Unexpected Breakage in Ceramic Enameled (Frit) HS IG Spandrels

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SUMMARY

- Spandrel glazing can create more thermal stress than can normally be resisted by heat strengthened (HS) glass with applied ceramic enamel (frit)
- Evolution of spandrel glazing
- Unexpected breakage in enameled Insulating Glass IG spandrels
- Finite Difference method for computing thermal stress
- Possible causes of the weakening of heat treated (HT) glass with applied ceramic enamel
- Suggested design changes to eliminate breakage

EVOLUTION OF SPANDRELS

High reflectivity, low light transmission, 1st surface coating, single glazed spandrel glass, covering floor slab edges



2nd Surface Reflective Coated Vision and Spandrel Glass



OPACIFICATION

- Single glazing, organic paint opacifier #2 surface sometimes bubbled and peeled with age.
  (The first molecule of paint the sun's UV strikes is the one holding the paint to the glass)
- Black stick-on, opacifier scrim, water based or solvent based adhesives, could be more reliable

- Ceramic enamel on #2 surface of spandrels avoided opacifier durability issues
- Not good with reflective coated glass. Reflective coating not compatible with frit
- Reflectivity changed by the application of the enamel.

- High solar thermal stress required heat treatment (HT)
- Fully tempered (FT) glass can have rare spontaneous breakage
- Toronto, Canada Building Code required scrim backing on FT spandrel glass after some broke.
- HS glass breaks into small particles.
  Less likely to fall out of the framing

(Design glass not to break.
Design for consequences of unexpected breakage)

Shadow Box Spandrels

- External viewer sees through the spandrel glass
- Dark, non-reflective material behind transparent spandrel glass gave better visual match between the vision and spandrel
- Reflected light from within the box eliminated by using dark materials :
- Black tar Paper over insulation
- Three layers of Fiberglass insect screen over insulation

Very high temperatures (>100 °C) in a closed, insulated, shadow box generate volatile vapors from organic materials



High spandrel temperatures (>100 °C) melt foam plastic insulation

(Photo Credit: Tim Moore)



Enameled IG
Shadow Box Spandrels

- Better visual match between vision and spandrel with HT IG instead of single glazed spandrels
- Low-e and reflective coatings match the vision glass.

IG Shadow boxes with opaque ceramic enamel frit on #4 surface were more thermally stable and avoided visible condensation.

Sealed IG requires a high performance edge seal to withstand the high temperatures of in-service spandrels
Note: ASTM 2188 only tests to 140 F (60 C)

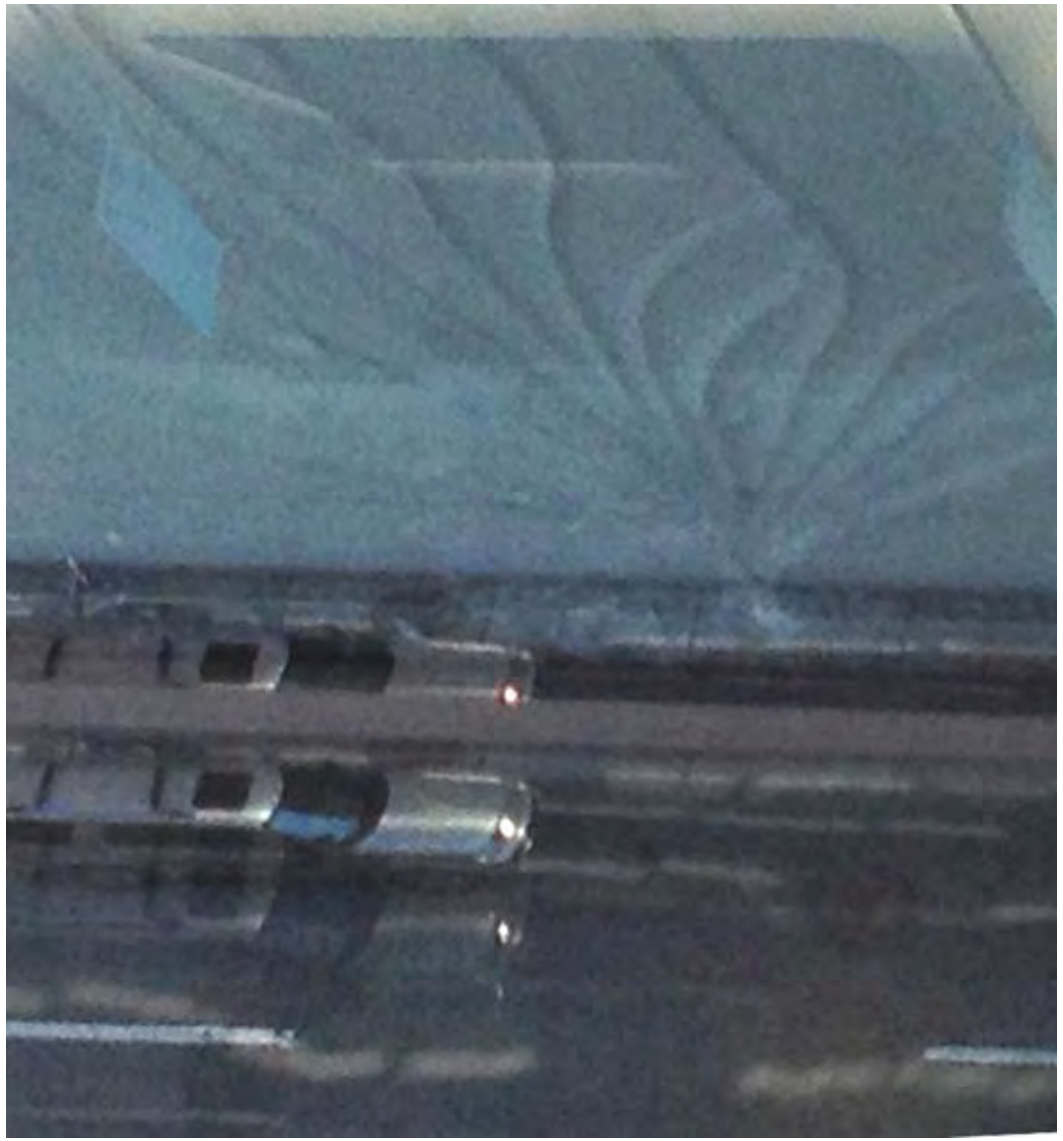
Enamel on #4 surface usually insufficient to block all transmitted light when viewed from the interior.

