McGinnis Chen Associates LLP
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15 November 2005

Mr. Tom Piette
Department of General Services – State of California
RESD/State Owned Buildings Planning Unit
The Ziggurat, 707 3rd Street, Suite 4-405
Sacramento, CA 95605

Re: BOE Building 450 N Street – 05167.00 RP
Subj: Glass Breakage Evaluation Report

Dear Mr. Piette:

Per your request, McGinnis Chen Associates, Inc. (MCA) conducted an investigation of the glass breakage at the Board of Equalization (BOE) Building (Project) located at 450 N Street in Sacramento. The following is our evaluation report for your review.

PROJECT BACKGROUND

The BOE building was built in 1991. The original construction, as pertinent to the curtain wall construction, is as follows:

Architect:	Dreyfus Blackford Architects
Curtain wall Consultant:	Eschbach Company, Inc.
General Contractor:	Hensel Phelps Construction Co.
Glazing Subcontractor:	Architectural Glass & Aluminum (AG&A)
Curtain wall Manufacturer:	Kawneer
Glass Supplier:	Tempglass Eastern, Inc.

The curtain wall system has experienced leaks in the past few years but there has not been any concern with the glass breakage issue until this year. A brief history of the glass breakage at the BOE building is listed below:

1.	1999	September	East, 7th floor	
2.	2001	August	South, 7th/8th floor	
3.	2001	August 14	West, 8th/9th floor	
4.	2005	January	South, 7th/8th floor	
5.	2005	September 21	South, 10th floor	(*2)
5A.	2005	September 24	South, 10th floor	(*1)
6.	2005	September	South, 7th/8th floor	(*2, *3)

*1: Replacement glass at this location cracked again, primarily due to observed edge defect at the window head.
*2: This location has been boarded up with plywood at this time.
*3: This pane broke after #5 broke (after 21 September) and is the pane that showed classic thermal break pattern as documented by Jeff Martin of MCA.

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Glass breakage occurrence has been sporadic in the early years of the building and was within the industry standard and expectation. As a reference point, industry standard allows 8 breaks in 1000 panes of glass (0.8%) in service situation. The BOE building has over 1,900 panes of spandrel glass and the failure percentage (6/1900 = 0.3%) is still entirely within the allowable industry standard. However, due to the quick succession of the last two breakage incidents and breakage of a replacement piece (5A, due to edge defect), there is an apparent serious condition that the glazing system maybe on the verge of an accelerated failure path. This would be a serious public safety issue that would require immediate attention.

A day after realization of the second incident of glass breakage, on emergency basis, DGS authorized MCA personnel to assess the glass breakage condition. MCA documented the cracked panel of spandrel glass in place and examined the cracked glass after its removal from the curtain wall. Subsequently, MCA conducted survey on the curtain wall to determine if there was other glass that maybe in imminent danger of cracking and falling out. After four days of survey on 9 drops of the curtain wall, covering 1364 windows, MCA feels reasonably sure that there were no signs to indicate further imminent glass breakage.

Further, as a safety measure, DGS erected pedestrian protection around the BOE tower on the North and East sidewalks and on the West side parking deck.

The following is MCA's analysis on the glass breakage issue at the 450 N Street building:

TECHNICAL BACKGROUND

Pertinent technical background information is provided here as basis for further discussion of the investigation work.

1. The building curtain wall consists of Kawneer 1600 series system, with a custom gold-color bull nose trim. The vision glass is a double pane insulation glass unit (IG unit) and the spandrel glass is a single pane heat strengthened glass with ceramic frit on the backside. MCA understands that glass breakage has occurred only at the spandrel glass, not at the vision glass.

2. Heat strengthened glass has a compression "skin" completely surrounding the central core of glass that is in tension. This compression skin imparts higher strength to resist failure by bending, impact, and thermal stress than conventional annealed glass. By ASTM C 1048 standards, heat strengthened glass has surface compression of 3,500 to less than 10,000 psi (pound per square inch) and edge compression between 5,000 and 9,750 psi. Fully tempered glass has surface compression of 10,000 psi or more. Heat strengthening in the range of 4,000 to 7,000 psi is probably the most desirable for most uses.

