NGA GLASS CONFERENCE™
ISLE OF PALMS | CHARLESTON

FEBRUARY 5-8, 2024

NGA
NATIONAL GLASS ASSOCIATION with GANA

A Proposed Method for Predicting the Load Resistance of a Particular Type of Ceramic Enamel Coated Glass

A. William Lingnell, P.E.
Lingnell Consulting Services

Background

- ASTM E1300 *"Standard Practice for Determining Load Resistance of Glass in Buildings"*
  - *Conservative glass thickness selection procedure*
    - *Flat glass*
    - *Uniform pressure loads*
- *All published problems with ceramic enameled glass*
  - *Thermal stress*
  - *Heat Strengthened*
- *No published problems with ceramic enameled glass*
  - *Uniform pressure loads*
  - *Fully Tempered*

Proposed Modifications to ASTM E1300 for Ceramic Enameled Glass

- Calls for strength reduction factor
- Based on comparison of uncoated vs ceramic enameled glass
  - Mean strengths
  - Freshly Manufactured
- The strength of **freshly manufactured** ceramic enameled glass is less than the strength of **freshly manufactured** uncoated clear glass
  - Assuming same type and geometry
- ASTM E1300 recommendations are based on strength of **in-service** glass and not the strength of **freshly manufactured** glass
- No clear evidence for need to modify ASTM E1300 for use with ceramic enameled glass

Proposed Modifications to ASTM E1300 for Ceramic Enameled Glass

- Added note on ceramic enamel coatings
  - States ceramic enamel coatings are known to affect glass load resistance
  - Contact glass manufacturer for guidance on specific products

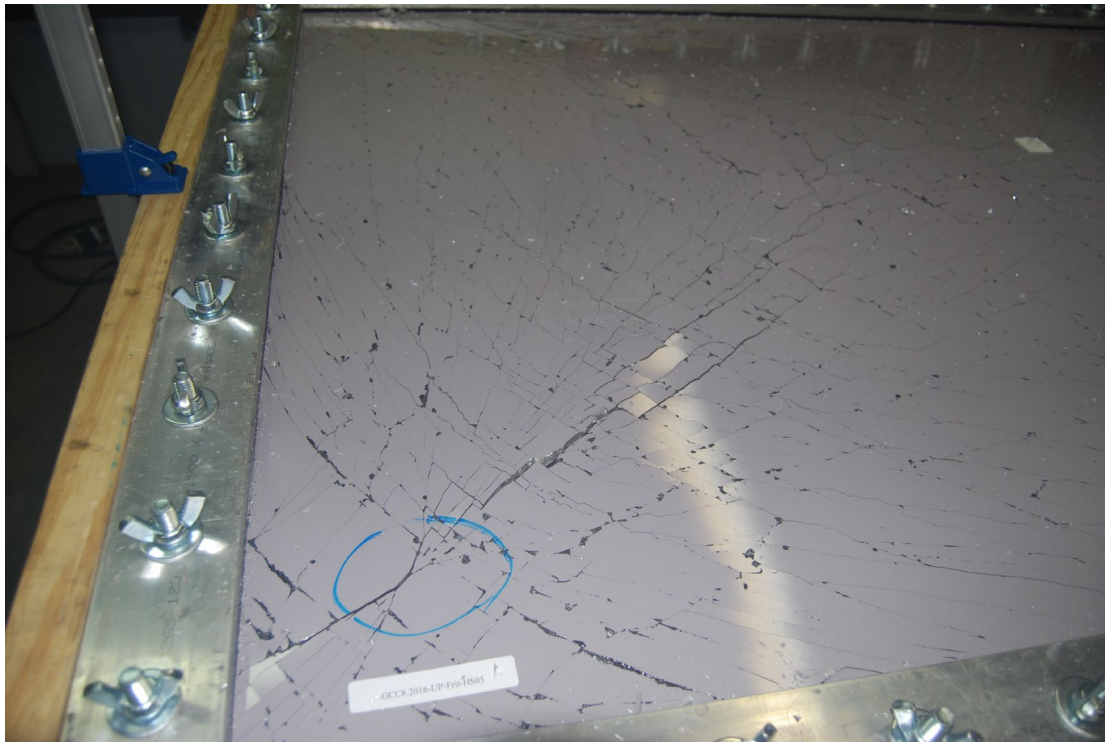
What Now…

- The direct way to evaluate the applicability of ASTM E1300 to ceramic enamel glass is compare
  - Measured loads on full-scale ceramic enameled glass plates
  - Design loads predicted by ASTM E1300