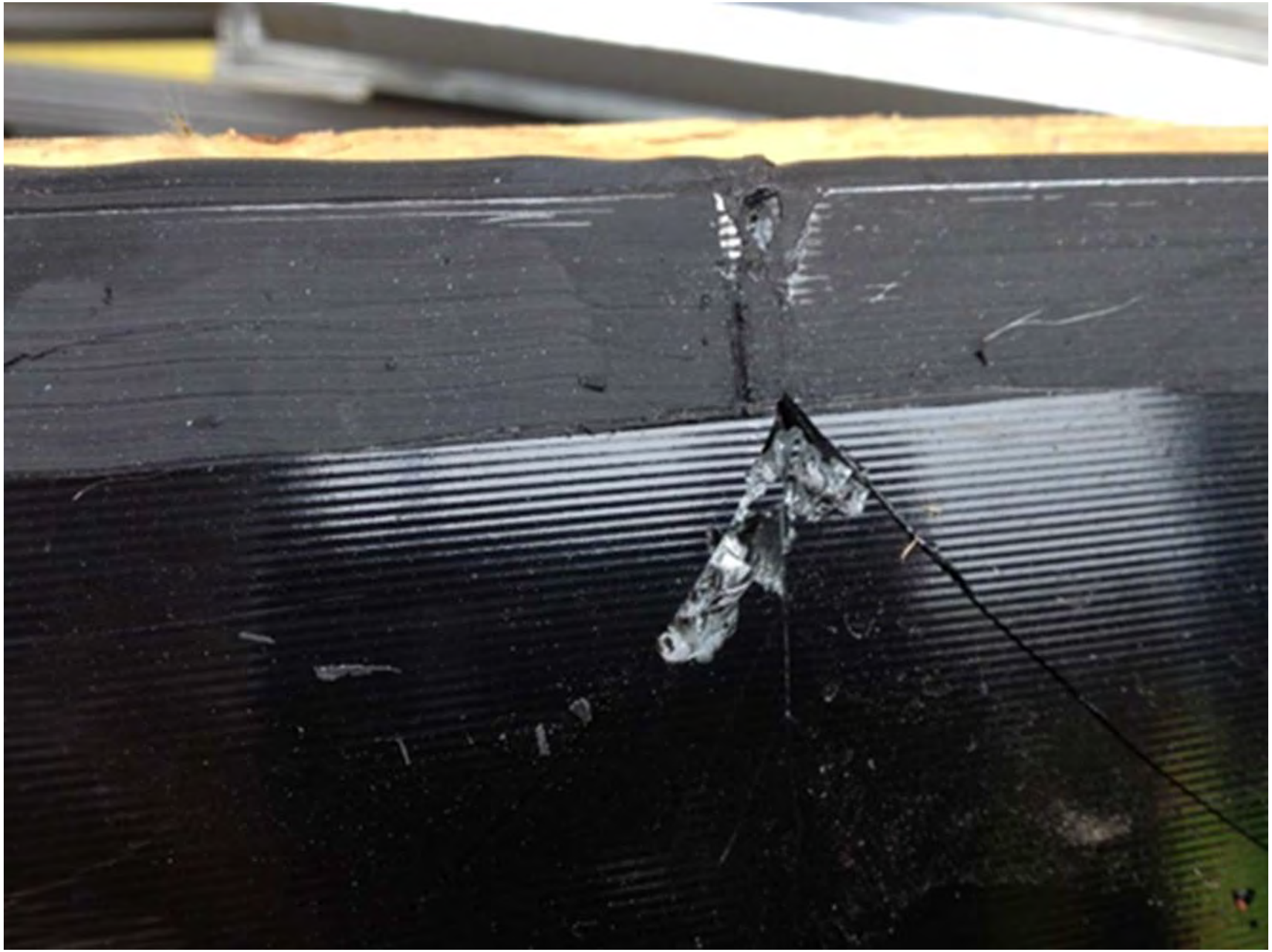
Note changed exterior appearance with degree of opacification





