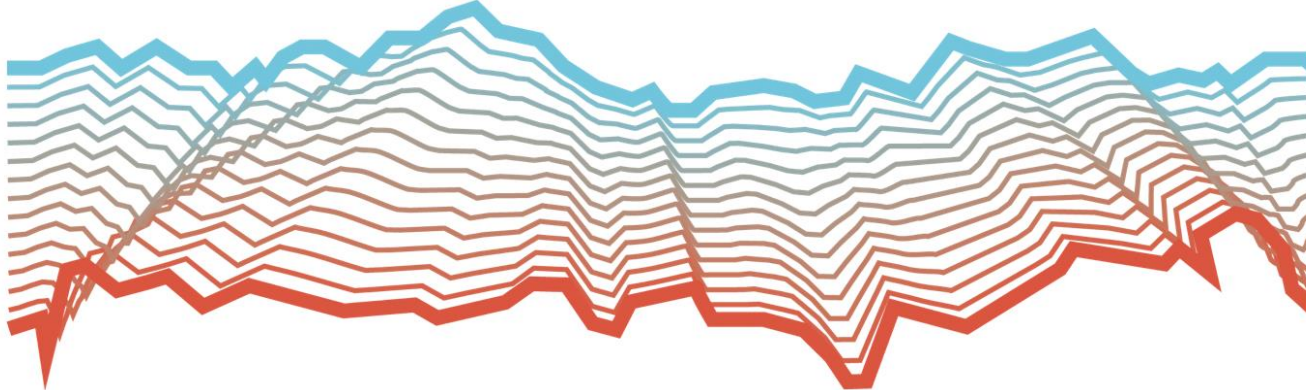
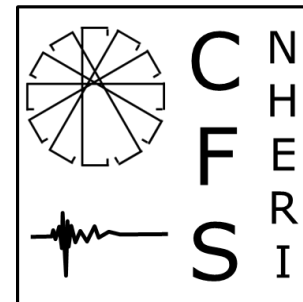




12th National Conference on Earthquake Engineering

Salt Lake City, Utah
27 June - 1 July 2022

Reimagining Risk and Resilience



Finite Element Modeling and Validation of CFS-framed Multi-story Buildings

Amanpreet Singh
University of California San Diego
June 30, 2022

UC San Diego **JOHNS HOPKINS**
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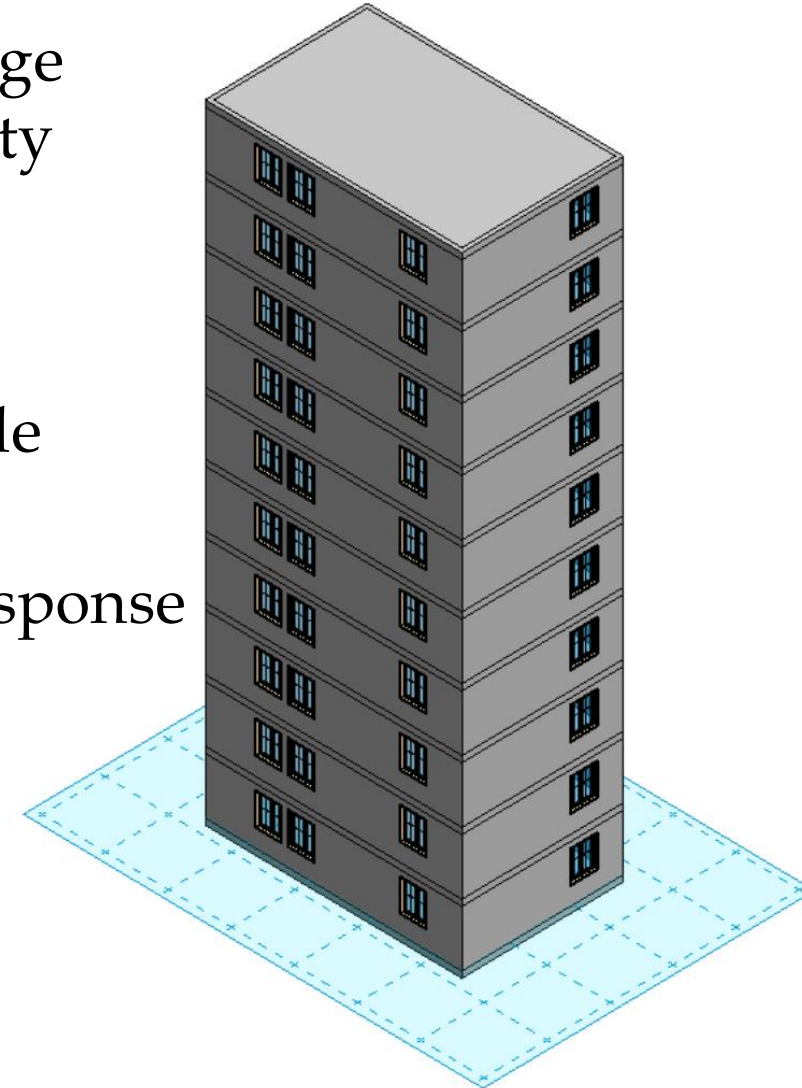


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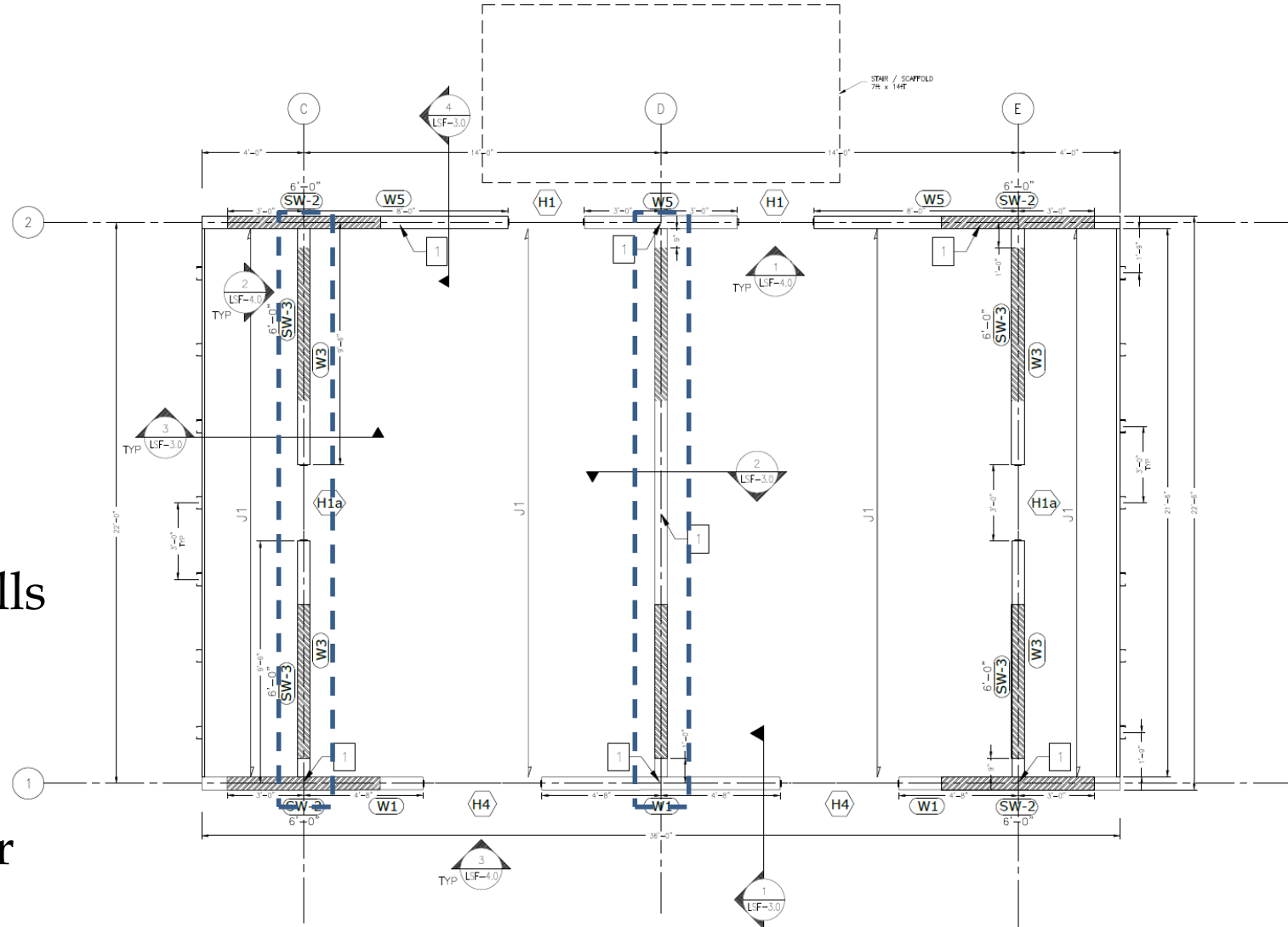
10-story CFS-NHERI Building Test: *Planned for 2023*

