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CHARLES PANKOW FOUNDATION
Building Innovation through Research

FEMA P695 Study
Ductile Coupled Walls

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BSSC PUC Meeting
December 4, 2018

UCLA ENGINEERING
Civil and Environmental

Recap of Previous Presentations

■ Project Kickoff	April 2017
■ Advisory Meetings	
■ Archetype Designs	Nov. 10, 2017
■ Preliminary Analysis	April 12, 2018
■ LA Tall Buildings Conference	May 4, 2018
■ 11NCEE, Los Angeles	June 28, 2018
■ 90% Report Submittal	September 2018
■ BSSC PUC Meetings	
■ San Francisco	August, 16, 2018
■ IT 4 Meeting, Seattle	Sept. 5, 2018
■ Today…	

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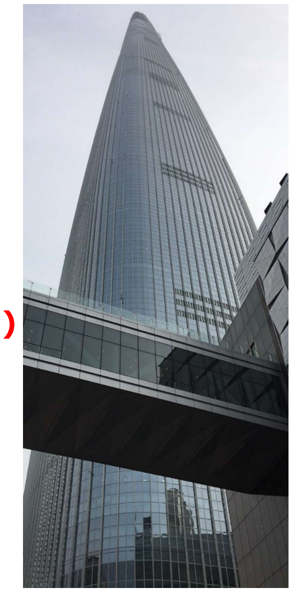
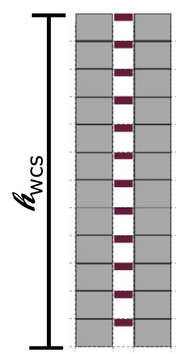
Project Overview

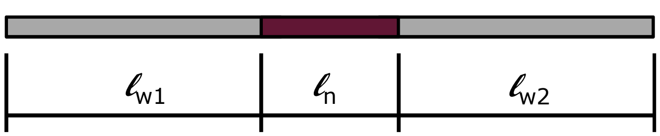
- Design of Coupled Walls
  - Currently: R=5 or 6, C_d = 5, Ω_0 = 2.5
  - More sophisticated design provisions
- ACI 318 + ASCE 7 Coordination
- FEMA P695 Process
  - Archetype Designs **R = 8 , C_d = 8 , (Ω_0 = 2.5)**
  - Nonlinear Modeling
  - Failure Modes (collapse assessment)
  - Analysis Results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



ACI 318 Definition

- Ductile Coupled Wall:
  - A seismic force resisting system consisting of special structural walls linked by coupling beams
  - Wall pier aspect ratios, h_{wcs} / ℓ_w ≥ 2.0
  - Coupling beam aspect ratio:
    - $\ell_n/h \geq 2$ satisfied at all levels
    - $\ell_n/h \leq 5$ satisfied at > 90% of levels



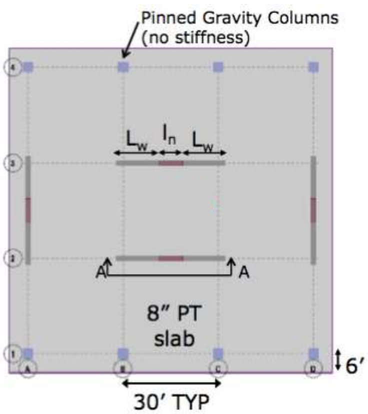


FEMA P695 Study

Archetype Design Overview

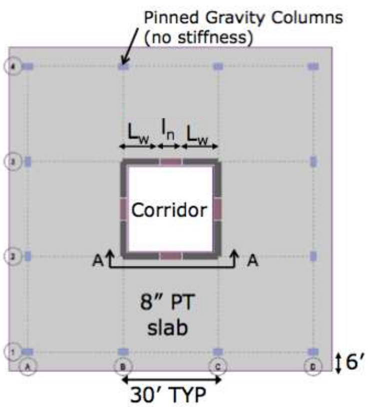
Building Configurations

Planar Walls

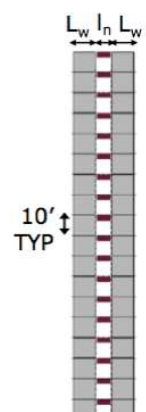


Typical Plan View

Flanged Walls



Typical Plan View



Section A-A
Wall Elevation View

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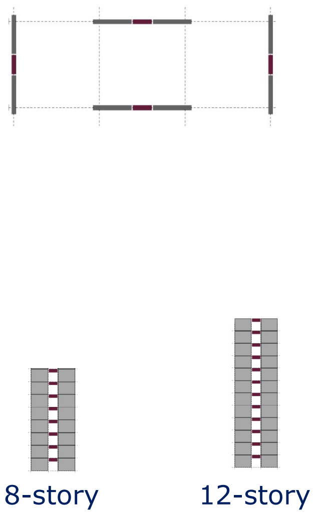
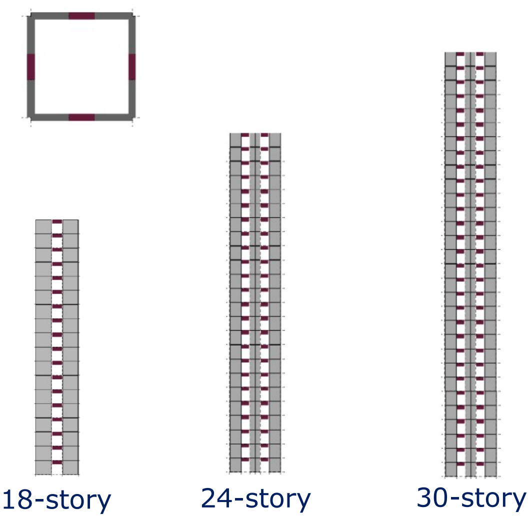
Building Heights & Wall Configurations

Planar Walls

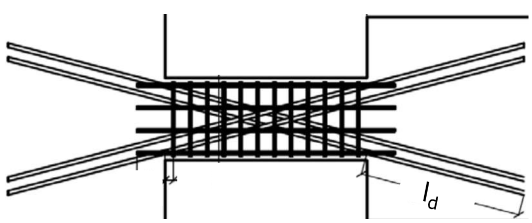


Core Walls



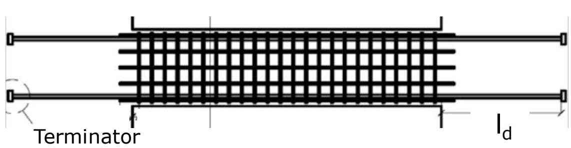
Coupling Beam Configurations

- 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)

