Designing with Structural Glass

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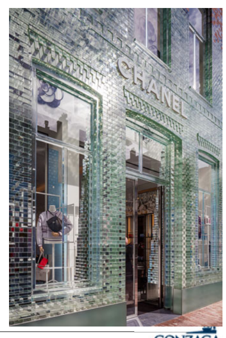
Overview

- A bit about Glass
- Glass design over the past century
- Use of Glass in buildings today
- How is Glass designed for use in buildings
  - Basic Method Overview
  - Analytical Method Overview
  - Analytical Method vs. Basic Method
- Ongoing and Future Research



A bit about Glass

A brittle material,
Fractures at relatively low tensile stresses,

Common Glass Material Properties *(Soda-Lime)*

- Young's Modulus, $E = 10.4 \times 10^6$ psi (71.7×10^9 Pa)
- Poisson's Ratio, $\nu = 0.22$ (0.21 to 0.26)
- Density, $\rho = 156$ lbm/ft^3 (2500 kg/m^3)

Glass design over the past century

- Limited primarily windows
  - Before 1950s - specified by the manufacturer
  - 1950s to 1980s - empirical models based on a limited number of specimens
  - 1980s to now – probabilistic methods

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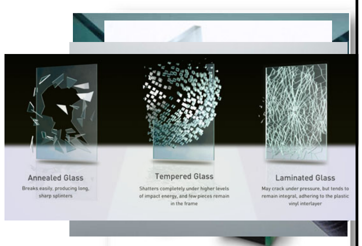
Use of Glass in buildings today

Windows and cladding

- Glazing construction types
  - Single glazed
  - Insulating glass units
- Laminated glass
- Strengthened glass
  - Heat treatment
  - Chemically strengthened



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Architectural Glass

- Typically limited to glass infill panels that transparently separate the interior and exterior, e.g. windows, skylights
- Designed to resist self weight and environmental loads

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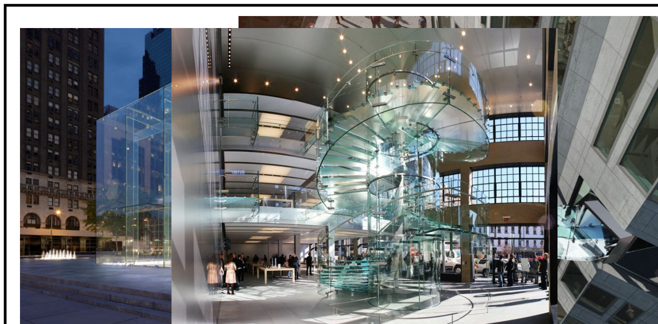
The Shard, London The Spheres, Seattle The Farm, Netherlands

Structural Glass

- Includes glass components that resist the loads from other building components, e.g. beam, and/or resist occupant live loads in addition to self weight and environmental loads
- Surface flaws are primary source of failure, not necessarily point of highest stress.
- Need to use statistical modeling to obtain EFL via GFPM

$$\text{DESIGN FACTOR} = \frac{\text{AVERAGE BREAKING STRESS}}{\text{STRESS CORESPONDING TO MAXIMUM ALLOWABLE BREAKING PROBABILITY}}$$

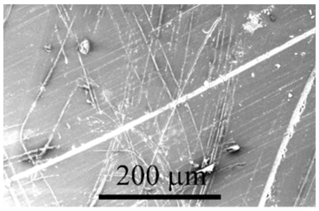


Apple Store, New York Apple Store, Boston Glass SkySlide, Los Angeles

How is Glass designed for use in buildings

What causes the Fractures at relatively low tensile stresses?

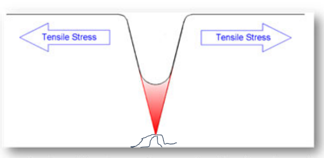
Surface Flaws



Naturally occur as glass solidifies

How is Glass designed for use in buildings

Surface Flaw Geometry



As tensile stress is applied to the flaw tip, the radius decreases magnifying the stress at the tip, resulting in breakage

Codes and standards

- New York City Building Code

Latest version, based on: IBC "International Building Code, 2016"

- ASCE 7

"Minimum Design Loads for Buildings and Other Structures."

- ASTM E 1300

"Standard practice for determining load resistance of glass in buildings."

- AS 1288 Standards Australia.

"Glass in Buildings Selection and Installation."

