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CHARLES PANKOW FOUNDATION
Building Innovation through Research

FEMA P695 Study
Ductile Coupled Walls

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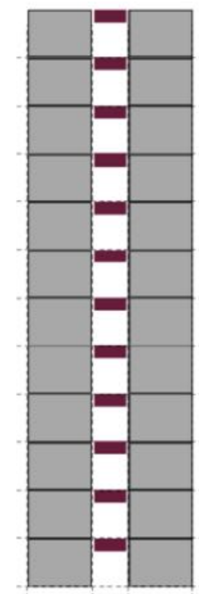
UCLA ENGINEERING
Civil and Environmental

Project Overview

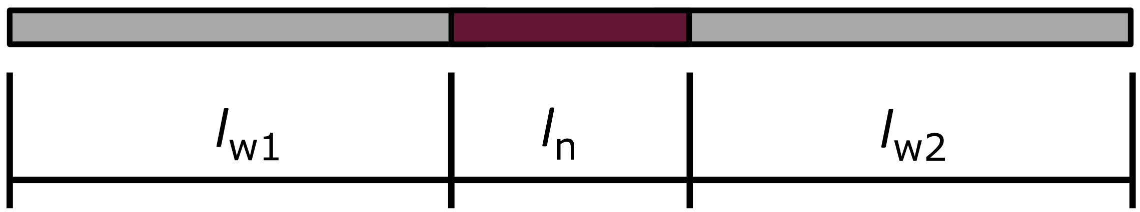
- Design of Coupled Walls
  - Currently: R=5 or 6, C_d = 5, Ω_0 = 2.5
  - More sophisticated design provisions
- ACI 318 + ASCE 7 Coordination
- FEMA P695 Process
  - Archetype Designs **R = 8 , C_d = 8 , (Ω_0 = 2.5)**
  - Nonlinear Modeling
  - Failure Modes (collapse assessment)
  - Analysis Results (collapse margin ratio)
  - Additional design requirements

ACI 318 Definition

- Ductile Coupled Wall:
  - An assembly of special structural walls linked by coupling beams
  - Wall pier aspect ratios, h_{wcs} / l_w > 2.0
  - Coupling beam aspect ratio: 2 < l_n/h < 5
    - Satisfied at > 90% of levels
  - Length ratio limit:



$$\sum \frac{l_n}{l_w} \geq 15\%$$

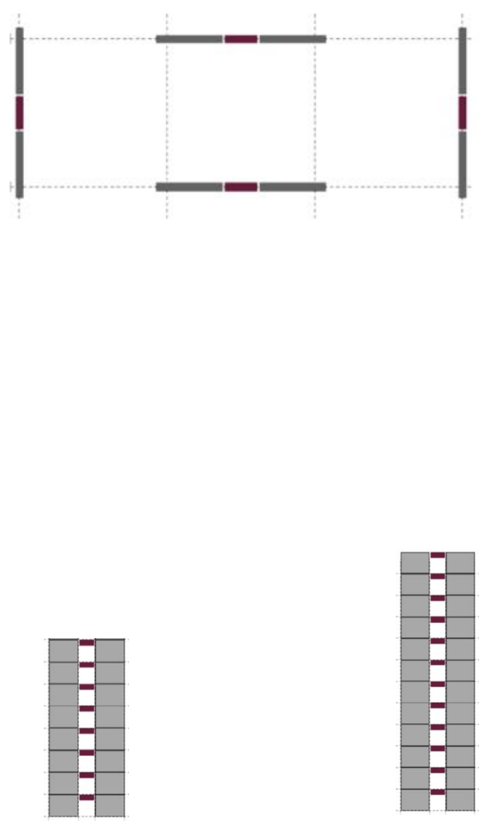


FEMA P695 Study

Overview

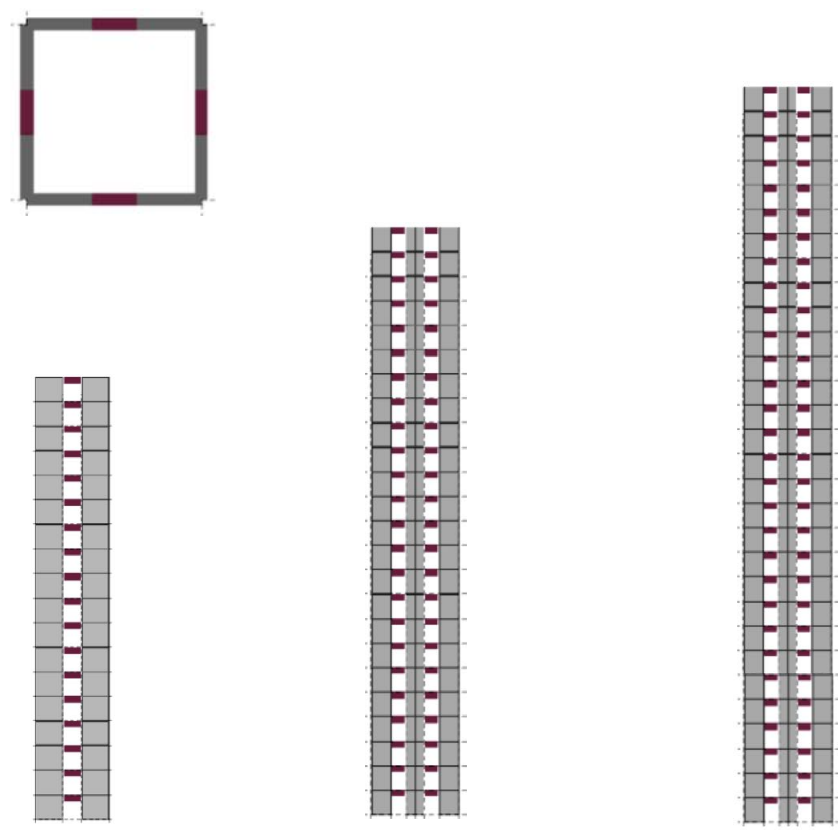
Building Heights & Wall Configurations

Planar Walls



8-story 12-story

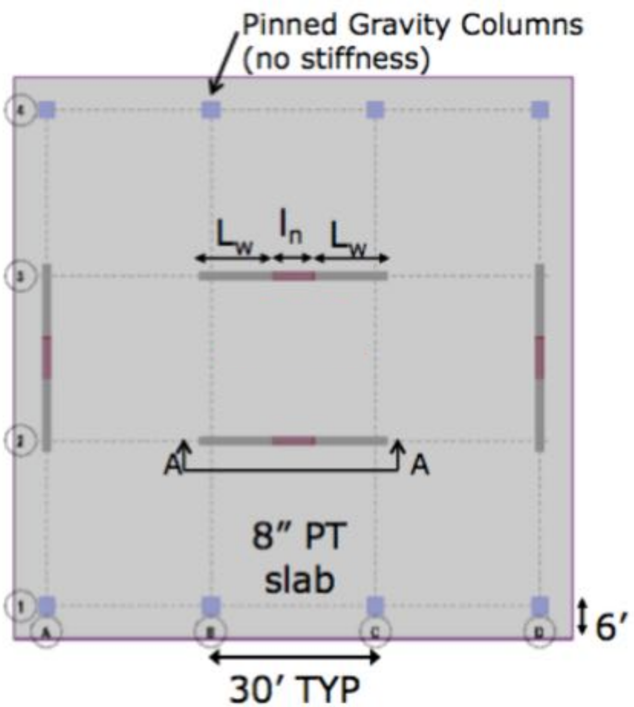
Core Walls



18-story 24-story 30-story

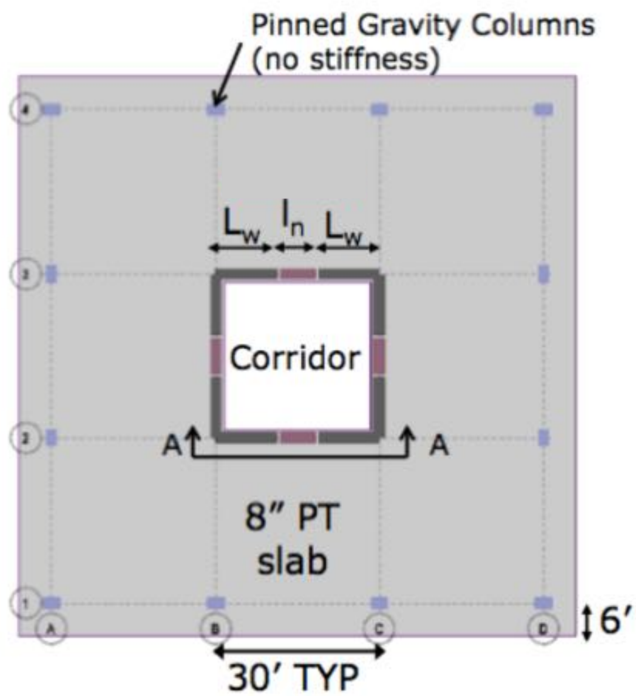
Building Configurations

Planar Walls

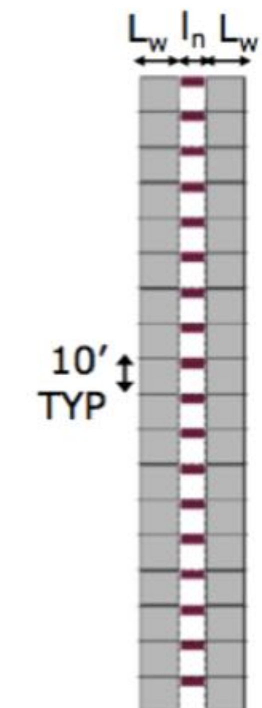


Typical Plan View

Flanged Walls



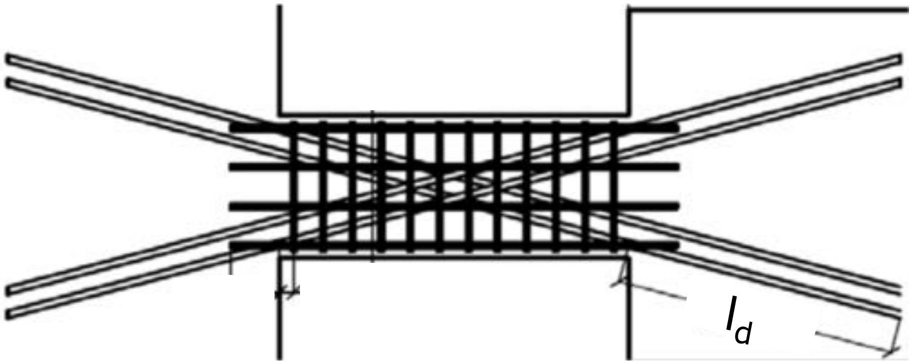
Typical Plan View



Section A-A
Wall Elevation View

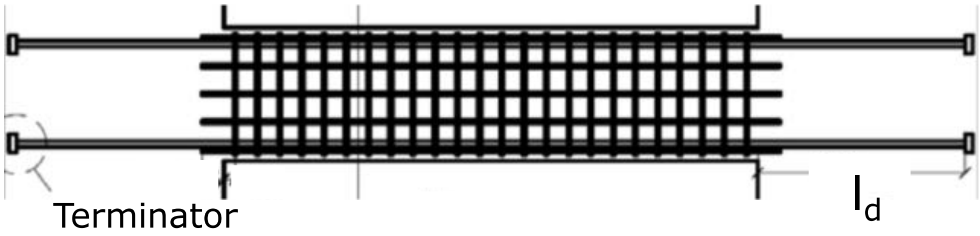
Coupling Beam Configurations

- Diagonally Reinforced:



l_n/h = 2.0,2.4,3.0,3.3

- Conventionally Reinforced:



l_n/h = 3.3,4.0,5.0

(Naish, 2010)