Full-Scale Ceramic Enameled Glass Plate Tests

- 1,016 mm X 1,524 mm X 6-mm (40” X 60” X ¼”) Specimens
  - Set of 10 uncoated glass plates
    - Freshly Manufactured
    - Heat Strengthened
  - Set of 10 ceramic enameled glass plates
    - Light grey
    - Roll-coater applied
    - 4-5 mils wet film
    - Full-flood coverage
    - Heat Strengthened
- Provided by Glass Coatings & Concepts, LLC
- Tested by Beason Brackin & Associate, LLC

Full-Scale Ceramic Enameled Glass Plate Tests



Full-Scale Ceramic Enameled Glass Plate Tests

	Mean 3-sec Breakage Load	COV of 3-sec Breakage Load	Probability of Breakage Design Load	Design Load Greater Than Required by ASTM E1300
Uncoated Glass	24 KPa (501 psf)	8.1%	19.3 KPa (403 psf)	3.66 X
Ceramic Enamel Glass	13.8 KPa (288 psf)	2.9%	12.8 KPa (268 psf)	2.44 X

However…

- Testing full-scale glass plates
  - Challenging
  - Expensive
  - Unnecessary
- Testing smaller glass beams
  - Conservatively compares to full-scale test data
  - Represents the strength of ceramic enamel coated glass
- Both methods show an approximate 40% reduction in strength compared to freshly-manufactured, uncoated clear glass

Proposed Design Procedure for Ceramic Enamel Glass

- Rational evaluation procedure for ceramic enamel coated glass
- Employs the use of
  - Simple four-point beam tests
  - Common load-duration corrections
  - Standard normal statistical applications
  - ASTM E1300

Proposed Design Procedure for Ceramic Enamel Glass

- STEP 1: Select representative specimens
- STEP 2: Measure RCSS of each specimen
- STEP 3: Subject specimens to four-point bend tests
- STEP 4: Calculate net breakage stress for each specimen
- STEP 5: Adjust stress data for 3-sec load duration
- STEP 6: Calculate mean and standard deviation for 3-sec stress data
- STEP 7: Determine the net design stress for 8 lites per 1,000 breakage probability and 3-sec load duration
- STEP 8: Calculate the design stress by adding the net design stress (Step 7) to RCSS (Step 2)

Proposed Design Procedure for Ceramic Enamel Glass

- STEP 9: Determine the design pressure for specific glass plate
  - Geometrically non-linear plate analysis
  - Design stress (Step 8)
- STEP 10: Use ASTM E1300 to determine design pressure
  - Uncoated clear glass plate
- STEP 11: Take the lowest design pressure from beam tests (Step 9) and ASTM E1300 (Step 10)

