FIU | Wall of Wind

NHERI Experimental Facility

SimCenter NHERI

Center for Computational Modeling and Simulation

# Experimental and Computational Simulation of Wind Damage to Façades

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In collaboration with
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Ali Bakhtiari, Krishna Sai Vutukuru, Kehinde Alawode, and WOW staffs

August 11, 2020
09:40 – 10:30am PDT

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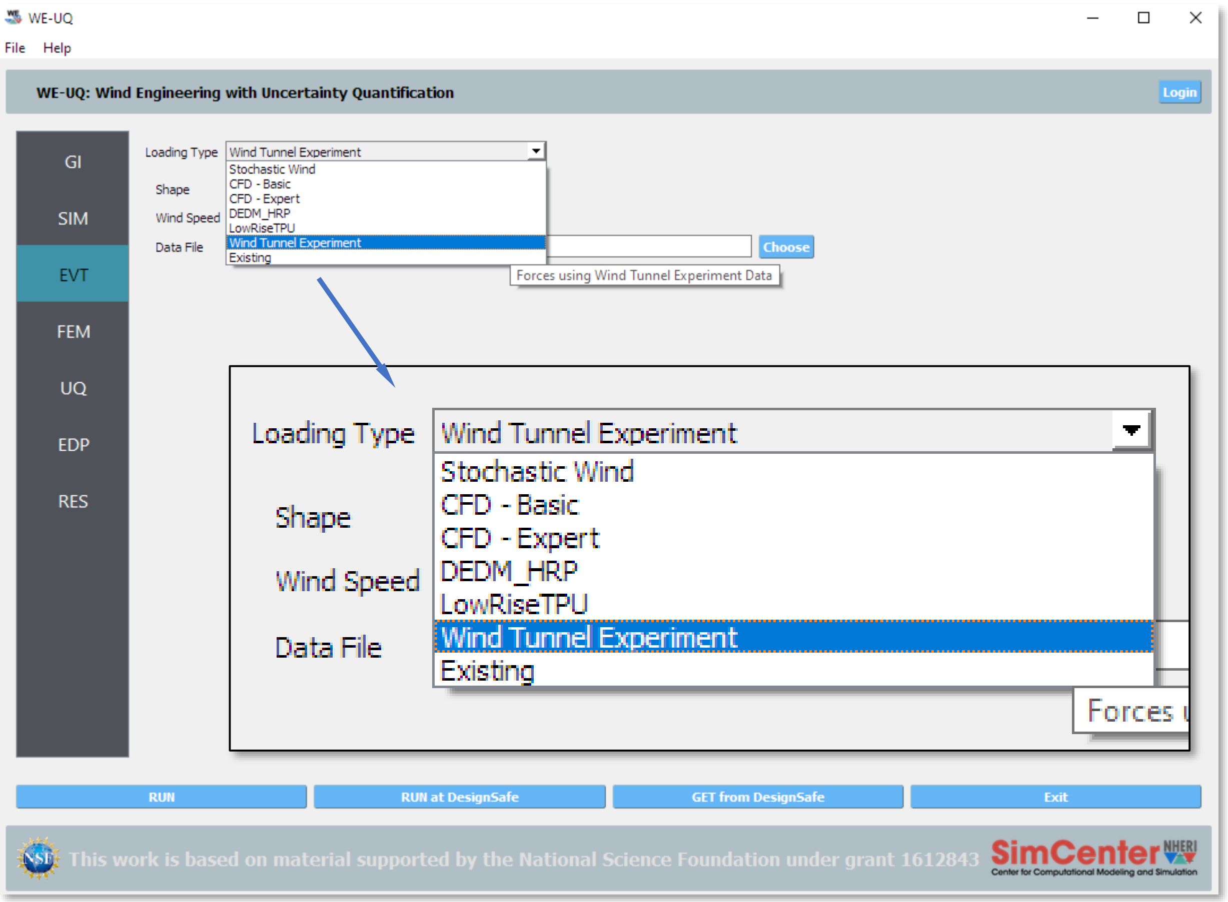
# WE-UQ: Wind Engineering with Uncertainty Quantification

- Streamlined experiment-to-simulation using WE-UQ




**Wind tunnel test data** (*.JSON file)

Specimen geometry

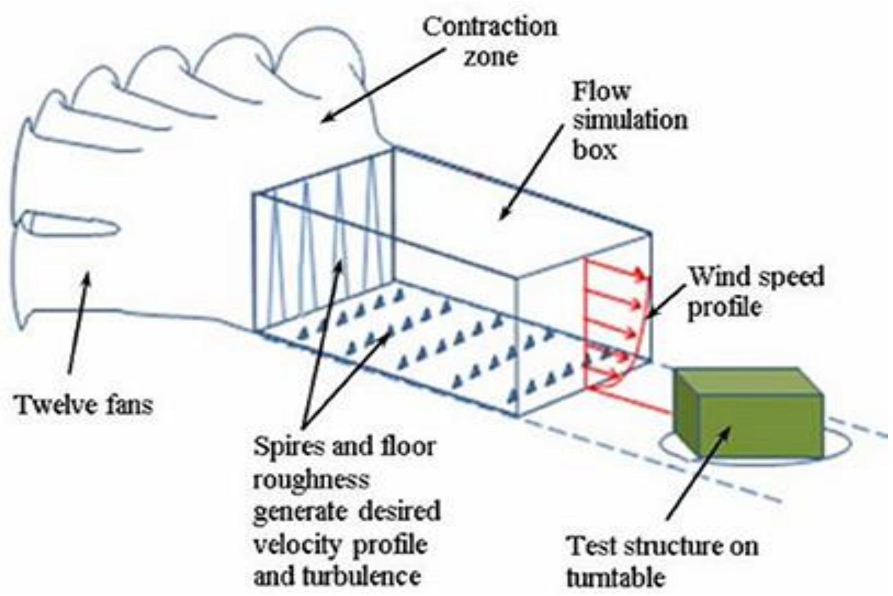
Pressure tap locations

Measured *Cp* values

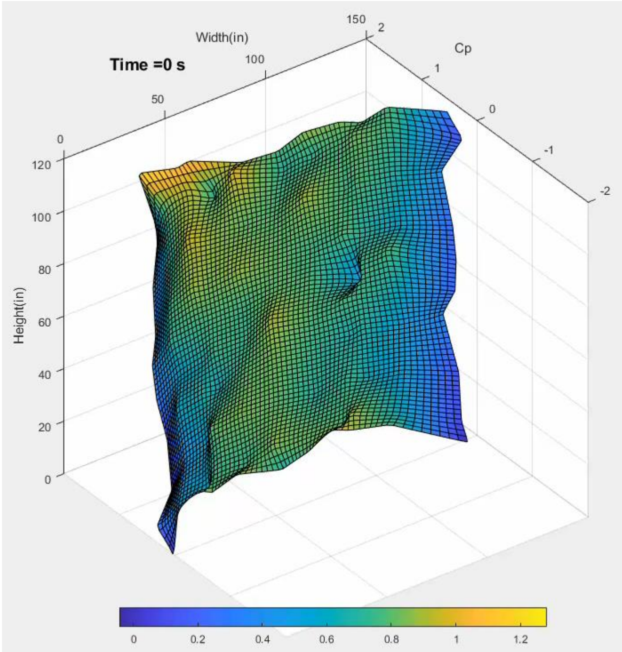

```
{
 "meanWindSpeed":22.000000,
 "shape":"Cuboid",
 "depth":24.000000,
 "height":12.000000,
 "breadth":16.000000,
 "frequency":600.000000,
 "period": 15.000000,
  "units":{
     "length":"m",
     "time":"sec"
  },
  "tapLocations": [
      {"id":1,"xLoc":1.000000,"yLoc":15.000000,"face":5},
      {"id":2,"xLoc":3.000000,"yLoc":15.000000,"face":5},
      ......
  ],
 "pressureCoefficients": [
      {"id": 1 , "data":[-1.083194,-1.372954, ....]},
      {"id": 2 , "data":[-1.181435,-1.164351, ....]},
      ......
   ]
}
```

# WE-UQ: Wind Engineering with Uncertainty Quantification

- Streamlined experiment-to-simulation using WE-UQ
  + FIU WOW EF can provide this wind tunnel test data for use in WE-UQ




Wall of Wind (WOW) testing




Example of Cp time history measured from WOW testing

**Wind tunnel test data** (*.JSON file)


```
{
 "meanWindSpeed":22.000000,
 "shape":"Cuboid",
 "depth":24.000000,
 "height":12.000000,
 "breadth":16.000000,
 "frequency":600.000000,
 "period": 15.000000,
  "units":{
     "length":"m",
     "time":"sec"
  },
  "tapLocations": [
       {"id":1,"xLoc":1.000000,"yLoc":15.000000,"face":5},
       {"id":2,"xLoc":3.000000,"yLoc":15.000000,"face":5},
       ......
  ],
 "pressureCoefficients": [
       {"id": 1 , "data":[-1.083194,-1.372954, ....]},
       {"id": 2 , "data":[-1.181435,-1.164351, ....]},
       ......
   ]
}
```

# Menu (Omakase)

- Appetizer
  - Damage to building envelopes under wind loads
- Entrée
  - Experiment-to-simulation of wind induced vibrations to façades
    - Experiment using NHERI FIU WOW EF
    - Numerical modeling/calibration/validation
- Dessert
  - Concluding remarks
  - Q&A / Discussion

# Wind damages to building envelopes

- Examples of damages to the envelopes of high-rise buildings
  + Curtainwall systems as the main cladding component
  + The most vulnerable part of the buildings under wind loads
  + Cladding failure is a leading contributor to the losses in wind events

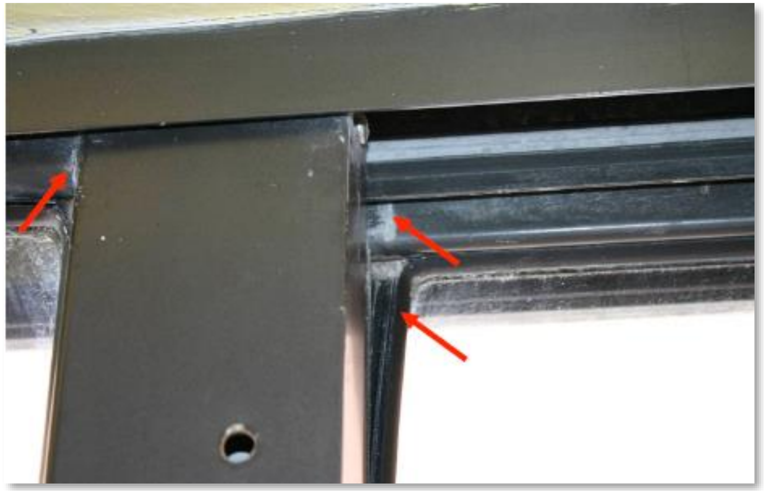

Building envelope damages after hurricane

# WIND DAMAGES TO BUILDING ENVELOPES

- Façade damage types

Frame deformation

Glass blowout



Separation at frame corner with displaced rubber seal (joint quality affected)

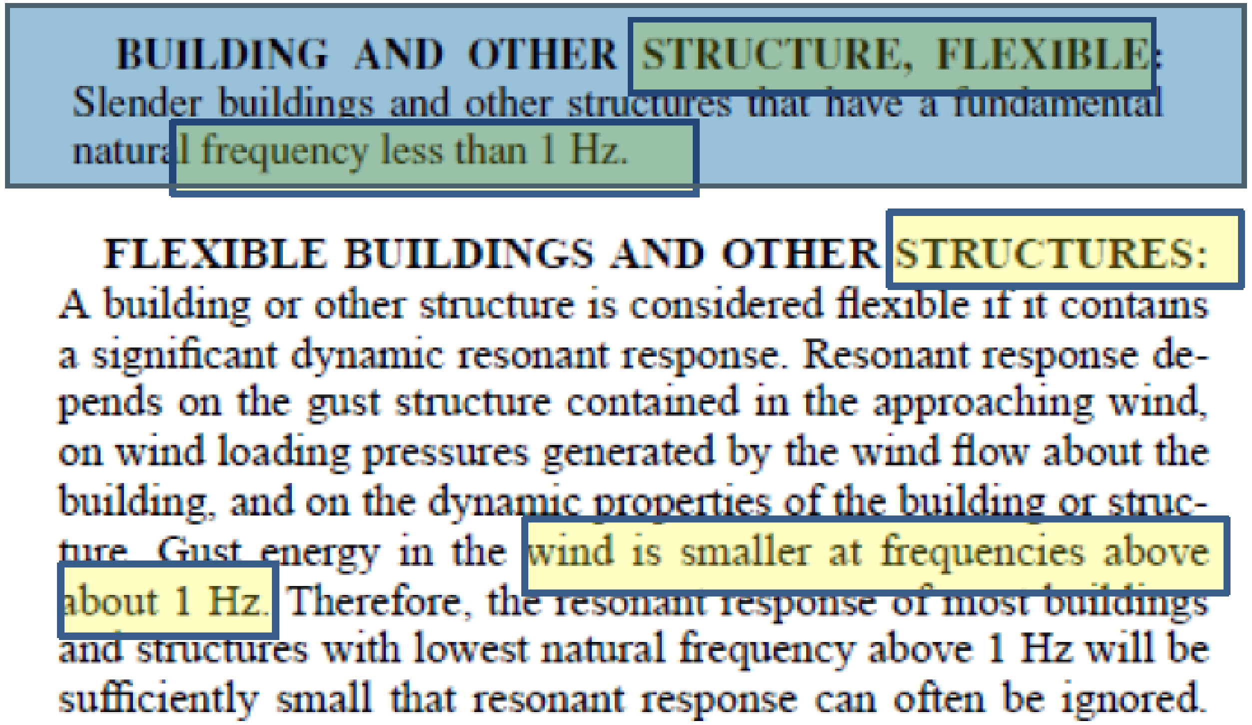
Operable part disengagement
(Photos by courtesy of Permasteelisa Group)

# Wind impact to building envelopes

- Research significance
  - + Building envelopes are the most vulnerable components under wind loads
  - + Wind-induced vibration impacts the water tightness
  - + Performance-based wind engineering (PBWE) framework
    - Majority of PBWE research has focused on structural building performance*
    - Current WE-UQ is limited to the assessment of the structural building response
  - + Building codes can be improved
    - Equivalent static analysis
    - ASCE 7 – Structures with natural frequencies above 1Hz do not need to be analyzed for wind-induced dynamic effects

* Ouyang, Z., and Spence, S. M. J. (2020). "A Performance-Based Wind Engineering Framework for Envelope Systems of Engineered Buildings Subject to Directional Wind and Rain Hazards." *ASCE Journal of Structural Engineering*, 146(5), 04020049.

# Current building code on the wind induced vibrations



**BUILDING AND OTHER STRUCTURE, FLEXIBLE:** Slender buildings and other structures that have a fundamental natural frequency less than 1 Hz.

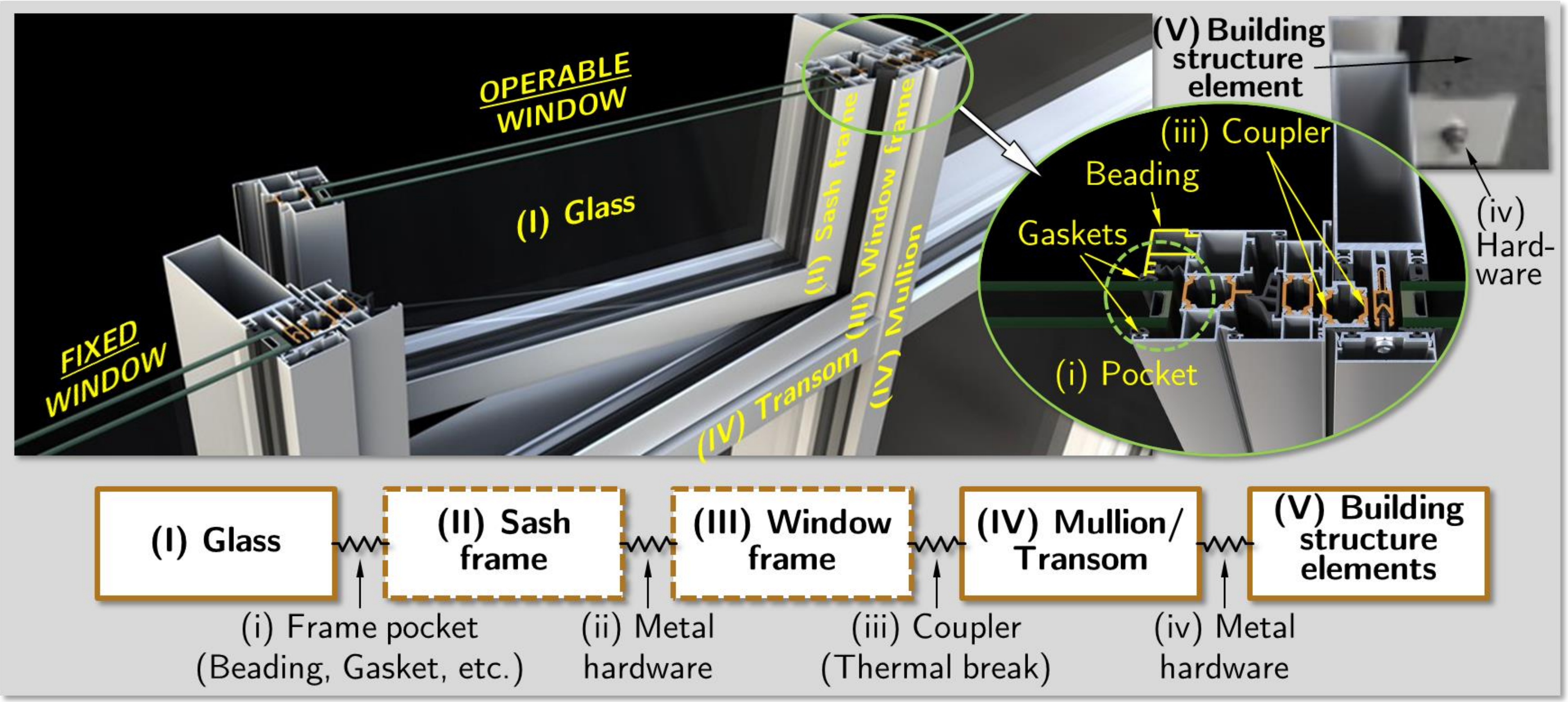
**FLEXIBLE BUILDINGS AND OTHER STRUCTURES:** A building or other structure is considered flexible if it contains a significant dynamic resonant response. Resonant response depends on the gust structure contained in the approaching wind, on wind loading pressures generated by the wind flow about the building, and on the dynamic properties of the building or structure. Gust energy in the wind is smaller at frequencies above about 1 Hz. Therefore, the resonant response of most buildings and structures with lowest natural frequency above 1 Hz will be sufficiently small that resonant response can often be ignored.

