7.3: LCD Ruggedization in Displays with Optically Bonded AR Glass Lamination

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Abstract: *Optical bonding of anti-reflective cover glass to LCD panels to improve sunlight readability is well known, though ruggedization benefits have seen little study. Detailed discussion of impact tests for notebook PC type displays with and without bonded cover glass will be presented as will vibration response data which show significant reduction in transmissibility as a result of viscoelastic damping in the optical adhesive.*

Keywords: ruggedized LCD; sunlight readable; optical enhanced display;

Introduction

A reduction in readability of electronic displays in bright ambient environments occurs primarily when the reflected ambient illumination overpowers the emitted luminance from the display thereby reducing the apparent contrast ratio. In the past, anti-reflective cover glass has been applied to CRTs and LCDs to reduce the reflectance from the display surface. Optical bonding of glass or plastic substrates directly on the top surface of an LCD display has been used to reduce the number of reflection reducing interfaces.

In displays using a non-bonded cover glass the ambient light reflects off three interfaces resulting in as much as 13.5% reflectance. Optical bonding eliminates the air gap between the two reflective surfaces of the cover glass and the LCD allowing great reductions in reflectance and reducing the number of anti-reflective treatments needed. With direct bonding the contrast ratio can increase by as much as 400% verses a non-bonded display as shown in Figure 1.

Figure 1. LCD module with bonded (L) and non-bonded (R) cover glass.

Optically bonding anti-reflection coated glass to the front of an LCD is not a new idea, it has been done by the Avionics Industry for years to improve the outdoor performance of their cockpit displays. The big difference between what has historically been done by the Avionics Industry and the current bonding suppliers is their bonding capacity and yield rates. It is not uncommon for applications like Tablet PC's to have requirements of 10,000 units per month, and customers expecting bonding yield rates in the range of 99%.

While optical bonding is generally used to improve sunlight readability, we are seeing a growing trend towards favoring its ruggedization benefits. Displays operating in challenging environments need to withstand impact, vibration, and extreme temperatures and humidity. Optical bonding increases the ruggedness and durability of LCD displays. Benefits resulting from the removal of the air gap include: the elimination of condensation, (a big concern in marine electronics), better viewing experience, thinner display designs and the reduction of parallax issues especially in tablet PC applications (Figure 2).

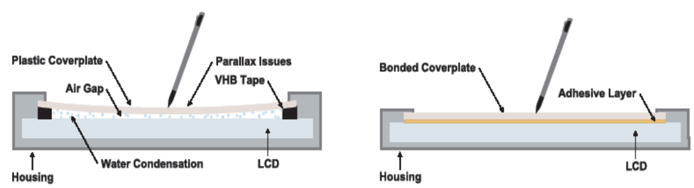

Figure 2. Benefit of bonded cover glass in tablet PC application.

Test Descriptions

Mechanical tests were performed to help understand and quantify changes in key performance metrics for displays which have been modified by optically bonding anti-reflective cover glass to the LCD front surface. It is generally understood that by bonding glass with thicknesses exceeding that of typical LCD substrates (i.e. >0.55 - 0.7mm) will increase the strength of the display. The applicable strength metric depends however on the end users' use environment. Typical measures of strength include structural rigidity, dynamic response and impact resistance. Results for enhanced displays were compared to similar performance metrics for stock, unbonded LCD modules.

Test Variables

Three notebook PC type LCD modules were tested: 4:3 aspect ratio 12.1" and 13.3" modules manufactured by BOE Hydis and AUO, respectively, and a 16:9 aspect ratio 14.1" module manufactured by Samsung. The 12.1" module uses a front mounting via tabs projecting from the right and left side edges. The 13.3" and 14.1" models used a side-mount fastening system. For all tests, the displays were mounted on the module mounting points on a relatively massive base. Due to its destructive nature, impact tests were performed last.

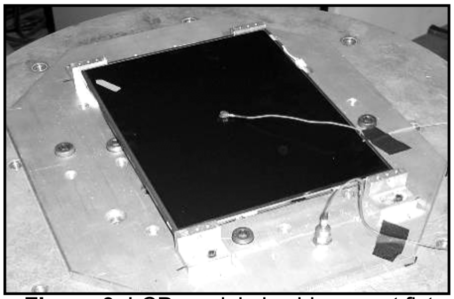

Figure 3. LCD module in side-mount fixture.

