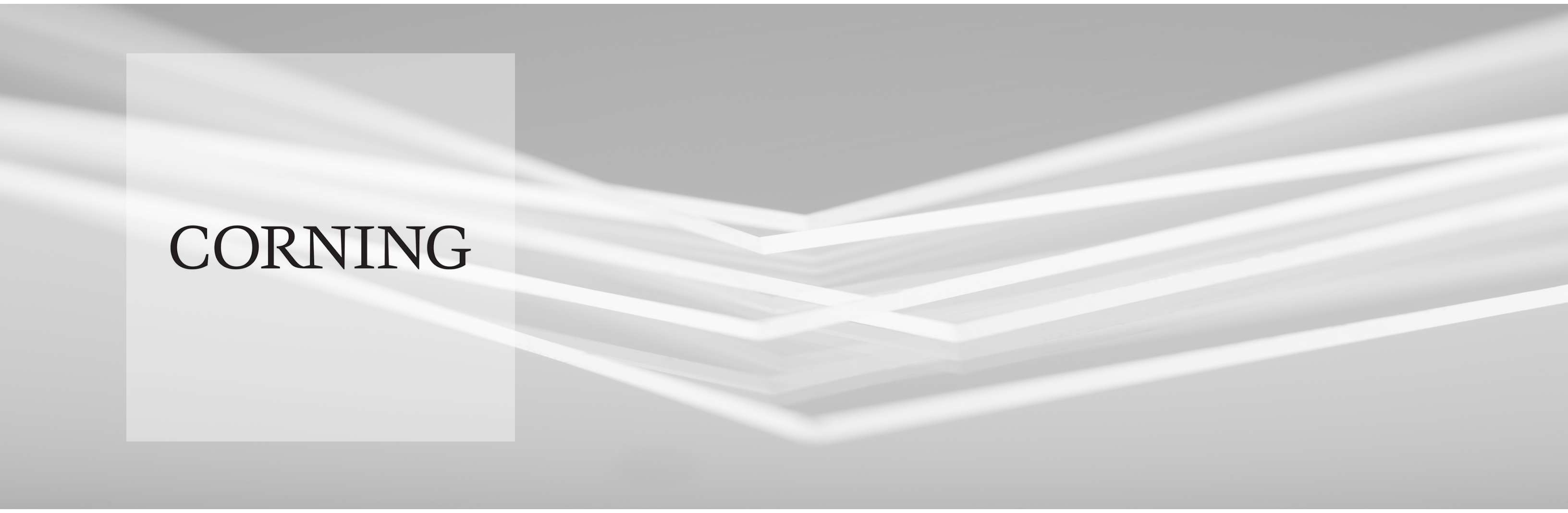
Behavior of LCD Panel During Bending



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Suresh T. Gulati, John D. Helfinstine, Toshihiko Ono, and Josef C. Lapp
Corning Incorporated, Corning, NY 14831, USA

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Abstract

When an LCD panel is subjected to pure bending, for example during strength measurement or proof testing, the question arises “does it behave as a monolith of twice the substrate thickness?" or "does it behave as two independent substrates?”. Both theory and experiment suggest that the panel behavior depends on how its edges are held together (i.e. well bonded or loosely held together). Indeed, the former renders the panel nearly twice as strong and four fold as stiff as the latter. This paper will provide the analysis of the bending behavior of a two-layer laminate using St. Venant flexure theory. Experimental data, using strain gages, will demonstrate that an LCD panel can behave either as a monolith of twice the substrate thickness or two independent substrates depending on how its four edges are held together in the support structure including the bezel. The paper derives appropriate equations for computing panel strength when it is bent to constant curvature or when its specimens are flexed in 4-point bending for both i) well bonded edges and ii) loosely held edges.

1. Introduction

Objectives and Background

The key objectives of this study are as follows:

i) to analyze stresses in LCD panel when it is bent to constant curvature,
ii) to compare stresses for two different edge conditions: a) edges are free to slide, i.e. loosely bonded and b) edges are well bonded,
iii) to measure strain components, using strain gages, and stresses during bending and compare them with those given by St. Venant flexure theory,
iv) to assess advantages of well bonded edges vs. loosely bonded edges, and
v) to provide appropriate equations for computing strength when the whole panel is bent to constant curvature or when finite size panel specimens are flexed in 4-point bending.

Some panel manufacturers have conducted strength tests using the horizontal 4-point bend fixture. However, their computed strength values are 50% lower than those estimated from mirror radii. Indeed, the computed values can be in error if the bonding nature of the substrates (loosely bonded vs. well bonded) is not taken into account.

2.