Unexpected Breakage









- No glass damage at fracture origin
- No inclusions at fracture origin
- Origin not at a high stress area for uniform lateral load
- Origin not at glass edge indicating no handling or installation issues
- Small mirror radius indicating high stress
- Break identified as high Thermal Stress

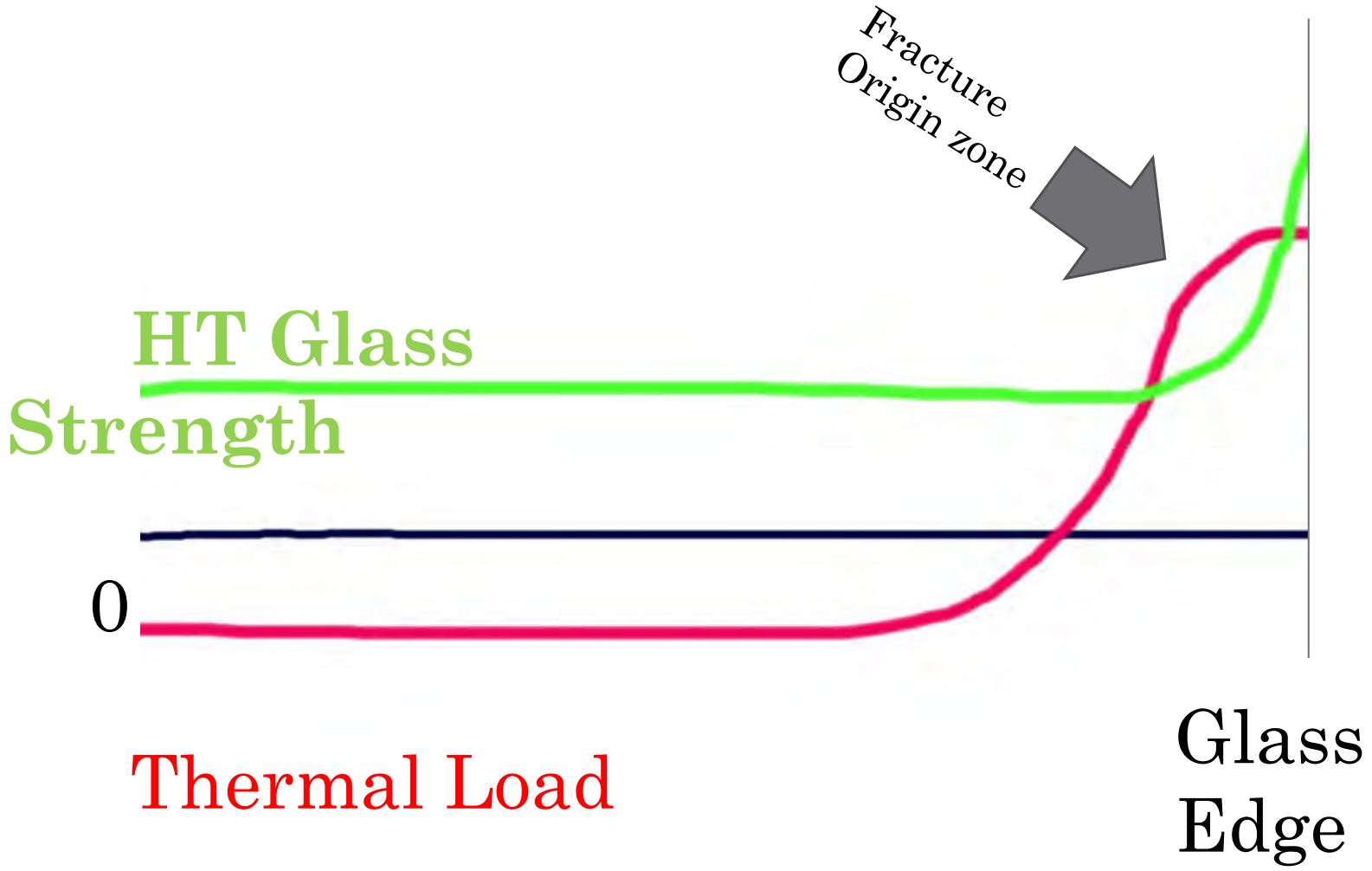
Cause of Fracture?