- SEI/ASCE 8-02 – for fittings

"Specifications for Design of Cold Formed Stainless Steel Structural Members."

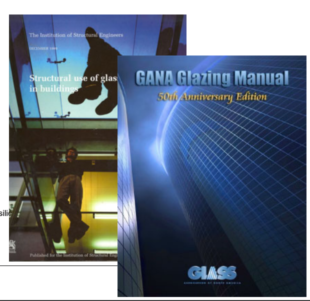
- AISC – for fittings

"Specifications for Design, Fabrication and Erection of Structural Steel."

- Dow Corning Manual / ETA Rule – for structural sili

(European Technical Approval)

- TRLV 2006 German Glass Standard



ASTM E1300

- **Standard Practice for Determining Load Resistance of Glass in Buildings**
  - **Uniform lateral load**
  - Applies to **monolithic** and **laminated** glass constructions of **rectangular shape** with continuous lateral support along **one, two, three**, or **four edges**
  - Applies to **insulating glass units** with **four-sided** edge support
  - **Does not apply** to, *balustrades, glass floor panels, aquariums, structural glass members, and glass shelves*
  - **Does not apply** to any form of *wired, patterned, etched, sandblasted, drilled, notched, or grooved glass with surface and edge treatments that alter the glass strength.*

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Original Procedure

Basic Procedure *(Section 6.2)*

- Determine non-factored load from charts
  - Monolithic glass or laminated glass (PVB)
  - Thickness
  - # of supported edges
- Factor NFL
  - Glass type
  - Load duration
  - IGU configuration
  - IGU load sharing

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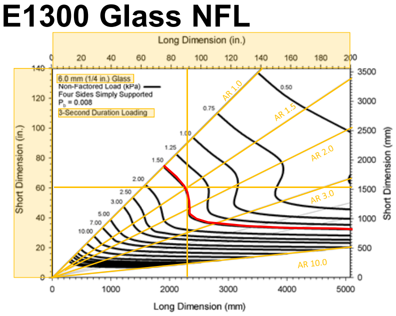
ASTM E1300 Glass NFL Chart



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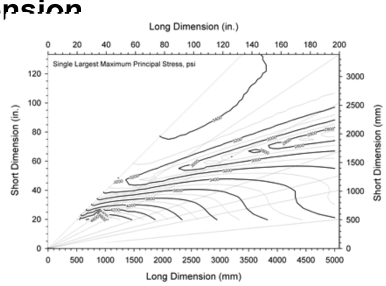
Variation of SLMPS with Rect. Dimension



Basic Procedure

- Heat-Treated
  - Heat-strengthened 31.3 psf X 2.0 = 63 psf
  - Fully Tempered 31.3 psf X 4.0 = 125 psf
- Duration factors combined with glass type factors
- Separate Charts for Laminated Glass (PVB only)
- Simple load share model *“cubed thickness”*
  - *Lites in symmetric IGUs share load equally*
  - *Not a function of construction orientation*

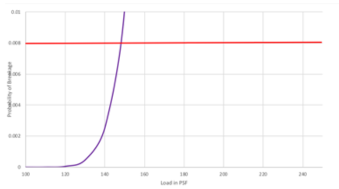
New Analytical Procedure

Analytical Procedure *(Section 6.3)*

- Limited to 4 sides supported, *currently*
- Directly uses the glass failure prediction model (GFPM)
- Incorporates residual compressive surface stress (RCSS) into the GFPM for heat treated glass.
- Provides procedures for *asymmetric* laminated glass (thickness and glass type)
- Allows for interlayer types *other* than PVB
- Requires methods based on the *ideal gas law* to determine the load sharing of lite comprising insulating glass units

New Analytical Procedure

Probability of Breakage must be < = 0.008 (8/1000) for all lites



E1300 - Glass Failure Prediction Model

$P_b = 1 - e^{-B}$ >= 0.008

$$B = k \cdot \sum_{i=1}^{N} \left(\left[c_i \cdot \left(\frac{t_d}{60} \right)^{\frac{1}{n}} \cdot \left(\bar{\sigma}_{\max_i} - RCSS \right) \right]^m \cdot A_i \right)$$

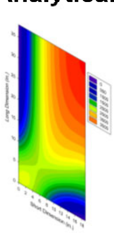
Same procedure used to create the Basic Method NFL charts

