Damage-Based Capacity Limit States for Nonductile Bridge Columns

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2023 PEER Annual Meeting

Outline of presentation

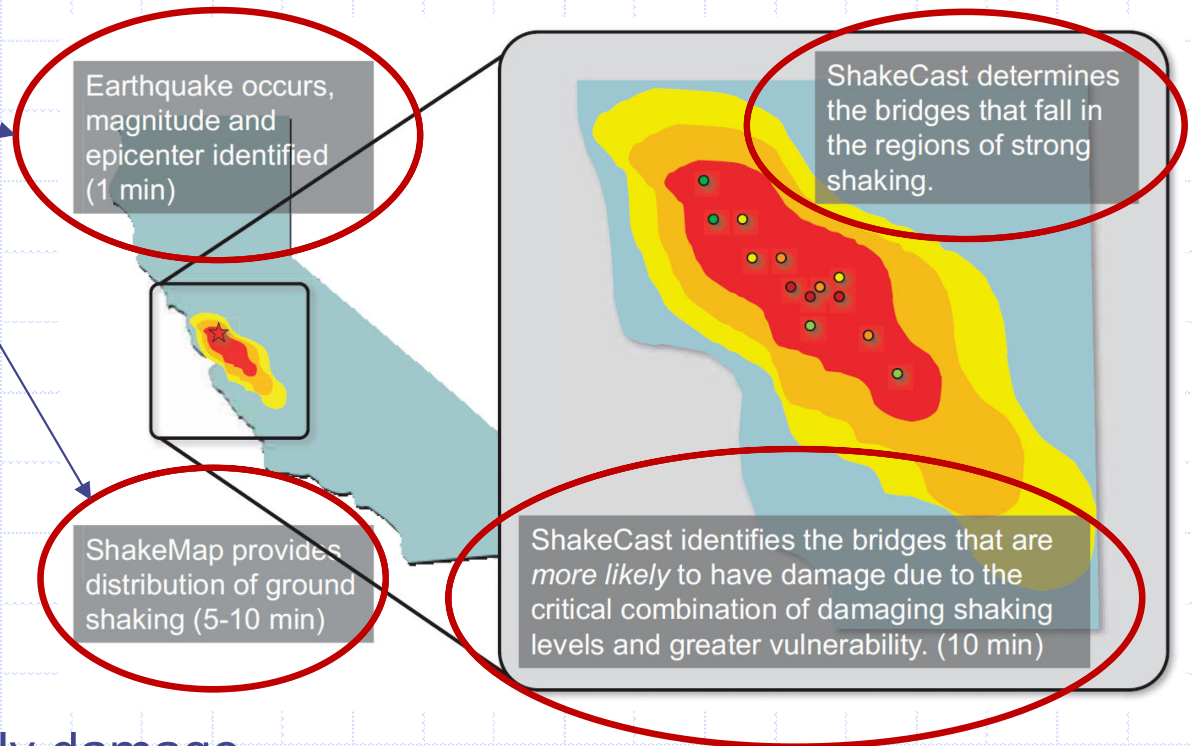
- Background - ShakeCast & next generation bridge system fragility relationships
- Developing component capacity limit state (CCLS) models
  - Conceptual basis for model development
  - Ductility & damage-based models
- Application to multi-column bents
- Project findings & future work

ShakeCast Analysis:
Near real-time damage assessment

Ground shaking data (produced by USGS)

ShakeCast inventory of existing bridges

Probabilistic seismic demand models for different bridge classes



Associating demand with likely damage

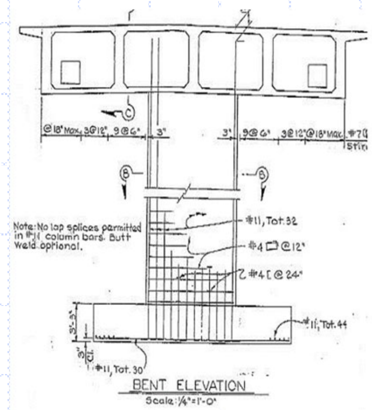
Need for component and system-level damage limit states

Development of component capacity limit state models based primarily on available experimental data (Caltrans/Georgia Tech & Rice efforts)

Lack of experimental data on older (pre-1971) California bridge columns

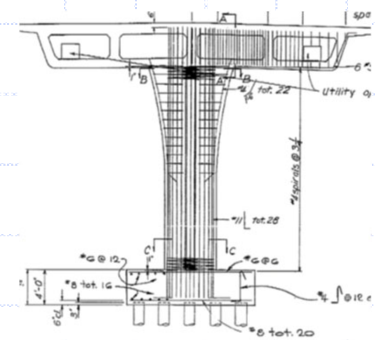
Hence, need to resort to numerical simulations

Non-ductile bridge columns



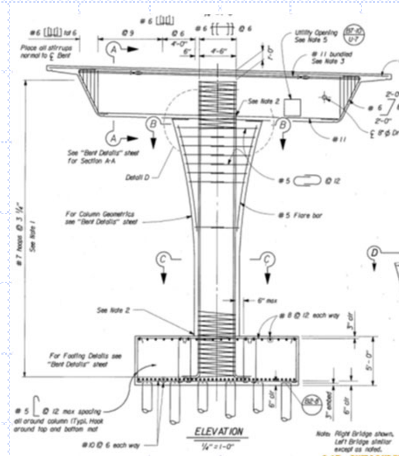
ERA-1 (pre-1971)

- Transverse Reinforcement Ratio: ~ 0.1% - 0.25%
- Characteristics: In some columns, the longitudinal reinforcing steel bars were lap spliced at base



ERA-2 (1971 - 1990)

- Transverse Reinforcement Ratio: ~ 0.3% - 1.0%

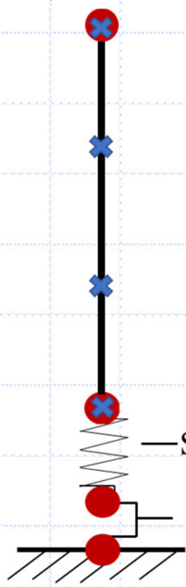


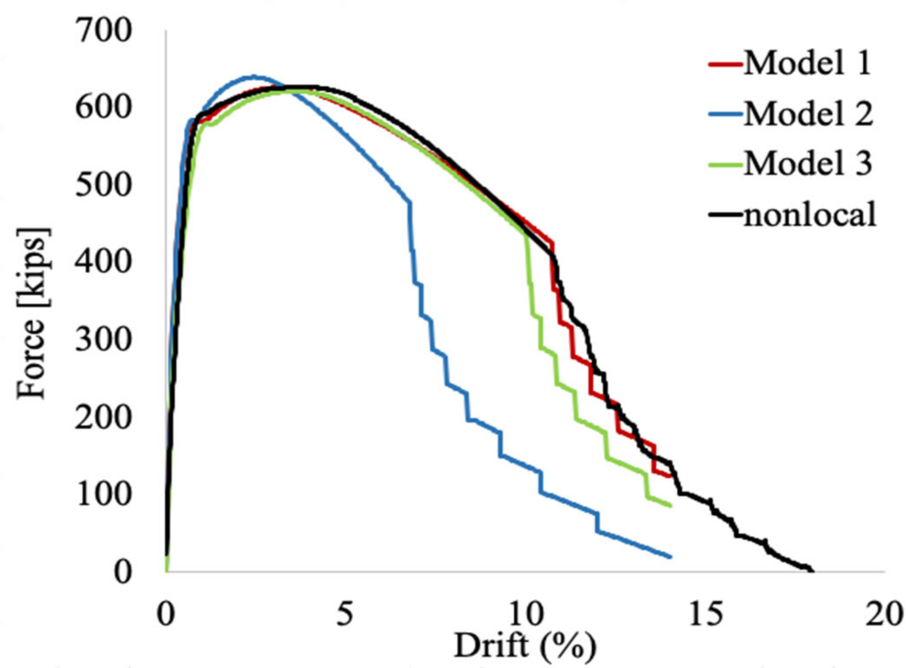
ERA-3 (post 1990)

- Transverse Reinforcement Ratio: ~ 0.5% - 1.35%

Modeling: Element model

Pushover analysis of a typical Era-1 column

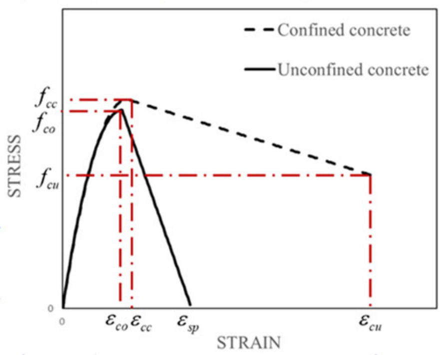




Kenawy, M Kunnath, SK et al. (2020). Concrete Uniaxial Nonlocal Damage-Plasticity Model for Simulating Post-Peak Response of Reinforced Concrete Beam-Columns under Cyclic Loading. *ASCE Journal of Structural Engineering.* 146 (5).