Building Archetypes

- FEMA P695 Performance Groups

<table>
<tr><th colspan="6">Performance Group Summary</th></tr>
<tr><th rowspan="3">Group No.</th><th colspan="4">Grouping Criteria</th><th rowspan="3">Number of Archetypes</th></tr>
<tr><th rowspan="2">Basic Configuration</th><th colspan="2">Design Load Level</th><th rowspan="2">Period Domain</th></tr>
<tr><th>Gravity</th><th>Seismic</th></tr>
<tr><td>PG-1</td><td>Planar walls,
diagonally reinforced
coupling beams with
l_n/h = 2.0,2.4, 3.0, 3.3</td><td>Typical</td><td>SDC D_{max}</td><td>Short</td><td>8
(8&12 story)</td></tr>
<tr><td>PG-2</td><td>Planar walls,
conventional. reinforced
coupling beams with
l_n/h = 3.3, 4.0, 5.0</td><td>Typical</td><td>SDC D_{max}</td><td>Short</td><td>6
(8&12 story)</td></tr>
<tr><td>PG-3</td><td rowspan="2">Flanged walls,
diagonally reinforced
coupling beams with
l_n/h = 2.0,2.4, 3.0, 3.3</td><td rowspan="2">Typical</td><td rowspan="2">SDC D_{max}</td><td>Short</td><td>4
(18 story)</td></tr>
<tr><td>PG-4</td><td>Long</td><td>8
(24 & 30 story)</td></tr>
<tr><td>PG-5</td><td rowspan="2">Flanged walls,
conventional. reinforced
coupling beams with
l_n/h = 3.3, 4.0, 5.0</td><td rowspan="2">Typical</td><td rowspan="2">SDC D_{max}</td><td>Short</td><td>3
(18 story)</td></tr>
<tr><td>PG-6</td><td>Long</td><td>6
(24 & 30 story)</td></tr>
</table>

Archetype Design Approach

Archetype Design Parameters

- Design Codes
  - ASCE 7-16
  - ACI 318-14 + ACI 318-19 (change proposals)
- Seismic Parameters
  - $R = C_d = 8$; $I_e = 1.0$; $\rho = 1.0$
- Site Parameters (ATC-63)
  - D_{max}: $S_{DS} = 1.0g$, $S_{D1} = 0.6g$
- ASCE 7 RSA (§12.9)
  - Scaled to 100% of ELF V_b (§12.8)
  - Accidental torsion (5% offset)
  - Gravity loads:
    - DL = 100 psf+25 psf, LL = 40,50 psf

(FEMA P695/ATC-63)

Member Properties for Elastic Design

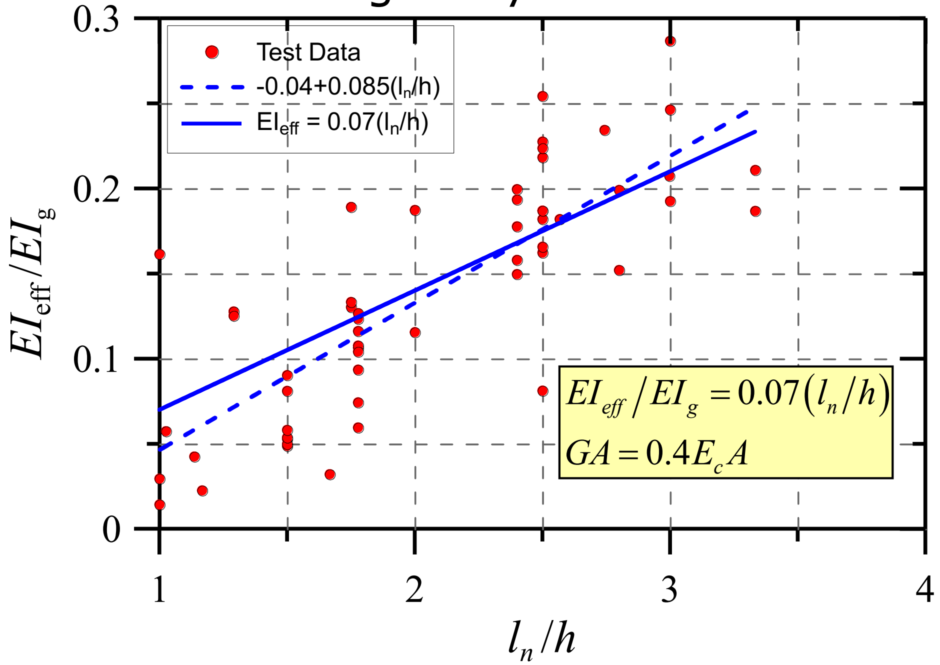
Effective Stiffness for Elastic Analysis

- Wall Piers:
  - Axial Stiffness: $1.00\ E_c A_g$
  - Shear Stiffness: $0.40\ E_c A_g$
  - Flexural Stiffness: $0.75\ E_c I_g$
  - Out-of-plane stiffness: $0.10\ E_c I_g$
- Gravity Columns: pinned, P-Δ effect only
- Rigid Diaphragm: 2-way slab

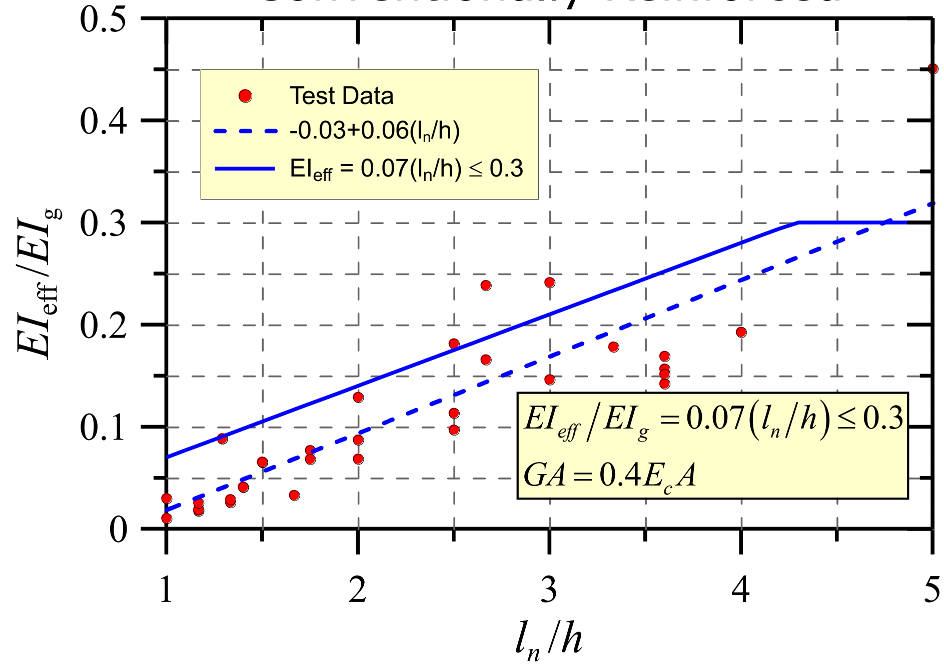
Member Properties for Elastic Design

- Coupling Beams:
  - Effective Flexural Stiffness: $EI_{eff} = 0.07\,(l_n/h)\,EI_g$
    - PEER TBI 2.0/LATB 2017
  - Trend validated with 100+ test specimen

Diagonally Reinforced

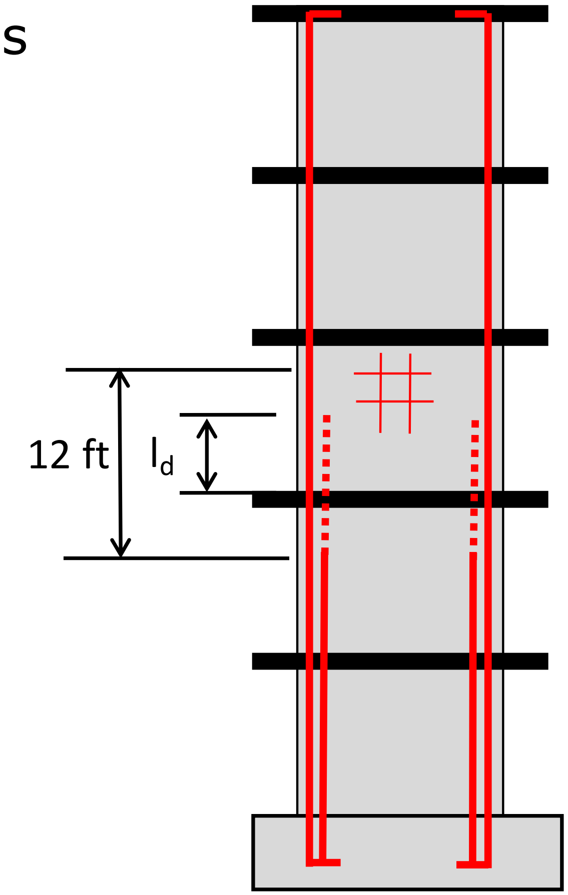


Conventionally Reinforced



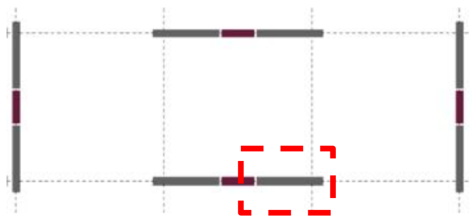
Wall Design Approach

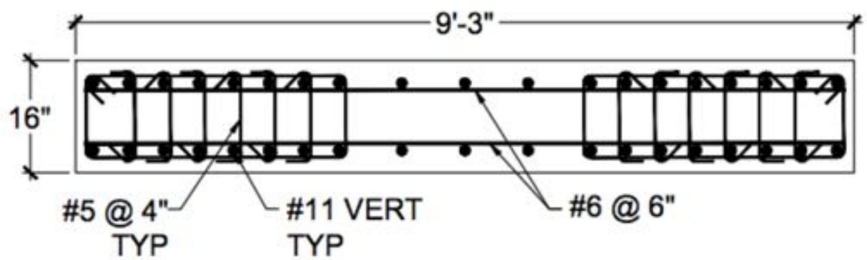
- Forces at wall centroid ± Accidental Torsion
  - 100% + 30% load combination for core walls
- Shear design - §18.10.3
  - ACI 318-19: CH-09 Wall Shear Amplification
- Drift capacity check - §18.10.6.2
  - ACI 318-19: CH-011
- Termination of wall longitudinal reinforcement
  - ACI 318-19: CH-10 l_d above floor level
- Detailing requirements - §18.10.6.4
  - ACI 318-19: CH-011 Overlapping Hoops