**ASCE 7-16**

- ASCE 7: 1Hz limit for the vibration effects → *Applicable to façade?*
- Wind induced vibrations of flexible/ slender elements like operable windows, fin, shades can damage façade frame and connections
- Significant vibrations may occur with natural frequencies above 1Hz (Simplified code methods does not capture the wind induced response)

# Anatomy of Curtain Wall Systems

- Many framing elements and mechanical connections




NOTE: : Parts for operable window only : Connection

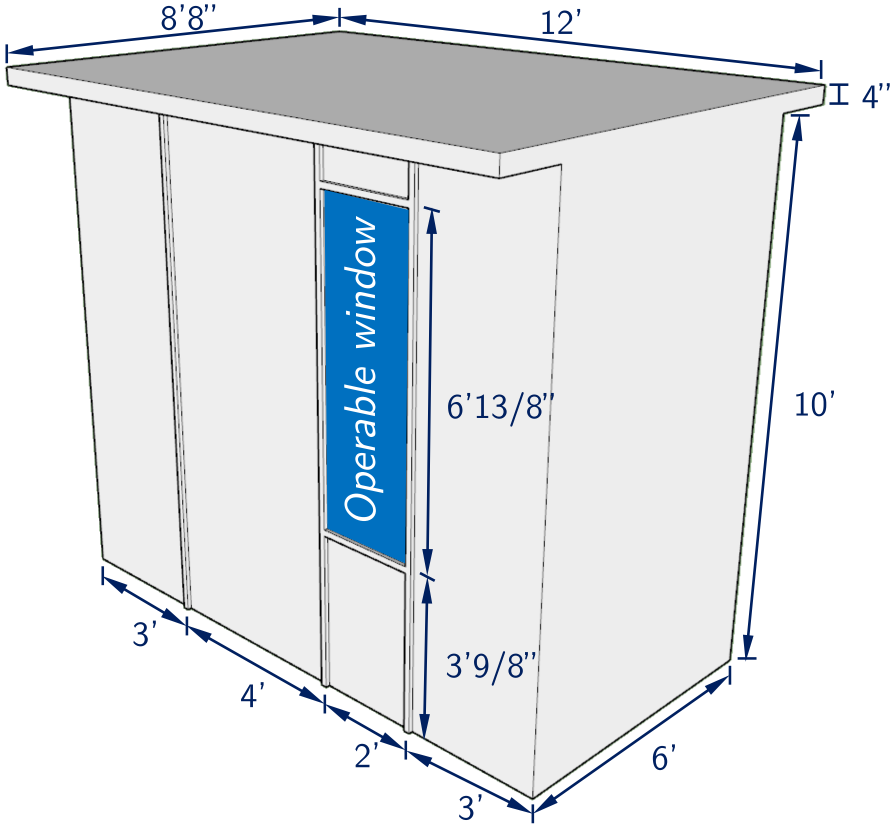
Modified from the original image of Alumil curtainwall

# Experiment-to-Simulation of Wind Induced Vibrations to Façades

- Two ongoing curtainwall research
  - NSF IUCRC WHIP (Wind Hazard and Infrastructure Performance) funded project
    - Title: Investigation of Wind-driven Rain and Wind-induced Vibrations Effects on Curtain Wall Systems
    - PIs: Amal Elawady & Seung Jae Lee
    - Co-PIs: Arindam Gan Chowdhury & Ioannis Zisis
    - Industry partner: Guido Lori (Permasteelisa Group)
    - WHIP center website: http://www.whipc.org/ (PIs: Kishor Mehta, Ioannis Zisis & Delong Zuo)
  - Florida Sea Grant funded project
    - Title: Full-Scale Experimentation and Advanced Computational Modeling to Mitigate Wind-Induced Vibrations and Their Effects on Curtainwall Window Systems
    - PI: Arindam Gan Chowdhury
    - Co-PIs: Peter Irwin & Seung Jae Lee
    - Industry partner: Guido Lori (Permasteelisa Group)

# FAÇADE EXPERIMENT AT FIU WOW EF

- Test specimen (full-scale)

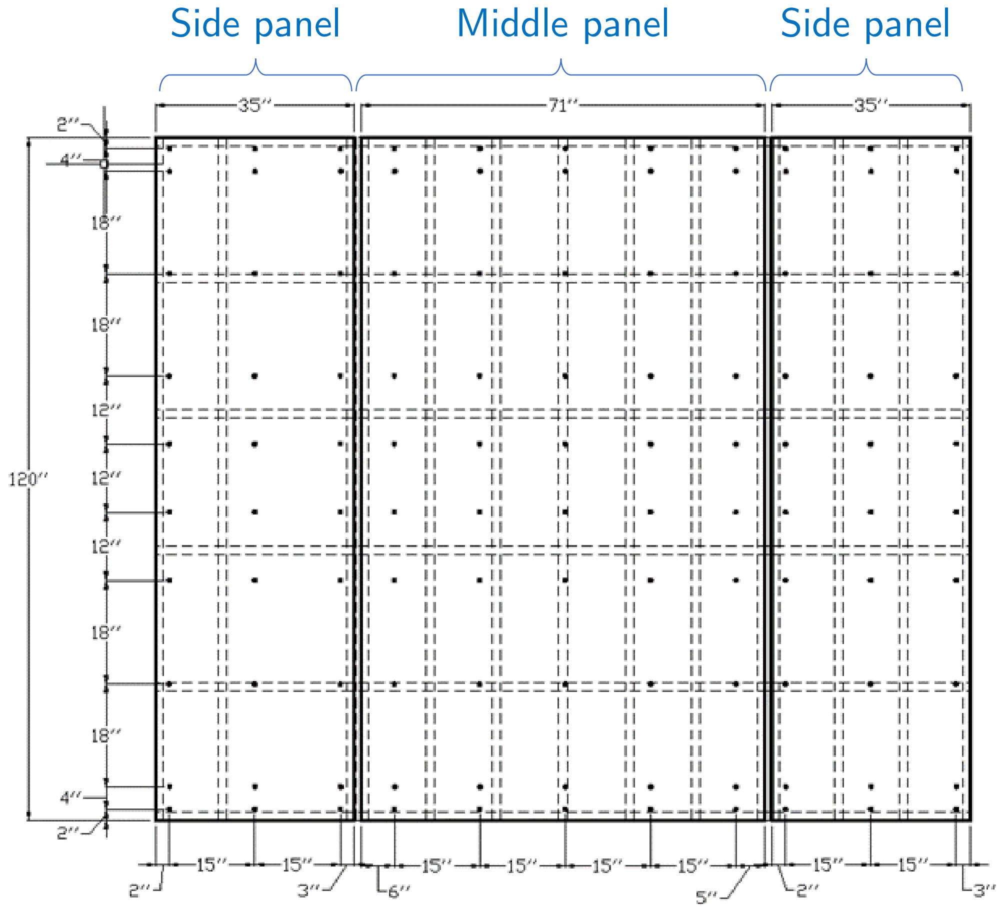


Overall dimension (12'W×6'D×10'H)

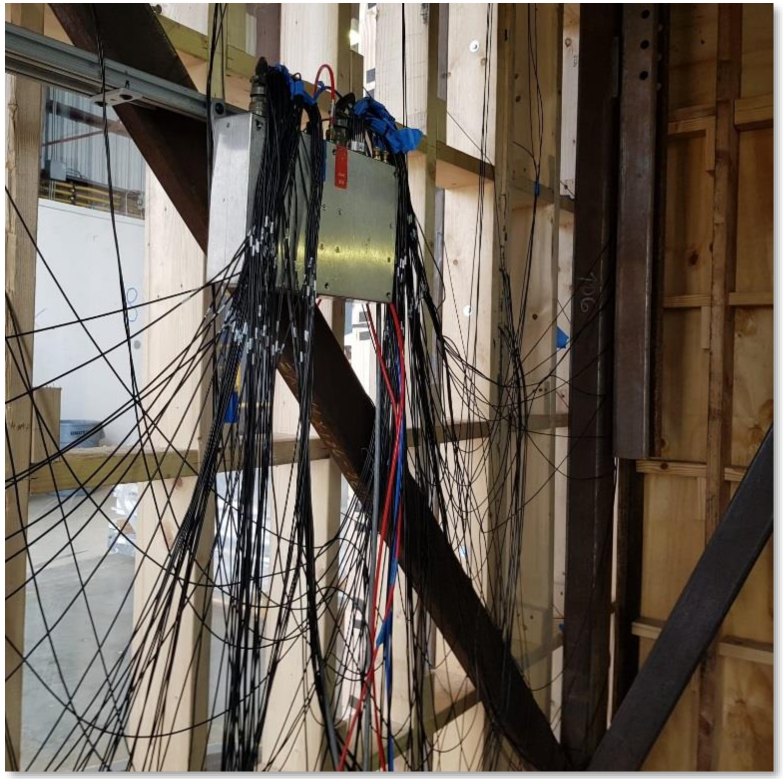

Front – actual curtain wall panels (accelerometers and strain gauges)


Rear – polycarbornate panels (pressure taps)

# INSTRUMENTATION OF PRESSURE TAPS



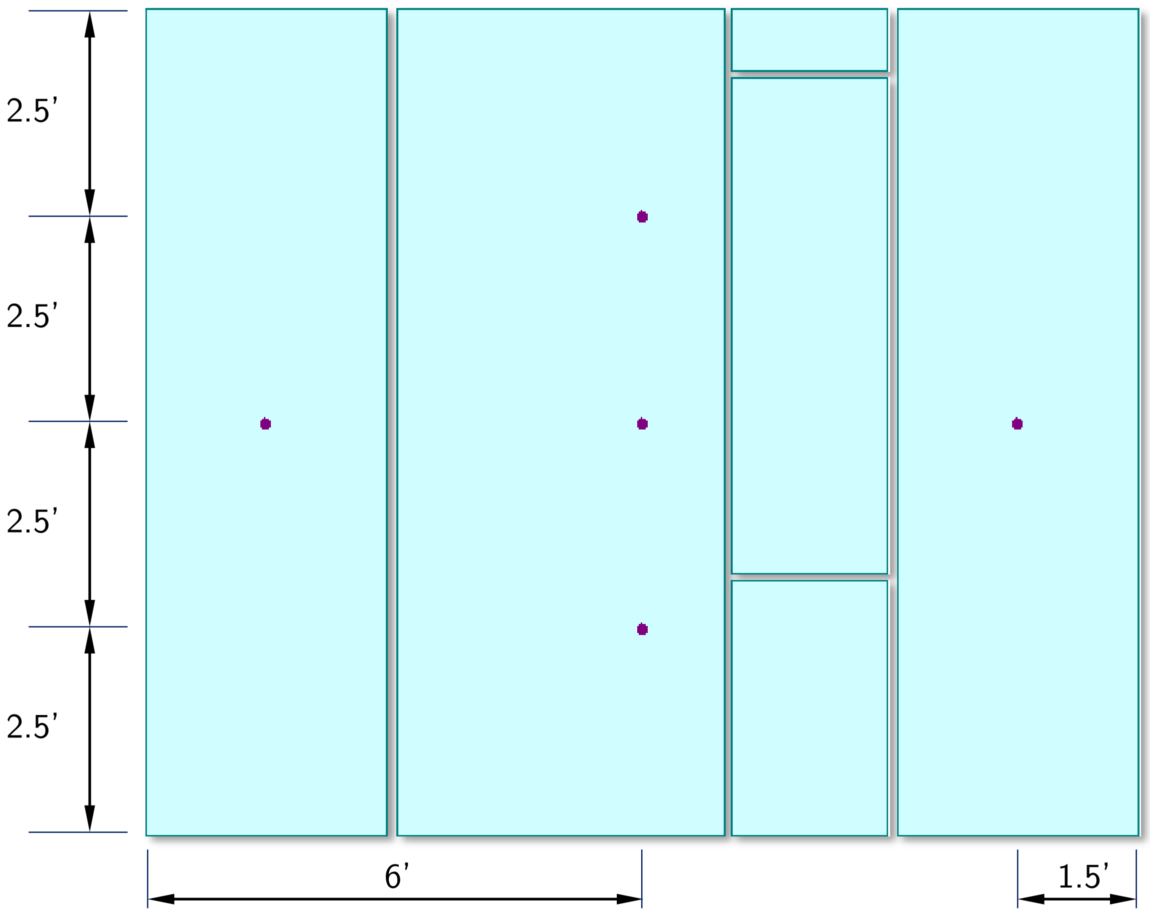

110 pressure tap locations on the polycarbornate panels



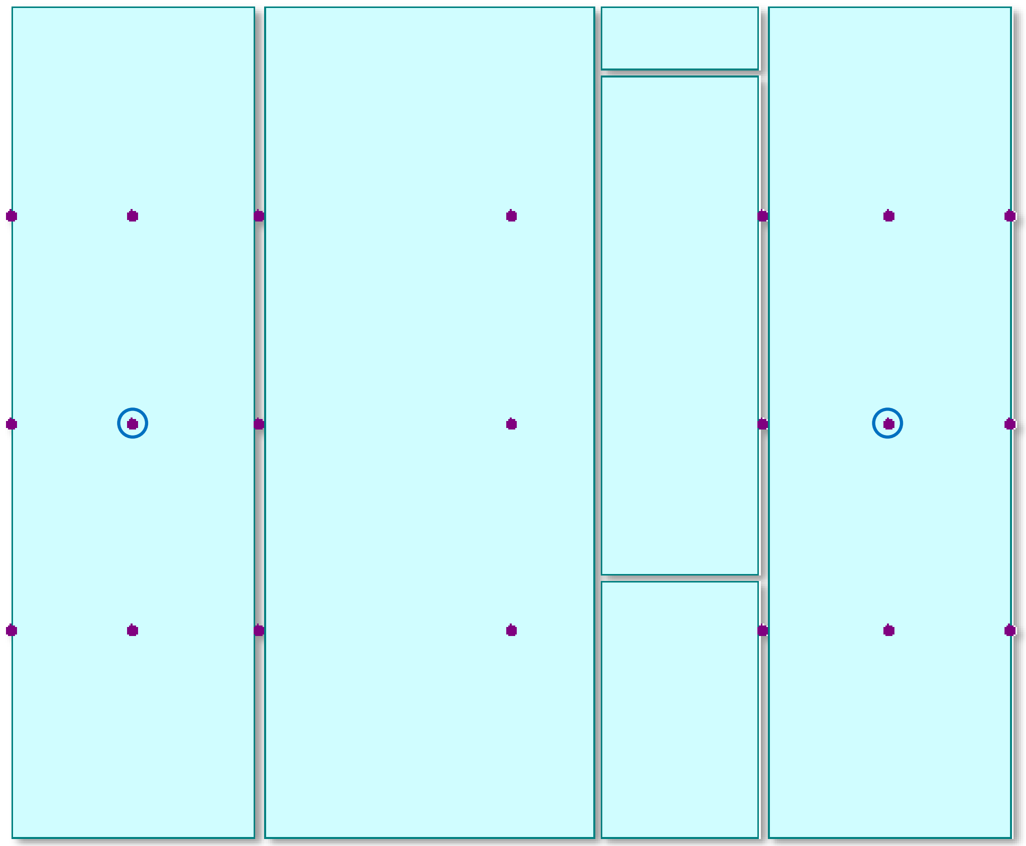
Installed pressure taps and data logging

# Instrumentation of accelerometers and strain gauges

- Accelerometers

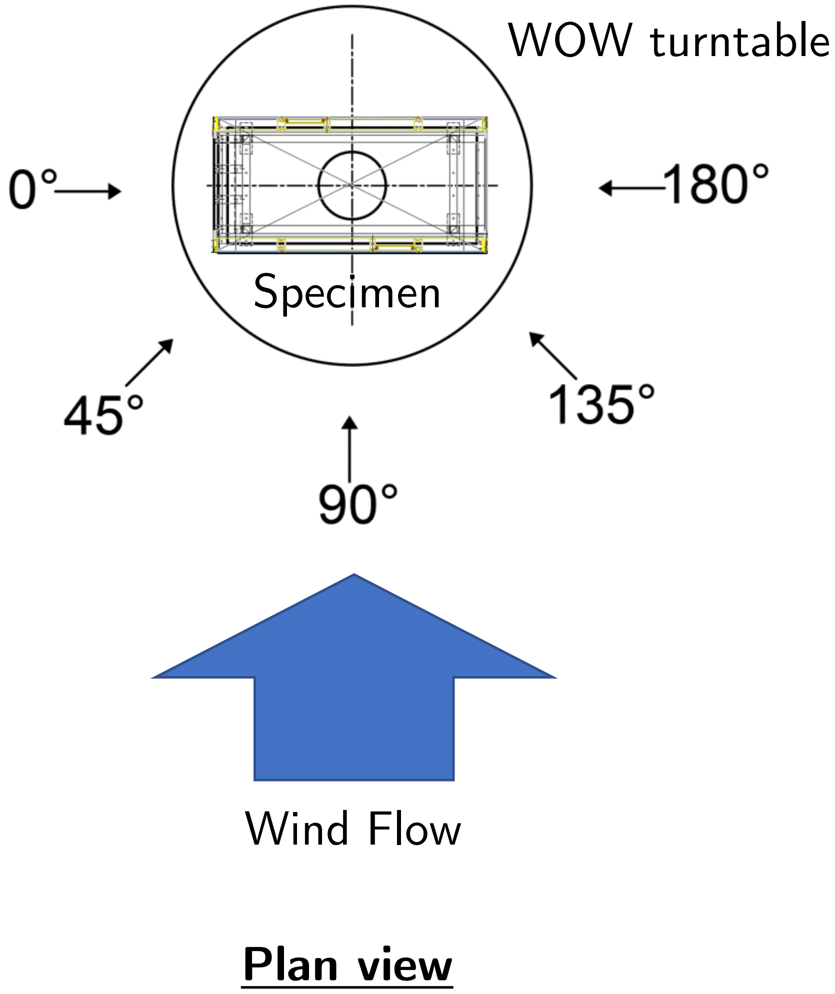



- Strain gauges



○: strain gauges for both inside and outside faces of glass

# TESTING PROTOCOL




- Pressure testing
  - Wind pressure coefficient (Cp)

| Wind speed (mph) | Angle of attack | Test duration |
|---|---|---|
| 50 | $0^\circ$ to $180^\circ$ with $15^\circ$ increment | 60 sec |