2.1 Analysis of Panel bent in a Cylindrical Bend Fixture

An LCD panel comprises of two glass substrates encompassing the liquid crystal layer. They are spaced apart by spacer posts. The liquid crystal and spacer posts exert little, if any, adhesive force on the glass substrates. The majority of the adhesive force holding the glass substrates together comes from the edges which are bonded using an epoxy seal. The properties of this seal (eg. it's stiffness) determine how well the edges are bonded (we will use the term edge fixity). This in turn determines whether the panel behaves as two separate substrates free to slide or as a monolith of double thickness when the panel is flexed to constant curvature either during strength testing [1-4] or during proof testing [5]. In what follows, we will develop an analytical solution for stresses in the panel using St. Venant flexure theory for pure bending of rectangular plates [6]. The basic equations of St. Venant flexure theory are

$$M / D = 1 / r = \sigma / (y E) \qquad (1)$$

where M denotes bending moment, r the radius of curvature of neutral axis of plate, σ the uniform bending stress at a distance y from its neutral axis, E the Young's modulus and D the bending rigidity of plate given by

$$D = E t^3 / [12 (1 - \nu^2)] \qquad (2)$$

in which t and ν denote plate thickness and Poisson's ratio of the glass substrates respectively.

If we treat the panel as two separate substrates, each of thickness t, with edges free to slide, then each substrate shares the applied bending moment M equally and is free to flex about its own neutral axis; see Figure 1. Furthermore, the bending rigidity of each substrate is equal and given by eqn. 2. Denoting the radius of curvature of top substrate by R, ignoring t relative to R and substituting in eqn. 1, we obtain the following equation for bending stresses in both substrates:

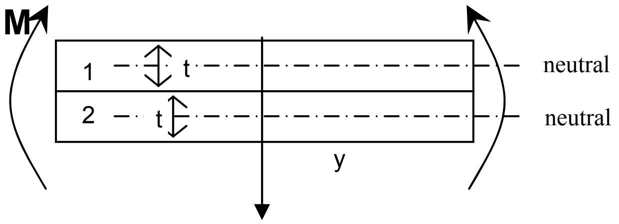

Figure 1. Bending of two separate plates, each of thickness t, with loosely bonded edges.

$$\sigma_1 = \sigma_2 = 0.5\, E\, t / R \qquad (3)$$

Hence, both substrates experience the same stress as long as they have identical thickness and are able to bend independently to the same radius of curvature R. The total bending rigidity of the panel, comprised of two substrates each of thickness t with edges free to slide, is simply

$$D = E t^3 / [6 (1 - \nu^2)] \qquad (4).$$

If we treat the panel as two substrates, each of thickness t, with well-bonded edges and subjected to bending moment M, the panel behaves as a monolithic piece of glass with thickness 2t and its bending rigidity is given by

$$D = 4 E t^3 / [6 (1 - \nu^2)] \qquad (5).$$

Comparison of eqns. 4 and 5 shows that the panel with well-bonded edges has 4X higher bending rigidity (i.e. it will not flex as much as that with edges free to slide). Hence, the radius of curvature of bent panel , R' , will be 4X larger (i.e. R' = 4R) for the same bending moment or applied load and the neutral axis of panel will be located in the liquid crystal plane with a radius of curvature given by

$$R = R' + t \qquad (6).$$

Substituting eqns. 5 and 6 into eqn. 1, the maximum bending stress at the bottom surface of panel, where y = t , is given by

$$\sigma = E t / (R' + t) \qquad (7).$$

Comparing eqns. 3 and 7, and neglecting t relative to R', the panel with well bonded edges will experience 2X higher stress than that with loosely bonded edges when both panels are bent to same radius of curvature (i.e. when R = R'). In other words, when the panel is proof tested in a cylindrical bend fixture of radius R [4] , it will experience 2X higher stress if its edges are well bonded compared to the one with loosely bonded edges. In that sense, the efficacy of the proof test is twice as high making it a beneficial test from mechanical reliability point of view.

2.2 Analysis of Panel Specimens bent in a 4-Point bend Fixture

Some OEMs test panel specimens in a horizontal 4-point bend fixture shown schematically in Figure 2. The bending stress in such case also depends on whether the specimen has loosely bonded or well bonded edges. Without going through a detailed derivation, the maximum stress during 4-point bending is given by

$$\sigma = 0.75\, P\, (L - \ell) / (w\, t^2) \text{ for loosely bonded edges} \qquad (8)$$

and

$$\sigma = 0.375\, P\, (L - \ell) / (w\, t^2) \text{ for well bonded edges} \qquad (9).$$

Comparing equations 8 and 9, it follows that panel specimens with loosely bonded edges will experience twice as much stress as that with well-bonded edges under the same applied load P. Hence, computation of failure stress from load P should make use of either eqn. 8 or eqn. 9 depending on edge fixity condition.

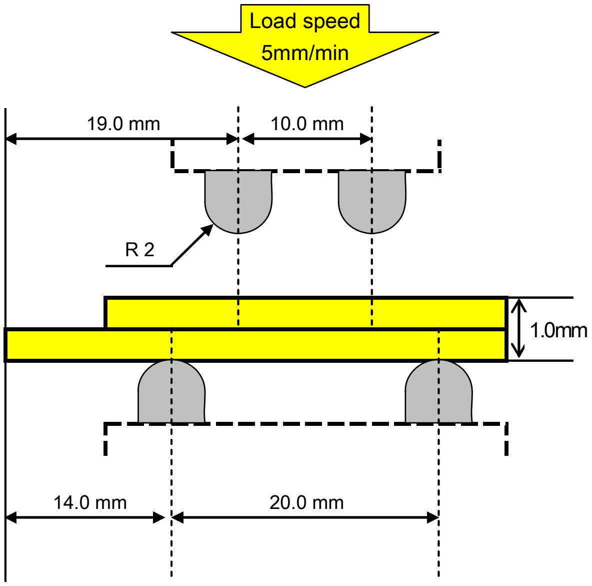

Figure 2. Horizontal 4-point bend fixture for measuring strength of panel specimens.