Was the glass too weak?

Or

Was the load too high?

Spandrel Glass Light



THERMAL STRESS LOAD

How Much Thermal Stress is generated in IG spandrel glass?

Thermal Stress Load Estimation

Finite Element Analysis (FEA) or simple Spreadsheet Finite Difference Method

Excel allows recursive, self-referential loops
Switch to Manual Calculation by

File / Options / Formulas / Calculation Options
/ Manual / Enable Iterative Calculation.

Set “Number of iterations” to 32,000 and “Maximum change” to 100.

$$T_{center} = (T_n + T_e + T_s + T_w)/4$$

Add an iteration counter, and a conditional check on each computed cell. Use a start cell, to reset all cells to zero at the start of each new series of calculations.

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10	8.4	7.3	6.6	6.2	5.8	5.6	5.4	5.2	5.1	5.1
10	7.5	6.4	5.9	5.6	5.4	5.3	5.2	5.1	5.1	5.1
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IG spandrel (Solar control Low-E coating on #2 surface, opaque grey ceramic enamel on #4 surface)

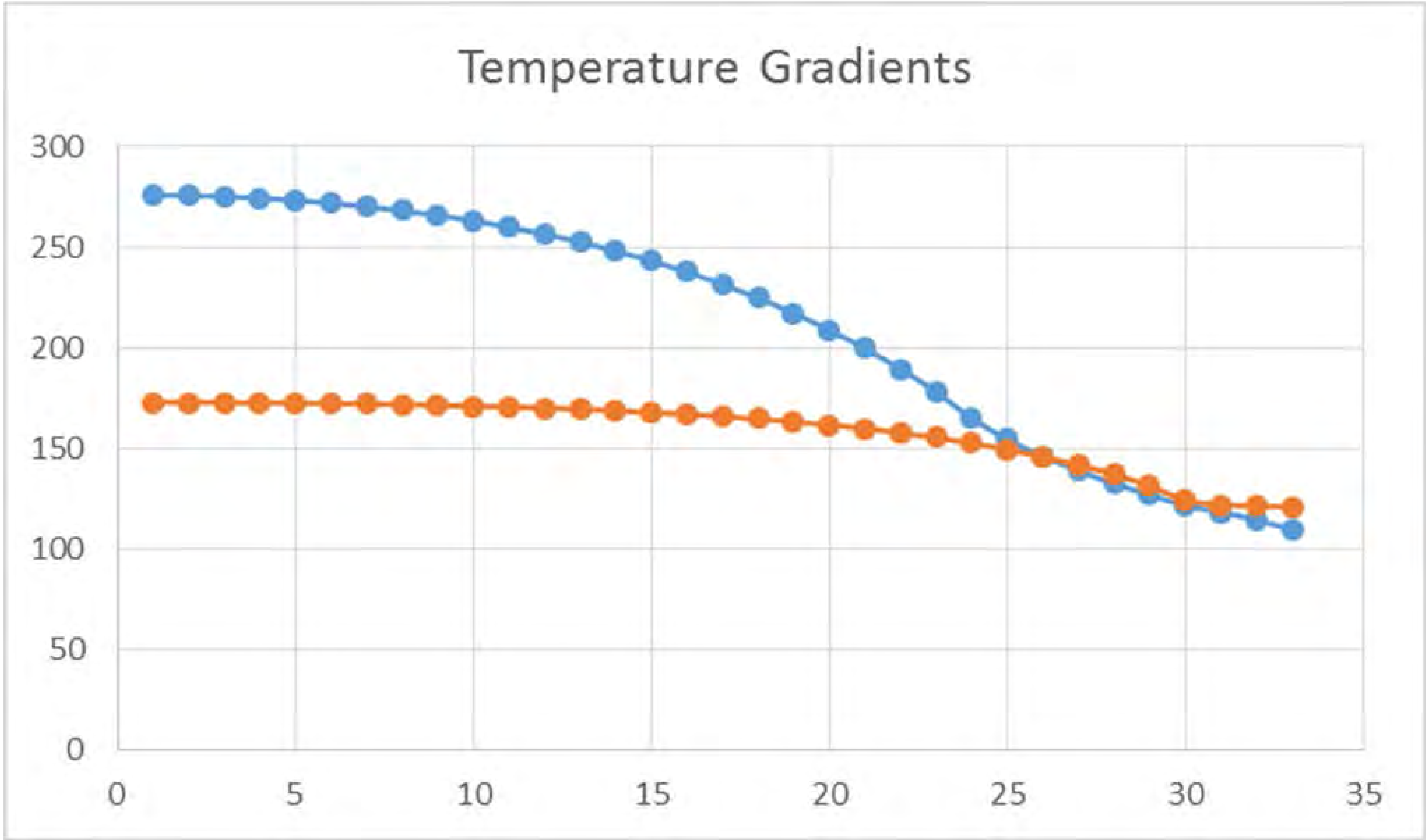
Structural silicone glazing (blue)