- Dynamic testing
  - Acceleration and strain

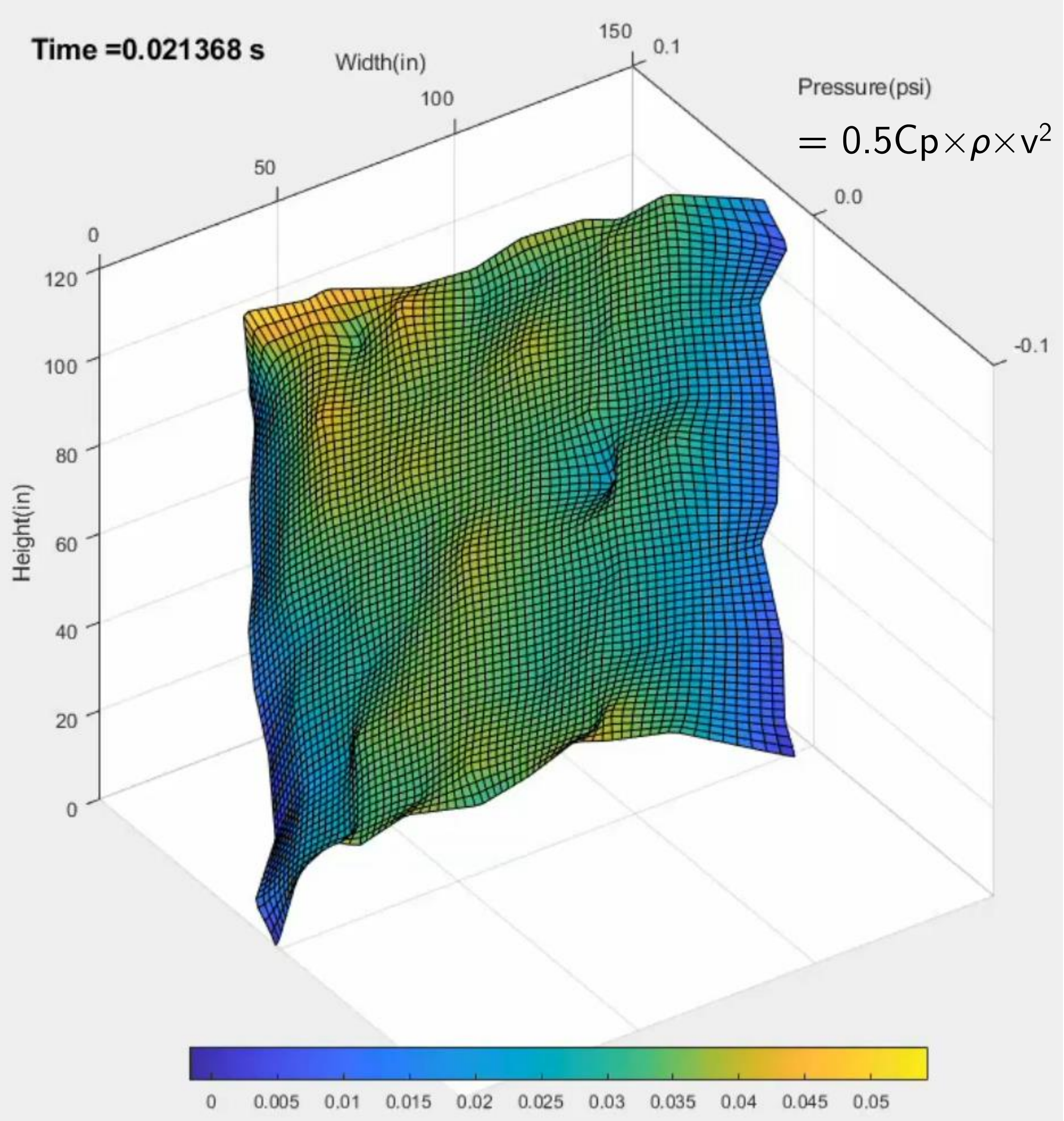
| Wind speed (mph) | Angle of attack | Test duration |
|---|---|---|
| 50, 70 | $0^\circ$ to $180^\circ$ with $45^\circ$ increment | 600 sec |
| 90 | | 300 sec |

# Test result - pressure

- Time history pressure distribution
  - 50 MPH / 90 degrees (normal to panels)


Cp

(Pressure coefficient)

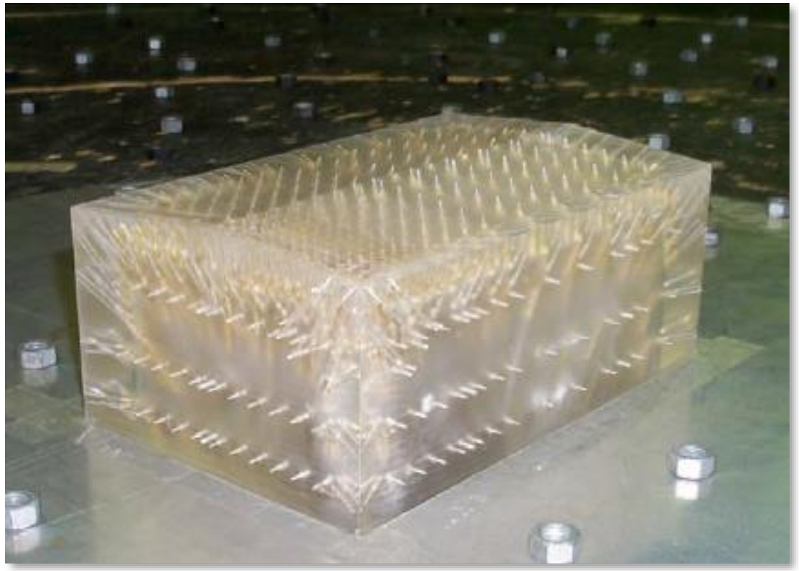



$= 0.5Cp \times \rho \times v^2$

# Test result - pressure

- NIST and WOW test parameters

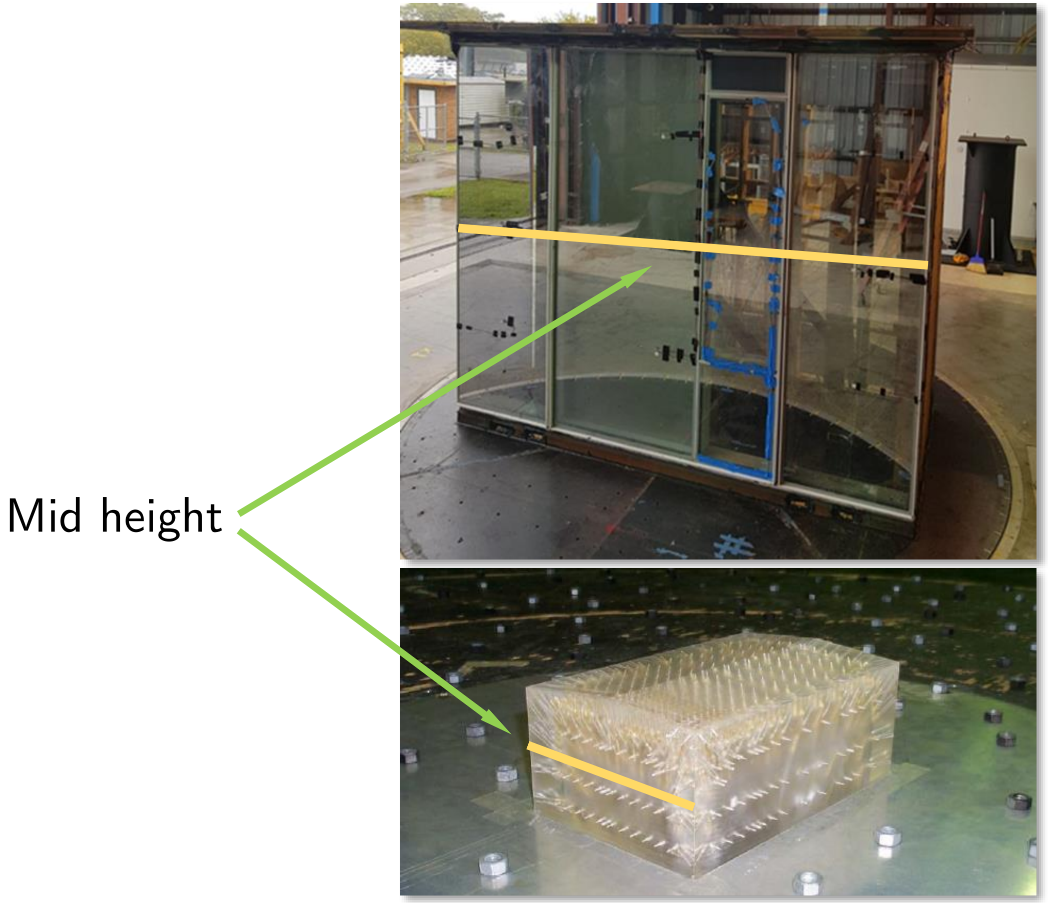
| | NIST | WOW |
|---|---|---|
| Wind Tunnel Size (Width x Height) | 3.4m x 2.4m | 6m x 4.3m |
| Model Size Scale | 1:100 | 1:1 |
| Height/Width Ratio | 1:1 | 1:1.2 |
| Wind Angle increment | 5° | 15° |
| Roof Type | Gable Roof | Flat Roof |
| Sampling Frequency | 500Hz | 520Hz |
| Turbulence Intensity (at roof height) | | 0.22 |
| Reference Height | Eave Height | Roof Height |
| Wind Tunnel Roof Height Velocity (Full scale) | 29.6m/s | 22.52m/s |
| Simulated Terrain | Open Country (Zo = 0.03m) | Open Country (Zo = 0.08m) |
| Reynolds Number | | |

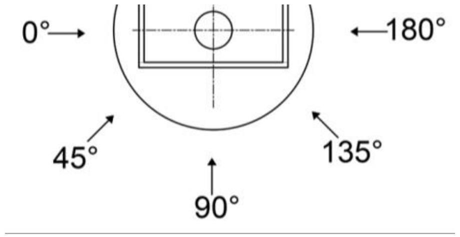


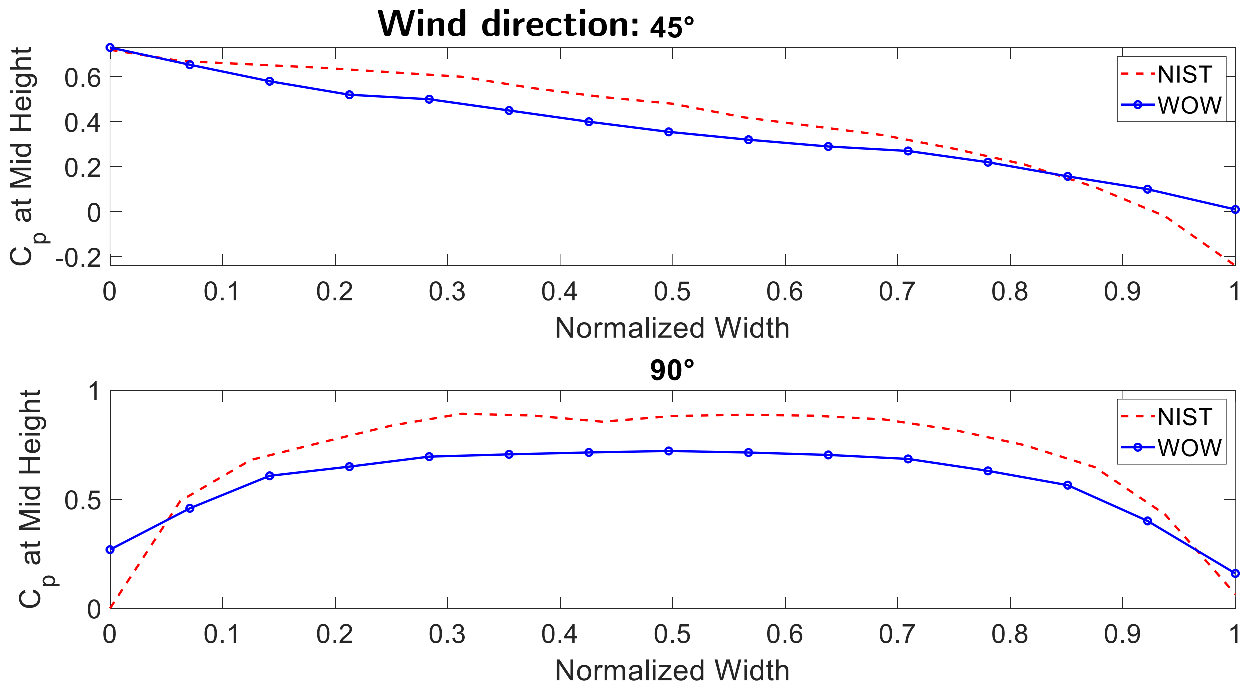
NIST Model

# Test result - pressure

- Verification of experiment result (Cp mean)

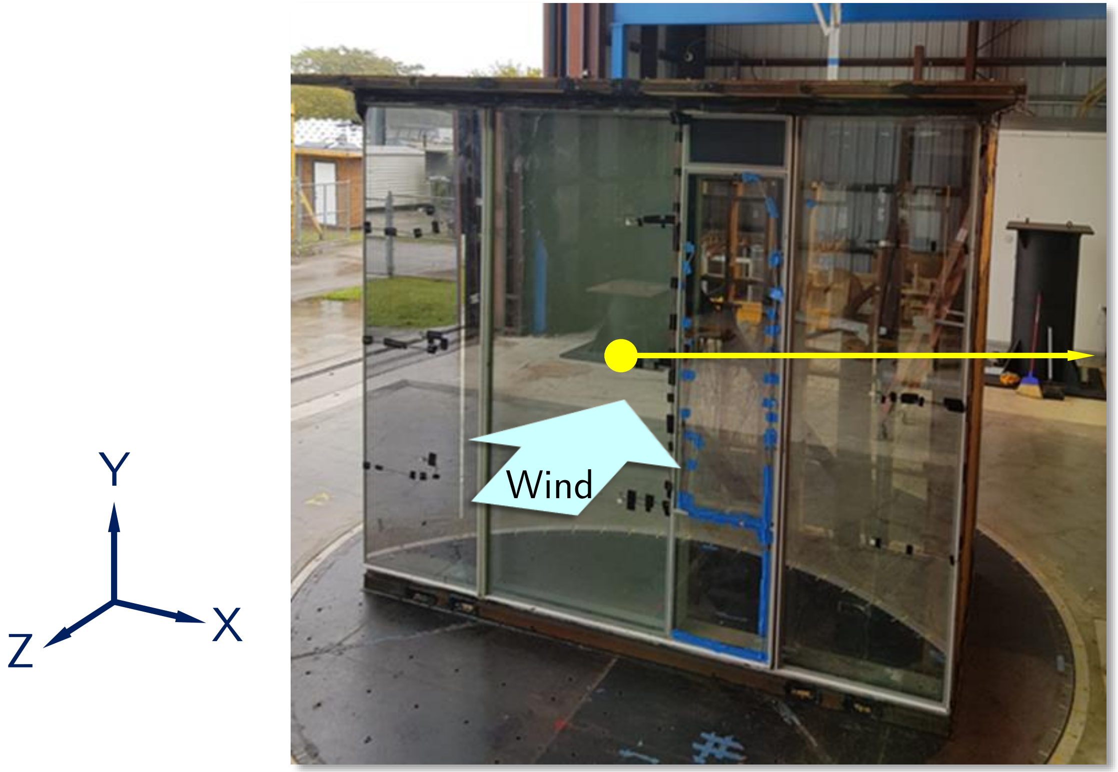


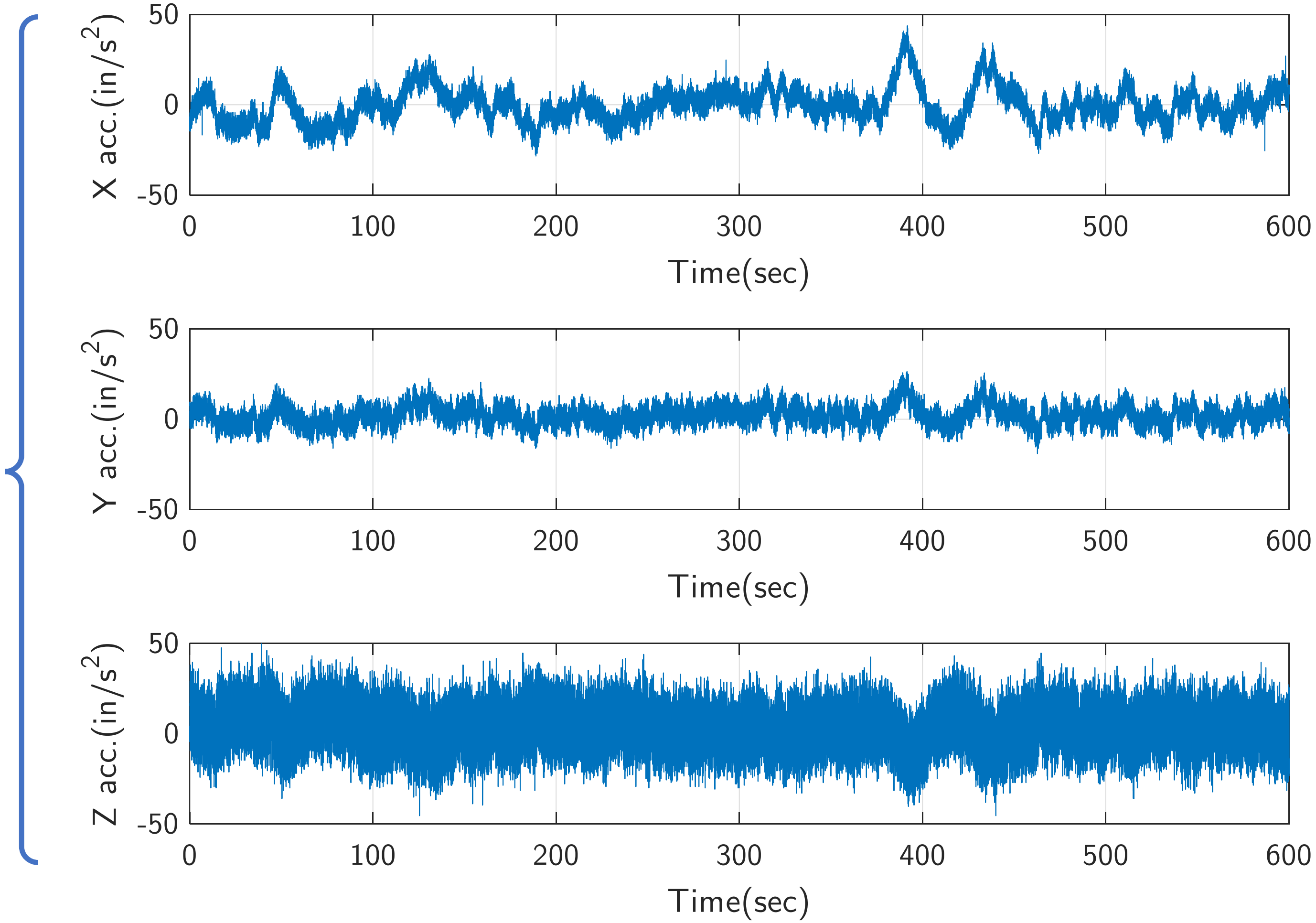



# Test result - acceleration

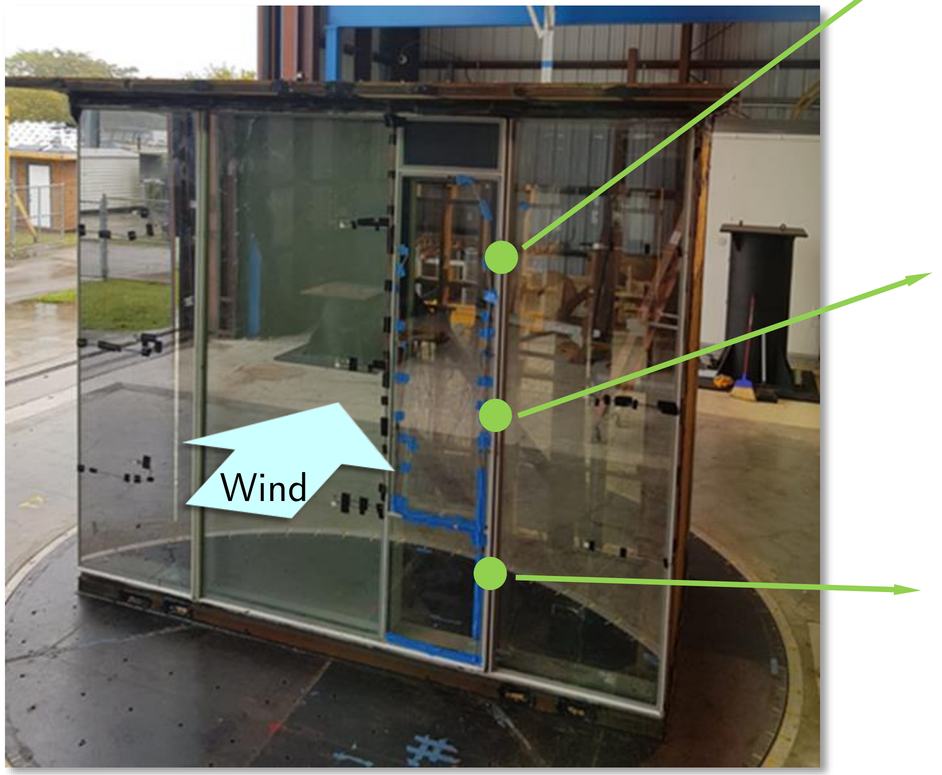
- Acceleration time history
  - + 50 MPH / 90 degrees

