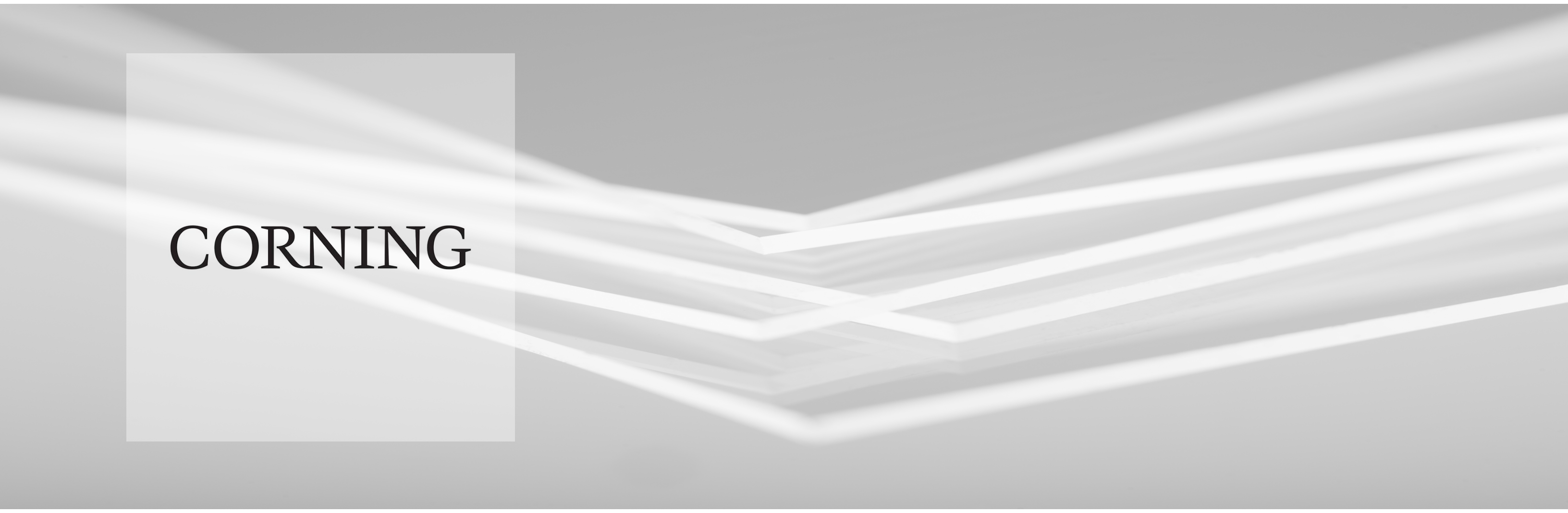
Best Practices in Strength Testing of LCD Glass



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Abstract

This paper provides general guidelines and watch outs while conducting strength testing on LCD glass. Importance of failure modes, large deflections, membrane stresses, failure locations, device design, fatigue, fractography and strain gauging are discussed in this paper. It also gives an example on why panels cannot be treated as monolithic glass when calculating the strength.

1. Introduction

Various strength testing methods include: [1] the two-point bend test [2], three-point bend test, four-point bend test, ring-on-ring test, ball-on-ring test, piston-on-three-balls test, ball-on-three-balls, ball-drop test [3], device-drop test etc. Of these the most popular tests are the four-point bend test for testing edge strength, and the ring-on-ring test for testing surface strength. There is a lot of information available in literature on how to conduct and analyze each of these tests. In this paper the authors present general guidelines and watch outs

while conducting strength tests on LCD glass. While these guidelines are tailored for glass used in liquid crystal panels, they can be used for other applications, too.

Selecting an appropriate strength test requires a through understanding of the failure modes. For example if the intent is to understand why certain panels break during a manufacturing process, then it is necessary to understand the primary source of failure. The following are some examples of questions to ask when analyzing the source of failure for LCD panels:

a) Are the panels breaking from the edge or from the surface?
b) Is the failure caused by bending or by impact?
c) Is the panel getting pinched by something that is causing failure?
d) Is the failure caused by thermal stresses?
e) Is the failure caused by film stresses?
f) Is it the color filter (CF) glass or TFT glass that is breaking?

g) Is the panel breaking from the outer (exposed) surfaces or from the inner (that are in contact with liquid crystal and spacers) surfaces?

Once the failure source is identified, then an appropriate strength test can be utilized to estimate the strength of glass in that particular failure mode.