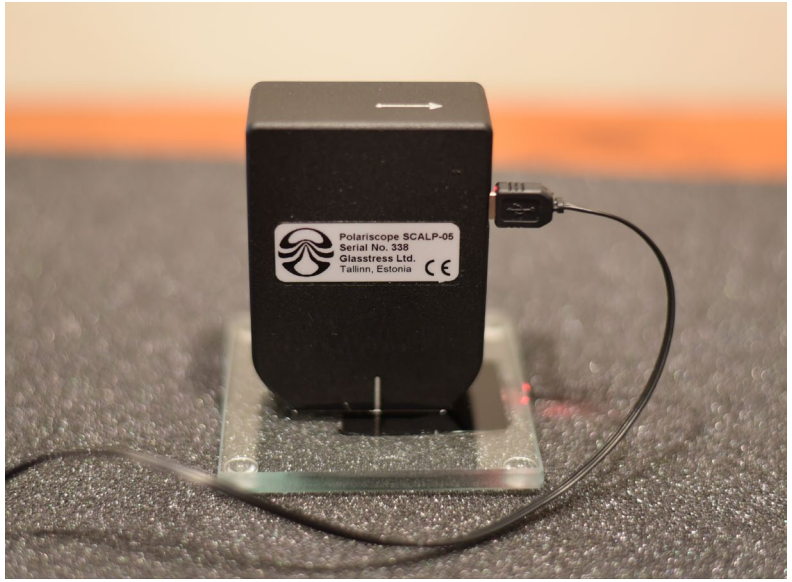
STEP 1: Select Representative Specimens

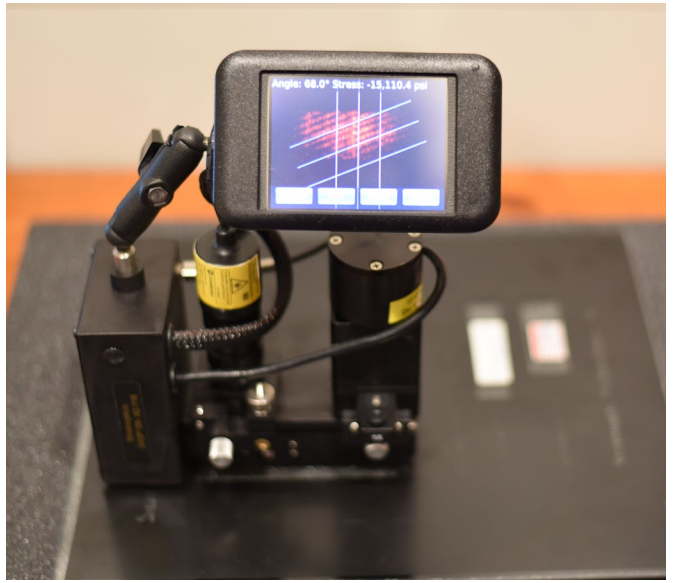
- Example of ceramic enamel glass beams
  - 305 mm X 610 mm X 6-mm (12 x 24 x ¼ in.)
  - Full-flood coverage
  - 4-5 mil wet film
  - Roll-coater applied
  - Heat Strengthened

STEP 2: Measure RCSS of each specimen

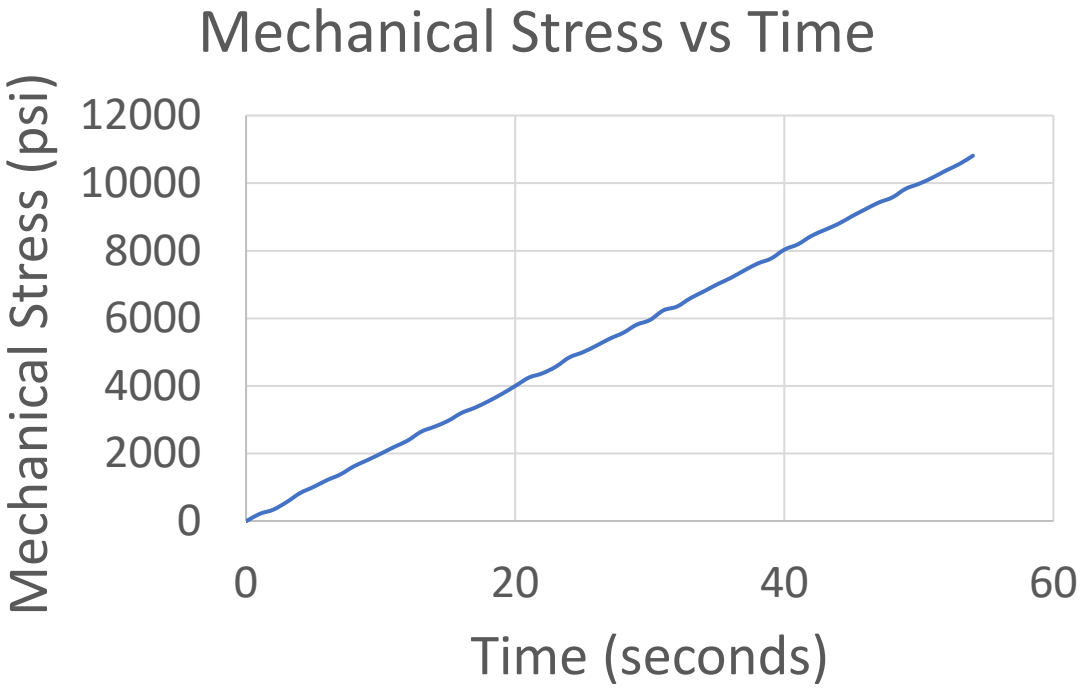
- *Determine the Mean Residual Compressive Surface Stress (RCSS)*