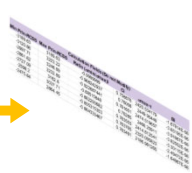
$$c_i = -0.005 \cdot r_i^6 + 0.022 \cdot r_i^5 + 0.055 \cdot r_i^4 + 0.039 \cdot r_i^3 + 0.031 \cdot r_i^2 + 0.06 \cdot r_i + 0.8$$

$$r_i = \frac{\left(\sigma_{\min_i} - RCSS \right)}{\left(\sigma_{\max_i} - RCSS \right)}$$

Values determined using numerical analysis

Analytical Procedure - Monolithic Glass





≤ 0.008 ✓

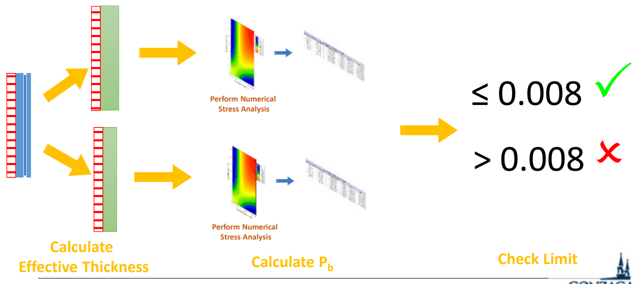
> 0.008 ✗

Perform Numerical Stress Analysis

Calculate P_b

Check Limit

Analytical Procedure – Laminated Glass



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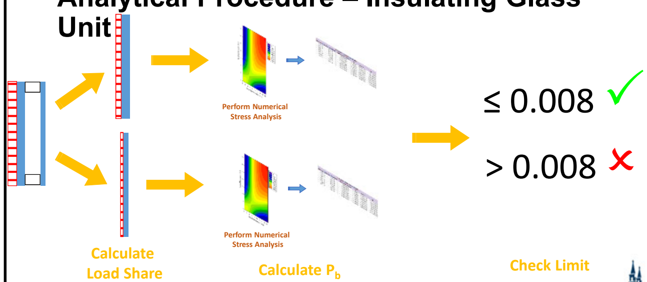
Analytical Procedure – Insulating Glass Unit



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Analytical Procedure Examples

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Monolithic Glass Example

- Geometry
  - Rectangular Lite, 38in. X 76in. X 1/4 in.
- Glass Properties
  - E = 10.4 x 10^{6} psi, ν = 0.22
  - m = 7; k = -1.365 x 10^{-29} (60s)
- Uniform Lateral load,
  - P = 40 psf, 3s duration
- Model Boundary Conditions
  - Simply Support on all edges
    - Lateral displacement = 0
    - In plane displacements and edge rotations unrestrained

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Monolithic Glass Example

- Perform stress analysis
- Use BFRM to calculate probability of breakage $P_b = 1 - e^{-B} = 6.48$ x 10^{-3}

Long dimension nodal coordinates, in.	Maximum principal stress, psi							
	Short dimension nodal coordinates, in.							
	0.0	2.7	5.4	8.1	10.9	13.6	16.3	19.0
0.0	3.81E-07	7.14E-07	3.01E-07	5.16E-08	3.15E-09	3.86E-11	9.91E-15	0.00E+00
2.7	7.61E-07	1.81E-06	1.14E-06	4.44E-07	1.18E-07	2.44E-08	5.29E-09	1.26E-09
5.4	4.07E-07	1.41E-06	1.63E-06	1.29E-06	7.68E-07	4.04E-07	2.31E-07	9.16E-08
8.1	1.19E-07	8.22E-07	1.83E-06	2.51E-06	2.44E-06	1.99E-06	1.61E-06	7.40E-07
10.9	2.13E-08	4.09E-07	1.78E-06	3.86E-06	5.24E-06	5.52E-06	5.29E-06	2.57E-06
13.6	2.53E-09	1.97E-07	1.66E-06	5.20E-06	8.99E-06	1.12E-05	1.19E-05	6.04E-06
16.3	2.15E-10	1.02E-07	1.55E-06	6.45E-06	1.33E-05	1.86E-05	2.13E-05	1.10E-05
19.0	1.42E-11	5.99E-08	1.47E-06	7.50E-06	1.76E-05	2.70E-05	3.26E-05	1.71E-05
21.7	7.60E-13	4.02E-08	1.41E-06	8.34E-06	2.16E-05	3.55E-05	4.47E-05	2.40E-05
24.4	3.19E-14	3.01E-08	1.36E-06	9.01E-06	2.51E-05	4.36E-05	5.69E-05	3.08E-05
27.1	9.05E-16	2.45E-08	1.34E-06	9.55E-06	2.82E-05	5.11E-05	6.89E-05	3.76E-05
29.9	1.22E-17	2.11E-08	1.32E-06	1.00E-05	3.08E-05	5.77E-05	7.96E-05	4.38E-05
32.6	3.58E-20	1.92E-08	1.31E-06	1.03E-05	3.28E-05	6.29E-05	8.82E-05	4.89E-05
35.3	2.03E-24	1.81E-08	1.31E-06	1.06E-05	3.41E-05	6.63E-05	9.39E-05	5.22E-05
38.0	0.00E+00	8.90E-09	6.55E-07	5.33E-06	1.73E-05	3.37E-05	4.79E-05	2.67E-05