Aluminum frame (red)

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Glass stress is approximated by:

Stress = E x Alpha x Delta T

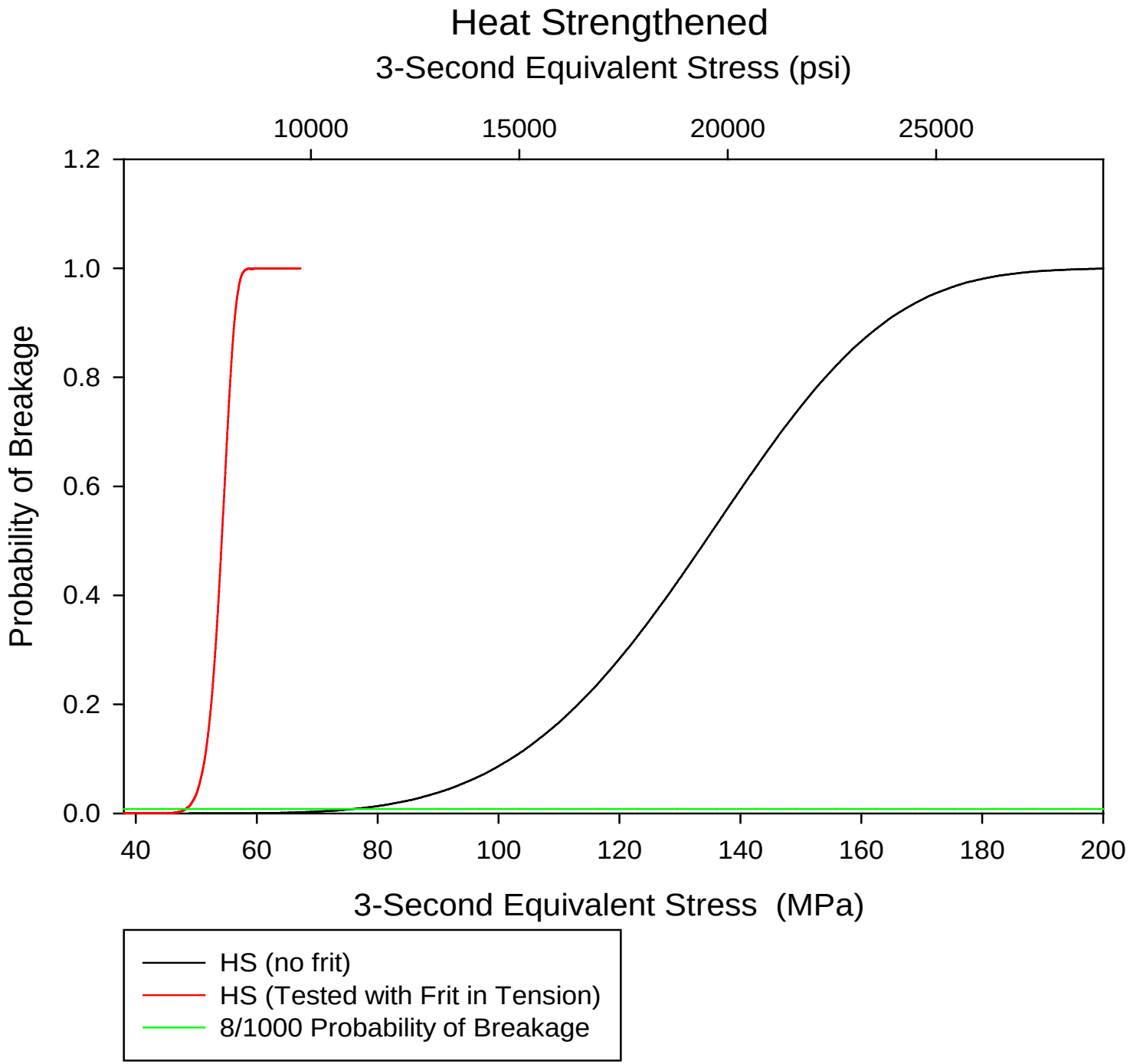
Where: E = Glass Modulus of Elasticity

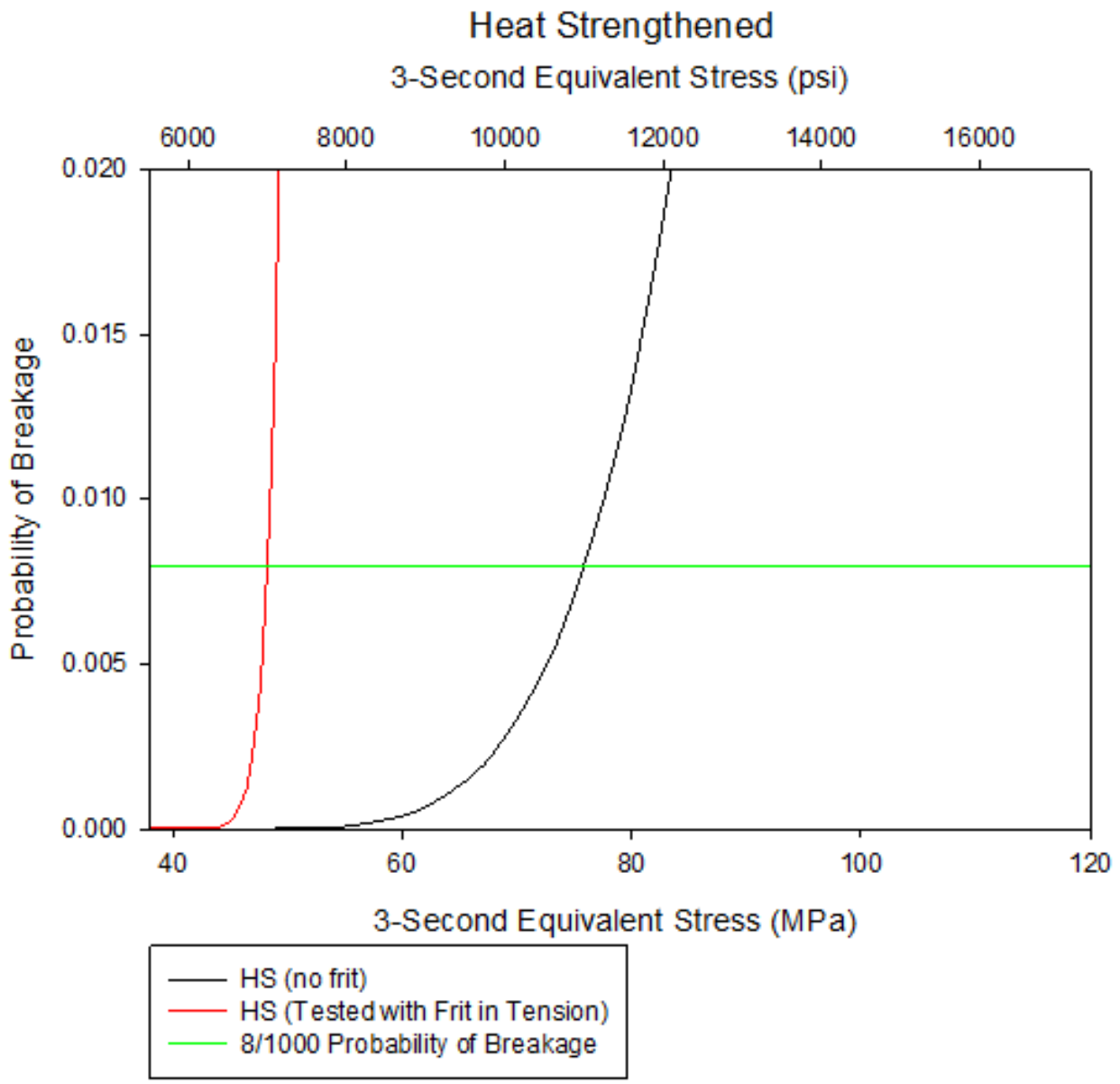
Alpha = Coefficient of Thermal Expansion