- 10-story CFS framed building test at upgraded 6-DOF Large High Performance Outdoor Shake Table (LHPOST6) facility
- Numerical modeling for benchmark seismic response predictions of 10-story building
- Model validation against available system-level shake table experiments
 - CFS-HUD (6-story): Documented complete building response
 - Extend to 10-story CFS-NHERI test building
- Guide ground motion scaling for shake table experiments
 - Choice of motions
 - Scale factors
 - Test protocol



CFS-NHERI 10-story Test Building: Overview

- Building height = 103ft,
Story height = 10ft
- Plan area = 36ft x 22.5ft
- Design location = Irvine, CA
($S_{DS} = 1.009g$, $S_{D1} = 0.452g$)
- $R = 6.5$, $\Omega_o = 3.0$, $C_d = 4.0$
- Lateral force resisting system:
steel sheet sheathed CFS shear walls
 - *Longitudinal walls*: use holdowns or plate holdowns attached to stud packs or HSS sections
 - *Transverse walls*: use floor-to-floor tension tie-rods



Wall-Line Tests: *Experiment Objectives*

- Characterize dynamic performance of CFS-framed **wall-lines** subjected to in-line earthquake motions of increasing intensity:
 - Effect of finishes and effect of openings on wall behavior
 - Comparison of Type I and Type II walls
 - Compare steel tension tie-rods assembly versus hold-down systems
 - Compare symmetrical and unsymmetrical walls
- Examine lateral load sharing between shear walls placed in-line with gravity walls
- In total, 18 test specimens; blend of dynamic (shake table) and quasi-static (inertial-induced displacement control) testing regimes

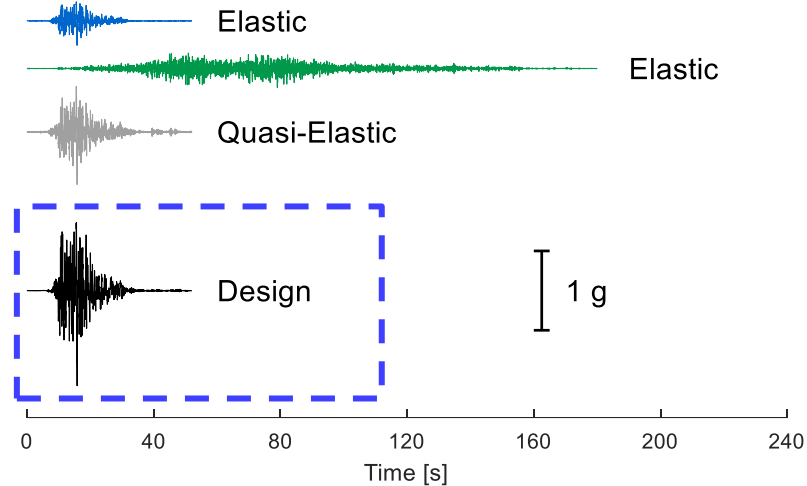


Singh, A., Wang, X., Zhang, Z., Derveni, F., Castaneda, H., Peterman, K. D., Schafer, B. W., and Hutchinson, T. C. (2021). "Steel Sheet Sheathed Cold-Formed Steel Framed In-line Wall Systems. I: Impact of Structural Detailing" *ASCE Journal of Structural Engineering*. (accepted)

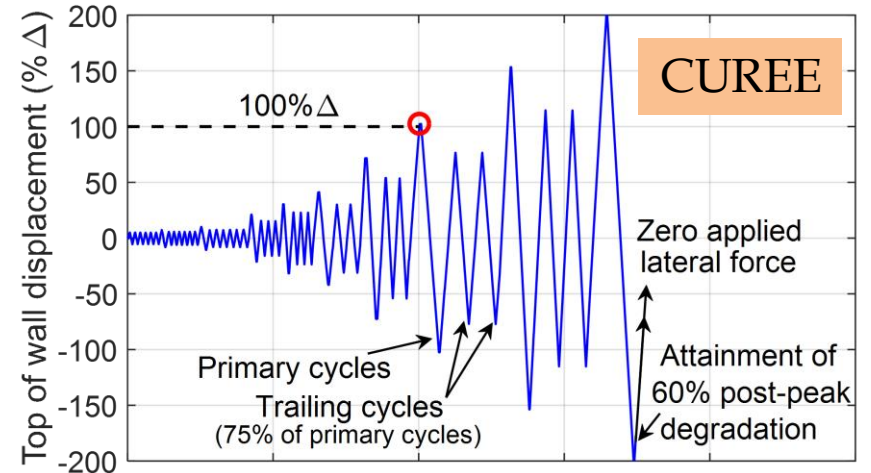
Singh, A., Wang, X., Zhang, Z., Derveni, F., Castaneda, H., Peterman, K. D., Schafer, B. W., and Hutchinson, T. C. (2021). "Steel Sheet Sheathed Cold-Formed Steel Framed In-line Wall Systems. II: Impact of Nonstructural Detailing" *ASCE Journal of Structural Engineering*. (accepted)