Kenawy M, Kunnath SK et al.. (2018). Fiber-Based Nonlocal Formulation for Simulating Softening in Reinforced Concrete Beam-Columns, *ASCE Journal of Structural Engineering*, 144 (12).

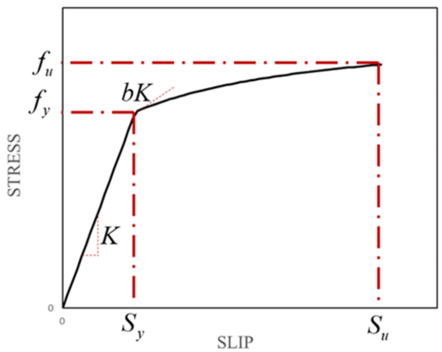
Material modeling



Confined concrete model

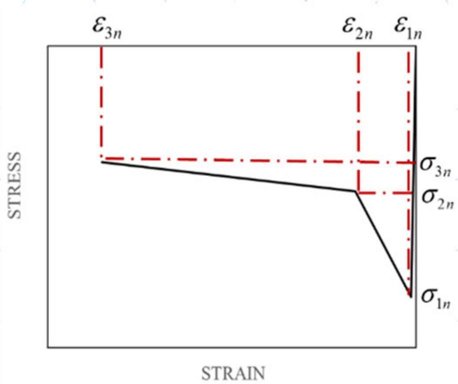
Scott, B. D., Park, R., and Priestley, M. J. N. (1982). “Stress-strain behavior of concrete confined by overlapping hoops at low and high strain rates.” *ACI Journal*, 79(1): 13–27.

Saatcioglu, M., and Razvi, S. R. (1992). "Strength and ductility of con- fined concrete." *J. Struct. Diy*., ASCE, 118(6), 1590-1607



Strain penetration model

Zhao, J., and S. Sritharan. (2007) Modeling of strain penetration effects in fiber-based analysis of reinforced concrete structures. *ACI Structural Journal*, 104(2), 133-141.

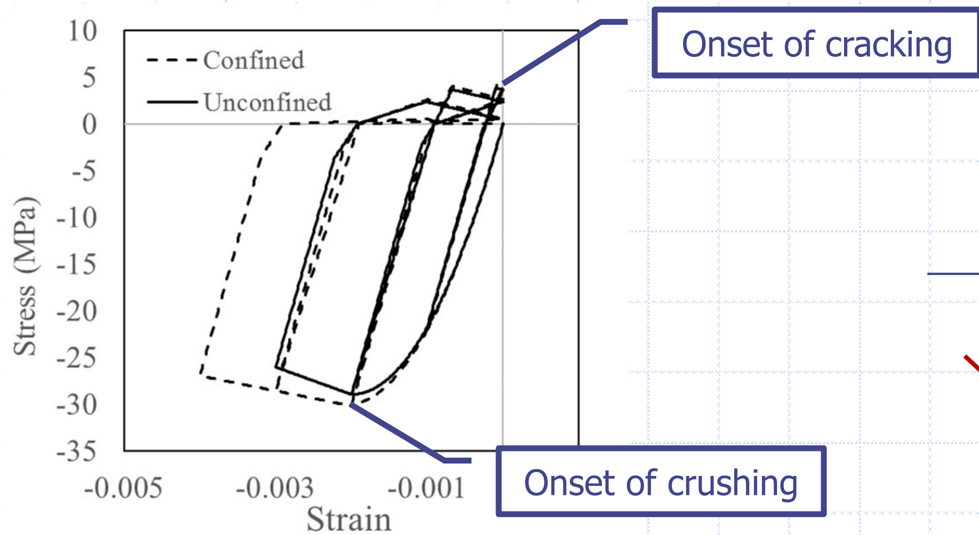


Rebar buckling model

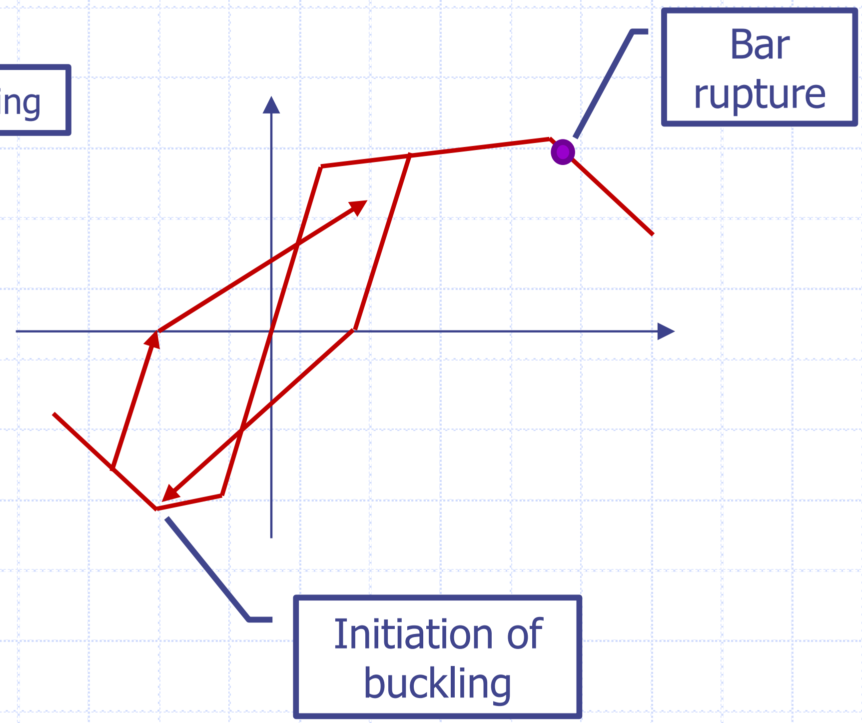
Zong, Z., Kunnath, S., and Monti, G. (2014). “Material Model Incorporating Buckling of Reinforcing Bars in RC Columns.” *Journal of Structural Engineering*, 140 (1).

Monitoring material response

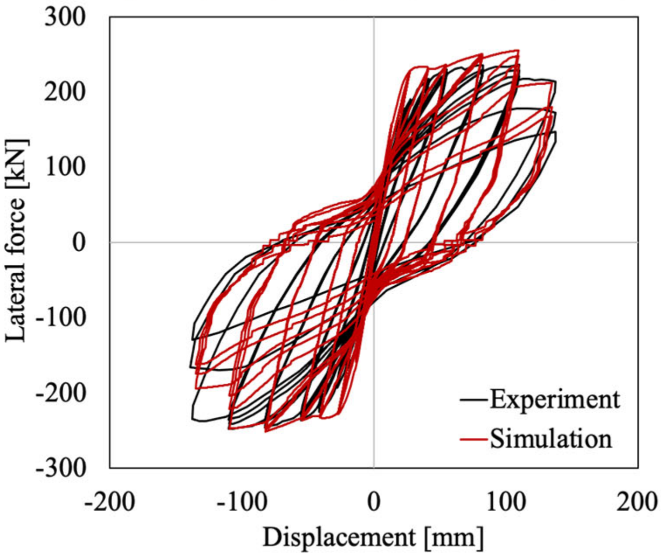
Concrete02 material for cover & core concrete



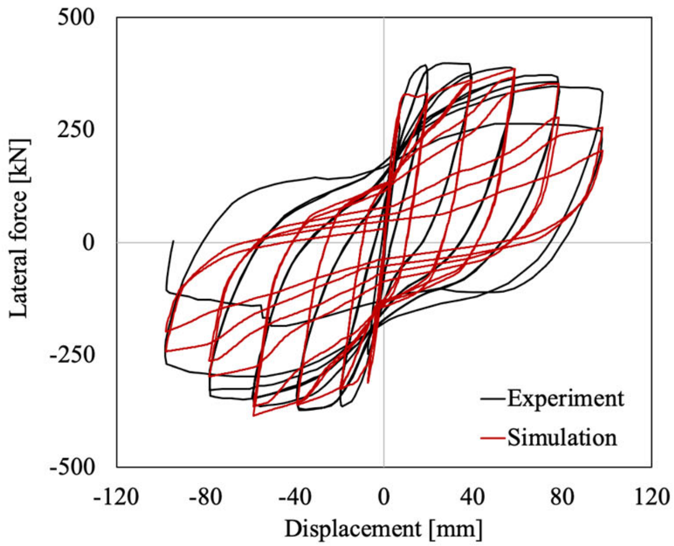
Hysteretic material for reinforcing steel



Model validation



(1)



