data with the appropriate statistical analysis (use the B0.15 in a Weibull curve fit, which indicates the 0.15 percentile failure strength). If this can be done, no life analysis or acceptance proof testing is required and a simple stress analysis of the glass part is sufficient.

An example of this application is for a small payload window which is pressurized to 0.1 MPa. The maximum stress in the window is 0.6 MPa. The hardware provider has no test-verified strength data for this window material as polished by the glass vendor, so 20 samples are tested in a biaxial ring fixture according to the DIN 52-292 standard. Figure 1.3 shows the results with a Weibull fit, and the B0.15 strength value of 50 MPa is more than sufficient to permit this hardware provider to forgo proof testing and further life analysis.
[figure 1.3]

1.3 Defining Loads and Environments

All structural designers need to know the loads and environments their hardware must perform in. Where glass and ceramics are concerned, the definition of these environments is critical with respect to understanding the operating conditions like vacuum or humid air that could interact with the material's flaw growth properties.

The designers should also be aware of any environments that will lead to surface damage, like atmospheric or spaceflight impacts or crew contact. Operating temperature is less of a concern, as the material strength and properties of glasses and ceramics do not typically vary over temperature to any great degree. For this reason, low-expansion glass is an excellent choice for the external pane of a re-entry vehicle window as compared to a transparent polycarbonate, which is much tougher than glass but intolerant of high temperatures. For example, the Space Shuttle windshield glass can exceed 650°C during re-entry, but the fused silica panes installed in the windshield have an annealing temperature of 1042°C and a softening point significantly higher than that (Corning data sheet 2003). These fused silica panes survive multiple re-entry events without being affected by the temperature or plasma environment.

1.3.1 Applied Environments

Applied environments should include thermal shock and structural loads due to thermal strain, pressure, vibration and acceleration. Space vehicles must launch, ascend, orbit, descend and land, and all of the environments must be considered. The specific hardware design might include a vacuum or pressure cycling, which must be included.

1.3.1.1 Stress Distribution Verification

Validating the stress distribution in glass and ceramic structures must be done by testing of flight or flight-like quality hardware. Experience over several major programs and vehicles has demonstrated that 10% or more of the stresses in any window come from the secondary effects of warping and deformation in the supporting structure. In testing a window installation, the glass panes are typically replaced by aluminum simulators, and strain gages are applied to provide sufficient data to confirm the stress distribution. In other structures, the design team can put strain gages directly on the glass components, but it is important to carefully control the process so as to prevent glass failure due to flaws induced or magnified

by the strain gage. It should be noted that these strain gages cannot be removed without introducing new damage to the glass.

1.3.1.2 Stress Analysis

Stress analysis of glass or ceramic parts follows a typical process. Only the ultimate load case is examined, and the strength value used here is the statistically valid rupture strength found in the materials characterization testing. An alternative is to use the initial flaw size verified by proof test and a calculated initial strength from equation 1.1. This calculation should be performed using K_{IC} minus 3-sigma from the materials characterization tests to ensure a conservative assessment of fracture strength.

1.3.2 Inadvertent Contact

Inadvertent contact during hardware processing or flight is one of the most difficult environments to manage. The design team must be cognizant of the fact that inadvertent contact will occur, and they must specify what kind of inspections will be performed to detect the inevitable damage due to this contact. They must also be able to calculate the strength and structural life loss caused by this contact and to manage that effect during the item's mission, or be prepared to replace damaged hardware. Some examples of inadvertent contact that has damaged glass components in NASA programs include dropped tools, grit contamination on a gloved hand, scratches due to cameras used on orbit, and tool scratches from ground processing on equipment adjacent to the glass parts. When the initial design of the hardware specifies an acceptable flaw size of 0.0018" depth, even a minor scratch can be a part killer if it's in the wrong place.

Inadvertent contact should be prevented by protective covers whenever practical. Ground processing of windows or other glass hardware should be reviewed so that adequate

protection can be provided for these items. In flight, transparent protective panes or covers or grills can be used to keep crew contact with the glass minimized.

