Seismic and Damage Analysis of Reinforced Concrete Wall Building Systems using the BTM-Shell Method

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American Concrete Institute
Always advancing

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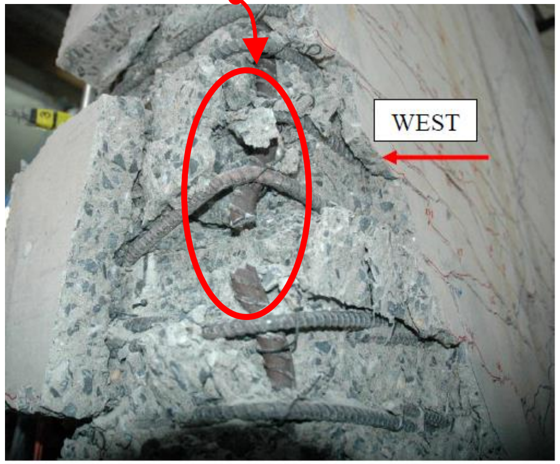
Reinforced Concrete Structural Walls

- Very popular lateral force system for new and existing buildings in earthquake-prone regions.
- Quantitative, probabilistic seismic risk evaluation requires extensive analyses of building systems.
- Data-driven and Machine Learning (ML) tools appear a good fit for this endeavor.
- The training of ML tools requires extensive data sets.
- Impossible to conduct adequate number of experimental tests for large-scale systems under dynamic loads.
- ***Accurate, computationally efficient analysis methods required!***

Damage Patterns in RC Walls

Failure of confined boundary regions

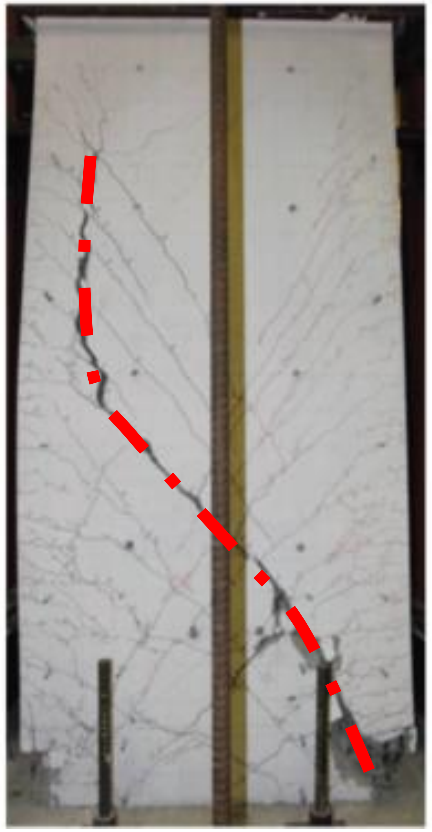
Vertical Bar buckling followed by rupture



Concrete crushing

Figures from Pakiding et al. 2014

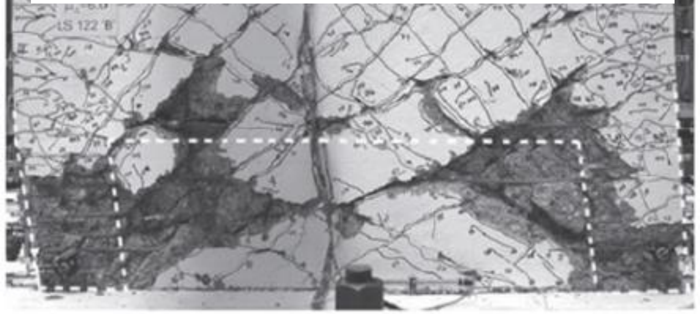
Diagonal tension failures



Wallace et al. 2015

Lu et al. 2014

Diagonal compression failures (web crushing)



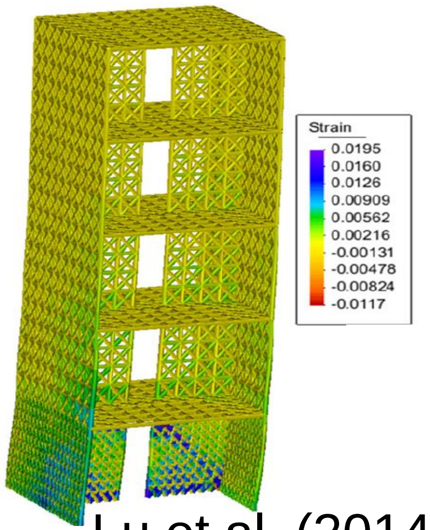
Beyer et al. 2006

Analysis of RC Walls

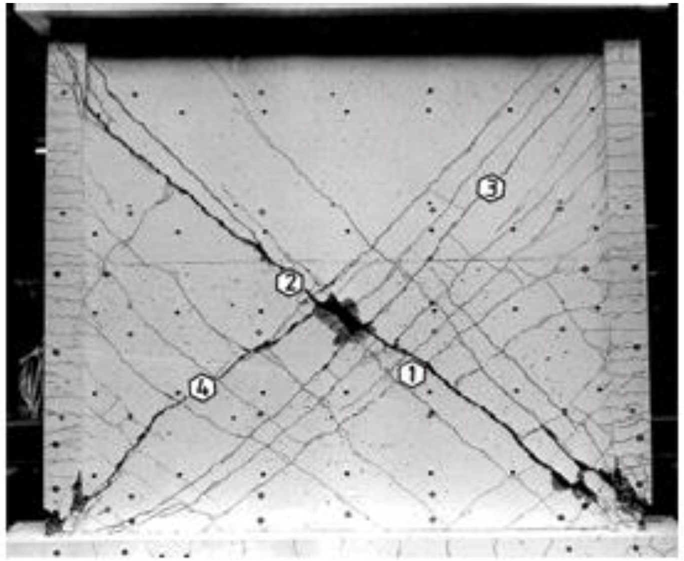
Different analytical approaches have been used:

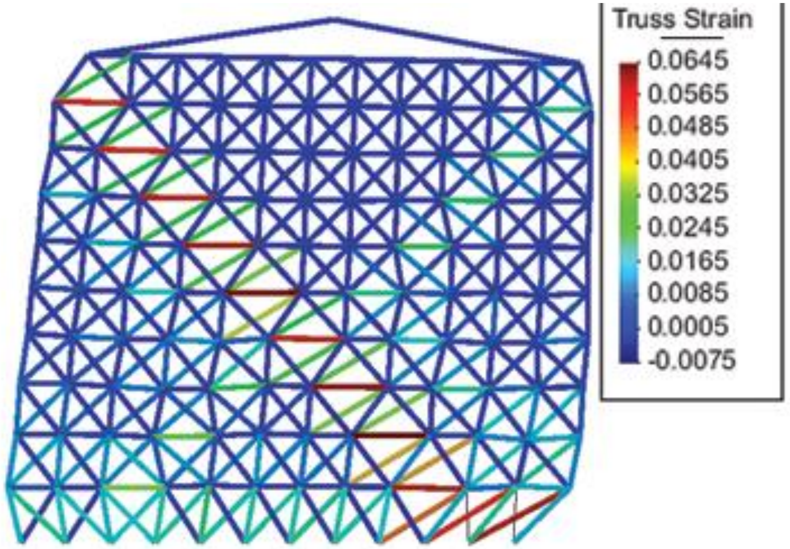
- Simplified (beam-based) models:
  - Numerically efficient and conceptually simple.
  - May not accurately capture some damage modes (especially those involving strength degradation due to large inclined cracks).
  - Enforcing plane-section hypothesis ***may not be accurate*** for damaged (cracked) RC wall sections.
- Continuum-Based FE models:
  - Can provide insights on both member-level and material response.
  - Computationally expensive.
  - May not accurately capture some damage modes (e.g., large inclined cracks)

Beam Truss Model (BTM) for RC walls



Lu et al. (2014)

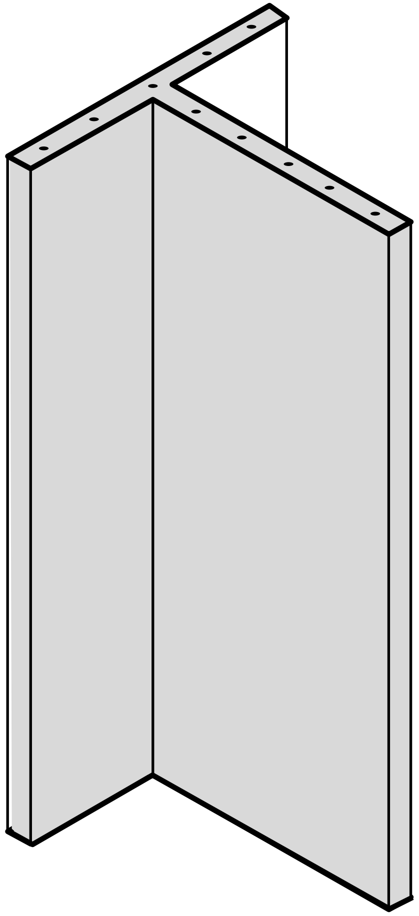




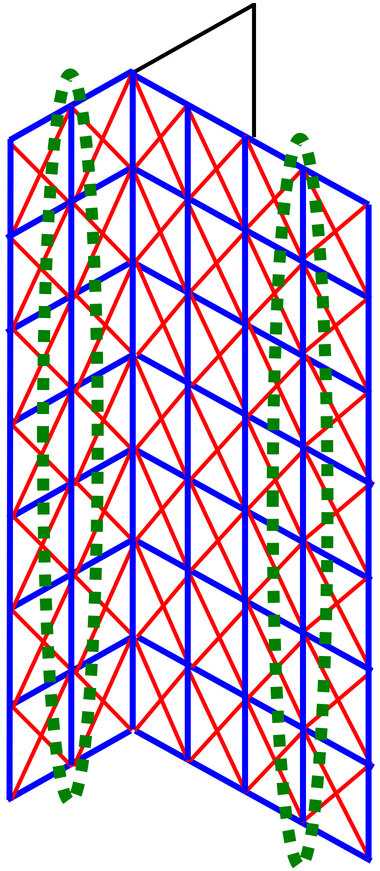
- Combine accuracy, conceptual simplicity and computational efficiency.
- **Core Idea:** represent wall as assemblage of **horizontal, vertical & inclined line elements**.
- Horizontal and vertical beam elements account for concrete and steel.
- Inclined (diagonal) truss elements account for compression field developing in, e.g., wall web.

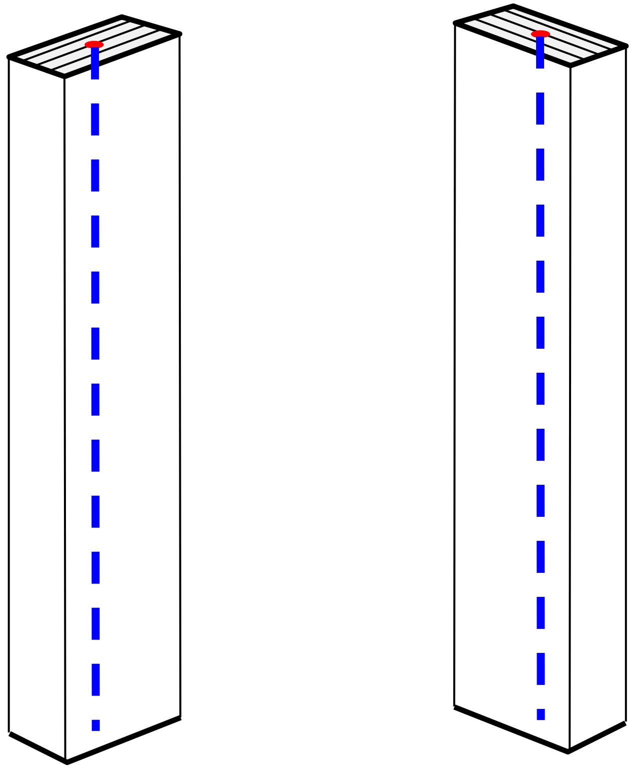
Beam Truss Model (BTM) for RC walls

RC Wall Component



BTM Assemblage



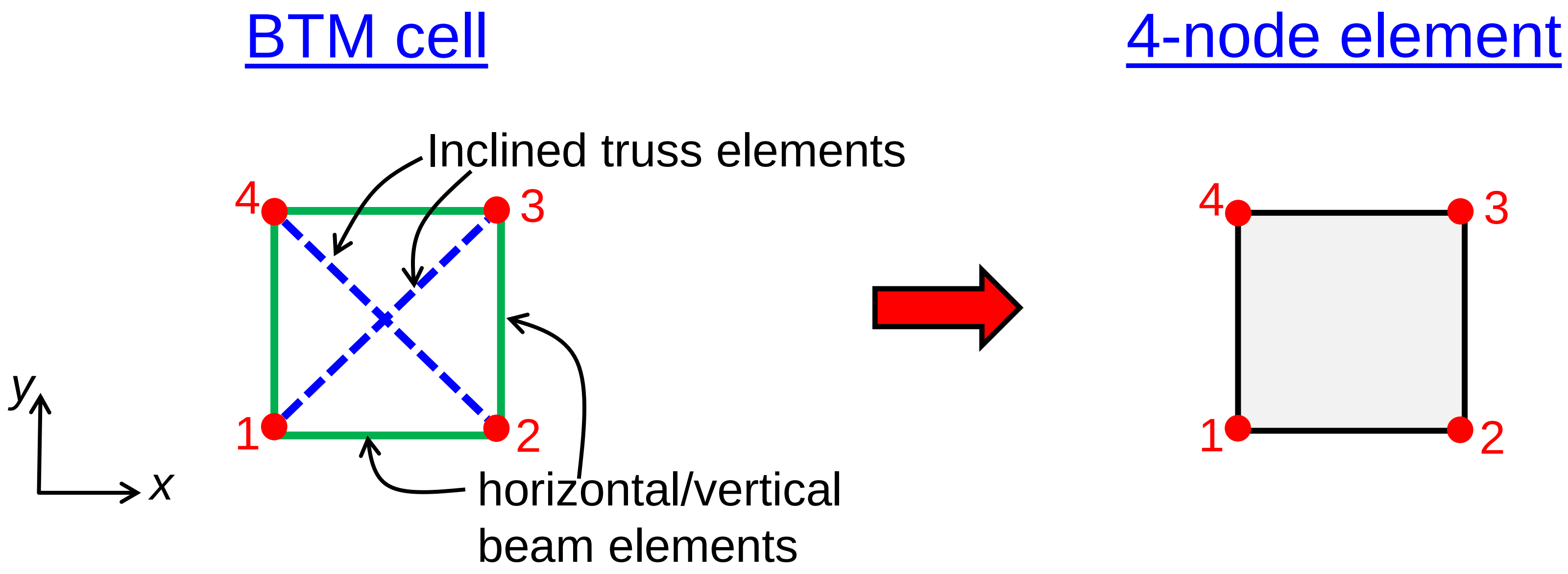


Beam elements with **fiber section**

for through-thickness (flexural) resistance

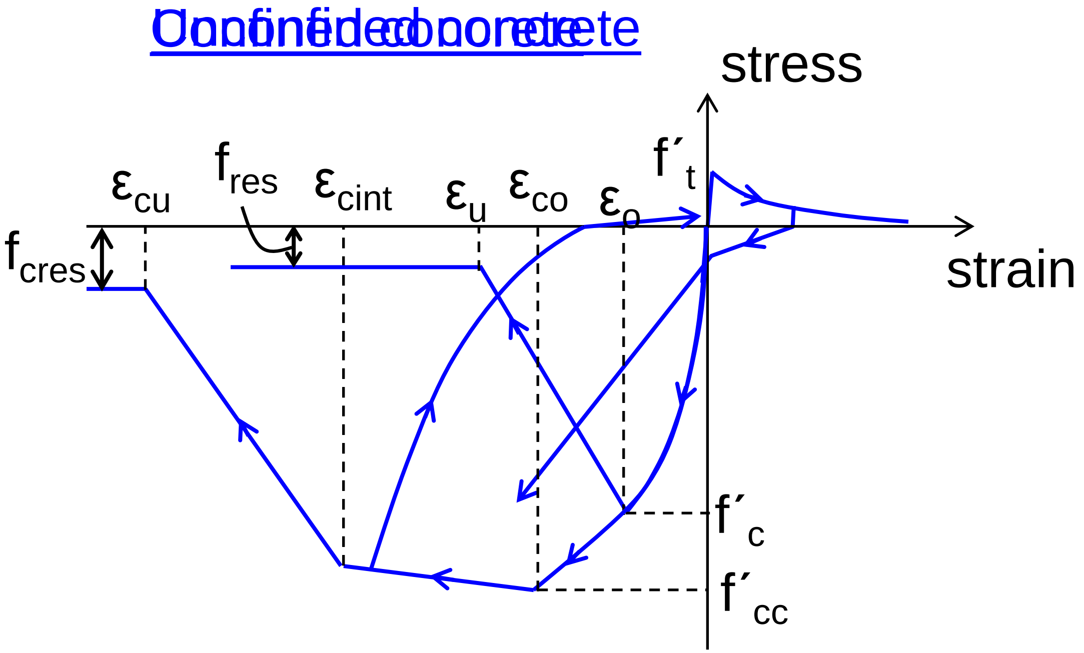
Building Analysis

- BTM (with necessary enhancements) to capture all common types of failure in core-walls.
- Analyses using the program *FE-MultiPhys* (Koutromanos and Farhadi 2018).
- Implementation as a ***4-node shell macroelement***:

