

Glass Breakage in Insulating Glazing Units in Spandrel Assemblies

George Torok, CET, BSS

Morrison Hershfield Corporation

200-2932 Baseline Road, Ottawa, ON Canada K2H 1B1

613-739-2910 • gtorok@morrisonhershfield.com



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ABSTRACT

Curtainwall and window wall systems today commonly use insulating glass units (IGUs) for vision glazing and for spandrel panel cladding. A risk for IGUs in insulated spandrels is higher thermal stresses on the glass lites, compared to older approaches with single glazing. When ceramic enamel (frit) opacifiers are used, there is increased stress from solar absorption. Thermal stress is generally addressed by heat-treating at least the opacified lite. Multiple incidences of thermal stress-related fracture of ceramic enameled spandrel glass in North America, Europe, and elsewhere have shown that ceramic enamel weakens glass, reducing the added benefit of heat treatment, so there remains a risk of in-service thermal stress breakage. This presentation will give examples of breakage, describe causes, show results of a test program that shows that ceramic enamel reduces the strength of heat-treated glass, and describe options to control the potential for in-service breakage. The discussion will be of interest to building owners, designers, and builders considering the use of curtainwall and window wall systems with opacified glass.

SPEAKER



George Torok is a façade specialist in the façade engineering team of his firm's Ottawa, Ontario, office. He provides specialist consulting services to architects, building owners, developers and builders, and façade system manufacturers across Canada and the U.S. He has over 30 years of experience in new building enclosure design and construction and existing building performance failure investigation, rehabilitation, and renewal. His specialty is fenestration systems, including windows, doors, skylights, curtainwalls, window walls, sloped glazing, and glazed architectural structures. He is a past president of the Ontario Building Envelope Council and the Building Envelope Council Ottawa Region, and he is a director of the Building Science Specialist Board.

Glass Breakage in Insulating Glazing Units in Spandrel Assemblies

THE PROBLEM

Curtainwall systems today commonly use insulating glass units (IGUs) for vision and spandrel glazing. Low-emissivity (low-e) coatings with increasingly lower U-factors and solar heat gain coefficients are used to meet modern energy code requirements. Thermal insulation is used behind spandrel IGUs to further control heat loss in spandrels. To conceal the insulation, the inboard lite of spandrel IGUs is often made opaque (opacified) by applying a ceramic enamel coating to the back face. Sometimes, the enameled glass fractures, even though the glass is heat-treated during enamel application.

This paper will give examples of breakage, describe causes, and discuss options to control the potential for in-service breakage.

WHAT ARE CERAMIC ENAMEL COATINGS?

A ceramic enamel coating is, essentially, a glassy paint fused onto the surface of a pane of architectural vision or spandrel glass. It is applied in liquid form and has the same fundamental components as any paint: pigments, vehicle, and various additives. The pigments (metal oxides) give color opacity or transparency. The vehicle or medium is the solvent into which the pigments and additives are dissolved for application to the glass surface. The main component of the vehicle by weight is ground-up glass (frit), which acts as a flux (it reduces the firing or fusing temperature of the compound), a binder (by melting and fusing with the glass surface, it holds other non-volatile components to the glass), and a durability enhancer, providing resistance to chemical and physical wear. Additives can perform many functions, depending on the needs of the finished product.

There are many ways to apply ceramic enamel to glass: screen printing (the traditional approach for patterns and repetitive

images), ink jet (the modern approach for both patterns and complex imagery) and roller, spray, and curtain coating (for uniform or “full-flood” coverage). After application, the enamel is dried (the solvent evaporates), and then the coated glass is heat-treated (heat-strengthened [HS] or fully tempered [FT]), which fuses the coating to the glass surface (as well as imparting resistance to thermal stress or impact to the glass substrate).