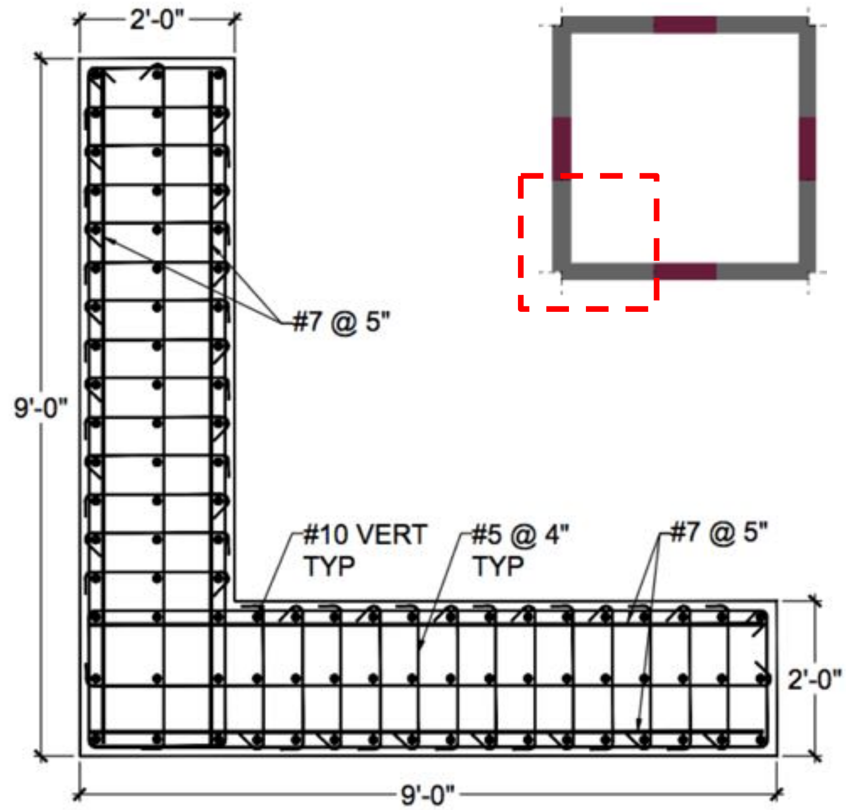
Typical Wall Details

CW-12H-3.0, Level 1



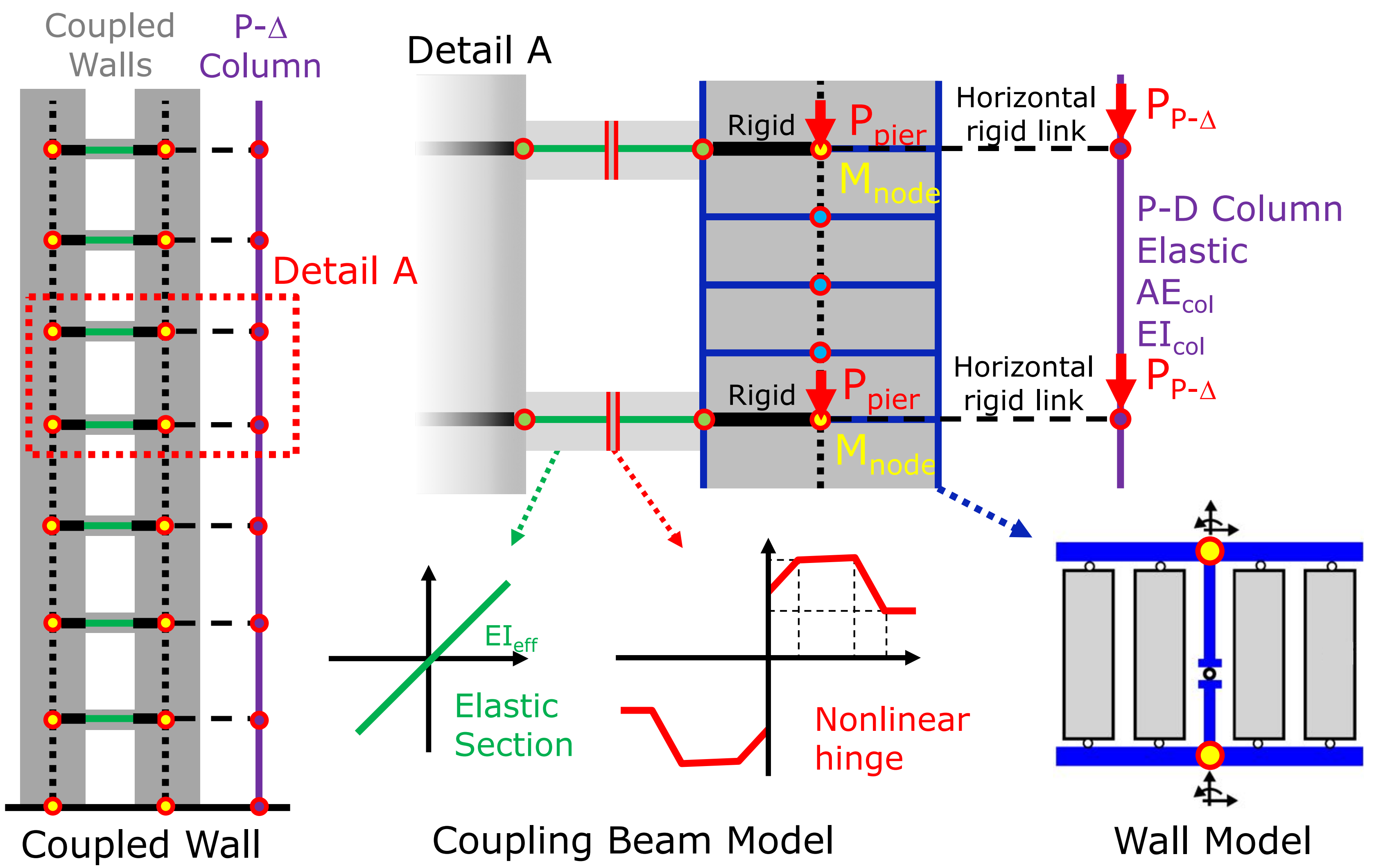


CW-18H-3.0, Level 1



Nonlinear Modeling

Nonlinear Modeling Approach



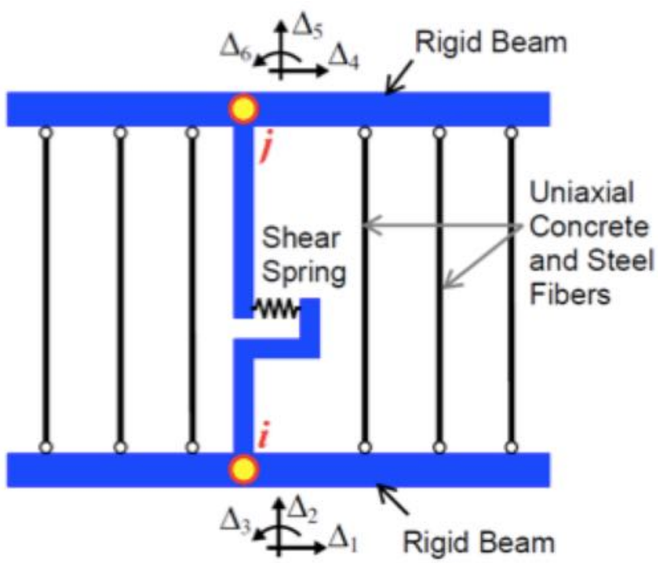
Nonlinear Models for Wall Piers

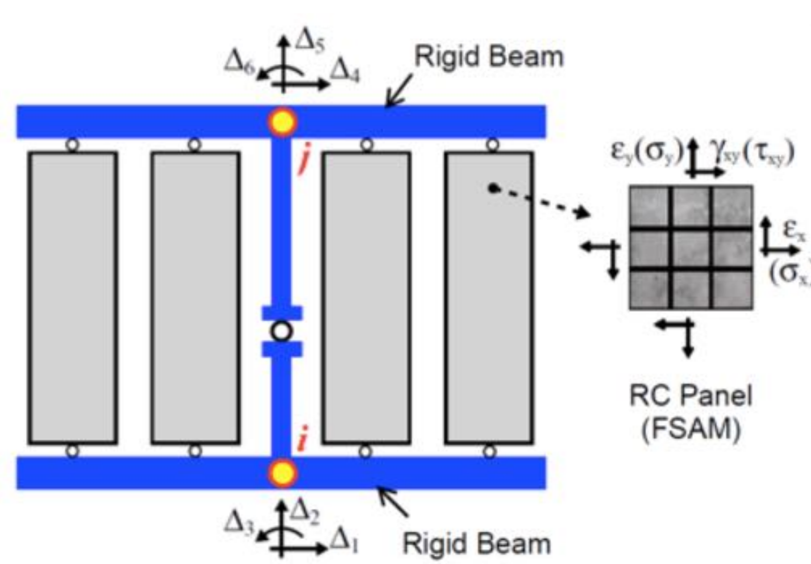
MVLEM

- P-M fiber section
- V - shear spring
- P-M and V uncoupled

SFI-MVLEM

- P-M-V coupled
- Nonlinear shear behavior
- Computationally demanding

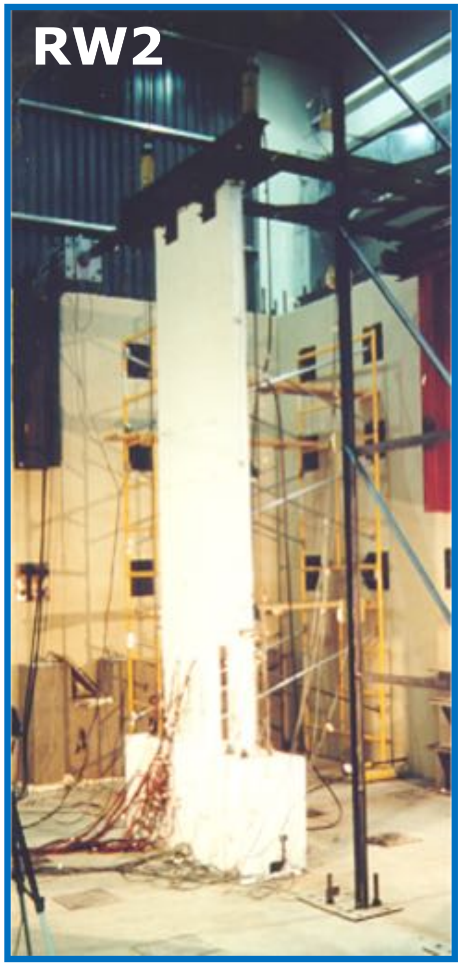


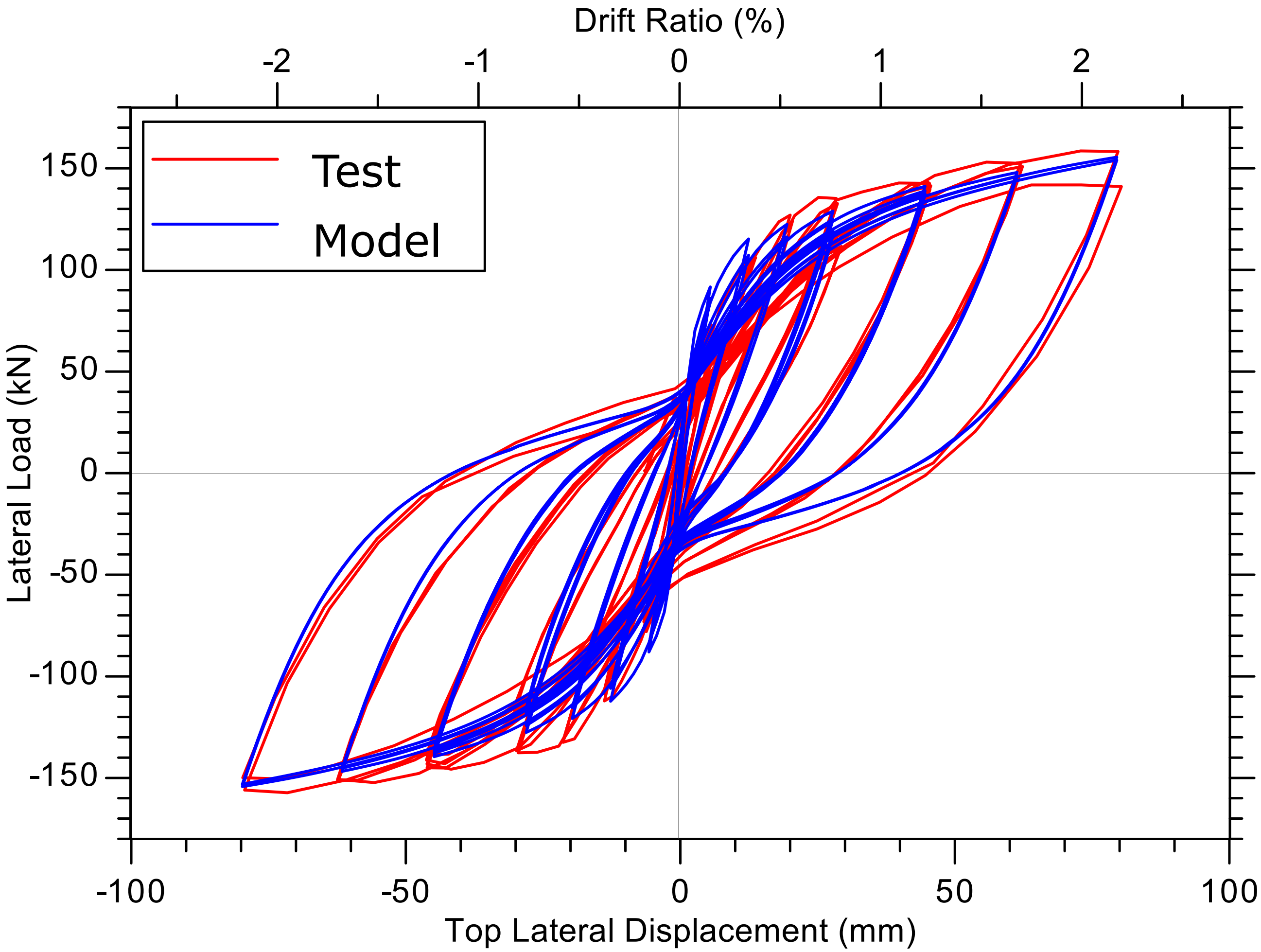


- Available in OpenSees (Kolozvari et al., 2018)