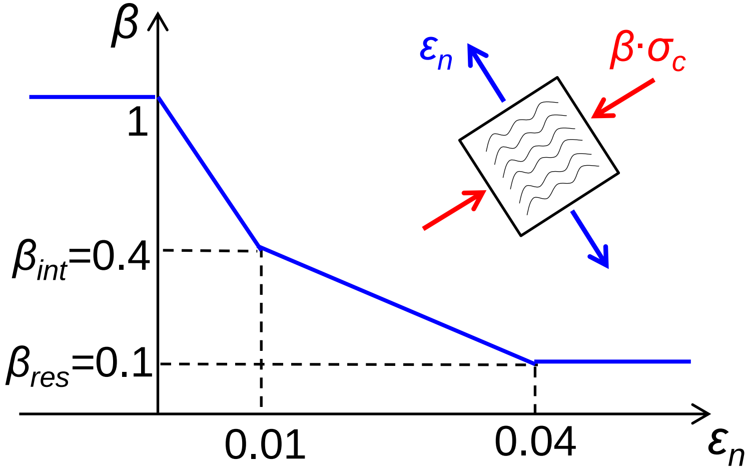


Material Model for Concrete

Model by Lu and Panagiotou (2014)



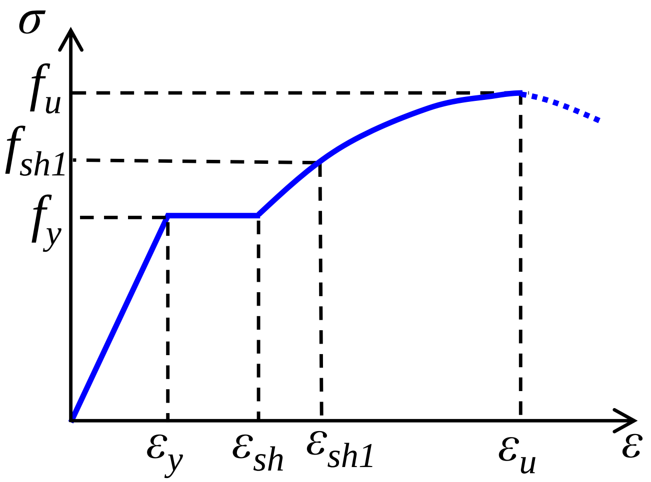
Effect of transverse tension to compressive stress of inclined truss elements:

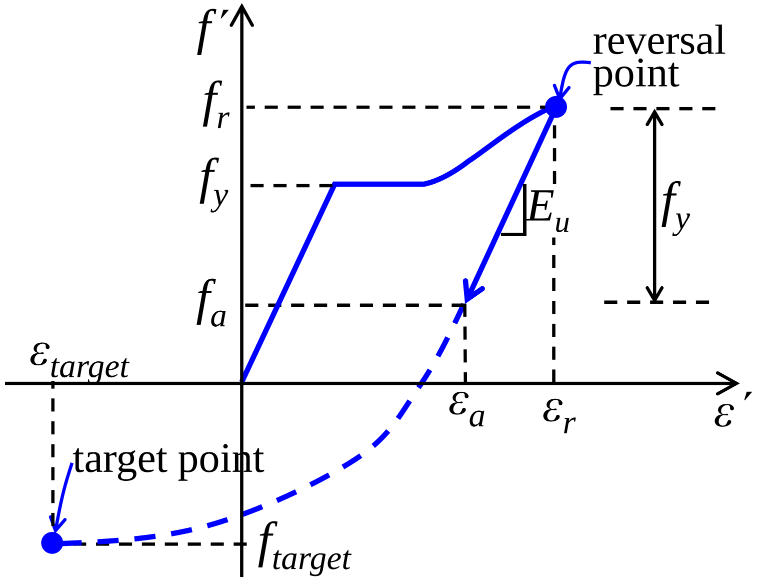


- Material law involves softening.
- Regularization procedure by Lu and Panagiotou (2014) to prevent spurious mesh-size effects.

Material Model for Reinforcing Steel

Model by Kim and Koutromanos (2016):





Can account for buckling at stress-strain level:

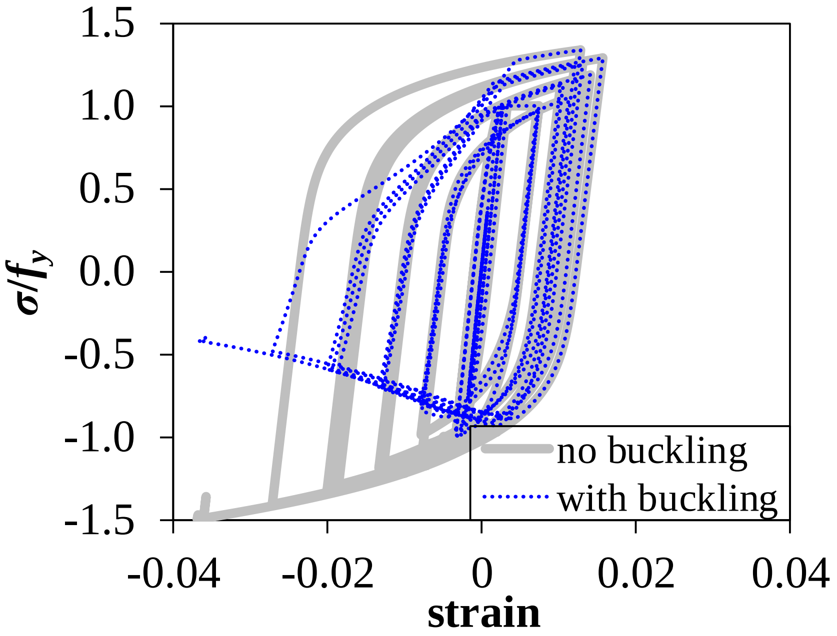


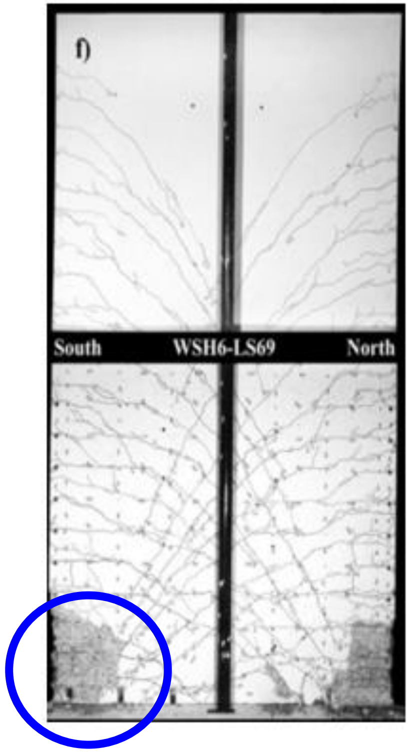
Figure from Girgin et al. 2018

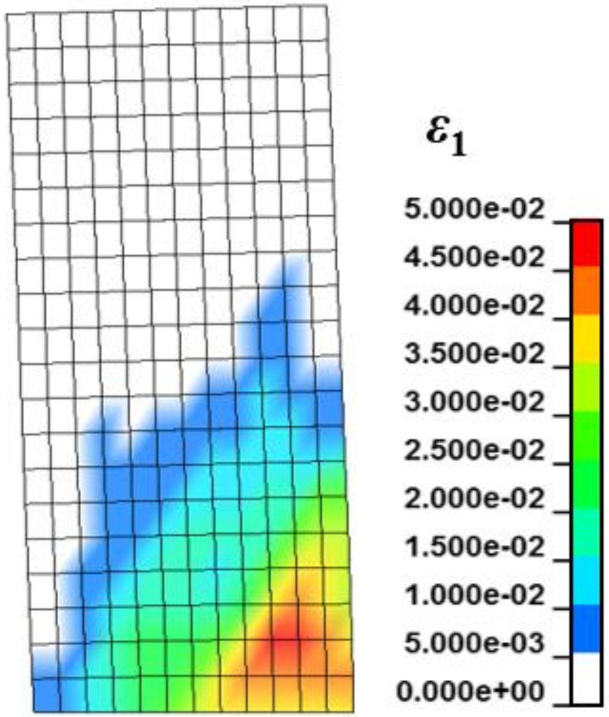
Model can also account for bar rupture under monotonic or cyclic loading

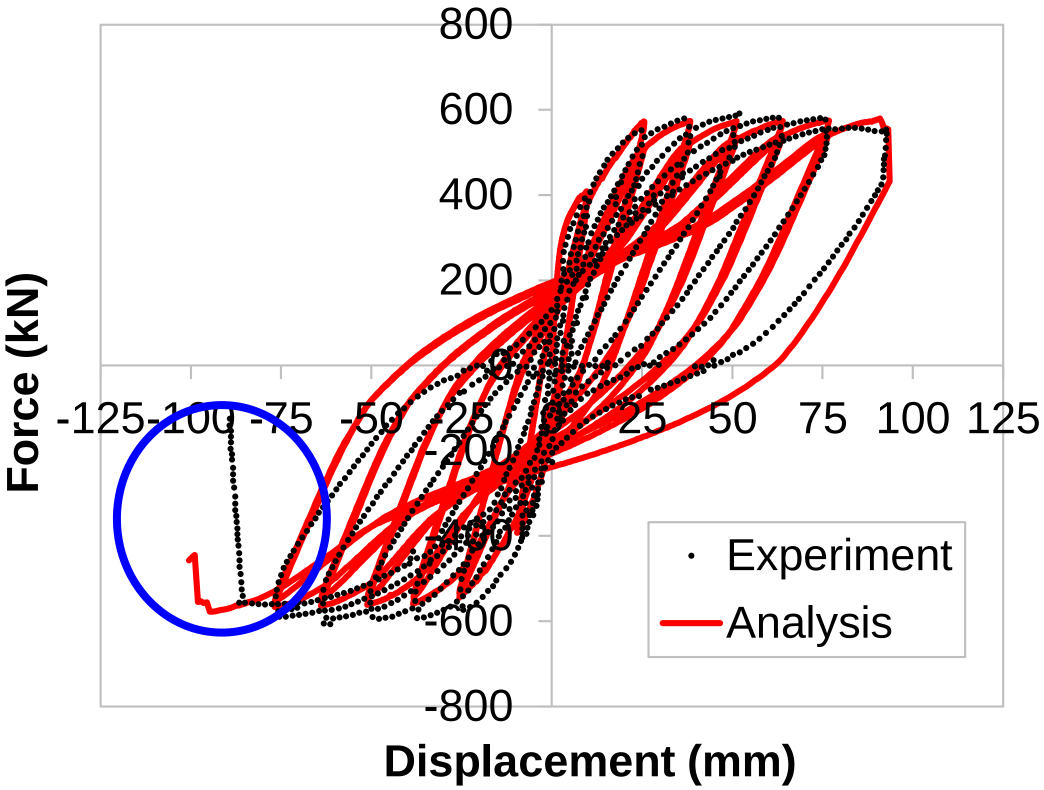
Validation Analyses

Wall tested by Dazio et al. (2009)

Flexure-dominated response, strength degradation due to crushing at the confined boundary





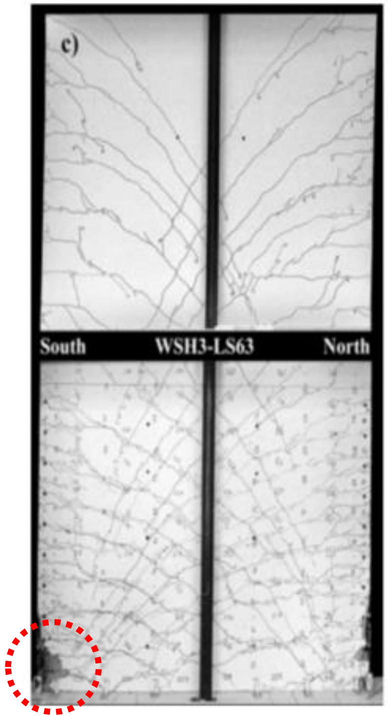


Validation Analyses (2)

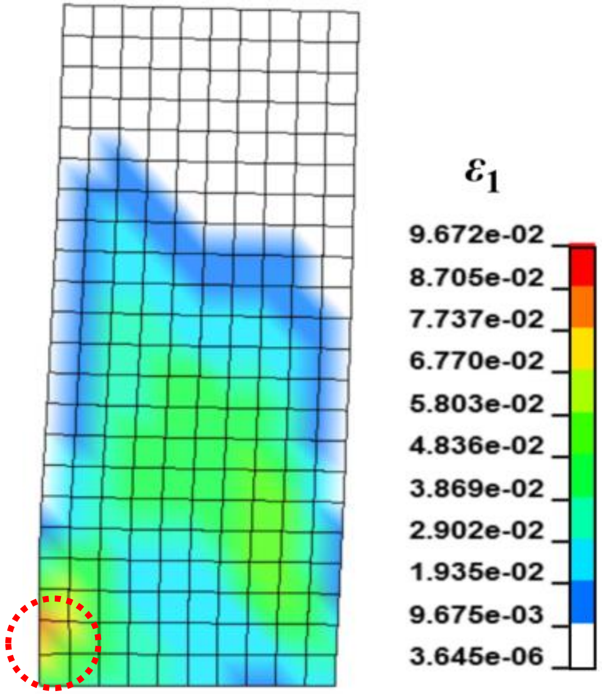
Wall tested by Dazio et al. (2009)

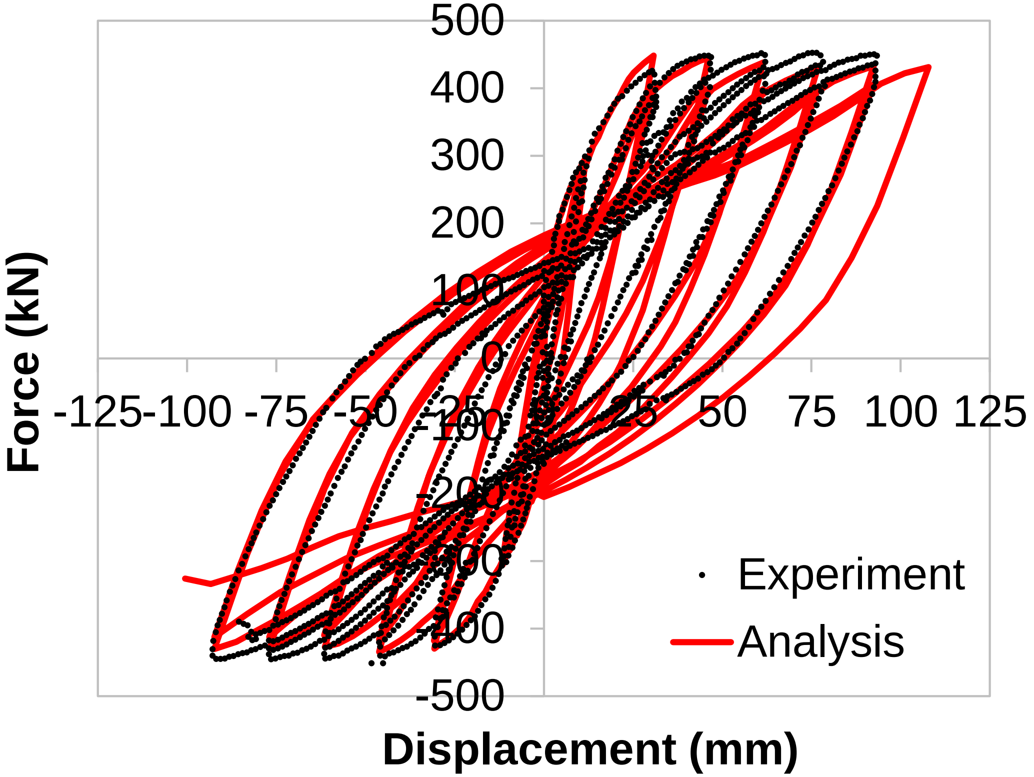
Flexure-dominated response, strength degradation due to vertical bar rupture.