$$\sigma_{RCSS} = 45.5\ MPa\ (6{,}595\ PSI)$$

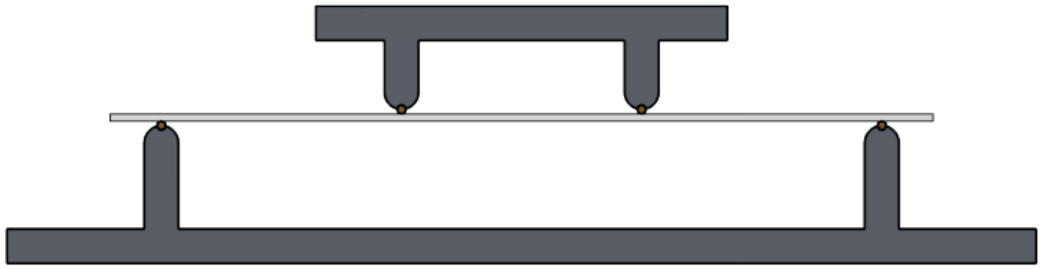




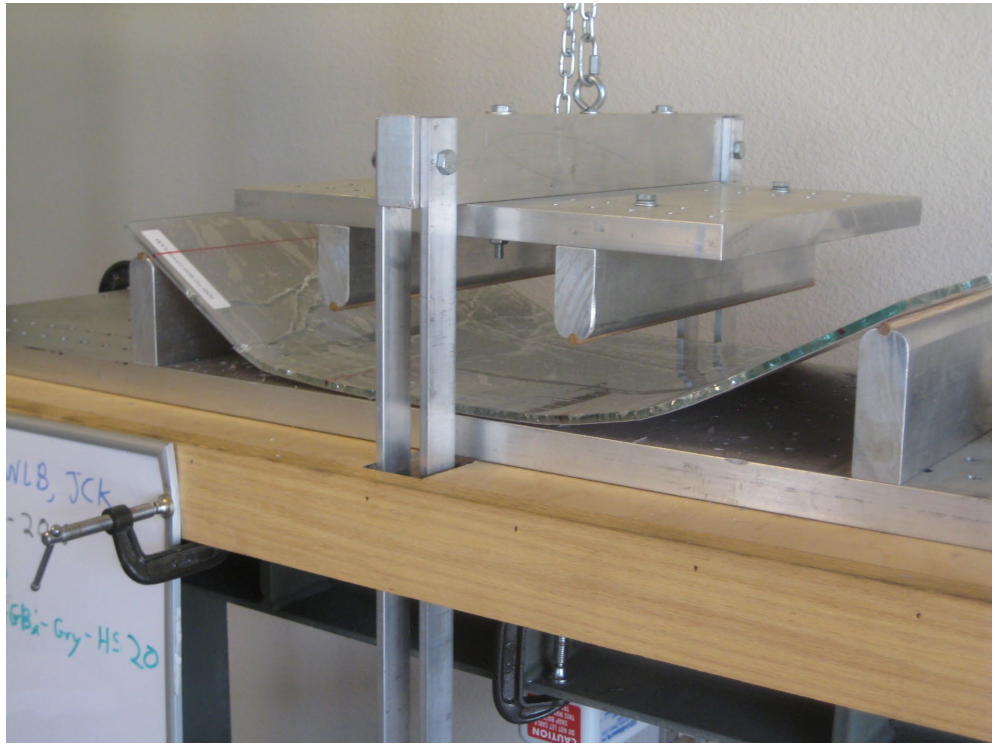
STEP 3: Subject specimens to four-point bend tests