OBSERVED BREAKAGE OF ARCHITECTURAL CERAMIC ENAMELED GLASS

When glass coated with ceramic enamel breaks, the breakage pattern is determined by the type of stress that occurred (thermal, mechanical) and the nature of

the glass substrate (HS, FT). Studies of ceramic enamel-coated glass that cracked in service indicate that thermal stress is usually the cause, although mechanical stress may be a contributing factor. Thermal stress cracks usually begin at the perimeter and progress inward toward the center-of-glass region. With repeated application of stress, cracks may branch, continue to another edge, and/or return to the same edge. HS glass breaks into pieces of various sizes—often quite large—characterized by flowing/curving cracks. The irregular shapes of broken HS glass shards tend to lock together, so for the most part, the broken glass stays in place (*Figures 1 and 2*). FT glass shatters into small pieces and usually falls out of the IGU or fenestration product frame.



Figure 1 – Fractured heat-strengthened glass in a single-glazed curtainwall spandrel panel. The crack likely started at the bottom, extending into the center-of-glass region, before branching and continuing across the unit to the top.

Figure 2 – Fractured heat-strengthened glass in an inboard pane of glass in an IGU of a curtainwall spandrel panel. The crack started at the upper left corner, to the right of the temporary restraint (dutchie) to the curtainwall frame behind, indicating a combination of thermal stress and mechanical stress contributed to breakage.



Close-up examination typically shows the crack origin is inward of the glass edge, at the enamel-coated face of the glass (*Figures 3 and 4*). The origin of the crack at the ceramic enameled surface indicates a damaging effect of the enamel to the glass surface. The specific nature of the damage is uncertain, but it may be related to intrusion of particles of frit into the glass surface, acting as stress concentrators. Research is ongoing.

STUDIES CONFIRMING THE EFFECT OF CERAMIC ENAMEL ON GLASS STRENGTH

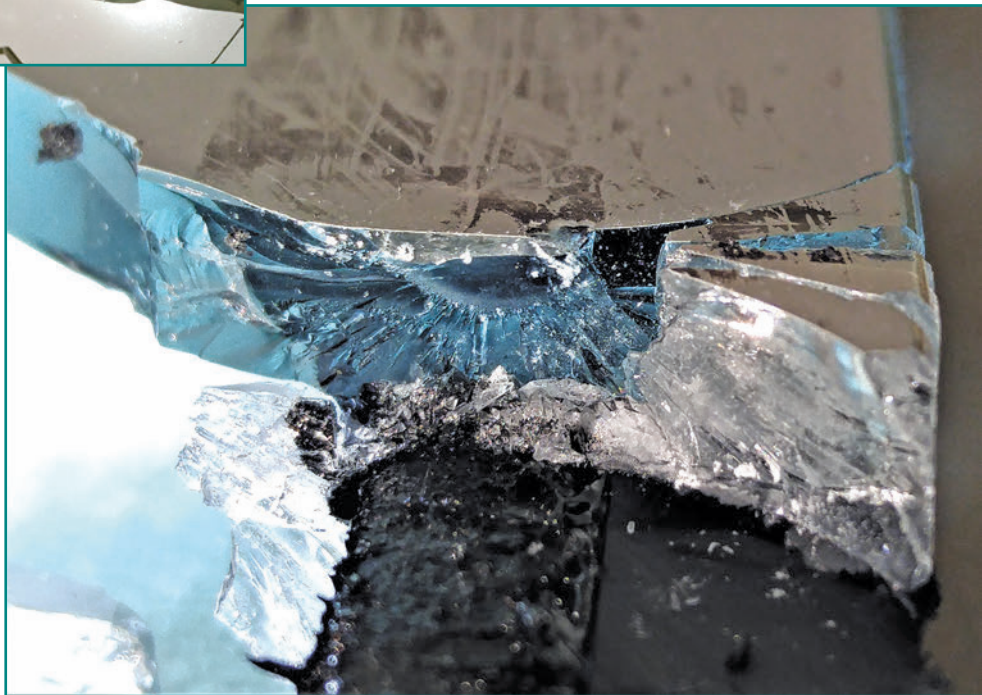
Breakage of this type has been observed in architectural spandrel glass with complete coverage of one of the flat faces (“flood coat”). It has also been observed in architectural vision glass with enamel applied in a pattern, such as for privacy or solar control and in automotive vision glass with ceramic enamel masking around the perimeter.