positive ← direction



vertical bar rupture

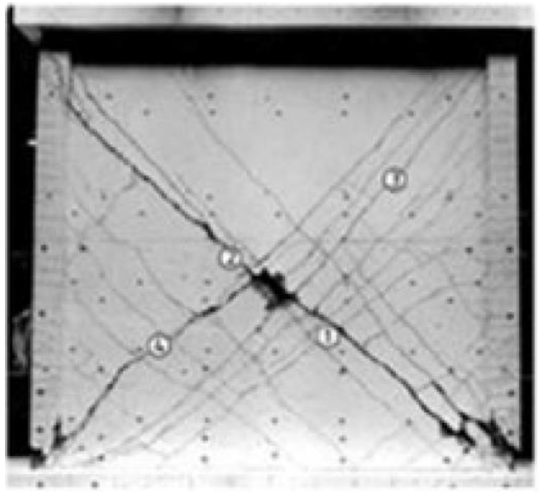


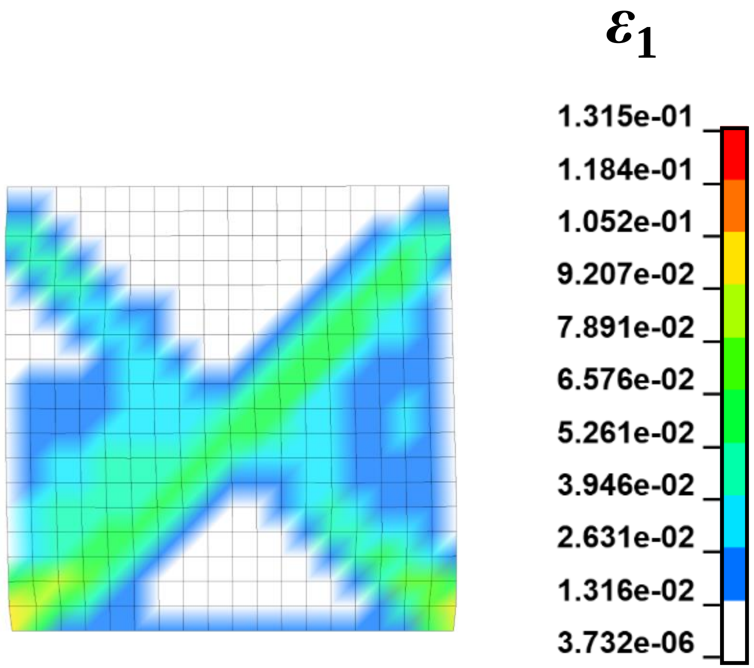


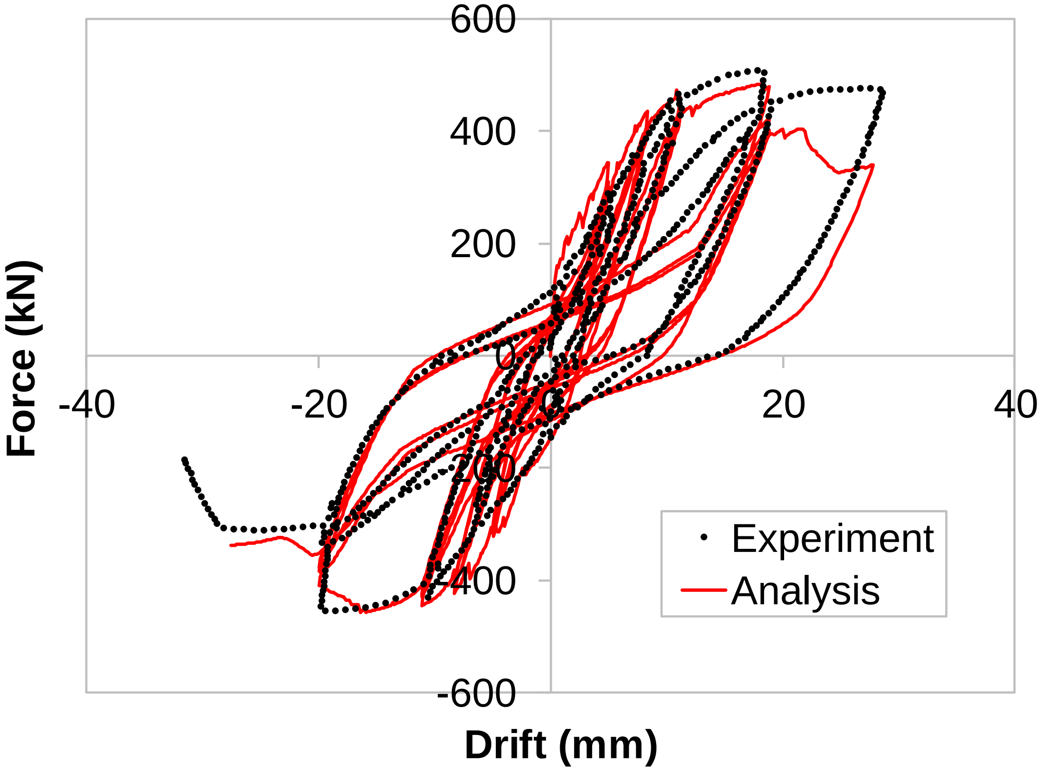
Validation Analyses (3)

Wall tested by Mestuyanek (1986)

Strength degradation due to diagonal tension failure.



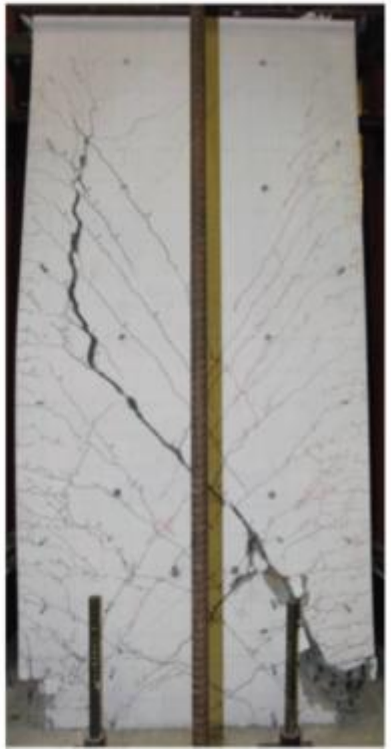


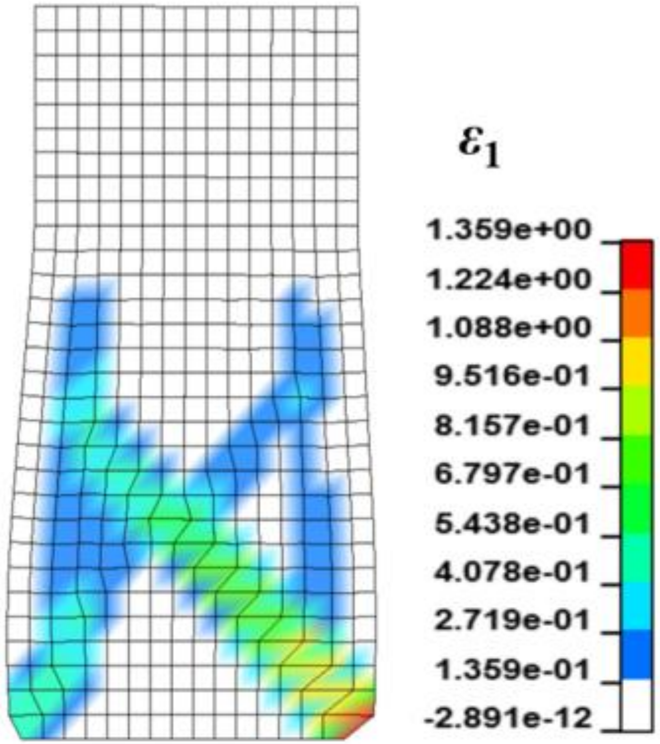


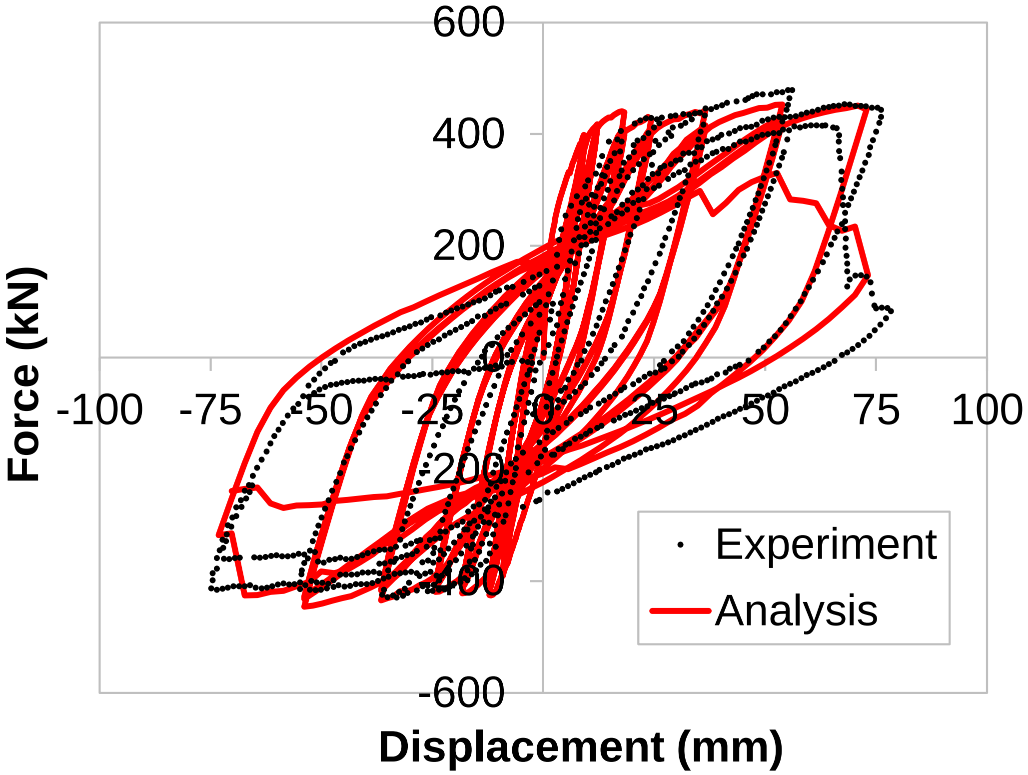
Validation Analyses (4)

Wall tested by Wallace et al. (2015).

Strength degradation due to diagonal tension failure, after development of inelastic flexural deformations.



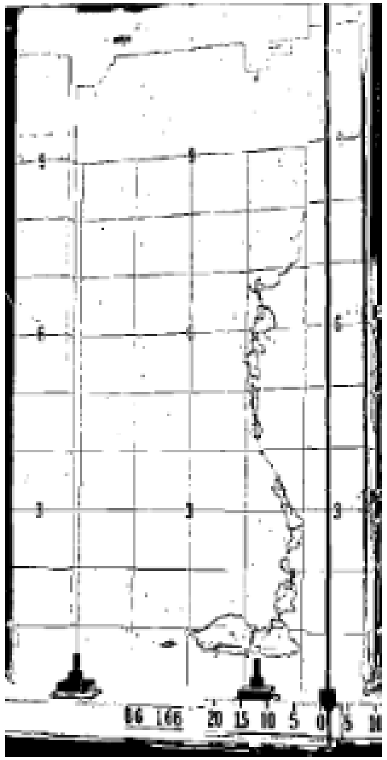


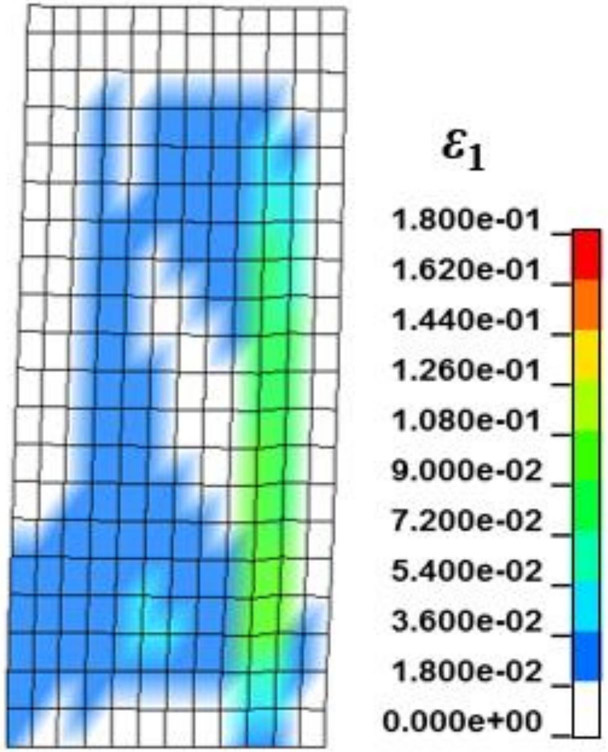


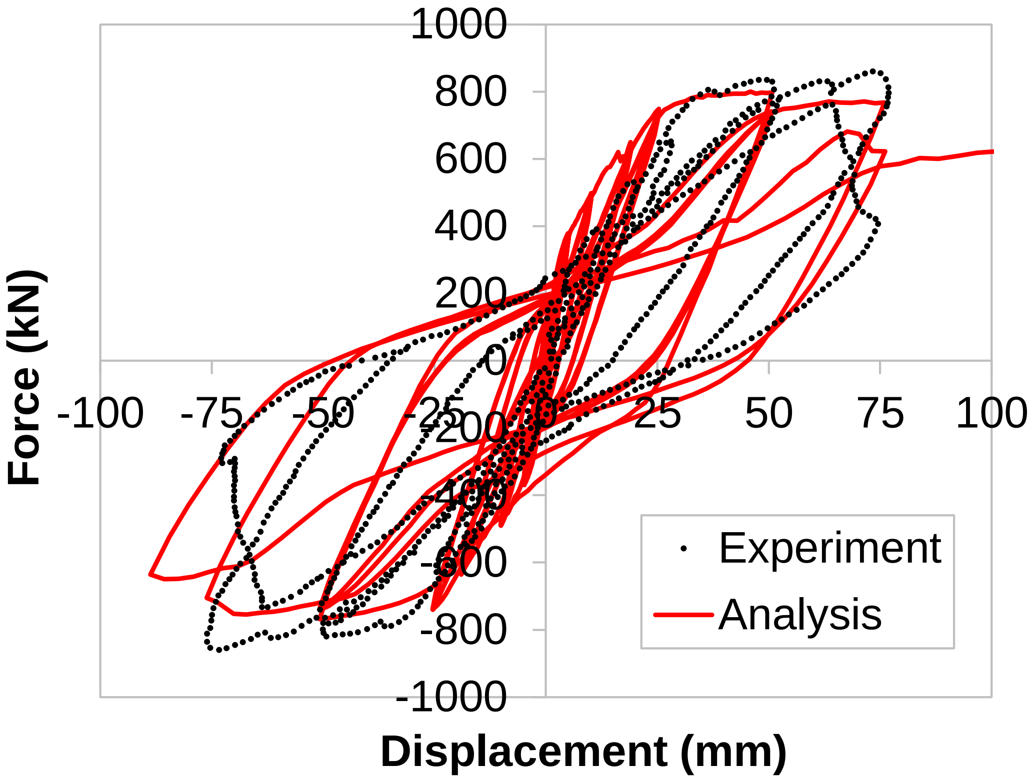
Validation Analyses (5)

Wall tested by Oesterle et al. (1976)

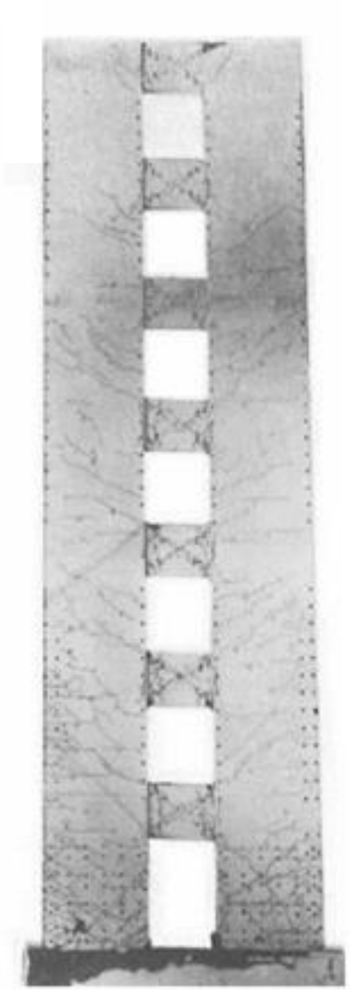
Strength degradation due to diagonal compression failure, after development of inelastic flexural deformations.



