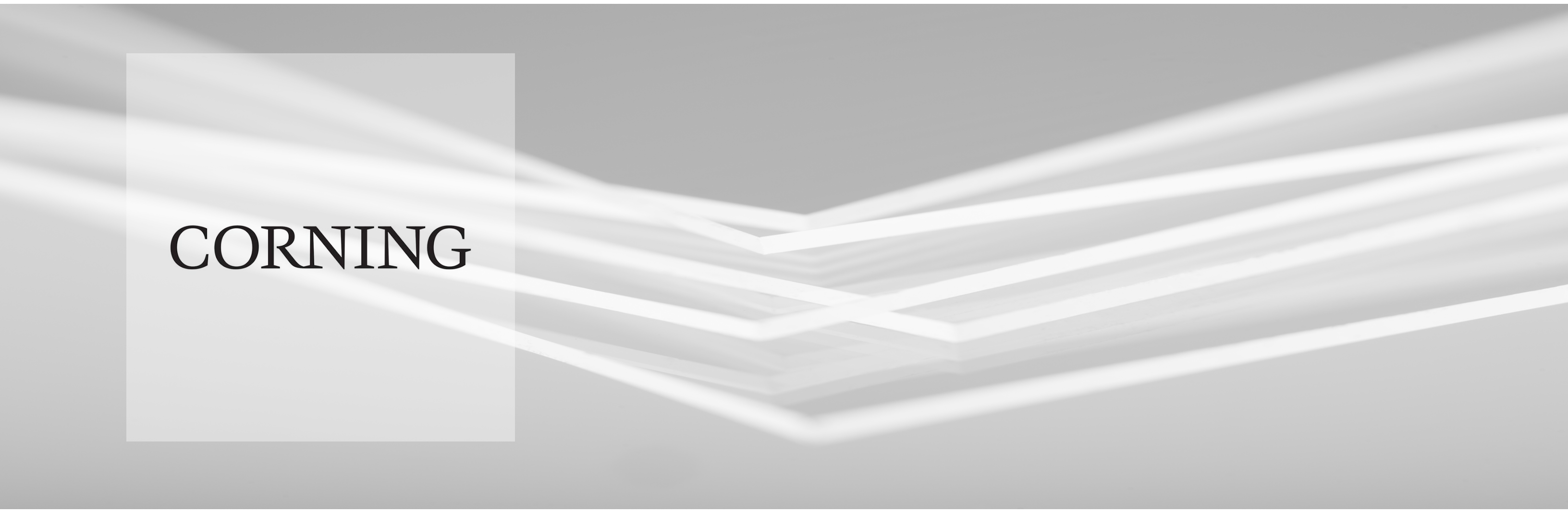
The Mechanical Reliability of Glass Displays in Bending



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Abstract

The mechanical reliability of glass under stress is controlled by the strength of the existing flaw population and the subcritical growth of those flaws under stress. Each glass application requires a mechanical reliability strategy that is optimized for that application. The purpose here is to establish that strategy for the case of glass in displays where the intent is to bend the display permanently. Fracture mechanics is used as a well-established framework for combining strength and fatigue effects on display glass sheets.

1. Introduction

Glass-based displays have historically been shielded from stress events through well-constructed device frames. Today, displays are increasingly being subjected to stress events where the mechanical reliability of the glass is of concern. One new source of stress is that resulting from the loss of structural isolation. The elimination of air gaps in mobile devices allows impact events to the device cover to reach the display and less robust frames allow the display to flex globally. A second form of stress is where the display is intentionally bent into a permanently deformed state. Televisions and monitors with curved displays are a good example of this form of stress. A key mechanical failure mode for glass under long-term stress is delayed failure from the well-known phenomenon of subcritical crack growth.1-6 Flaws under sufficient stress can grow subcritically and fail prematurely. The purpose of the analysis provided here is to provide a practical reliability strategy for applications where display glass is intended to be bent for long periods of time.

2. Mechanical Reliability Fundamentals

There are two approaches for making lifetime predictions for glass under stress. The “Minimum Strength” design assumes that the glass is no stronger than the largest flaw. It also assumes that one is able to establish a minimum strength through proof testing and maintain this minimum strength throughout the life of the glass. The maximum allowable stress, in this case, is based on the fatigue behavior of the largest flaw surviving proof testing. The "Failure Probability" design incorporates both fatigue and the probability of encountering a flaw weak enough to fail during the desired lifetime. The allowable stress, then, is established by determining the acceptable failure rate for a given flaw population. Key to this method is establishing a relevant strength distribution for the intended glass application.

2.1 Minimum Strength Design

Establishing a lifetime, tf that exceeds the specified in-service life begins with the static fatigue relationship,

$$\frac{\sigma_a}{\sigma_p} = \left(\frac{B}{t_f \sigma_p^{\ 2}} \right)^{1/n} \qquad (2).$$

Because of the known difficulties in determining crack growth parameters, Glaesemann and Gulati[7] developed a model based on the simple assumption that a low crack velocity is equivalent to a threshold for crack growth. Their ratio of applied stress to proof stress is shown in Figure 1 for a range of n values.

$$t_f = BS_i^{n-2} \sigma_a^{-n} \qquad (1)$$

where n and B are fatigue parameters, S_i is the initial or inert strength of the flaw under stress and σ_a is the applied stress.