The effect of cover glass composition, thickness and tempering were evaluated as was the effect of bonding method and adhesive thickness.

- Glass Thickness: 0.7, 1.1, 1.5, and 3.0mm
- Glass Type: Soda-lime, Borosilicate
- Tempering: None, Chemically strengthened
- Adhesive Thickness: Low, High, Air Gap

Figure 4 depicts a typical construction method for an optically bonded display where a cover glass is placed over the LCD bezel and the gap between the LCD front polarizer and the rear of the cover glass is filled with liquid adhesive and cured in place. The glass overlay provides protection to the LCD and offers improved environmental sealing as well. An alternate configuration would place the cover glass within the perimeter of the bezel opening thereby offering a thinner, lighter structure. Both configurations were tested for impact performance. The static and dynamic structural tests were performed on over-frame bonded units.

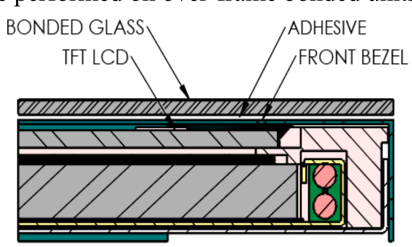

Figure 4. Typical over-frame bond on LCD module.

Structural Rigidity

LCD's are known to deflect under load even when mounted in the final product. For instance, tablet PC's see point loading by a stylus while a user interacts with the digitizer unit. Notebook PC's often see adverse loading in stowed conditions such as overhead luggage compartments in airplanes. Repeated deflections of the LCD glass assembly can eventually result in polarizer, optical film or internal cell damage or electronics failure.

This test evaluated changes in center deflection under load on 13.3" and 14.1"W notebook LCDs with over-frame bonded glass and side-mount fasteners. Center deflection was measured under two loads (applied as shown in Figure 5) for displays without a bonded cover glass and with 0.7mm and 1.1mm cover glass. Additionally, by disengaging the fastener(s) in one corner and similarly applying loads, the corner deflections for the two display types were assessed.

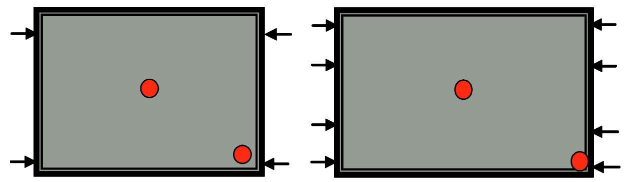

Figure 5. Set-up for center and corner deflection tests.

Dynamic Response

Notebook and tablet PC's utilize very thin LCD glass substrates to keep weight down and reduce cost. With glass as thin as 0.55mm, the cell is somewhat flexible and will deflect under static and dynamic loading. When subject to vibration environments such as experienced in a car trunk or airplane overhead, the display glass can be induced to vibrate at its natural frequency with resultant large displacements. At maximum displacements, the rear of the LCD glass can contact the backlight unit. It is believed that this phenomena may be responsible for film damage and resulting Mura defects seen in heavily traveled notebook PC's.

LCD dynamic response tests measured center accelerations and displacements of the LCD glass with the module mounted as shown in Figure 6. A Z-axis sinusoidal input of constant 0.5g was ramped from 5 to 500 Hz and the resulting responses monitored and recorded. The test evaluated differences in center accelerations and corresponding deflection due to input accelerations on 13.3" and 14.1"W notebook LCD modules again without cover glass and with bonded 0.7mm and 1.1mm cover glass.

Figure 6. Vibration table and mounting fixture with LCD.

Impact Performance

Ball drop impact tests were performed using 1.0" and 1.5" diameter steel balls (66g and 225g) following the successive drop method described by Gulati of Corning[1]. On each sample, ball drop height was increased 2 inches with each drop until failure occurred. In some cases where the LCD fractured prior to cover glass failure, testing continued until cover glass failure. Impact energy was calculated at the failure height. Samples of 12.1", 13.3" , and 14.1" notebook style LCDs with different glass thickness (0.7, 0.85, 1.1mm) and temper (annealed soda-lime and chemical strengthened soda-lime glass) were tested. The displays were mounted in the rigid mounting fixture of Fig. 1 on their standard mounting points (side mount – 13.3", 14.1" and front mount – 12.1").