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 of CM)
    - ASCE 7-16 §12.8.4.2 ($\Delta_{max}/\Delta_{avg}$ ~ 1.23)

(FEMA P695/ATC-63)

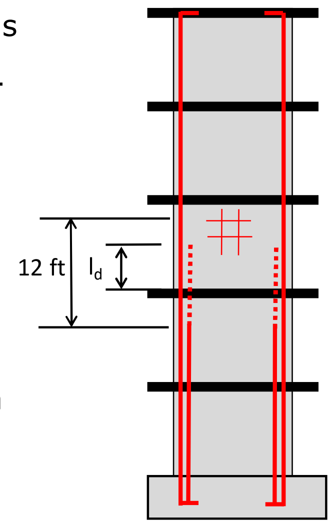
Member Properties for Elastic Design

Effective Stiffness for Elastic Analysis

- Wall Piers:
  - Flexural Stiffness: $0.75\ E_cI_g$
  - Axial Stiffness: $1.00\ E_cA_g$
  - Shear Stiffness: $0.40\ E_cA_g$
  - Out-of-plane stiffness: $0.10\ E_cI_g$
- Coupling Beams:
  - Flexural Stiffness: $(0.07l_n/h)\ E_cI_g$
- Gravity Columns: pinned, P-Δ effect only
- Rigid Diaphragm: 2-way slab

Wall Design Approach

- Forces at wall centroid
  - 100% + 30% load combination for core walls
- Detailing requirements - §18.10.6.4
  - ACI 318-19: CH-011 Overlapping Hoops
- Termination of wall longitudinal reinforcement
  - ACI 318-19: CH-10 ℓ_d above floor level
- 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



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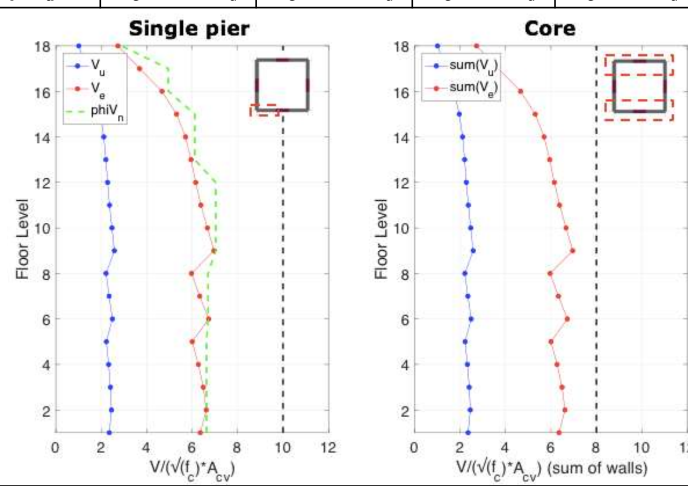
Wall Shear Amplification

- 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**$*V_u$



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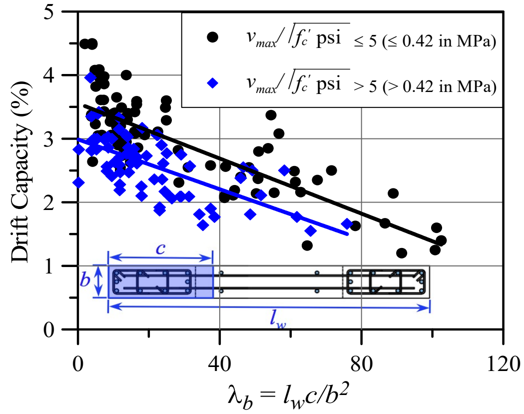
Drift Capacity Check

1. c/b

2. l_w/b

$$\lambda_b = \frac{l_w c}{b^2}$$



(a) Entire dataset ($M/Vl_w \geq 1.0$)

$$\frac{\delta_c}{h_{wcs}} = \frac{1}{100}\left(4.0 - \frac{1}{50}\left(\frac{l_w}{b}\right)\left(\frac{c}{b}\right) - \frac{V_u}{8\sqrt{f_c'}A_{cv}}\right)$$

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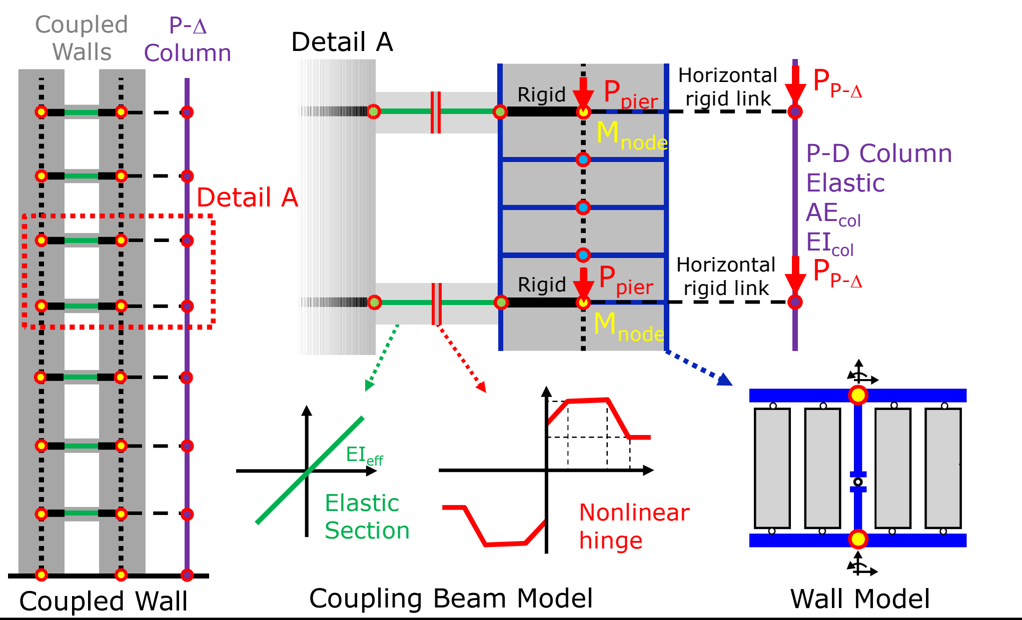
Design Summary