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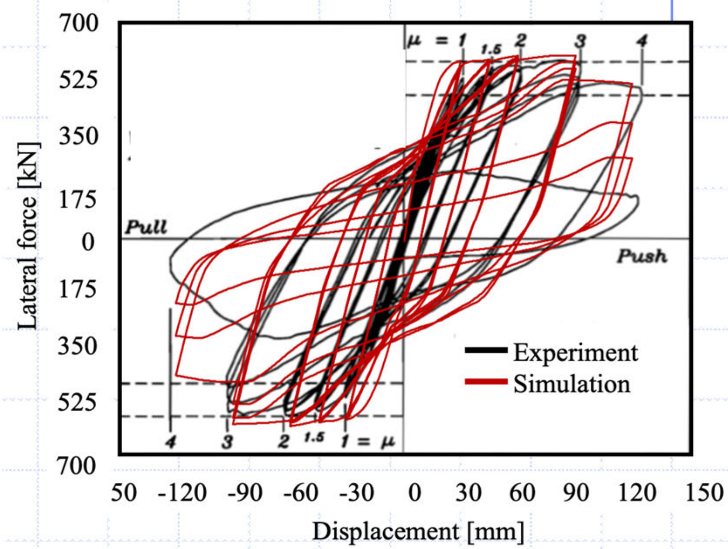
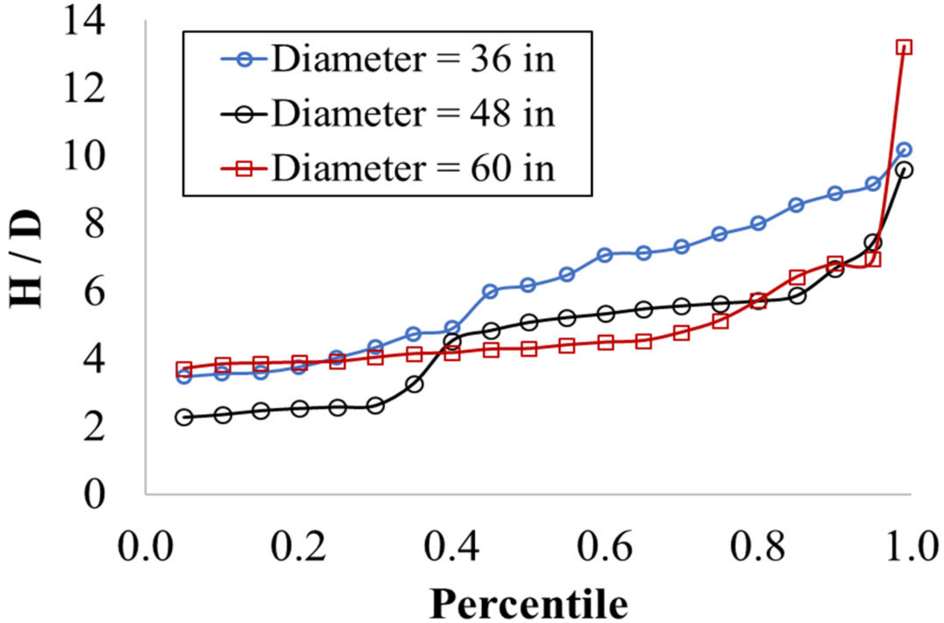
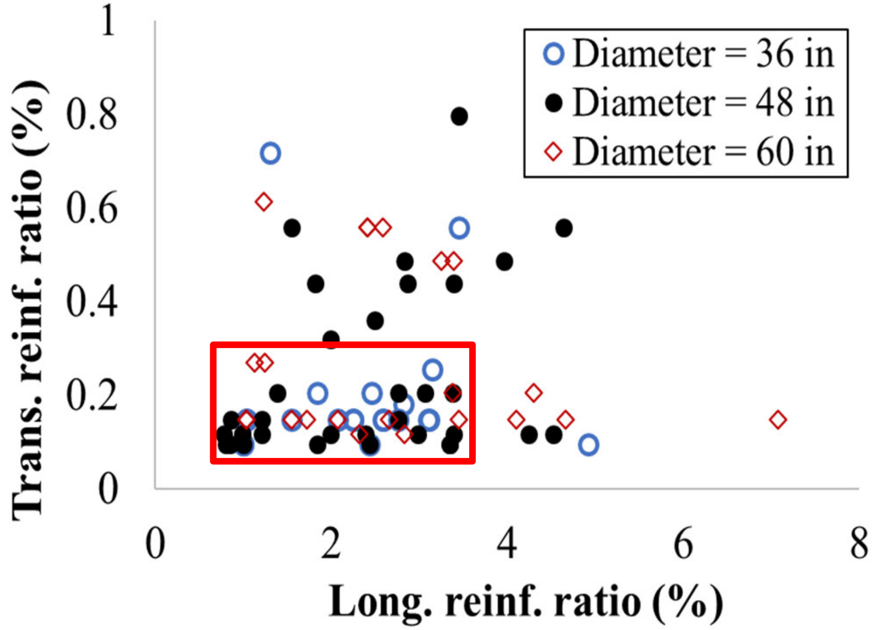


(3)

1. Chai, Y. H., M. N. Priestley and F. Seible (1991). "Seismic retrofit of circular bridge columns for enhanced flexural performance." ACI Structural Journal, 88(5).
2. Soesianawati, M.T.; Park, R; and Priestley, M.J.N. (1986). Limited Ductility Design of Reinforced Concrete Columns, Report 86-10, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand
3. Sun Z., Seible, F. and Priestley, M.J.N. (1993), “Diagnostics and retrofit of rectangular bridge columns for seismic loads.” Structural Systems Research Program, 93/07, University of California, San Diego.

Identification & selection of Era-1 columns





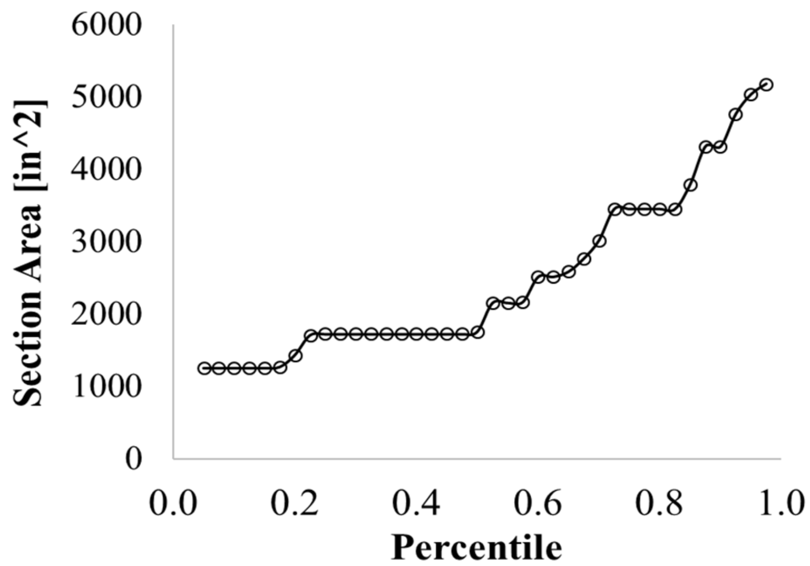
Simulation study: prototype models and parameters

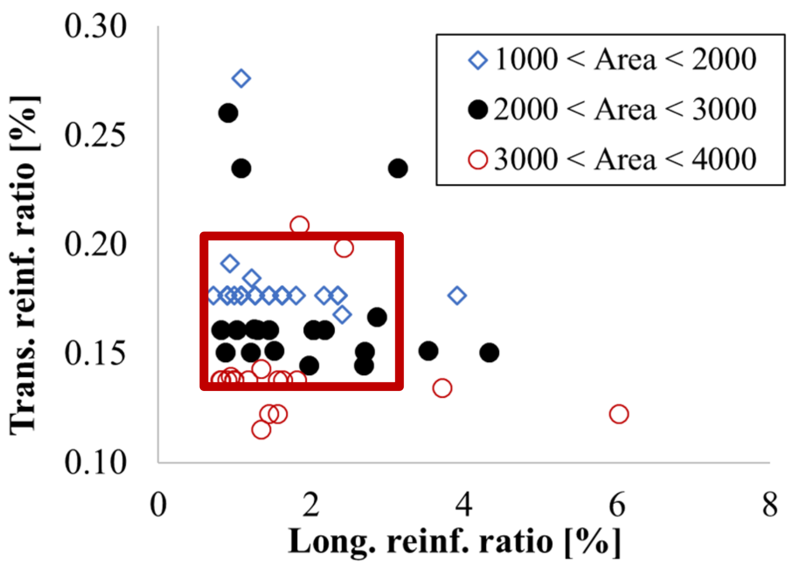
Column #	1	2	3	4	5	6	7
Trans. reinf.	#4	#4	#4	#4	#4	#7	#8
Spacing (in)	6	12	12	12	8	8	12
Trans. steel ratio	0.24%	0.12%	0.12%	0.12%	0.18%	0.55%	0.48%
Long. reinf.	32 # 14	11 # 14	32 # 14	21 # 14	30 # 18	19 # 10	45 # 14
Long. steel ratio	3.0%	1.0%	3.0%	2.0%	5.0%	1.0%	4.3%

Note: Hysteretic parameters for the reinforcing steel model were varied to generate 3 simulations each