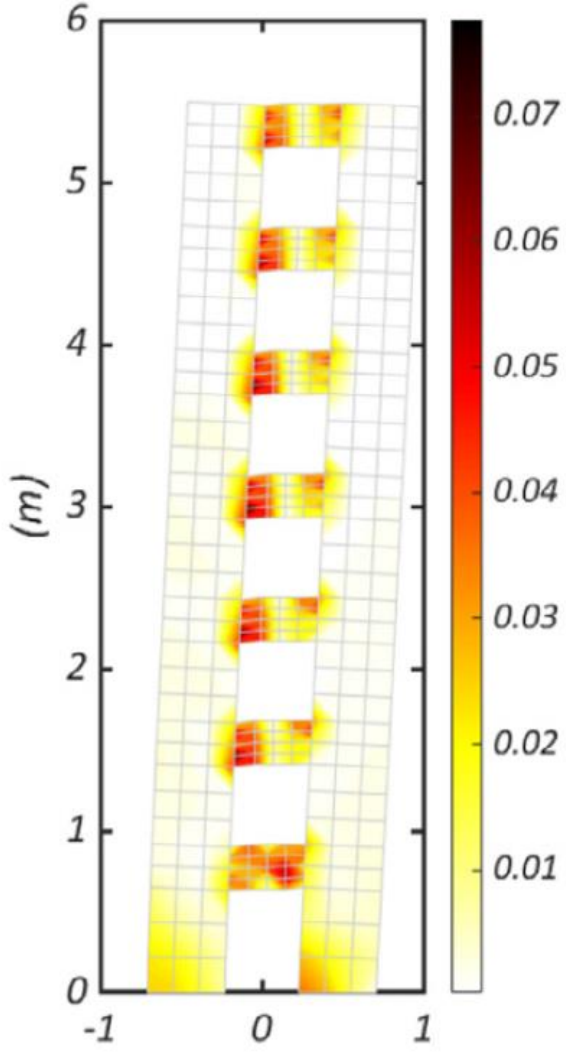


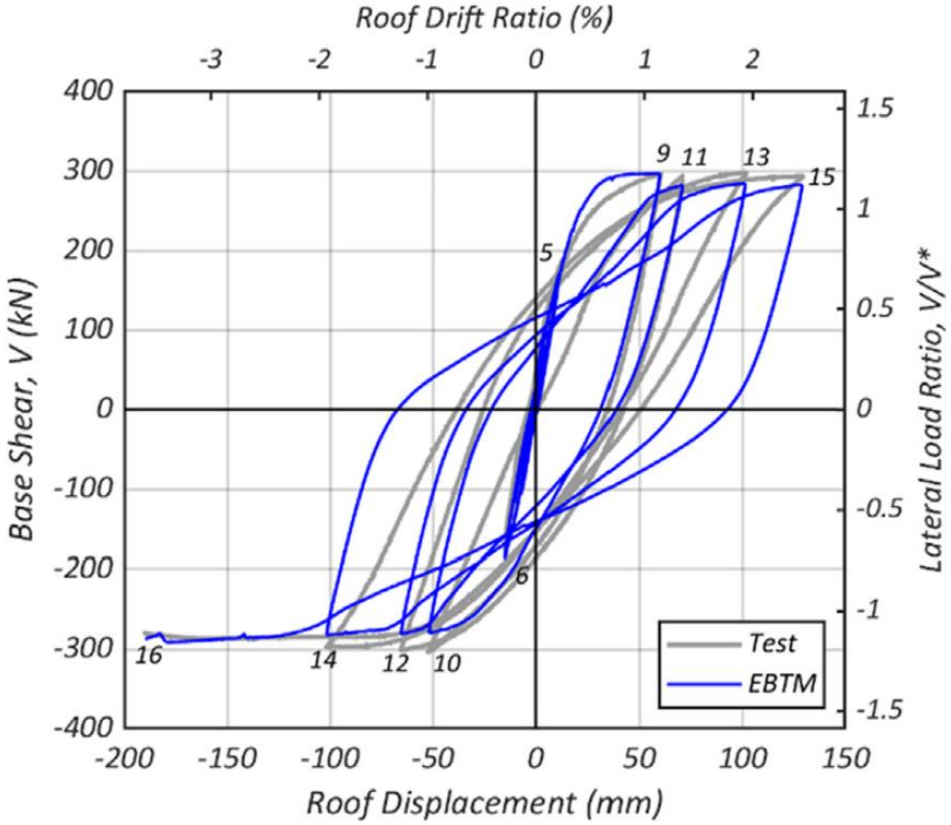


Capability to Simulate Coupled Walls



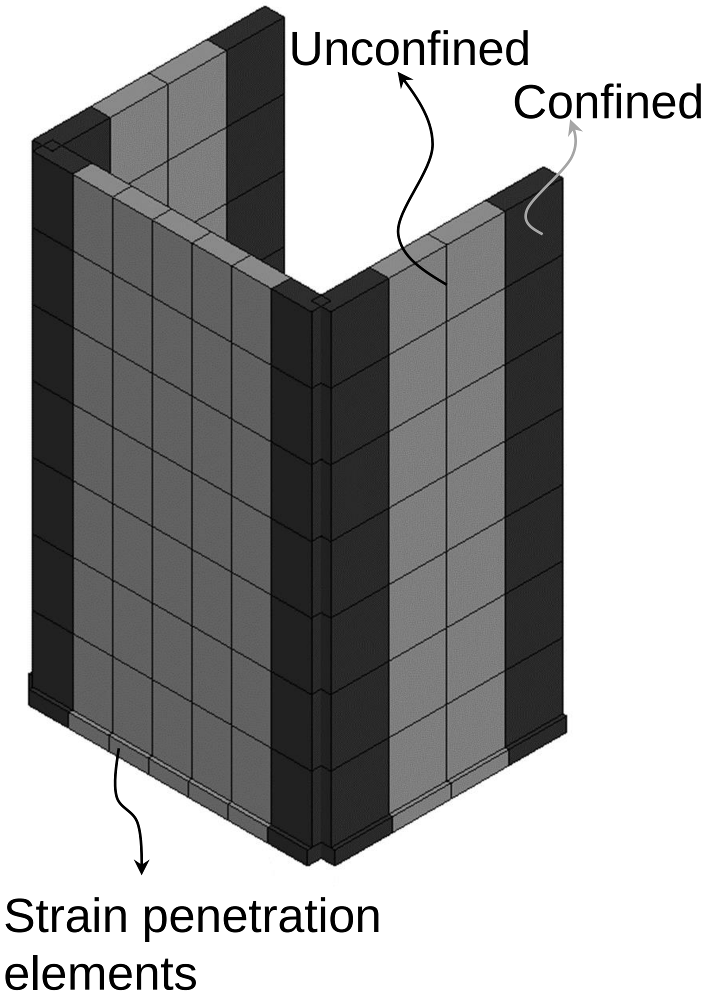
Specimen by Santhakumar (1974)



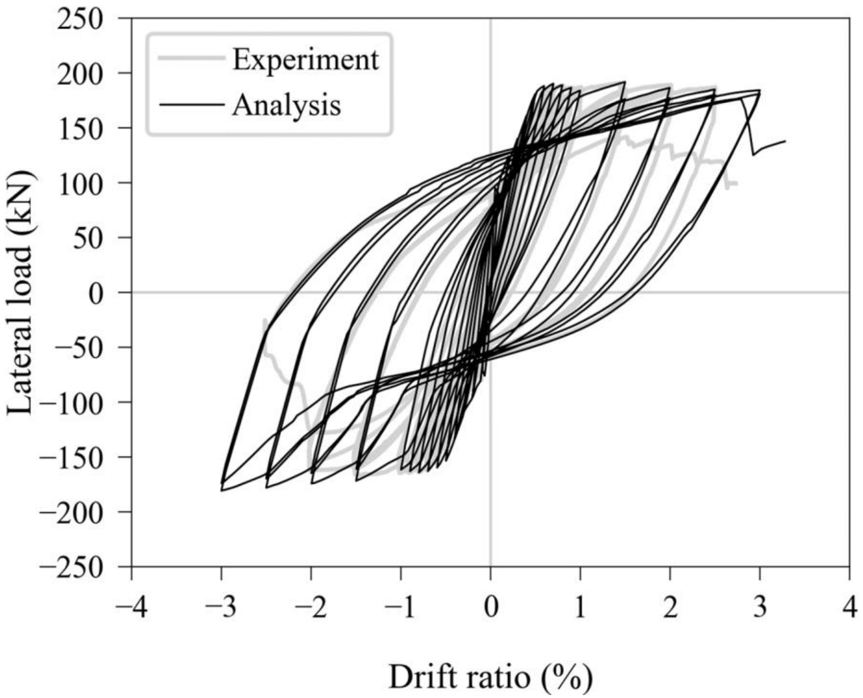


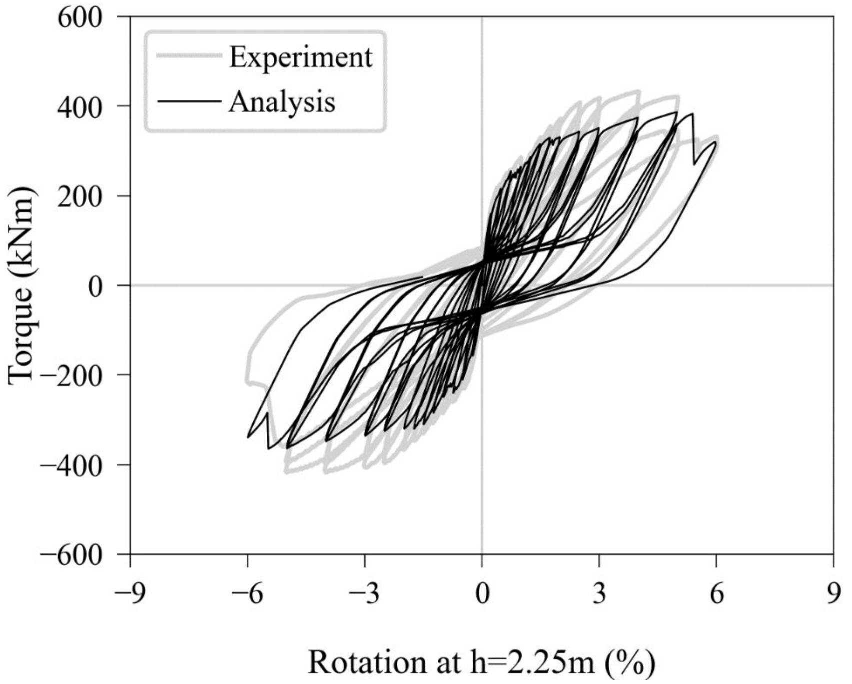
Alvarez et al. (2020)

Capability to Simulate Non-Planar Walls



Blind prediction competition by UC Louvain (Belgium)
2 C-shaped wall specimens





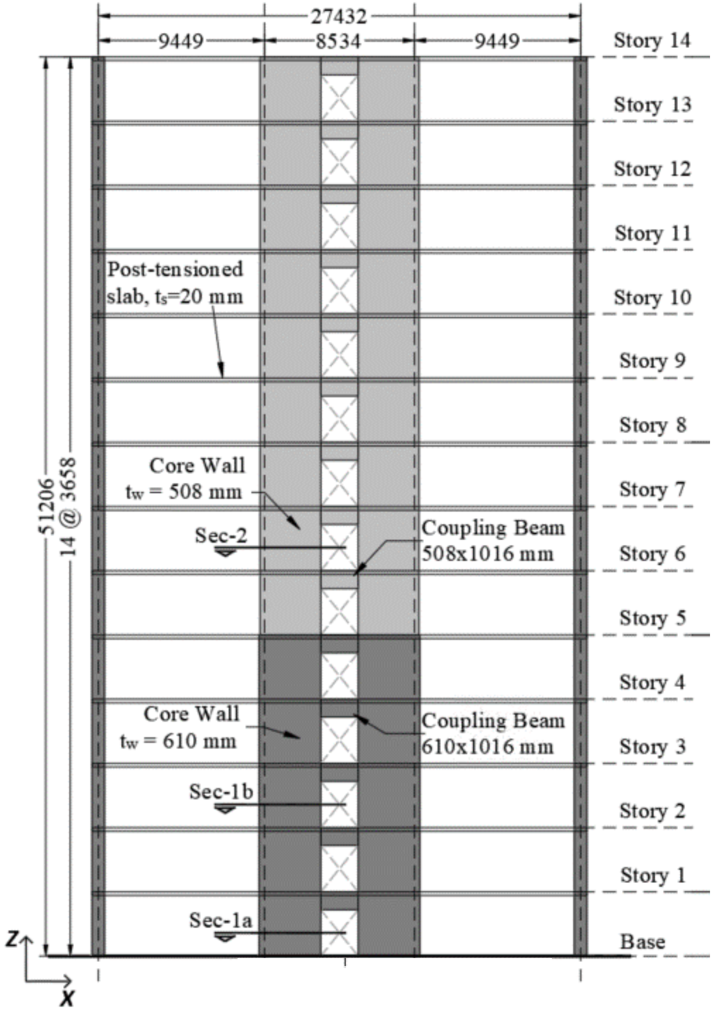
M. Mavros, J. Murcia-Delso and M. Panagiotou
Winners for both walls, using BTM in *FE-Multiphys*

Application to Analysis of Building Systems

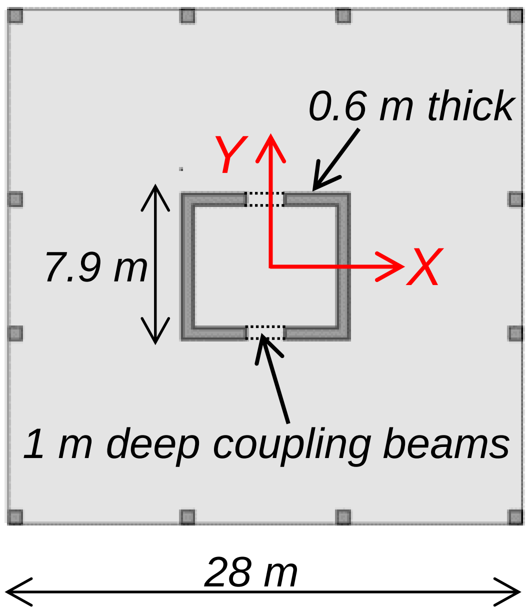
- Analysis of hypothetical 14-story, core-wall building (Mavros et al. 2022).
- Located in downtown Los Angeles, and designed per CBC.
- Conduct nonlinear static and dynamic analyses to investigate:
  - Flexure-shear interaction
  - Damage patterns
  - Effect of triaxial earthquake excitation