Test methods used to assess the weakening of glass with ceramic enamel coating include:



Figure 3 – View of the back side of the spandrel IGU in Figure 2, after it was removed from the curtainwall. The crack split toward the center-of-glass area, as seen in Figure 2 and also to the edge of the inboard pane, indicating the origin of the crack was inward from the edge.

Figure 4 – View of the crack face, exposed after glass on one side of the crack was removed. Visible are features typical of a crack origin (mirror, mist, and hackle),¹ which indicate the crack origin is at the top, at the flat face of the glass with the ceramic enamel coating, and with the fracture radiating away into the thickness of the glass, most clearly indicated by the ridges in the hackle. The origin is located within the depth of the perimeter spacer and sealants.



- **Uniform load deflection:** ASTM E998, *Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method*
- **Four-point bending:** ASTM C1161, *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature*
- **Impact:** GANA LD 100-06, *Standard Test Method for Ball Drop Impact of Laminated Architectural Flat Glass*; ASTM F3006, *Standard Specification for Ball Drop Impact Resistance of Laminated Architectural Flat Glazing*; and UN Global Technical Regulation No. 6, *Safety Glazing Materials for Motor Vehicle and Motor Vehicle Equipment*

These methods assess load capacity in bending, either through slow application of force (uniform load deflection) by four-point bending tests or rapid application by impact by ball drop tests. These test methods do not measure thermal stress capacity directly, but since thermal and mechanical stresses have the same effect on glass—increasing tensile stress—these bending tests can be used as surrogate test methods. Examples of studies demonstrating that ceramic enamel coatings weaken HS and FT glass, assessed by using these test methods, are given below.

UNIFORM LOAD TESTING (ASTM E998)

The four-point testing method involves sealing a glass pane against a chamber that is pressurized or depressurized, then measuring and observing the effects on the glass. In the study from which the graph in Figure 5 is taken, the chamber was evacuated until the glass samples broke. All samples were heat-treated. The ceramic-enamel-coated side faced into the chamber, so it was put into tension. The tests revealed that the failure load decreased as ceramic enamel frit coverage increased.

The graph is limited to the probability of breakage

up to 0.010, or 10 panes in 1,000, so it doesn't show the effect of breakage to failure (i.e., probability of breakage of 1.0). This is to more clearly show behavior in the region of most interest to structural design of glass for buildings which is typically limited to a maximum probability of eight breaks in 1,000.

Numeric analysis reveals that, at the 8/1,000 probability level, the bending strength of FT glass with partial coverage of ceramic enamel coating (dots, lines, holes) is about 80–85% of uncoated HS glass. The bending strength of FT with full coverage is approximately 63% that of the uncoated HS.

FOUR-POINT BENDING (ASTM C1161)

This test method involves breaking samples of glass in a four-point bending machine, in which the samples bridge

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across two static cylindrical pins, and a platen with two other similar pins spaced closer together is moved downward on the sample until it breaks. The break load is measured. Ceramic-enamel-coated glass is set face down so the enamelled face is put into tension. Similar to Figure 5, the graph compares probability of breakage against load, to highlight the effect in the 8/1,000 range used for structural design of glass. Four types of glass are compared: uncoated and 100% ceramic-enamel-coated