Identification & selection of Era-1 columns

Wide section:





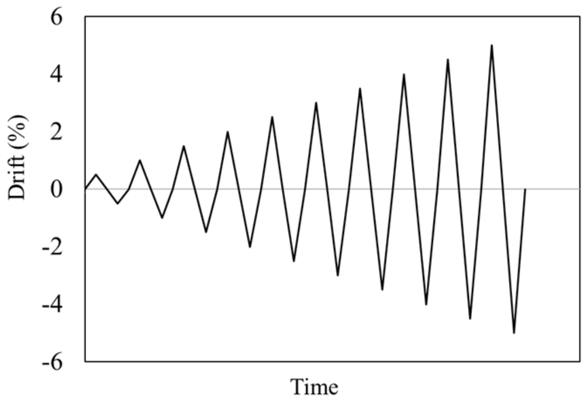
Simulation study: prototype models and parameters

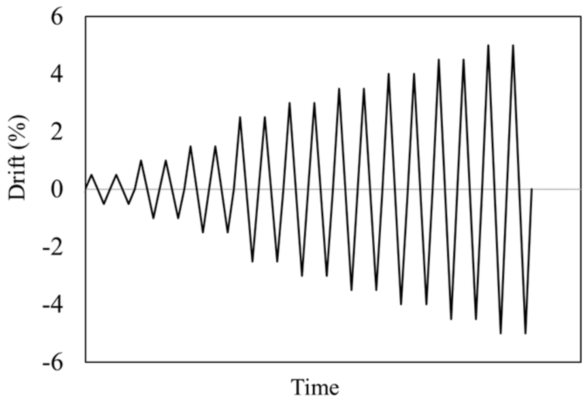
Wide section:

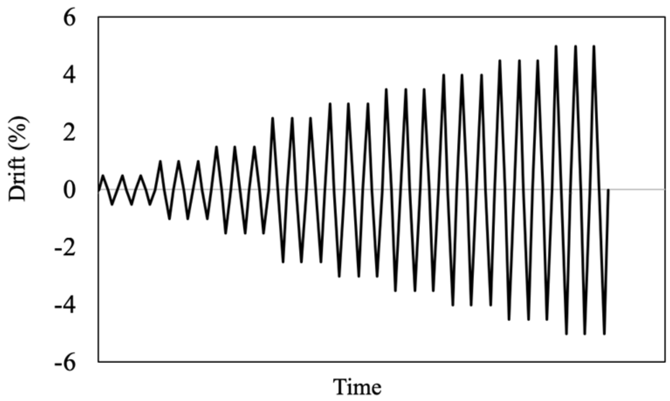
Column #	1	2	3	4	5
B (in)	36	36	36	36	36
D (in)	72	96	96	72	72
Height (ft)	36	48	48	36	36
Trans. reinf	# 4	# 4	# 4	# 4	# 4
Spacing (in)	12	12	12	15	15
Trans. Steel Ratio	0.23%	0.23%	0.15%	0.12%	0.12%
Long. Reinf	28 #14	26 # 11	20 # 11	28#14	40#14
Long. Steel Ratio	3.0%	1.4%	1.0%	3.0%	4.2%

Note: Hysteretic parameters for the reinforcing steel model were varied to generate 3 simulations each

Loading protocols: (a) cyclic loading







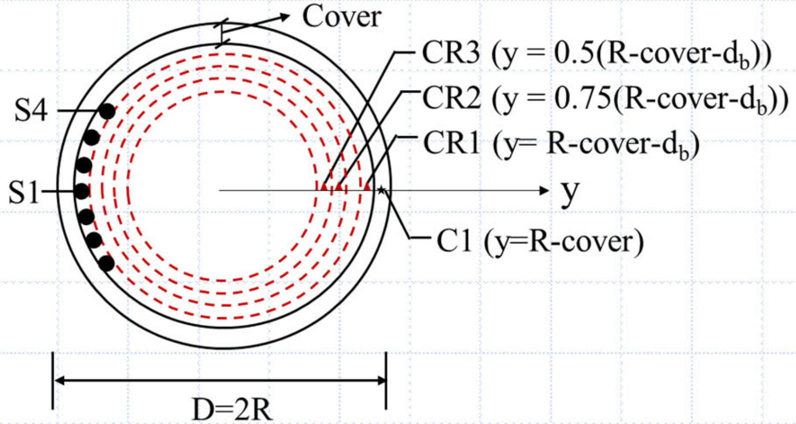
1 cycle @ each displacement level

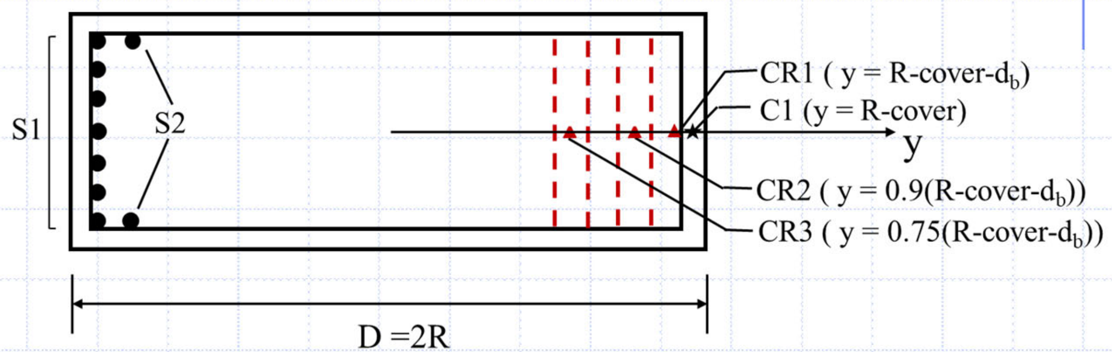
2 cycles @ each displacement level

3 cycles @ each displacement level

Hence, the column models were subjected to 9 simulations each – three modeling parameters and three loading histories

Monitored fibers



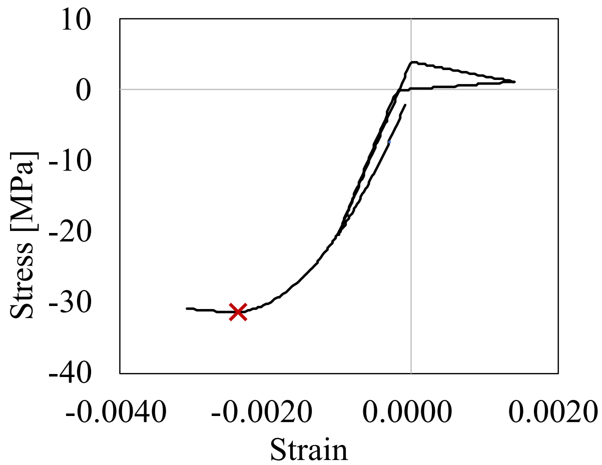
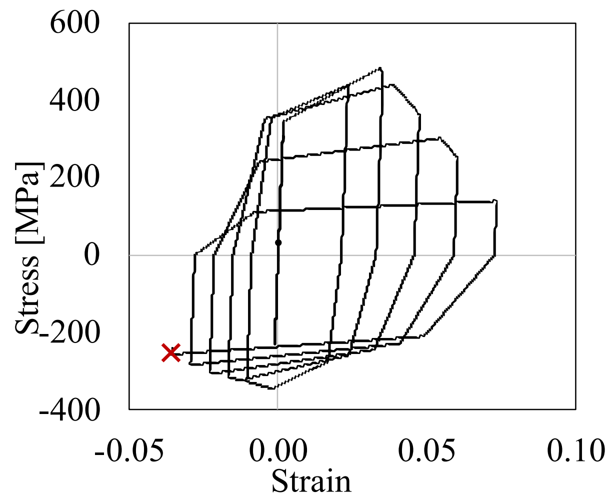