Wall-Line Tests: *Testing Phases*

Shake Table Tests
NHERI@UC San Diego



Quasi-static Tests
Powell Laboratory



NHERI@
UC San Diego

CFS-NHERI IN-LINE WALL SHAKE TABLE TESTS

SGGS-1 BASELINE SPECIMEN
1994 NORTHRIDGE (CANOGA PARK)
SCALED TO DESIGN PERFORMANCE LEVEL
OCTOBER 29, 2018

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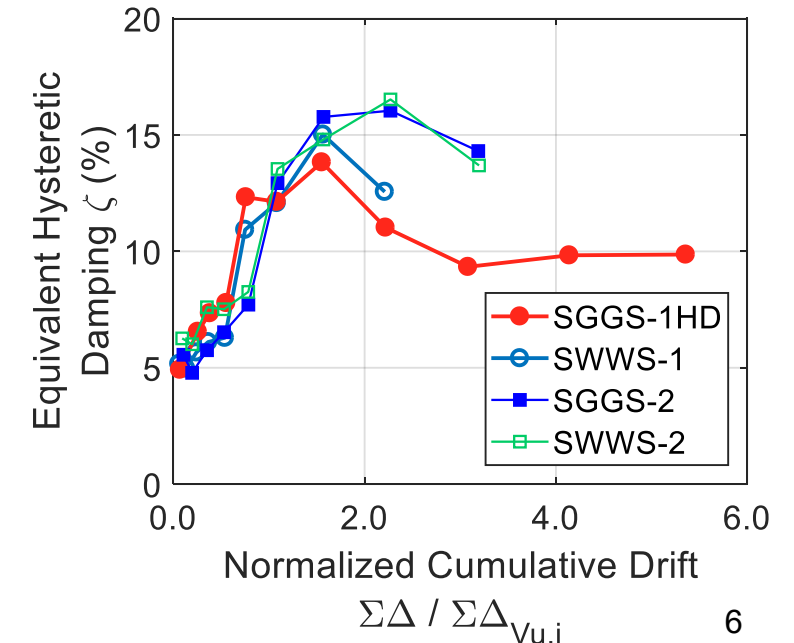
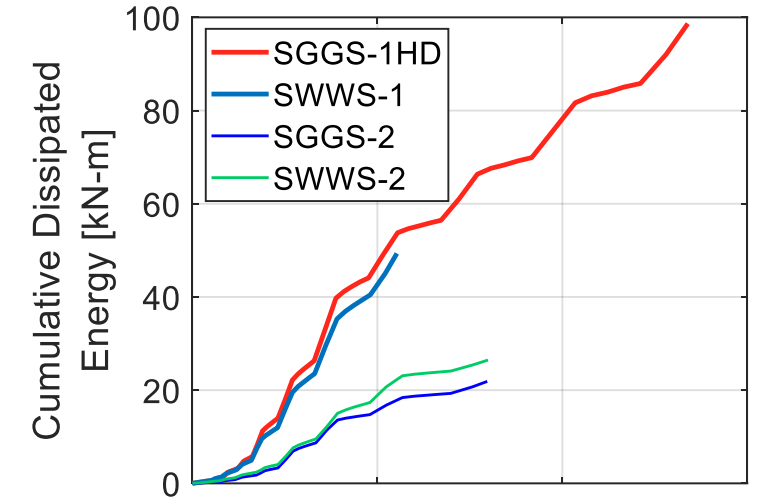
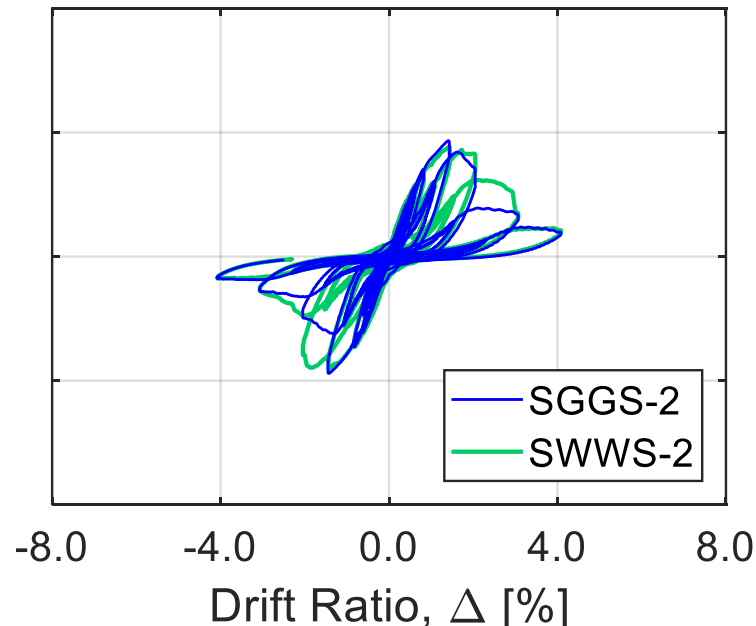
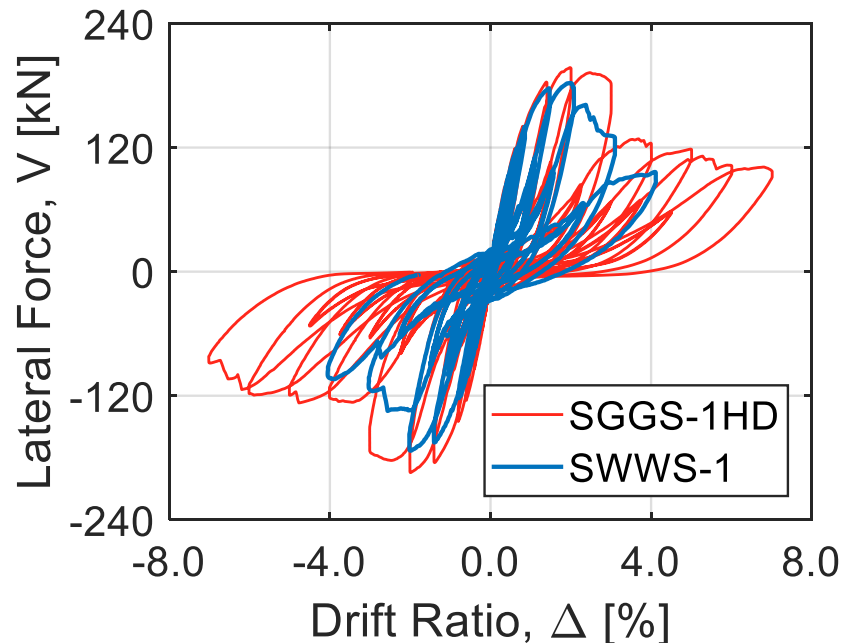
CFS-NHERI IN-LINE WALL QUASI-STATIC TESTS POWELL STRUCTURAL RESEARCH LABORATORIES