To get an understanding of the fracture energy as a function of cover glass thickness and adhesive thickness, the first series of tests bonded several different thicknesses of cover glass to thick, rigid substrates (not LCD panels) with a thin adhesive layer and a thick adhesive layer. In the bare glass tests, glass thickness, composition, and temper were varied along with adhesive thickness.

Test Results

Structural Rigidity Tests

Figures 7 and 8 present the results of the center (13.3" and 14.1"W LCD's) and corner deflection (14.1"W only) tests. The increased stiffness of 13.3" is evident for both the 0.7 and 1.1mm bonded glass thicknesses. The 1.1mm bonded panel showed a 50% reduction in deflection under a one pound load with an absolute deflection reduction roughly 0.015 inch. The change in slope of the force-deflection curves in both figures suggests the contact of the LCD glass with backlight unit (BLU) components at deflections of around 0.010".

LCD Module	Applied Load (oz.)	Center Displacement (in.)		
		LCD Only	LCD + 0.7mm Glass	LCD + 1.1mm Glass
13.3"	7.8	0.014	0.010	0.008
	18.3	0.029	0.020	0.012
14.1"	7.8	0.020	0.020	0.013
	18.3	0.039	0.033	0.024

Figure 7. LCD module center deflection under load.

The 14.1" panel also showed an increase in stiffness, though not as significantly as the 13.3" panel. In fact, the 0.7mm glass showed little improvement in stiffness over the bare module. This is most likely due to structural improvements in the later vintage 14.1" panel. Even so, with 1.1mm bonded cover glass, a 33% center deflection reduction was realized. A rough estimate of improvement in torsional rigidity is provided by the corner deflection test. The 14.1" module showed 38% corner deflection reduction under a one pound load with an absolute deflection reduction roughly 0.022 inch. The corresponding improvement in torsional rigidity should provide performance gains in hinge-up reliability tests on notebook PCs.

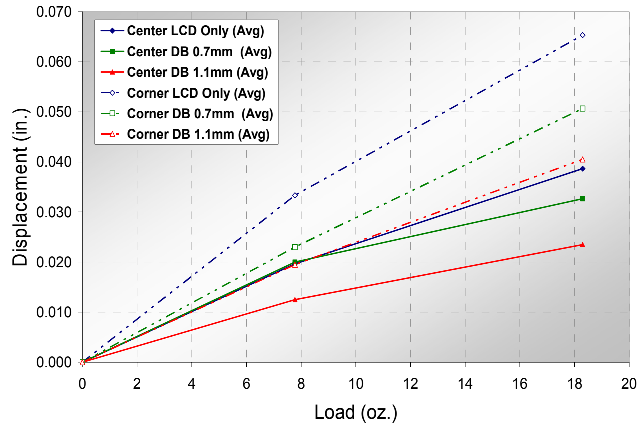

Figure 8. 14.1" LCD module center and corner deflection under load.

Dynamic Response Tests

Figures 9 through 13 compare 13.3" LCD panel center response to Z-axis sinusoidal vibration. Shown are plots for the LCD module and the module with 0.7 and 1.1mm bonded glass thicknesses. Three samples of each configuration were tested. The only significant differences in performance between similarly configured samples were seen in the non-bonded modules where small variations in the module mechanical assemblies caused slight shifts in resonant peaks (see Figure 9). Bonded samples showed no discernable differences between similar samples.

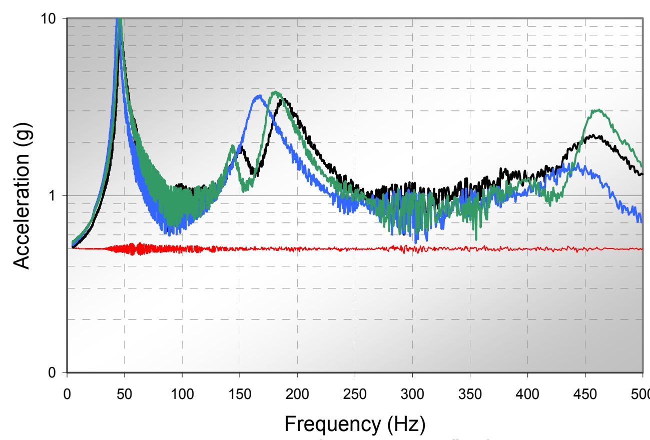

Figure 9. Vibration response for three 13.3" LCD modules.