New ACI 318-19 Provisions

improved & more stringent design requirements for structural walls

Nonlinear Modeling

Nonlinear Modeling Approach



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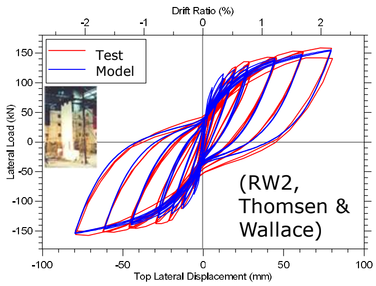
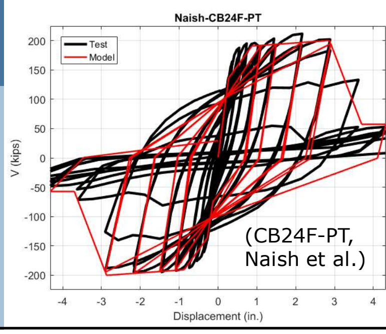
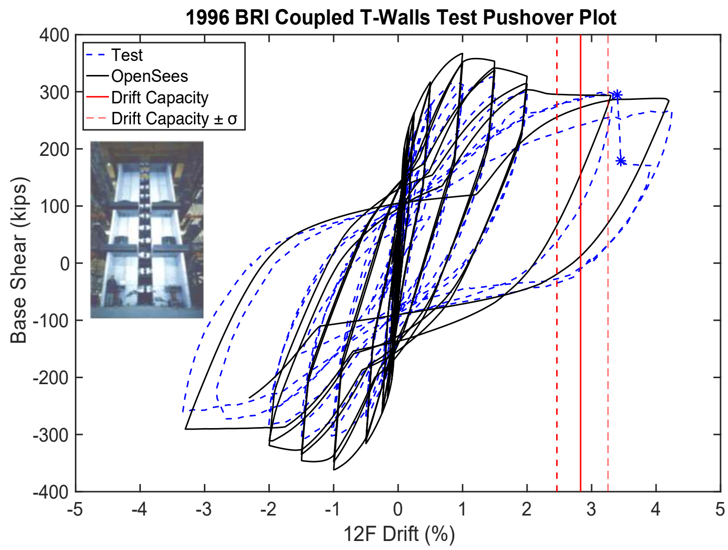
Model Validation







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Failure Assessment

Considered Failure Modes

- Statistical models
- Conservative approach
  - e.g., Initiation of strength loss

1. Flexural Failure
   - Drift/curvature capacity model (Abdullah & Wallace, 2018)
2. Wall Shear Failure
   - Shear demand versus wall tensile strain (LATBSDC, 2017)
3. Axial Failure
   - Shear friction model (Wallace, Elwood and Massone, 2008)

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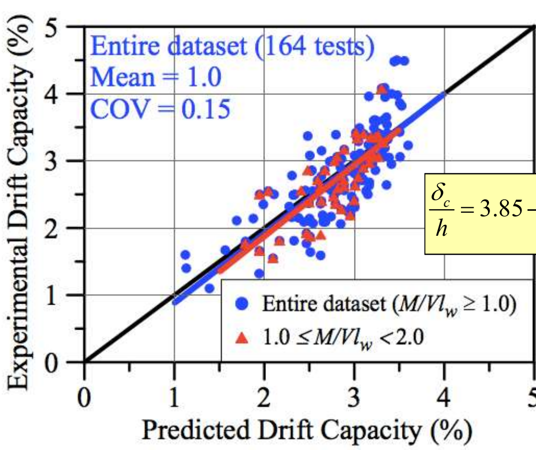
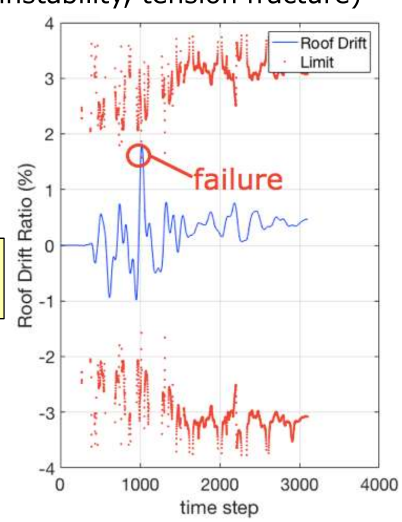
Flexural Failure Model

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



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



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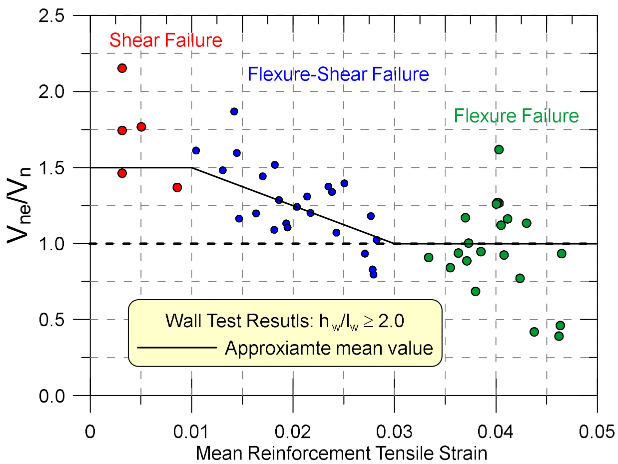
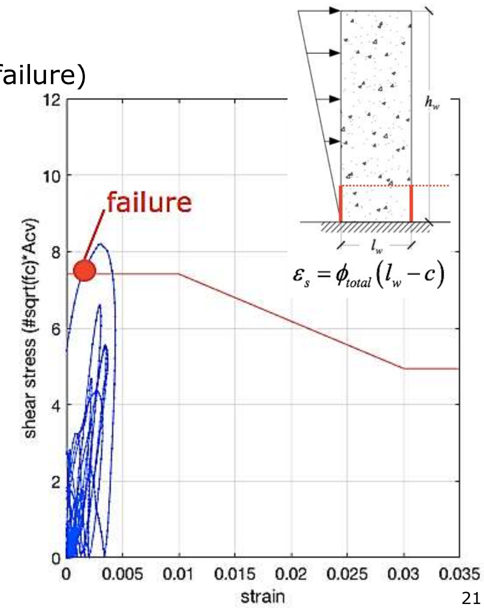
Shear Failure Model