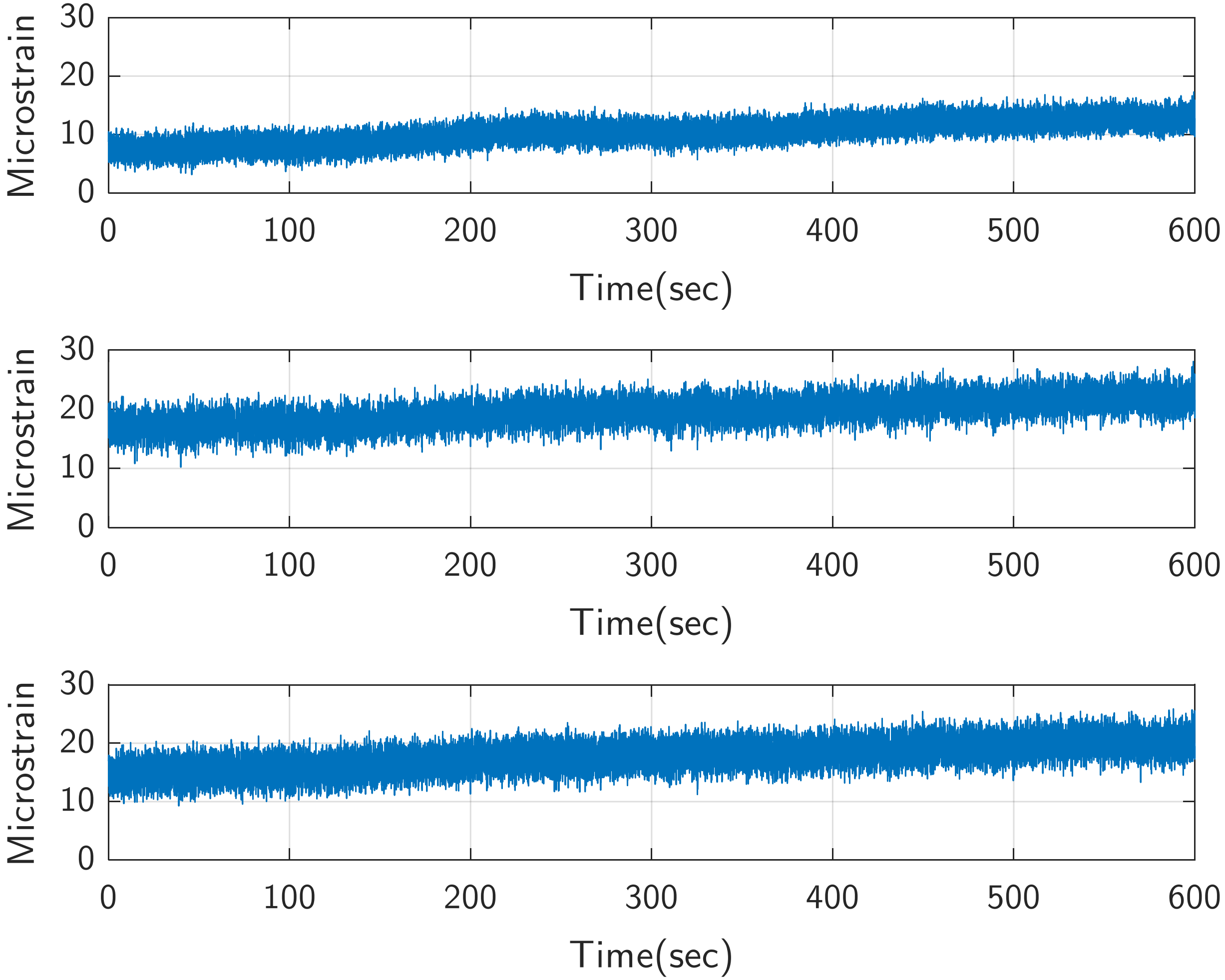


# Test result - strain

- Strain data
  + 50 MPH / 90 degrees

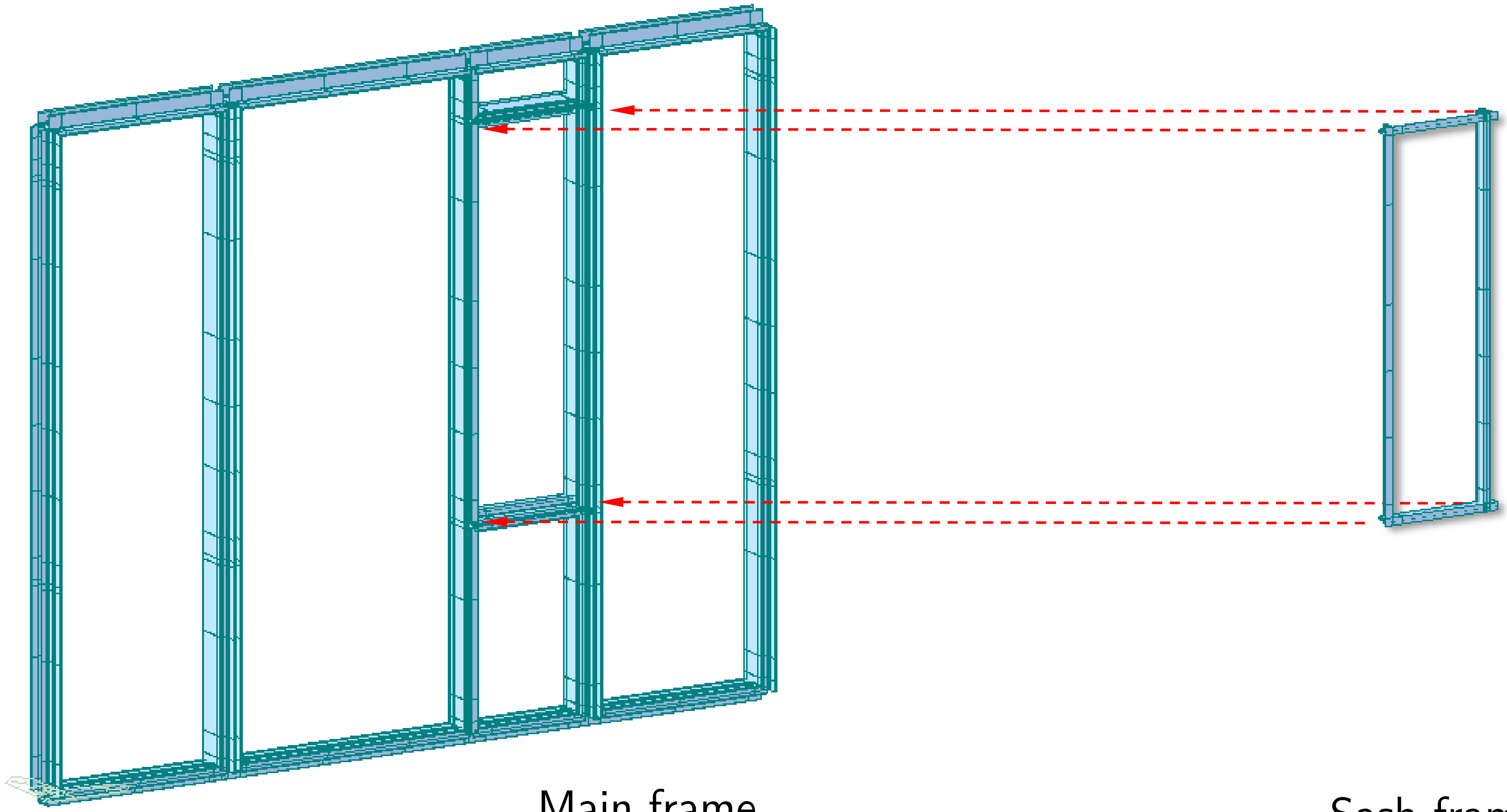



Longitudinal strain of mullion

# Modeled Geometry

- Main frame (Mullion/Transom) + Sash frame (operable part)



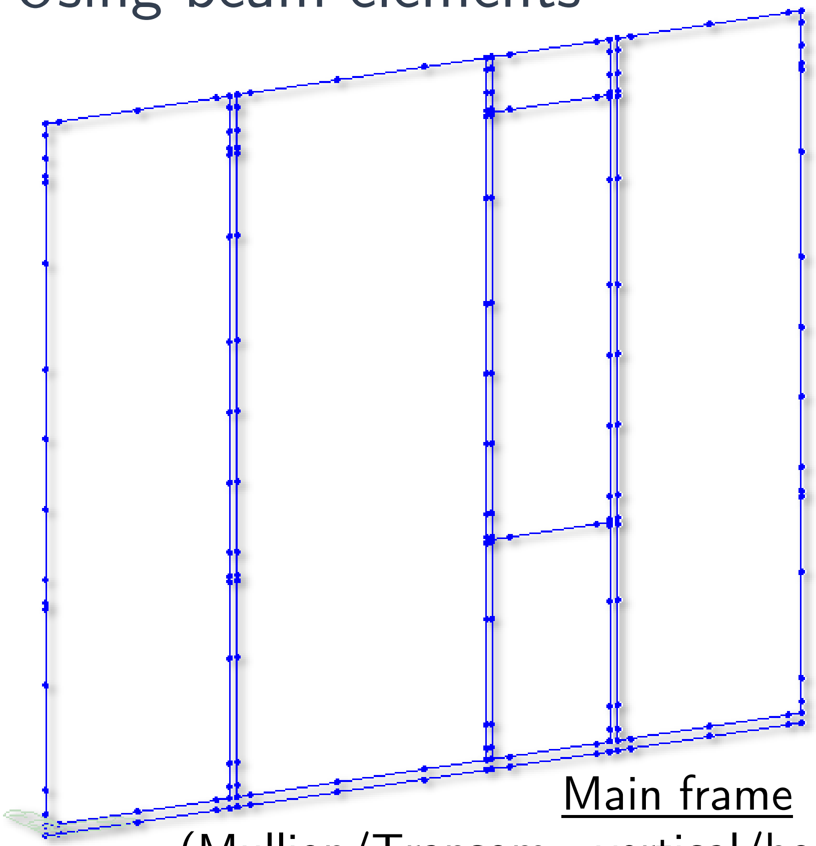
Main frame
(Mullion/Transom - vertical/horizontal members)

Sash frame

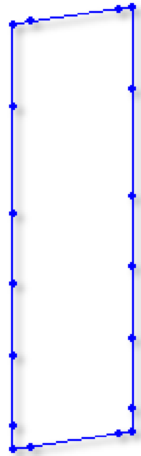
FE software: Midas GEN

# Modeled geometry

- Main frame (Mullion/Transom) + Sash frame (for operable window)
  - Using beam elements



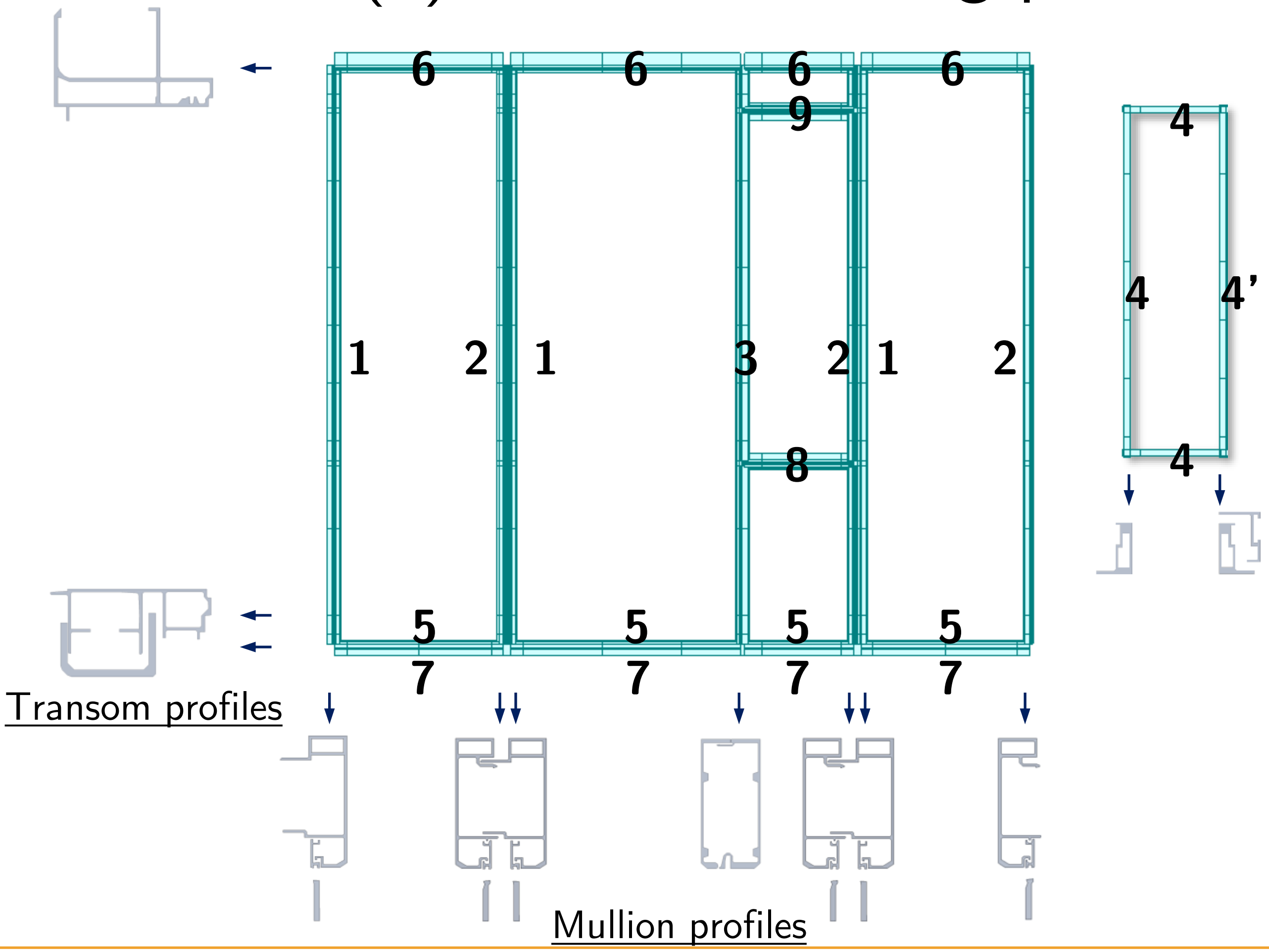
Main frame
(Mullion/Transom - vertical/horizontal members)

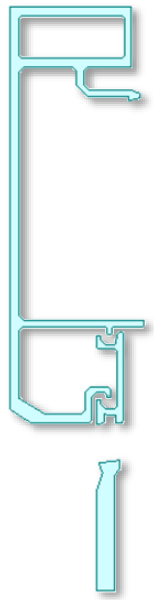


Sash frame

# Modeled Geometry

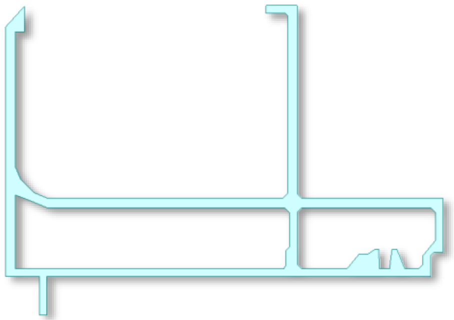
- Nine (9) different framing profiles



Profile #2 (mullion)

| | |
|---|---|
| Area | 2.402 $in^2$ |
| Ixx | 0.182 $in^4$ |
| Iyy | 16.921 $in^4$ |
| Izz | 0.952 $in^4$ |
| ... | ... |

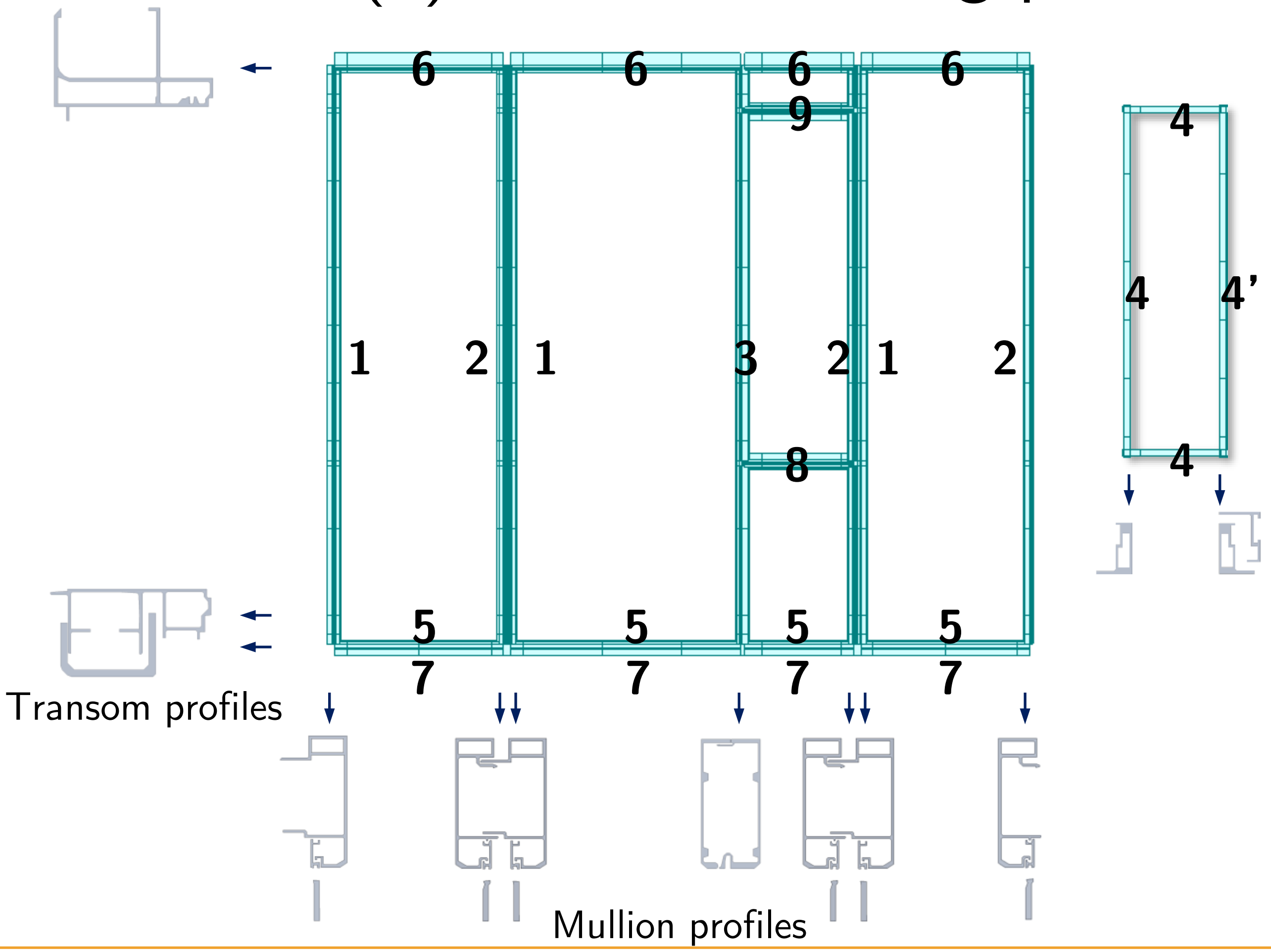


Profile #6 (transom)

| | |
|---|---|
| Area | 2.396 $in^2$ |
| Ixx | 0.936 $in^4$ |
| Iyy | 8.313 $in^4$ |
| Izz | 2.282 $in^4$ |
| ... | ... |