14-Story Building

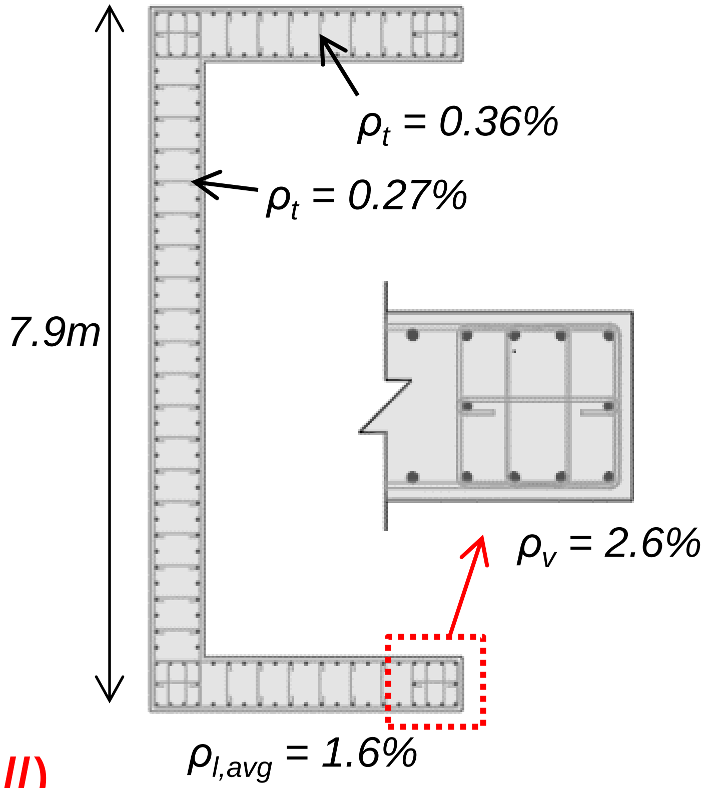
Building elevation



floor plan view



core wall reinforcement

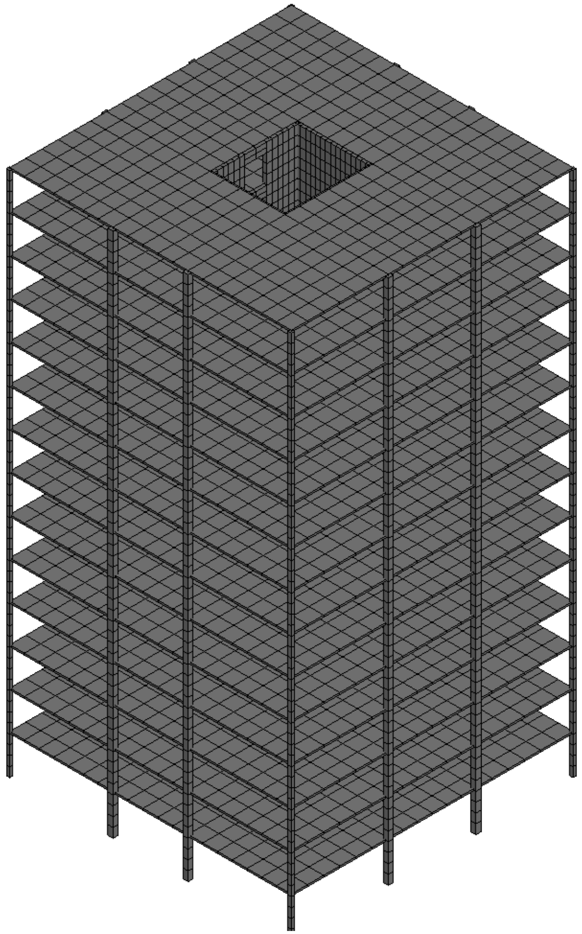


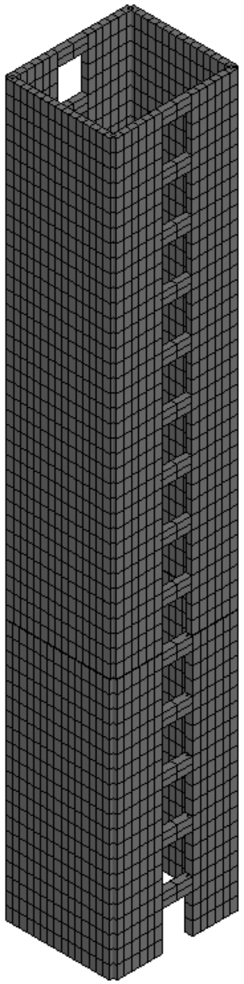
$f'_{c,exp} = 62.7$ MPa (core wall)

$C_s = 0.13$

Building Model

8820 nonlinear elements in total



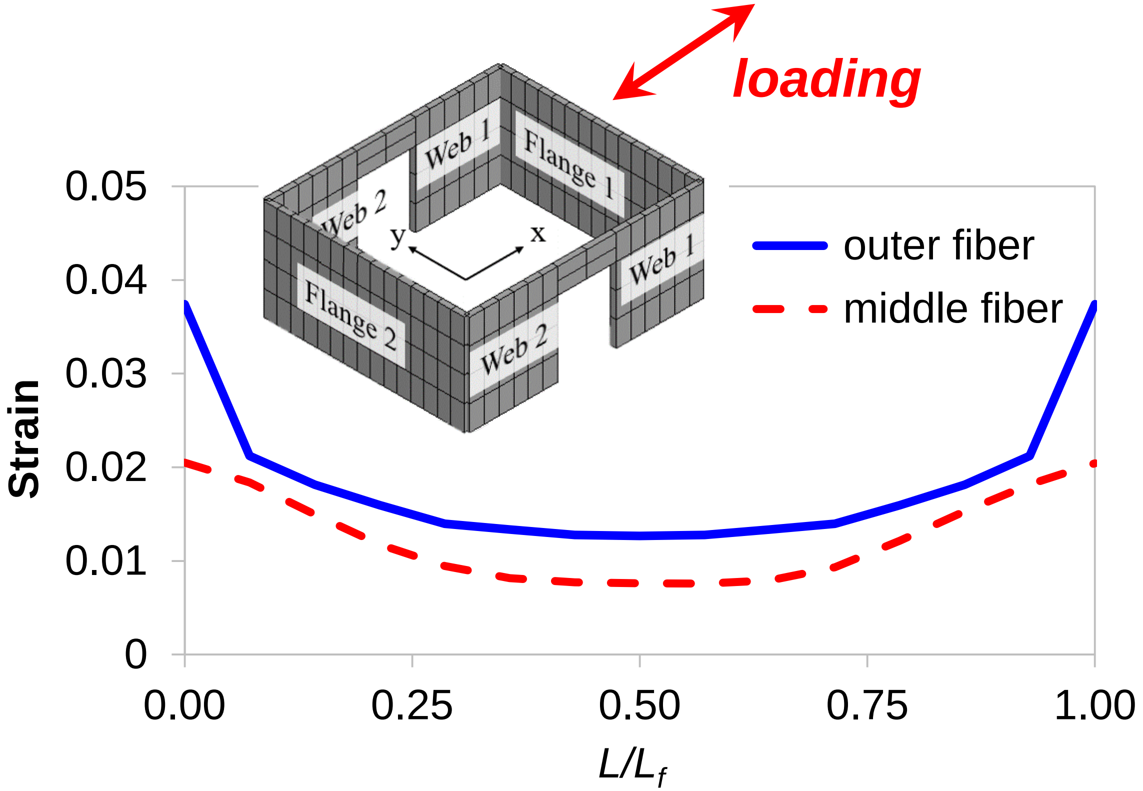


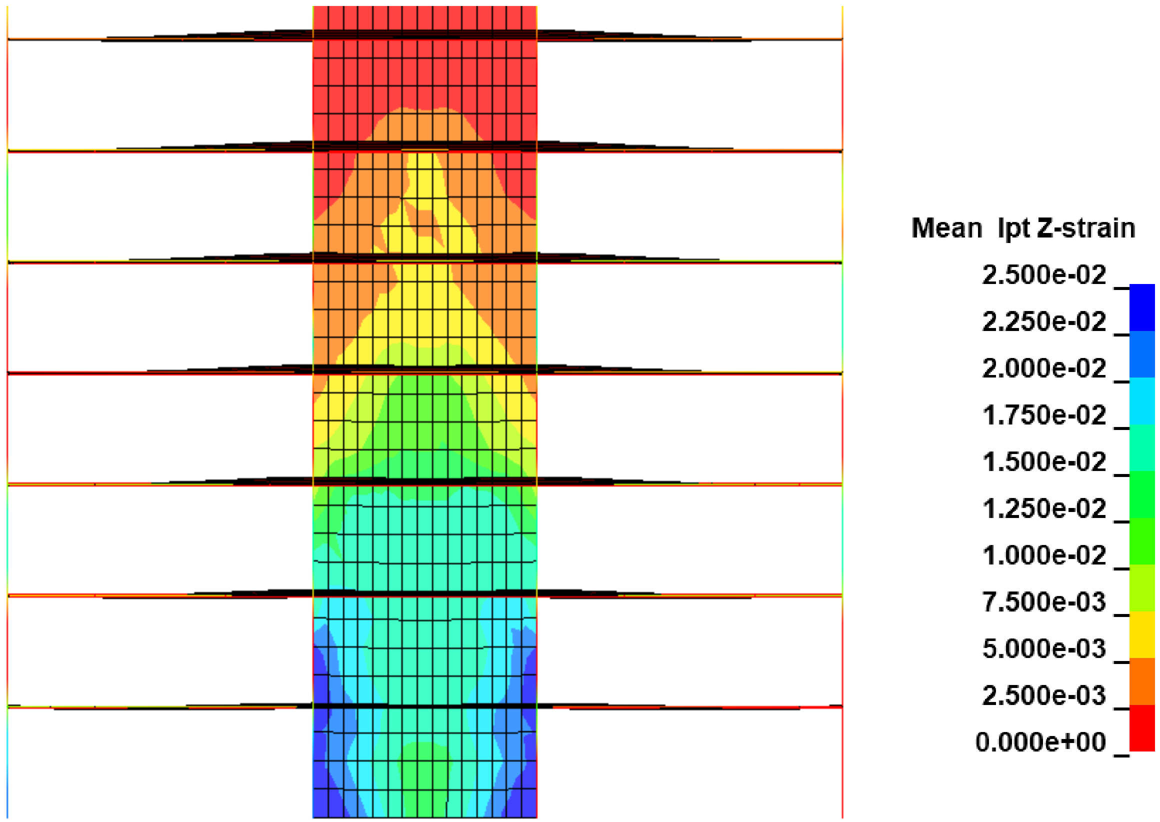
BTM-shell elements for core-wall, slabs and coupling beams

Beam elements with fiber section for columns

Geometric nonlinearity (P-Δ effects) accounted for

Vertical Strains

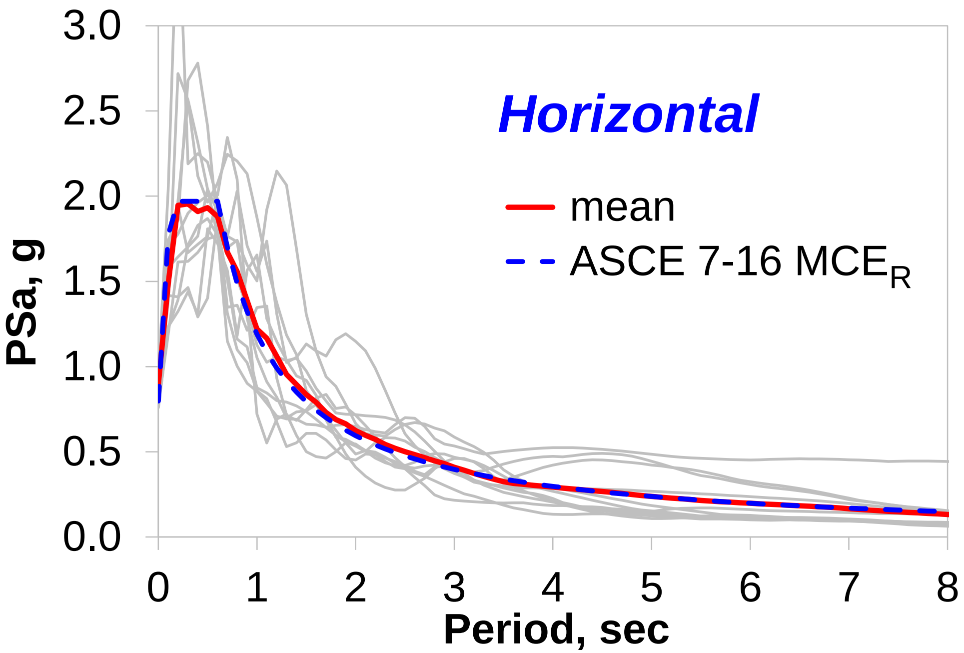


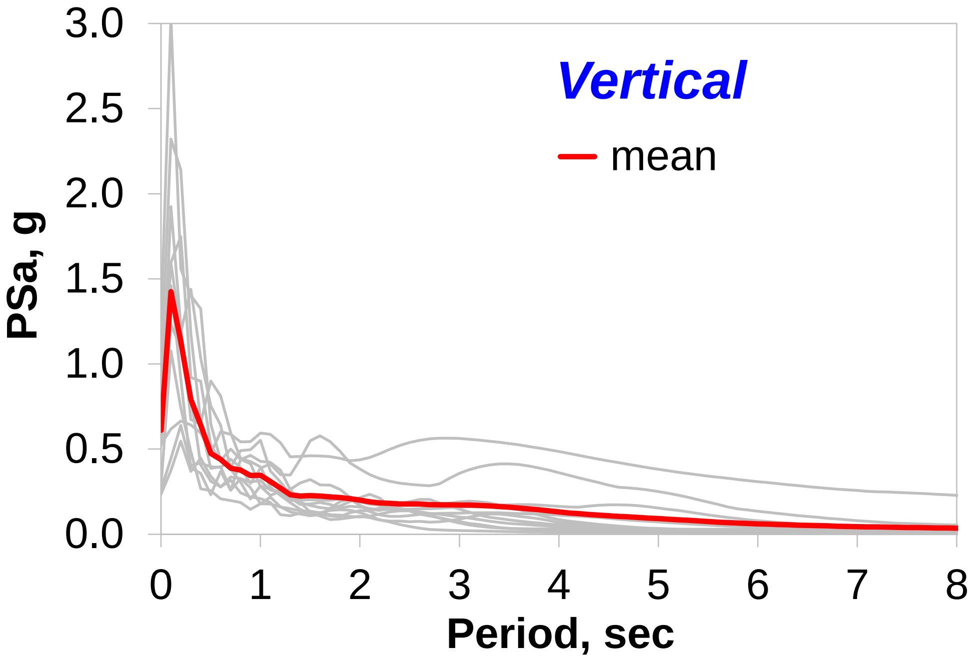


Plane sections do NOT remain plane !

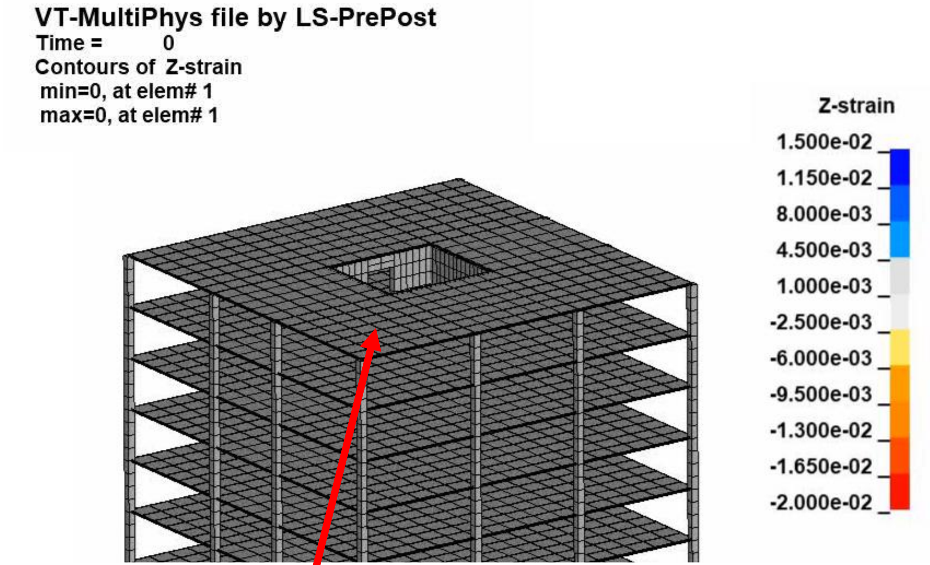
Dynamic Analysis

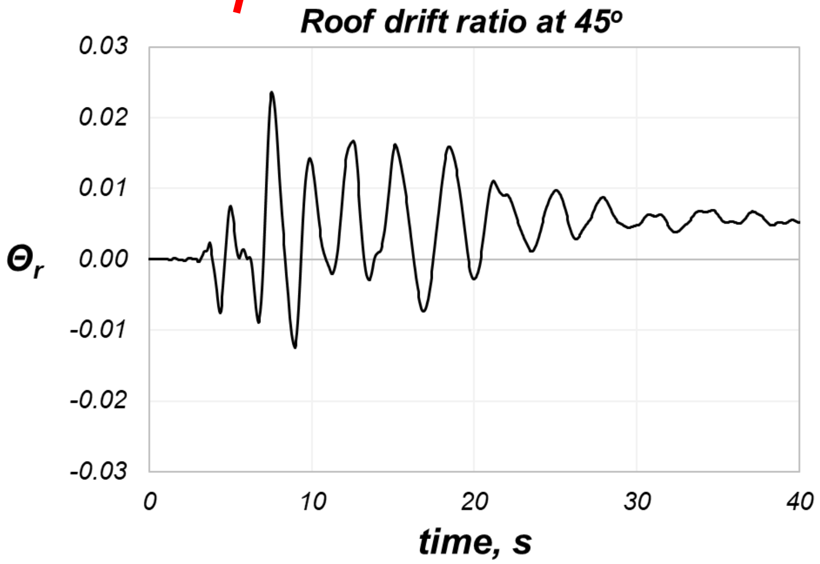
- Triaxial ground motions.
- 11 records from previous earthquakes
- Scaled to match the MCE_R design spectrum of ASCE 7-16 for Downtown Los Angeles, CA.