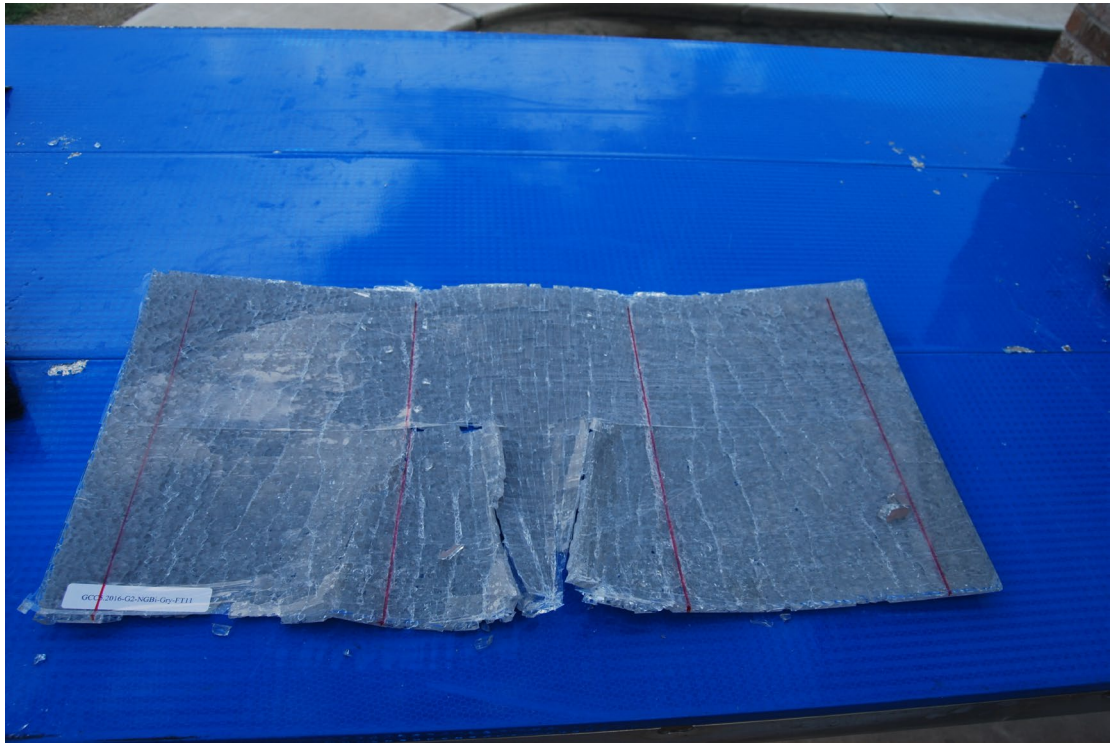


- This testing results in a mechanical stress, $\sigma(t)$, vs time, t, relationship up to the point of failure.



STEP 3: Subject specimens to four-point bend tests





STEP 4: Calculate net breakage stress for each specimen

- Calculate net tensile breakage stress for each specimen

$$\sigma_{net}(t) = \sigma_{BR}(t) - \sigma_{RCSS}$$

- Here σ_{BR} could also be called “mechanical stress”

STEP 5: Adjust Measured Stress Data for 3-sec Load Duration Equivalent Failure Stress

- Calculate net 3-sec equivalent failure stress

$$\sigma_{net_{3\ sec}} = \left[\frac{\int_0^{t_f}[\sigma_{net}(t)]^n dt}{3}\right]^{1/16}$$

- σ_{net} is taken to be zero if it is less than zero
- In no case, so far, has a ceramic enamel glass beam failed at a stress level that is less than the measured RCSS
- No risk of failure until the mechanical stress exceeds the RCSS and the surface of the glass is subjected to tension.

