Abstract
The four-point bending test, pure bending, is one kind of common test to evaluate LCD panel strength. From lots of four-point bending experiments, we conclude that LCD panel strength is strongly correlated with manufacturing process. Also, St Venant flexure theory could not have properly analytical result to explain physical defect symptom of LCD panel after bending tests. This article aims at finding a numerical model to align both numerical and experimental results and obtains fracture stress under stabilized manufacturing condition.

Introduction
TFT-LCD is numerously being applied in handheld, laptop and other popular display devices nowadays. To ensure the mechanical reliability of variable conditions, designers are willing to enhance the robustness of LCD panel through various ways. The strength of LCD panel is carefully been maintained to prevent glass broken in manufacturing, transportation and daily use by customers, etc.

The mechanical structure of LCD panel is comprised of two glass substrates to encompass the liquid crystal inside and seals by using an epoxy sealant on the edges to keep the distance between two glasses appropriately and prevent liquid crystal leakage, as Fig. 1 shows. Therefore, loosely bonded or well bonded edges could not accurately describe realistic composition. The reason that general computed strength values is 50% lower than those estimated from mirror radii [1] is inappropriate boundary condition of edge assumptions introduced in analysis model. So that, the computed stresses would be in error even edge assumptions are taken into account.

Numerical computing introduction
There is difficult to build ideal physical specimens of well bonded and loosely bonded edges for experiments, thus detail LCD structure is implemented virtually to compare with former edge assumptions. Three cases are analyzed to check with analytical solution: 1) Well bonded edge which no separation between glasses interface. 2) Loosely bonded edge that allows two glasses to slide but no separation. 3) Detailed LCD panel that glasses are glued by sealant and liquid crystal layer is slide allowed, no separation, between two glasses.

The numerical model, panel size is 53.94mm wide x 80mm long and 0.2mm thickness for each glass substrate. For detailed panel model, there contains 4μm height sealant and liquid crystal layer between two glasses. All analysis cases are performed four-point bending test numerically, which is illustrated as Fig. 2.

Fig. 1 Mechanical structure of LCD panel

Fig. 2 Schematic of four-point bending test

The analytical solutions are shown as equation (1) and (2), St. Venant flexure theory, to represent corresponding edge conditions, and all numerical results are compared in Table 1.

\[
\sigma = 0.75 \frac{P(S_{bot} - S_{top})}{Wt^2} \quad \text{for loosely bonded edges (1)}
\]

and

\[
\sigma = 0.375 \frac{P(S_{bot} - S_{top})}{Wt^2} \quad \text{for well bonded edges (2)}
\]

Table 1 Comparison of panel strength based on different edge assumptions

<table>
<thead>
<tr>
<th>Panel edge bonded conditions</th>
<th>Well bonded</th>
<th>Loosely bonded</th>
<th>Detailed LCD panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sbot = Distance between spans on bottom side (mm)</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop = Distance between spans on top side (mm)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W = Width (mm)</td>
<td>54.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t = Glass thickness (mm)</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analytical bending stress (MPa) 86.0 172.0 N/A
Numerical bending stress on TFT panel center (MPa) 86.2 146.0 102.2
Numerical bending stress around load span (MPa) N/A N/A 194.8
Numerical bending stress on TFT edge center (MPa) 86.7 146.0 154.1
Numerical bending deflection (mm) 0.25 0.94 0.63

The computed results of Table 1 show that the bending stress is strongly depended on different edge assumptions. There is high tensile stress concentration nearby panel edge, which around load span in detailed LCD panel model, shown in Fig.
and it matches the initial crack, origin location, with mostly panel specimens after bending test. The boundary condition of well bonded edge, monolithic panel, is not suitable for evaluating the bending strength. In addition, the loosely edge assumption could not accurately describe the stress contribution of laminated construction.

![Fig. 3 The bending stress contour represents on TFT](image)

**Comparison of panel strength based on [1]**

Panel specimens, 35mm wide x 48.5mm long and 0.5mm thick for each substrate, were flexed in four-point bending using a support span of 20mm and load span of 10mm. [1] The numerical model of different edge assumptions was performed to compare with the stress value computed from the mirror radius which shown as Table 2.

![Fig. 4 Panel strength calculated from failure load vs. mirror radius and detailed LCD panel numerical results](image)