3. All heat-treated glass will break when the compression skin layer is penetrated. The edge of glass is especially vulnerable. Chips, scratches, or gouges that do not completely penetrate the compression layer can slowly propagate by external forces and result in breakage. These forces include wind pressure, thermal, and impact stress.

4. According to various sources of the glazing industry, heat strengthened glass can withstand temperature difference (Delta T or ∂ T) of 150 degrees F from center of glass to edge of glass, based on the 0.8% failure rate specification. The ∂ T calculation is a function of the glass' intrinsic material property (thermal expansion coefficient) and is not affected by the glass thickness.

5. A 1°F temperature difference introduces approximately 50 psi of tensile stress. A clean-cut annealed glass edge will resist a tensile stress of 2,400 psi. Assume glass edge T of 75 ° F and glass center T of 125 °F will introduce 2,500 psi of tensile stress, enough to crack anneal glass thermally. As a result, anneal glass is not used in spandrel glass application. The typical heat strengthened glass edge of 5,000 psi to 9,750 psi of compression is akin to the pre-stressing process to provide opposite (compressive) strength to resist the potential thermal tensile stress.

6. Glass in spandrel application can reach 200 to 220 °F in service condition. Aluminum frame, depending on color, can reach 160 to 180 °F in service.

7. There are specific pattern of thermal stress breakage for heat-strengthened glass. The typical pattern at the edge is a short (1" or so) clean and straight break at 90-degree angle to the edge of the glass. The break through of the glass is also at a 90-degree angle to the plan surface of the glass at the break.

   The break then travels in a long smooth curve across the glass and branches off in random directions (see Figure 1: Appendix C for typical thermal breakage).

8. There are patterns of exterior shadow that fall into three categories:

   a. Acceptable Shading: More than 50% of the glass is in shade.
   b. Marginal Shading: More than 25% of the glass is in shade.
   c. Harmful Shading: Less than 25% of glass area is in shade and more than 25% of the glass perimeter (linear edge footage) is in shade.

   The logic is that when large portion of the glass is in shade, the thermal gradient would not be large. The last category of harmful shading has large area of glass NOT in shade - meaning heat build up in the glass and large percentage of the glass edge in shade - meaning low temperature at the edge. The combination of the high center temperature and low edge temperature produces the highest thermal gradient and highest thermal stress.

INVESTIGATION

I. Methodology

MCA conducted a variety of tasks in the investigation of the spandrel glass breakage issue, including:

A. Examination of actual crack glass on the building
B. Survey of a large percentage of the spandrel glass on the building
C. Review of the original curtain wall shop drawings and available pertinent submittal

D. Extensive research of the glass breakage (result is summarized in the Technical Background above)
E. Computer simulation of the in-service thermal environment of the curtain wall
F. Field temperature measurement of exterior and interior spandrel surfaces

All of the above tasks contribute to the final evaluation and conclusion of the glass breakage study. Findings of each task are documented below.

II. Cracked Glass Observations

On 28 September, Jeff Martin of MCA rode the house swing stage to examine the cracked spandrel glass at 7th/8th floors on the south side of the building. The spandrel glass cracked in multiple branches starting at the lower left hand corner of the pane (Photos 1-2: Appendix B, and Figure 2: Appendix C). The break was within 3" to 4" of the splice joint between two vertical sections of the aluminum window frame (see Photo 1: Appendix B).

The glass was removed from the curtain wall frame. The broken glass edge was examined and photographed. It was noted that the glass had broken in the classic pattern attributable to thermal stress - 90-degree break both to the edge and surface of the glass (Photos 3, 4, and 5, Appendix B). There was noticeable chip at the edge of the glass, unfortunately, it could not be determined if the chipped edge was there before the break, thus contributing to the break, or caused by crushing during the break (Photo 5: Appendix B).

The outside temperature of 28 September reached 97 °F, and Mr. Martin reported that the glass temperature was extremely high on the outside surface. At the initial glass removal process, a cold blast of air was evident at the backside of the spandrel glass, and the ceiling soffit/plenum space is apparently somehow communicative with the interior air-conditioned space. The observed conditions set up a high temperature differential from center to edge of the spandrel glass.