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Laminated Glass Example

- Geometry
  - Rectangular Lite, 38in. X 76in. (1/8 in. | 0.03 PVB | 5/32 in.)
- Glass Properties
  - E = 10.4 x 10^{6} psi, ν = 0.22
  - m = 7; k = -1.365 x 10^{-29} (60s)
- Interlayer Properties
  - G = 61.9 psi
- Uniform Lateral load,
  - P = 50 psf, 3s duration
- Model Boundary Conditions
  - Simply Support on all edges
    - Lateral displacement = 0
    - In plane displacements and edge rotations unrestrained

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Laminated Glass Example

- Calculate the effective thickness for each glass ply
  - h_1,eff,σ = 0.255 in.
  - h_2,eff,σ = 0.241 in.
- Calculate the probability of breakage for each glass ply
  - pb_1 = 0.0071 < 0.008 Works
  - pb_2 = 0.011 > 0.008 Does not Work

This configuration does not work

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Laminated Glass Example

- Change a ply thickness, interlayer type or glass type
  - Ply 2 thickness = 0.180 in. (3/16 in.)
    - h_1,eff,σ = 0.292 in. → pb_1 = 0.0020 < 0.008 Works
    - h_2,eff,σ = 0.263 in. → pb_2 = 0.0056 < 0.008 Works
  - Interlayer G = 3800 psi
    - h_1,eff,σ = 0.290 in. → pb_1 = 0.0021 < 0.008 Works
    - h_2,eff,σ = 0.293 in. → pb_2 = 0.0018 < 0.008 Works
  - Ply 2 RCSS = 3500 psi
    - h_1,eff,σ = 0.256 in. → pb_1 = 0.0071 < 0.008 Works
    - h_2,eff,σ = 0.241 in. → pb_2 = 2.00×10^{-9} < 0.008 Works

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Insulating Glass Example

- Geometry
  - Rectangular Lite, 38in. X 76in. (5/32 in. | 1/2in AS | 5/32 in.)
- Glass Properties
  - E = 10.4×10^6 psi, ν = 0.22
  - m = 7; k = -1.365×10^{-29} (60s)
- Uniform Lateral load,
  - P = 50 psf, 3s duration
- Model Boundary Conditions
  - Simply Support on all edges
    - Lateral displacement = 0
    - In plane displacements and edge rotations unrestrained

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Insulating Glass Example

- Calculate the load carried by each glass ply
  - L_1 = 25.5 psf (50.9 %)
  - L_2 = 24.5 psf (49.1 %)
- Calculate the probability of breakage for each glass ply
  - pb_1 = 0.0048 < 0.008 Works
  - pb_2 = 0.0042 < 0.008 Works

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Comparison of Basic and Analytical results for select glazing constructions

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Select Glazing Constructions

- Monolithic
  - 1/4 in. – Annealed (RCSS = 0)
  - 1/4 in. – Heat-strengthened (RCSS = 3500 psi)
  - 1/4 in. – Fully-Tempered (RCSS = 10000 psi)
- Laminated
  - 1/8 in. | 0.060 in. PVB | 1/8 in.
  - 5/32 in. | 0.060 in. PVB | 5/32 in.
  - 1/8 in. | 0.060 in. PVB | 3/16 in.
- Insulating Glass Unit
  - 1/8 in. | 3/8 in. | 1/8 in.
  - 1/8 in. | 3/8 in. | 1/4 in.
  - 1/8 in. | 3/8 in. | 5/32 in. | 3/8 in. | 3/16 in.