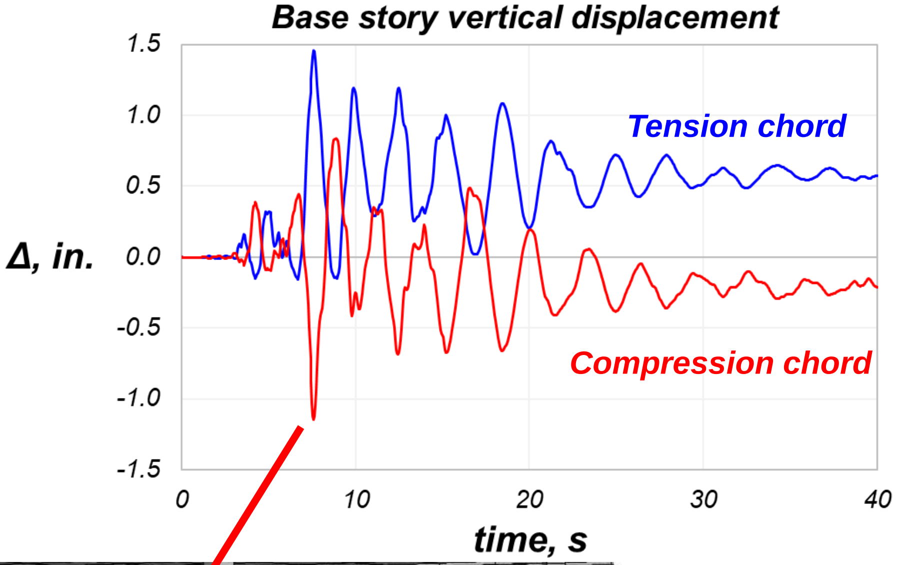


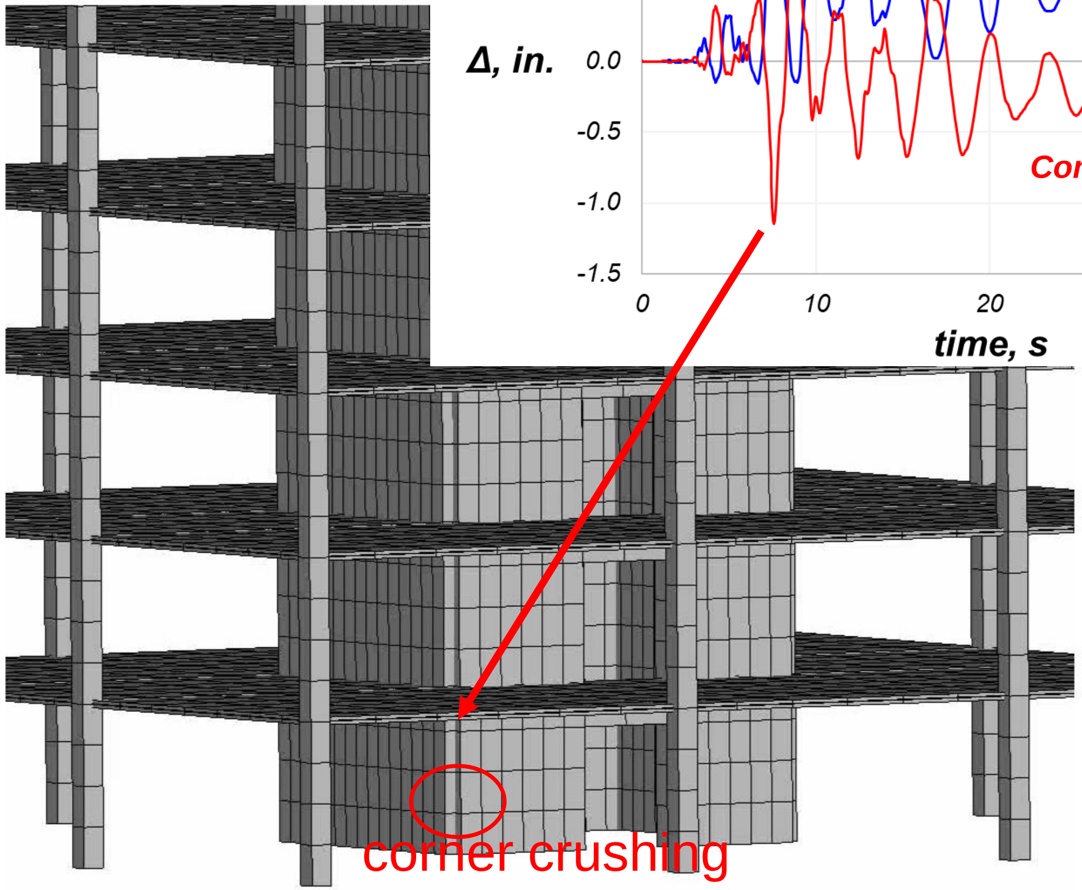


Dynamic Analysis Results





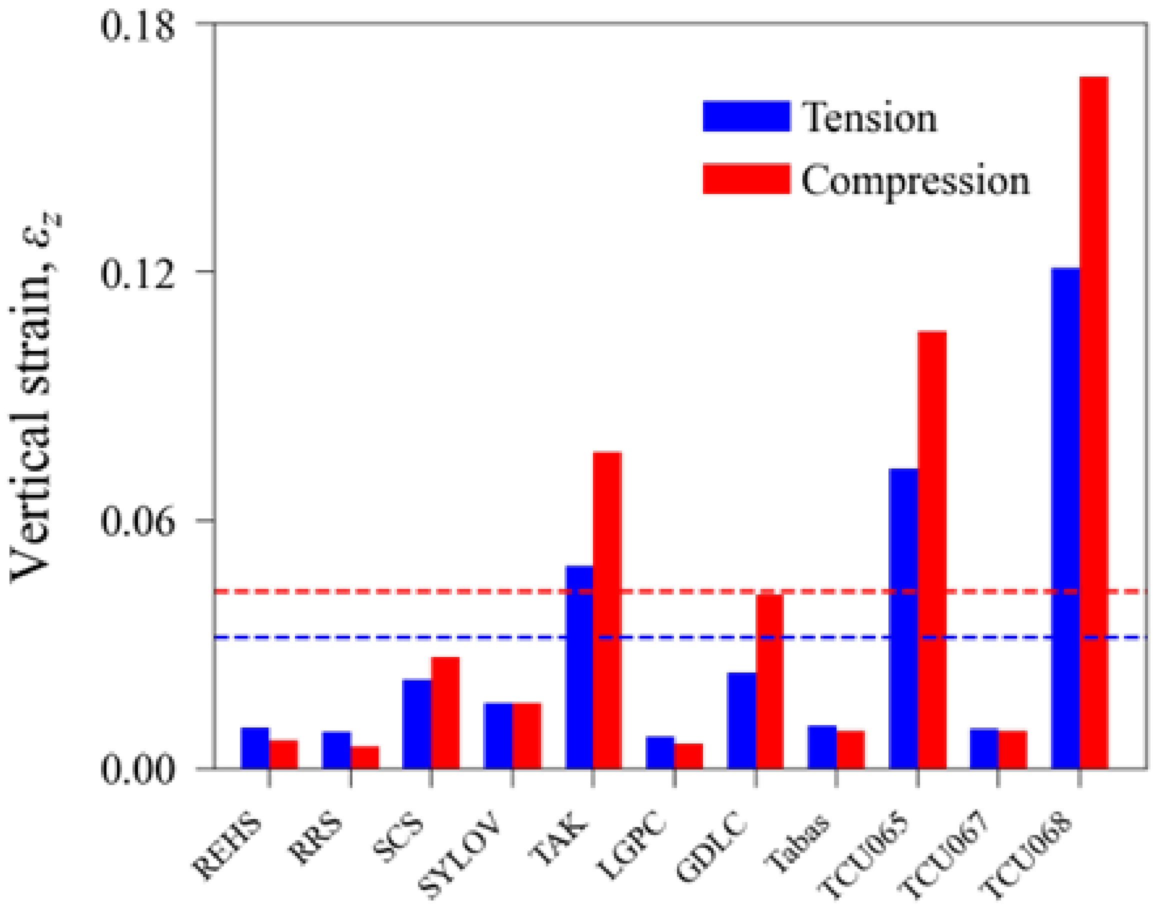


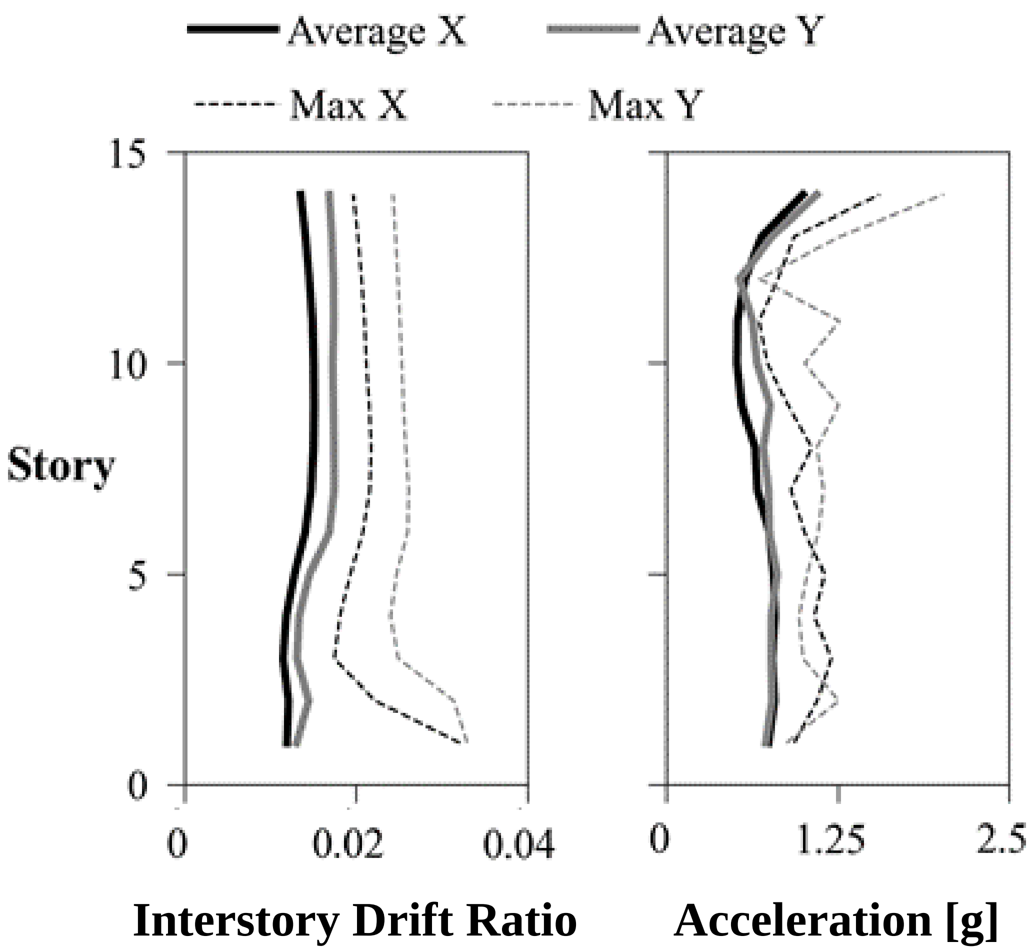


Bottom five stories of the core wall

Summary Results for 11 Motions

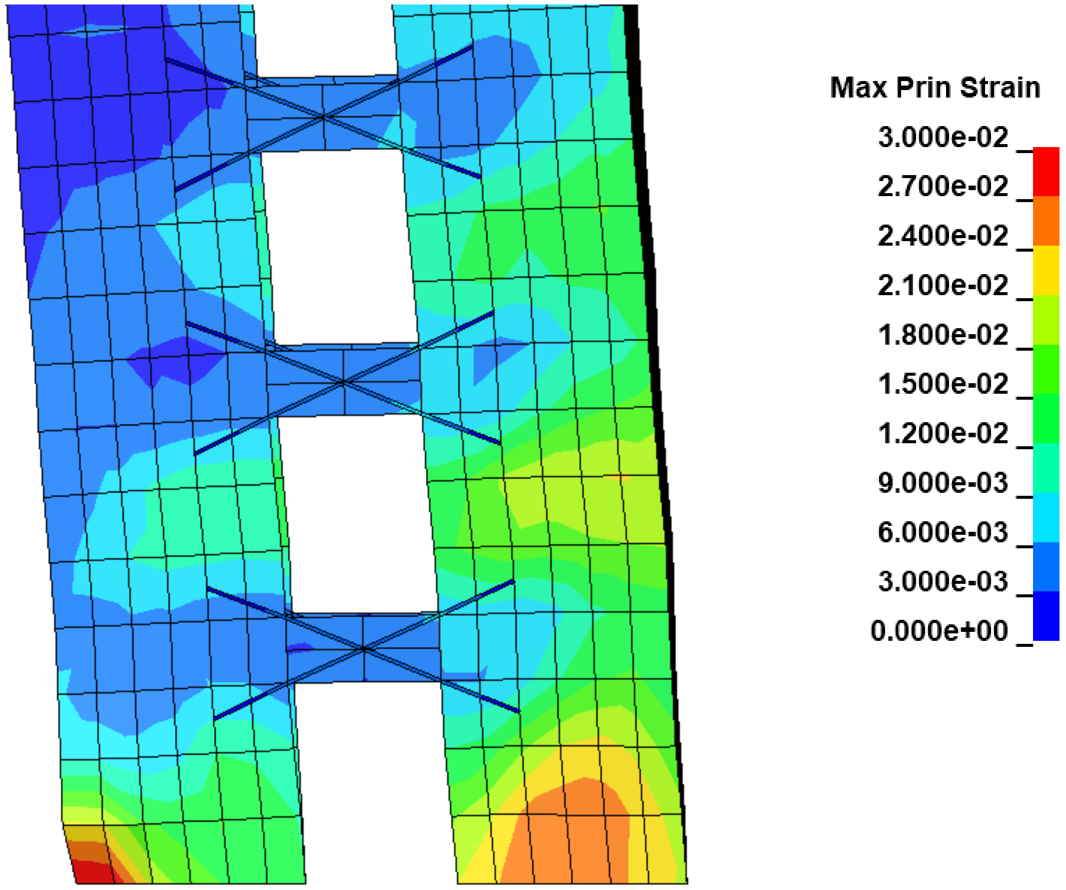
Maximum vertical strains





Dynamic Analysis Results

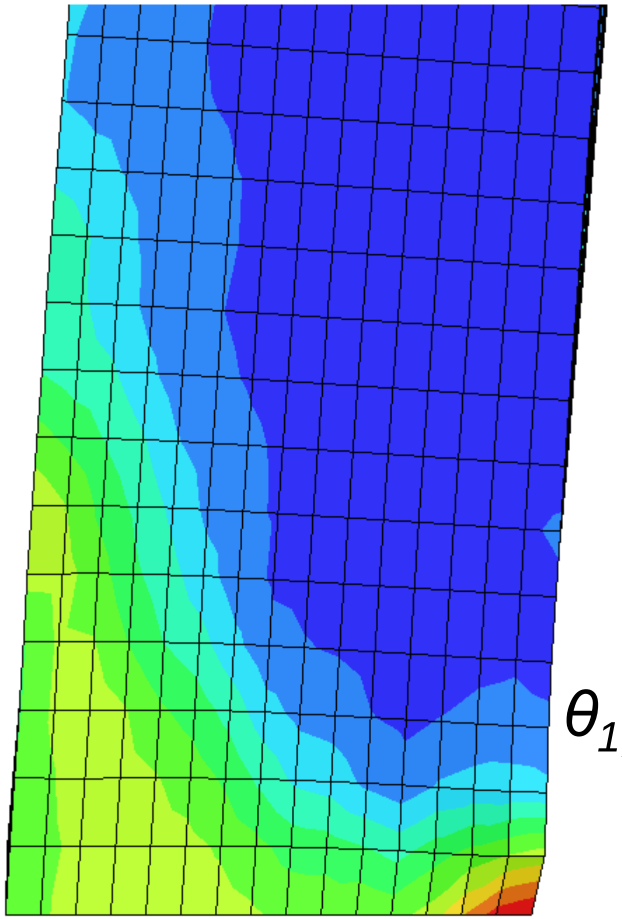
X-direction



$\theta_{1,X}$ = 1.6%

50% of the base story deformations due to shear !

