Mechanical Reliability of Glass in Curved Displays

Issued: April 2021
Supercedes: August 2020

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This paper was presented at SID Display Week 2020.

Abstract

The paper talks about Corning's approach and recommendations regarding the mechanical reliability of glass for curved displays.

1. Introduction

Free-form displays have become popular as consumers seek-display designs that seamlessly integrate to the user interface. Auto Interior (AI) applications are good examples. Consumers of the gaming industry seeking for an immersive experience are also driving the development of curved displays. Despite the advent of many popular display technologies, liquid crystal display (LCD) is often the choice of design due to its low cost, robustness and technical maturity. While the early versions of curved LCDs had large radius of curvatures, recent AI display applications require smaller radius of curvatures and lower failure rates due to safety concerns and/or high costs of failure. Recent gaming monitors also require small radius of curvatures. As the design specs are getting tighter, ensuring the display's long-term reliability is critical.

When it is bent, many areas of the LCD slowly start to deteriorate due to mechanical stress. For example, the optical performance of the display may change overtime because of sealant delamination [1]. The glass substrate could also experience sub-critical crack growth, fatigue and could spontaneously break if the glass quality is not well managed [2]. To prevent this, a holistic reliability strategy is required.

This paper focuses on Corning's approach and recommendations regarding the mechanical reliability of glass for curved displays. We also explain glass fatigue fundamentals. The scope of this paper is limited to the LCD glass only and is not applicable to the cover glass, which will have different mechanicals behaviors and failure modes.

2. Glass fatigue

Strength of glass is generally measured by dynamic tests such as two-point/four-point bending tests which apply an increasing load until failure. If a static stress is applied for a long period of time, glass may break at a much lower strength due to fatigue [2]. To put glass under a constant stress in applications that require a high reliability, the fatigue of flows needs to be considered even for low stress situations.

Fatigue is a stress-corrosion reaction that occurs over time for pre-existing flaws in the presence of stress and humidity. Water molecules (H_2O) at the crack tip react with Si-O-Si bonds to form Si-OH bonds. In the presence of stress, this reaction drives the crack forward one bond at a time perpendicular to the direction of stress.

Even low levels of humidity are enough to cause fatigue. If the glass is stressed extremely quickly or in an inert environment, the glass will fracture following the stress intensity (K_I) equation

$$K_I = Y\sigma_a\sqrt{a} \quad (1)$$

where Y is a shape parameter, σ_a is the applied stress felt at the crack tip and a is the crack length. K_I increases with increasing stress and/or increasing crack length. When the stress intensity equals the fracture toughness of glass ($K_I = K_{IC}$), the crack will grow to failure almost instantly. In cases where $K_I < K_{IC}$, the crack will not fail rapidly but slowly grow sub-critically through fatigue. The velocity of the crack growth can be described relative to the stress intensity by a power-law equation,

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

where V is the crack velocity or change in crack length over time da/dt, A is a constant, n is the fatigue resistance exponent. Initially, the sub-critical crack growth can be very slow in the order of A/s, but as the crack grows, the velocity increases exponentially to the order of n. As an example, the strength of glass with different initial flaw sizes are shown as a function of time when they are subjected to constant stress (Figure 1).

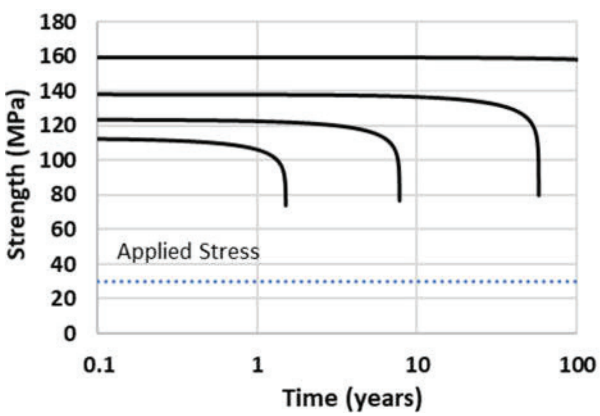

Figure 1. The strength of the glass with different initial flaw sizes as a function of time when subjected to a constant stress.