The allowable stress, σ_a, for, say, a 25-year lifetime of a flaw with a pre-fatigue strength, S_i, can be calculated provided the crack growth parameters are known. The most conservative approach to reliability modeling, known as the "minimum strength design", is to assume that a flaw that just survives proof testing will experience the maximum applied stress. The strength, S_i, is set to the proof stress, σ_p, and the allowable stress is expressed as a fraction of the proof stress,

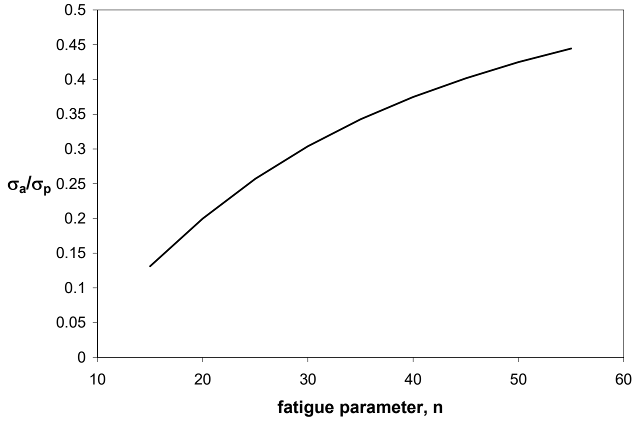

Figure 1. Allowable safe stress to proof stress ratio for proof stress level flaws and a lifetime of 25 to 40 years.[7]

Display glass has an n value of approximately 20; and therefore, the allowable applied stress is 1/5 the proof stress for stress events lasting years. One can generate similar guidance for shorter-term stress events. One can stress display glass to about half the proof stress during processing (the 1 second line in Figure 2) and 1/3 the proof stress during installation or assembly (the 4 hour line). These allowable stress guidelines can be used to establish appropriate proof stress levels for, say, curved displays where the glass is bent to a given radius as shown in Figure 3.

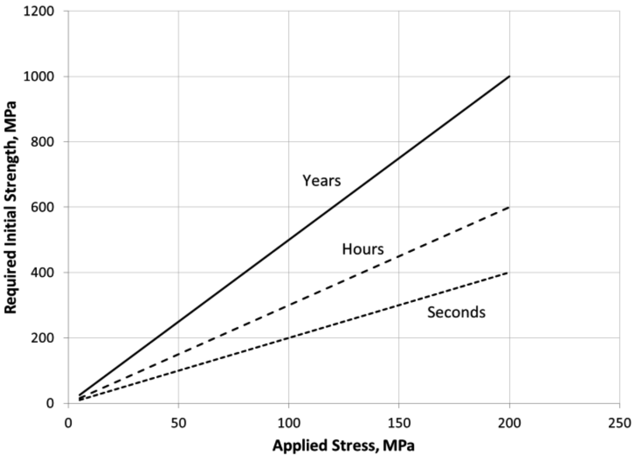

Figure 2. Allowable stress as a function of proof stress for common stress events.

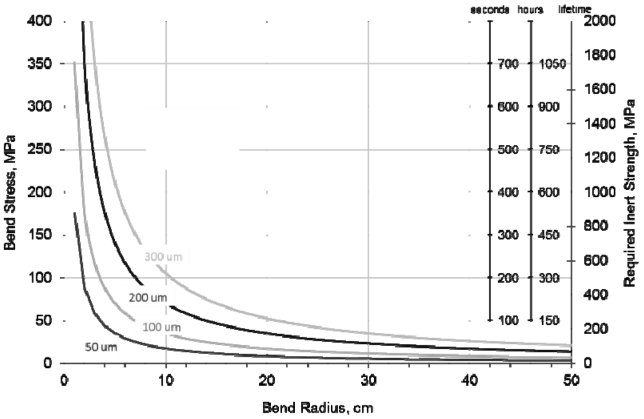

Figure 3. Required inert strength of proof stress expressed in term of bend-induced stress for several stress durations and glass thicknesses.

Whereas this analysis is quite simple, the successful implementation of such a proof stress requires more thought. First, proof testing is done for the purpose of establishing a minimum strength. Maintaining this minimum strength during subsequent processing and deployment requires that no new flaws be introduced after proofing. In practical terms, it means that glass handling practices have to be carefully established. There are some situations where proof testing, or re-proof testing, is performed just before installation so as to eliminate the most recent flaws. Breaking glass, at this point, can be expensive as this is the point where one has invested the most in the glass. Second, proof testing has to be performed in such a way that it does not introduce damage. Third, the proof test method is best performed in a short period of time. A short proof test event minimizes sub-critical crack growth during this stress event. Excessive strength degradation from fatigue can cause flaws that would be strong enough to survive the life of the product to fail during proof testing. This leads to reduced proof test selects and is unnecessary. Fatigue can also allow flaws to grow during unloading. However, it has been shown that the probability of ever having flaws in this position is difficult and rare, especially with the relatively low Weibull modulus of cut glass edges.