Fiber strip dimension = $2d_b$

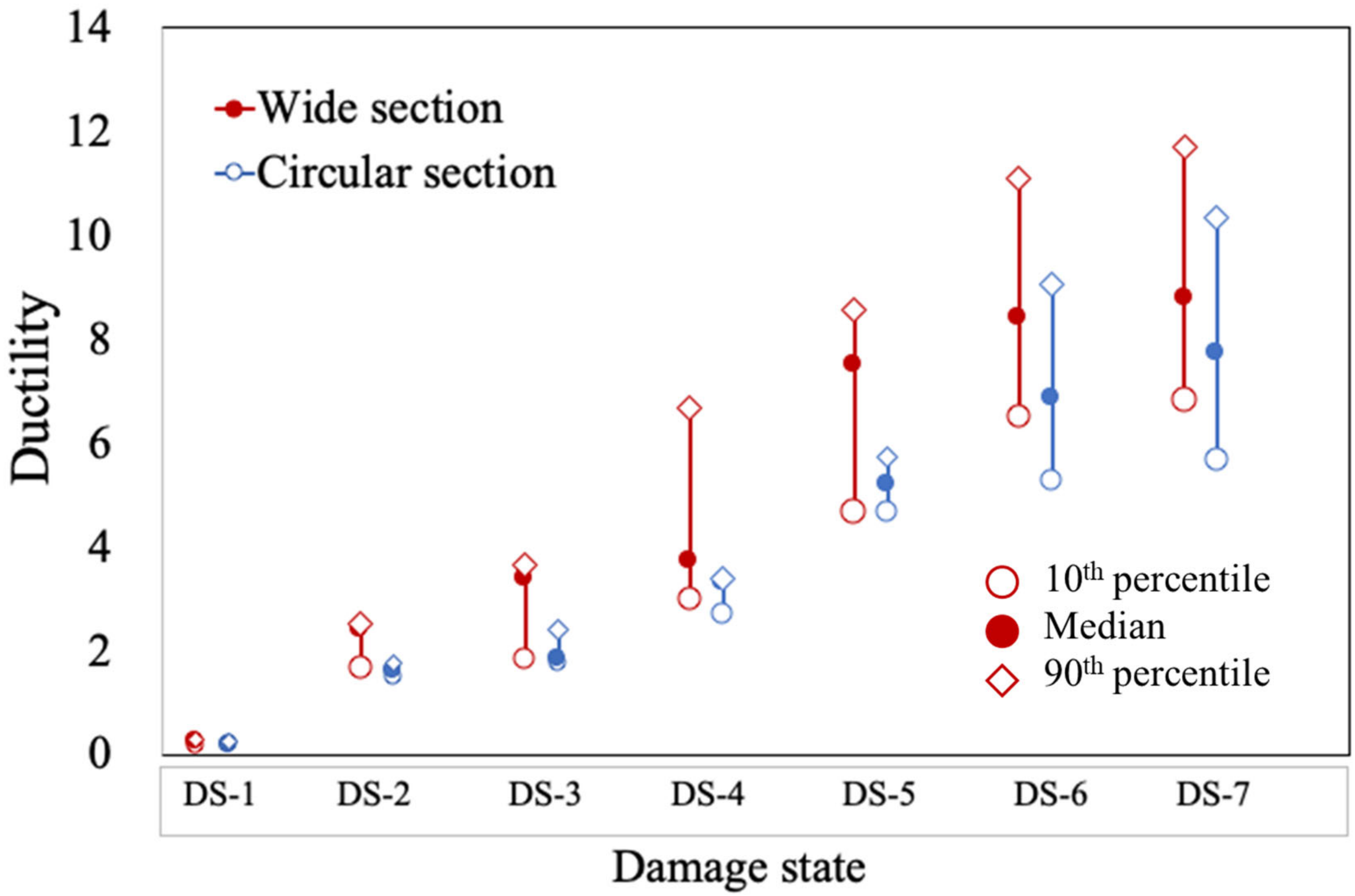
Damage States

Notation	*Damage state*
DS-1	Negligible
DS-2	Minor
DS-3	Minor to moderate
DS-4	Moderate to severe
DS-5	Severe, but stable
DS-6	Extremely severe with likely instability of system
DS-7	Collapse

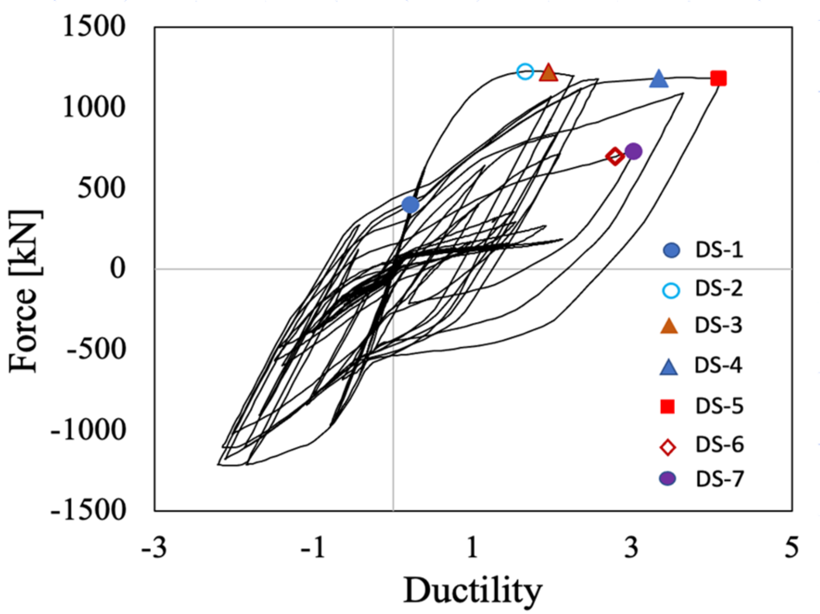
Limit state calibration: Phase I
Damage correlated to ductility demand

DS-3	Minor to moderate (*remove damaged concrete, patch & paint*)	Major spalling: Confined concrete in fiber CR2 exceeds compressive strength and longitudinal steel in fiber S1 yields	
DS-5	Moderate to severe (*strengthening likely*)	Buckling of outermost longitudinal bar S1	

Circular versus Wide Rectangular Sections



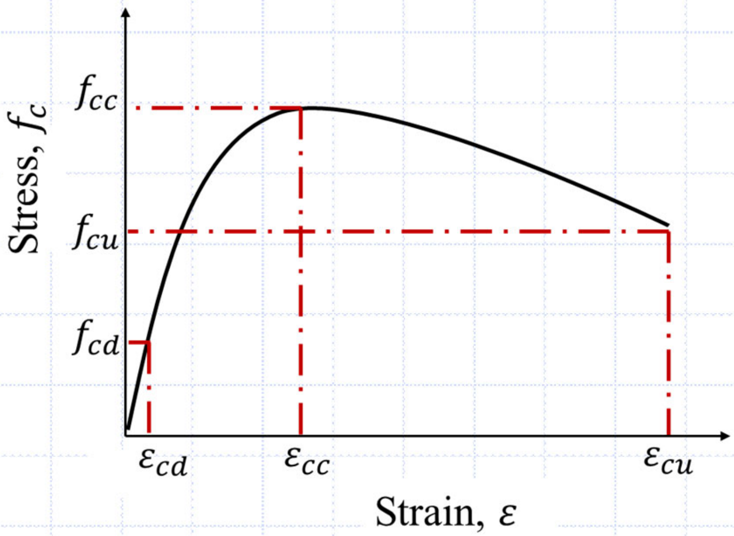
Application of ductility-based calibration to earthquake loading

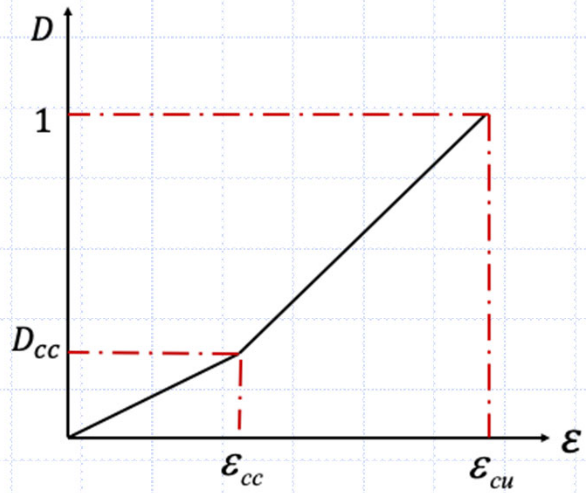


Column damage state		DS-1	DS-2	DS-3	DS-4	DS-5	DS-6	DS-7
Definition		Cracking of cover	Minor Spalling	Major Spalling	Exposed core	Bar buckling	Multi-bar rupture	Column collapse
Ductility Demand	***Mean of cyclic loading***	0.23	1.67	1.90	3.32	4.80	6.10	7.82
	Seismic loading	0.22	1.70	1.95	3.32	4.15	4.15	4.15

Damage-based development of limit states

Concrete damage





$$D_{ci} = \frac{D_{cc}(f - f_{cd})}{(f_{cc} - f_{cd})} \quad for\ \varepsilon \leq \varepsilon_{cc}$$

$$D_{ci} = 1 + \frac{(1 - D_{cc})(f - f_{cu})}{(f_{cu} - f_{cc})} \quad for\ \varepsilon > \varepsilon_{cc}$$