1.3.3 Glass-to-metal Contact

Glass-to-metal contact should be prevented in the design of any structural glass component. Glass is extremely brittle and will fracture readily if even a small point load is applied. If the assembly includes a glass component supported by metallic structure, designers should provide a pliable interface of some kind between the two parts.

1.3.4 Seals and Cushions in Assemblies with Glass

The seals and cushions used in assemblies with glass must be selected with the temperature extremes of the hardware in mind. Select materials that will remain pliable at the coldest expected temperature. Most elastomers have a glassy transition point where they become quite hard and this transition point should be avoided in selecting materials for the required design environment.

1.3.5 Special Considerations for Coatings

Coatings have been shown to propagate pre-existing surface flaws in glass when the coated surface is under tension. If coatings are to be used, it is best to apply them to the surface that will be in compression.

1.4 Design Factors

As with all structural design efforts, factors of safety, uncertainty factors and other factors are always specified. For glass and ceramic components these may have one value for the beginning of life and a different value for the end of life in an attempt to address static fatigue concerns. Since glasses and ceramics are brittle materials, no “yield factor” need be considered, since no yielding will ever occur. It is only necessary to assess the ultimate load condition for strength, and the limit load condition for life.

There may be an uncertainty factor applied to the operating stress for the life analysis. In the ISS program NASA specified different uncertainty factors for parts with differing life requirements. Short-life components have higher uncertainty factors, and the windows that were required to perform for the full 15 years of the ISS life had the lowest uncertainty factor at 1.1. This uncertainty factor was intended to address the discrepancies in the models used to predict crack growth. See section 1.2.4 for more discussion on this topic.

1.4.1 Factors of Safety for Annealed Glass

The minimum ultimate factor of safety at the beginning of life for annealed glass used in structural applications in NASA programs has been 3.0 for the ISS and for payload hardware. Other programs have specified lower design factors, but they have been overridden by acceptance proof test requirements, which typically drive the factor higher than 3.0. This will be discussed later in the chapter. The end-of-life factor of safety for most NASA programs has been 1.4 or less.

1.4.2 Factors of Safety for Tempered [strengthened] Glass

Usually the magnitude of the surface compression in chemically tempered glass is quite high compared to the expected operating stress, and NASA programs have specified that the surface shall not go into tension at twice the operating stress. However, there is also a factor of safety requirement, and the most recent glass design requirements document specifies an ultimate safety factor of 3.0 at the beginning and end of life. No static fatigue strength degradation is ever expected for tempered panes, since the surface should never be in tension, therefore prohibiting static fatigue crack growth.

1.4.3 Other Factors

Unique hardware designs may require other factors. For example, glass windows in NASA spacecraft are always made redundant, so that a single pane failure will not be catastrophic.

Design requirements for these window systems specify a dynamic factor to be applied to the load on the redundant pane, because in a failure event nothing is static. Payload providers might face similar issues and should carefully consider all of the operational scenarios their hardware must survive.

1.5 Meeting Life Requirements with Glass and Ceramics

Structural components made of glass or ceramics will be considered fracture critical and will be required to analytically demonstrate adequate life. Generally this means that the hardware provider must determine the maximum initial flaw size present in the final part and must perform a numerical analysis of flaw growth, using commercially available software or another proven method applying accepted models of crack growth in glass or ceramics. This section describes the aspects of life verification for glass structures in NASA programs.

Alternative approaches to life certification are available in special circumstances; one was described in section 1.2.5.

1.5.1 Scatter Factor

Typically, a scatter factor of four is required to demonstrate adequate life. This means that if the hardware has a required mission life of 1 year, the analysis must show that at the end of four years the part has residual strength adequate to meet the limit load times a specified “end-of-life” factor of safety.

1.5.2 Proof Test

Each piece of glass or ceramic structure delivered for the flight hardware must have acceptance proof testing performed unless a special approach like the one described in section 1.2.5 is approved by NASA. The acceptance proof test will demonstrate that the maximum initial flaw size present in the hardware will not propagate to failure during the life of the part.