**Table 2 Comparison of panel strength based on [1] and detailed LCD structure**

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Failure Load, P</th>
<th>Strength as two sheets, MPa</th>
<th>Mirror Radius, Rm, mm</th>
<th>Strength as LCD@Center, MPa</th>
<th>Strength as LCD@Edge, MPa</th>
<th>Strength as LCD@Rod, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>160</td>
<td>66.6</td>
<td>133.2</td>
<td>0.100</td>
<td>207</td>
<td>84.9</td>
</tr>
<tr>
<td>1-10</td>
<td>182</td>
<td>78.0</td>
<td>156.0</td>
<td>0.185</td>
<td>152</td>
<td>96.4</td>
</tr>
<tr>
<td>1-8</td>
<td>239</td>
<td>102.4</td>
<td>204.8</td>
<td>0.100</td>
<td>207</td>
<td>126.6</td>
</tr>
<tr>
<td>2-2</td>
<td>161</td>
<td>69.3</td>
<td>139.0</td>
<td>0.208</td>
<td>128</td>
<td>85.3</td>
</tr>
<tr>
<td>2-12</td>
<td>197</td>
<td>84.4</td>
<td>168.8</td>
<td>0.141</td>
<td>174</td>
<td>104.4</td>
</tr>
<tr>
<td>2-10</td>
<td>252</td>
<td>108.0</td>
<td>216.0</td>
<td>0.067</td>
<td>253</td>
<td>133.5</td>
</tr>
<tr>
<td>3-10</td>
<td>179</td>
<td>76.7</td>
<td>193.4</td>
<td>0.141</td>
<td>174</td>
<td>84.8</td>
</tr>
<tr>
<td>3-8</td>
<td>185</td>
<td>79.3</td>
<td>158.6</td>
<td>-</td>
<td>98.0</td>
<td>133.3</td>
</tr>
<tr>
<td>3-12</td>
<td>225</td>
<td>96.1</td>
<td>136.2</td>
<td>0.066</td>
<td>211</td>
<td>121.3</td>
</tr>
</tbody>
</table>

From Table 2, we could notice that strength values calculated from the mirror radius are mainly located within load span area. But there were not placed the fracture origin positions, thus this will be clarified in the fracture analysis discussion.

![Fig. 5 The strength influence of various sealant materials](image)

**Experiment of panel assembly**

A TFT-LCD panel is made through lots of facility process. For realizing the relationship of panel strength and production parameters, the manufacturing parameters are defined in Table 3. Eight sets of experiments that planed by Taguchi method are proceeded to find out optimum controllable parameters in product manufacturing process.

![Fig. 6 Schematic illustration of LCD panel assembly for four-point bending test](image)

**Table 3 Manufacturing parameters chosen to verify the bending strength of panel assembly**

<table>
<thead>
<tr>
<th>Manufacturing Parameters</th>
<th>Bending Pressure</th>
<th>Glass Scribing Depth</th>
<th>Glass Scribing Speed</th>
<th>Cutter Life</th>
<th>Polish Method</th>
<th>Glass Supplier</th>
<th>OLB Beveling</th>
</tr>
</thead>
</table>

The panel assembly, polarizer attached, specimens of 13.3-inch NB panels with 0.3mm thickness for each glass substrate, support span of 200mm and load span of 100mm is tested [2]. The definition of loading direction is shown as Fig. 6a-6b. The experiment will evaluate both normal and transverse sides to recognize how panel strength behaves under four-point bending test.

According to the test results, failure probability plot for bending load could be fitted and identified by Weibull distribution, which is defined as equation (3).

\[ P(x) = 1 - e^{-\alpha x^\beta} \]  

Where x is the failure load, P(x) is the failure probability,
constant $\alpha$ is the location parameter and constant $\beta$ is the shape parameter.

Fig. 7 Summary plot of failure bending load at $P=10\%$

After bending tests, the connection between test set and 10\% failure bending load could be figured out as Fig. 7. The bending strength shows dramatically difference among test sets, even normal and transverse sides are varied in test results.

Fracture analysis of failure samples

When panel is processed bending test, glass substrate will be broken eventually and there could have crack branching on glass surface. Four types of forking map are concluded to estimate origin, the initial crack position. Then, the origin location is measured by digital vernier caliper. For normal side, the TFT side is upward to inspector. For transverse side, the CF side is upward. The origins are all recorded from TFT left edge as shown in Fig. 8a-8d.

(a) Type A, origin at top
(b) Type B, origin at bottom
(c) Type C, origin at in-plane
(d) Type D, complex forking

Fig. 8 Forking map of 13.3-inch panel assembly after four-point bending test

There are thirty-five panel specimens performed the bending test for each condition. All dots represent the fracture origin location on glass substrate, and red dots mean the bending load of origin is less than 10\% failure bending load, shown as Fig. 9a-9b. The origin location of test specimens is built to help aware the relative position. The numerical result that used edges assumption of detailed LCD panel is very similar with these four-point bending test results.

(a) Normal side test (TFT)  (b) Transverse side test (CF)

Fig. 9 The corresponding origin location, dots, in Set G with viewpoint from support span through load span

Fracture stress criteria

In this article, fracture origin location and bending load from experiments is collected. Then, the stress of panel assembly should be computed by appropriate boundary condition and fracture stress on specific origin location could be outputted to perform failure probability analysis, as Fig. 10 shows.

Fig. 10 Failure probability plot of fracture stress

Conclusions

From lots of experiment results, the bending strength would not have impressive improvement even if LCD panel were combined two glasses as one. The panel strength is subjected to behave the strength of single glass substrate mostly. Also, the discussion of panel strength through numerical model is not meaningful that discards solid test results performed first. Finally, fracture stress under stabilized manufacturing condition could be obtained and used to evaluate the risk of LCD module in variable test conditions.
References