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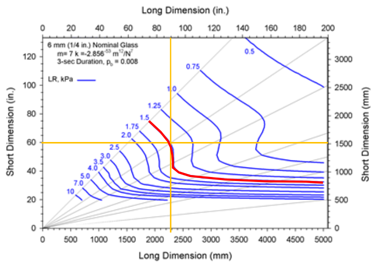
Monolithic ¼ in. – (RCSS = 0)



No Change

Analytical Procedure returns the same results as the NFL Charts

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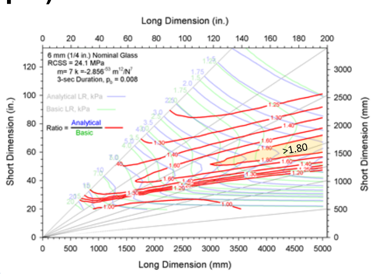
Monolithic ¼ in. – (RCSS = 3500 psi)



Ratios > 1.0 Indicate Analytical Method LR is larger than Basic Method

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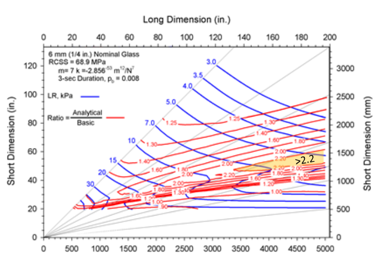
Monolithic ¼ in. – (RCSS = 10000 psi)



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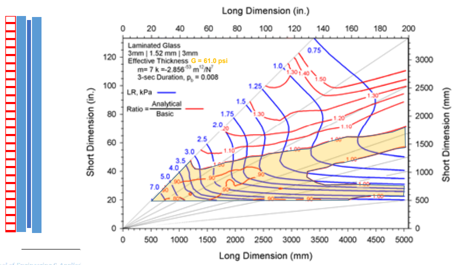
Laminated 1/8 in. | 0.060 in. PVB | 1/8 in.



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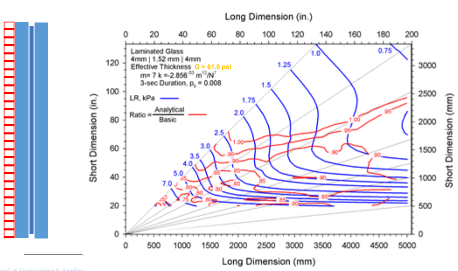
Laminated 5/32 in. | 0.060 in. PVB | 5/32 in.



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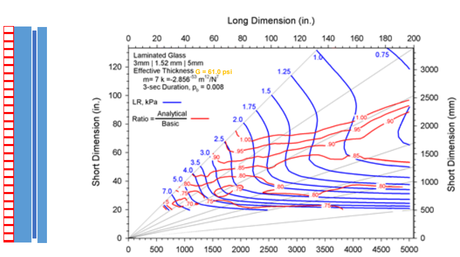
Laminated 1/8 in. | 0.060 in. PVB | 3/16 in.



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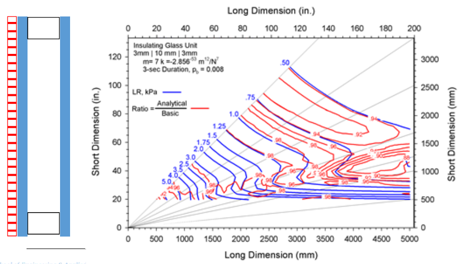
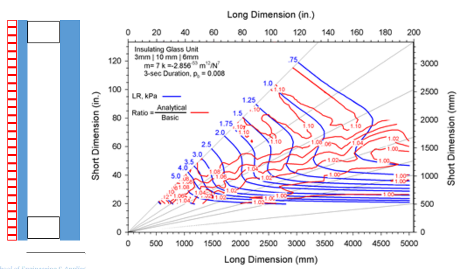
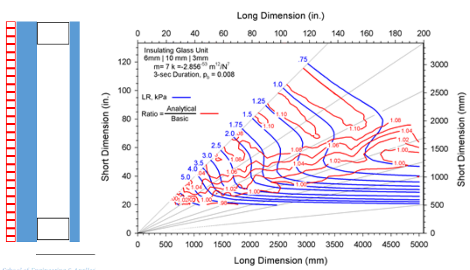
Insulating Glass Unit 1/8 in. | 3/8 in. | 1/8 in.