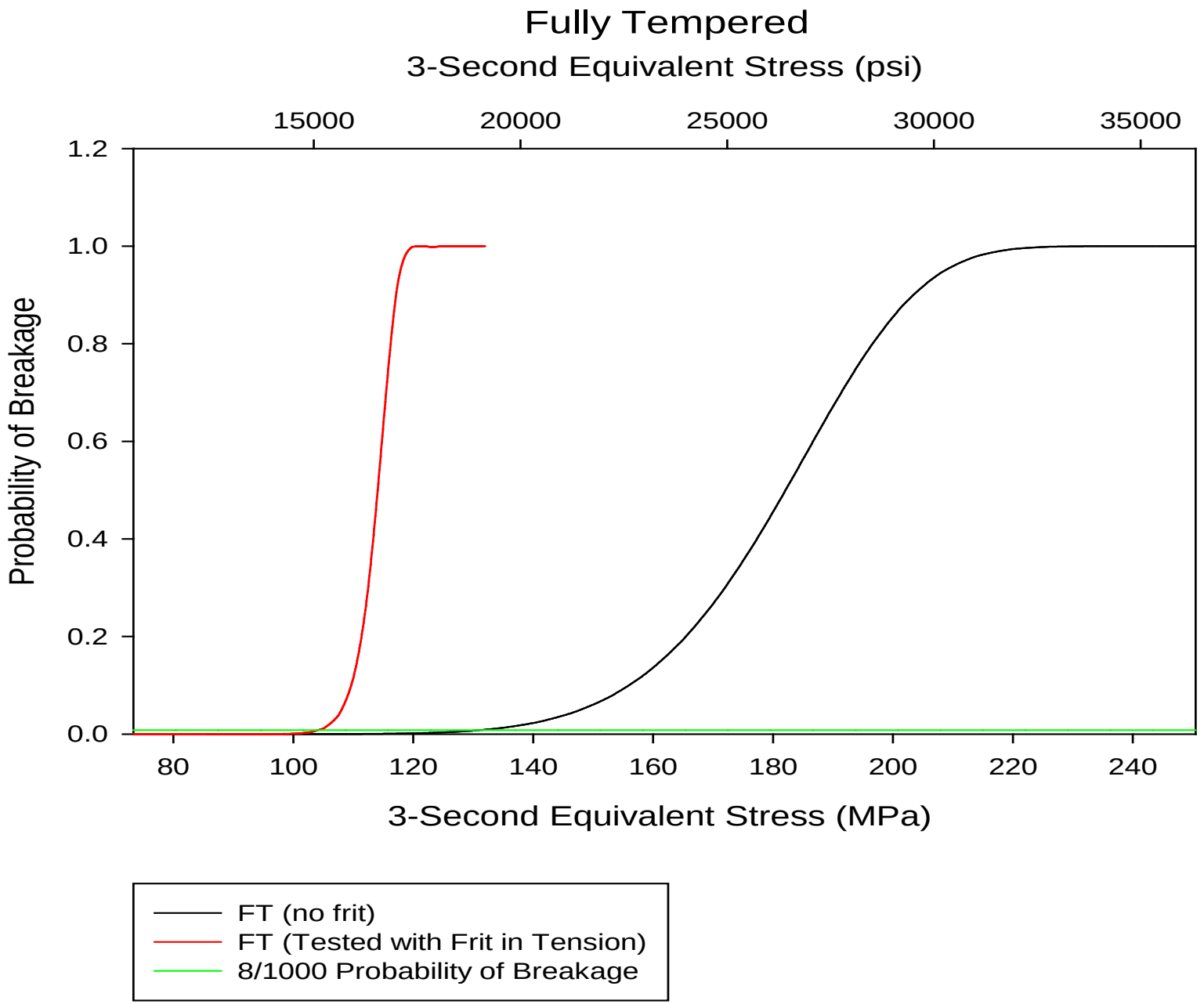
Delta T = Temperature difference

10.4E6 x 4.6E-6 x (270 – 120) = 7,176 psi

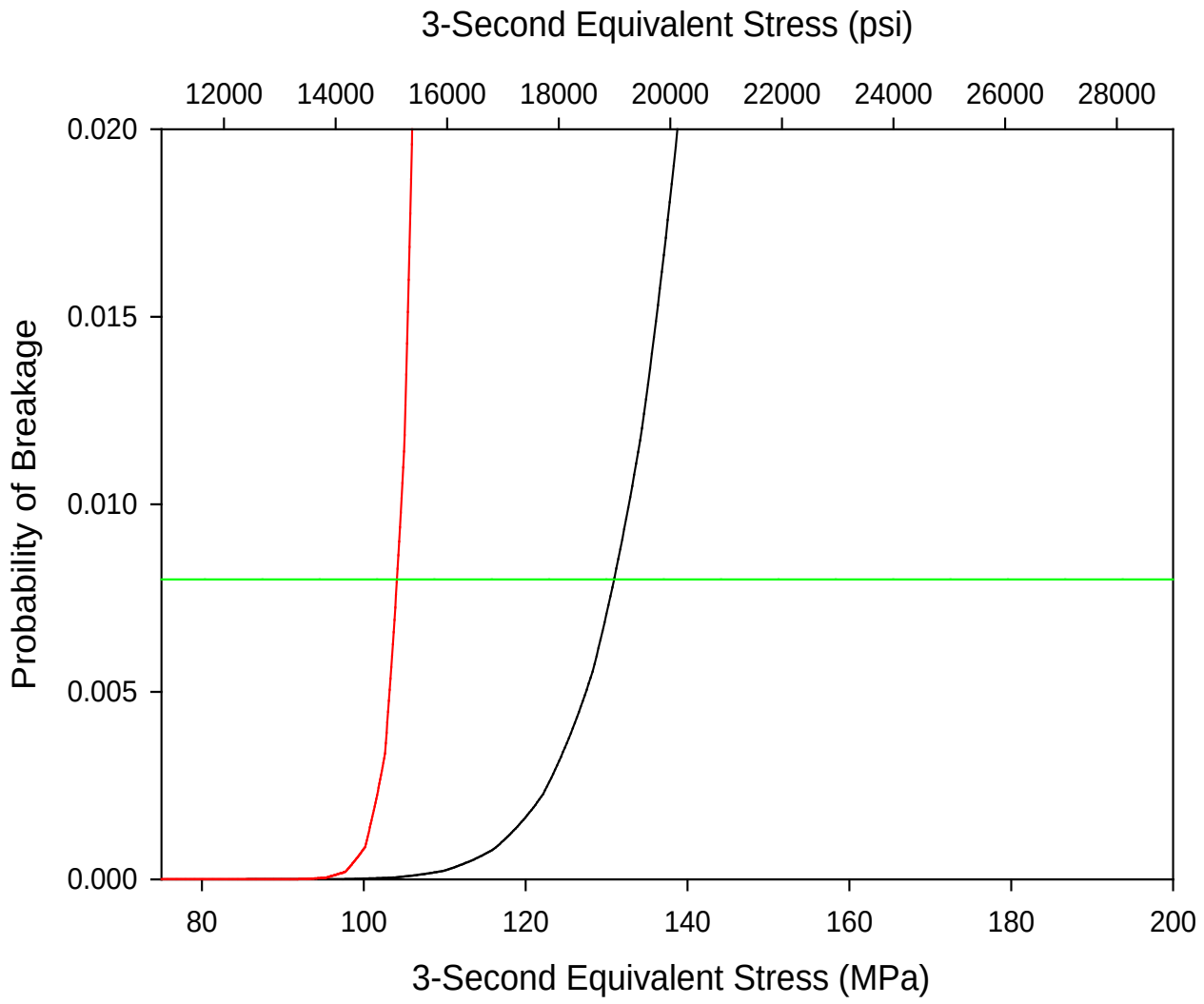
STRENGTH TESTS OF HT ENAMELED GLASS


Heat Strengthened
3-Second Equivalent Stress (psi)
10000
15000
20000
25000
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Probability of Breakage
40
60
80
100
120
140
160
180
200
3-Second Equivalent Stress (MPa)
HS (no frit)
HS (Tested with Frit in Tension)
8/1000 Probability of Breakage


Heat Strengthened
3-Second Equivalent Stress (psi)
6000
8000
10000
12000
14000
16000
0.020
0.015
0.010
0.005
0.000
Probability of Breakage
40
60
80
100
120
3-Second Equivalent Stress (MPa)
HS (no frit)
HS (Tested with Frit in Tension)
8/1000 Probability of Breakage


Fully Tempered
3-Second Equivalent Stress (psi)
15000
20000
25000
30000
35000
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Probability of Breakage
80
100
120
140
160
180
200
220
240
3-Second Equivalent Stress (MPa)
FT (no frit)
FT (Tested with Frit in Tension)
8/1000 Probability of Breakage

Fully Tempered



How Much Weakening?

HS Mean Strength – >50%

HS 8/1000 Design Strength – 36%

FT Mean Strength – 35%

FT 8/1000 Design Strength – 21%

EN and DIN 18008 HS – 36%

EN and DIN 18008 FT – 38%

HOW CAN CERAMIC ENAMEL WEAKEN HT GLASS?

- Inhomogeneous enamel has less strength than homogenous float glass