2.2. Failure Probability Design

It is recommended that the minimum strength design be considered before the failure probability design. If the anticipated failure during proof testing is high, then the predicted failure probability for unproofed glass will be high as well and reliability targets will not be achieved. With this consideration, one can avoid performing the extensive testing required for the failure probability design.

One can consider using a failure probability design methodology when the risk of encountering a flaw that will grow and fail is at an acceptably low level. Failure probability is incorporated into Eq. (1) through the inert strength, S_i,

$$t_f = B\left(F\left\{S_i\right\}\right)^{n-2}\sigma_a^{-n} \qquad (3).$$

3. Establishing the Mechanical Reliability of Curved Displays

Consider the case of a display panel bend to a pre-determined bend radius. What follows is guidance on creating a failure probability design diagram for this application based on the above subcritical crack growth modeling approach. First, the bend-induced stress is rather complex as the stress near the edge is higher than in the middle of the display due to two pieces of glass being bonded together by epoxy. Also, the display may not be placed in a constant bend radius over its length. Consequently, one may make use of strain gauges and modeling to fully characterize the stress distribution of the panel.

Next, the strength distribution has to be representative of the actual flaw population placed in bending. The edge has a different flaw population than that of the surface of the display and, therefore, a relevant strength distribution would include data from regions. For the strength distribution to be relevant, no additional flaws can be introduced after the strength distribution is obtained. Mechanical reliability is strongly linked to handling practices. It is useful to conduct a process handling audit to continually decrease the probability of early, unanticipated failures. It is also important to note that the strength distribution will be unique to the process creating the panel. The strength of 'score and break' edges are in the range of 50 to 150 MPa depending on score tools and handling. One can also expect the amount of strength testing to be more thorough than what is typically used for strength comparisons.

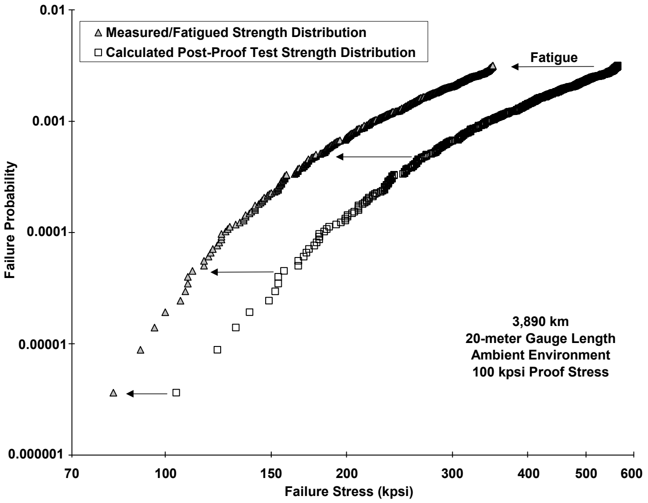

Figure 4. Strength distribution of almost 4000 kilometers of fiber using a suspended test method.[10] All failures below ~2400 MPa shown. A fiber length passing this stress level is recorded and accounted for when determining the failure probability of the failures. The triangles represent the measured fatigue strength and the squares are the predicted initial or inert strength before strength testing (i.e. the actual post proof-test strength distribution).

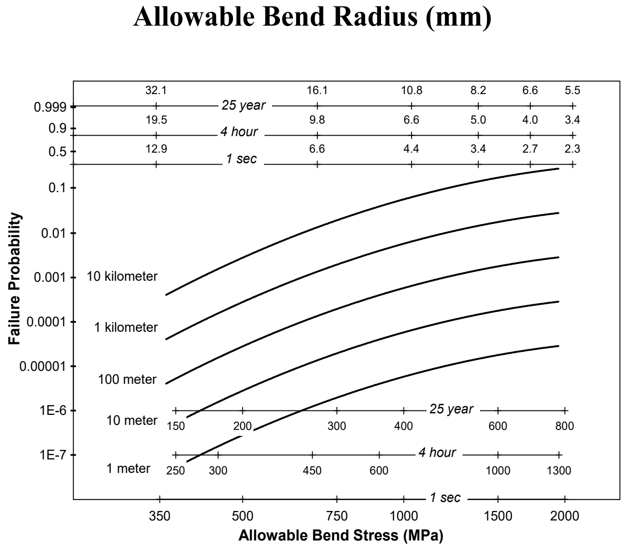

Figure 5. Design diagram for various fiber lengths subjected to bending. 125 um silica-clad optical fiber proof tested to 700 MPa.[11]

4. Summary

The reliability of intentionally stressing glass displays can be established using previously derived strategies for managing the effects of fatigue in other glass systems. Key to the success of this effort is handling practices that preserve the strength distribution throughout the manufacturing process. It is recommended that one first consider using the Minimum Strength Design for establishing reliability. The location of the proof test in the process would be based on the ability to maintain the strength of the glass, cost and convenience. If the proof test failure rate is initially high, then one can produce high reliability product while working to improve the strength distribution. Once the proof test failure rate becomes acceptably low, it can be removed in favor of a failure probability design.

5. References

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