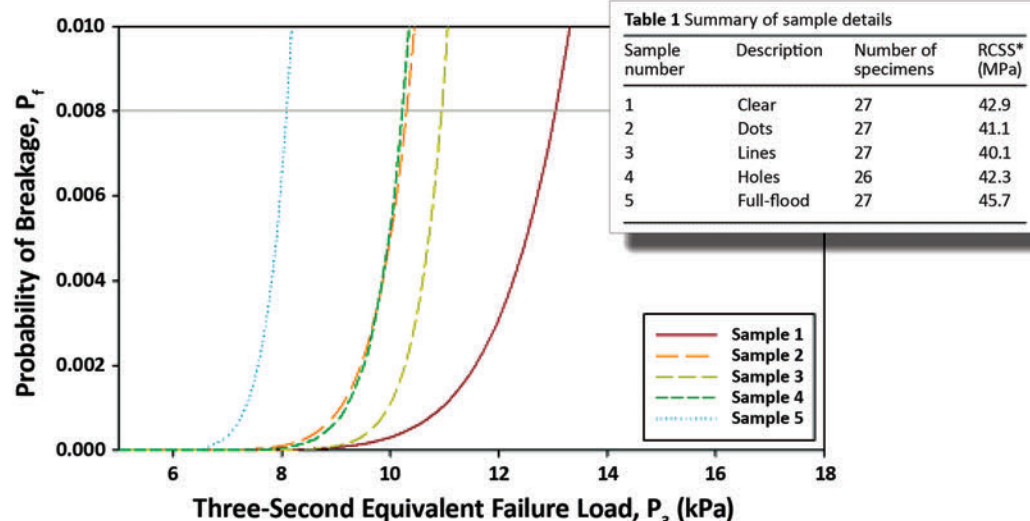


Figure 5 – Probability of breakage vs. three-second equivalent failure load. This graph shows the results of uniform load bending to failure, for heat-treated glass without ceramic enamel coating (clear) and glass with different extents of ceramic enamel coating coverage (dots = 40%, lines = 50%, holes = 60%, full-flood = 100%). The horizontal line at 0.008 probability of breakage represents the normal allowable breakage limit of eight breaks in 1,000 for glass design in buildings (from Bergers, Natividad, Morse, and Norville, 2016).