- Crack starting at lower stress in weaker enamel propagates into the intimately bonded glass
- Enamel with higher modulus of elasticity would be more stressed than the substrate glass when bent
- Chemically or mechanically, the frit damages the glass surface
- Enamel with a different emissivity than plain glass would alter the heat flow during quenching

CONSEQUENCES OF STRENGTH REDUCTION

- Reduced load capacity for thermal stresses
- Reduced wind load capacity (bending stress)
- Possible Reduced impact load resistance.

Note: No glass breakage has been reported in service for HT glass with ceramic enamel under wind or impact load

Conclusions

- Reduced glass strength in ceramic enameled HT glass in spandrel glass breakage and in laboratory bending tests
- Potential strength reductions for enameled HT glass under wind loads and impact loads
- Potential strength reduction for re-annealed enameled bent glass

RECOMMENDATIONS

- Do not use ceramic enameled HS glass in IG insulated Spandrels
- Consider FT glass for the enameled lite of an IG spandrel
- Consider Heat Soaking FT enameled glass
- Consider opacifying #4 surface with water based silicone
- Reduce allowable max stress (both from uniform wind or snow load, and thermal loads) by about 40 % with ceramic enamel on HT glass, unless other test data is available.
- Check impact performance of enameled FT Safety Glass
- Check the strength of re-annealed bent enameled glass