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Seismic Assessment of Existing Reinforced Concrete Buildings - New Developments, Part 1 of 3

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Dr. Elwood received his Ph.D. in Civil Engineering from the University of California, Berkeley in 2002, M.S. from the University of Illinois at Urbana-Champaign in 1995, and B.A.Sc. from the University of British Columbia in 1993. Dr. Elwood is actively involved in research related to the seismic response of concrete and masonry buildings, in particular the assessment of older buildings not designed to modern seismic design criteria. Dr. Elwood is a member of several building code committees in Canada and the United States, including Standing Committee for Earthquake Design for the National Building Code of Canada, ASCE 41 Standards Committee for Seismic Evaluation and Retrofit, and ACI 318H Subcommittee on Seismic Effects for Building Code Requirements for Structural Concrete. Dr. Elwood is also a member of the Board of Directors of the Earthquake Engineering Research Institute.

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Assessment of ASCE/SEI 41 Concrete Column Provisions using Shaking Table Tests

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Reno, 23 March 2014

Shake Table Tests

PEER, 2002

NCREE, 2005

PEER 2006

NCREE, 2009

Dynamic Column Database

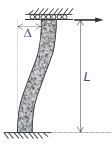
Flexible Beam

	Test programs	No. of Specimens	No. of Columns	Per Specimen: No. of Ductile Columns	Per Specimen: No. of Non-Ductile Columns	Per Column: No. of Test series
1	NCREE 2009	4	3	0	3	2
2	NCREE 2007	1	3	2	1	2
		2	2	0	2	1
3	NCREE 2005	2	4	2	2	2
4	NCREE 2004	2	2	0	2	1
5	PEER 2006	1	4	2	2	4
6	PEER 2005	4	2	2	0	1
		4	2	1	1	1
		3	2	0	2	1
7	PEER 2002	2	1	0	1	1
Total		25	59	20	39	88

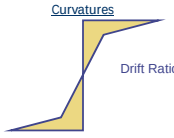
21 flexural failures | 33 flex-shear failures | 5 shear failures

Beam flexibility

Rigid beams:



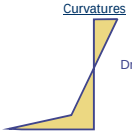
Curvatures



Drift Ratio (Δ/L) = Deformation

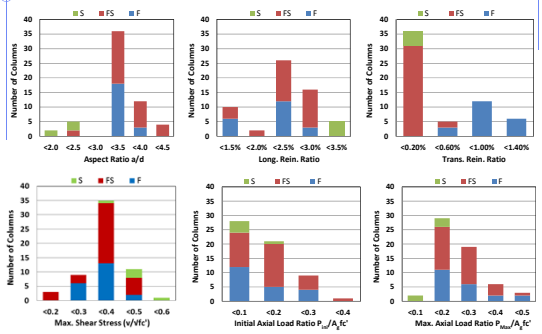
Flexible beams:

Curvatures

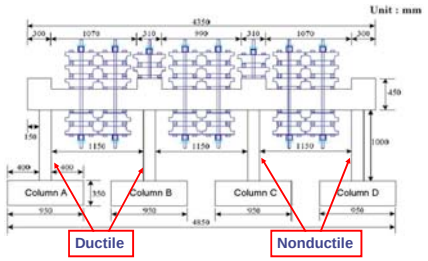


Drift Ratio (Δ/L) = Deformation + **Rigid Body Rotation**

Dynamic Column Database



Shake Table Collapse Test at NCREE (2005)

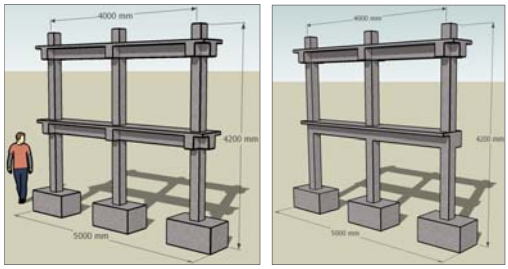


- Why include ductile columns?
  - Not all components in a building will fail at same time.
  - To allow for load redistribution during failure.

Wu et al, 2008

NCREE (2005) Test 2

NCREE (2009) Shake Table Tests



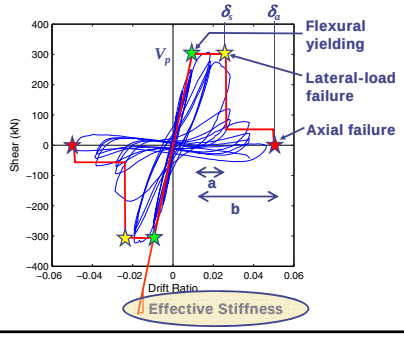
Column Failures:
Moderate Axial Load
High Axial Load

Joint/Column Failures:
Moderate Axial Load

NCREE (2009)

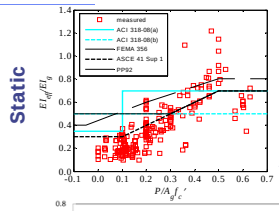
High Axial Load
Confined Joints
Flexure-**S**hear Columns

ASCE 41 Backbone Model



Effective stiffness

Static

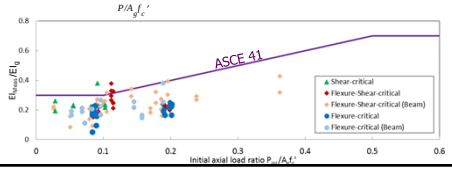


PEER Column database (static):