SGGS-1HD: TYPE I SPECIMEN WITH HOLDOWNS
DECEMBER 18, 2019

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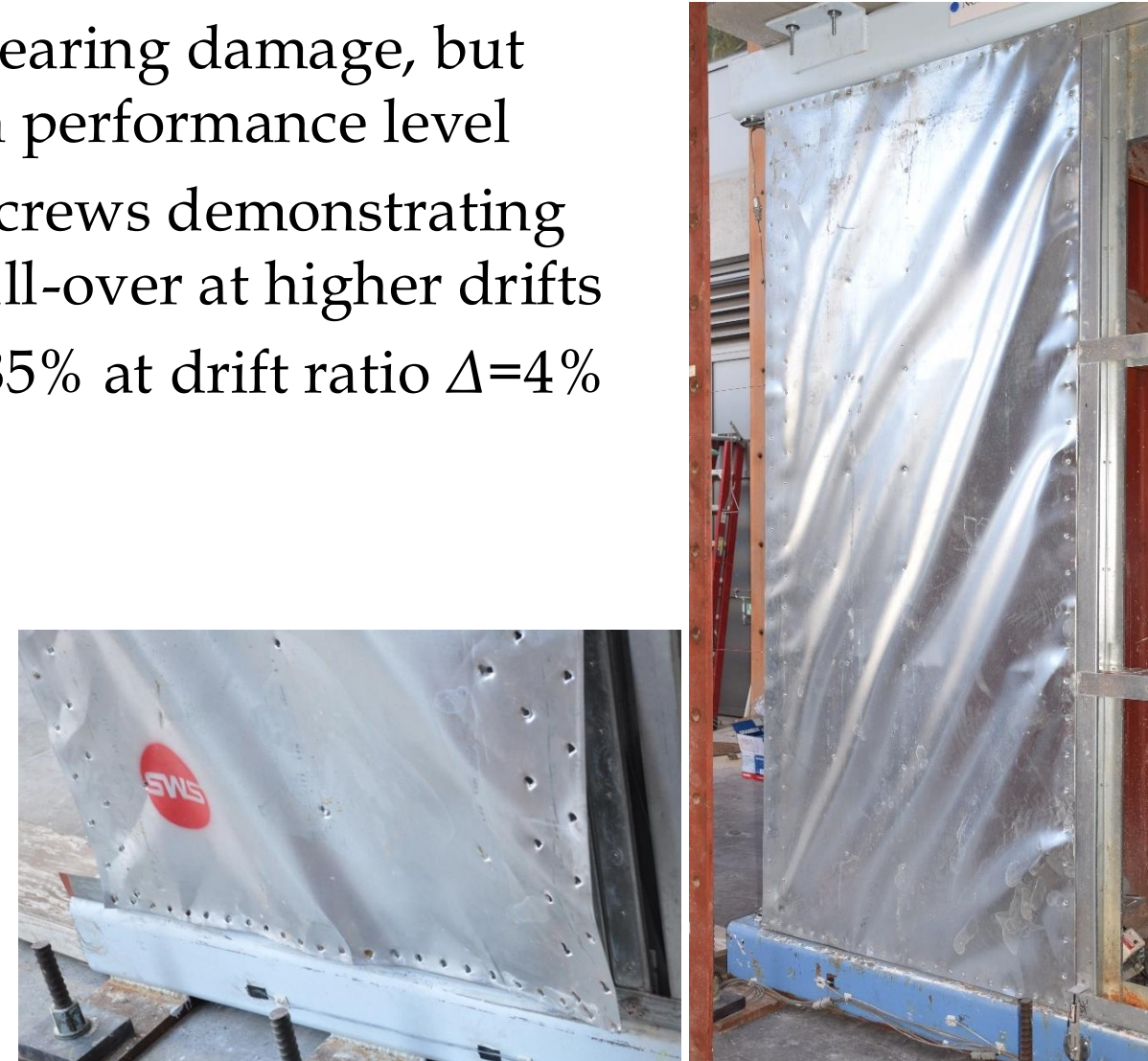
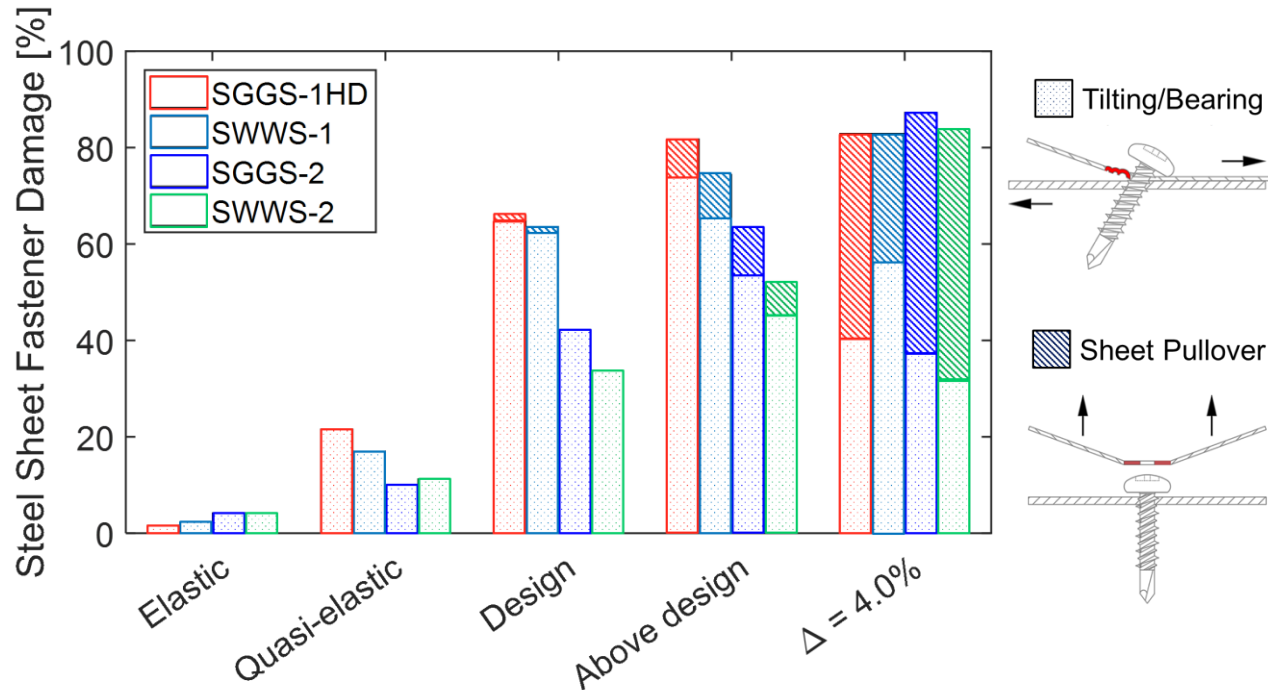
Wall-Line Tests: *Hysteretic Response*

Specimen	Wall strength, V_u [kN]	Drift ratio at strength Δ_{vu} [%]	Residual strength at $\Delta=4\%$ [kN]	Elastic stiffness, K [kN/cm]
SGGS-1HD	195.8	2.00	123.0	86.2
SWWS-1	177.9	1.98	99.0	74.8
SGGS-2	112.6	1.42	22.2	45.3
SWWS-2	107.2	1.43	23.2	53.4



Wall-Line Tests: *Fastener Damage*

- 30-60% fasteners expected to have tilting/bearing damage, but little to no sheet pull-over failures at design performance level
- Damage mode for a significant fraction of screws demonstrating bearing/tilting initially changes to sheet pull-over at higher drifts
- Percentage of screws damaged reaches 80-85% at drift ratio $\Delta=4\%$