Validation of RC Wall Models

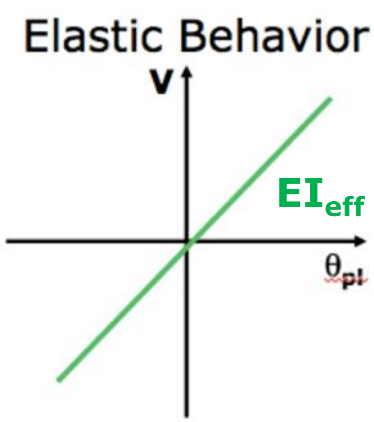
- Validation: Thomsen and Wallace

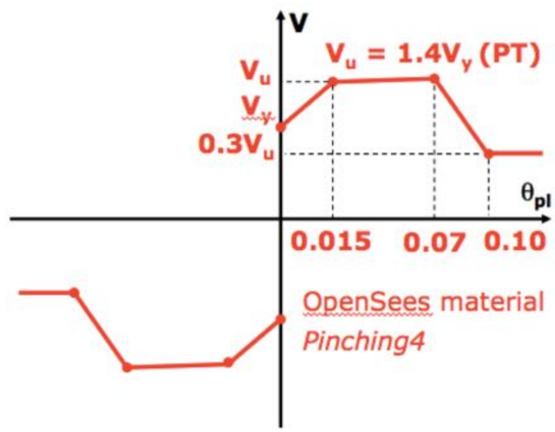


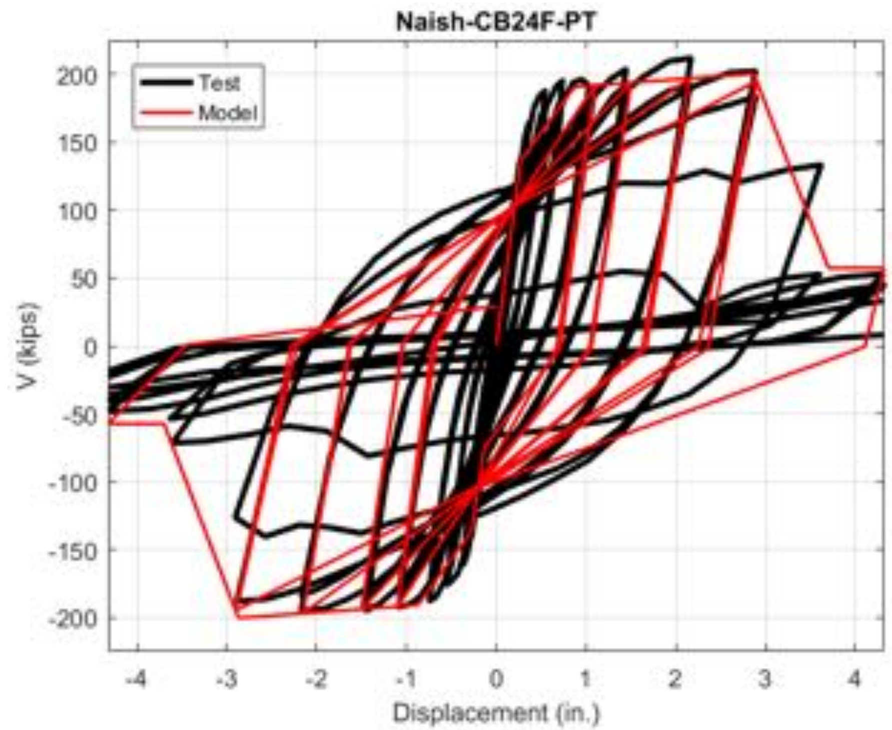


Nonlinear Model for Coupling Beams

- Modeling parameters per Naish et al. (2010)



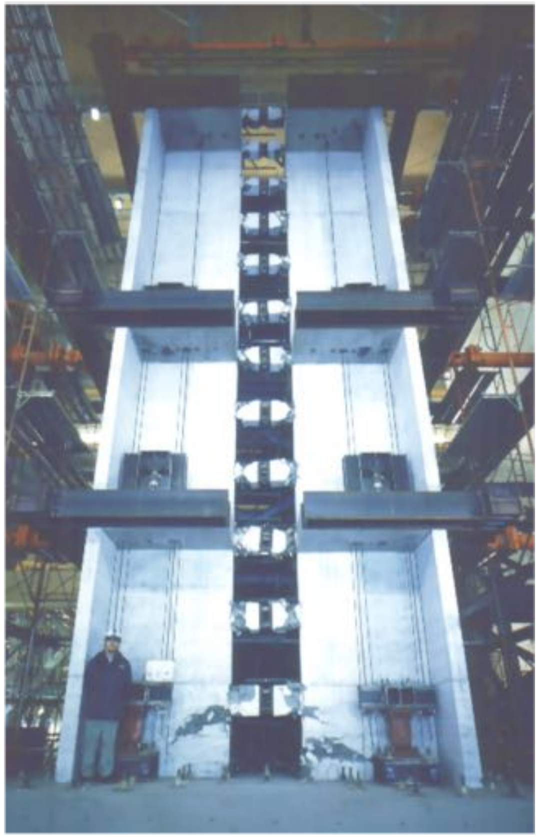




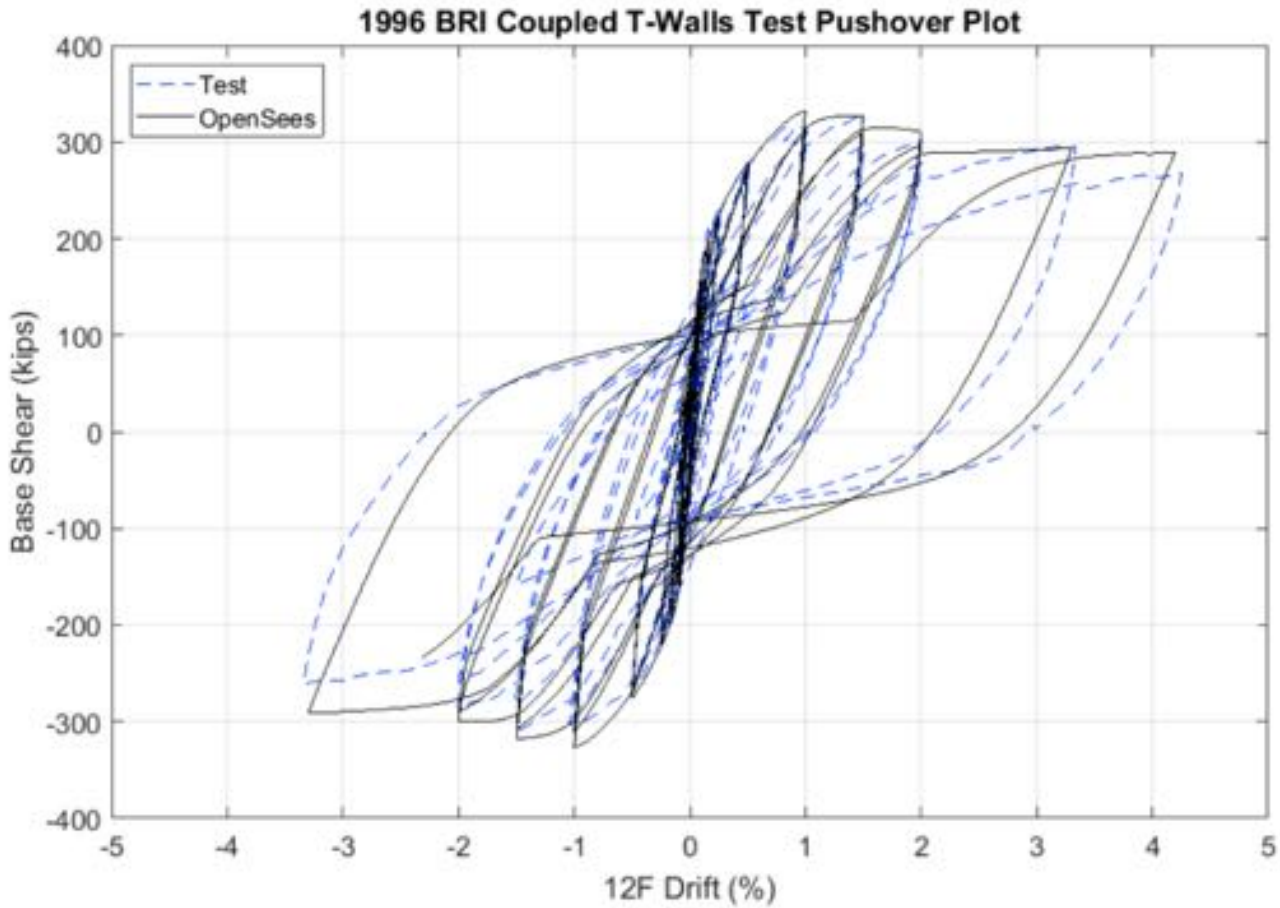
Representative validation results

Validation of Coupled Wall Model

- BRI 12-Story Coupled T-Walls Test



Sugaya et al. (1996)



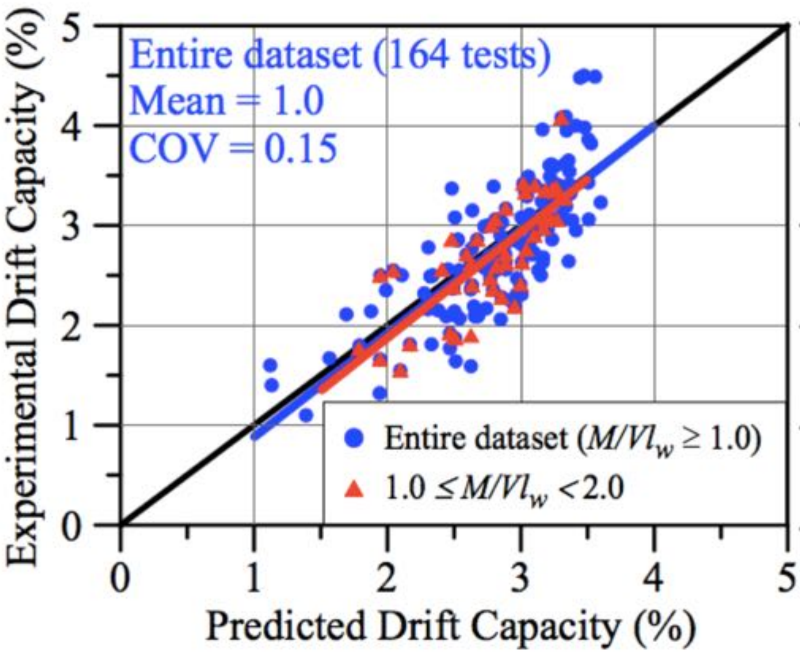
Failure Assessment

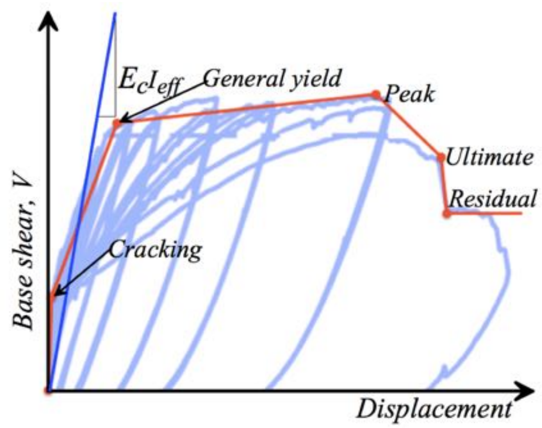
Considered Failure Modes

- Statistical models vs. explicit modeling of failure
- Conservative approach, denotes initiation of loss
- Flexural Failure
  - Drift/Curvature capacity model (Abdullah & Wallace, 2018)
- Wall Shear Failure
  - Shear demand versus wall tensile strain (LATBSDC, 2017)
- Axial Failure
  - Shear friction model (Wallace, Elwood and Massone, 2008)