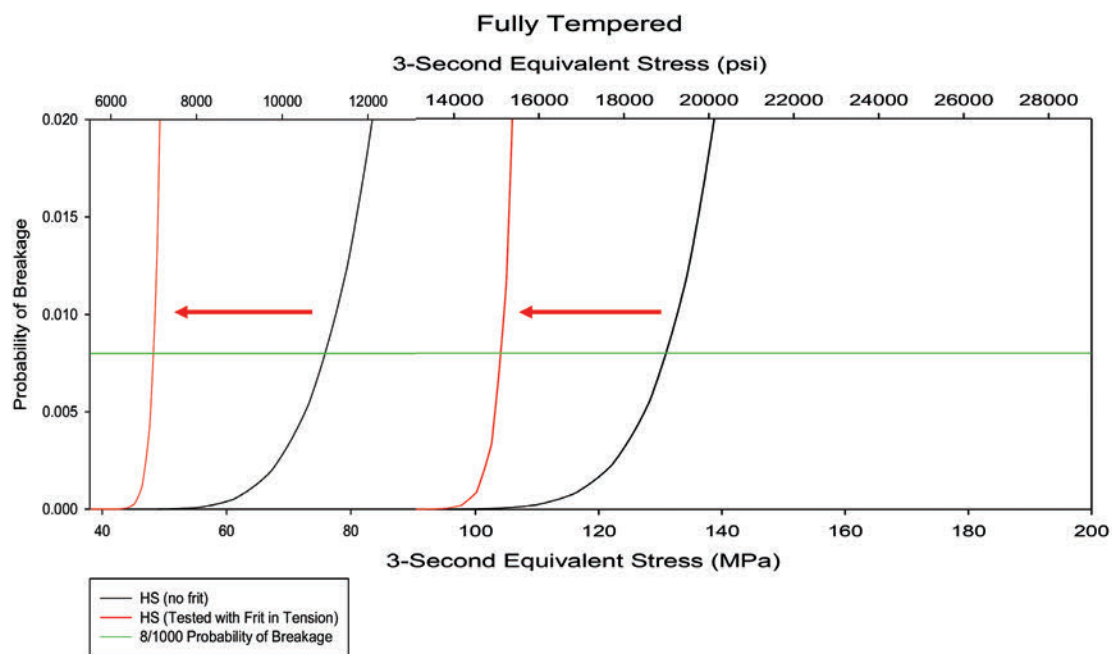


Figure 6 – Probability of breakage vs. three-second equivalent stress load. This graph shows the results of four-point bending until breakage, for uncoated and 100% ceramic-enamel-coated, HS glass, and uncoated and 100% ceramic-enamel-coated FT glass (from Barry, 2015).

heat-strengthened glass, and uncoated and 100% ceramic-enamel-coated FT glass.

The graph shows that the load at which breakage occurs, in general, is reduced for both ceramic-enamel-coated, HS and FT glass, compared to uncoated versions of the same glass type.

In a 2018 paper, Barry—the author of the paper from which Figure 6 is taken—summarizes the results of 10 studies of uniform load tests (i.e., ASTM E998) and four-point bending tests (ASTM C1161) for HS glass with and without ceramic-enamel coating. Design strength (i.e., at 8/1000th probability of breakage level) reductions range from 2% to 60%, with an average of about 31%.

BALL DROP (GANA LD-100, ASTM F3006, UN GLOBAL TECHNICAL REGULATION NO. 6)

In these standards, a similar test method is used which involves placing samples of glass on a four-sided frame and dropping a steel ball onto the sample. The height at which the ball is dropped is increased in a step-wise fashion until the sample breaks. The drop height at breakage is recorded. Ceramic-enamel-coated glass is set face down so the enamelled face is put into tension by the impact of the steel ball on the opposite (upward-facing) side. Figure 7 shows results of a test

program that the author's firm participated in. Similar to Figure 5, the graph compares probability of breakage against load, to highlight the effect in the 8/1000 range used for structural design of glass. Four types of glass are compared: uncoated and 100% ceramic-enamel-coated, HS glass, and uncoated and 100% ceramic-enamel-

coated FT glass. The study addressed breakage of automobile sunroofs with ceramic enamel masking around the perimeter to conceal adhesive bonding to the vehicle frame. The study compared uncoated annealed glass, uncoated FT glass, and perimeter-coated, ceramic-enamelled FT glass. The results of this test