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





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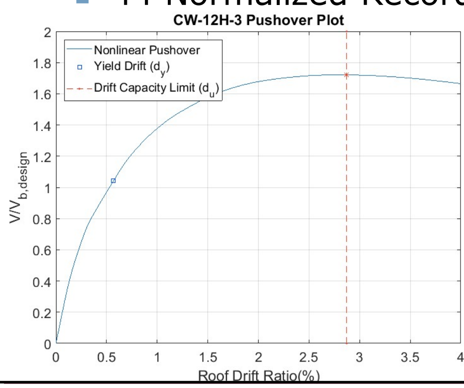
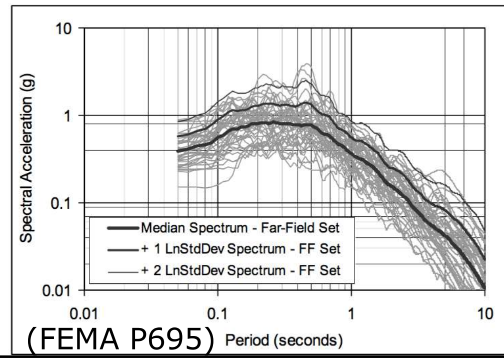
Nonlinear Analysis

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)

Collapse Assessment Results

- ACMR of all archetypes > $ACMR_{10\%}$=1.96

Archetype ID	Pushover Results		IDA Results			Acceptability			
	Static Ω	μ_T	S_{MT} [T]	S_{CT} [T]	CMR	SSF	ACMR	Accept. ACMR	Pass /Fail
8H-DR-2.0	2.12	6.27	1.20	1.85	1.54	1.32	2.03	1.56	Pass
8H-DR-2.4	2.07	6.00		1.85	1.54	1.31	2.02		Pass
8H-DR-3.0	2.21	5.28		1.90	1.58	1.29	2.03		Pass
8H-DR-3.3	2.12	5.46		1.85	1.54	1.29	1.99		Pass
Mean:	**2.13**	**5.75**				**Mean:**	**2.02**	**1.96**	**Pass**
8H-CR-3.3	1.68	7.68	1.20	1.85	1.54	1.38	2.12	1.56	Pass
8H-CR-4.0	1.66	7.43		1.85	1.54	1.37	2.10		Pass
8H-CR-5.0	1.52	7.09		1.85	1.54	1.35	2.08		Pass
Mean:	**1.62**	**7.40**				**Mean:**	**2.10**	**1.96**	**Pass**
12H-DR-2.0	1.44	6.62	0.89	1.29	1.46	1.41	2.05	1.56	Pass
12H-DR-2.4	1.49	6.02		1.29	1.46	1.38	2.01		Pass
12H-DR-3.0	1.61	5.46		1.33	1.50	1.36	2.03		Pass
12H-DR-3.3	1.67	5.90		1.36	1.53	1.38	2.11		Pass
Mean:	**1.55**	**6.00**				**Mean:**	**2.05**	**1.96**	**Pass**
12H-CR-3.3	1.35	[illegible]	0.89	[illegible]	[illegible]	[illegible]	[illegible]	1.56	Pass
12H-CR-4.0	1.37	7.68		1.22	1.38	1.46	2.01		Pass
12H-CR-5.0	1.31	7.59		1.22	1.38	1.45	2.01		Pass
Mean:	**1.34**	**7.76**				**Mean:**	**1.99**	**1.96**	**Pass**
18H-DR-2.0	1.79	7.22	0.65	0.91	1.39	1.55	2.15	1.56	Pass
18H-DR-2.4	1.78	5.95		0.91	1.39	1.48	2.05		Pass
18H-DR-3.0	1.84	5.35		0.91	1.39	1.44	2.00		Pass
18H-DR-3.3	1.93	5.46		0.91	1.39	1.45	2.01		Pass
Mean:	**1.83**	6.00				**Mean:**	**2.05**	**1.96**	**Pass**
18H-CR-3.3	1.53	6.38	0.65	0.91	1.39	1.50	2.08	1.56	Pass
18H-CR-4.0	1.51	6.18		0.91	1.39	1.49	2.07		Pass
18H-CR-5.0	1.55	5.88		0.91	1.39	1.47	2.04		Pass
Mean:	**1.53**	6.15				**Mean:**	**2.07**	**1.96**	**Pass**
24H-DR-2.0	1.44	13.63	0.53	0.75	1.42	1.61	2.29	1.56	Pass
24H-DR-2.4	1.39	10.13		0.75	1.42	1.61	2.29		Pass
24H-DR-3.0	1.69	8.35		0.75	1.42	1.61	2.29		Pass
24H-DR-3.3	1.64	8.19		0.75	1.42	1.61	2.29		Pass
Mean:	**1.54**	9.54				**Mean:**	**2.29**	**1.96**	**Pass**
24H-CR-3.3	1.36	10.28	0.53	0.74	1.40	1.61	2.26	1.56	Pass
24H-CR-4.0	1.36	9.62		0.74	1.40	1.61	2.26		Pass
24H-CR-5.0	1.49	8.30		0.75	1.42	1.61	2.29		Pass
Mean:	**1.40**	9.40				**Mean:**	**2.27**	**1.96**	**Pass**
30H-DR-2.0	1.20	14.86	0.45	0.80	1.81	1.61	2.91	1.56	Pass
30H-DR-2.4	1.24	13.71		0.80	1.81	1.61	2.91		Pass
30H-DR-3.0	1.31	11.43		0.80	1.81	1.61	2.91		Pass
30H-DR-3.3	1.49	9.27		0.80	1.81	1.61	2.91		Pass
Mean:	**1.31**	12.32				**Mean:**	**2.91**	**1.96**	**Pass**
30H-CR-3.3	1.24	14.38	0.45	0.75	1.68	1.61	2.71	1.56	Pass
30H-CR-4.0	1.27	10.29		0.75	1.68	1.61	2.71		Pass
30H-CR-5.0	1.42	10.15		0.73	1.64	1.61	2.64		Pass
Mean:	**1.31**	11.61				**Mean:**	**2.69**	**1.96**	**Pass**