# Modeled Geometry

- Nine (9) different framing profiles
- Interaction between frames

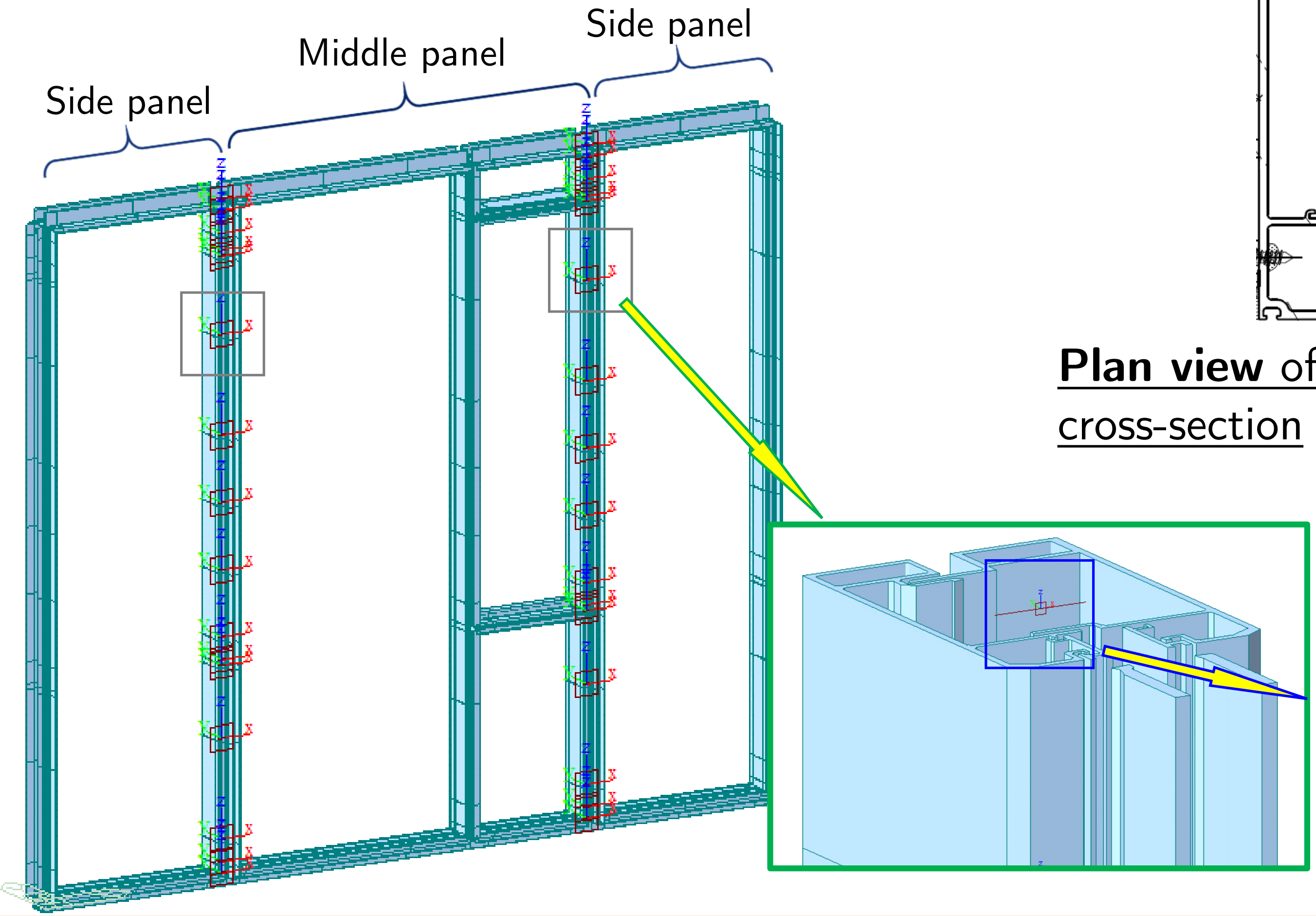


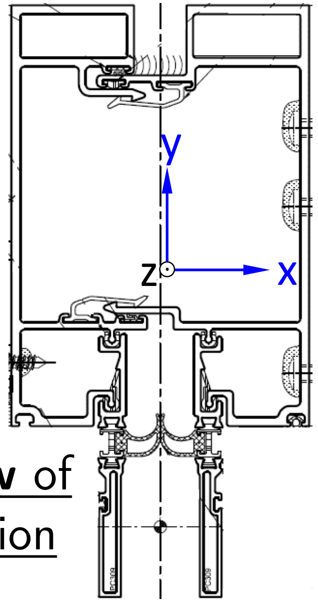

Profile interaction table
(where springs need to be modeled)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | X | | | | | | | |
| 2 | | | | O | | | | | |
| 3 | | | Δ | O | | | | | |
| 4 | | | | | | | | O | O |
| 5 | | | | | | | + | | |
| 6 | | **Symm.** | | | | | | | |
| 7 | | | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |

# Modeling the interactions between profiles

- Interaction of the mullions between panels




**Plan view** of cross-section

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | X | | | | | | | |
| 2 | | | | O | | | | | |
| 3 | | | Δ | O | | | | | |
| 4 | | | | | | | | O | O |
| 5 | | | | | | | + | | |
| 6 | | | | | | | | | |
| 7 | | Symm. | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |

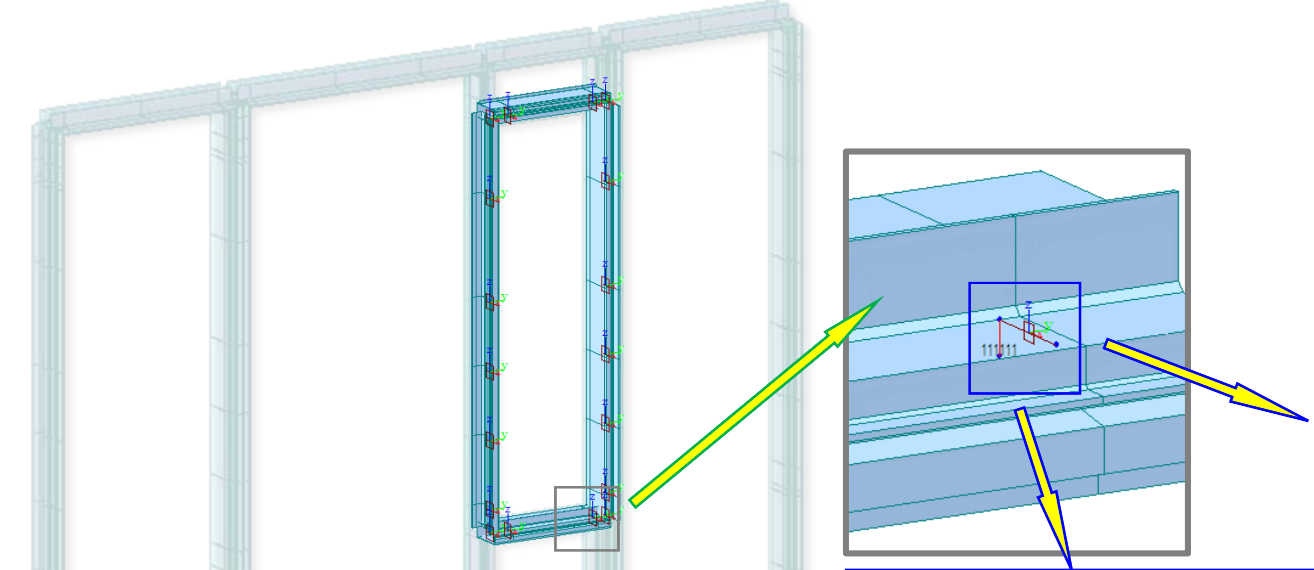
Translational & rotational springs for x, y, & z directions

- Translational springs (x & z)
- Rigid coupling (y direction)
- Rotational springs

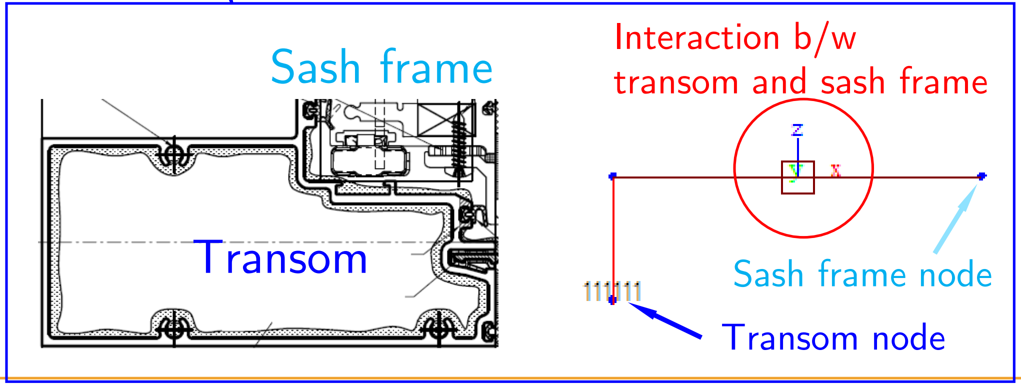
# MODELING THE INTERACTIONS BETWEEN PROFILES

- Interaction of main frame and sash frame

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | X | | | | | | | |
| 2 | | | | O | | | | | |
| 3 | | | Δ | O | | | | | |
| 4 | | | | | | | | O | O |
| 5 | | | | | | | + | | |
| 6 | | | | | | | | | |
| 7 | | Symm. | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |

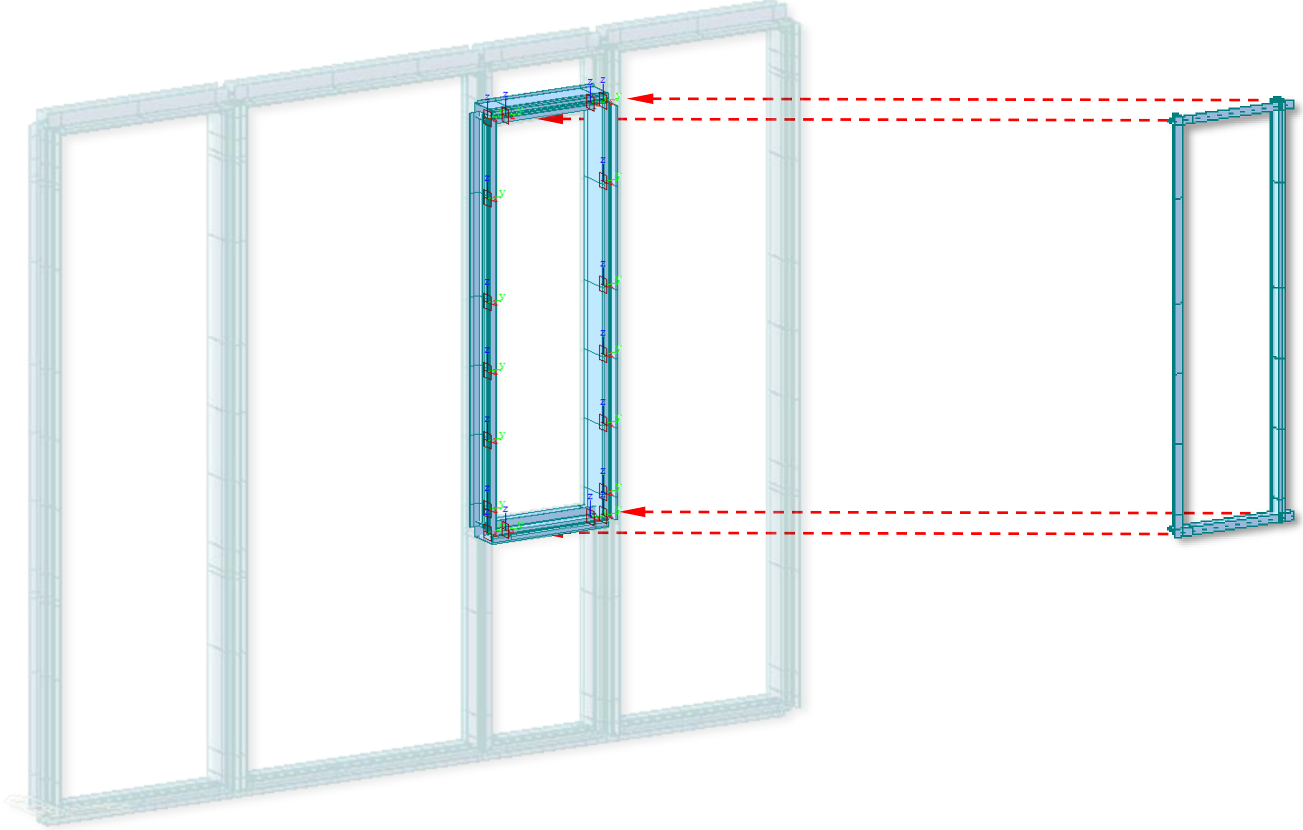


Translational springs only
- No rotational springs



# Modeling the interactions between profiles

- Assembling the sash frame to the main frame

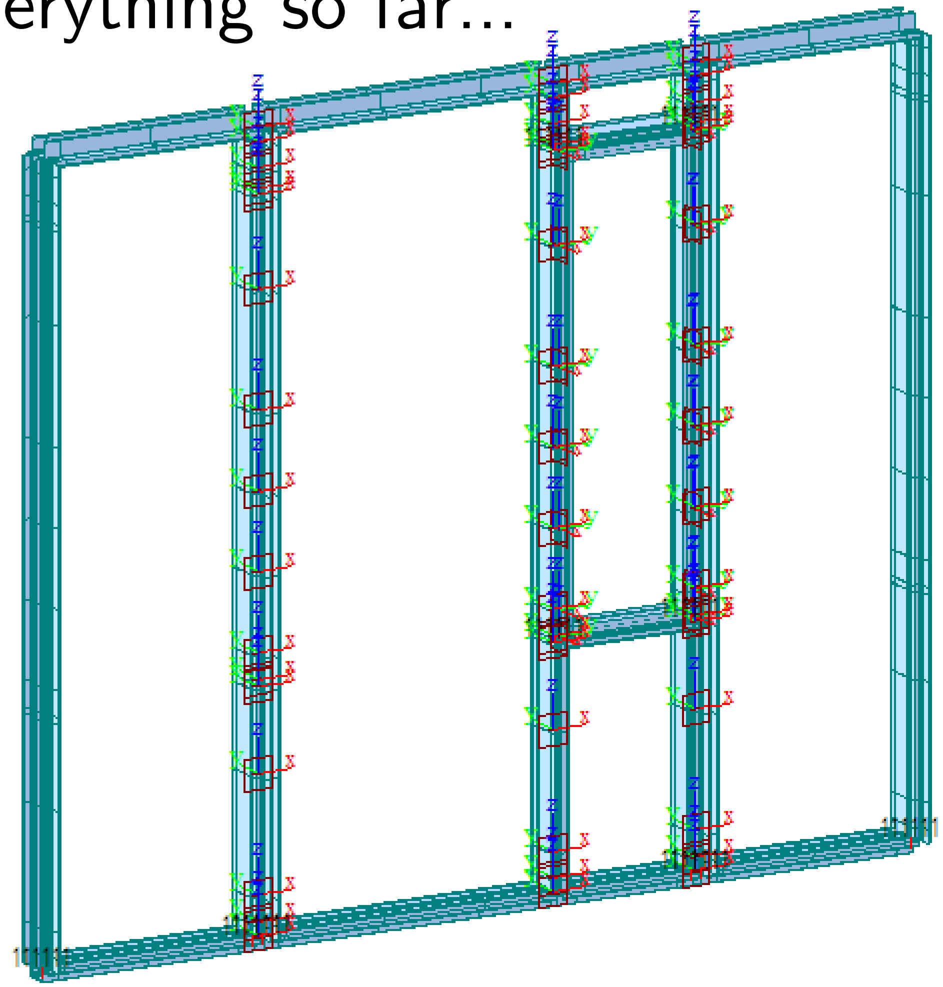


# Curtainwall system modeling

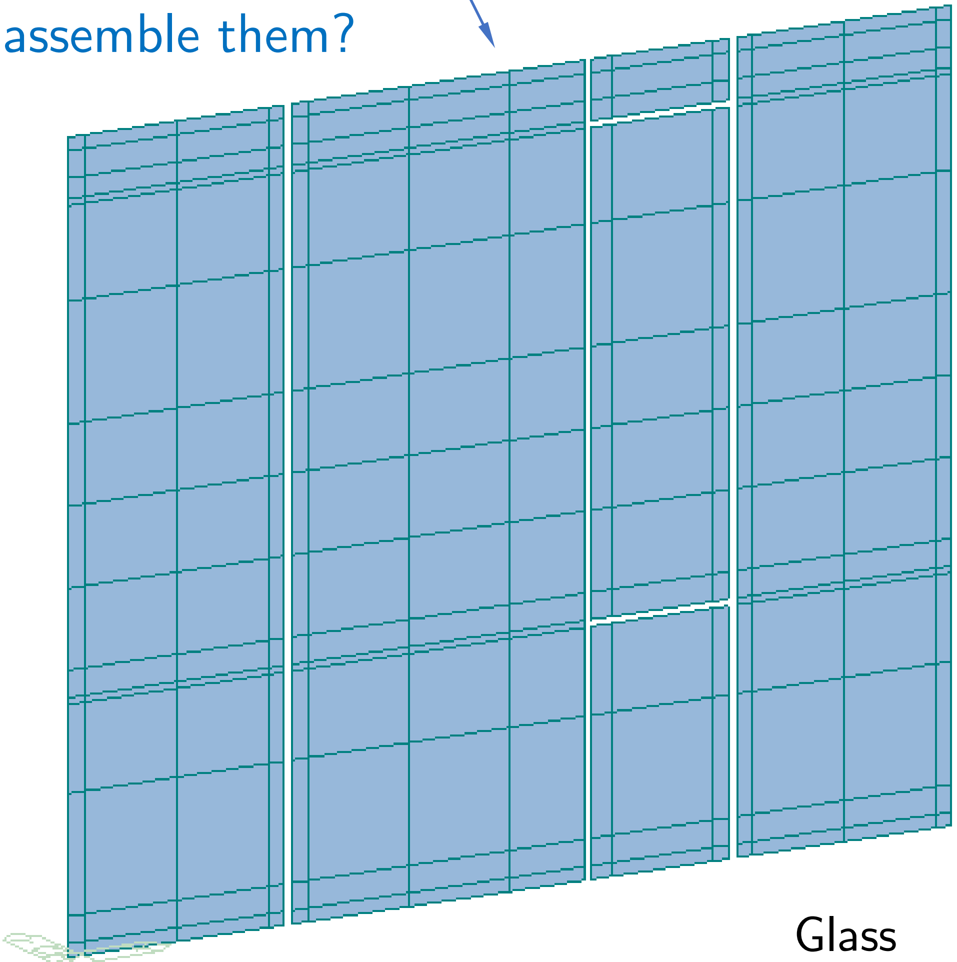
- Everything so far...