(a) Effect of *n* on lifetime: Since n is the exponent in the power law relation, small changes can have significant impacts in the crack velocity and lifetime for given flaw size. Changing the fatigue resistance through composition, however, can be difficult where most glasses have fatigue resistance between 15 and 20. It has been observed that the flaw size can also affect the fatigue resistance; the fatigue resistance of small and large flaws has been observed to differ by a much as 20 for silica glass [2]. This dependence makes it important to measure the fatigue resistance of flaws relevant to the application. In display glasses, a trend of decreasing fatigue resistance with increasing flaw size has been observed.

(b) Effect of initial strength of lifetime: It is generally easier to try and control the flaw size, where the crack velocity changes with flaw size proportional to $a^{n/2}$. Decreasing the flaw size, and thus K_I, significantly slows crack growth through fatigue. Thus, 1) controlling the introduction of flaws into the glass and 2) assessing the glass performance under fatigue is key to understand long-term produce performance and to ensure the glass reliability.

3. Reliability approach

Since fatigue lowers the strength of glass over time and it is impractical to test the panel over its lifetime, an alternate reliability approach must be used. Figure 2 outlines the reliability approach for brittle failure modes in glass. To predict the failure probability and assess its appropriateness, one needs to understand both the applied stresses (usually done by finite element modeling) and the fatigue behavior as discussed in Section 2 (typically supplied by the glass maker). Additionally, the allowable failure rate must be known to determine a relevant strength distribution and reliability approach.

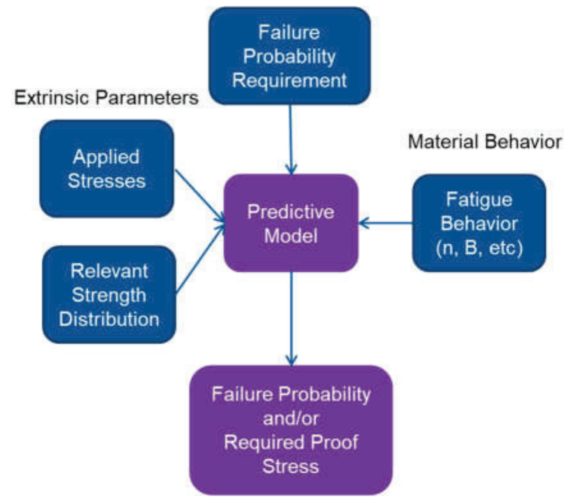

Figure 2. Reliability approach for brittle failure modes in glass.

(a) Proof-test approach: If the allowable failure rate is very low (<100 ppm) or the consequences of failure are high (i.e., loss of life or product recall), a proof stress approach is typically preferred. Proof testing eliminates any unviable product from reaching the market through a 100% screening process. A proof stress five times greater than the design stress must be applied to the glass to remove all product that would mechanically fail in the field over a lifetime of years via fatigue mechanisms [2]. Proof testing can often be difficult, requiring that the load is applied and removed very quickly to prevent fatigue of flaws that would not normally have failed in the field. Figure 3 shows the strength of glass with various initial strengths as a proof stress is being applied. Scenarios b, c and d represent the fatigue of flaws that may occur during proof testing. Proof testing must also not introduce an additional law population, so no contact can be made with the glass during proof testing. This is often accomplished through polymeric coatings that protect the glass. Finally, proof testing cannot unnecessarily accelerate other failure modes. Corning's experience with attempted proof testing of display panels is that it will generate delamination of the epoxy, sealant or cracks in the thin film transistor (TFT) films before the glass would fail. The additional stress needed to proof test the glass is not relevant for the acceleration of the failure modes for delamination of thin films and would negatively/unacceptably reduce the yield of the product through proof testing.