2. Notation

Figure 1 shows the notation used in this paper to refer to different surfaces of the panel. The top surface of the CF glass is denoted as “surface-1”, the bottom surface of the CF glass is denoted as “surface-2, the top surface of the TFT glass is denoted as "surface-3" and the bottom surface of the TFT glass is denoted as "surface-4".

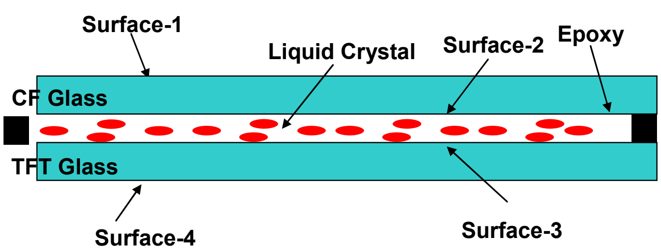


Figure 1. Notation used to refer to different surfaces in an LCD panel.

3. Strength of glass

The theoretical strength of glass is between 14 to 30 GPa, whereas, the practical strength of glass is between 40 to 150 MPa. This huge difference is because of the fact that the strength of glass is an extrinsic property. This means that the glass strength is controlled by the flaws introduced during handling and manufacturing (scoring, grinding, polishing, washing etc) processes. Sometimes impact damage and frictive damage could also be the sources. Because the flaws are created by chance, they are random in nature. Hence, glass strength is discussed in terms of failure probability using Weibull statistics. For this reason, the more samples tested, the better the estimate of failure probability.

4. Fatigue

Much like any material, glasses are also prone to fatigue during long-term loading, i.e. their strength is reduced over time. This is particularly true if the tensile stress they are subjected to exceeds a “threshold” value which, in turn, depends on fatigue constant “n” for a particular glass. The fatigue constant is a function of glass composition which depends on whether the glass contains alkali or not. The LCD glasses which are free from alkali, like Na2O, have a respectable fatigue constant of 21 [4], which means their threshold stress is a higher fraction of their strength. Also, in the case where the applied stress exceeds the threshold value, the rate of strength loss due to fatigue is relatively low.

The glasses with high silica content have higher fatigue constant and their rate of strength loss is lower. On the other hand, glasses like soda-lime have a fatigue constant of 16 and, hence they readily fatigue. Figure 2 taken from [5] shows the fatigue curve for different glasses including soda-lime, borosilicate, and 100% silica glasses (fused silica). It is clear that the softest of these glasses (soda lime) experiences higher fatigue loss than harder glasses like fused silica. The curves in Figure 2 are based on fatigue degradation governed by Equation 1.

$$S^n t = \text{constant} \qquad (1)$$

The symbol S denotes the strength of the glass after it is subjected to fatigue for time t. Thus, the longer the fatigue duration, the lower the strength S will be. Hence, during strength measurement, depending upon the test duration, the specimen being tested is subjected to some fatigue degradation. Typically, the ASTM test calls for strength measurement for 20 to 30 seconds. Most glasses lose a third of their strength in the process of strength measurement due to fatigue unless the strength is measured in infinitesimally small time or in inert environment (i.e. zero humidity or liquid nitrogen temperature) which is difficult to achieve in standard test labs.

It is clear from equation (1) that when n equals infinity, there is no fatigue, i.e. the measured strength is the actual fatigue-free strength. Most silicate glasses have an n value ranging from 10 to 50. Depending on the environment and the amount of stress the glass is subjected to, there may or may not be fatigue damage. Thus, when analyzing field failures or when selecting testing conditions, it is important to pay attention to test speed, test environment, and magnitude of stress.

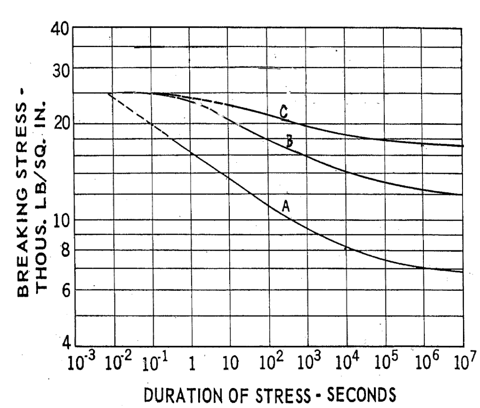


Figure 2. Strength loss due to fatigue [5] (A) soda-lime glass; (B) borosilicate glass; (C) fused silica glass.