Column Damage Index

Reinforcing steel damage

$$D_{si} = \frac{1}{\sum_{j=1}^{n}\left(2N_f\right)_j}$$

Aggregate material damage

$$D_c = \sum_{i}^{n} w_{ci} D_{ci} \qquad D_s = \sum_{i}^{m} w_{si} D_{si}$$

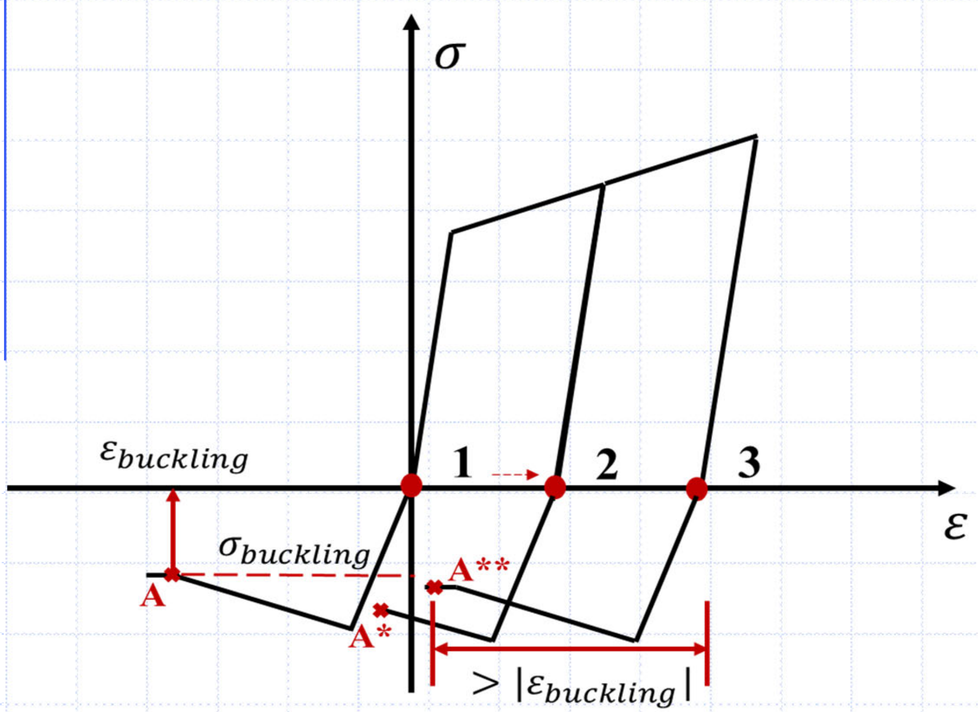
$$w_{ci} = \frac{\alpha_i D_{ci}}{\sum_i^n \alpha_i D_{ci}} \qquad w_{si} = \frac{\beta_i D_{si}}{\sum_i^m \beta_i D_{si}}$$

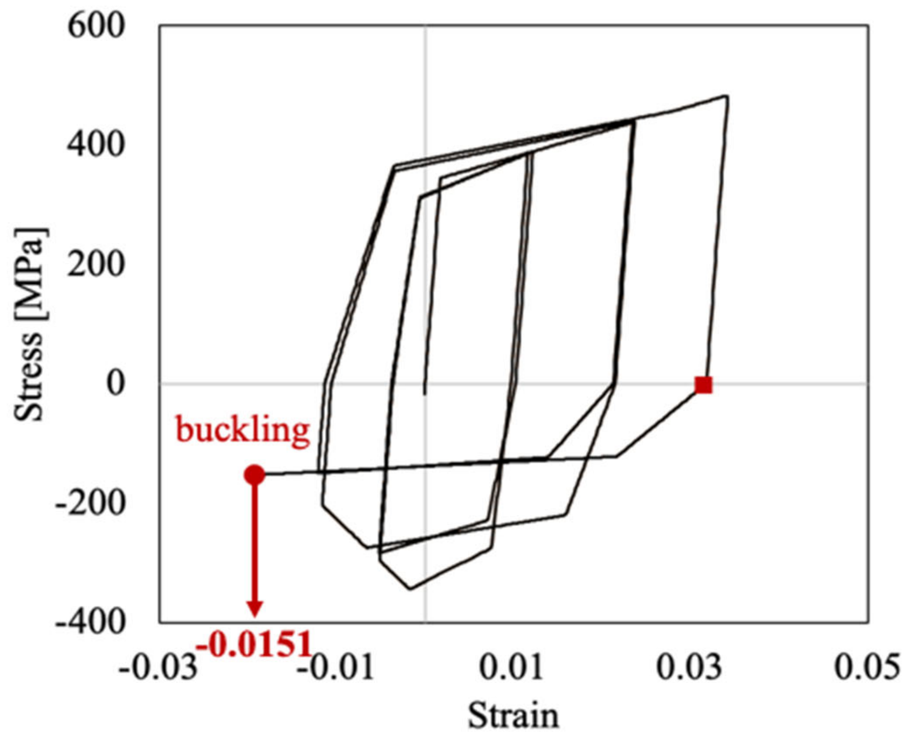
Column damage

$$DI = W_c D_c + W_s D_s$$

$$W_s = \frac{D_s}{D_s + D_c} \;, W_c = \frac{D_c}{D_s + D_c}$$

Modeling buckling in longitudinal bars





Definition of damage limit states

Damage state	**Damage description**		**Damage criteria in critical fiber**	
DS-1	*Cracking in cover*	Slight	C1	Tension cracking in fiber C1, $D_{c_{C1}} \geq 0.01$
DS-2	*Minor Spalling*	Moderate	CR2	$D_{c_{CR2}} \geq D_{cu_{CR2}}$
DS-3	*Major Spalling*		CR3	$D_{c_{CR3}} \geq D_{cu_{CR3}}$
DS-4	*Bar buckling*	Extensive	S1	See Section 4.5.1
DS-5	*Exposed core / first-bar rupture*		S1	$D_{s_{s1}} \geq 1$
DS-6	*Multi-bar rupture*	Complete	S_i , $d_{si} \geq 0.2R_c$	$D_{s_{si}} \geq 1$
DS-7	*Column collapse*			50% loss in lateral strength in load-displacement response

Calibration of damage limit states

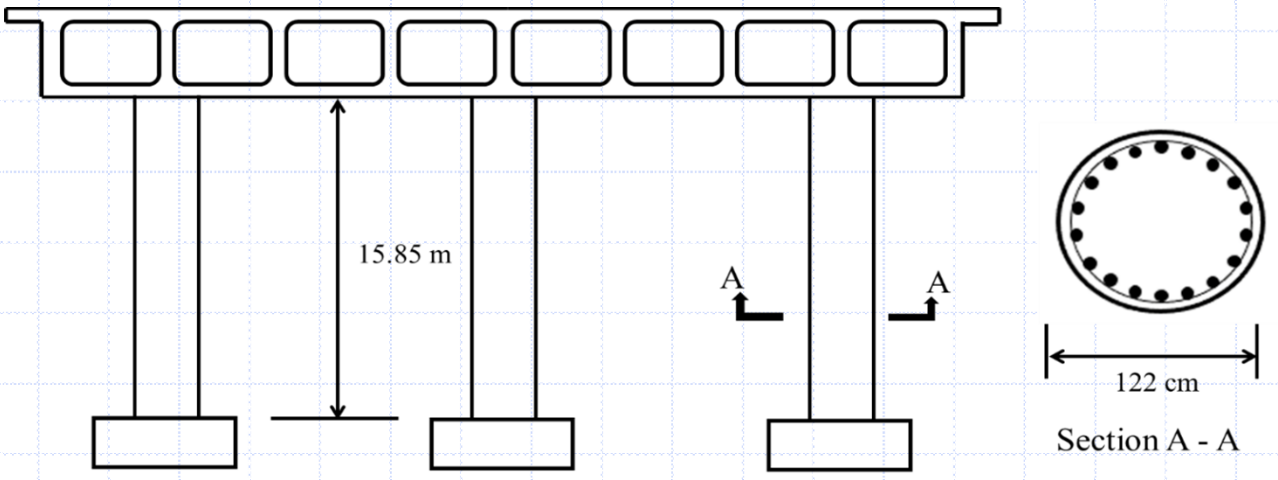
Column damage state	*Definition*	Ranf et. al	Chai et. al
DS-1	*Cracking of cover*	0.01	0.03
DS-2	*Minor Spalling*	0.07	0.07
DS-3	*Major Spalling*	0.19	0.24
DS-4	*Bar buckling*	0.40	0.57
DS-5	*Exposed core / first-bar rupture*	0.72	0.75
DS-6	*Multi-bar rupture*	1.26	1.03
DS-7	*Column collapse*	2.05	1.22