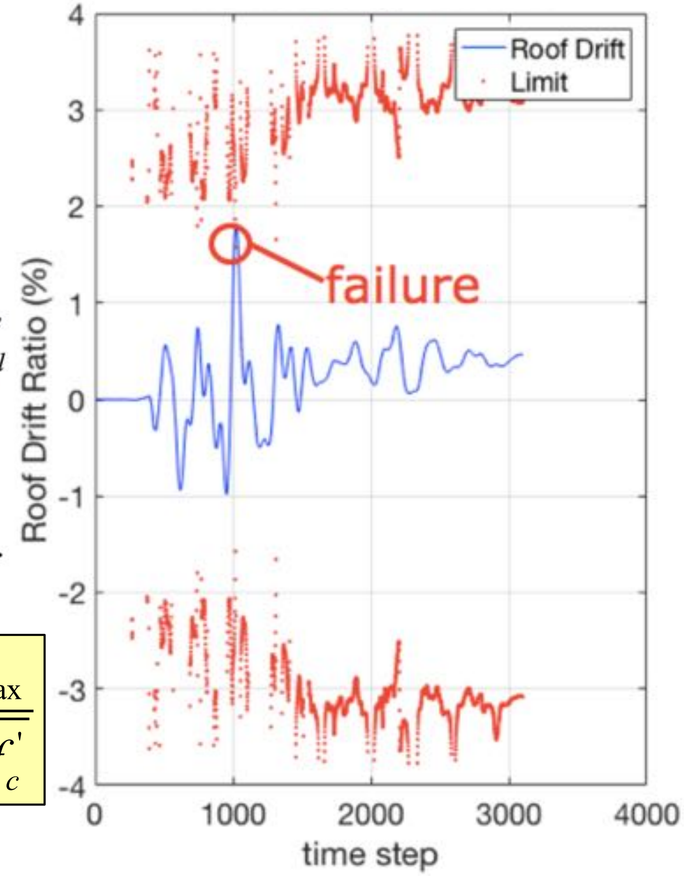
Flexural Failure Model

- Drift capacity model by Abdullah & Wallace (2018):
  - Crushing, buckling, and lateral instability
  - UCLA Wall Database: 164 walls w/ SBEs



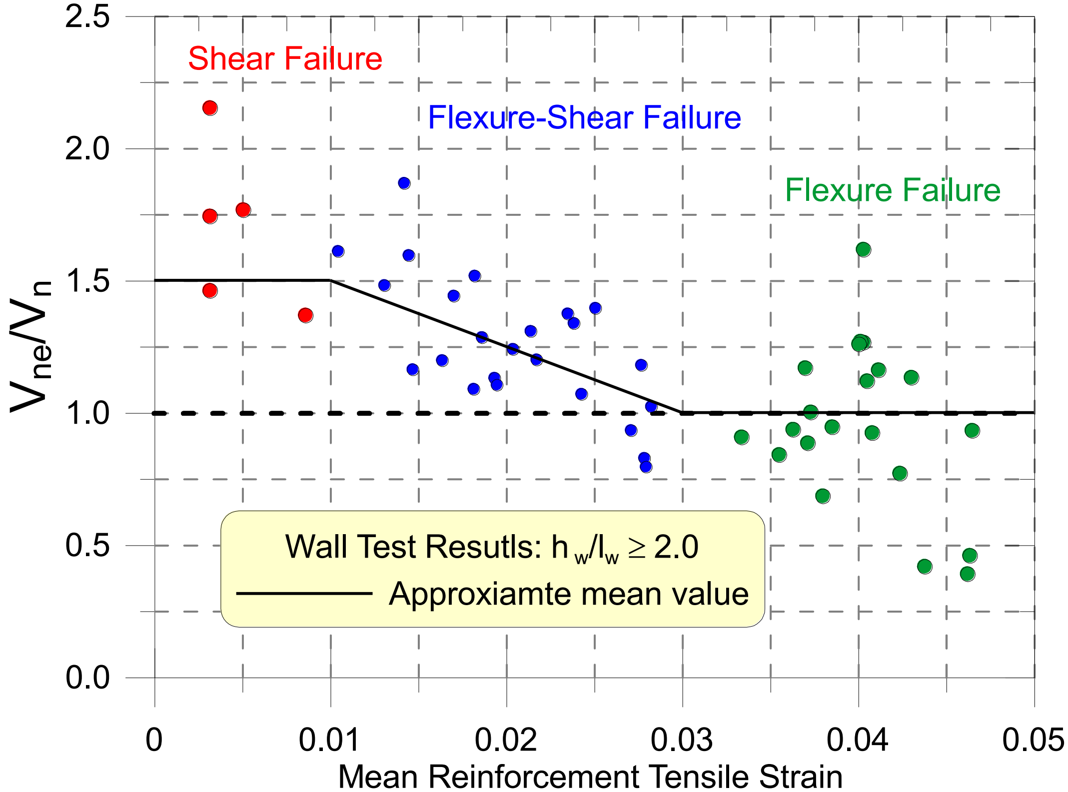


$$\frac{\delta_c}{h} = 3.85 - \frac{c\ L_w}{50\ b^2} - \frac{v_{u,\max}}{8\sqrt{f_c'}}$$

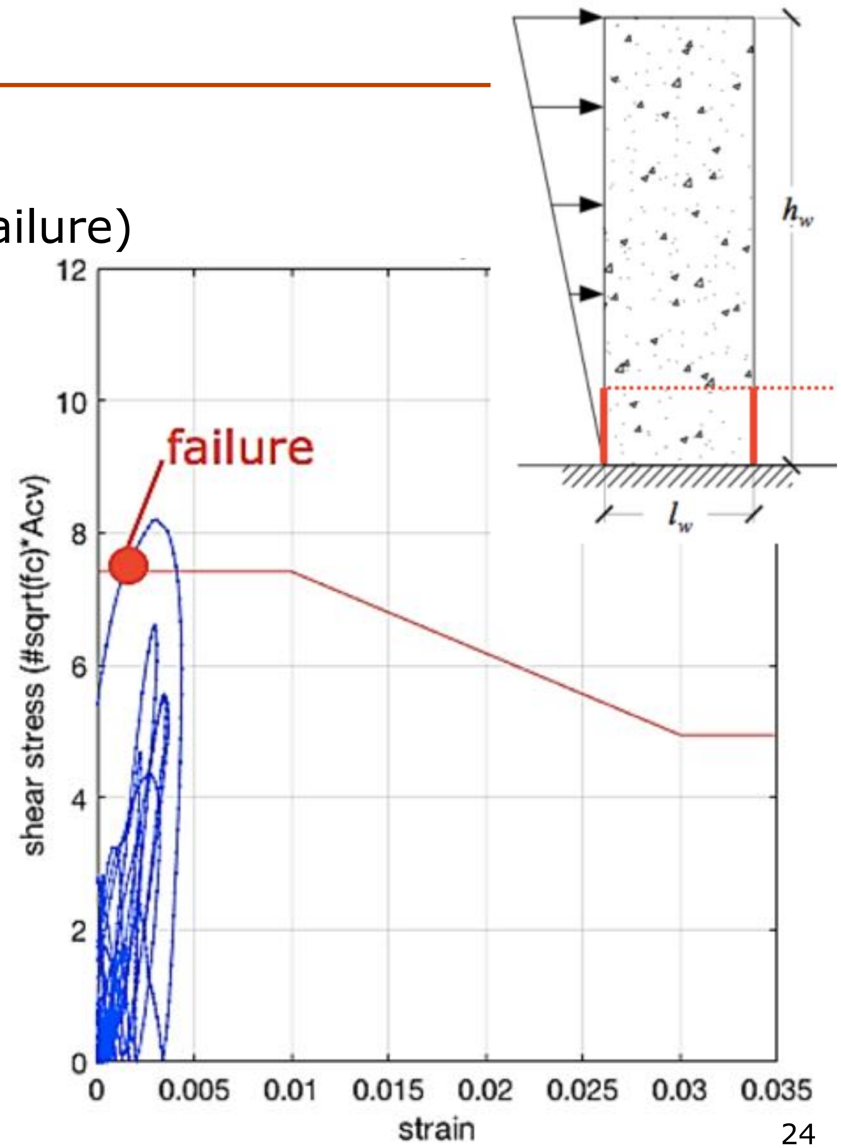


Shear Failure Model

- LATBSDC (2017), Appendix A:
  - UCLA Walls Database (51 tests: shear failure)
  - Shear demand vs wall tensile strain

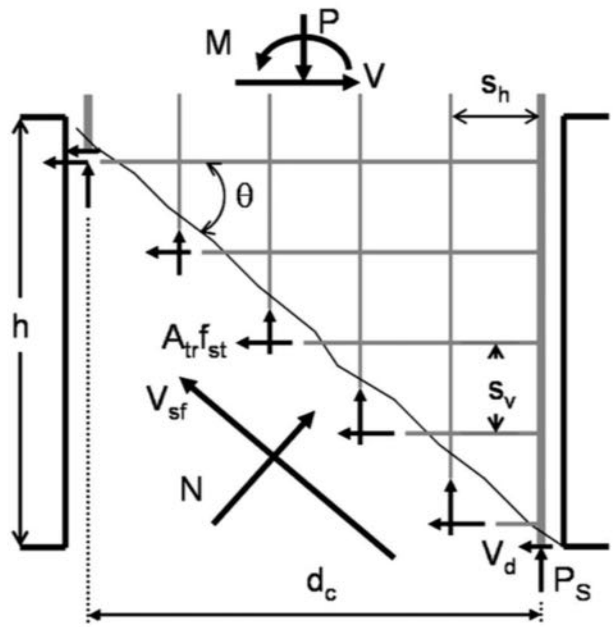


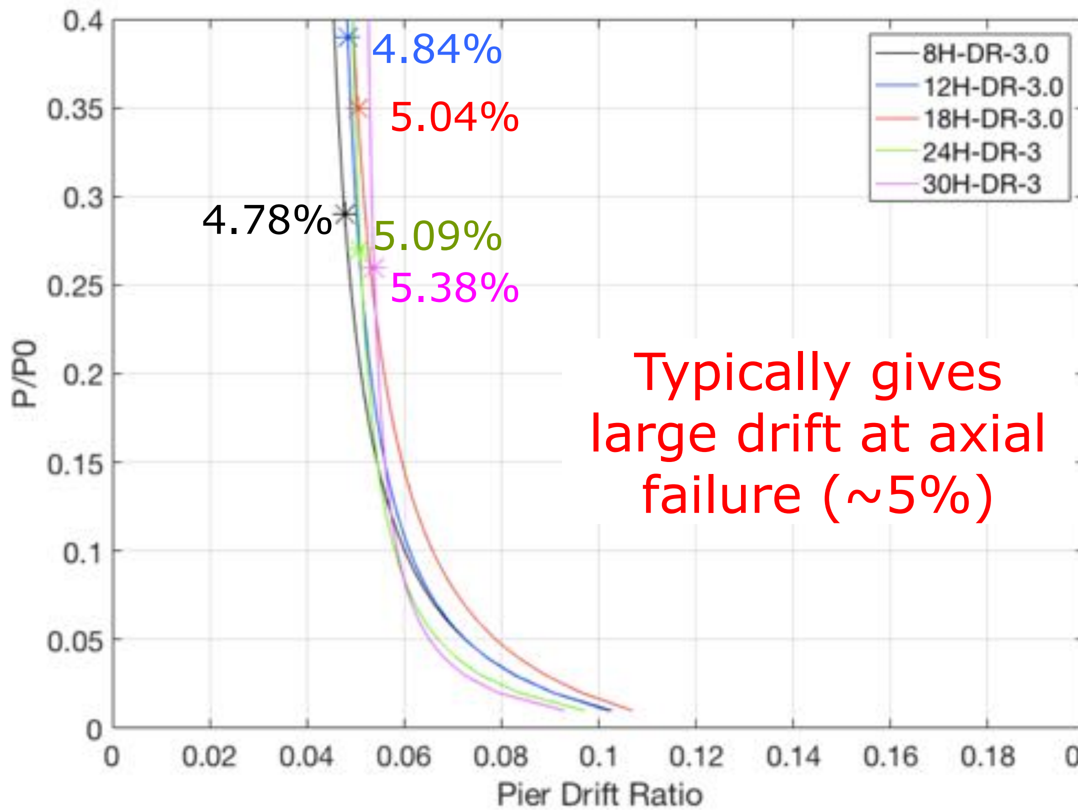
$$\varepsilon_s = \phi_{total}\left(l_w - c\right)$$