Most notable in the vibration response of the LCD modules is the significant reduction of the primary resonant peak and almost complete elimination of the secondary peaks. For the 13.3" module, a four-fold reduction in response at resonance was obtained using either bonded glass thickness. Additionally, the primary peak moved to a slightly higher frequency (~15Hz higher) and the secondary peak shifted up almost 100Hz. Similar performance for the acceleration was seen for the 14.1" LCD module as shown in Figure 9.

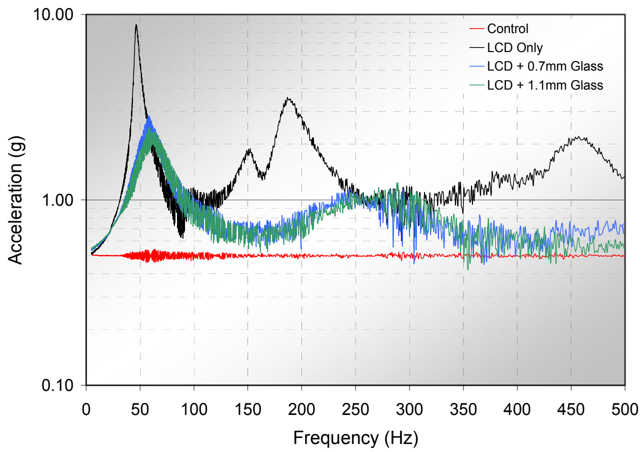

Figure 10. Vibration response (acceleration) for 13.3" LCD modules with and without bonded cover glass.

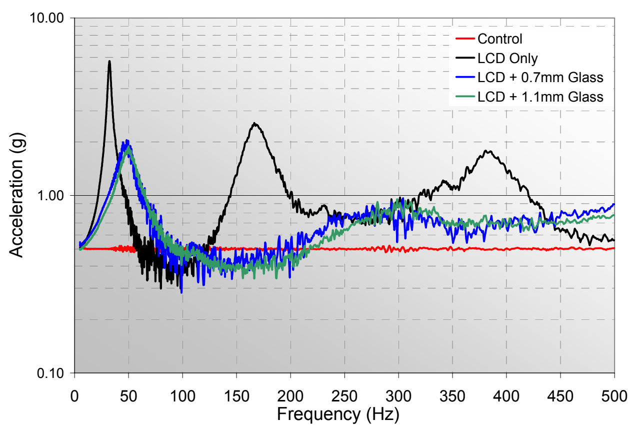

Figure 11. Vibration response (acceleration) for 14.1" LCD modules with and without bonded cover glass.

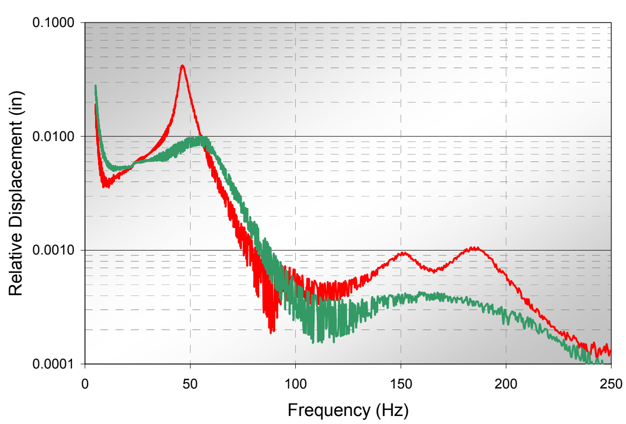

Figure 12. Center displacement for 13.3" LCD module and module with 0.7mm bonded cover glass.