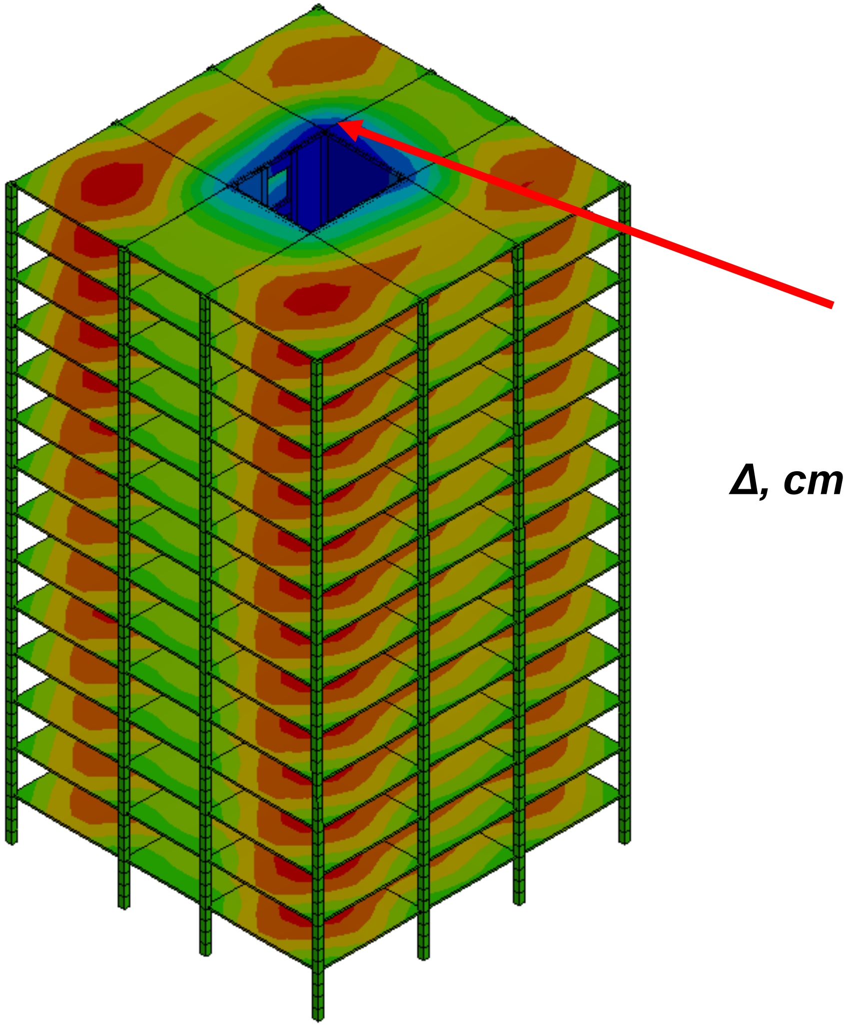
Y-direction

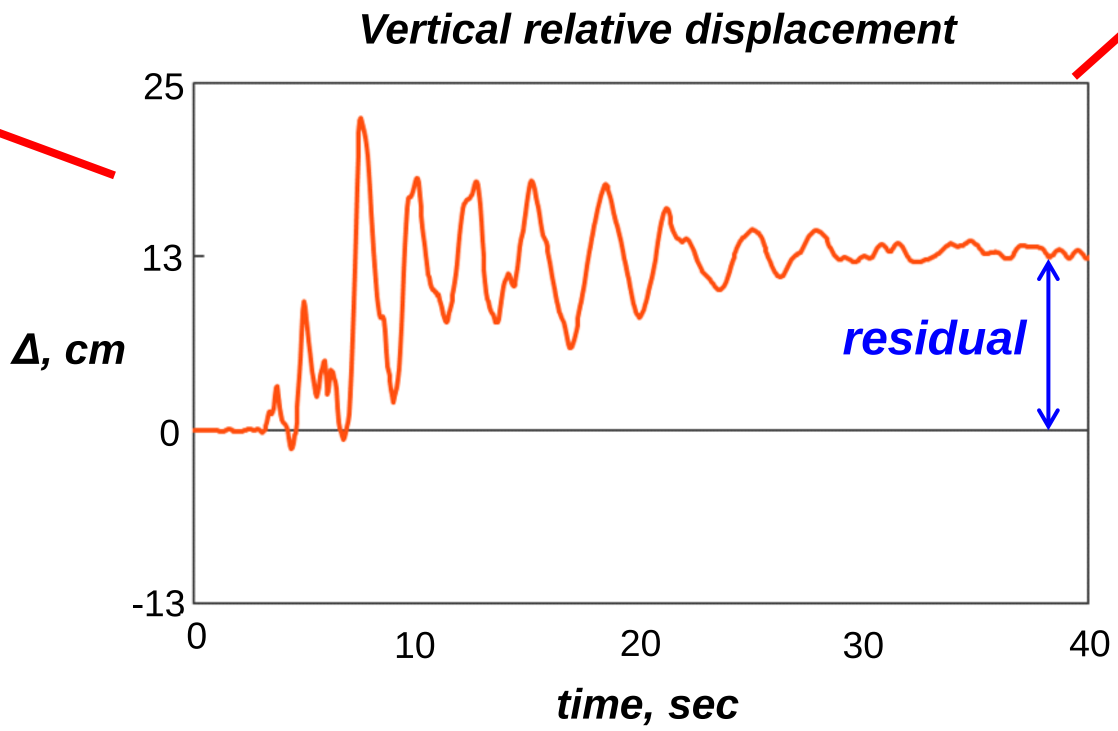


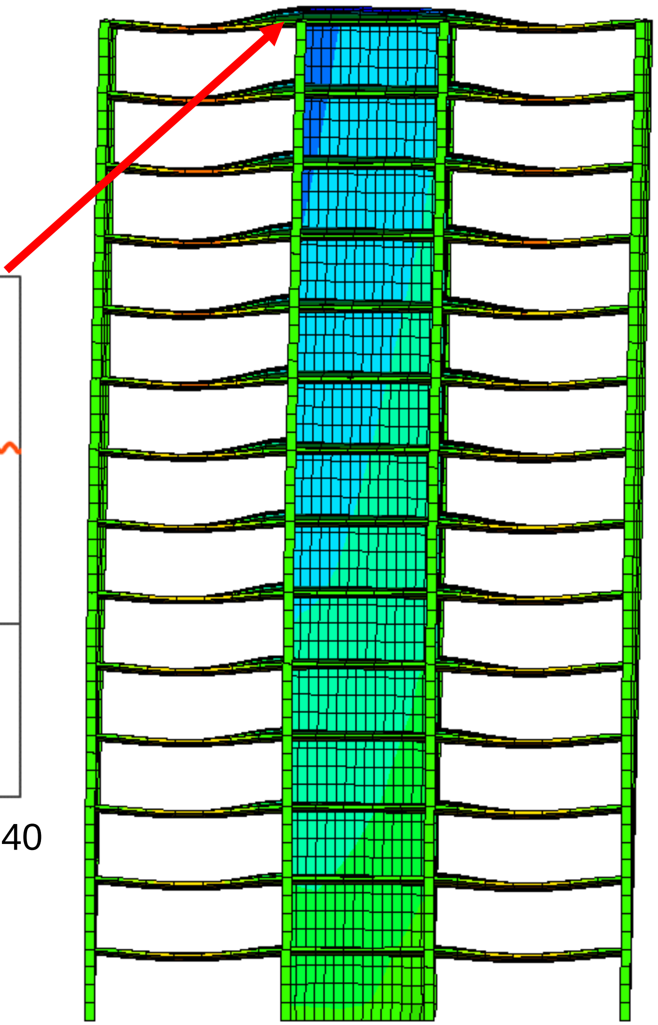
$\theta_{1,Y}$ = 1.5%

65% of the base story deformations due to shear !

Dynamic Analysis Results



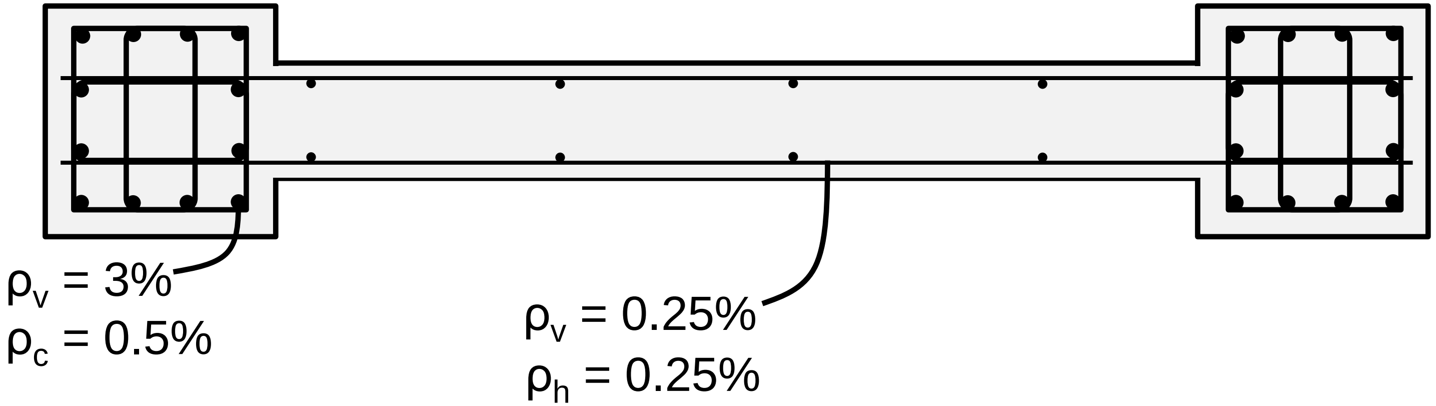




Visual amplification factor = 5

Analysis of Older RC Walls

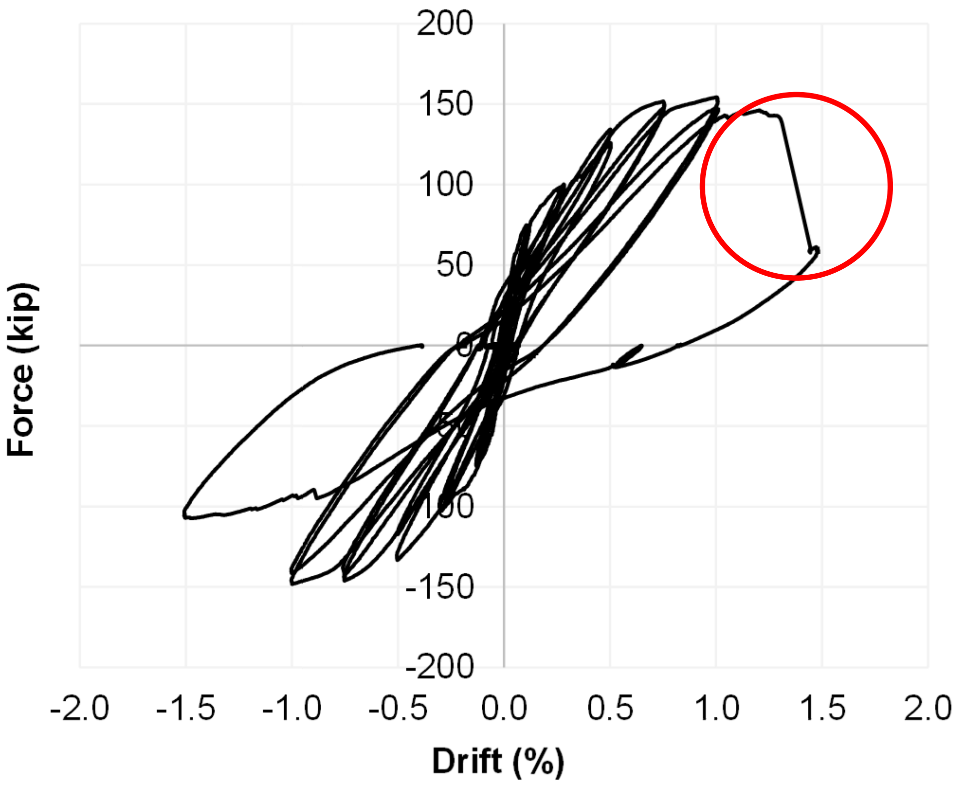
- Experimentally tested RC wall specimen at Virginia Tech.
- ½-scale representation of wall from 8-story building.
- Representing practice in the mid-1950s.



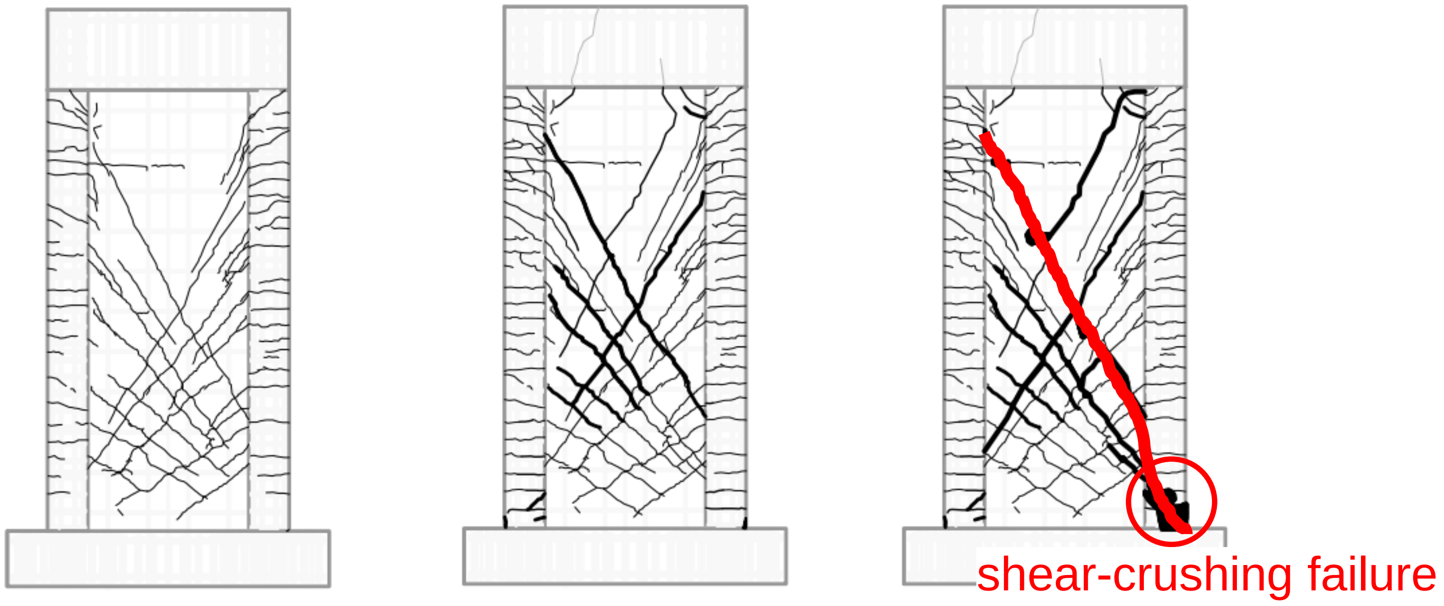
Steel quantities for intermediate grade bars