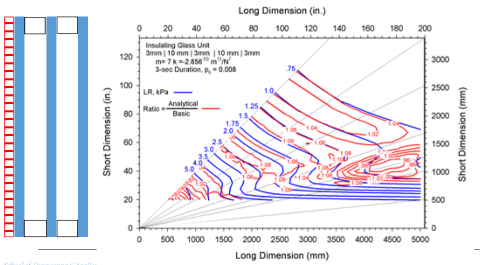
Insulating Glass Unit 1/8 in. | 3/8 in. | 1/4 in.



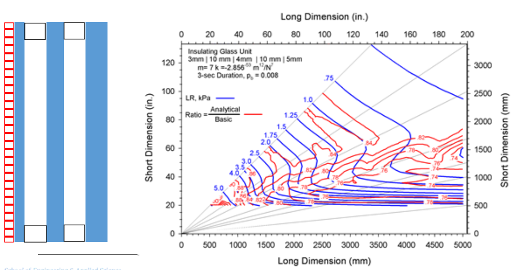
Insulating Glass Unit 1/4 in. | 3/8 in. | 1/8 in.



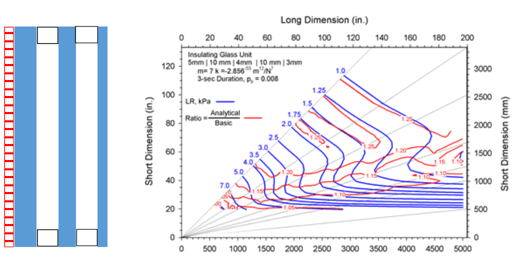
Insulating Glass Unit 1/8 in. | 3/8 in. | 5/32 in. | 3/8 in. | 3/16 in.



Insulating Glass Unit 1/8 in. | 3/8 in. | 5/32 in. | 3/8 in. | 5/16 in.



Insulating Glass Unit 3/16 in. | 3/8 in. | 5/32 in. | 3/8 in. | 1/8 in.



Analytical Method Summary

- Heat Treated Glass
  - Up to 1.8 – 2.2 X larger when using the minimum RCSS
  - Increase varies with thickness, aspect ratio and area
- Laminated Glass
  - LR ratio varies with thickness, aspect ratio and area
  - Symmetric constructions
    - Smaller LRs for smaller dimensions
    - LRs increase over 1.0 as area increase for ARs near 1.0
  - Asymmetric constructions
    - LRs generally slightly larger LR
- Insulating glass
  - Symmetric IGUs LRs generally slightly smaller
  - Asymmetric IGUs LRs generally larger
  - Construction orientation affects load sharing

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Proposed Updates to E1300

- Extended NFL Charts
- GFPM Model for Edges
  - Address free or partially supported edges

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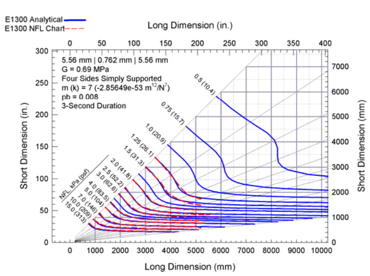
Proposed Extended NFL Charts



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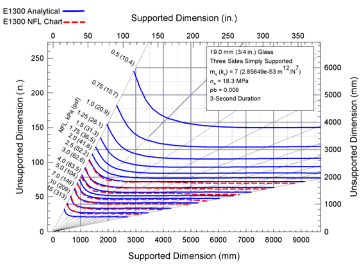
Proposed Extended NFL Charts



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Ongoing and Planned Research

- Architectural Glazing
  - Point Supported Glass
  - IGU load sharing with partial edge supports
  - Curved Glass Load Resistance
    - Cold, Hot Rolled
  - Load Resistance of Glass with Ceramic Frit
  - Vacuum IGUs
- Structural
  - Load Resistance of Glass Edges

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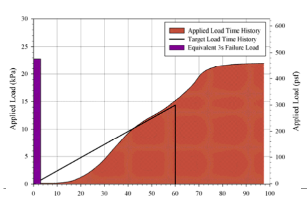
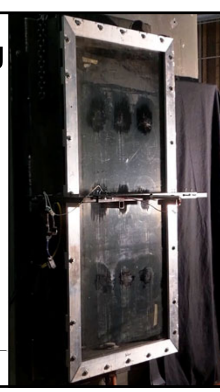
Destructive Load Testing

Uniform pressure was applied to the specimens by monotonically evacuating the chamber pressure until the specimens failed





Glass / Façade Curriculum

- Developing courses to address the growing need for engineers designing facades and components with glass – Running Spring of 2020 Gonzaga

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