Edge Strength Measurement of Free-form Displays

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B. Jang, R. Priestley, D. Liu, T. Ono, M.Segar, B. Sundaram
Corning Incorporated, Corning, NY 14831

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Abstract

The Edge Strength Measurement System (ESMS) is proposed as a method for measuring the edge strength of free-form displays. Its feasibility on free-form monolithic glass samples with varying radius of curvatures is demonstrated. Finite element modeling and digital image correlation are performed to determine the load-to-stress correlation and understand the measurement sensitivity. ESMS can provide full edge testing which can help detect weak flaws and improve product reliability of free-form displays.

1. Introduction

Free-form displays are ones that have non-rectangular shapes with curved edges. They are widely adopted for automotive display applications. There shapes can range from ones having simple round corners to those having varying curvatures on all four sides including negative curvatures. Free-form displays are often made into a curved display resulting in a surface curvature as well. For displays that use glass substrates, this means that the glass will experience a static bending stress over its lifetime which increases the risk of having a fatigue driven glass failure [1]. Maintaining the glass strength through process optimization/quality control and conducting fatigue analysis based on the measured edge strength can considerably reduce the risk.

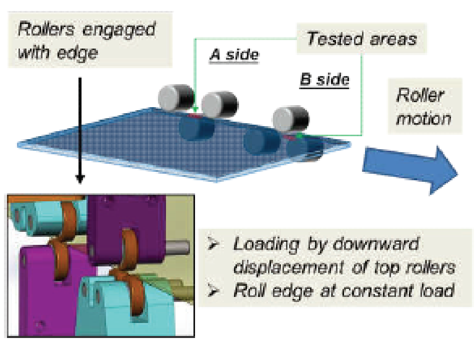

Figure 1. Edge Strength Measurement System (ESMS)

Edge quality is often the limiting factor in determining the strength of a display glass as it contains more severe flaws resulting from the "score and break" process often used to separate individual display panels. Three-point/four-point bend tests are commonly used to measure the edge of strength of rectangular liquid crystal display (LCD) panels. However, these test methods have limitations due to their limited test regions and large deflections resulting in significant errors in estimation of edge strength. Corning developed the Edge Strength Measurement System (ESMS) to measure the edge strength of thin panels with large test areas (Figure 1) [2.3]. A load can be applied using the rollers at a given location along the edge

(Static) or while they are transversing along the entire edge (Dynamic). Using the failure load and a pre-determined load-to-stress correlation, the edge strength is obtained. The load-to-stress correlation is determined by utilizing digital image correlation (DIC), finite element analysis (FEA) and fracture surface mirror radius measurements.

This paper describes the feasibility of applying ESMS to measure the edge strength of free-form displays having curved edges. Feasibility is demonstrated by a series of modeling and experiments on free-form monolithic glass sheets. The feasibility tests address potential concerns and check agreement between predicted and measured strengths. Although future work remains to test actual panels, the mechanical behavior of well-bonded panel edge can be closely approximated to that of a monolithic piece of glass [4].

2. Feasibility Study

Five areas of concern were studied: (a) influence of the radius of curvature (RoC) of the edge, (b) influence of the glass overhang, (c)influence of roller alignment, (d) comparison of stresses predicted between FEA model and DIC based measurement, and (e) effect of roller scrubbing.

(a) Edge Radius of curvature: A free-form panel can have regions along the edge with varied RoCs as shown in Figure 2a. Understanding the ability of the ESMS rollers to engage to a certain curvature was the first step undertaken in understanding measurement feasibility.

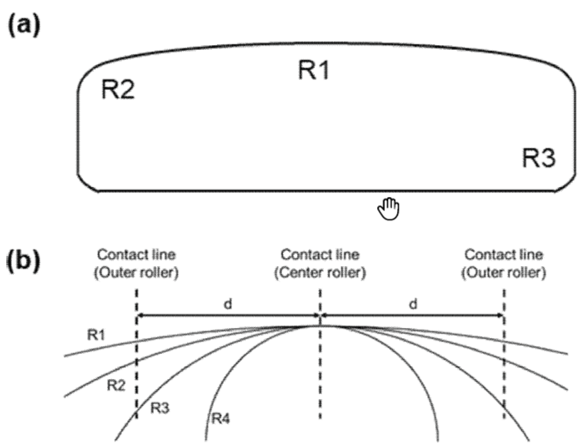

Figure 2. (a) An example of a free-form panel having edges with multiple RoCs and (b) with contact lines of the ESMS rollers overlaid.