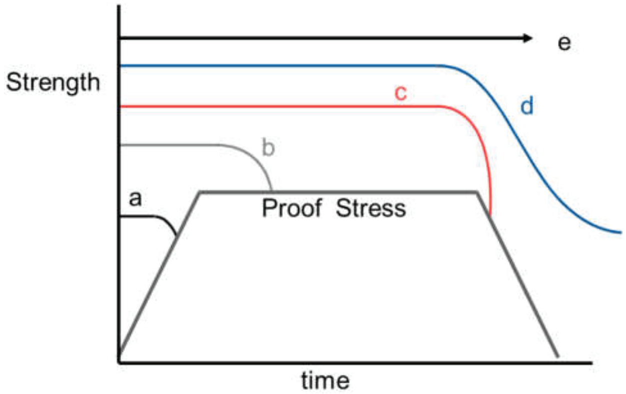

Figure 3. The strength of glass with various initial strengths as a proof stress is being applied: (a) loading failure, (b) dwell failure, (c) unloading failure, (d) passes proof test, but degrades to unacceptable strength during unloading and (e) passes proof test and strength stays at an acceptable level.

(b) Failure probability approach: If the allowable failure rate is high (>1,000 ppm), and consequences of failure are low (i.e. dissatisfied customer), a failure probability approach is typically preferred. This means sampling at an appropriate level to have no/minimal extrapolation of failure probability. Typical sampling sizes of 20-30 pieces only predicts behavior well down to approximately 10% failure rate. After that, extrapolation errors increase the likelihood that the actual failure rate may not be acceptable. For instance, one can assume a typical score and break edge strength Weibull distribution with a Weibull modulus of 5 and a characteristic strength of 150. This is modeled in Figure 4 for 4 different sampling sizes (N=10, 30, 100 and 1000).

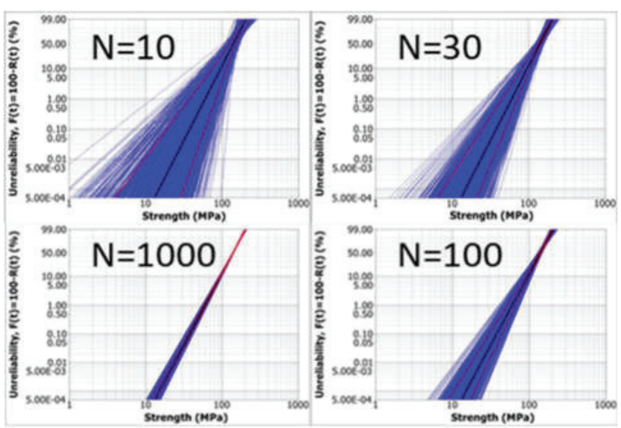

Figure 4. Weibull distributions for the same ideal distribution (m=5, σ0=150) with sample sizes of 10, 30, 100 and 1000 (clockwise, from top left)

For each sampling size, 1,000, possible different Weibull predictions were simulated using Monte Carlo sampling from 10,000 point parent population. The parent population is shown in black, Monte Carlo simulation Weibull distributions are in blue and the confidence limits on the simulated data is shown in red. As figure shows, when the sampling size increases, it decreases the confidence bound widths. This effect is magnified as the allowable failure probability decreases, say from 1% failure rate to 0.1%. This highlights the increasing need for larger sample sizes as the allowable failure rate decreases.

As more samples are tested, the certainty around the strength distribution increases, higher design limits can utilized and less risk is carried into production. It is also important to note the extrapolation strategies detailed in teh chart are only relevant when there is one flaw population and distribution. It has been our experience that flaw populations are generally multi-modal, with low Weibull modulus populations arising from very random or infrequent events that can significantly skew the lower end of the strength distribution (Figure 5).