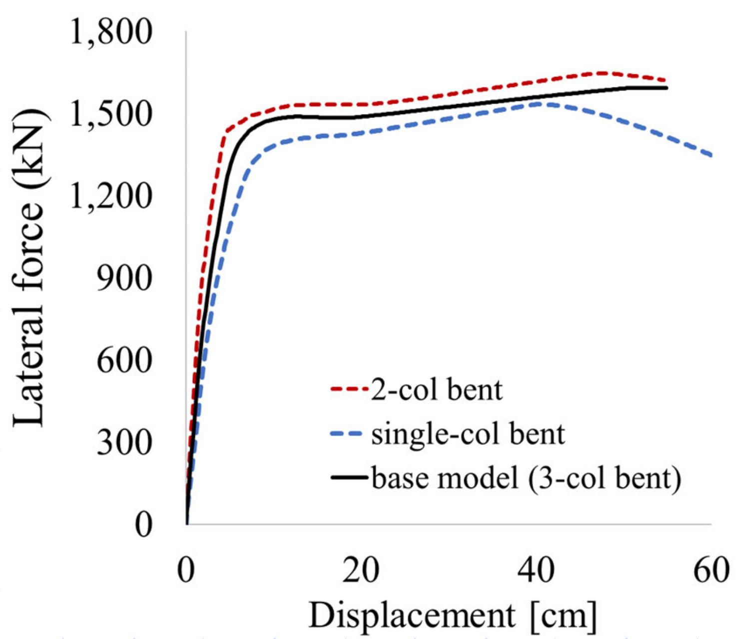
Calibration with shaking table test

Column damage state	Damage description	Computed Damage Index		
		GM1	GM2	GM3
DS-1	*Cracking of cover*	0.01	0.01	0.01
DS-2	*Minor Spalling*	0.02	0.03	0.02
DS-3	*Major Spalling*		0.11	0.22
DS-4	*Bar buckling*		0.58	0.53
DS-5	*Exposed core*			0.97
DS-6	*Multi-bar rupture*			1.76
DS-7	*Column collapse*	*Did not occur*		

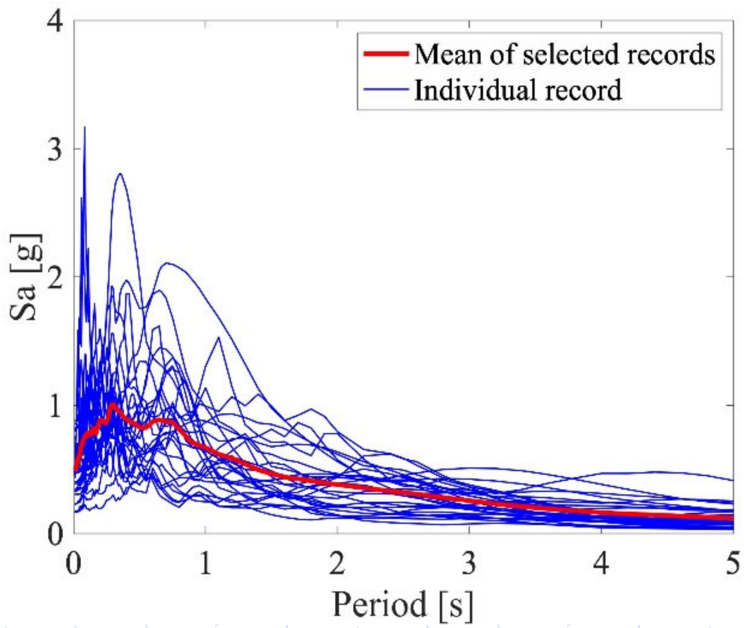
Schoettler, M. J., J. I. Restrepo, G. Guerrini, D. Duck, and F. Carrea. 2015. A full-scale, single-column bridge bent tested by shake-table excitation. PEER Rep. 2015/02, Pacific Earthquake Engineering Research Center, Univ. of California.