A schematic showing plots of various RoCs overlaid with the contact lines of the ESMS rollers are shown in Figure 2b. The line along which the 3 cylindrical rollers contact the glass are called the contact lines. The distance between each adjacent roller is d. While the outer rollers contact the glass with radii R1 and R2, they do not with radii R3 and *R4.* Hence, cannot engage with the latter. The rudimentary understanding provided the baseline for the limits of RoCs within which an ESMS measurement could be performed.

(b) Glass overhang: For edge strength measurement on ESMS, the glass is held in place using a fixed stage while the measured edge is extending out from it. Its measure is called the glass overhang (figure 3a). On a rectangular stage, straight edges have constant overhangs while curved edges will have varying overhangs. (Figure 3b). For curved edges, at edge regions where the overhang is too short, the stress induced by the rollers may interact with the stage and the measurement could be influenced. At positions where the overhang is too long, excessive sagging may occur. We used a FEA based model to qualitatively understand the effect of overhang on a 0.3 mm thick rectangular piece of glass whose edge was overhanging from a rectangular stage. Both short and long overhangs were modeled with respect to a nominal overhang distance.

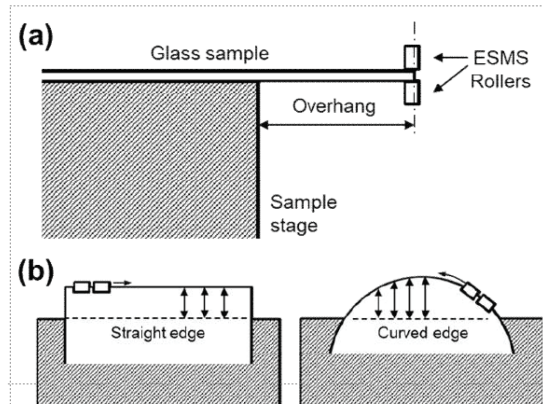

Figure 3. The edge of a glass sample overhanging from a rectangular stage while engaged with the ESMS rollers: (a) Side view and (b) top view.

Figures 4a and 4b show the stress contours on the glass for short and long overhangs, respectively. In both cases, the rear face of the glass was fixed to simulate the glass being held firmly to the stage. First, as the overhang was set short, the stress increased at areas outside the test area. While the area of maximum tensile stress is at the apex of the single roller as shown on the left side of Figure 4a, the tensile stress on the bottom surface increased as the overhand decreased (Figure 4a, right). This creates new potential failure locations away from the region of interest which would require the identification of the break location. As the overhang was increased back to its nominal value, the magnitude of stresses on the bottom side surface decreased to a point where these potential failure modes subsided.

As the overhang became long, the stress distribution in the glass changed resulting from the weight of the glass within the overhang, leading to glass slippage from the rollers. While the overhang cannot be larger than the dimensions of the glass, we used an overhang of 100 mm as our upper limit (Figure 4b). In this case, the rollers were positioned at one of the corners of the edge to simulate the extreme condition where slippage of glass is most likely. Under no load from the rollers, maximum sagging occurred at the corner away from the rollers as shown by the deformation contours in Figure 4b. Meanwhile, glass slippage was negligible with only a maximum of 6 μm in the direction away from the rollers. Subsequently, as load was applied through the rollers, small amounts of tensile stress were introduced to the top surface of the glass from sagging but was negligibly small as evident from the minimal change in the load-to-stress correlation between the glass with and without sagging (Figure 4c). Thus, it was apparent that for overhangs less than 100 mm, the impact from sagging was negligible. This provided the upper and lower limits for permissible overhangs while using ESMS for free-form edge strength measurements.