Axial Failure Model

- Wallace, Elwood and Massone (2008):
  - Drift at axial failure once V_{sf} > capacity: $\frac{\Delta}{\mathrm{L}} = \frac{(1 + C_1 tan\theta) + (P/C_3)(C_1 - tan\theta)}{C_2(P/C_3 + tan\theta)}$



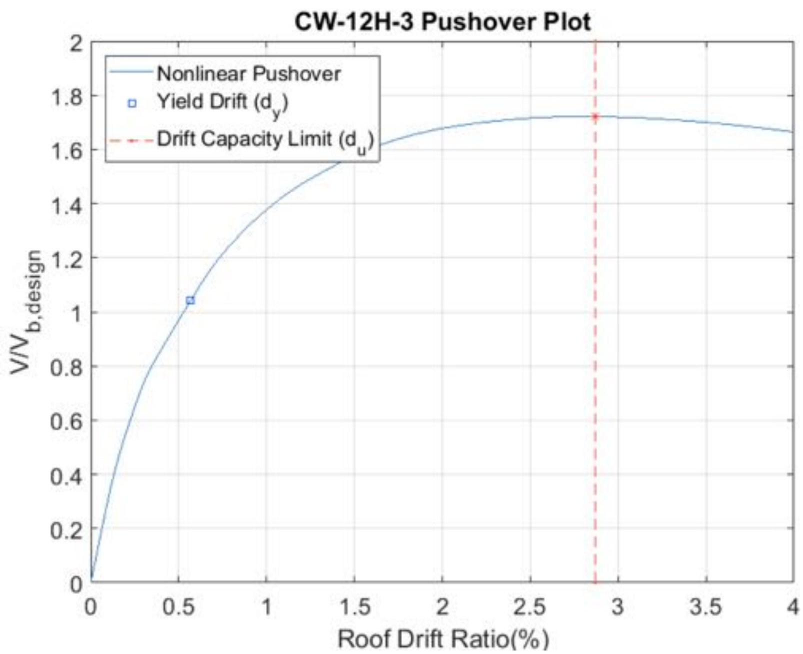


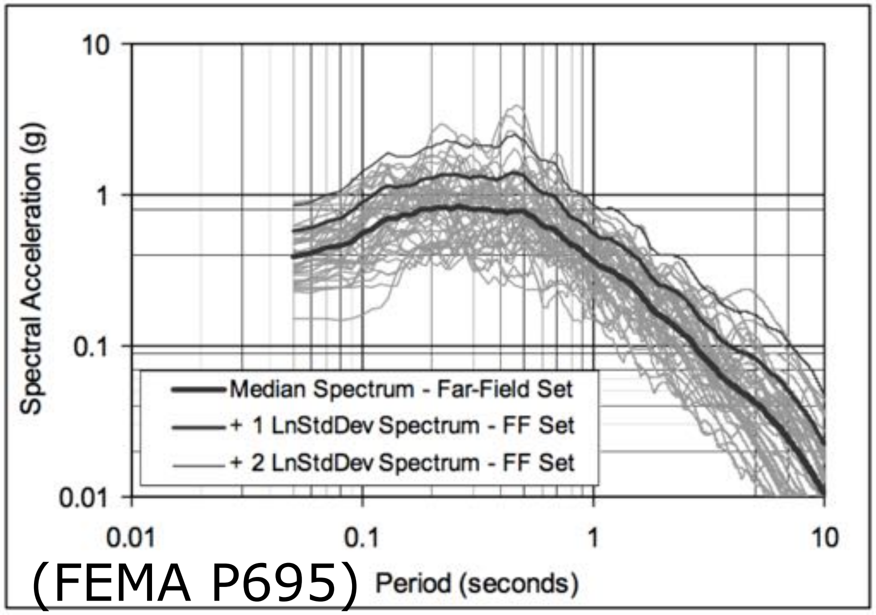
- Validation with tests by Tran & Wallace (2012)
- No dynamic tests

Nonlinear Analysis

Nonlinear Analysis

- Nonlinear Pushover
  - System Overstrength factor: $\Omega_0 = V_{max}/V_b$
  - Period-based ductility: $\mu_T = \delta_u/\delta_{y,eff}$
- Nonlinear RHA – Incremental Dynamic Analysis
  - 44 Normalized Records incrementally scaled until 50% fail





(FEMA P695)

FEMA P695 IDA Acceptability Criteria

- Total System Uncertainty, β_{TOT}:
  - β_{RTR}: 0.4 (ATC 76-4 project advisory committee)
  - β_{DR}: 0.2 Good (completeness & robustness of design reqs.)
  - β_{TD}: 0.2 Good (completeness & robustness of test data)
  - β_{MDL}: 0.2 Good (modeling)

$$\beta_{TOT} = \sqrt{(\beta^2_{RTR} + \beta^2_{DR} + \beta^2_{TD} + \beta^2_{MDL})} = 0.525$$

- Acceptable ACMR per FEMA P695 Table 7-3

Total System Collapse Uncertainty	Collapse Probability				
	5%	10% ($ACMR_{10\%}$)	15%	20% ($ACMR_{20\%}$)	25%
0.500	2.28	**1.90**	1.68	**1.52**	1.40
0.525	2.37	**1.96**	1.72	**1.56**	1.42

  - Individual Archetype ACMR > 1.56 (20% PC)
  - Performance Group Mean ACMR > 1.96 (10% PC)

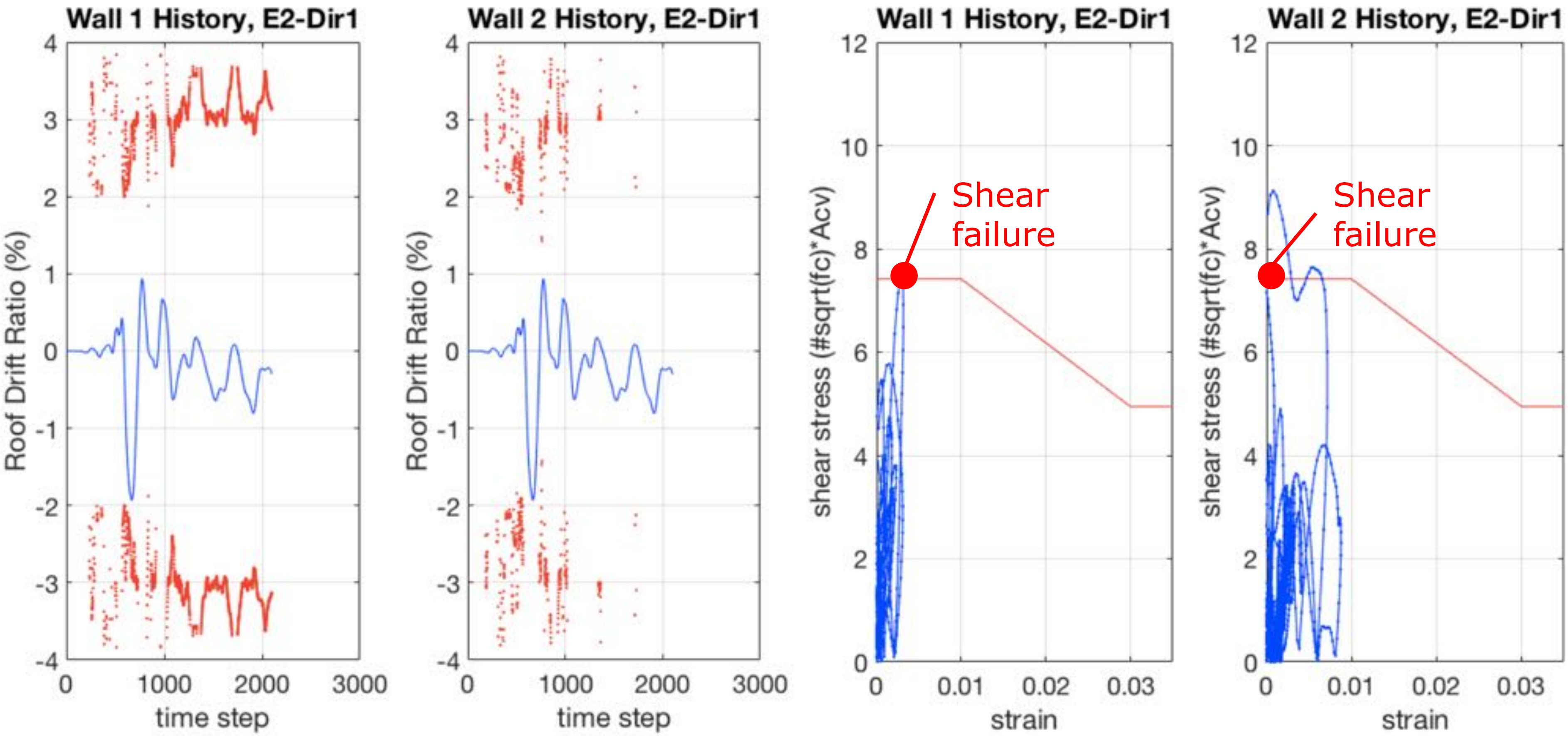
FEMA P695 IDA Results

Initial Analysis Results

ASCE 7-16 and ACI 318-14

Initial Analysis Results

- Sample RHA result for CW-12H-3.0 Archetype:
  - For E2,Dir1 at SF = 2.59: No drift failure, but shear failure



Initial Analysis Results

- IDA Results: Limited Archetypes (SDC-D_{max})
- ACI 318-14 shear design provisions

Original Archetypes	Ω_0	S_{MT} [T]	S_{CT} [T]	**ACMR**	**Arch. Pass?** ACMR>1.56?	**P.G. Pass?** ACMR>1.96?
CW-8H-3 (planar walls)	2.04	1.20	1.22	1.27	Fail	Fail
CW-12H-3 (planar walls)	1.65	0.89	0.68	0.96	Fail	Fail
CW-18H-3 (flanged walls)	1.77	0.65	0.67	1.58	Pass	Fail
CW-24H-3 (flanged walls)	1.79	0.53	0.59	1.80	Pass	Fail
CW-30H-3 (flanged walls)	1.81	0.45	0.51	1.84	Pass	Fail

Options?