The significant reduction in resonant response of the bonded LCD panels is attributable primarily to the damping effects of the adhesive layer and secondarily to the increased stiffness due to the cover glass. Energy absorption by the viscoelastic adhesive layer is also responsible for reducing LCD center deflections at resonance. As shown in Figure 12, the 13.3" module deflection peak had a five-fold reduction (from 0.050" to < 0.010") at resonance.

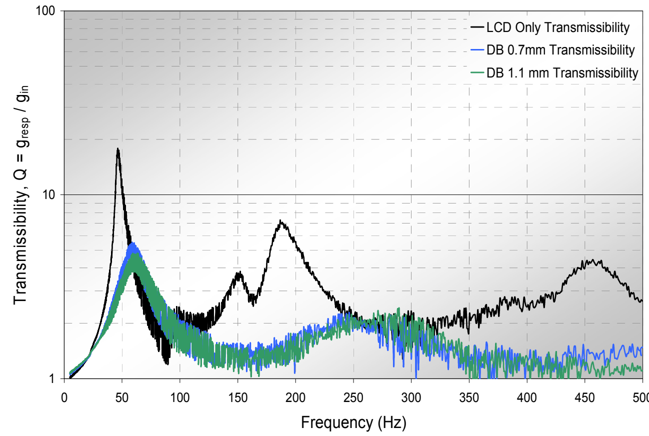

Figure 13. Transmissibility of response for 13.3" LCD module.

Figure 13 summarizes the effect of bonding a cover glass to the LCD using viscoelastic adhesive. The damping properties are clearly evident in the transmissibility plots for the bare LCD module and modules with bonded cover glass. The transmissibility, which is a ratio of the response acceleration to the forcing acceleration, is quite close to unity for frequencies above 100 Hz. This suggests an almost complete isolation of the LCD from resonant effects.

Since the LCD to BLU clearance in most LCD modules is less than the 0.05 inch deflection seen at resonance, it is clear that the rear surface of the LCD panel will contact the BLU films during resonance for even mild vibrations. The damping effect of the bonded cover glass will reduce the deflection to levels which will prevent film damage during vibration. More thorough investigation of these benefits should be conducted using prolonged dwells of broad spectrum random vibration input.

Impact Tests

Figures 14 - 16 depict the impact performance of the 13.3", 12.1" and 14.1" LCD modules when subjected to ball drop impact tests on the bare LCD module and the modules with various configurations of bonded cover glass.

Impact tests on the 13.3" LCD module compared bare module performance (LCD glass = 0.7mm) to bonded cover glass versions using 0.7mm and 1.1mm annealed soda-lime glass and 0.85mm chemically strengthened glass. While the average LCD fracture height was substantially higher for the bonded cover glass samples, the sample-to-sample variation on the 0.7mm cover glass units was so large that it overlapped with the non-bonded modules. The 1.1mm bonded cover glass modules provide a two-fold increase in LCD fracture height with much less spread in fracture energy. Most notable was the result for the 0.85mm chemically strengthened glass samples which showed a 2x improvement in average fracture height relative to the bare module but had the smallest spread of all the samples tested.

The 0.85mm CS glass performed equivalently to the 1.1mm annealed glass at roughly 75% of the weight per unit area.

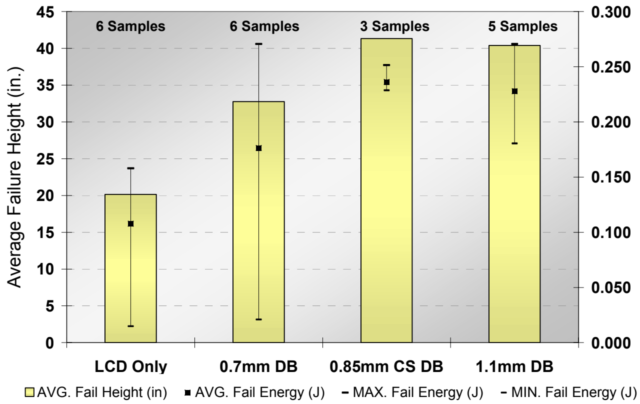

Figure 14. Failure height and energy for 225 gram ball drop impact on 13.3" LCD modules.