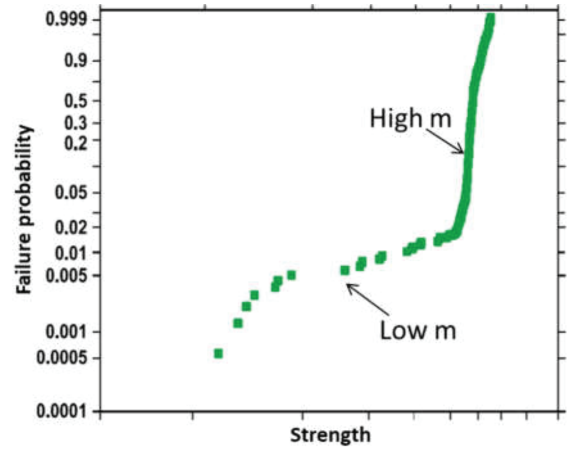

Figure 5. Example of a multi-model flaw population having different Weibull slopes (m).

(c) Strength testing strategy: To build a relevant strength distribution, a testing strategy is required. There are several conventional tests such as four-point bend test that can be used. The advantage of four-point bend test is its acceptance as a standard through the American Society for Testing and Materials (ASTM) [3]. As glass panels decrease in thickness and/or increase in strength, four-point bend testing begins to introduce significant errors [4]. These errors can be mitigated by reducing the span between loading rods, but that can significantly reduce the test area. Area correction factors can be applied to translate between the test area and the relevant surface areas/edge lengths. However, those again require extrapolation of the data. This is of concern when combined with failure probability extrapolation, which increase the uncertainty even further. Additionally, it assumes that the flaw population in the area tested is relevant for the whole edge/surface. Our experience has been that the edge strengths can vary along with edge, particularly near the corner, due to support and break configurations.

Another option is the two-point bend test. Again, this test is an ASTM standard test that has industry acceptance and is designed specifically for highly flexible systems less than 0.5mm thick [5]. However, it creates high transverse shear in the systems, which can often cause delamination of panels before the glass breaks. While the acceleration in stress is needed due to fatigue of the glass, it is not an appropriate acceleration for the adherent in the panel as discussed before and will not provide relevant strength data.

The Edge Strength Measurement System (ESMS) is a relatively new testing strategy developed by Corning which can help conduct line audit for edge flaws and overcome limitation in four-point bend and two-point bend tests. It has a localized stress field, a, the edge which allows for testing of almost the entire panel edge, without delamination [6].

4. Best practices

Since both proof testing and failure probability approaches have their limitations, they must be supplemented with preventive measures to minimize the product failure risk. Here are some of our recommendations.

(a) Stress Reduction: Reducing the stress on glass will lower the probability of breakage. Equation 3 shows the maximum bending stress on a curved substrate with thickness *t,* modulus *E* and curvature *R*.

$$\sigma = \frac{Et}{2R} \quad (3)$$

The same equation can be used for the LCD panel, where an effective thickness is used instead of the total panel thickness to account for the stiffness of the sealant [7,8]. The panel acts as a monolithic piece of glass when the sealant is fully cured (well bonded). When the sealant is partially cured (loosely bonded), the panel acts as 2 separate pieces of glass. This difference causes different bending stresses under the same curvature - a well bond panel can have almost double the stress compared to a loosely bonded panel.

Mis-match in the coefficient of thermal expansion (CTE) among components, such as glue or tapes comprising of LCD module, can also induce stresses. The behavior of the parameter is complicated due to the difference in designs, materials and applied areas. Its impact is especially non-negligible in the automobile due to large temperature gradients ranging from 50 C to -40 C. One must try to avoid local bending stresses/curvatures and try to maintain a uniform structure. If not well designed, even the structure of the device module may induce additional stresses on the glass. Better module designs can reduce stresses by minimizing the local deflection.

(b) Flaw reduction and process audit: The strength of a panel changes during each TFT process step (Figure 6).