1. Shear failure OK if no axial failure (~5%)

OR

2. Revise designs to reduce incidence of shear failure

Shear Amplification: ACI 318 Proposal

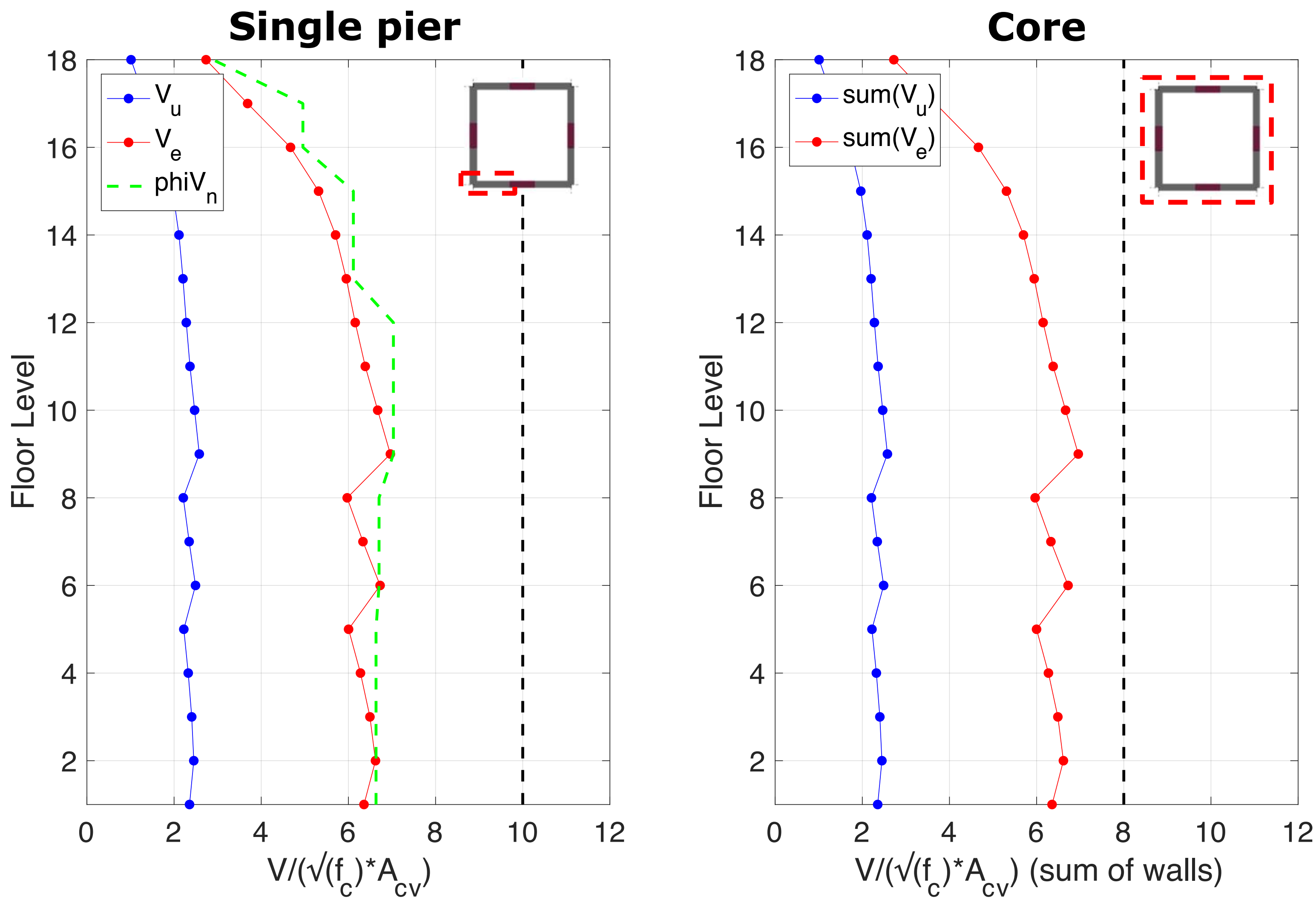
- CH-09: Passed 318H (March 2018); 318 ballot
- Similar to NZS 3101 and CSA A23.3-14

ACI 318 18.10.3 code change proposal

Design Shear force: $V_e = \varphi_0 \omega_v V_u \quad \leq 2.7V_u \ (1.5 \times 1.8)$

- V_u: shear from code lateral analysis (factored loads)
- φ_0: overstrength factor = $M_{pr}/M_u \geq 1.5$
- ω_v: dynamic shear amplification factor: $h_w/l_w \geq 2.0$:
  - $\omega_v = 1.3 + n_s/30 \leq 1.8 \qquad (n_s > 6)$

Revised Designs for Shear



Revised Designs for Shear

- Amplified shear demand: V_e/V_u = 2.35 ~ 2.70

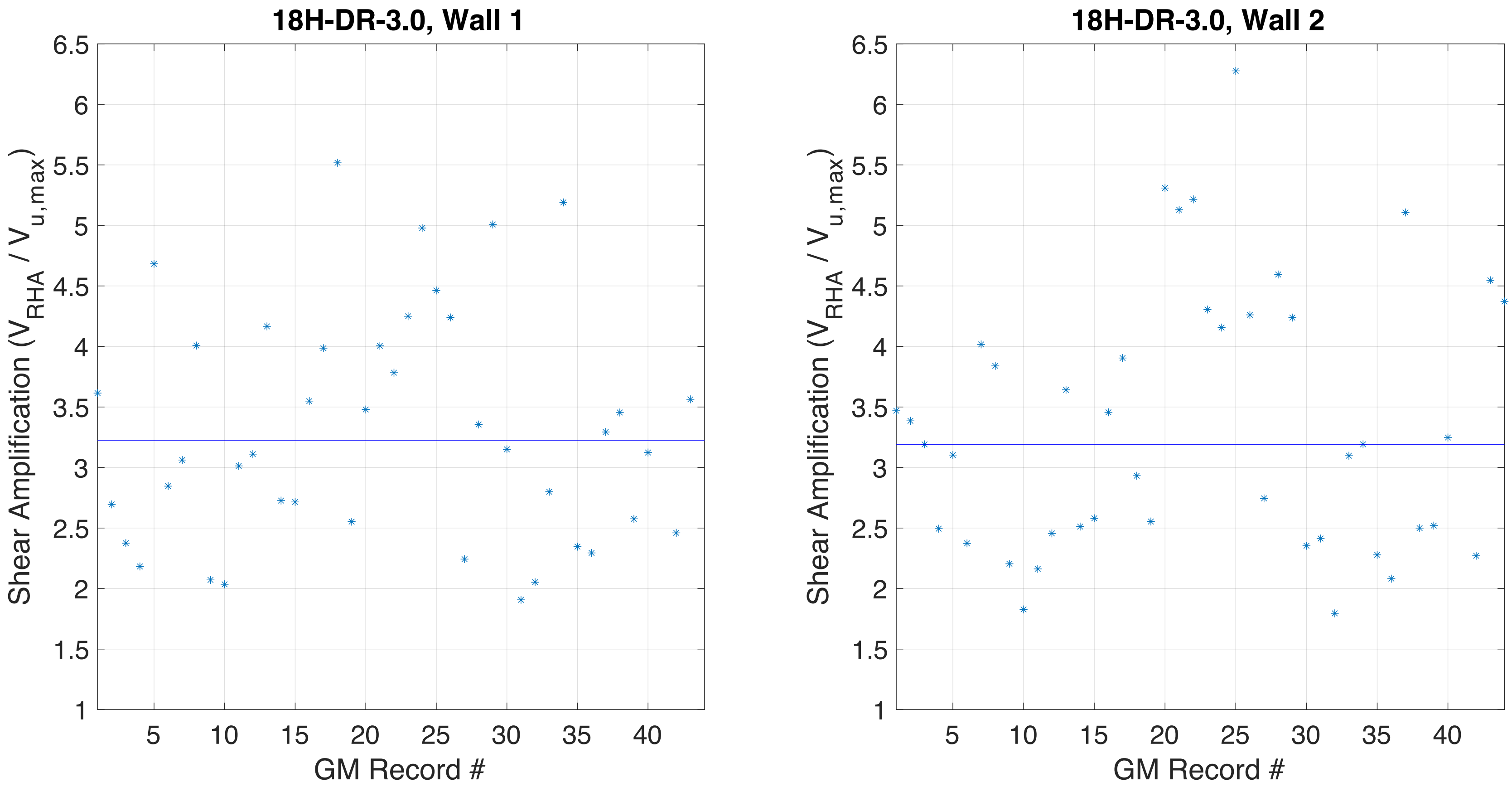
Shear Amplification	8-Story	12-Story	18-Story	24-Story	30-Story
$V_e=\varphi_0*\omega_v*V_u$	V_e=**2.35***V_u	V_e=**2.55***V_u	V_e=**2.7***V_u	V_e=**2.7***V_u	V_e=**2.7***V_u

- Revised wall designs:
  - Increase wall shear reinforcement ~ 3 times
  - Increase wall thickness at lower levels (shear stress)

Archetype	Preliminary Design			Revised Design		
	t_w (in.)	Wall ρ_t (%)	f_v ($\#\sqrt{f'_c}A_{cv}$)	t_w (in.)	Wall ρ_t (%)	f_v ($\#\sqrt{f'_c}A_{cv}$)
8H-3.0 @ Level 2	10	0.50	3.99	14	1.05	6.82
12H-3.0 @ Level 1	12	0.37	3.44	16	0.92	6.60
18H-3.0 @ Level 1	16	0.48	4.06	24	1.00	6.36