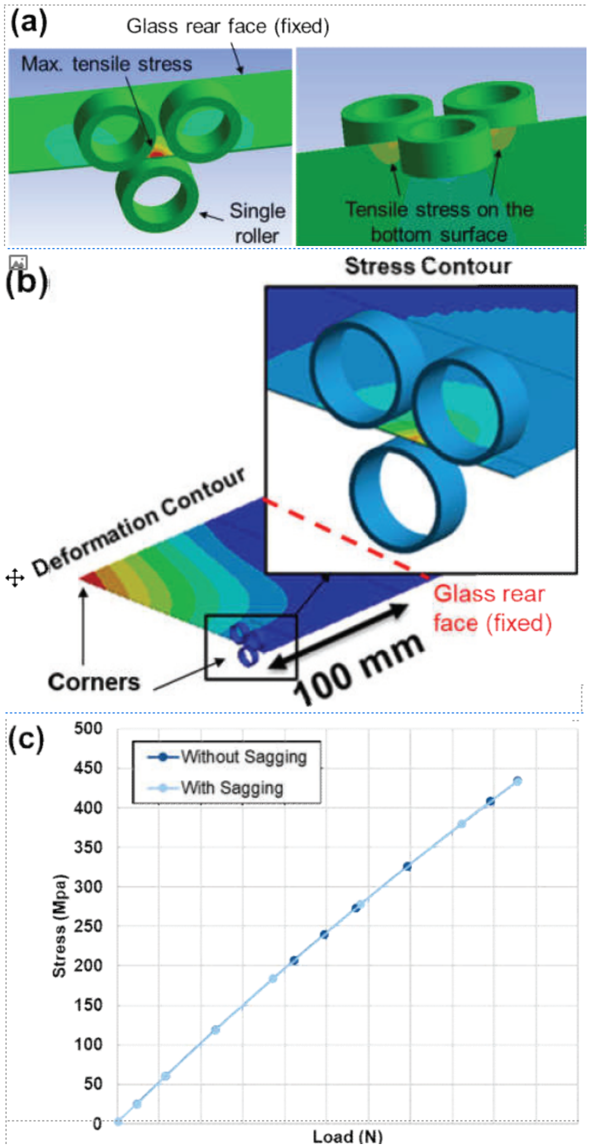

Figure 4. (a) Stress contours on top (left) and bottom surface (right) of the glass at a short overhang. (b) Deformation and local stress contours for 100 mm overhang (with saggining). (c) Load-to-stress correlation for an overhang of 100 mm with and without sagging as the rollers approach the corner.

(c) Roller alignment: The effect of roller alignment along the glass edge on the measurement sensitivity of peak stress was studied. The alignment of the ESMS rollers with the curved edge can be defined based on two parameters: Roller engagement and tilt angle (Figure 5). FEA modeling and DIC measurements were performed on a glass edge with 100 mm RoC with varied roller alignment. Figure 6a shows the max, principle strain measured on the surface of the glass using DIC, while Figure 6b and 6c show the load-to-stress correlation as a function of roller engagement and tilt angle, respectively. One parameter was fixed while the other was varied. For both parameters, the DIC and FEA model showed good agreement. While a roller engagement variation of + 1mm from the nominal case had a ± 15% effect on the load-to-stress correlation, the roller tilt angle variation of ± degree had minimal effect on the load-to-stress correlation.

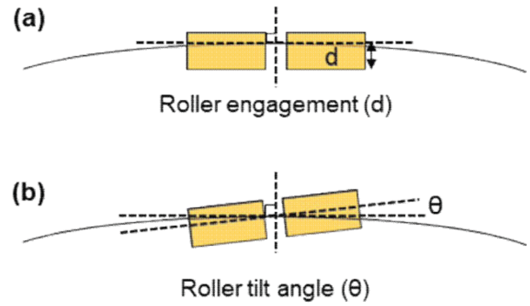

Figure 5. The parameters that define the alignment of the ESMS rollers with a curved edge: (a) Roller engagement d and (b) tilt angle θ