Archetype ID	Pushover Results		IDA Results			Acceptability			
	Static Ω	μ_T	S_{MT} [T]	S_{CT} [T]	CMR	SSF	ACMR	Accept. ACMR	Pass /Fail
8H-DR-2.0	2.12	6.27	1.20	1.85	1.54	1.32	2.03	1.56	Pass
8H-DR-2.4	2.07	6.00		1.85	1.54	1.31	2.02		Pass
8H-DR-3.0	2.21	5.28		1.90	1.58	1.29	2.03		Pass
8H-DR-3.3	2.12	5.46		1.85	1.54	1.29	1.99		Pass
Mean:	**2.13**	**5.75**				**Mean:**	**2.02**	**1.96**	**Pass**
8H-CR-3.3	1.68	7.68	1.20	1.85	1.54	1.38	2.12	1.56	Pass
8H-CR-4.0	1.66	7.43		1.85	1.54	1.37	2.10		Pass
8H-CR-5.0	1.52	7.09		1.85	1.54	1.35	2.08		Pass
Mean:	**1.62**	**7.40**				**Mean:**	**2.10**	**1.96**	**Pass**
12H-DR-2.0	1.44	6.62	0.89	1.29	1.46	1.41	2.05	1.56	Pass
12H-DR-2.4	1.49	6.02		1.29	1.46	1.38	2.01		Pass
12H-DR-3.0	1.61	5.46		1.33	1.50	1.36	2.03		Pass
12H-DR-3.3	1.67	5.90		1.36	1.53	1.38	2.11		Pass
Mean:	**1.55**	**6.00**				**Mean:**	**2.05**	**1.96**	**Pass**

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Collapse Assessment Results

- <u>Results for a subset of archetypes:</u>

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)	2.21	1.20	1.90	2.03	Pass	Pass
CW-12H-3 (planar walls)	1.61	0.89	1.33	2.03	Pass	Pass
CW-18H-3 (flanged walls)	1.84	0.65	0.91	2.00	Pass	Pass
CW-24H-3 (flanged walls)	1.69	0.53	0.75	2.29	Pass	Pass
CW-30H-3 (flanged walls)	1.31	0.45	0.80	2.91	Pass	Pass

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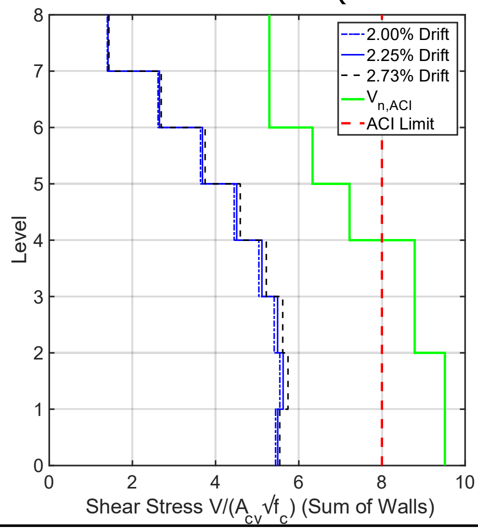
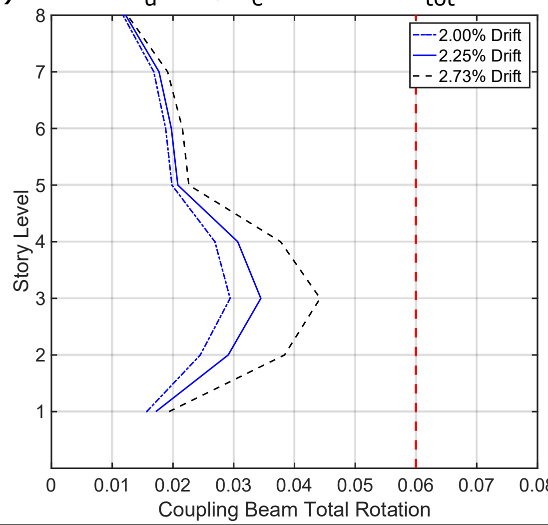
Analysis Results - Pushover

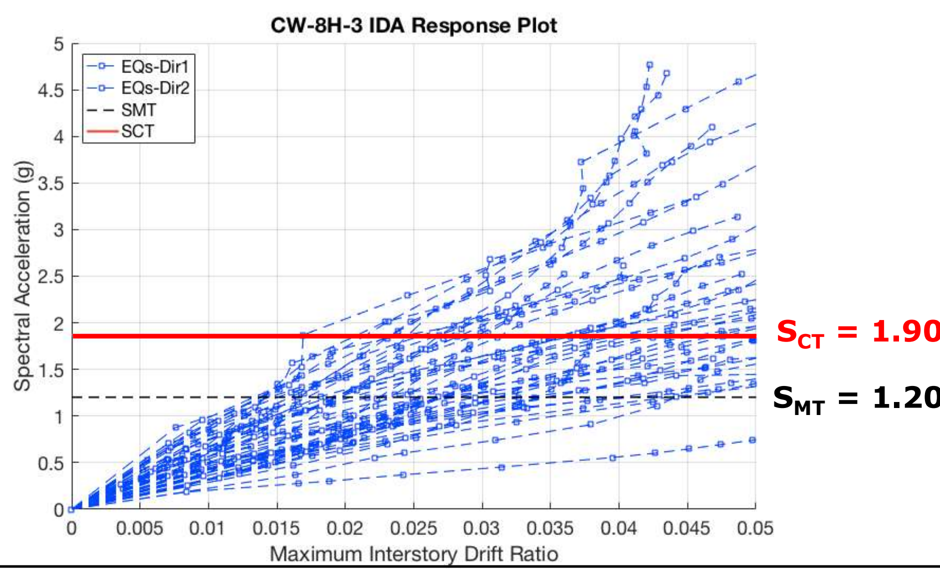
- Example for CW-8H-3.0
  - At 2.73% drift ("failure"): Wall $v_u < 6\sqrt{f'_c}$ and CB $\theta_{tot} < 0.06$