As glass was removed, the cavity showed that a 4" section of the interior gasket has fallen away from the glass. The frame splice joint has a gap of 1/2" or so and the gasket is not being supported continuously at these locations. With the exterior glazing gasket suffering from accelerated deterioration and providing less pressure, the loose interior gasket was not unexpected. This loose gasket provides a path for the interior cold air to reach the glass edge, again further adversely impacting the thermal gradient.

Of importance is the position of the fiberglass insulation. The fiberglass blanket is in tight contact with the backside of the spandrel glass; this condition promotes build up of heat within the glass, especially in the middle region of the glass. The edge of the insulation is likely not perfectly cut and not as well insulated as compared to the center region of the glass. The insulation position further increases the thermal gradient from center to edge of the spandrel glass.

III. Survey of Spandrel Glass

As noted earlier, as long as the compression skin of the heat strengthened glass is not broken, small fissures or defects within the glass will not cause glass breakage. MCA personnel survey the spandrel glass to visually look for visible fracture in the spandrel glass and to physically impact the glass to promote incipient crack to emerge. Throughout the survey and impact-check, no additional cracked glass was found. It appears that the areas examined are not in imminent risk of experiencing another break.

On the other hand, this survey does not preclude occurrence of thermal glass breakage that may still occur given the right combination of conditions.

IV. Review of Shop Drawings

In reviewing the original shop drawings, MCA learned that there are typical locations where a portion of the aluminum frame is ground away to allow structural attachment of the curtain wall frame to the floor slab (see Figure 3: Appendix C). As the frame is ground flat at the attachment point, a 10" or so portion of the frame does not have any means to hold the interior-glazing gasket. This condition allows every spandrel glass at least two locations of zero gasket contact. Gasket can become loose in such locations, providing less glazing support and allowing cold air to reach the glass edge.

V. Research Information

A brief summary of pertinent thermal-break information is provided in the Technical Background. MCA can provide further research information in our collection on request.

Aside from the technical background, sun-angle and building orientation was examined for the 450 N Street building. The research indicates that on a September day (September 1st, to be exact), sun reaches the south wall by approximately 8:45 a.m., becomes perpendicular to the south wall by 12:45 p.m., and continues to reach the south wall until sunset.

The sun angle is shallower in the morning (38° or so) and more up right (60° or so) during the mid day. By looking at the sun's path over the sky, the middle of the glass is almost always exposed to the sun (from 9:00 a.m. on - given that the frame protrudes 4" beyond the plane of glass - to possibly 5:00 p.m. or later, for approximately 8 hours). The left side of the glass - the west edge of the glass, in contrast, ceased to be exposed to the sun by 12:45 p.m. and stays in the shadow for the remainder of the day. The left edge thus receives about 3 3/4 hours of thermal exposure then cools down, while the center continues to build up with thermal exposure. This condition also adversely affects the spandrel glass thermal gradient.

By looking at the sun angle to the glass, it can be seen that less than 25% of the glass is in shade and, by 12:45 p.m. of a typical September day, the edge of the glass under the head section and next to the west jamb section would be in shade (50% of glass perimeter). This shade pattern is considered "harmful" by the glazing industry. This is yet another factor that adversely affects the thermal gradient within the spandrel glass.

VI. Thermal Stress Analysis Field Measured Temperature Data

MCA utilized a computer program available from Lawrence Berkeley Laboratory called THERM to approximate the thermal environment of the curtain wall. The purpose of the

THERM analysis is to establish a theoretical range of "in-service" temperature that the various part of the curtain wall may experience.

The analysis provides a graphic and numeric printout of the glass edge temperature under various conditions prescribed to simulate the service condition. A copy of the analysis is attached to this report as Appendix A.

In summary, the THERM analysis indicates that, for a given exterior surface temperature range of 120° to 180° F at the aluminum frame, with gasket in place and insulation in position, the edge of the glass in the shade will be approximately 114° to 165° F. This is calculated at the continuous aluminum frame - exterior gasket - spandrel glass - interior gasket - blanket insulation - interior cold air profile. The temperature at the middle of the spandrel glass could range between 160° and 220° F. (The 160° F is conservatively low for spandrel glass low temperature, corresponding to the 120° F of aluminum frame.) This would produce a temperature difference (from center to edge) of 46° F (160 -114 for the low range) to 55° F (220 - 165 for the high range) - enough to crack annealed glass, but quite safe for heat-strengthened glass.