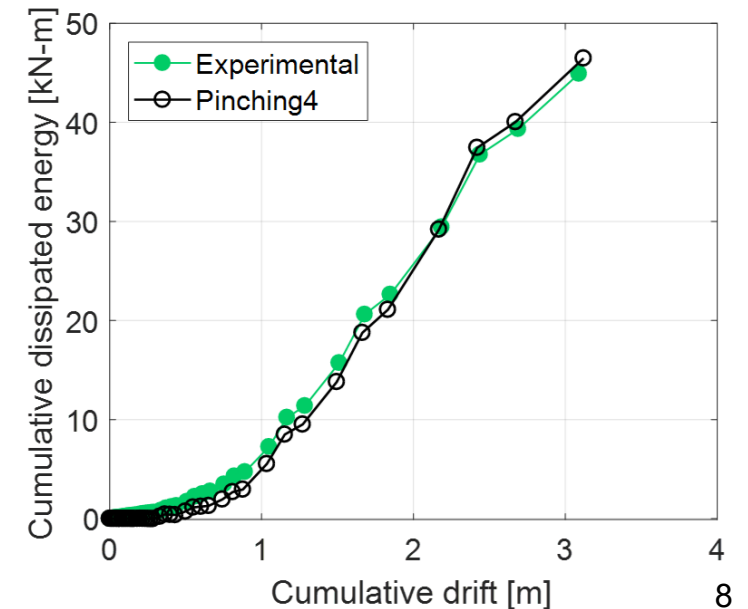
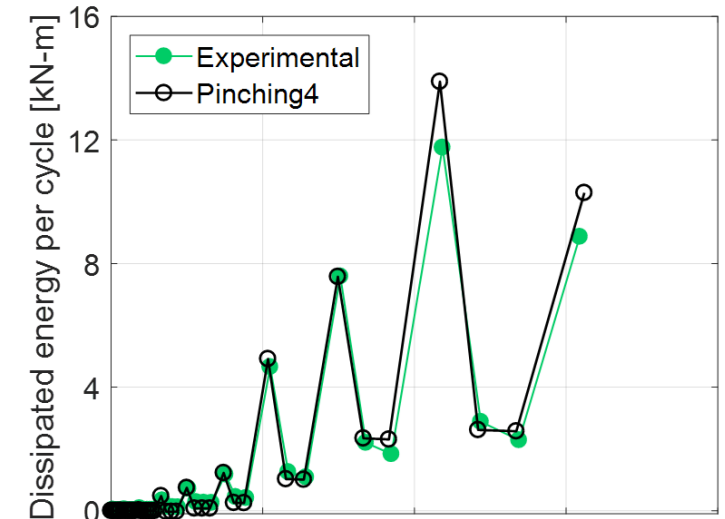
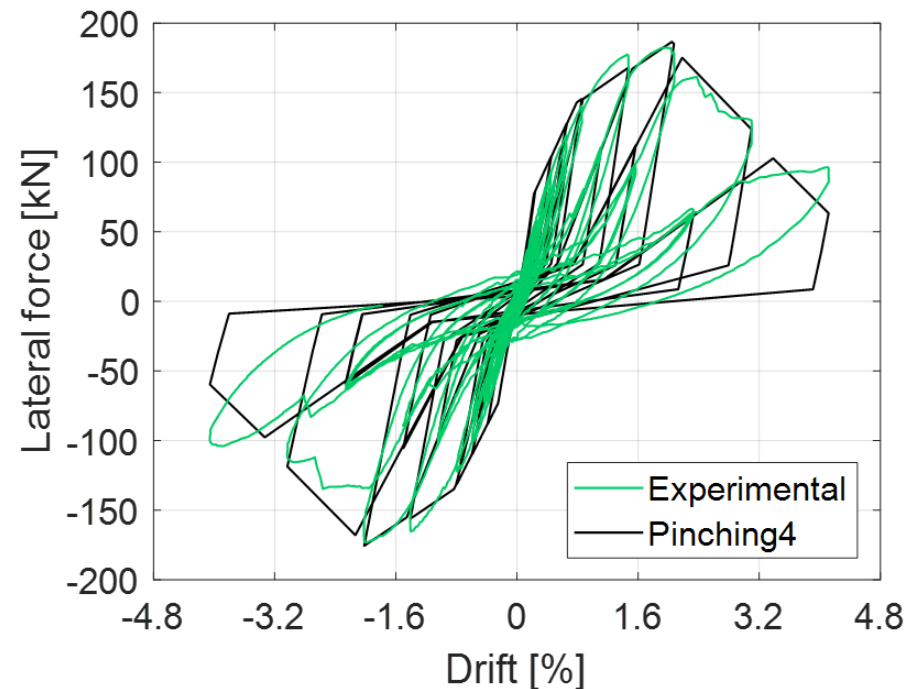


Wall-Line Tests: *Nonlinear Behavior Calibration*

- Nonlinear hysteretic springs for shear wall elements with *Pinching4* material model in OpenSees
- Material parameters calibrated to achieve optimal match between experimental and simulation hysteresis backbone, as well as cumulative and per cycle dissipated energy of the hysteretic loops

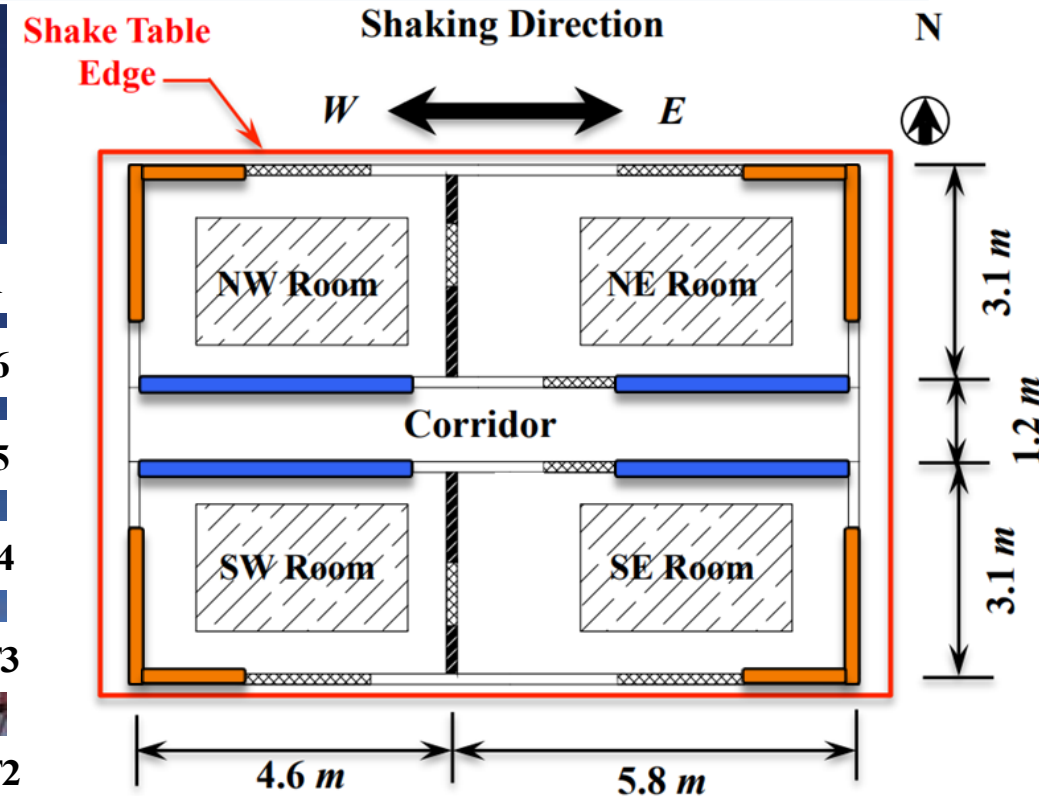
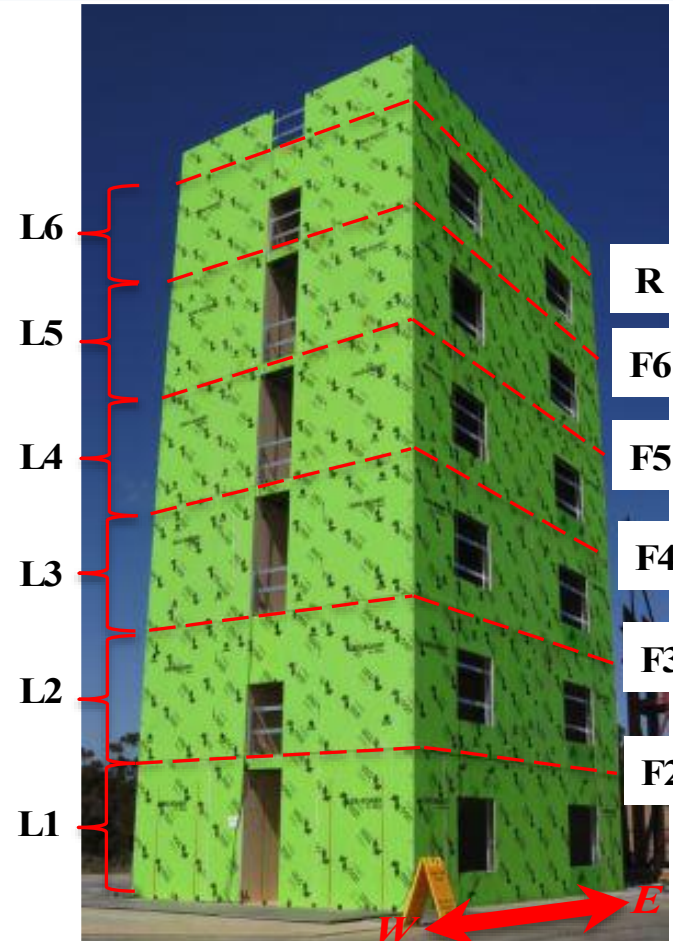