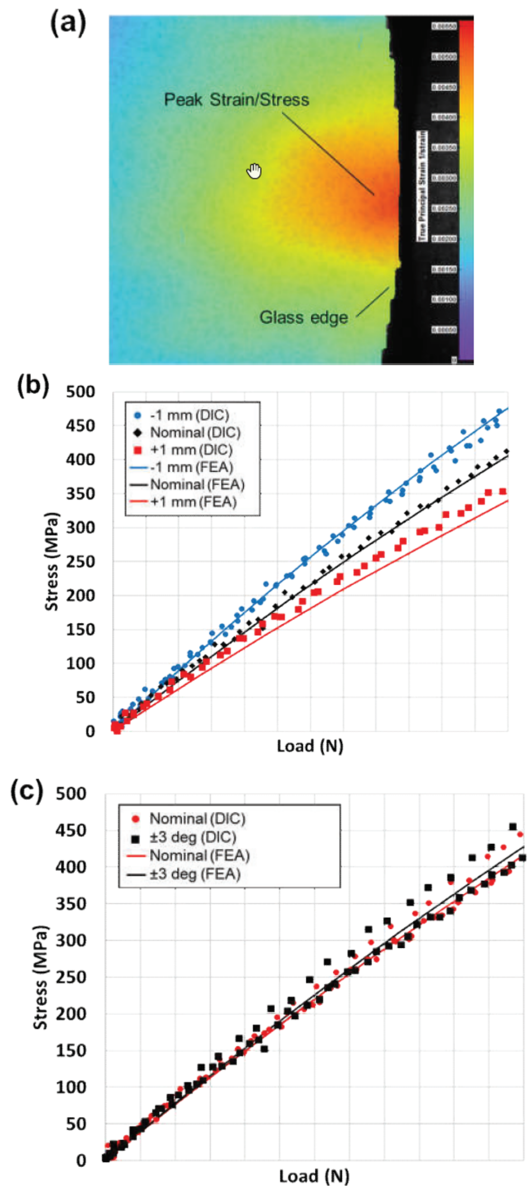

Figure 6. (a) Max. principle strain measured on the surface of the glass using DIC. Change in the load-to-stress correlation as a function of (b) roller engagement and (c) tilt angle.

Further, using the FEA based model, the load-to-stress correlation was obtained for a wider range of glass RoCs while using a nominal roller engagement and tilt angle (Figure 7). Glass sheets with RoCs of 30mm, 100mm and 1000mm were studied along with a straight edge. The spread in the load-to-stress correlation was within 5~10% for all radius of curvatures studied, which demonstrated the minimal sensitivity of RoCs on the load-to-stress correlation.

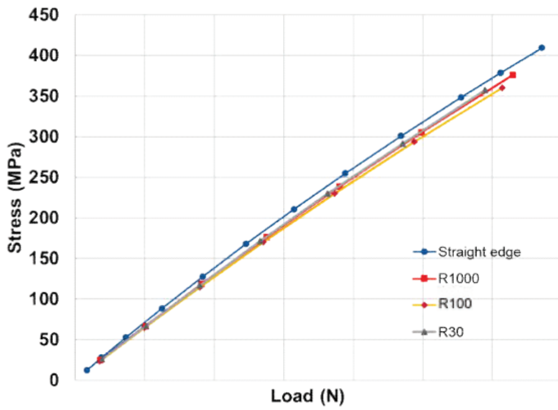

Figure 7. The load-to-stress correlation for different radius of curvatures at a given roller engagement and tilt angle.

(d) Peak stress determined using fractured surface mirror radius: To better understand the load-to-stress correlation and measurements sensitivity, the edge strength of glass samples with RoCs of 10mm, 15mm and 30 mm were measured on ESMS under static mode and then compared with failure stress as determined from the fractured surface mirror radius measurements [5]. First, the glass samples were positioned on a stage with an appropriate overhang as determined from section 2b. Next, the rollers were aligned to the glass edge with nominal engagement and tilt angle. Finally, an increasing load was applied to the edge through the roller until the glass fractured. For statics ESMS, the location of the break along the edge was also determined for accurate failure stress (sometimes breaks occur off-apex). The tensile stress on the edge of the glass drops off as it gets further away from the roller apex (Figure 8).

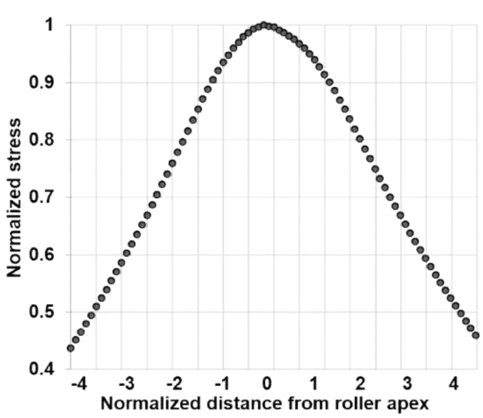

Figure 8. Decrease in tensile edge stress as a function of distance from roller apex (for static ESMS)

Figure 9 shows the comparison between the edge strength determined by the ESMS and that obtained from mirror radius measurements. For all RoCs, the edge strengths from both techniques agreed well within experimental errors as shown by the error bars. Horizontal error bars of $\pm$ 10% were applied to ESMS measurements, while a vertical error bar of -10% was applied to the failure stresses determined from the fracture surface mirror radius measurement.