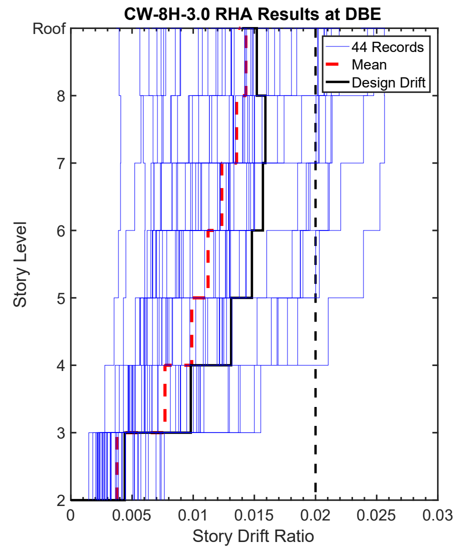
IDA Analysis Results

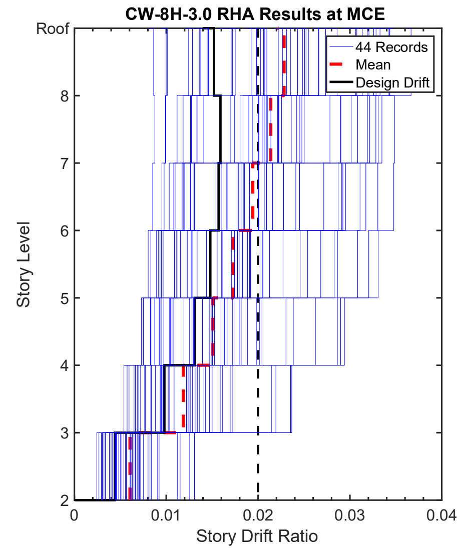
- Sample CMR Plot



IDA Analysis Results – Drift

- Mean of maximum story drifts: DBE ≤ 2%





IDA Analysis Results – Drift

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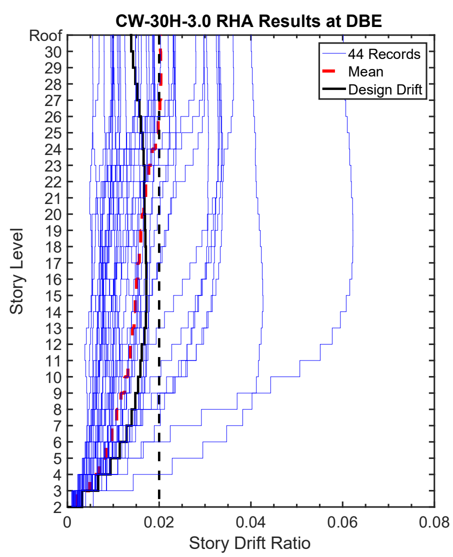
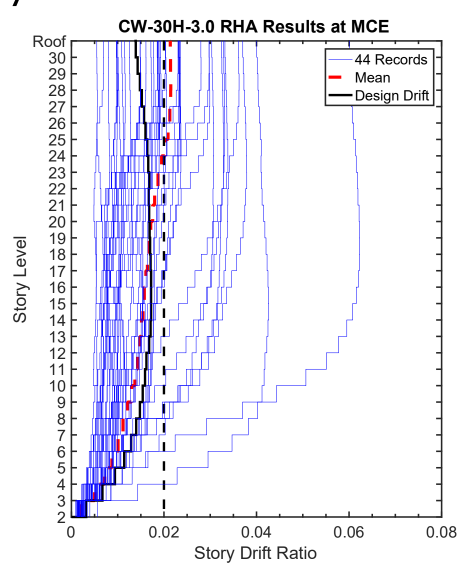
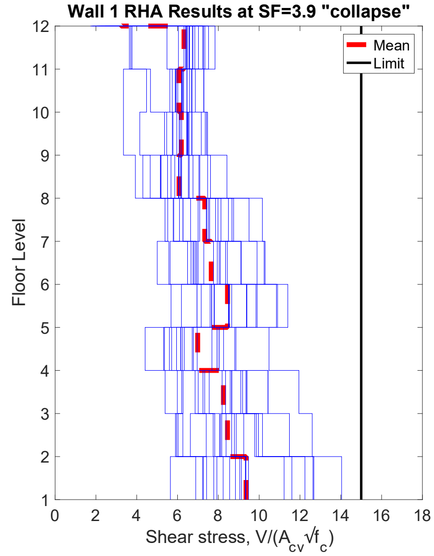
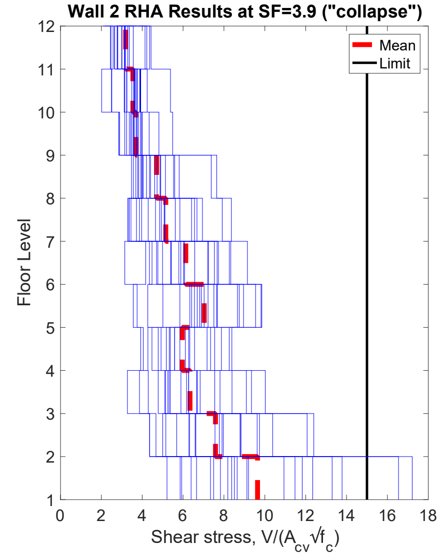




IDA Analysis Results – Wall Shear

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





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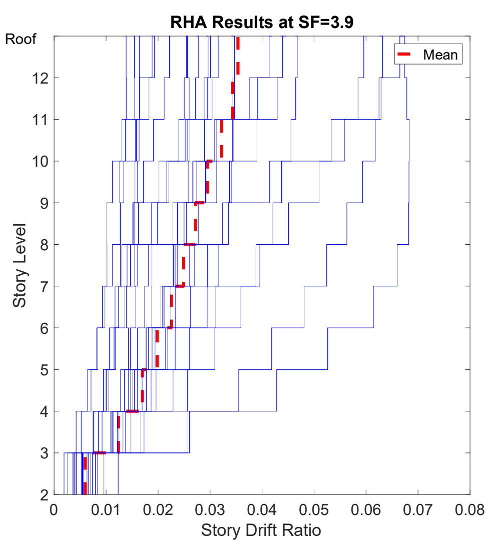
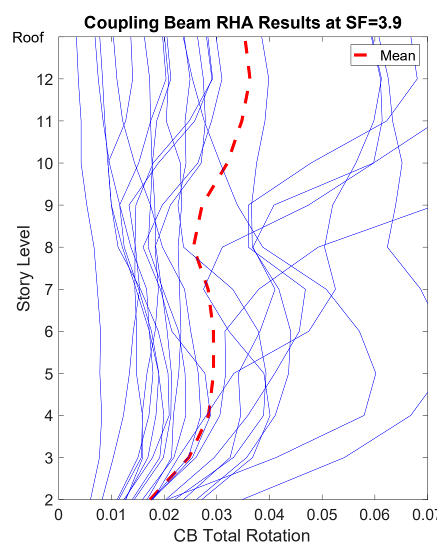
IDA Analysis Results – CB Rotation

