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, \(E = 10.4 \times 10^6 \text{ psi} \ (71.7 \times 10^9 \text{ Pa})\)
- Poisson’s Ratio, \(\nu = 0.22 \ (0.21 \text{ to } 0.26)\)
- Density, \(\rho = 156 \text{ lbm/ft}^3 \ (2500 \text{ kg/m}^3)\)
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

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

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
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.
How is Glass designed for use in buildings

What causes the Fractures at relatively low tensile stresses?

Surface Flaws

Naturally occur as glass solidifies

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 "IC "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
  "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 (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.

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

ASTM E1300 Glass NFL Chart
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 lites comprising insulating glass units
New Analytical Procedure
Probability of Breakage must be $\leq 0.008$ (8/1000) for all lites

E1300 - Glass Failure Prediction Model

$$P_b = 1 - e^{-B} \geq 0.008$$

$$B = 4 \sum \left( c_i \left( \frac{1}{600} (\sigma_{RCS} - RCSS) \right)^2 \right)$$

$c_i = -0.005, x_1^2 + 0.022, x_1^4 + 0.055, x_1^6 + 0.039, x_2^2 + 0.031, x_2^4 + 0.06 - c_1 + 0.8$

$c_i = \frac{\sigma_{max}}{\sigma_{CSS}}$ Values determined using numerical analysis

Same procedure used to create the Basic Method NFL charts

Analytical Procedure - Monolithic Glass

Perform Numerical Stress Analysis
Calculate $P_b$ Check Limit

$\leq 0.008 \checkmark$
$> 0.008 \times$
Analytical Procedure – Laminated Glass

Perform Numerical Stress Analysis

Calculate $P_b$ ≤ 0.008 ✓

> 0.008 ×

Calculate Effective Thickness

Perform Numerical Stress Analysis

Check Limit

Analytical Procedure – Insulating Glass Unit

Perform Numerical Stress Analysis

Calculate $P_b$ ≤ 0.008 ✓

> 0.008 ×

Calculate Load Share

Perform Numerical Stress Analysis

Check Limit

Analytical Procedure Examples
Monolithic Glass Example

- Geometry
  - Rectangular Lite, 38in. X 76in. X 1/4 in.
- Glass Properties
  - E = 10.4 x 10^6 psi, v = 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
  - In plane displacements and edge rotations unrestrained

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, v = 0.22
  - m = 7; k = -1.365 x 10^-29 (60s)
- Interlayer Properties
  - G = 0.22 psi
- Uniform Lateral load,
  - P = 40 psf, 3s duration
- Model Boundary Conditions
  - Simply Support on all edges
  - In plane displacements and edge rotations unrestrained
Laminated Glass Example

- Calculate the effective thickness for each glass ply
  - $h_{1,\text{eff,}\sigma} = 0.255$ in.
  - $h_{2,\text{eff,}\sigma} = 0.241$ in.

- Calculate the probability of breakage for each glass ply
  - $p_{b1} = 0.0071 < 0.008$ Works
  - $p_{b2} = 0.011 > 0.008$ 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.)
    - $h_{1,\text{eff,}\sigma} = 0.292$ in. $p_{b1} = 0.0020 < 0.008$ Works
    - $h_{2,\text{eff,}\sigma} = 0.263$ in. $p_{b2} = 0.0056 < 0.008$ Works
  - Interlayer $G = 3800$ psi
    - $h_{1,\text{eff,}\sigma} = 0.290$ in. $p_{b1} = 0.0021 < 0.008$ Works
    - $h_{2,\text{eff,}\sigma} = 0.293$ in. $p_{b2} = 0.0018 < 0.008$ Works
  - Ply 2 RCSS = 3500 psi
    - $h_{1,\text{eff,}\sigma} = 0.256$ in. $p_{b1} = 0.0071 < 0.008$ Works
    - $h_{2,\text{eff,}\sigma} = 0.241$ in. $p_{b2} = 2.00\times10^{-9} < 0.008$ 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
  - $E = 10.4 \times 10^6$ psi, $v = 0.22$
  - $m = 7$, $k = -1.355 \times 10^{-11}$ (60s)

- Uniform Lateral load,
  - $P = 50$ psi, 3s duration

- Model Boundary Conditions
  - Simply Support on all edges
    - Lateral displacement = 0
    - In plane displacements and edge rotations unrestrained
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
  - $p_b_1 = 0.0048 < 0.008$ Works
  - $p_b_2 = 0.0042 < 0.008$ Works

Comparison of Basic and Analytical results for select glazing constructions

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. | 5/32 in. | 3/8 in. | 3/16 in.
Monolithic ¼ in. – (RCSS = 0)

No Change
Analytical Procedure returns the same results as the NFL Charts.

Monolithic ¼ in. – (RCSS = 3500 psi)

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

Monolithic ¼ in. – (RCSS = 10000 psi)
Laminated 1/8 in. | 0.060 in. PVB | 1/8 in.

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

Laminated 1/8 in. | 0.060 in. PVB | 3/16 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 LRgs generally slightly smaller
  - Asymmetric IGUs LRgs generally larger
  - Construction orientation affects load sharing

Proposed Updates to E1300

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

Proposed Extended NFL Charts
Proposed Extended NFL Charts

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

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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