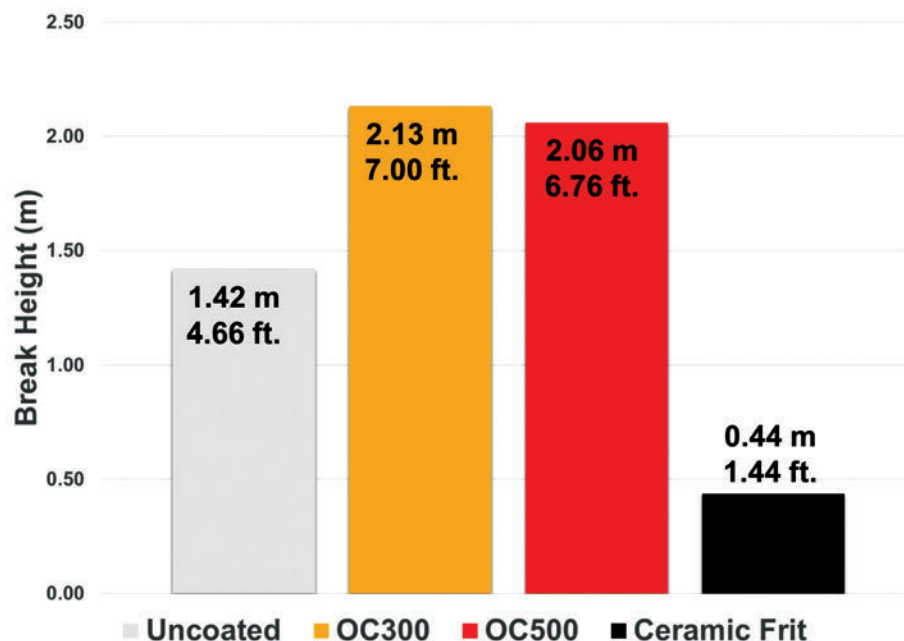


Figure 7 – Break height during ball-drop tests of FT glass, uncoated (left, grey bar), coated with two versions of silicone coating (middle orange and red bars), and ceramic enamel (right, black bar) (from Vockler, Krytenberg, Norville, Blanchet, Swanson, Barry, Carbury, Hoffman, Torok, and Fronsoe, 2017).

show that the impact resistance of FT glass with a perimeter ceramic-enamel coating is reduced to less than that of uncoated, annealed glass (Figure 8).

- In summary, the studies reveal that:
- Ceramic enamel coating reduces bending strength and impact resistance of HS and FT glass.
 - Weakening occurs with full coverage and partial, patterned coverage. Roughly, the reduction in load capacity is proportional to the extent of coverage of the glass surface by ceramic enamel.
 - If HS glass is needed for improved thermal stress and/or mechanical stress, given the strength reduction that occurs with ceramic enameling, consideration should be given to using FT glass instead; but beware of unintended consequences (see Recommended Practice below).

GUIDANCE FOR THE DESIGN PROFESSIONAL

In Europe, the governing standard for FT glass (known as “toughened” glass) is EN 12150, *Glass in Building – Thermally Toughened Soda Lime Silicate Safety Glass*. That standard requires a load reduction of 38% for ceramic enamelled glass, which is within the broad range of capacity reductions revealed in the studies discussed previously.

Despite the approach taken in Europe and a growing body of empirical evidence and the results of studies just described, discounting the thermal stress and/or bending stress capacity of glass during the design of fenestration systems remains controversial in North America. In late 2018, the committee that oversees ASTM E1300, *Standard Practice for Determining Load Resistance of Glass in Buildings*, began to study the issue, with a goal to revise the standard to include provisions for addressing the strength of ceramic-enamelled architectural glass. That work is ongoing. In the meantime, how should a design professional proceed? Three approaches are outlined below.

- 1. Consider using other coatings.**
- If simple full-flood coverage is needed, two alternatives are liquid-applied silicone coating or a polyester film (“scrim”) opacifier. The study by Vockler et al., cited earlier in Figure 7, shows

The result of a 227g ball drop test by height

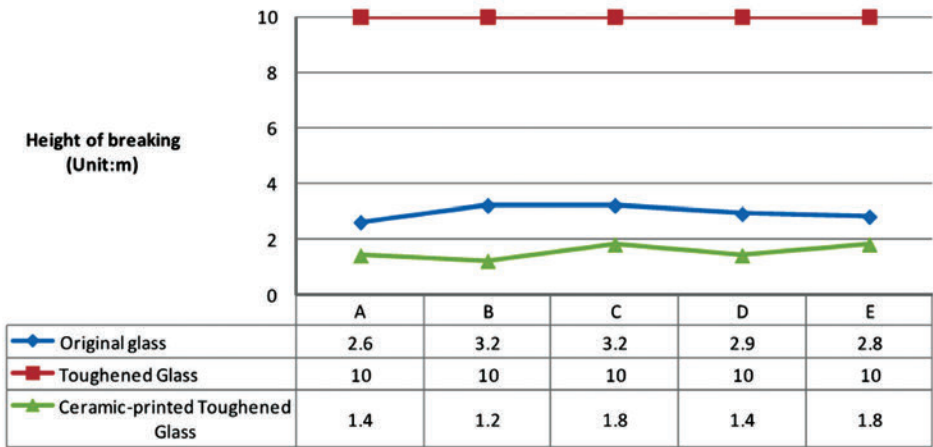


Figure 8 – Break height during ball drop tests for uncoated annealed (“original”) glass, uncoated FT (“toughened”) glass, and FT glass with a full ceramic-enamel coating (“ceramic-printed toughened glass”) (from Kwang-bum, Hae-boung, Ho-soon, Sang-woo, and Young-sam, 2015).