When the interior gasket and edge of the insulation is removed, the range of glass edge temperature drops to approximately 110° (109.8) to 158° (158.4) F. This increased the differential to 50° F (160 -110 for the low range) to 62° F (220 - 158 for the high range).

Two factors not accounted for in the THERM are the dynamic flow of constant cool air from the air condition system and the moving shadow that put the south wall west edge of the spandrel glass in the shade for half of a day. Field temperature measurements were taken to supplement the computer analysis.

The field temperature measurement is listed as follows:

Temperature measurements were taken from 10:00 a.m. to 10:30 a.m. (after approximately of 1 hour of sun exposure on the south elevation). Ambient exterior air temperature was 70°F.

1.	Exterior center of spandrel glass:	109
2.	Exterior edge of spandrel glass in morning sun:	110
3.	Exterior edge of spandrel glass in shade:	89
4.	Exterior aluminum frame:	98
5.	Interior center of spandrel glass:	94
6.	Interior edge of spandrel glass in morning sun:	98
7.	Interior edge of spandrel glass in shade:	87
8.	Interior ceiling:	77

- The center-to-edge in shade difference is (109 - 87) = 21° F after only brief sun exposure.

- There is a temperature difference of 15° F (109-94), 12° F (110-98), and 2° F(89-87) from exterior to interior surfaces at center of glass, edge in sun, and edge in shade respectively. The higher the exterior temperature, the larger the temperature difference between the exterior and the interior surfaces.

If the aluminum frame temperature rises to 160° F, one can expect the glass to reach 200° F, with the glass center portion being fully exposed to sun for the rest of the day. At the time just before the left edge of the glass goes into shade, one would expect the temperature there to be roughly equivalent to the center of glass. With half of its total daily sun exposure, the surface temperature would not be at the high temperature yet. However, a temperature of 180° F would seem reasonable.

The center of glass temperature would continue to climb to reach 200° F, while the edge in mullion's shade would drop for the rest of the day. The west edge of spandrel glass in shade would likely drop from 180° F down to temperature somewhat higher than the interior air temperature (the interior ceiling temperature was 77° F). And as noted earlier, the higher the exterior surface temperature, the larger the interior and exterior temperatures difference would be. If the glass edge drops to 158° F (based on THERM), the field data indicate a possible further lowering of the interior surface temperature.

For exterior surface temperature of 89° F, the measured interior temperature difference was 2 degrees. For exterior surface temperature of 109° F, the measured interior difference was 15. One would expect that for an exterior temperature of 158° F, a measured interior temperature difference could be in the range of 30° F or more. This could drop the interior glass edge temperature to 128° F or so, creating a spandrel center to edge difference of (200 - 128) = 72° F.

Under more extreme conditions, when the exterior temperature rises beyond 100° F, which is not unusual in Sacramento, the interior air conditioned space will remain relatively unchanged (with HVAC system), the temperature difference could reach well into 90° F plus. At that range, the actual temperature difference is beginning to get closer to the design limit of 150° F (as noted by a glazing manufacturer).

EVALUATION & RECOMMENDATIONS

After reviewing the field data, research information, shop drawings, actual building configuration, and weather parameters, MCA believes that the glass breakage is a thermal stress break. Although the break is not caused solely by thermal stress, all factors combined to cause the breakage observed recently.

The likely scenario is summarized as follows:

- The heat strengthened spandrel glass has a compression skin layer surrounding the entire piece of glass. This compression layer imparts greater strength to the glass to resist breakage due to bending, impact, and thermal stress. This compression layer is approximately 20% of the glass thickness on each side and as long as this compression skin is not fully penetrated, the glass will remain intact. It is possible that a small chip at the glass edge may have been present before the break.

- Small edge or surface defects, such as scratches, gouges, or chips, if contained within the compression layer, will not break the glass. However, over time, bending, thermal, and impact stresses may propagate the small cracks through the compression layer and then cause what appears to be spontaneous break.

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