How to model the glass properties?

How to assemble them?



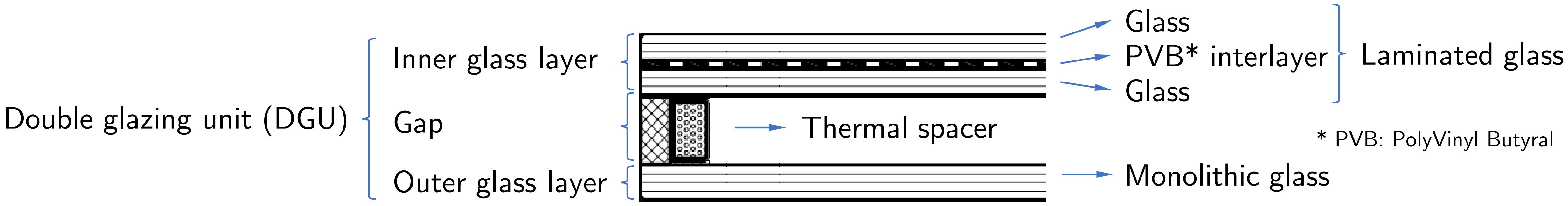
+



Glass

# Glass modeling

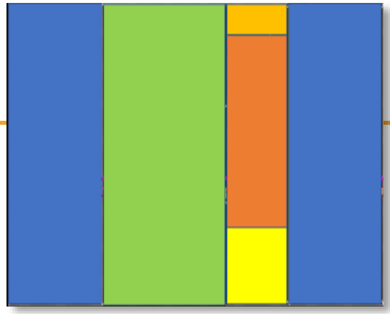
- Equivalent glass thickness?
  - + Glass covers the most part of façade
    - Important to accurately model the properties (mass, stiffness, ...)
  - + Multiple layers are used with insulated laminated glass




  - + Effective thickness of laminated glass → Galuppi and Royer-Carfagni (2012)
  - + Equivalent thickness of DGU → Annex C of Eurocode prEN 16612
    - Back-calculation of the overall effective stiffness

Galuppi, L., and Royer-Carfagni, G. F. (2012). "Effective thickness of laminated glass beams: New expression via a variational approach." *Engineering Structures*, 38, 53–67.

# GLASS MODELING

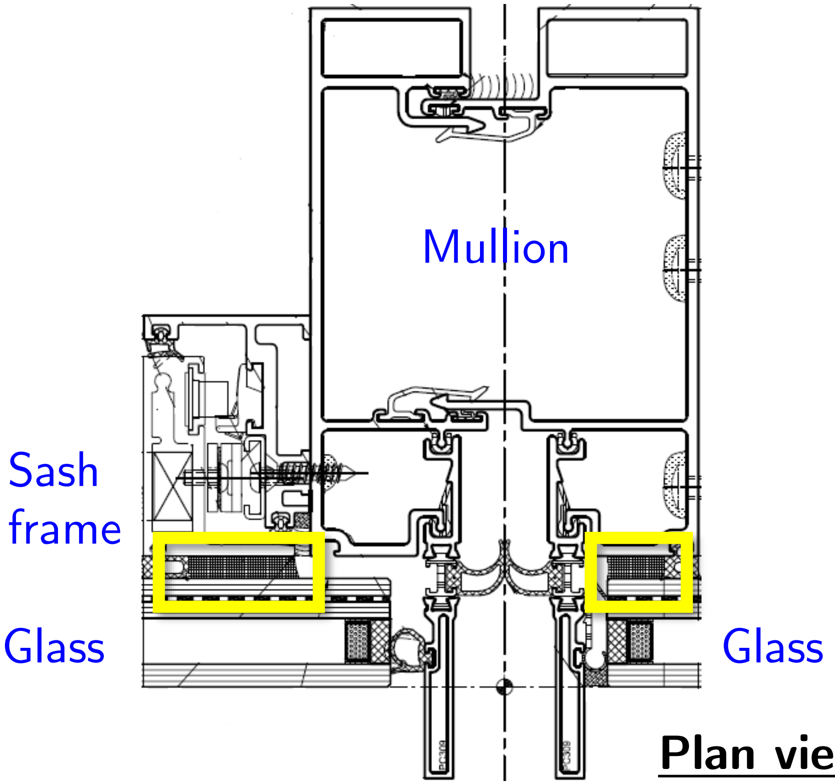


- Equivalent DGU thicknesses

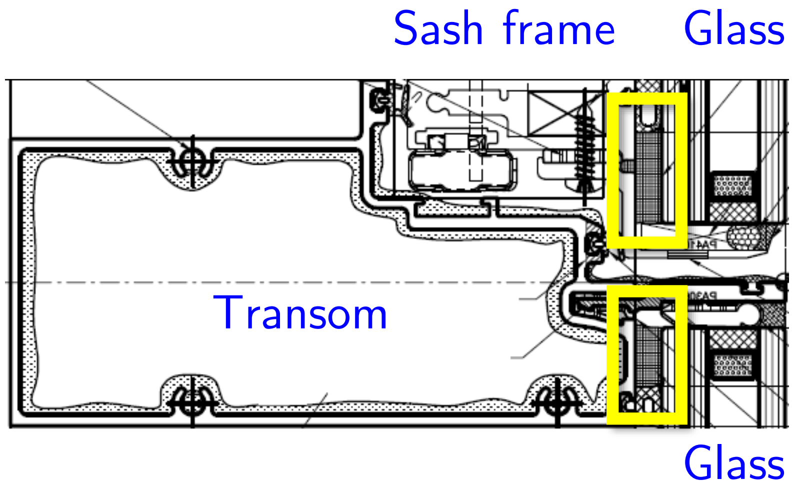
| | Outer layer | Gap | Inner layer (w/ PVB) | Equivalent Inner layer thickness | Equivalent DGU thickness | Thickness ratio R (R<1 → thinner) | Scaled Unit weight (pci) |
|---|---|---|---|---|---|---|---|
| | 0.25 in (6.35 mm) | 0.5 in (12.7 mm) | 0.405 in (10.29 mm) | 0.384 in (9.75 mm) | 0.4094 in (10.4 mm) | **0.646** = 0.4094/(0.25+0.384) | **0.1239** |
| | 0.1875 in (4.76 mm) | 0.625 in (15.88 mm) | 0.1875 in (4.76 mm) | 0.1875 in (4.76 mm) | 0.2258 in (5.73 mm) | **0.602** | **0.1329** |
| | 0.25 in (6.35 mm) | 0.5 in (12.7 mm) | 0.405 in (10.29 mm) | 0.365 in (9.27 mm) | 0.3754 in (9.53 mm) | **1.028** | **0.0778** |
| | 0.25 in (6.35 mm) | 0.5 in (12.7 mm) | 0.405 in (10.29 mm) | 0.357 in (9.068 mm) | 0.3495 in (8.87 mm) | **0.576** | **0.1389** |
| | 0.39 in (10 mm) | 0.47 in (12 mm) | 0.236 in (6 mm) | 0.236 in (6 mm) | 0.42 in (10.72 mm) | **0.667** | **0.1200** |

# Modeling the interactions between frame and glass

- Silicone joints (highlighted in yellow)
  + Located b/w glass and sash frame *or* b/w glass and main frame



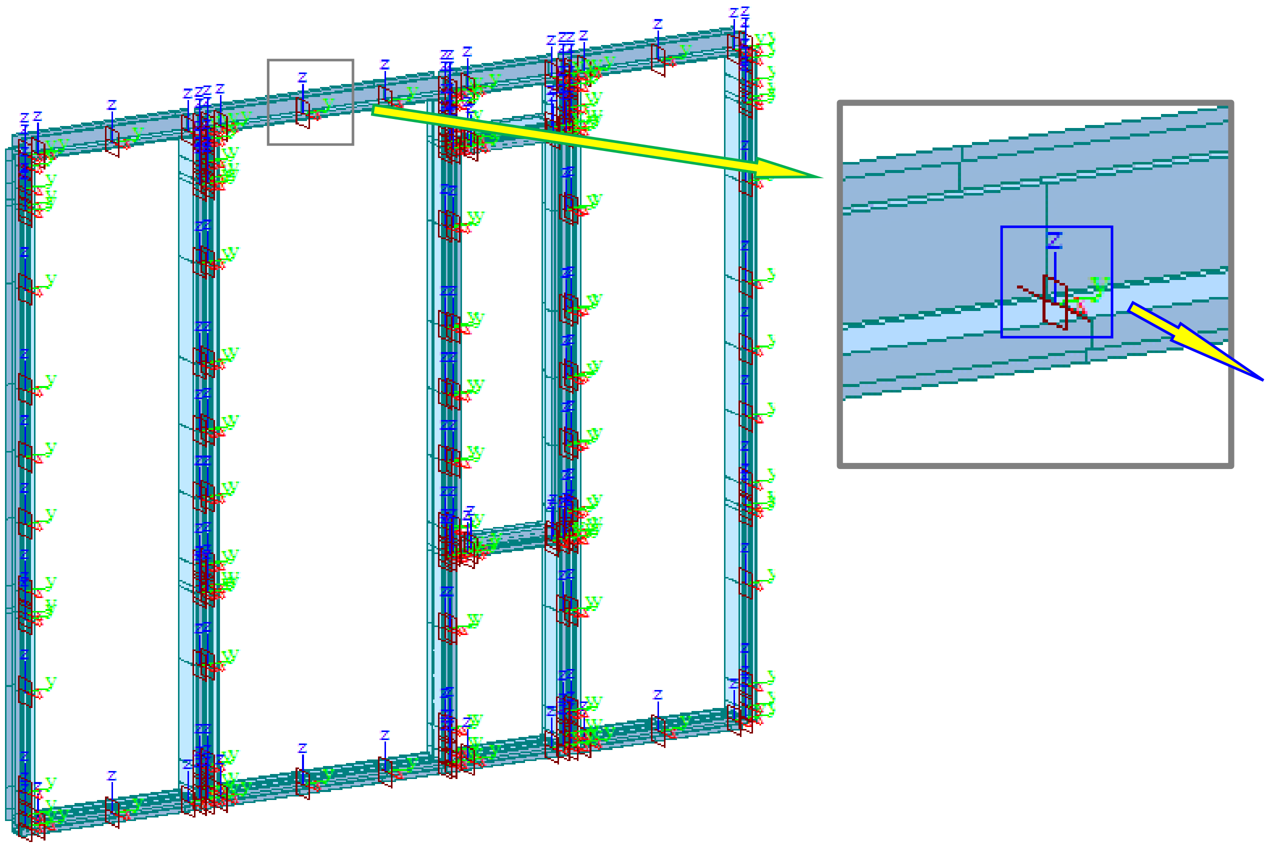

**Plan view** of cross-section




**Elevation view** of cross-section

# Modeling the interactions between frame and glass

- Silicone joints
  + Modeling using a set of translational and rotational springs

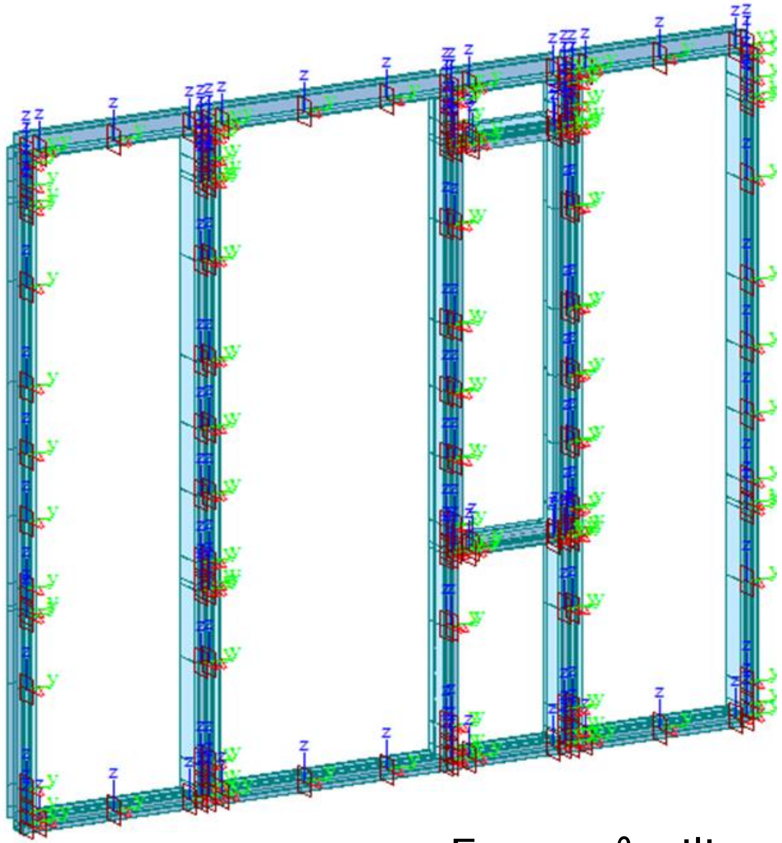


Translational & rotational springs for x, y, & z directions

- Translational springs (x, y & z)
- Rotational springs
  - Minimal rotational resistance (x, y & z)