5. Small vs. large deflections

As the display industry moves towards thin glass, the existing tests lead to large deflections of the test samples. As a rule of thumb, large deflection is defined as a deflection greater than half the thickness of glass. While this rule works most of the time, in some cases judgment from the analyst is required to distinguish between small and large deflections. During large deflections, standard linear equations that are used for calculating stress from force become invalid. The contribution of membrane stresses will not be accounted when using standard (linear) equations. As an example, figure 3 taken from [6] shows the stresses at the center of surface-4 for a panel made with 0.25 mm CF glass and a 0.25 mm TFT glass. It can be seen that linear theory overestimates the failure stress by a significant amount. Most of the total stress is from the contribution of membrane stress. The contribution of bending stress is only 4% of the total stress. Reference [6] also shows that the peak stress occurs under the load ring (on surface-4) and not inside the load ring (on surface-4). Hence, in cases where large deflections are applicable, non-linear equations or finite element analysis will be required for converting the applied force into stress.

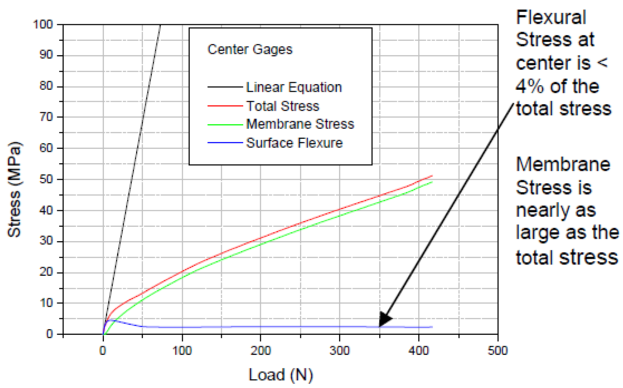
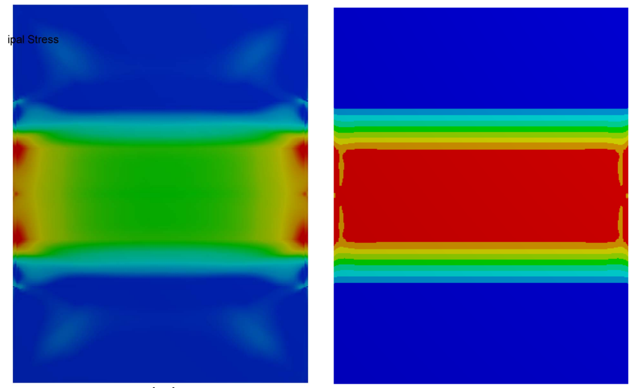


Figure 3. Not accounting for large deflections can result in estimated stress to be off by a significant amount [6] .

6. LCD Panels vs. Monolithic Glass

In a very basic form, an LCD panel is defined as two pieces of glass (color-filter glass and TFT glass) with liquid crystal between them. To prevent the leaking of liquid crystal, both glasses are glued together along the perimeter using epoxy. *Figure 4* qualitatively shows the difference in stress distribution between a panel and a monolithic glass during a four-point bend test [7-8]. While the actual stress numbers were not provided in this paper, references [7-8] shows that in some locations, assuming a panel as a monolithic glass can underestimate or overestimate stresses by a factor of two. Therefore, panels can not be assumed as monolithic glass when calculating strength.



(a) (b)

Figure 4 [7-8]:.(a) Stress distribution during a four-point bend test of a panel (surface-4 which is bottom of TFT glass is under tension); (b) Stress distribution during a four-point bend test of a monolithic glass of same size.

7. Failure locations

Panels and thin glass may not experience uniform stress in the testing span. Hence, it becomes important to pay attention to failure locations. The following two examples shed more light on this topic:

Example 1: If the intent is to measure the strength of surface-4 using the ring-on-ring test, then it is important to check if the failure is happening on CF glass or on TFT glass. If it is happening on the TFT glass, it has to be checked if it happening on surface-3 or on surface-4. All the samples that fail any where other than surface-4 should not be considered when reporting strength.

Even when the samples break from surface-4, it should be verified if they broke inside the load ring or outside the load ring. The samples that break from under the load ring or outside the load ring should be discarded. For the samples that break inside the load ring on surface-4, it should be checked if the panel is experiencing large deformations, in such cases the stress may not be uniform inside the load ring and it should be calculated based on the distance from the center of the ring (which will require non-linear analysis).

Example 2: Figure 5 shows an example where the objective is to find the strength of machined edge (edge-1) of the sheet. The location of a test sample that is cut from the glass sheet is also shown in figure 5. If the intent is to measure the strength of edge-1 (machined edge) using four-point bending, then it is important to eliminate all the samples that fail from edge-2 or from surface failures. The samples that fail under the loading pins or outside the loading pins should also be ignored.