Designing the acceptance test involves controlling the environment and determining the necessary delta pressure or other external load to achieve the appropriate screening stress. Typically the glass vendor will determine the polishing process, which defines the population of flaws in the surface. The maximum initial flaw size in the final polished item should be approximately three times the size of the final grit. So it is necessary for the proof test to reach a pressure that will cause failure for a part where the flaw sizes exceed the vendor's specification. Items that fail the acceptance proof test do so destructively, assuring that what is delivered for flight meets the requirements.

To calculate the proof stress and envelope the rather large scatter inherent in glass properties, use the K_{IC} resulting from material characterization tests and add a single standard deviation. This provides some conservatism in the screening process.

$$\sigma_{proof} = \frac{\left(K_{IC} + 1 \cdot sigma\right)}{Y\sqrt{\pi a_{initial}}} \tag{1.4}$$

The proof load can be applied as slow or fast as desired, but once the proof stress is reached, the test must be ended as quickly as possible. Flaws will propagate during the proof test, so it is imperative to limit the time of the test following the proof stress to as little as is physically possible.

It is also important to keep moisture out of the proof test environment. To this end, NASA windows are heated in an oven for several hours before a proof test, and when the dewpoint reaches -35°C, the test is begun. In a pressure test of a NASA window, only dry nitrogen gas is used.

1.5.3 Life Analysis

Life analysis is typically performed using numerical analysis codes. The most widely used is NASGRO, which will calculate subcritical flaw growth in glass or ceramic materials and output a flaw size at the end of the analysis. This code compares stress intensity values against the critical stress intensity for the material.

If the NASGRO analysis is successfully completed, an end-of-life flaw size is reported. With this end-of-life flaw size, the end-of-life strength can be computed using the relationship between flaw size and stress intensity.

$$\sigma_{end-of-life} = K_{IC} \Big/ Y\sqrt{\pi \cdot a_{end-of-life}} \tag{1.5}$$

From this strength value and using the required end-of-life factor of safety, the hardware provider calculates the end-of-life margin of safety. A negative result indicates that the part may fail at the end of its life, and a redesign is necessary to lower the operational stresses. In the cases where this issue has arisen, it is usually true that a single high stress event in the part's design life causes the majority of the crack propagation. Judicious redesign can focus on those few high stress cases.