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





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Summary & Conclusions

- P695 Study (Completed; Documentation)
  - More sophisticated design provisions: ACI 318-19
    - Shear amplification (CH-09), drift capacity check (CH-22), detailing (CH-11), boundary longitudinal bar termination (CH-10)
  - Conservative failure assessment
    - Statistical models (strength loss) vs. 5% drift for axial collapse
- Ductile Coupled Walls
  - ACI 318 Definition approved (CH-20)
  - ACMRs: 1.96-2.91 > $ACMR_{10\%}$=1.96 → R=8, C_d=8
  - Mean Ω_0 of PGs: 1.31-2.13 → Ω_0 = 2.5

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Additional Studies

Uncoupled vs. Coupled Walls

Uncoupled Cantilever Wall

- Recap of Collapse Assessment:

<u>This FEMA P695 study</u>

Ductile Coupled walls
- "Collapse" defined at strength loss
- Drift capacity model
- Shear failure model

<u>2010 NIST study</u>

Special reinforced RC Walls (4,8,12H)
- "Collapse" associated with axial failure at a drift of 5%
- lack of test data to support other failure criteria

- e.g., 12-story coupled wall archetypes had drift capacity failures at ~3% drift (vs. 5% drift)
- Additional study:
  - Compare ACMR results of uncoupled vs. coupled walls with the same failure criteria used in this study

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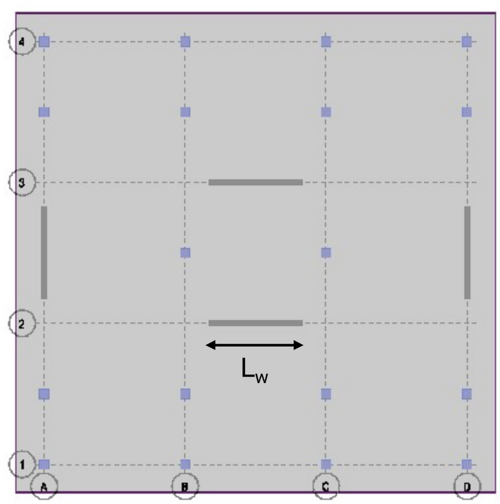
Uncoupled Cantilever Wall

- SW-12H Archetype:
  - Same design & analysis approach as CWs
  - $R = 6$, $C_d = 5$

Design Parameter	ELF	RSA
L_w	23′	20′
t_w	L1-4: 18″ L5-6: 14″ L7-12: 12″	L1-4: 16″ L5-12: 12″
c	$0.29L_w$	$0.32L_w$
$V_{u,max}$	$2.5\sqrt{f'_c}A_{cv}$	$3.1\sqrt{f'_c}A_{cv}$
δ_c/h_w	2.15%	2.04%



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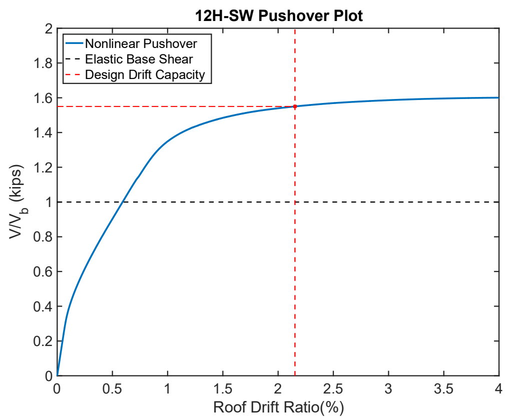
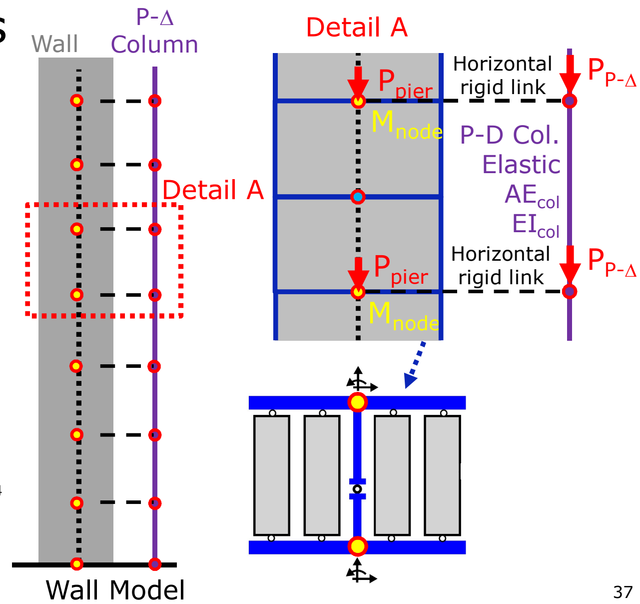
Uncoupled Cantilever Wall

- Nonlinear Analysis





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Uncoupled Cantilever Wall

- Performance of Uncoupled vs. Coupled Walls
  - IDA Results:

Archetype	S_{CT}	ACMR	$ACMR_{20\ (1.56)}$	$ACMR_{10\ (1.96)}$
CW-12H-RSA	~1.3	~2.0	Pass	Pass
SW-12H-RSA	1.02	1.56	Pass	Fail
SW-12H-ELF	1.22	1.82	Pass	Fail

- Using consistent design & collapse assessment
  Coupled Wall ACMR > Uncoupled Wall ACMR