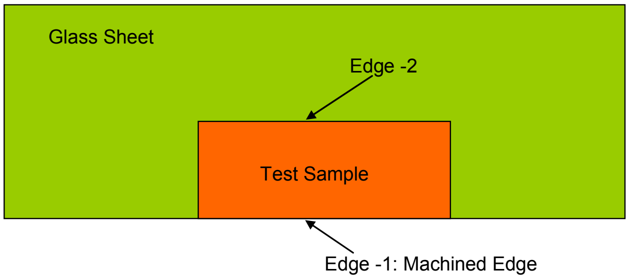
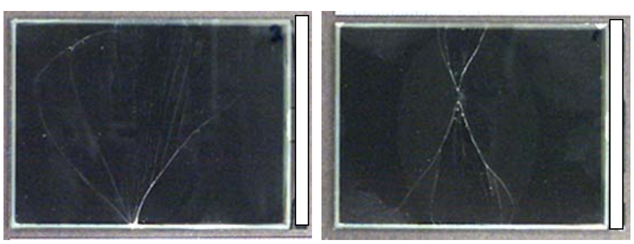


Figure 5: If the objective is to find the strength of edge-1, then, only the samples that fail from edge-1 and which are inside the load-span should be used for reporting the strength.

8. Fractography

It is recommended that the failed glass samples be analyzed by fractography [9]. By looking at the forking pattern, the fracture origin can be determined. Generally a single-crack initiates from the origin and the length of the single-crack can be correlated to failure stress. Typically, fracture origin is located at the center of the single-crack. After the single-crack propagates a certain distance, both the vertices of the single-crack start to branch out. The number of branches can also be correlated to failure stress. When the crack origin is located on the edge, only the vertex (of single-crack) that is away from the edge starts to branch out. This difference in forking pattern can be used to distinguish between edge failure and surface failure (*figure 6*).



(a) (b)

Figure 6. Typical forking pattern (a) Failure origin on the edge; (b) Failure origin on the surface.

Fastidious care has to be taken while handling the broken samples to minimize secondary damage on the fracture surface. Fractography can also help identify sources like scratches, imperfections, frictive damage and inclusions that initiated the failure. The failure stress is calculated from mirror radius, which is the distance between the origin and the edge of mist hackle. When the mirror radii are different on left and right sides, an average of them is used as representative mirror radius. Figure 7 shows a typical fracture pattern when seen under a microscope. The estimated failure stress, σ can be calculated with equation (2), where A is mirror constant which depends on the type of glass, and r is mirror radius in millimeters. The mirror constant for EAGLE XG® glass is 65.3 MPa·mm½ [10].

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$$\sigma = \frac{A}{\sqrt{r}} \qquad (2)$$

Since the mist hackle doesn't have a clear border, mirror radius measurement-method has to be consistent between different samples. Generally, a measurement accuracy of two decimal places is enough when measuring the mirror radius in millimeters. Once the location of the origin is identified, it to should be verified that it is inside the targeted loading span (in between the loading knifes for a four-point bend test and inside the load ring for a ring-on-ring test). If the origin is outside the targeted loading area, then the sample should be rejected and should not be used for reporting the strength. When testing panels, they generally tend to fail from surface-4 (which is the targeted surface). However, it should be checked if the failure is originating from surfaces other than surface-4.

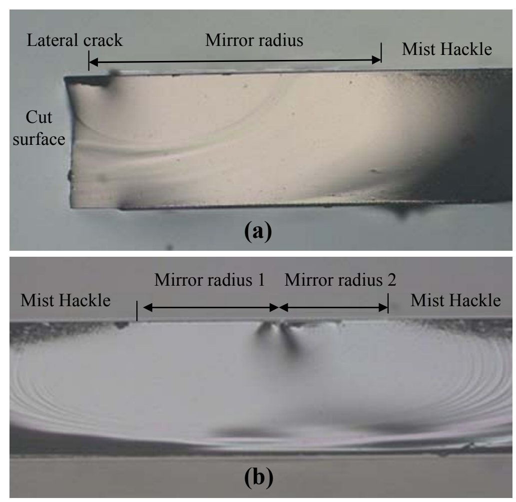

Figure 7. Typical fracture pattern when surface-4 is seen under a microscope (fracture was initiated from surface-4) (a) Failure origin on the edge; (b) Failure origin on the surface.