Analysis of Older RC Walls

Results of Test



Damage Pattern



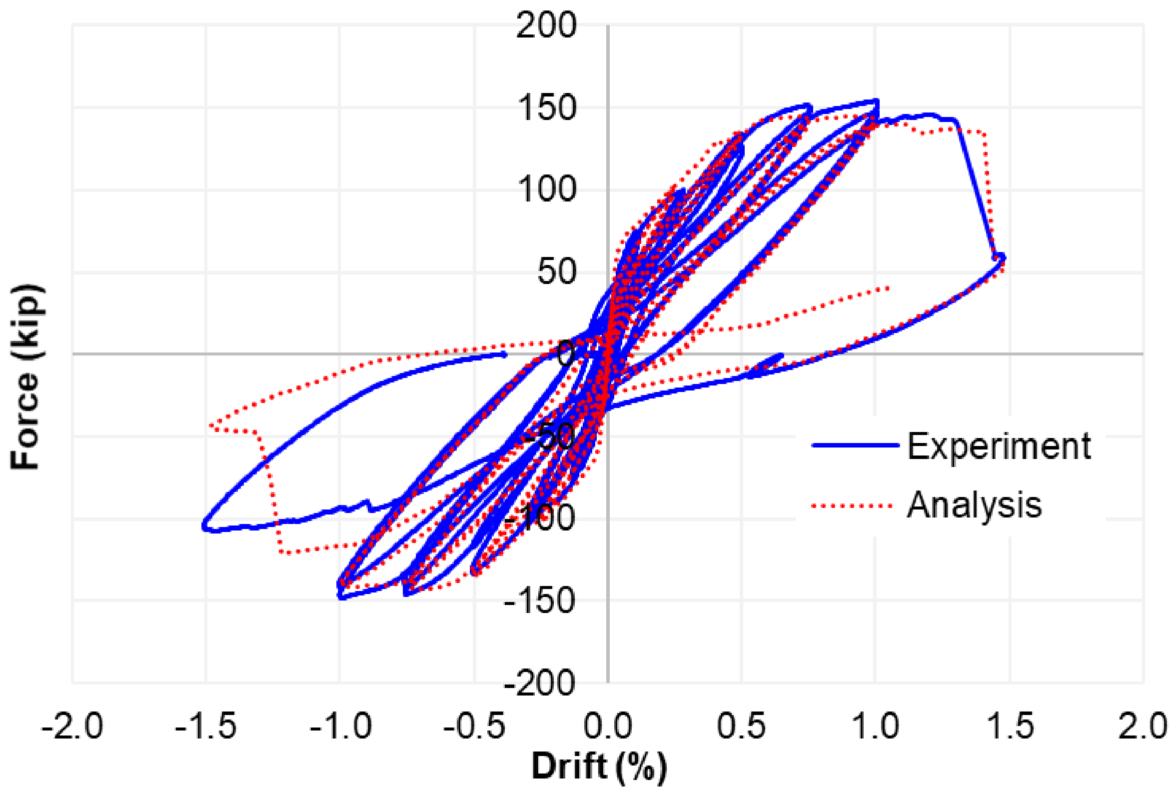
0.5% drift

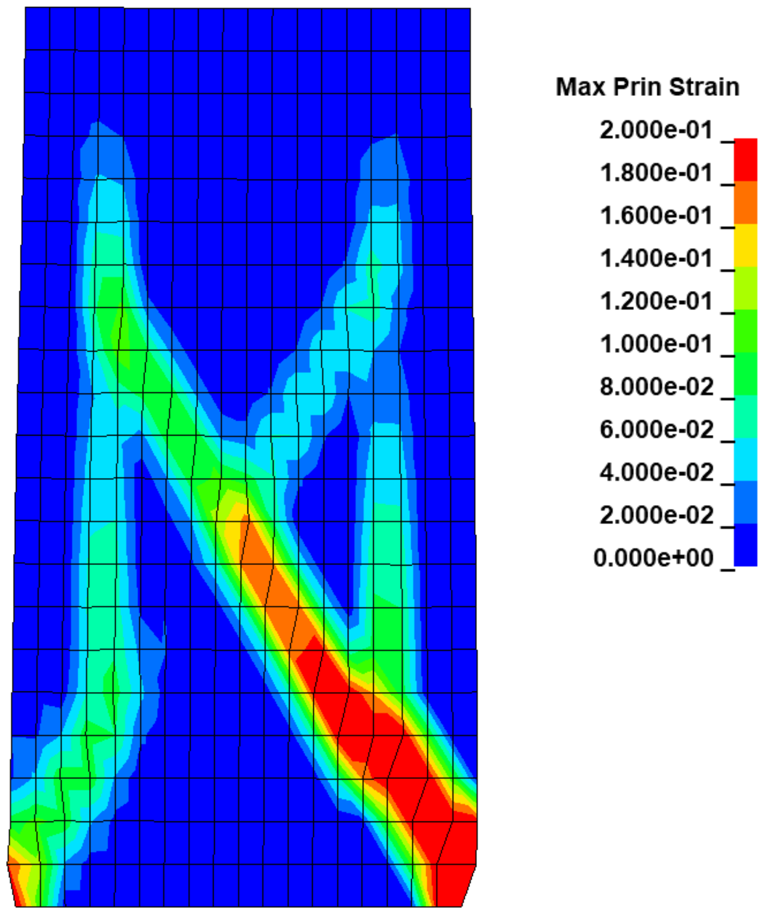
1.0% drift

1.5% drift
(end of test)

Analysis of Older RC Walls

Analysis - **actual** material properties:

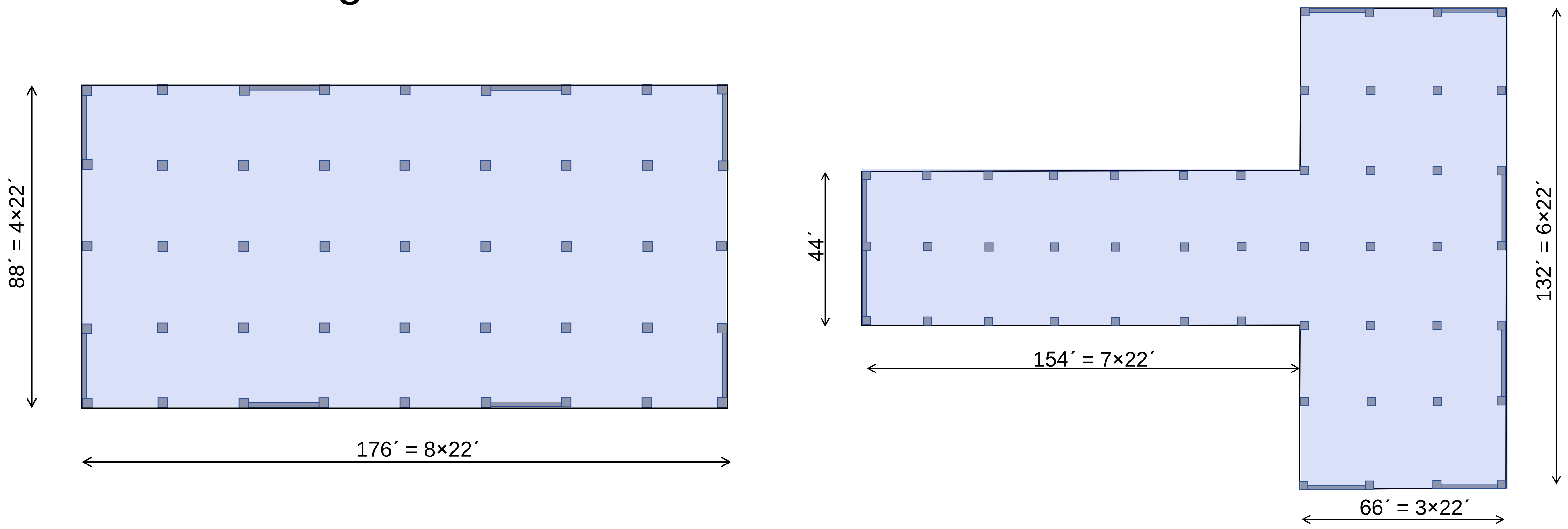




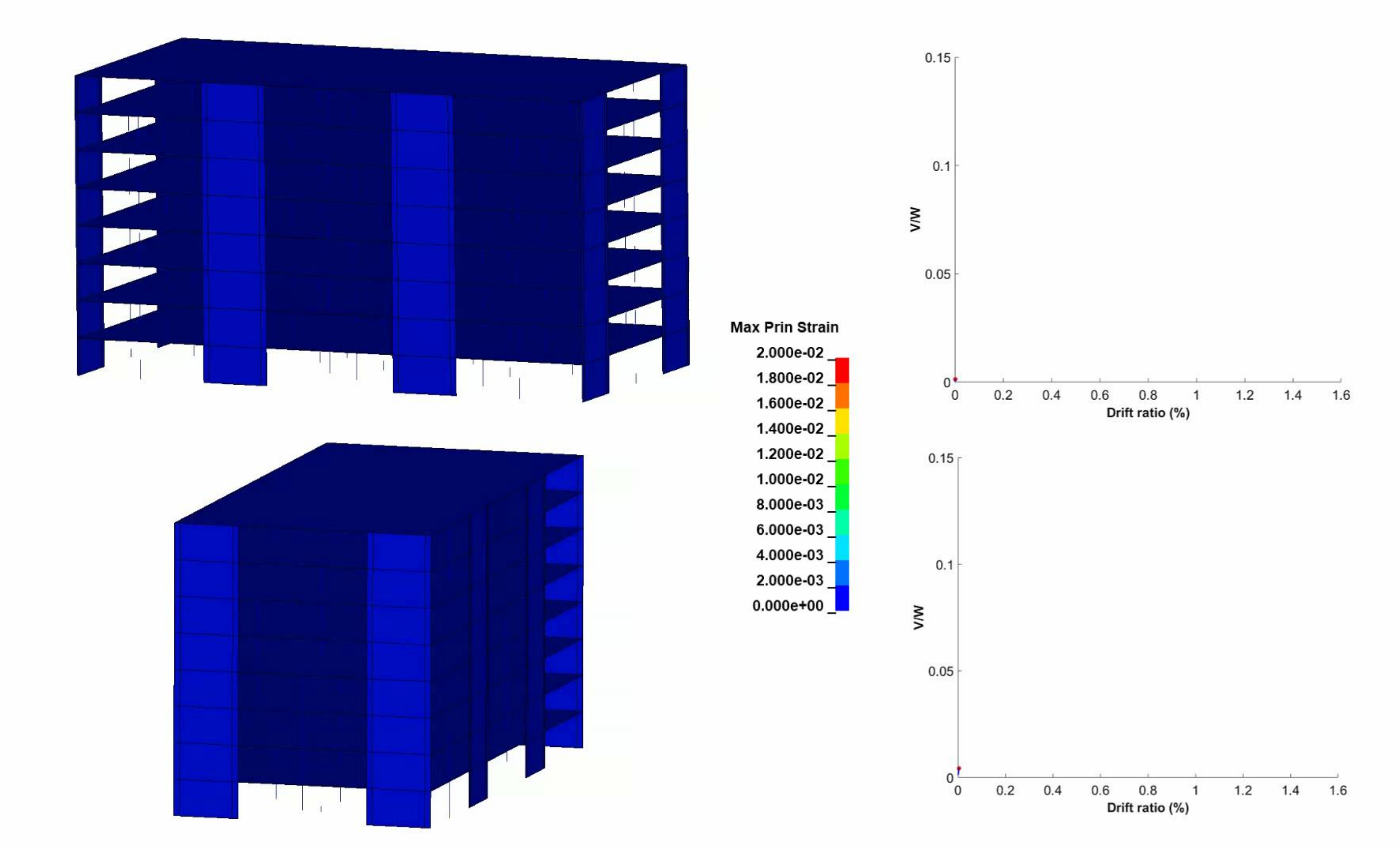
Ongoing Investigations

Analyses of 8-story buildings from 1950s-1960s

Plan Configurations:

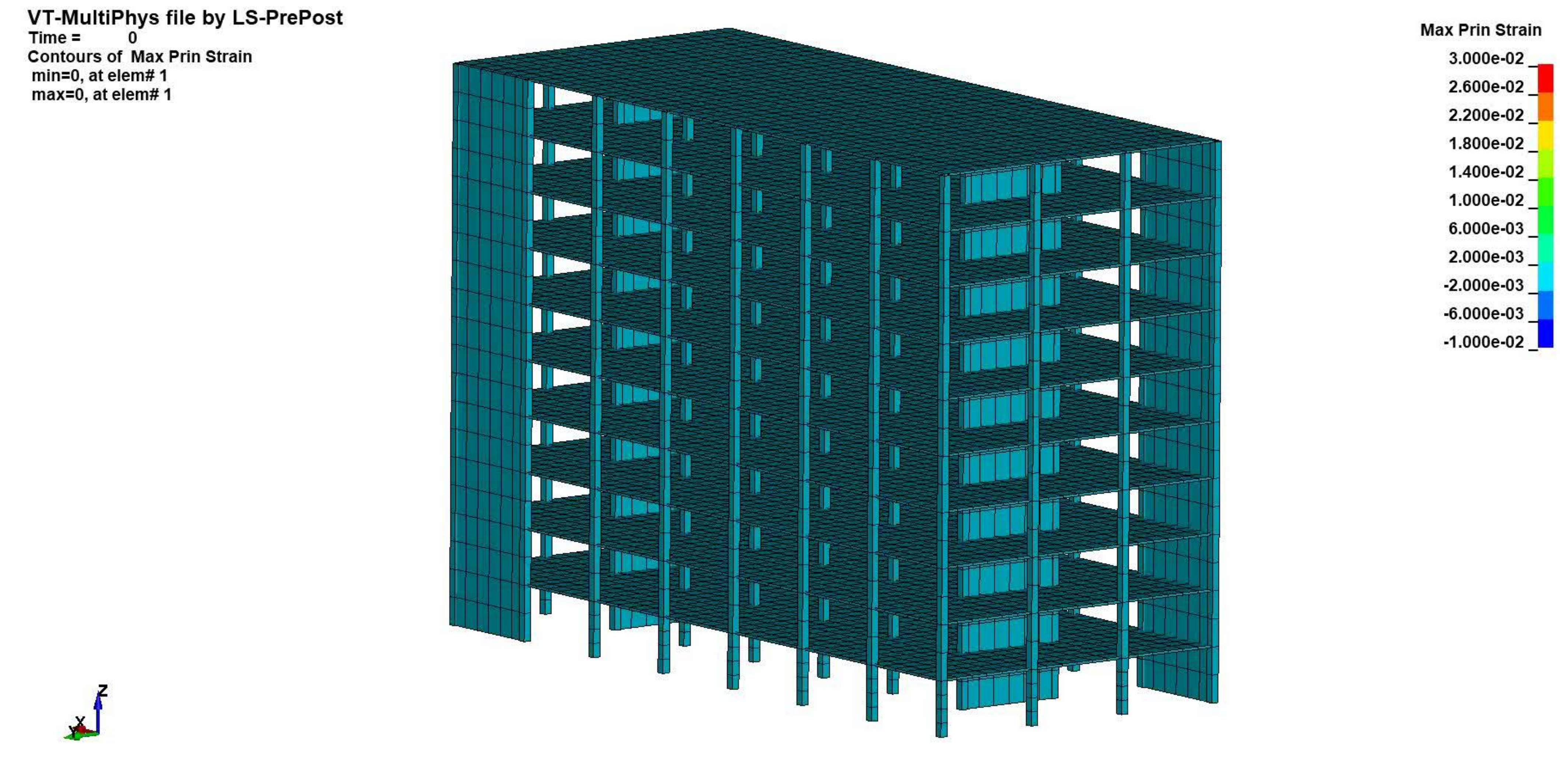


Ongoing Investigations



Example Analysis of Full Collapse

10-story, 1950s RC wall building under MCE motion:



Concluding Remarks

- Analysis approach combines accuracy with computational efficiency.
- It enables extensive parametric analyses of entire structural systems up to collapse.
- The method is better-tailored for modeling shear-flexure interaction, non-planar walls etc. compared to other simplified analysis approaches.
- Provides unifying framework for simulation of both isolated wall components and wall building systems.
- Its computational efficiency renders it suitable for generating training/validation data for ML algorithms.

THANK YOU

- Questions?

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Remark

- The material law for concrete involves softening.
- The regularization procedure by Lu and Panagiotou (2014) is used to prevent spurious mesh-size effects.
- Verification using analyses for different element size “a”…