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Additional Studies

SDC D_{min} Archetypes

SDC D_{min} vs. D_{max} Archetypes

- Same codes & provisions (ASCE 7-16, ACI 318-19)
- Same seismic response parameters ($R = C_d = 8$)
- Same plan configuration, heights, gravity loads
  - D_{min}: Shorter & thinner wall piers due to reduced demands
- Site Parameters (ATC-63)
  - **D_{min}: S_{DS} = 0.5g, S_{D1} = 0.2g**
  - D_{max}: S_{DS} = 1.0g, S_{D1} = 0.6g
- Wind load considerations
  - Important to check for taller D_{min} Archetypes
  - 700-year MRI 90mph for strength check
  - 10 - year MRI 72mph for drift check ($\Delta < h/400 = 0.25\%$)

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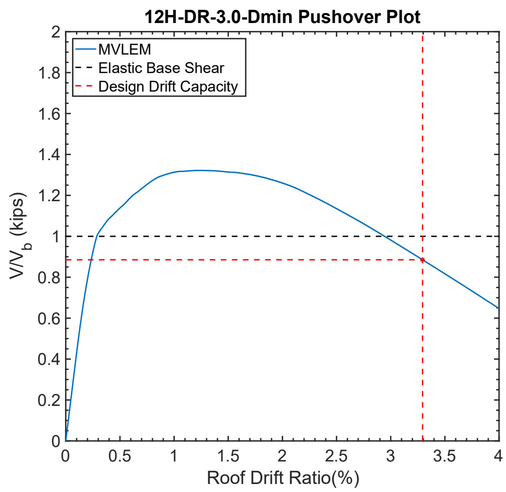
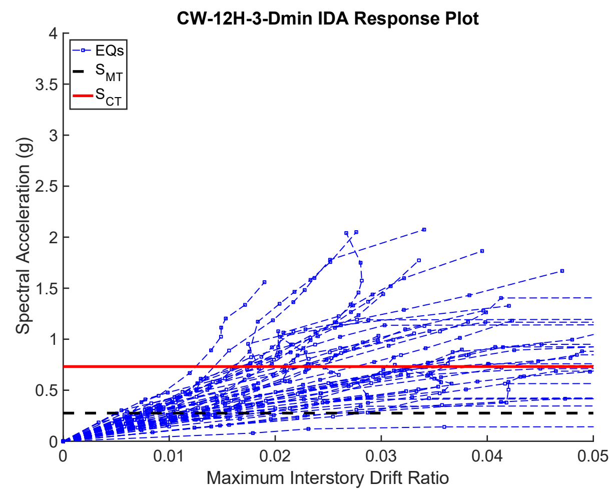
SDC D_{min} Archetypes - Results

- Nonlinear Pushover & IDA results:





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SDC D_{min} Archetypes - Results

- Nonlinear Pushover & IDA results:

Archetype	Ω_0	μ_T	S_{MT}	S_{CT}	ACMR	$ACMR_{20}$ (if > 1.56)	$ACMR_{10}$ (if > 1.96)
12H-3.0-$\mathbf{D_{min}}$	1.32	9.36	0.28	0.76	**4.02**	Pass	Pass
12H-3.0-D_{max}	1.61	5.46	0.89	1.33	2.03	Pass	Pass

Archetype	Ω_0	μ_T	S_{MT}	S_{CT}	ACMR	$ACMR_{20}$ (if > 1.56)	$ACMR_{10}$ (if > 1.96)
24H-3.0-$\mathbf{D_{min}}$	1.37	9.14	0.16	0.53	**5.20**	Pass	Pass
24H-3.0-D_{max}	1.69	8.35	0.53	0.75	2.29	Pass	Pass

- ACMRs of D_{min} Archetypes > ACMRs of D_{max} Archetypes
  - D_{min} Archetypes do not control this study’s collapse assessment ✓

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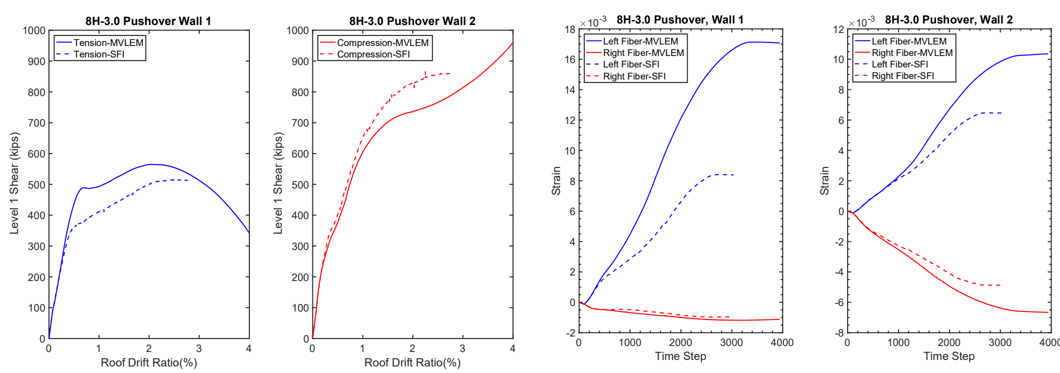
Additional Studies

Model with Shear-Flexure Interaction

MVLEM vs. Model with SFI effects

- CW-8H-3.0 MVLEM vs. SFI Model
- Nonlinear Pushover



  - SFI: Higher V in compression wall, lower V in tension wall
  - SFI: Lower strains

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MVLEM vs. SFI Model

- MVLEM vs. SFI Model
  - e.g., 8-story & 12-story archetypes with CB ln/h=3.0

Archetype	Ω_0	μ_T	S_{MT}	S_{CT}	ACMR	$ACMR_{20}$ (if > 1.56)	$ACMR_{10}$ (if > 1.96)
8H-3.0-MVLEM	2.21	5.28	1.20	1.90	2.03	Pass	Pass
8H-3.0-**SFI**	2.89	3.89		1.95	2.04	Pass	Pass
12H-3.0-MVLEM	1.61	5.46	0.89	1.33	2.03	Pass	Pass
12H-3.0-**SFI**	2.0	5.0		1.36	2.05	Pass	Pass

- Slightly higher S_{CT}
  - Lower strains with SFI model → higher drift capacity
  - Fewer shear failures predicted with SFI model

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Thank you

Questions?