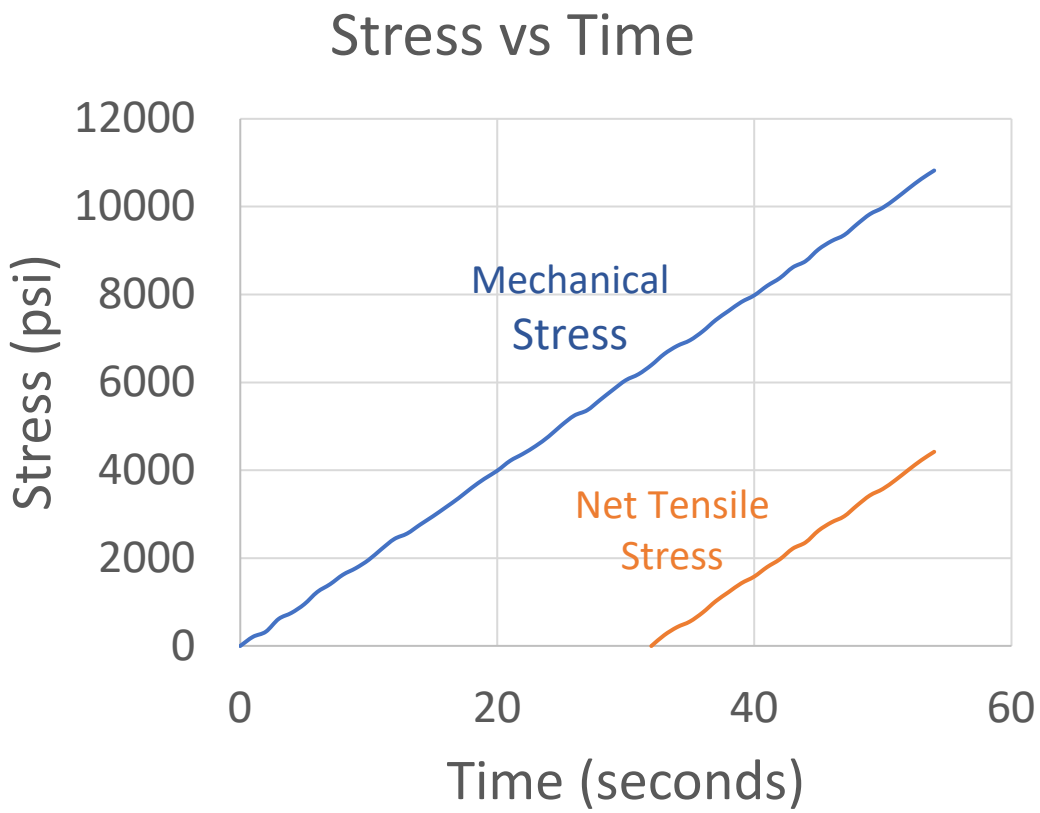
STEP 5: Adjust Measured Stress Data for 3-sec Load Duration Equivalent Failure Stress

- Remember the net tensile stress value is found by subtracting the RCSS from the mechanical stress

$$\sigma_{net} = \sigma_{BR} - \sigma_{RCSS}$$

- It is the net tensile stress variation with time and the RCSS which control the behavior of the glass
- The 3-sec duration equivalent mechanical failure stress is determined by adding back the RCSS as follows.

$$\sigma_{3\ sec} = \sigma_{net_{3\ sec}} + RCSS$$



STEP 6: Calculate Mean and Standard Deviation for 3-sec Stress Data

- Summary of 3-sec load duration mechanical stress results
  - N = 20
  - Mean = 75.7 MPa (10,973 psi)
  - Standard Dev = 2.96 MPa (429 psi)
  - COV = 3.9%
- Summary of 3-sec load duration net tensile stress results
  - N = 20
  - Mean = 30.2 MPa (4,378 psi)
  - Standard Dev = 2.96 MPa (429 psi)
  - COV = 9.8%