Quasi-static test wall-line specimen SWWS-1



CFS-HUD 6-story Test Building: Overview

- Building height = 64ft, Story height = 10ft
- Plan area = 34ft x 24ft
- Building design location = Downtown Los Angeles
- $S_{DS} = 1.53g$, $S_{D1} = 0.81g$
- $R = 6.5$, $\Omega_o = 3.0$, $C_d = 4.0$
- Lateral force resisting system: CFS shear walls
 - *Corridor walls*: primary lateral resisting elements
 - *Exterior walls*: resist transverse & torsional loads

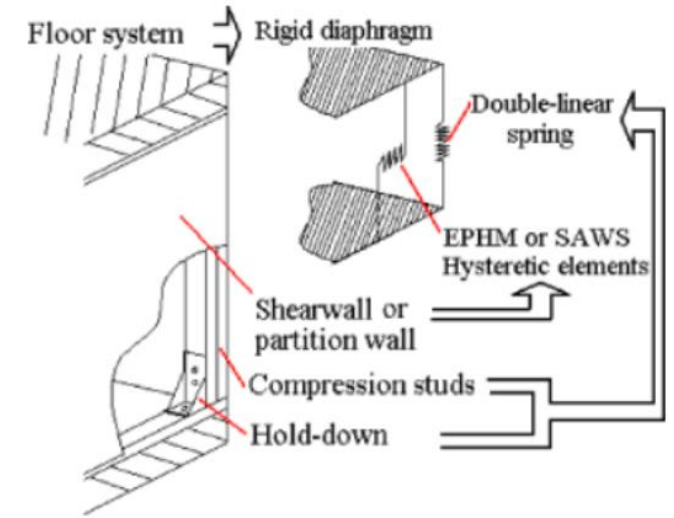


Hutchinson, T. C., Wang, X., Hegemier, G., Kamath, P., & Meacham, B. (2021). Earthquake and postearthquake fire testing of a midrise cold-formed steel-framed building. I: Building response and physical damage. *Journal of Structural Engineering*, 147(9), 04021125.

Wang, X., & Hutchinson, T. C. (2021). Earthquake and Postearthquake Fire Testing of a Midrise Cold-Formed Steel-Framed Building. II: Shear Wall Behavior and Design Implications. *Journal of Structural Engineering*, 147(9), 04021126.

Numerical Modeling: *Simplified Model*

- Simplified model for multi-story building dynamic analysis
 - Nonlinear hysteretic springs for shear wall elements
 - Nonsymmetric linear springs for each uplift restraints
 - ✓ Important for tall buildings
 - Rigid diaphragms for the roof and floors
- OpenSeesPy for numerical modeling of structural components for benchmark predictions of building response
- Use non-linear spring elements validated against component-level experiments



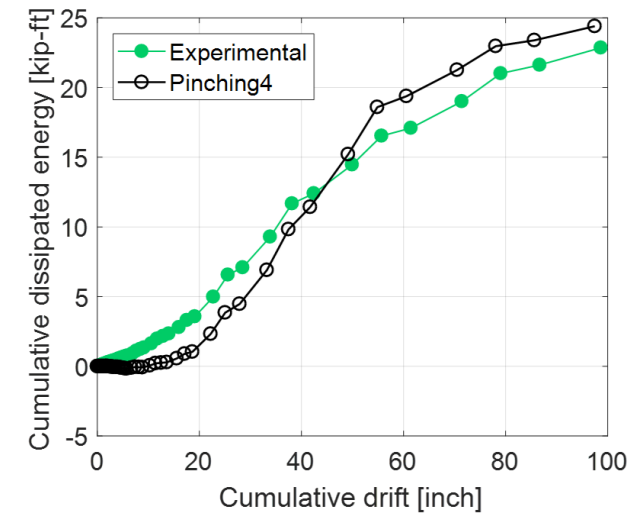
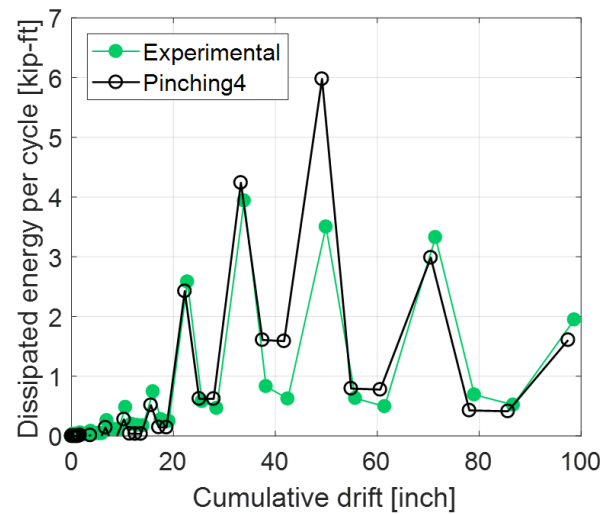
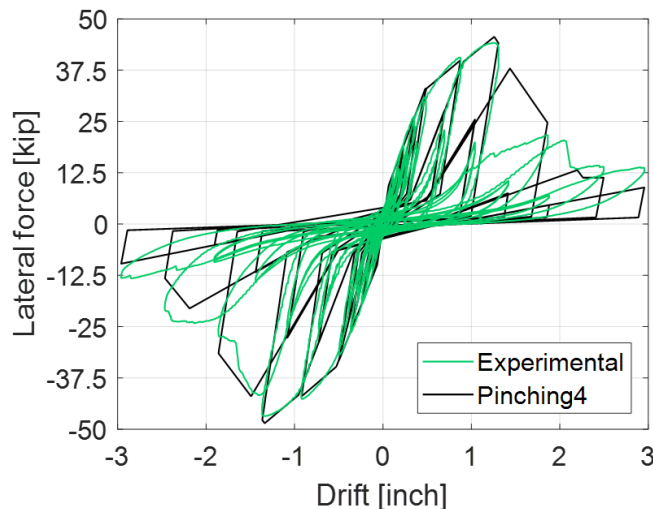
Modeling elements in
SAPWood (Pei et al. 2010)