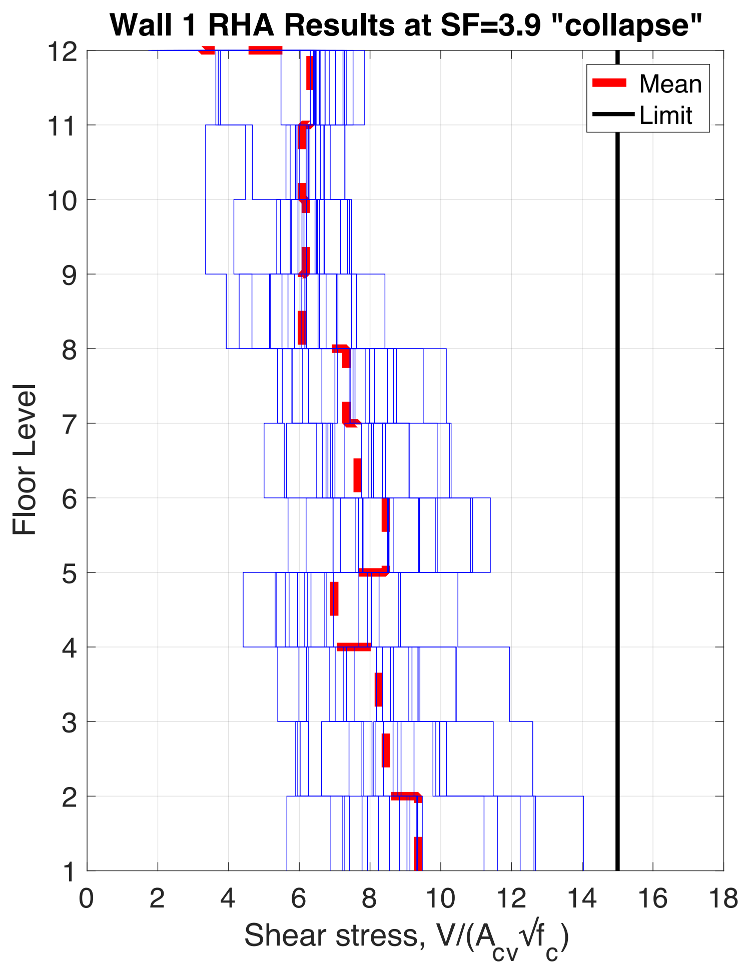
Analysis Results

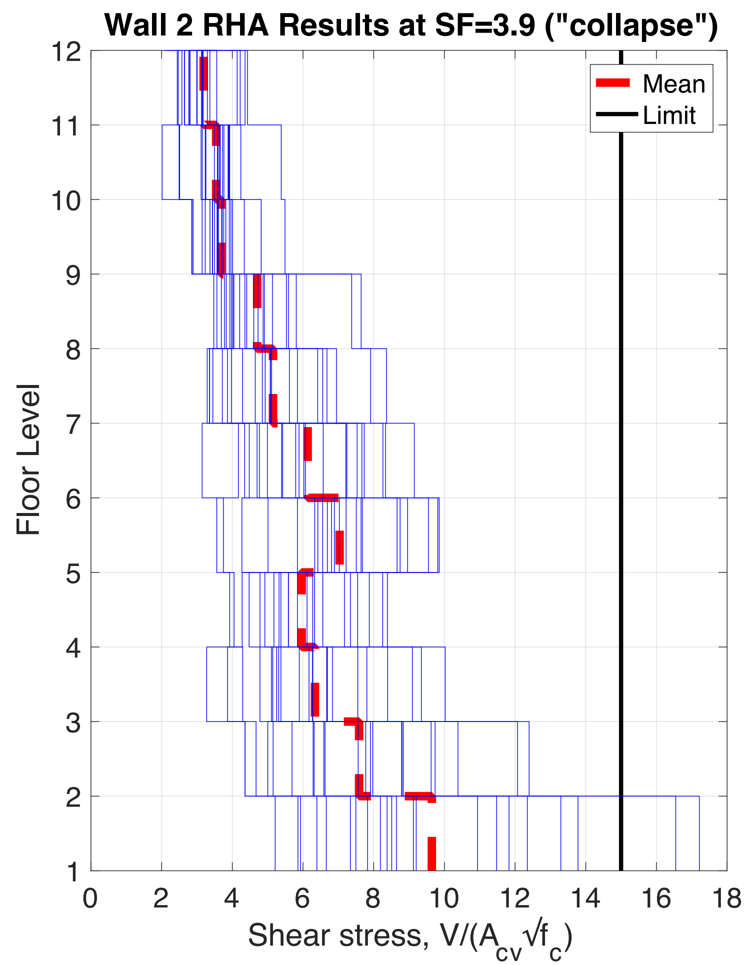
- Shear amplification at DBE
  - Sample results for CW-18H-3.0: Median ~ 3.2



Analysis Results

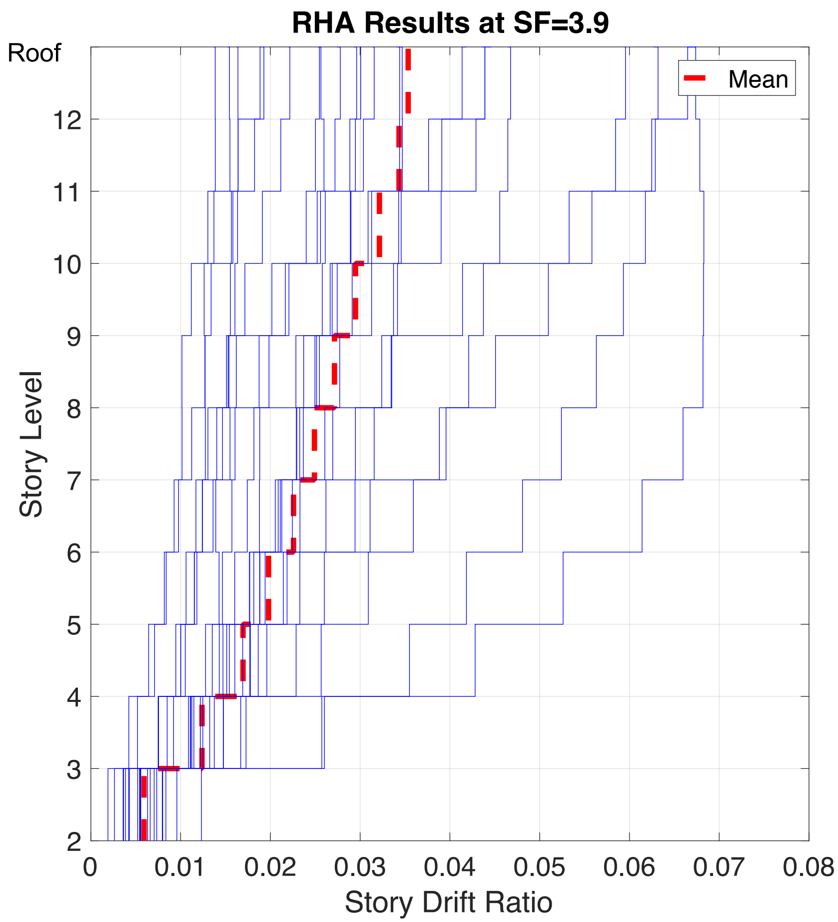
- Sample Results for CW-12H-2.0 at "collapse":

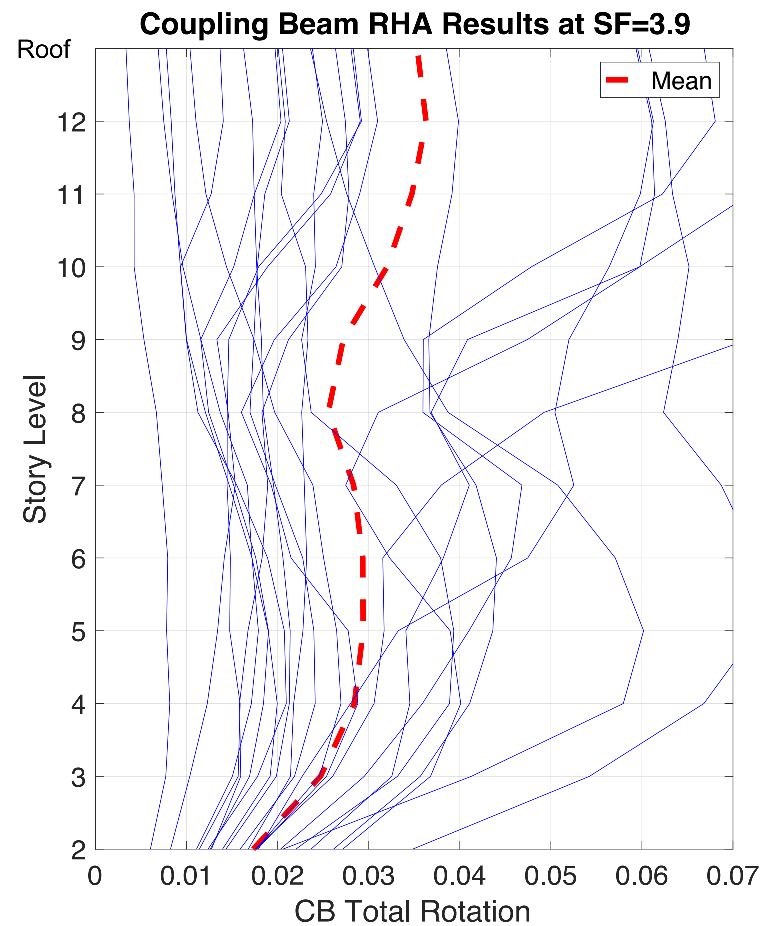




Analysis Results

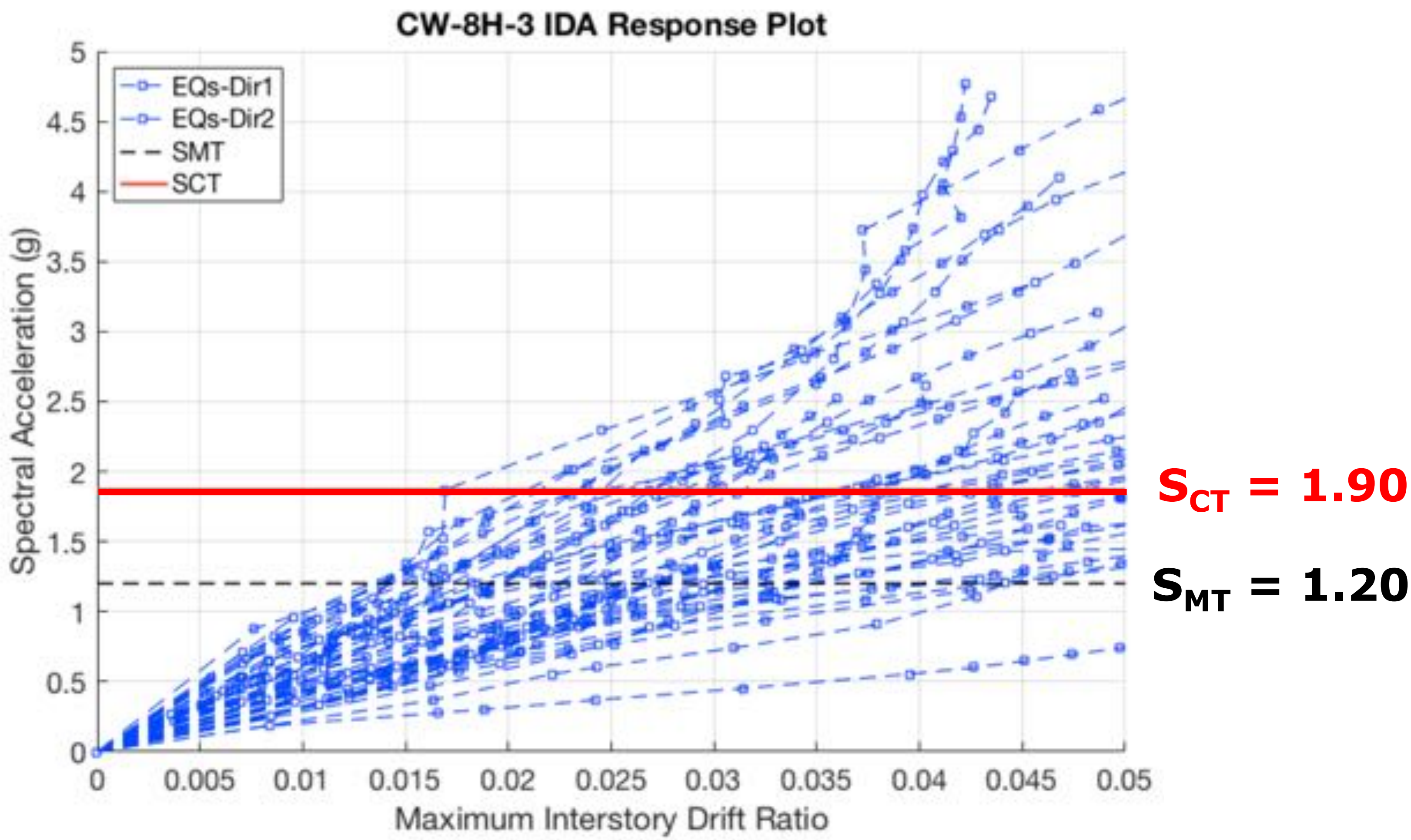
- Sample Results for CW-12H-2.0 at “collapse”:





Analysis Results

- Sample CMR Plot



IDA/Collapse Assessment Results

- Results for a subset of archetypes:

REVISED Archetypes	Ω_0	S_{MT} [T]	S_{CT} [T]	**ACMR**	**Arch. Pass?** (ACMR>1.56?)	**P.G. Pass?** (ACMR>1.96?)
CW-8H-3 (planar walls)	2.37	1.20	1.90	2.01	Pass	Pass
CW-12H-3 (planar walls)	1.72	0.89	1.33	2.00	Pass	Pass
CW-18H-3 (flanged walls)	1.84	0.65	0.91	2.20	Pass	Pass
CW-24H-3 (flanged walls)	1.60	0.53	0.73	2.22	Pass	Pass
CW-30H-3 (flanged walls)	1.31	0.45	0.58	2.10	Pass	Pass

Summary

- Super Special Coupled Walls
  - R=8 C_d=8 Ω_0 =2.5 (< 2.5 possible)
  - ACI 318 Definition is being balloted
- P695 Study
  - More sophisticated design provisions
    - Shear amplification, drift capacity check, detailing
  - Conservative failure assessment
    - Statistical models vs. 5% drift for axial collapse used typically
  - Designs 100% completed, analysis 70% completed

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