3.

3.1 Results

Panel specimens, 35 mm wide x 48.5 mm long and 1.0 mm thick (glass substrate = 0.5 mm thick), scored with a Penet score wheel, were flexed in 4-point bending using a support span of 20 mm and load span of 10 mm. Their edges were assumed to be well bonded (i.e. specimens were treated as a monolith). Consequently, eqn. 9 was used to compute the strength from failure load P. The fracture origins of test specimens were also examined and the mirror radius R_m measured for each specimen. Figure 3 illustrates a typical origin with the mirror marked. The strength of these specimens can also be estimated from mirror radius using the empirical equation

$$\sigma_m = A / R_m^{0.5} \qquad (10)$$

where A is the mirror constant for panel glass with a value of 65.4 MPa mm$^{1/2}$[7]. A comparison of strength values calculated from eqns. 8, 9 and 10 is shown in Table 1.

Table 1. Comparison of Panel Strength based on equations. 8, 9 and 10.

Specimen ID	Failure Load, P	Strength as one piece, σ_1, eqn.9	Strength as two sheets, σ_2, eqn. 8	Mirror Radius, R_m	Mirror Strength, σ_m eqn. 10	Strength ratio, σ_1/σ_m	Strength ratio, σ_2/σ_m
	N	MPa	MPa	mm	MPa		
1-1	160	6	137.2	0.100	207	0.33	0.66
1-10	182	0	156.0	0.185	152	0.51	1.02
1-8	239	1 4	204.8	0.100	207	0.49	0.99
2-8	161	0	138.0	0.259	128	0.54	1.08
2-12	197	4	168.8	0.141	174	0.49	0.97
2-10	252	1 0	216.0	0.067	253	0.43	0.85
3-10	179	7	153.4	0.141	174	0.44	0.88
3-8	185	79	158.6	--	---	---	
3-12	229	1	196.2	0.096	211	0.46	0.93
					mean ratios	0.46	92

It is clear from Table 1 that strength values calculated from the mirror radius (eqn. 10) are considerably higher than those predicted by eqn. 9 which assumes a monolithic panel. On the contrary, the mirror strength is closer to that given by eqn. 8 (i.e. the panels are behaving as if their edges were loosely bonded). This is also validated by the observation that, in most cases, the bottom substrate failed first in the 4-pt bend fixture. Figure 4 compares strength values given by eqns. 8 and 9 with those estimated from mirror radius (eqn. 10) indicating that eqn. 8 (loosely bonded edges) is more valid for the specimens tested.

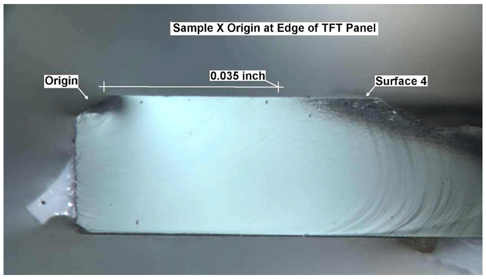

Figure 3. Fracture origin and mirror radius for edge flaw.

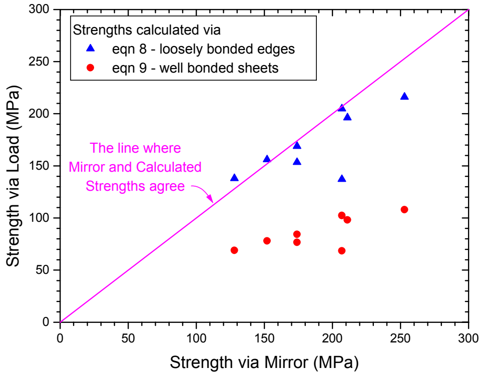

Figure 4. Panel strength calculated from failure load vs. mirror radius.

3.2 Impact and Summary

The analysis of bending stresses in LCD panels, whether tested in a cylindrical bend fixture or horizontal 4-point bend fixture, shows that the equation for strength computation depends on edge fixity. If the edges are loosely bonded, then each substrate bends independently of the other thereby permitting relative slip at the interface. In such a case, the stress is considerably higher for a given applied load. If, on the other hand, the edges are well -bonded, then the panel bends as a monolith of double thickness and does not permit relative slip at the interface; the stress generated is approximately 50% lower than that for loosely bonded edges. Experimental data for a given set of panel specimens show that these behave as two separate substrates bending independently of each other. However, one should not generalize from this one example that all panels behave as if their edges were loosely bonded. The paper provides appropriate equations for computing panel strength for both the loosely bonded and well bonded edges.

3.3 Acknowledgments

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4. References

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