that liquid-applied silicone opacifiers available from one manufacturer do not adversely affect bending or impact performance of tempered glass as does ceramic enamel. The author is not aware of incidences of polyester film opacifiers weakening heat-treated glass.

- If patterns, photographic images, or artwork images are desired, laminated glass with the images printed on the inter-layer material is a possibility. However, laminated glass is normally made with regular annealed glass and so would not resist the elevated levels

of thermal stress in spandrel panel glazing. It is possible to laminate with HS or FT glass to provide the necessary thermal stress resistance, but in turn, there are some fabrication challenges to address (matching roller wave and edge lift distortions, for example) and the interlayer material must then be capable of resisting high temperatures that develop in spandrel glazing. The assistance of a heat treatment glass processor and inter-layer manufacturer should be obtained when considering this approach.

Despite the approach taken in Europe and a growing body of empirical evidence and the results of studies just described, discounting the thermal stress and/or bending stress capacity of glass during the design of fenestration systems remains controversial in North America.

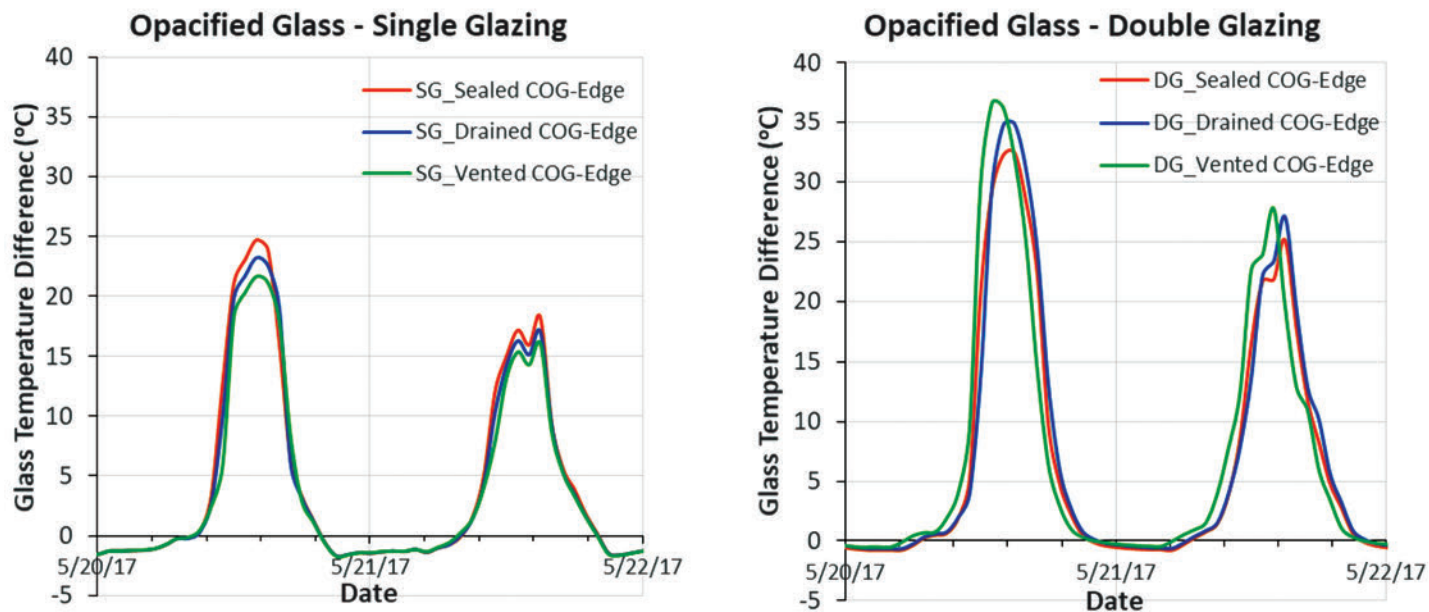


Figure 9 – Center-of-glass to edge-of-glass temperature differentials for spandrel IGU with opacifier on surface four. At left, single-glazed spandrel glass; and at right, double-glazed sealed IGU spandrel glazing. Three conditions were studied: glazing sealed on all four sides to the curtainwall frame, drained through the sill, and drained through the sill and vented through the head. Little difference was found among the options (from Schwartz, Roppel, Hoffman, and Norris, 2018).

2. Design for reduced load capacity.

- Reduce the bending stress load capacity of the glass at the design stage, following European practice (i.e., discount bending strength by 38%).
- If load capacity is reduced, compensating actions may be needed. For example, for mechanical stress (wind load), some lost load capacity could be restored by increasing glass thickness. However, increasing glass thickness does not improve thermal stress resistance.
- If HS glass is required for thermal stress or wind load resistance, increase to FT. However, this introduces a risk of spontaneous breakage due to nickel sulphide (NiS) inclusions. It is possible to control—but not prevent—this risk by further processing FT glass using the European heat soak test, EN 14179-1, *Glass in Building: Heat-Soaked Thermally Toughened Soda Lime Silicate Safety Glass*.

3. Reduce applied loads.