Numerical Modeling: *Component-Level Validation*

- *Pinching4* material model for shear wall elements
 - Validated against NIST wall lateral & fire testing
 - 12' x 9' shear walls
 - Steel sheathed composite sheathing (SureBoard) panels using #8 screws @ 3" / 12"
 - Similar to levels 1-3 corridor SW CFS-HUD building
 - Quasi-static lateral displacement (CUREE protocol)

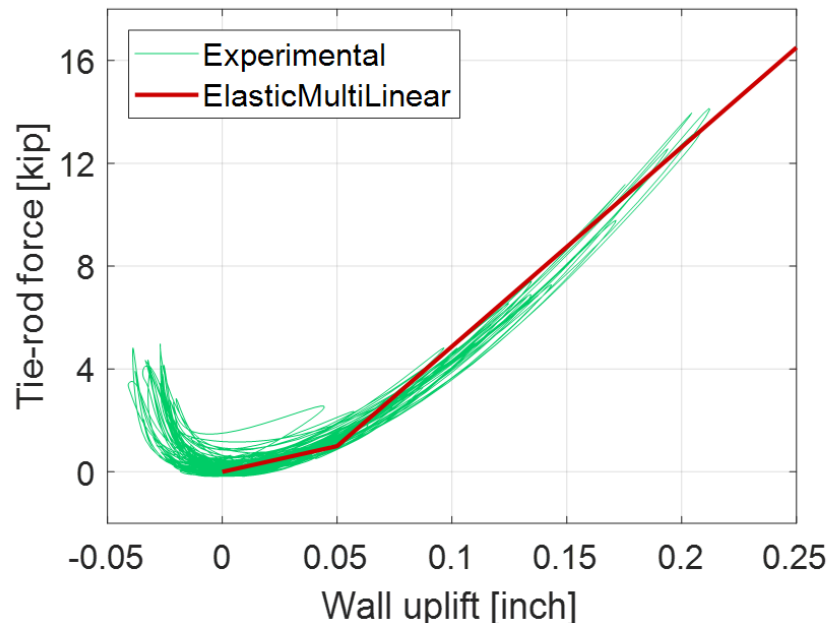


Hoehler, M. S., Smith, C. M., Hutchinson, T. C., Wang, X., Meacham, B. J., & Kamath, P. (2017). Behavior of steel-sheathed shear walls subjected to seismic and fire loads. *Fire safety journal*, 91, 524-531.



Numerical Modeling: *Component-Level Validation (continued)*

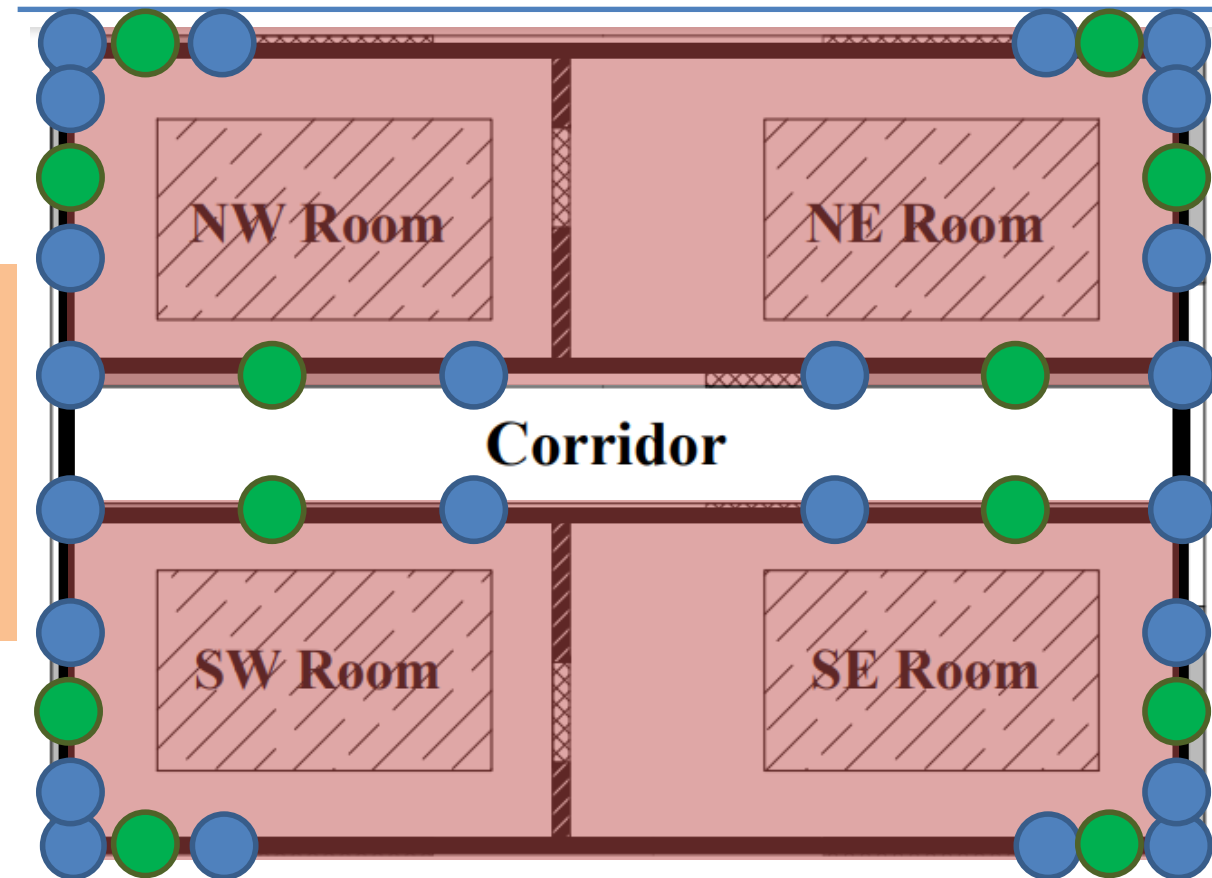
- *ElasticMultiLinear* material model for tie-rod elements in tension
 - Validated against CFS-NHERI shake table wall-line testing
 - 16' x 9' wall-lines with f1-1/4" tension tie-rods
 - ✓ Similar to tie-rods in corridor SW at levels 4-5
 - Steel sheathed shear walls using #10 screws @ 2" / 12"



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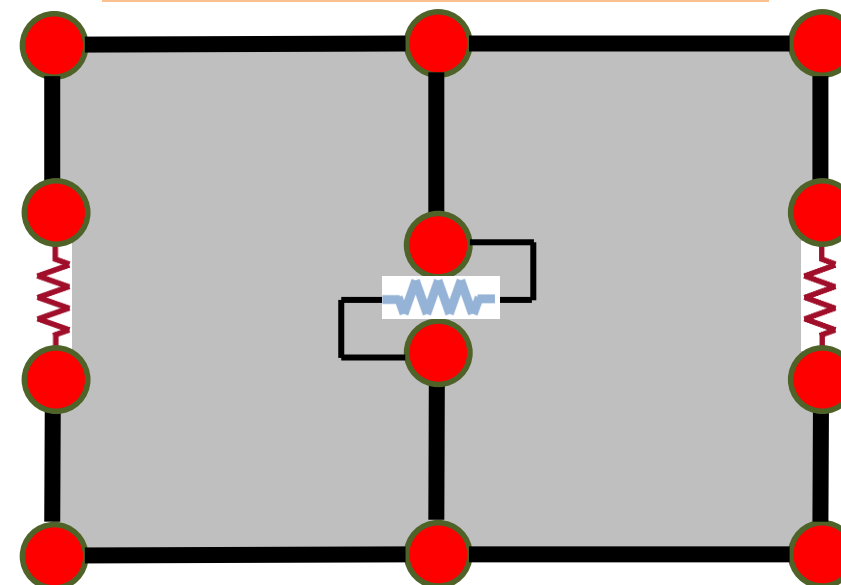
Numerical Modeling: Model Schematics (Ongoing)