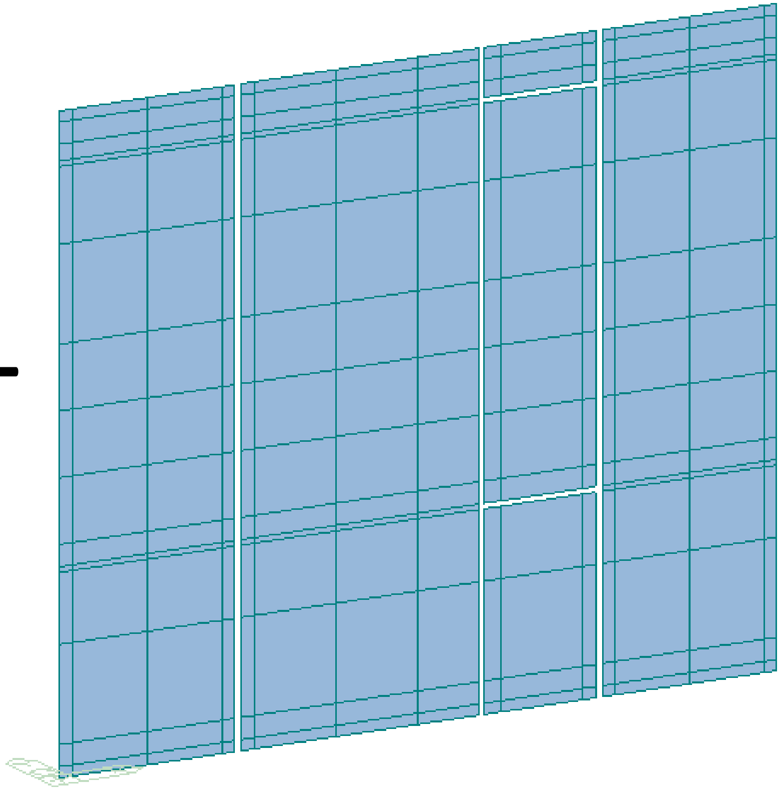
# Curtainwall system modeling

- Assembling all together



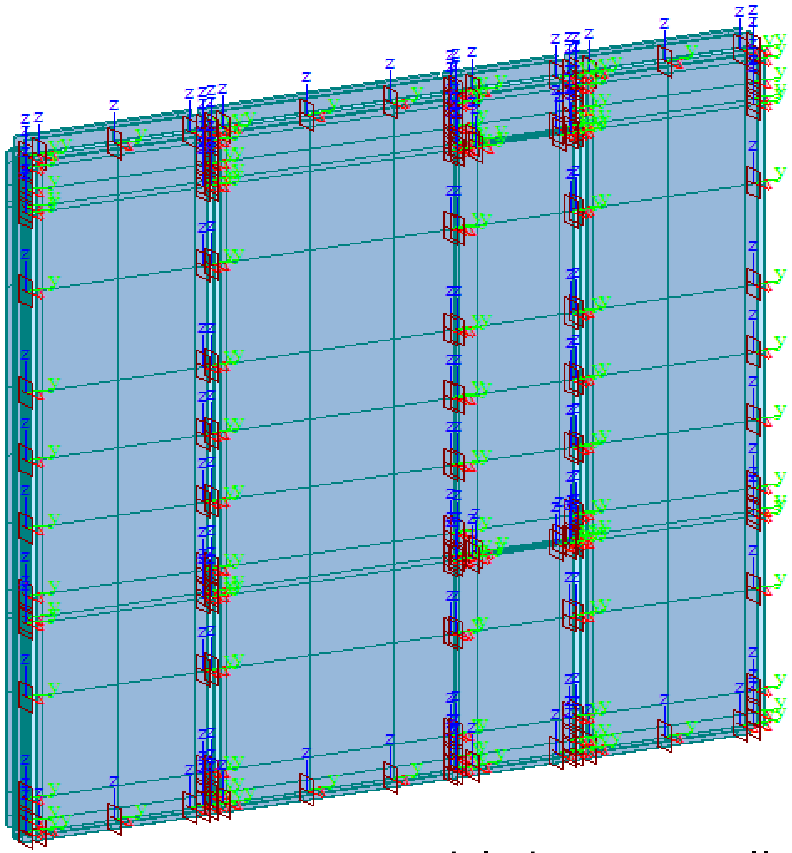
Frames & silicone

+



Glass

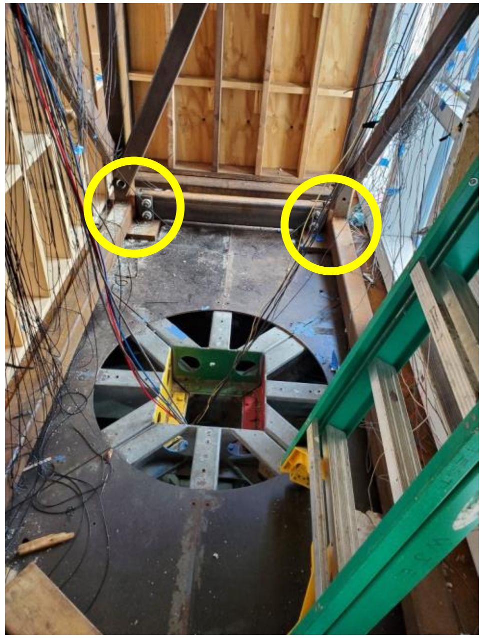
=



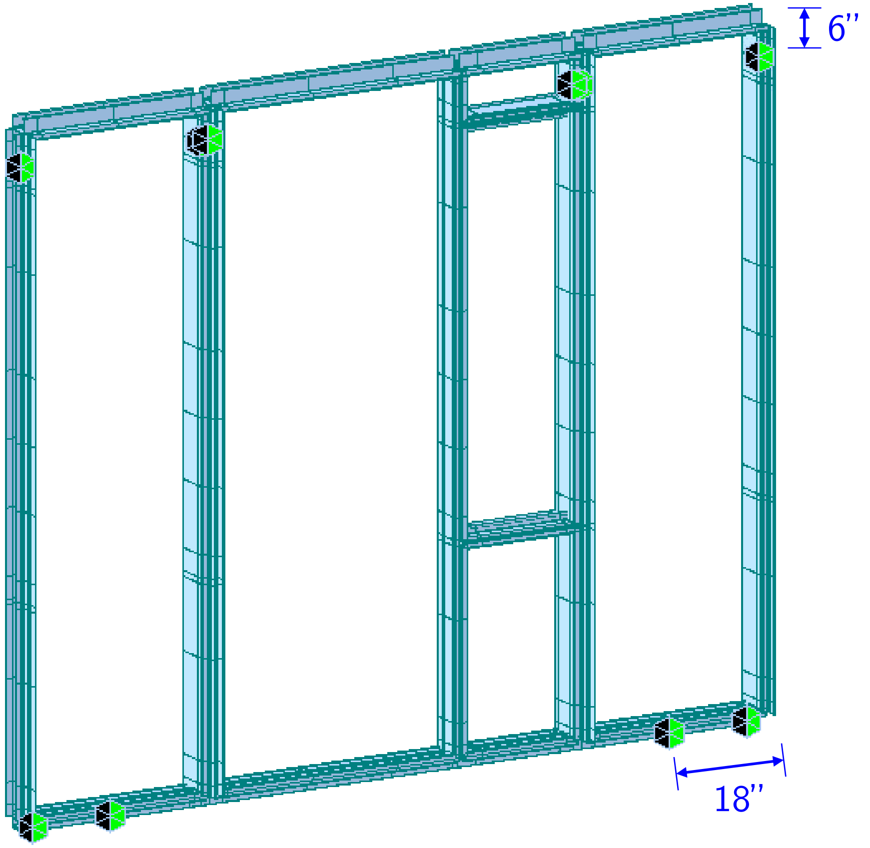
Modeled curtainwall

# Boundary condition

- Modeled boundary condition
  - Simple supports
  - No vertical deflection along the bottom transom



Connections to the steel structure; Top (left figure) & Bottom (right)



# Eigen analysis result

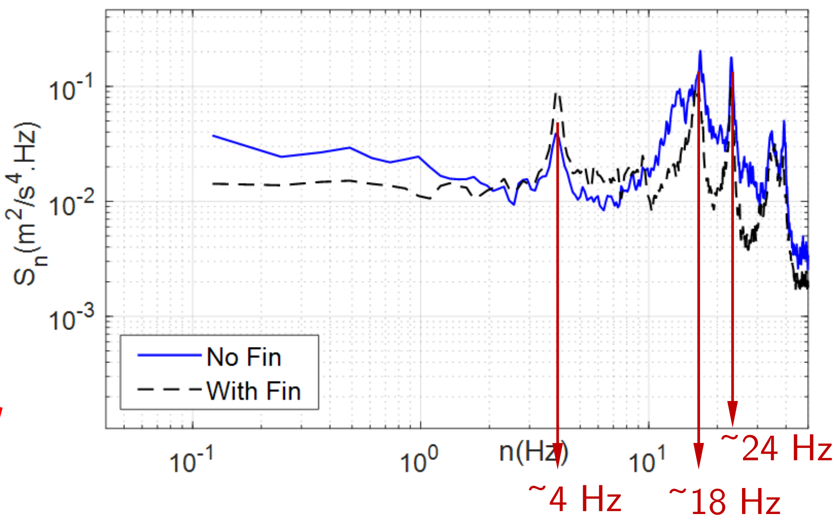
- Eigenvalues

| Mode: | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| f (Hz) | 5.0057 | 17.5723 | 22.9353 | 24.8018 | 25.3669 |

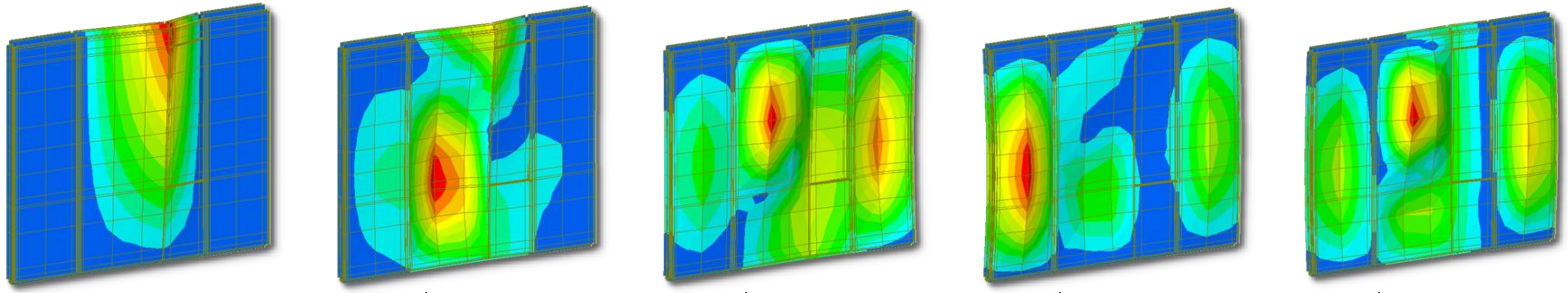
+ Major frequencies
  - ~5Hz & ~18Hz: Middle panel is excited
  - ~24Hz: All panels are excited

**Overall agree with the PSD spikes observed from the WOW testing.**

Acceleration at the center (WOW)