- The key to controlling thermal stress in fenestration glazing is to reduce center-of-glass to

edge-of-glass temperature differences. That can be achieved by reducing the temperature at the center of the spandrel glazing, increasing the temperature at the edge of the glazing, or a combination of the two.

- Center-of-glass temperature rise can be controlled by the use of reflective coatings or pyrolytic low-e coatings for single glazing, and sputtered low-e coatings in sealed IGUs. However, it must be kept in mind that an IGU with low-e-coated glass restricts the loss of heat gain from solar exposure back to the exterior, and insulation behind the spandrel glazing restricts heat loss to the interior, so the spandrel glass center-of-glass temperature can still become quite hot.
- Some curtainwall systems include vents at the top and bottom of the spandrel cavity in an attempt to allow solar heat gain to escape to the exterior. However, research conducted by the author's firm has shown this is not an effective approach (Figure 9).
- Edge-of-glass temperature can be increased by reduc-

ing thermal bridging through the fenestration product frame and, if used, through the IGU spacer and sealants. A frame with higher-performing thermal breaks and an IGU with a warm-edge spacer could be used.

A growing body of experience and research shows that ceramic-enamel coatings on heat-treated architectural glass reduce thermal stress, bending stress, and impact resistance capacities. Care should be taken when considering ceramic-enamel coatings on architectural glass subject to such stresses, especially where one or more may be present at elevated levels, which is often the case in spandrel panel glazing. Some guidance is provided in this paper, based on experience and on European practice to reduce the risk of breakage. When in doubt, seek the assistance of a design professional. 

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FOOTNOTE

1. The mirror, mist, and hackle derive their names from their appearance, when a crack is separated and

the edges examined. The mirror is smooth and reflective to the naked eye, the mist appears similar to condensation on a mirror, and the hackle is roughly textured like broken shards of glass oriented in the direction of crack movement. Each feature represents stages in the progression of the crack from explosive release of pent-up stress (the mirror) and increasing turbulence as the advancing energy dissipates and spreads through the glass (mist and hackle). These three features identify the origin of a crack and can be analyzed to reveal the type and amount of stress present at the moment of fracture, from which the cause of fracture can be determined.