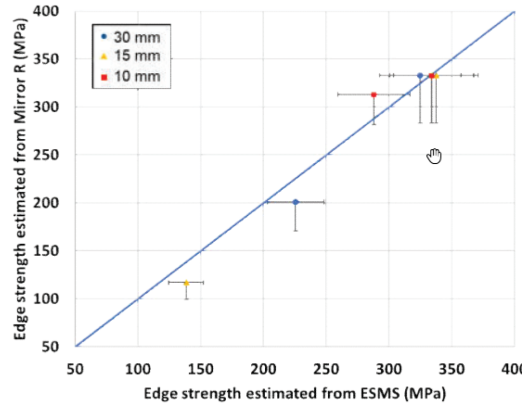

Figure 9. Correlation of edge strengths estimated by ESMS and mirror radius measurement on glass with different radius of curvatures.

(e) Low possibility of roller scrubbing: Scrubbing may occur on a curved edge when rollers traverse dynamically along it because of the inward radial force on the rollers. This is analogous to a car tire leaving scrub marks on the ground when it makes a sudden turn. Scrubbing could introduce damage to the glass edge and artificially lower the measured strength. To verify if indeed scrubbing was a concern, a worst-case scenario was studied where a glass sheet was pushed through the rollers with it being pinched in-between the rollers as shown in Figure 10. To assess the damage introduction and potential reduction in strength, subsequent strength testing was performed on these samples after scrubbing. Also, some glass samples were etched in a hydrofluoric acid solution to reveal any flaws potentially introduced from this [6]. Both strength testing and etching revealed neither reduction in strength nor new damage introduction due to scrubbing. This suggests that scrubbing and its potential effect on the edge strength was a low concern for dynamic ESMS measurement.

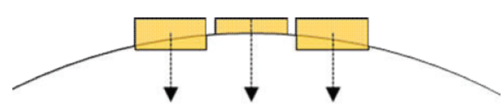

Figure 10. Scrubbing test performed on a curved glass edge by pushing the rollers inward while pinched by the rollers.

3. Conclusion

This study demonstrates the feasibility of using ESMS for free-form panel edge strength measurement. FEA, DIC and fracture surface mirror radius measurements were used to measure the failure stress and thus understand the load-to-stress correlation along with measurement sensitivity. Dynamic ESMS can provide full edge coverage which can help detect weak flaws and improve product reliability of free-form displays.

4. Acknowledgments

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5. References

1. G. S. Glaesemann, H. Vepakomma. The Mechanical Reliability of Glass Displays in Bending. SID Symposium Digest of Technical Papers; 2015 vol. 46, no.1, 1063-1066 p.
2. B. Jang, R. Priestley, A. Tremper, T. Ono, Y. Shu, B. Sundaram. Edge Strength Measurement of Ultra-thin LCD Panels. SID Symposium Digest of Technical Papers; 2019 vol. 50, no. 1, 664-667 p.
3. G. Agnello, A. Tremper, W. Li, P. Knowles. Improved Methodology for Testing Edge Strength for Ultra-Thin Panels. SID Symposium Digest of Technical Papers; 2018 vol.49, no.1, 1496-1498 p.
4. S. Gulati, J. Helfinstine, T. Ono, J. Lapp. Behavior of LCD Panel During Bending. SID Symposium Digest of Technical Papers; 2007 col. 38, no. 1, 1508-1511 p.
5. J. Wachtman, R. Cannon, J. Matthewson. Mechanical Properties of Ceramics. Wile; 2009 2nd edition.
6. H. Vepakomma, G.S. Glaesemann, D. Clark, A. Gallagher. High Strength Damage REsistant Display Panels. SID Symposium Digest of Technical Papers; 2016 vol. 47, no.1, 1358-1360 p.