1.6 References

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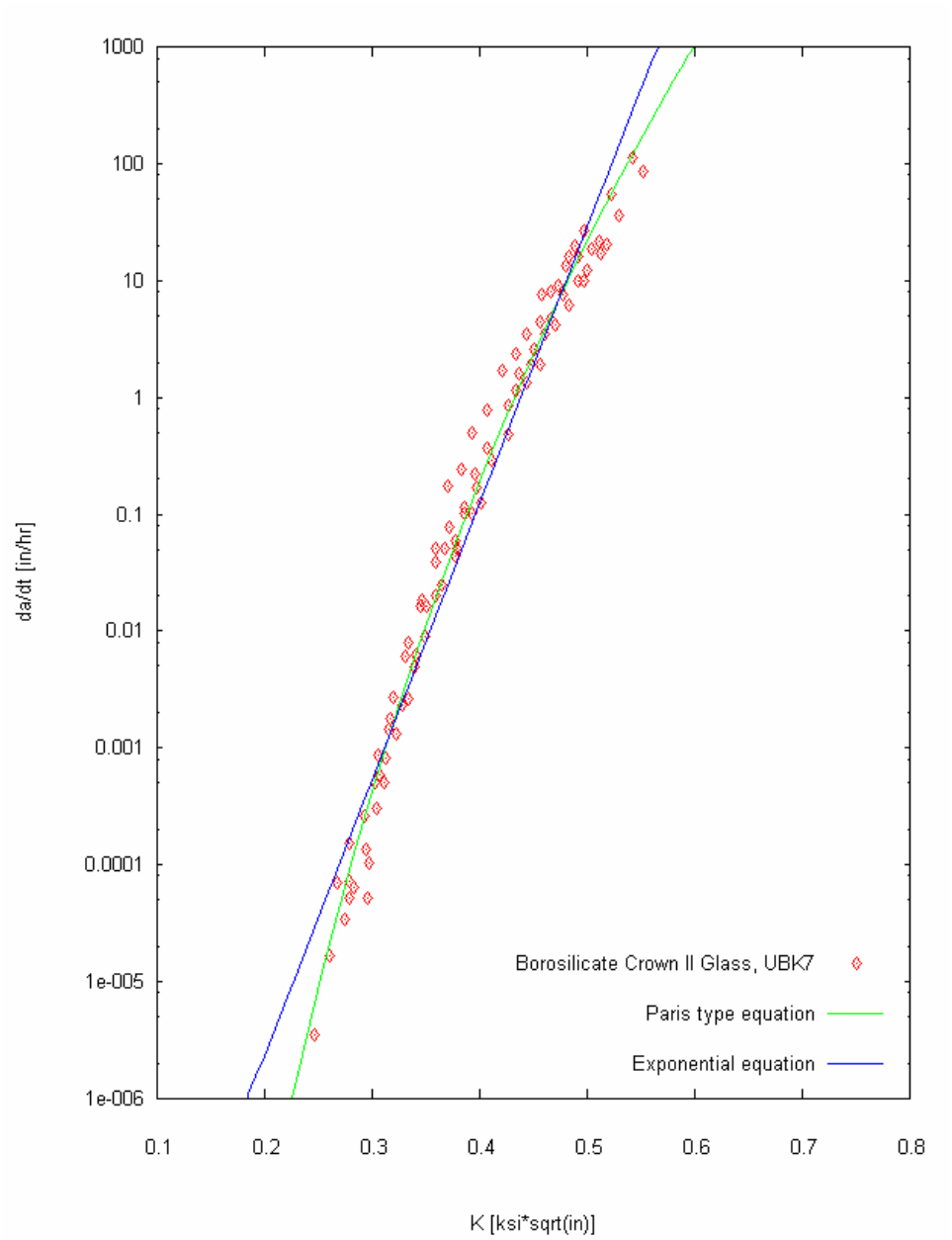