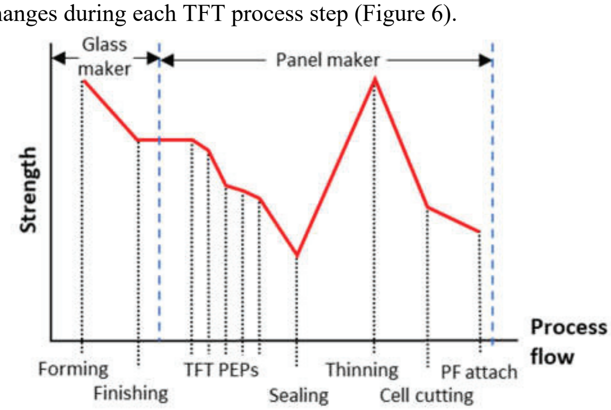

Figure 6. The change in strength of a panel through the TFT process.

The panel strength is a combination of surface and edge strengths. Surface strength is generally weaker than that of the original glass substrate due to contact damage generated by glass handling parts such as lift pins, arms, rollers and belts. The existence of contact damage is typically a sign of a maintenance issue since the glass surface is damaged by contaminants on the handling parts. Contact damage can also be generated from sliding motions which occur when glass is conveyed between two transportation stages being at different heights and speeds. Sliding may also occur when a cooler glass is placed on the hot plate. The edge strength of the panel relies on the cell separation and handling processes. These two processes are also critical for the surface strength, especially after the thinning process.

After the CF/TFT processes, the panel strength is recovered to its original glass strength by the thinning process which chemically heals existing flaws. Maintaining a pristine surface quality after thinning is critical to increase the panel surface strength. As such, minimizing damage is the fastest way to increase the panel strength.

Conducting a line audit is an efficient way to determined process steps that are potentially generating damage. Prior to the audit, identifying the damage location by Failure Mode Analysis (FMA) after strength testing and mapping all glass contact locations from the process are necessary steps. The ESMS method with dynamic mode can efficiently find the critical flaw locations [6].

5. Risk assessment of curved panels

Lastly, we introduce our assessment of risk of glass failure on panels having different bend stresses [9]. For the assessment, we used the failure probability approach outlined in section 3b while incorporating the following assumptions: 1. Panel strengths are equal to those obtainable from typical TFT processes; 2. Initial panel strength must have 5 times the bending stress to survive a lifetime of years; and 3. The failure probability must be at or below the typically allowable failure rates of the end user market. Figure 7 shows the results of our assessment. When the bending stress is lower than 15 MPa, the risk is low and minimum process improvements are required. When the bending stress is between 15 to 30 MPa, the risk is moderate and the target reliability can be achieved with known process improvements such as fine edge grinding and preventative measures such as line audit. When the bending stress is over 30 MPa, the risk becomes high and significant process improvements are likely required to achieve the target reliability. These categories are based upon Corning's experience with typical flaws that occur at edges and on surfaces and how those flaws fatigue over time.

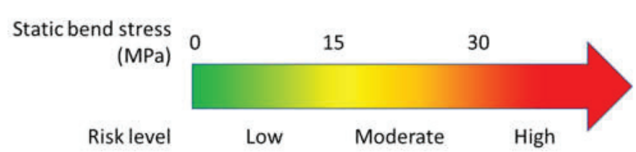

Figure 7. The risk associated to panels with different bend stresses in not being able to achieve a lifetime of years.

6. Conclusion

Glass breakage due to fatigue can become an issue for panels with small bend radii if the quality of glass is not well managed. Best practices to ensure the mechanical reliability of the panel a long strength/proof testing including reducing the bending stress, reducing the number and sizes of flaws and conducting process auditions using appropriate test methods.

7. Acknowledgments

The authors appreciate the support of this work, as well as permission to present it by the Display Division of Corning Incorporated. We would also like to thank Scott Glaesemann fo rhis use of the reliability schematic and multi-modal flaw population data.

8. Reference

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This paper was first presented at SID Display Week 2020.