9. Device design

Advances in glass technology are making it possible to manufacture thin glass, which begs the question whether thin glass is strong or not. It is important to distinguish between "load-to-failure" and "stress-to-failure" (strength). The strength of glass has nothing to do with thickness; it depends on how the glass was handled and what types of flaws were introduced by handling. However, it is true that thinner glass takes lower loads than thicker glass before it fails. But if the handling processes were the same for both the thicknesses, then upon converting the failure load to stress (strength), the thinner glass should perform similar to the thicker glass. For a given load, the thinner glass deflects more and hence, experiences higher stress. Thus, to avoid failure (for a given load) of the thinner glass, its strength has to be higher than the thicker glass. An alternative to increasing the strength of thin glass is to design equipment and devices that can carefully handle thin glass. In fact, depending on the loading and boundary conditions, thin glass can sometimes have an advantage over thick glass.

Figure 8 from reference [3] compares a panel made with 0.5 mm thick glass (0.5 mm CF and 0.5 mm TFT) and a panel made with 0.7 mm thick glass (0.7 mm CF and 0.7 mm TFT). It compares maximum stress experienced by the panels when a steel ball is dropped onto them. Two scenarios were studied; in one case there was a rigid back plate behind the panel at a distance of 2.8 mm from surface-4 and in the other there was no plate behind the panel and it was free to deflect.

In the "no-back-plate" scenario, the panels behaved as expected; the 0.5 mm case experienced higher stress than the 0.7 mm case because it deflected more. For the scenario where a back plate was placed behind the panel, the deflections for both the panels were restricted to 2.8 mm and so the thinner panel experienced less stress for the same deflection than the thicker panel. This example demonstrates that device design plays an important role and sometimes it may be easier to change the device design and improve the reliability of the glass.

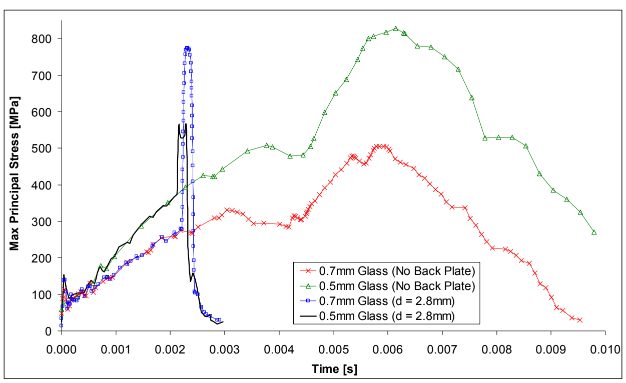

Figure 8. Comparison of maximum principal stress for panels made with 0.7 mm and 0.5 mm thick glass sheets [3]. Also shown is a comparison between having a back plate at a distance of 2.8 mm from surface-4 and not having a back plate.

10. Strain Gauging

Strain gauges are used as a common practice to monitor applied stresses during testing. When utilizing strain gauges there are several subtleties to keep in mind. Gauge length is an important criterion depending on the variation of the stress gradient. Gauge alignment with the axis of stress is also critical for assuring proper readings. Prior to performing the actual test, a proper shunt calibration has to be performed to make sure that all the appropriate gauge inputs have been used and the gauge is reading correctly. A strain gauge is glued to the glass surface and so the strain measured by the strain gauge is actually at a distance, "d" from the glass surface. "d" depends on the strain gauge thickness and the glue thickness. Generally, the ratio of "d" to the glass thickness, "t" is very small, and so its affect on the strain measurements can be ignored. But as glass gets thinner, d/t ratio becomes large and it starts to influence the strain measurements. So, when testing thin glass, the measured strain should be adjusted for gauge thickness. Transverse sensitivity of the gauge [11] is another important factor that can influence the measured strain. This is applicable when the stress field is bi-axial in nature, for example during surface strength measurements. In case of impact testing, it should be checked that the speed of the data acquisition system is fast enough to capture the impact event. As an alternative to strain gauges, non-contact strain monitoring systems such as digital image correlation (DIC) are becoming popular measures for full field views of the stress profile.

11. Conclusions

General guidelines and watch outs while conducting strength test by understanding the failure modes is a necessary first step. As display industry is moving towards thin glass it becomes necessary to account for large deflections and membrane stresses. Use of non-linear equations, strain gauges, finite element analysis, or fractography may be required. When testing panels for calculating strength, they can not be assumed to be monolithic glass. Panels and thin glass may not experience uniform stress in the testing span. Therefore it becomes important to pay attention to failure locations. Device design plays an important role and sometimes it may be easier to change the device design and improve the reliability of glass than changing something else. Fatigue should be considered when analyzing field failures or when selecting testing conditions: the reported strength can be affected by test speed, test environment, and magnitude of stress. Whenever possible, strain gauging and fractography should be conducted to verify that the experiment is working in the intended fashion and reported strength values are accurate.

12. Acknowledgment

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13.References

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