Figure 0.1.1 BK7 Fatigue Data

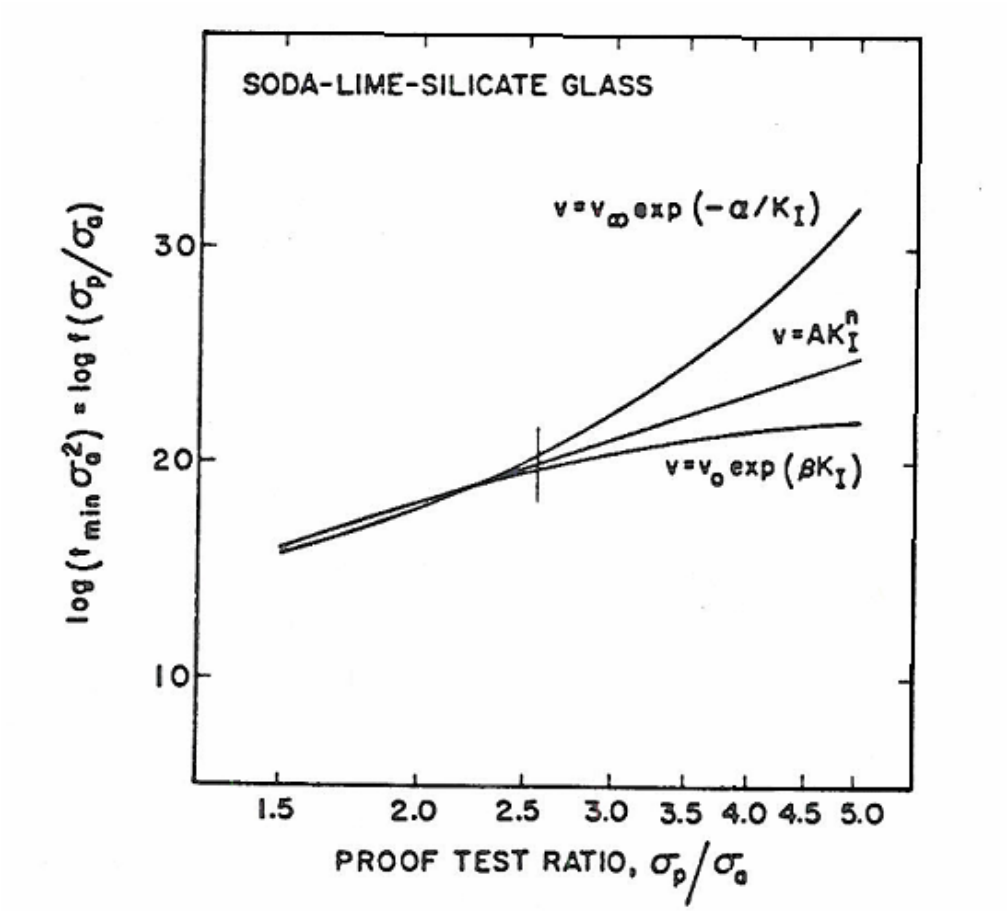

Figure 1.2 Time to Failure for soda-lime silicate glass

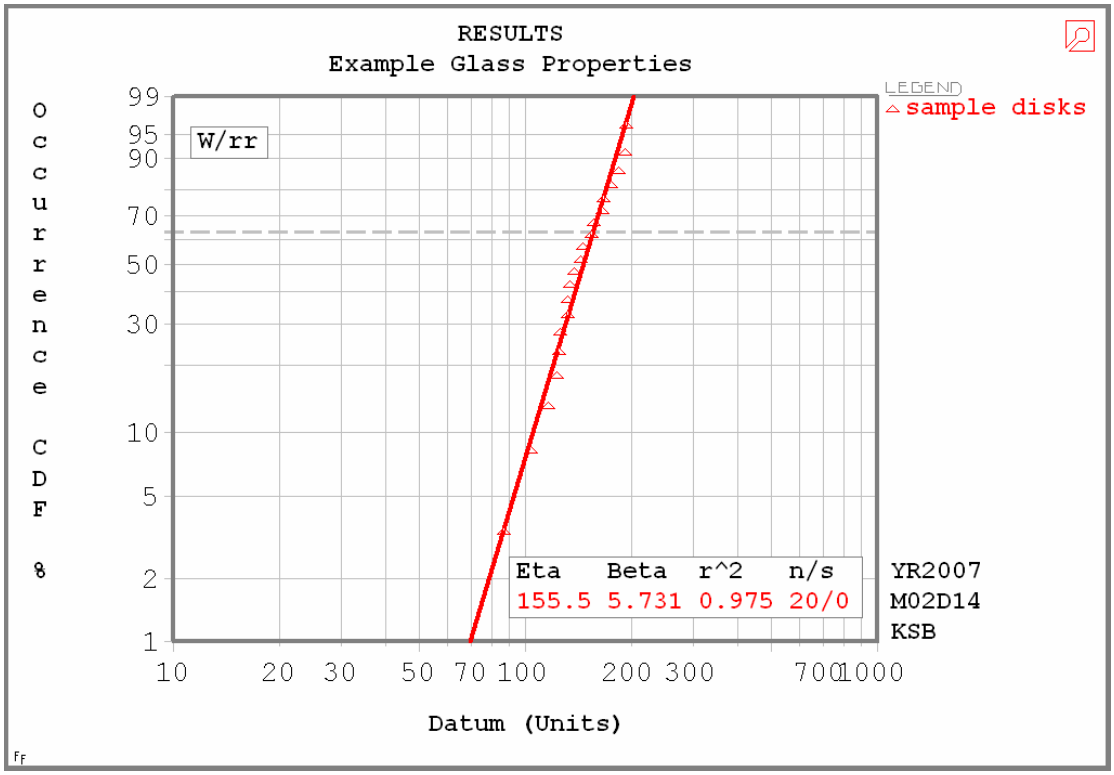

Figure 1.3 Weibull Plot of Glass Rupture Strength