Post-earthquake assessment of bridge bents

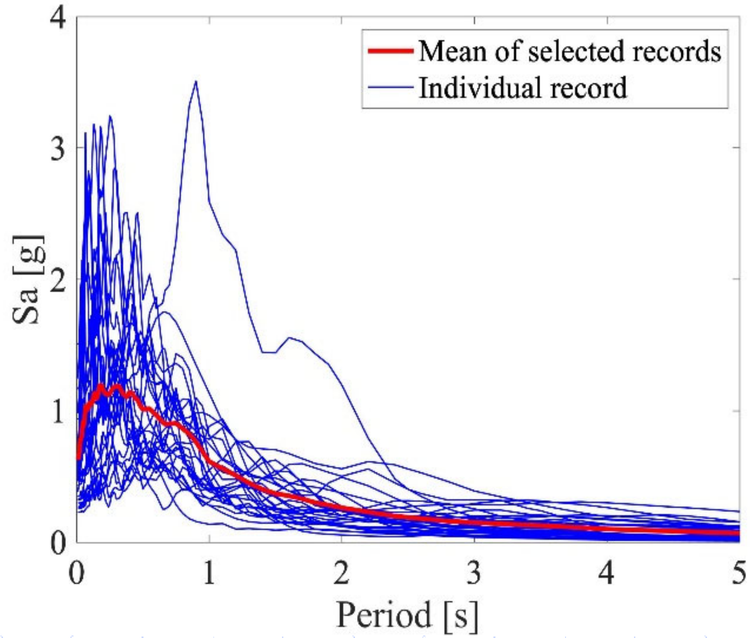




FEMA P-695 Ground Motions

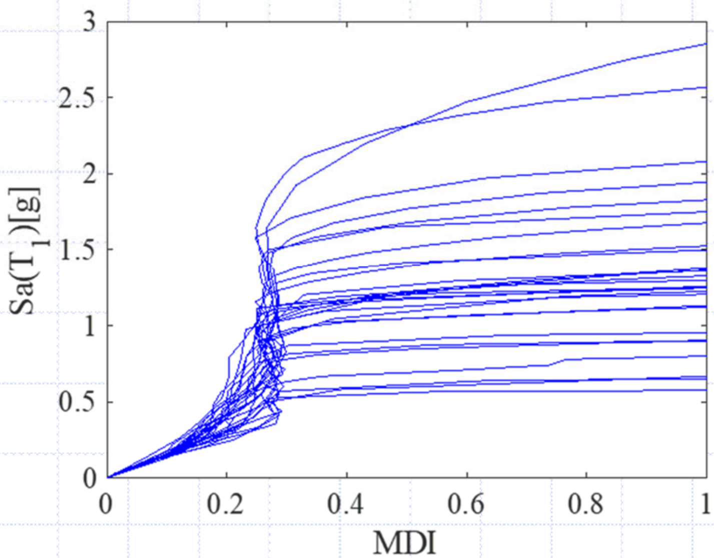


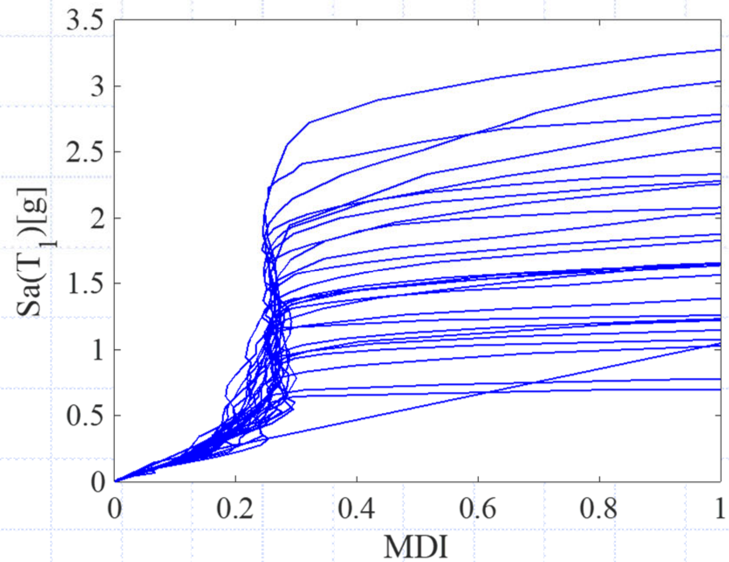
Pulse-like motions



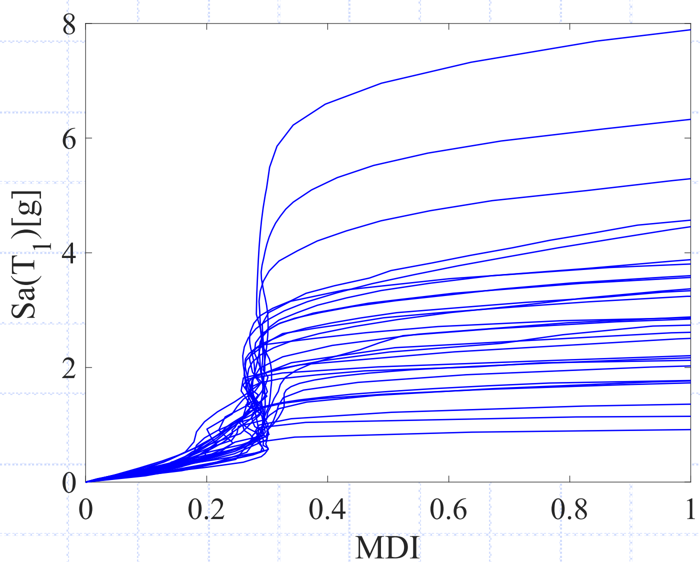
Non-pulse motions

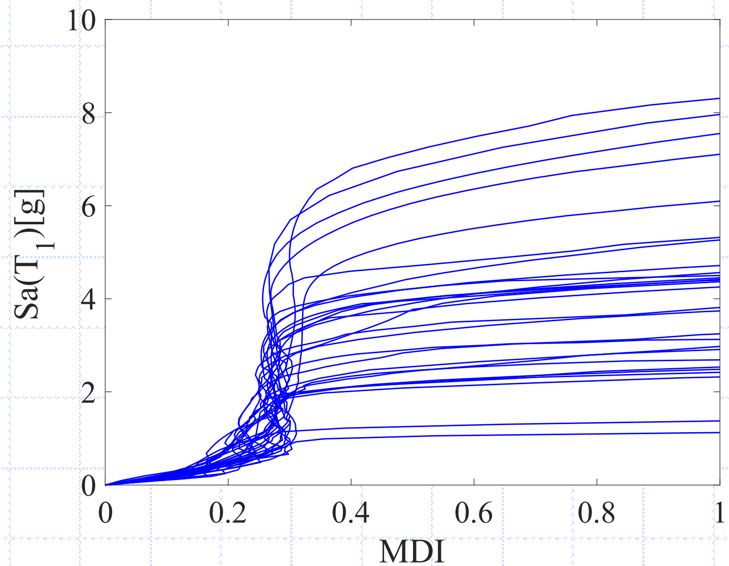
Summary of IDA simulations





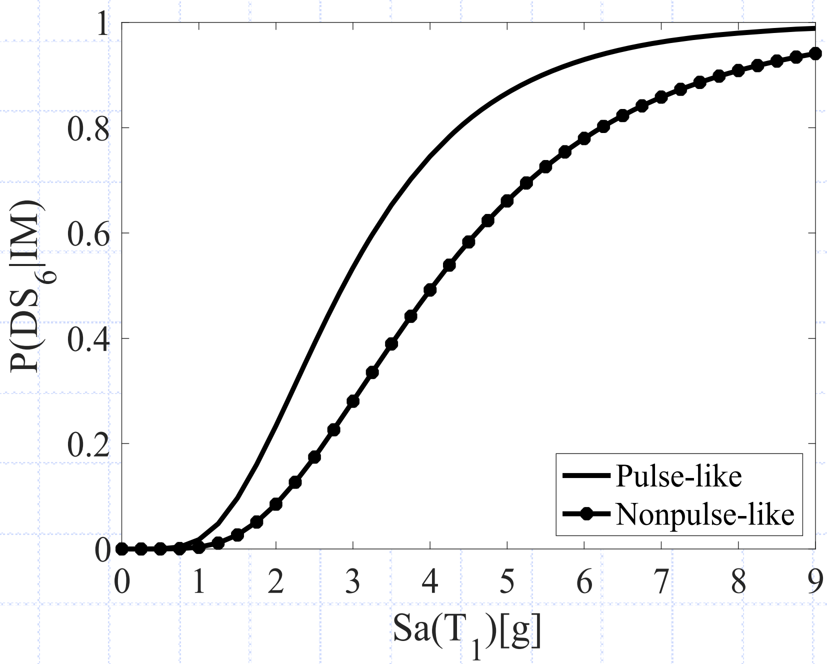
Single column bents

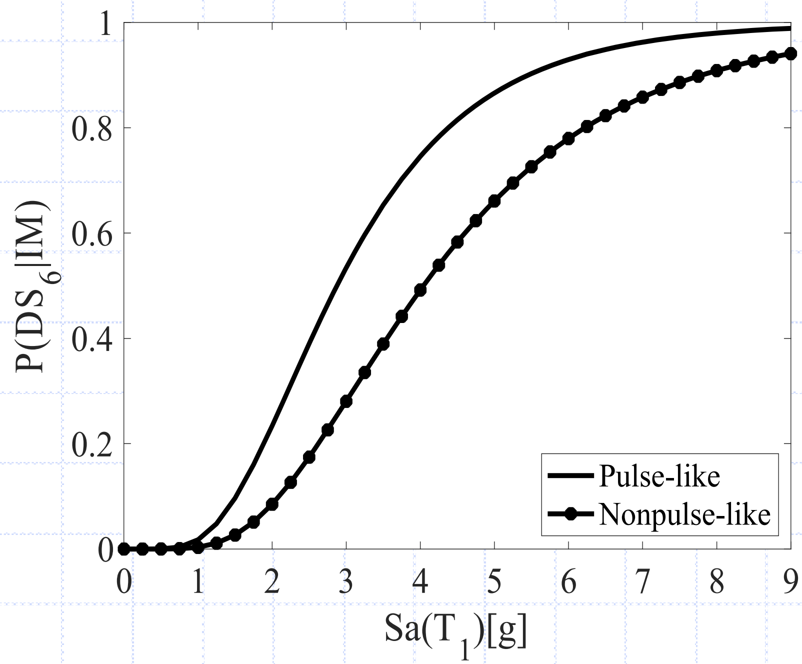




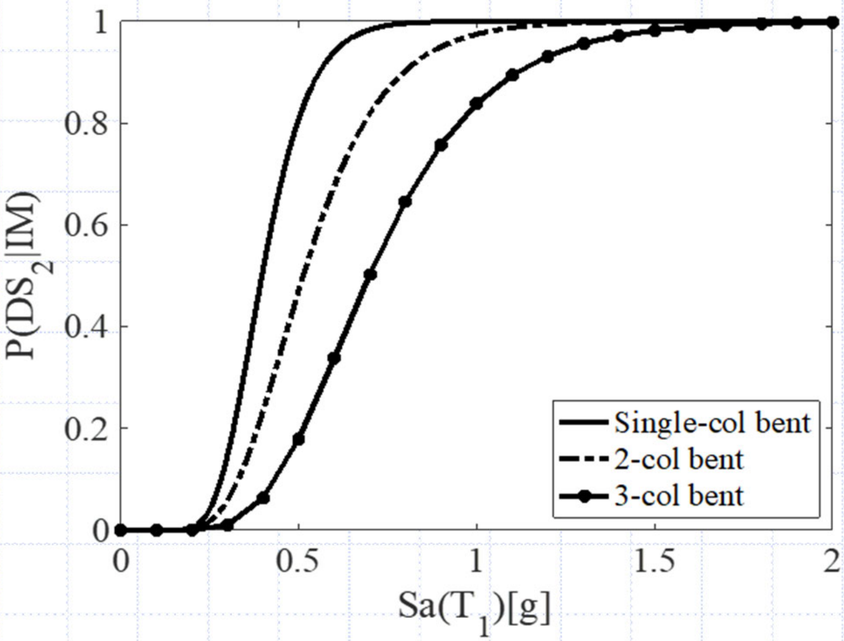
Three column bents

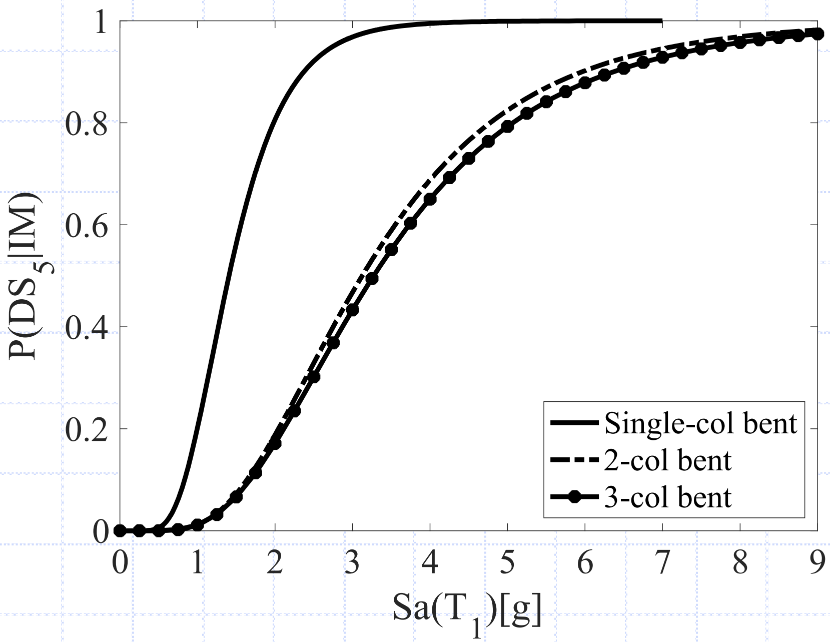
Fragility functions: GM considerations





Fragility functions: Bent Type





Summary of findings & future work

- Ductility-based limit states are unreliable for earthquake loading
- The proposed damage-based limit states were shown to be independent of failure mode and loading protocol
- Redundancy provided by multi-column bents indicate 2-column bents provide additional margin of safety for all damage states but no further enhancement is achieved with 3-column bents
- *Ongoing & future work: refine damage model for early damage states; analysis of additional cross-sections, shear and mixed failure modes; compare with work on Damage Indices by Farzin at UCI*

Acknowledgements

- Cliff Roblee *(Caltrans)*
  Chuang-Sheng (Walter) Yang & Qiu Zheng *(Georgia Tech)*

Thank you!