STEP 6: Calculate Mean and Standard Deviation for 3-sec Stress Data

- Note the mean RCSS plus the mean net 3-second duration stress is equal to the mean of the 3-second duration mechanical stress as follows:

$$45.5\ MPa\ (6{,}595\ PSI) + 30.2\ \text{MPa (4,378 psi)} = 75.7\ \text{MPa (10,973 psi)}$$

STEP 7: Determine the Net Design Stress for 8 Lites Per 1,000 Breakage Probability and 3-sec Load Duration

- The 3-sec load duration strength of ceramic enamel glass is controlled
  - RCSS
  - Variability associated 3-sec net tensile stress values
- Symmetrical normal distribution
  - Design stress corresponding to 8 lites per 1000 probability of breakage
  - Universally accepted
  - Fit examined with seven statistical tests

STEP 7: Determine the Net Design Stress for 8 Lites Per 1,000 Breakage Probability and 3-sec Load Duration

- The 8/1000 probability of failure stress-over design value

$$\sigma_{net_{3\ sec}} = 30.2 \text{ MPa (4,378 psi)} - 2.41\ x\ 2.96 \text{ MPa (429 psi)}$$

23.1 MPa (3,346 psi)

STEP 8: Calculate the Design Stress

- The 3-second duration mechanical design stress, σ_Design, is found by adding the RCSS to the 8/1000 probability of failure stress-over design value as follows:

$$\sigma_{Design} = 45.5\ MPa\ (6{,}599\ psi) + 23.1\ MPa\ (3{,}346\ psi)$$

$$68.6\ MPa\ (9{,}945\ psi)$$

STEP 8: Calculate the Design Stress

- ASTM E1300 provides a conservative allowable design stress
  - Corresponds to 8/1000 probability of breakage
  - Special glass shapes
  - Loads not covered

$$\sigma_{HS_{Design}} = 46.5\ MPa\ (6{,}750\ psi)$$

- Measured 8/1000 design load for 3-sec load duration for ceramic enamel glass is 47.3% greater than ASTM E1300 allowable stress

$$47.3\% = \frac{9{,}945\ psi - 6{,}750\ psi}{6{,}750\ psi}$$

$$47.3\% = \frac{68.6\ MPa - 46.5\ MPa}{46.5\ MPa}$$

STEP 9: Determine the Design Pressure for Specific Glass Plate

- Geometrically non-linear plate analysis
  - 1,016 mm X 1,524 mm X 6-mm (40” X 60” X ¼”)
  - Four sides simply supported
- Design stress from Step 8
  - $68.6\ MPa\ (9{,}945\ psi)$

$$9.72\ KPa\ (203\ psf)$$

STEP 10: Use ASTM E1300 to Determine Design Pressure

- Uncoated, clear glass
  - 1,016 mm X 1,524 mm X 6-mm (40” X 60” X ¼”)
  - Four sides simply supported

$$5.27\ KPa\ (110\ psf)$$

STEP 11: Take the Lowest Design Pressure from Beam Tests and ASTM E1300

- Glass beams

Width	Height	ASTM E1300 Load Resistance	Ceramic Enamel Load Resistance	Design Load Greater Than Required by ASTM E1300
305 mm (12 in.)	610 mm (24 in.)	5.27 KPa (110 psf)	9.72 KPa (203 PSF)	1.85 X

- Full-scale glass plates

Width	Height	ASTM E1300 Load Resistance	Ceramic Enamel Load Resistance	Design Load Greater Than Required by ASTM E1300
1,524 mm (60 in.)	1,016 mm (40 in.)	5.27 KPa (110 psf)	13.8 KPa (288 PSF)	2.62 X

Thank you!

A. William Lingnell, P.E.
Lingnell Consulting Services