Plan View



- Blue circle: Tie-rods/compression posts as multi-linear elements
- Green circle: Shear walls as spring elements (*pinching4*)
- Black line: Rigid link
- Pink square: Rigid diaphragm

Shear wall schematic
Elevation View



- Blue wavy line: zero-length element (shear wall)
- Red wavy line: zero-length element (tie-rod)
- Red circle: Node
- Black line: Rigid link

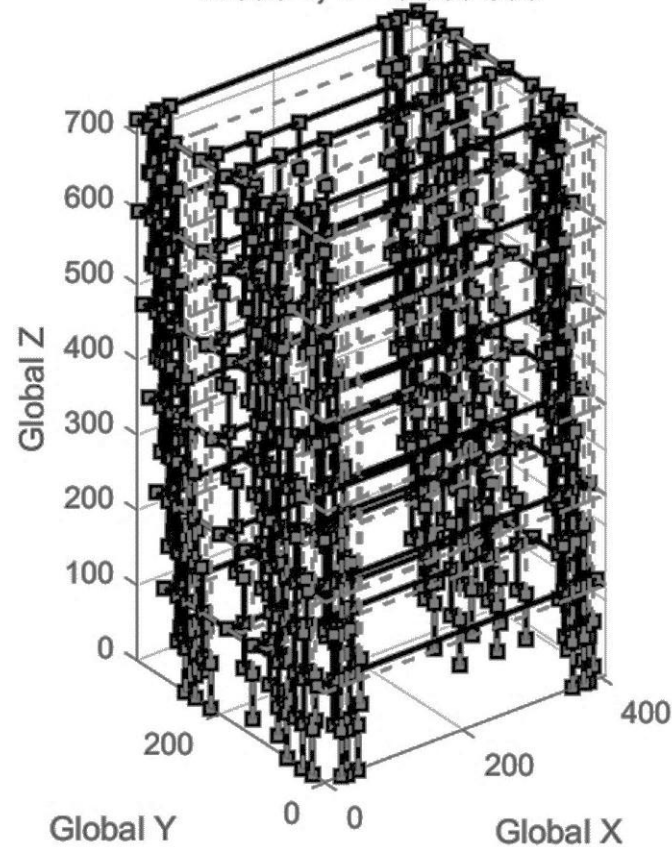
Numerical Modeling: *Modal Analysis*

Mode Shape
System ID

Transverse

0.45s

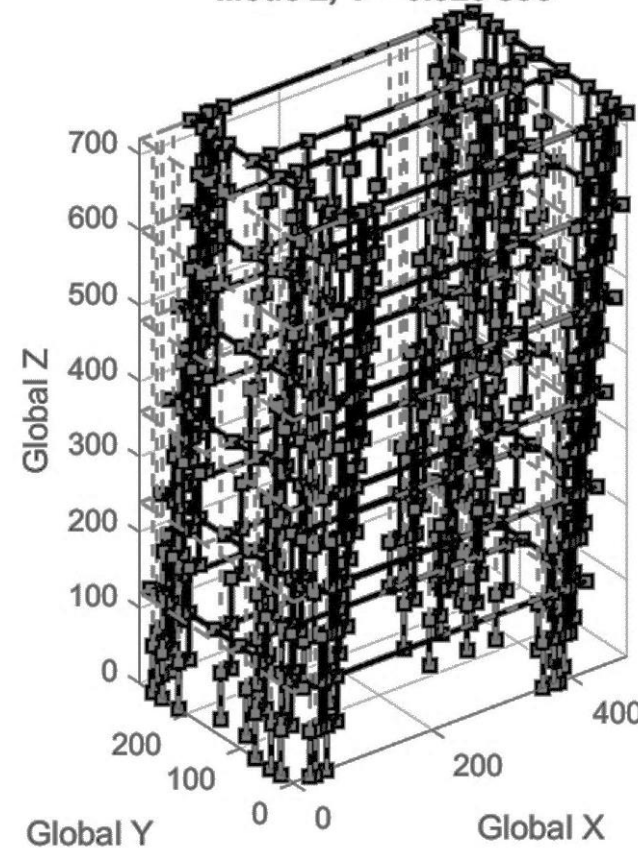
Mode 1, T = 0.599 sec



Longitudinal

0.26s

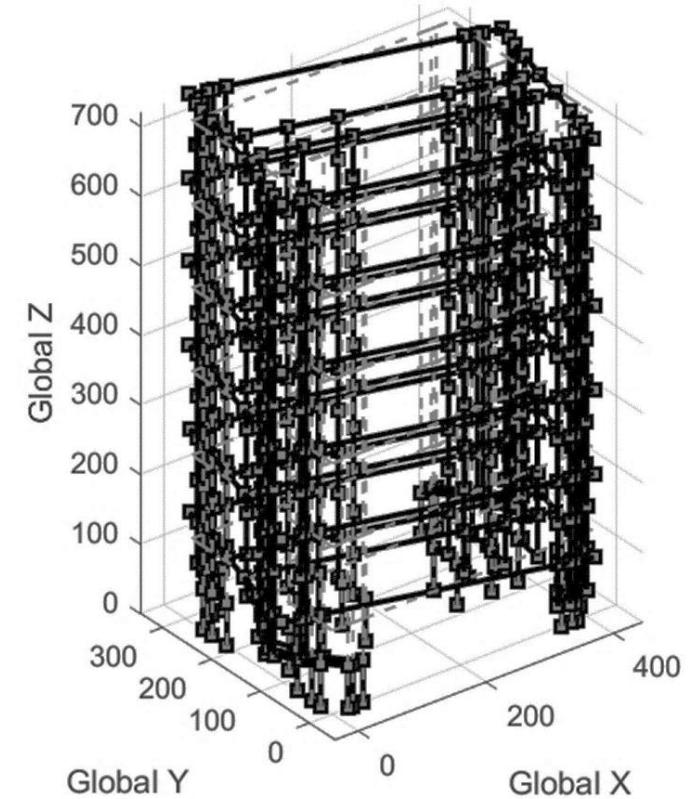
Mode 2, T = 0.323 sec



Torsional

0.23s

Mode 3, T = 0.276 sec

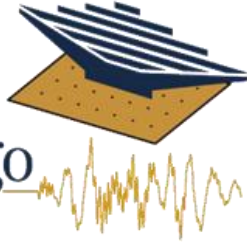


Wang, X., & Hutchinson, T. C. (2020). Evolution of modal characteristics of a mid-rise cold-formed steel building during construction and earthquake testing. *Earthquake Engineering & Structural Dynamics*, 49(14), 1539-1558.

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