Impact tests on the 12.1" LCD module compared bare module performance (LCD glass = 0.55mm) to bonded cover glass versions using 1.1mm annealed soda-lime glass and 0.85mm chemically strengthened glass. Additionally, an air-gap cover glass configuration was tested using 1.1mm glass. Figure 15 plots both the LCD failure height and cover glass failure height for each of the three modified modules. Again the average LCD fracture height was substantially higher for the bonded cover glass samples. The module with the air-gap cover glass showed insubstantial improvement in fracture height relative to the bare module. Both the 0.85 and 1.1mm bonded cover glass modules provide a 7x increase in LCD fracture height, however, the chemically strengthened 0.85mm glass had the best average cover glass fracture height (54") and low sample-to-sample variation.

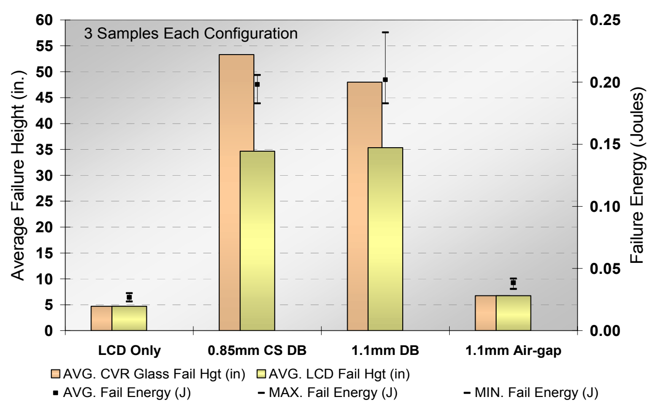

Figure 15. Failure height and energy for 225 gram ball drop impact on 12.1" LCD modules.

Finally, Figure 16 plots both the LCD failure height for the 14.1" LCD module. In this case, the viability of the 0.7mm cover glass configuration is established by the clear improvement in failure height (~2.5x) relative to the bare module. Due to the low sample quantity for the 14.1" module, accurate estimates for actual performance gains can not be made, though in light of the tests on the other modules, it is clear that increases in impact resistance are obtained with bonded cover glass. It is also obvious that thicker cover glass increases the impact resistance over thinner cover glass.

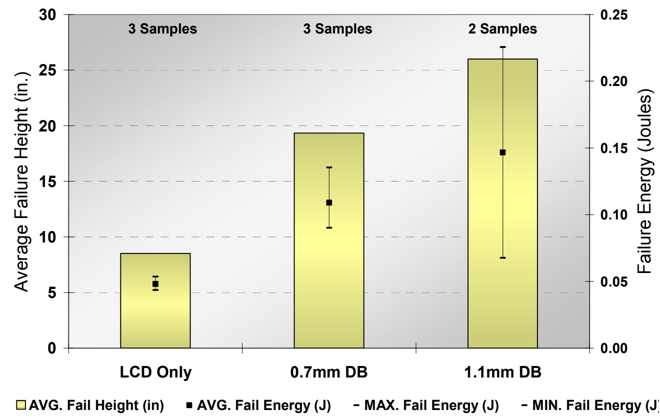

Figure 16. Failure height and energy for 225 gram ball drop impact on 14.1"W LCD modules.

Discussion and Conclusions

The benefits of optical bonding of anti-reflective cover glass to commercial off-the-shelf LCD modules extend well beyond improvements to bright ambient readability. Increases in stiffness and torsional rigidity and four-fold reduction in displacement at resonance will aid in preventing mechanically induced electrical and optical failures. Impact resistance of some LCD modules may be increased dramatically when using bonded cover glass to protect the LCD glass. In fact, with as little as a 1mm increase in module thickness, a 7-fold increase in impact strength of the LCD may be obtained. Chemically strengthened glass was shown to have the most repeatable impact performance and could be used in thinner substrates than annealed soda-lime glass achieving comparable impact strength. However, the cost adder (~35-40%) for chemically strengthened glass may make it attractive only in situations where weight or thickness concerns necessitate the added cost.

References

1. S. T. Gulati, et.al., "Mechanical Reliability of LCD Panels under Static Loading," *2004 SID Paper 62.1*