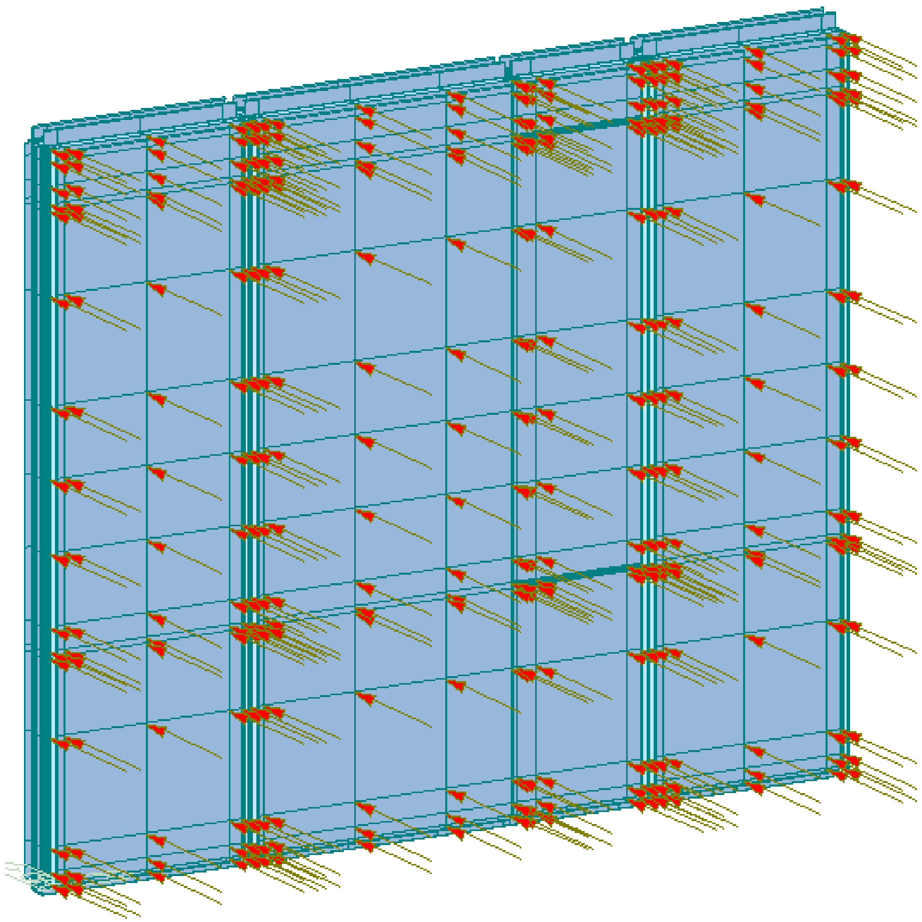

- Eigenmodes

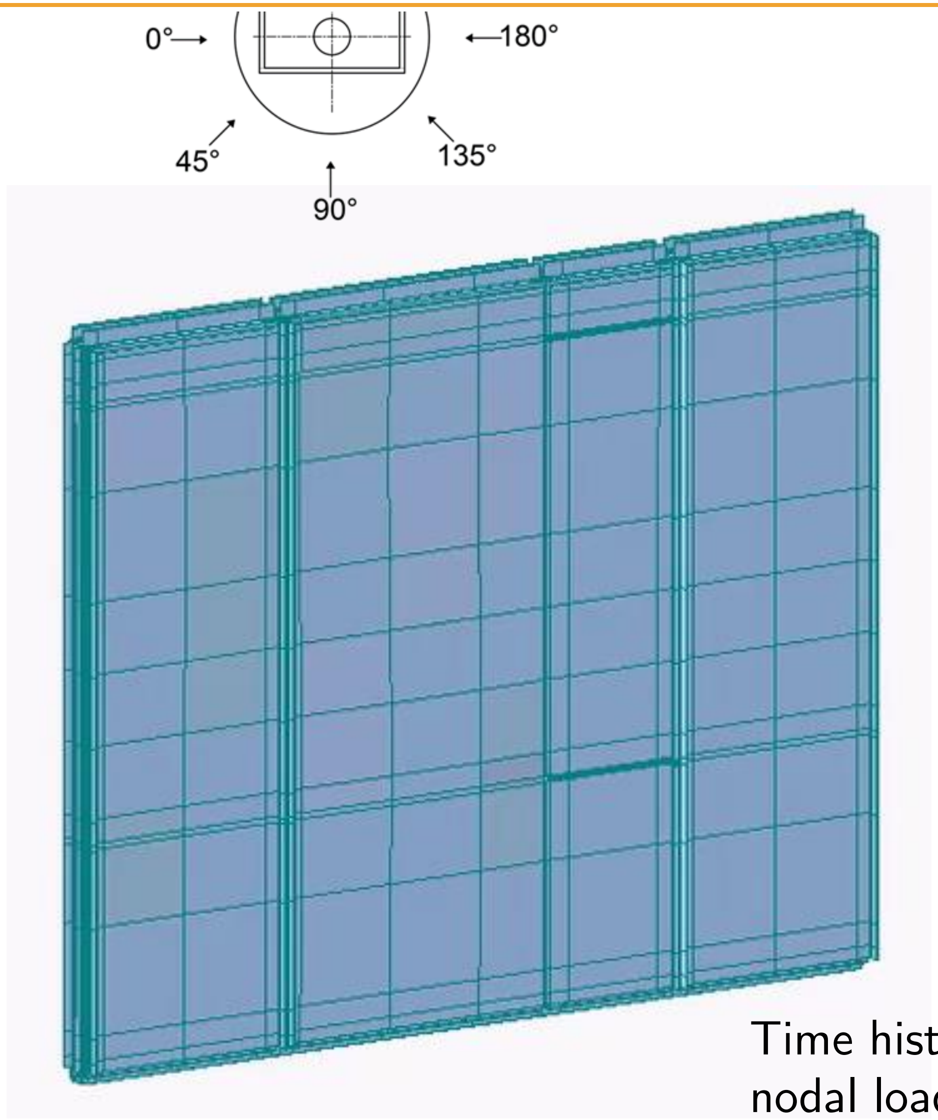


1st mode  2nd mode  3rd mode  4th mode  5th mode

# Time history analysis

- 50 MPH / 90 degrees

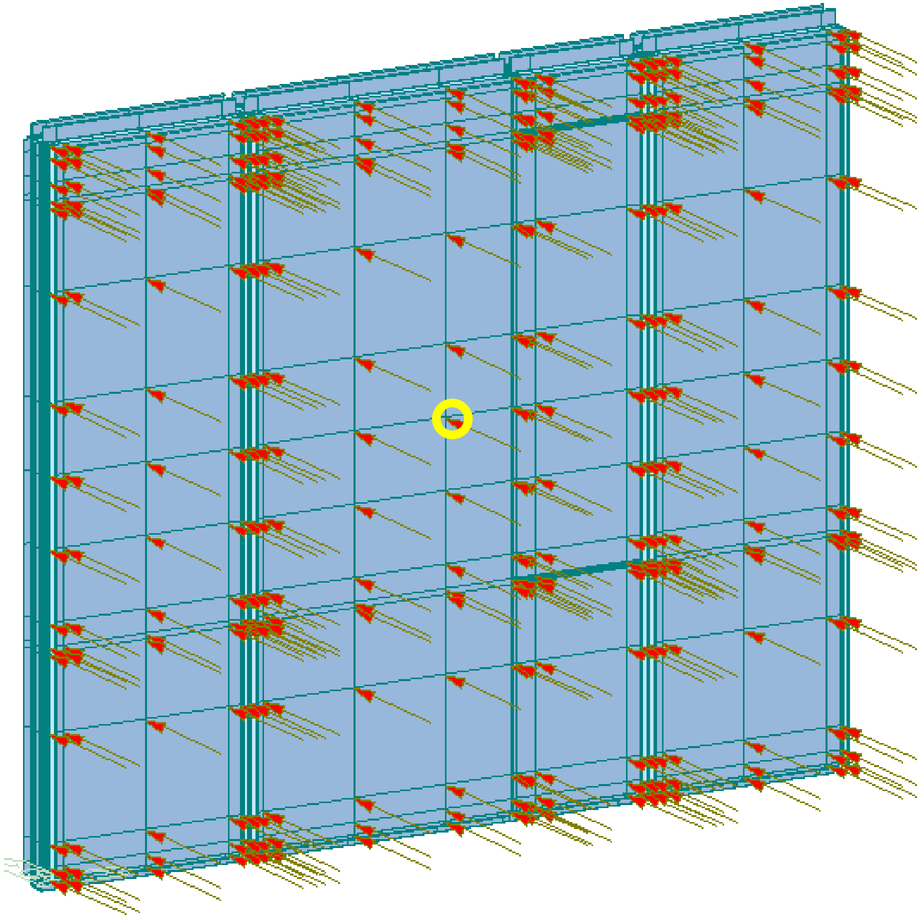


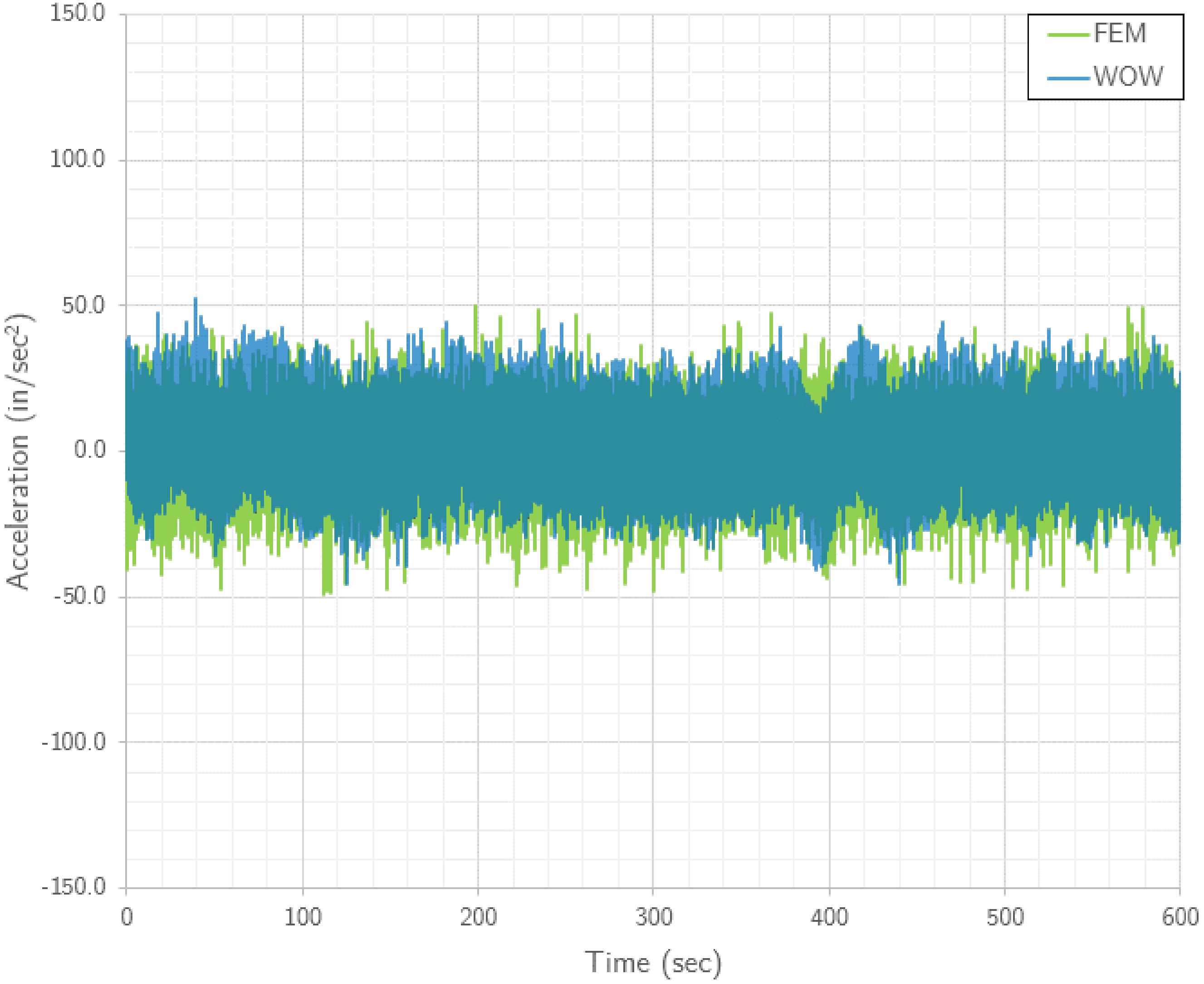



Time history nodal loads applied

# Time history analysis

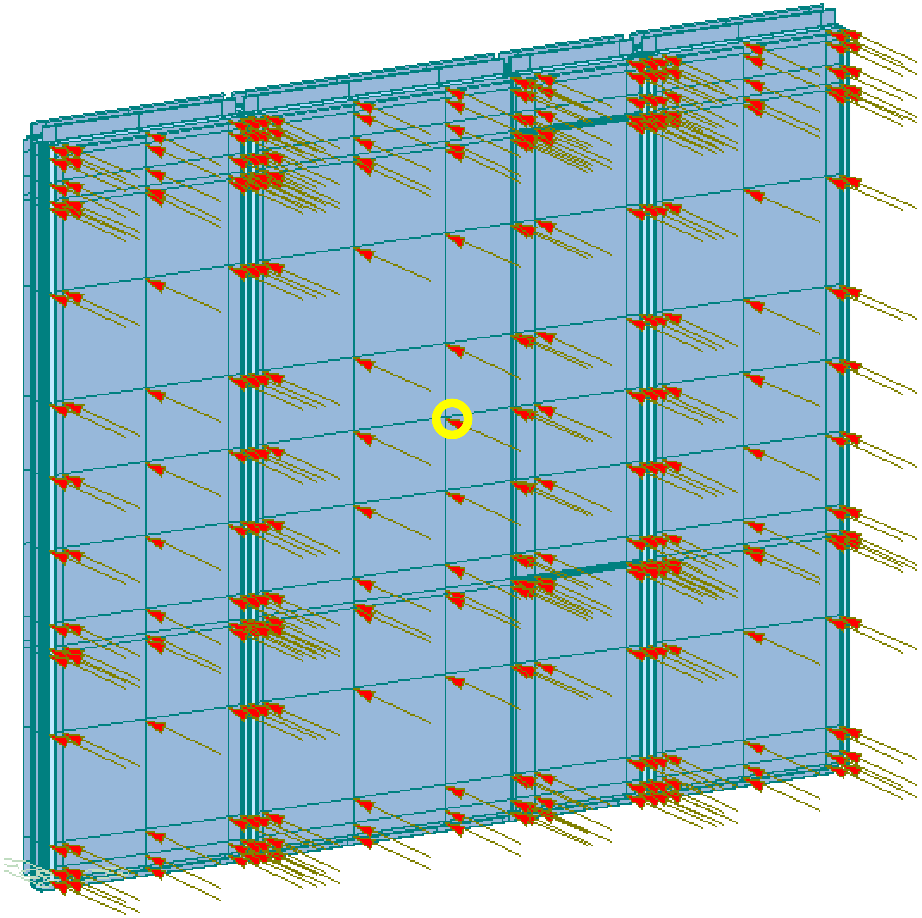
- Acceleration

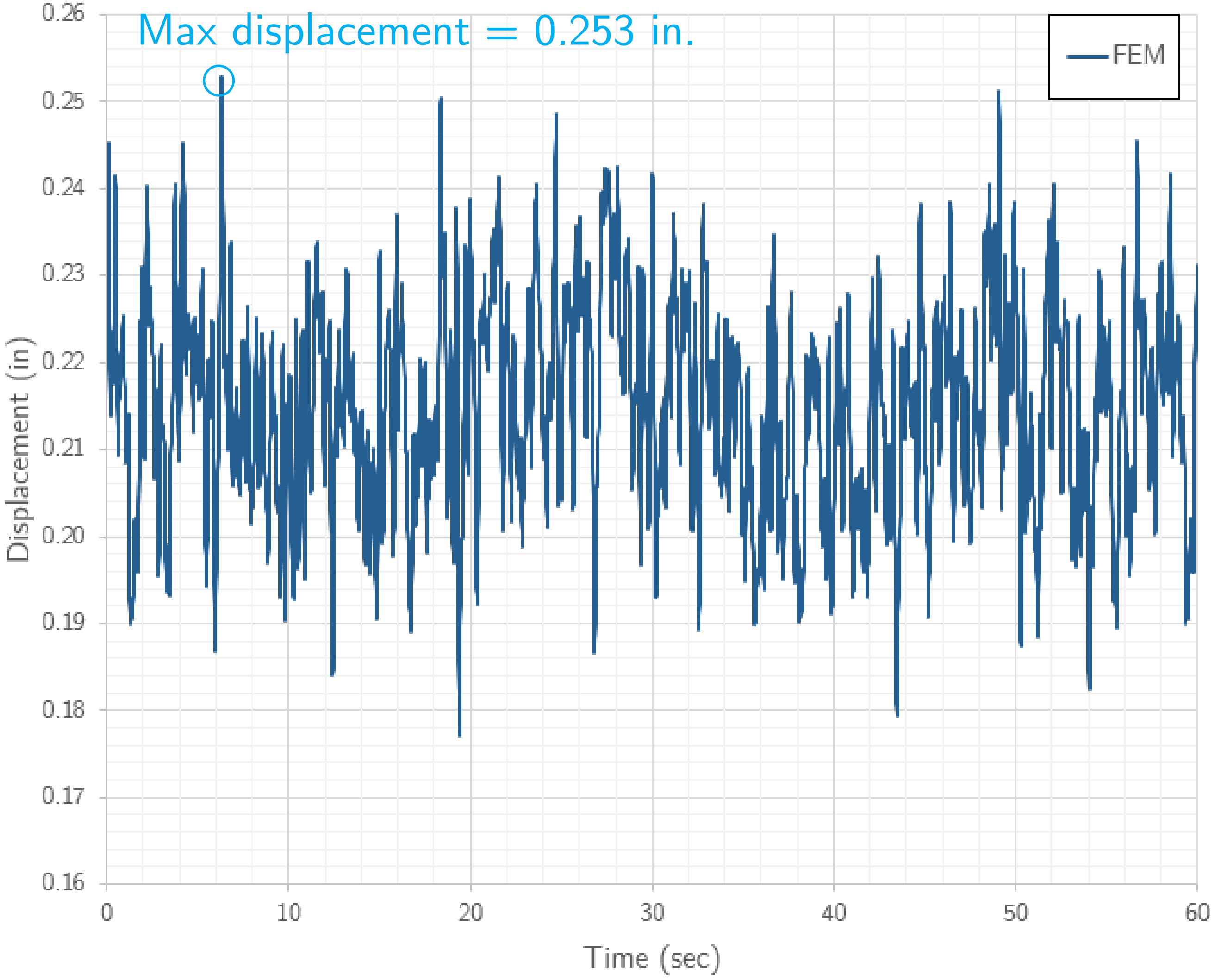




# Time history analysis

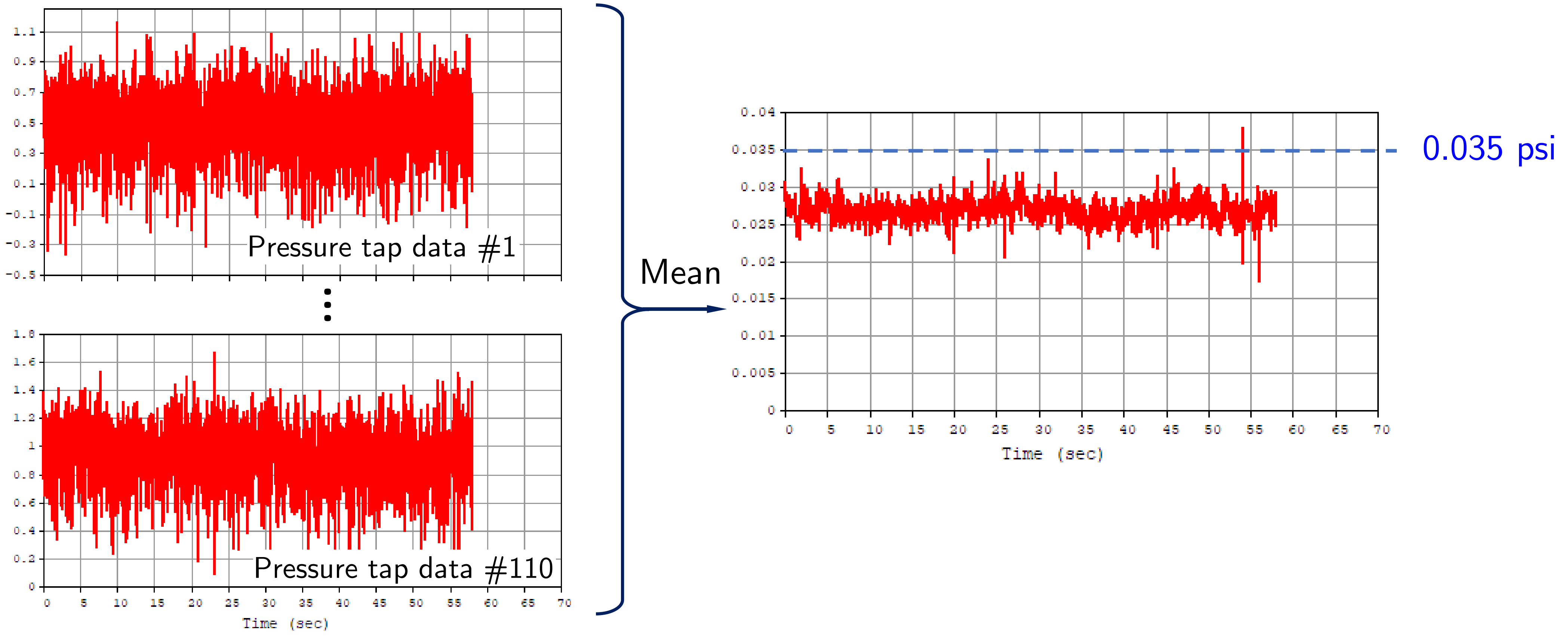
- Displacement





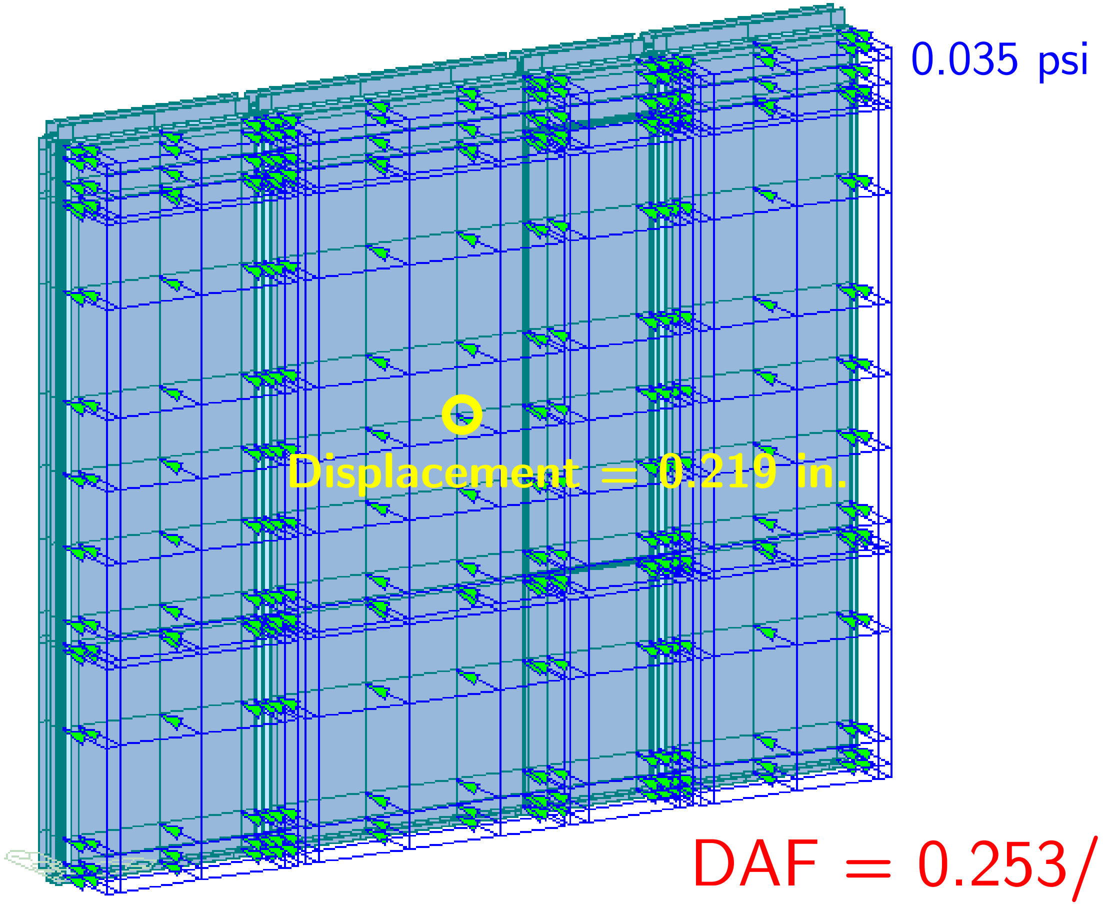
# Time history analysis

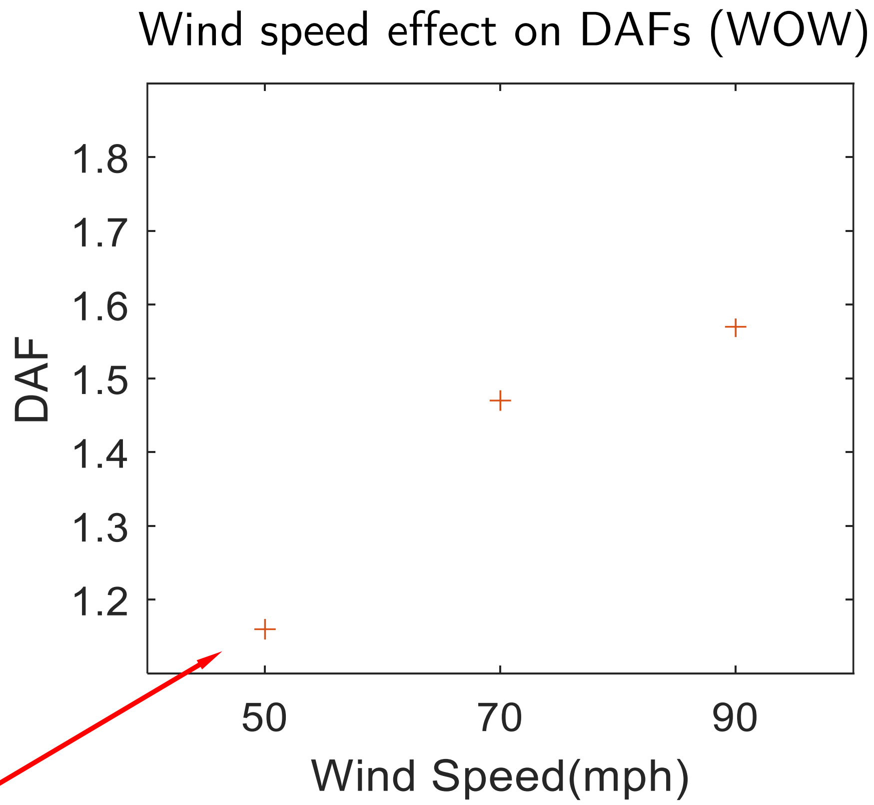
- Dynamic Amplification Factor
  - Quasi static pressure computation (Max)



# Time history analysis

- Dynamic Amplification Factor

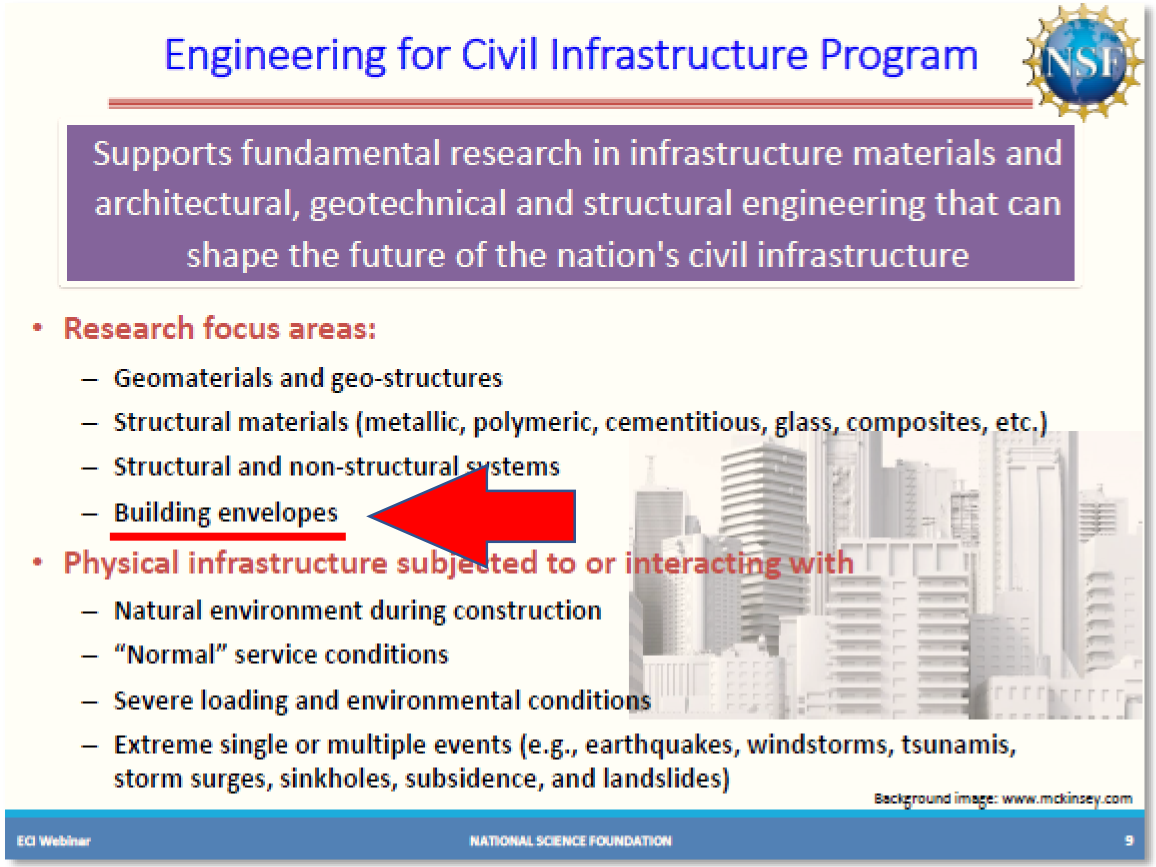



DAF = 0.253/0.219 = 1.15

# Concluding remarks

- Building envelopes: the most vulnerable components under wind loads
- High complexity and uncertainty in the response under wind loads
- Relatively unexplored area
  + NSF ECI clearly indicated "building envelopes" as one of 4 research foci
  + Great research topic!
- FIU WOW EF with capability of full-scale envelope testing and numerical modeling




NSF ECI Webinar slide (May 11, 2020)


Courtesy of **Nathan H. Lee**