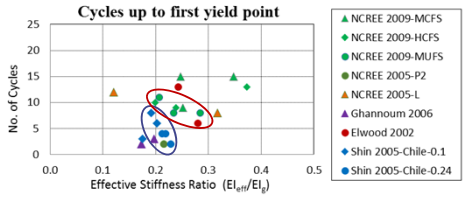
✓ ASCE 41 EI_{eff} > $EI_{eff\ measured}$

Elwood and Eberhard (2009)

Dynamic



Effective stiffness - # of cycles

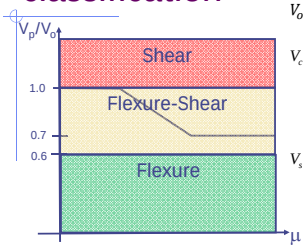


✓ Only consider cycles over $0.3V_{max}$

✓ Need to group by axial load, aspect ratio, and test setup

✓ No clear relationship with number of cycles

ASCE 41 Failure mode classification



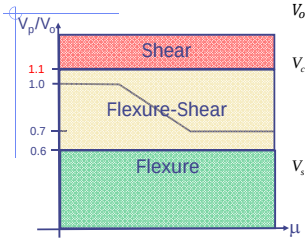
$$V_o = V_n/k = V_c + V_s$$

$$V_c = \lambda\left(\frac{0.5\sqrt{f_c'}}{M/Vd}\sqrt{1+\frac{N_u}{0.5\sqrt{f_c'}A_g}}\right)0.8A_g$$

$$V_s = \begin{cases} \frac{A_v f_y d}{s} & \leftarrow (s/d) \le 0.5 \\ 0.5\frac{A_v f_y d}{s} & \leftarrow 0.5 < (s/d) \le 1.0 \\ 0 & \leftarrow (s/d) > 1.0 \end{cases}$$

		ASCE/SEI 41 Classification			
		Flexure	Flexure-Shear	Shear	Total
Observed Failure Type	Flexure	0	2	0	2
	Flexure-Shear	0	4	23	27
	Shear	0	0	5	5
	Total	0	6	28	34

Modified Failure mode classification



$$V_o = V_n/k = V_c + V_s$$

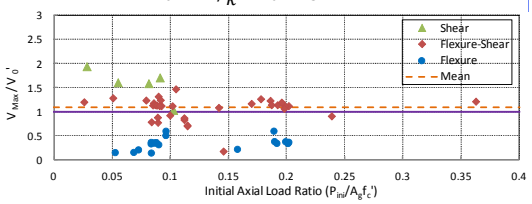
$$V_c = \lambda\left(\frac{0.5\sqrt{f_c'}}{M/Vd}\sqrt{1+\frac{N_u}{0.5\sqrt{f_c'}A_g}}\right)0.8A_g$$

$$V_s = \begin{cases} \frac{A_v f_y d}{s} & \leftarrow (s/d) \le 0.5 \\ 0.75\frac{A_v f_y d}{s} & \leftarrow 0.5 < (s/d) \le 1.0 \\ 0 & \leftarrow (s/d) > 1.0 \end{cases}$$

		Modified ASCE/SEI 41 Classification			
		Flexure	Flexure-Shear	Shear	Total
Observed Failure Type	Flexure	0	2	0	2
	Flexure-Shear	0	27	0	27
	Shear	0	0	5	5
	Total	0	29	5	34

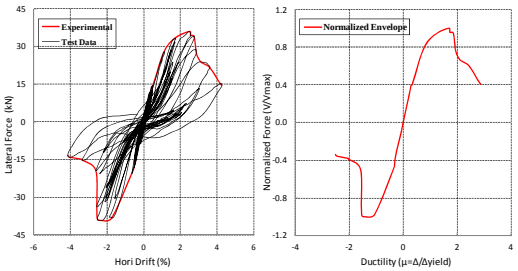
Shear strength

$$V_o = V_n/k = V_c + V_s$$

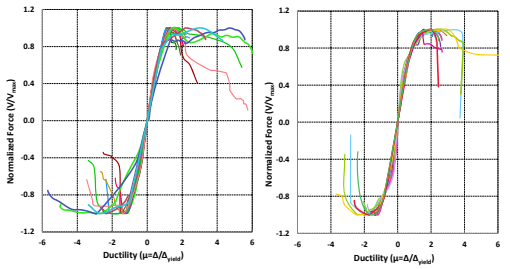


✓ Higher shear strength due to strain rate effects

Envelope



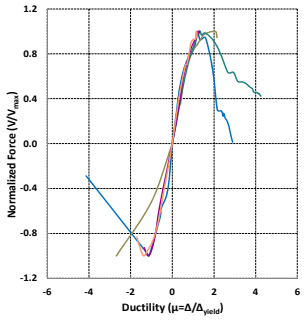
Flexure-shear failure



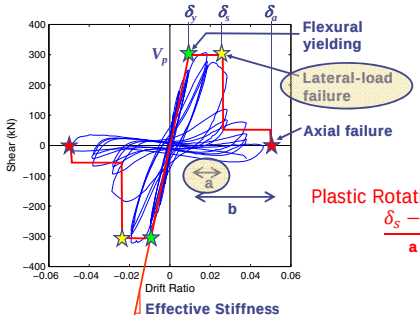
Rigid Beam

Flexible Beam

Shear-critical

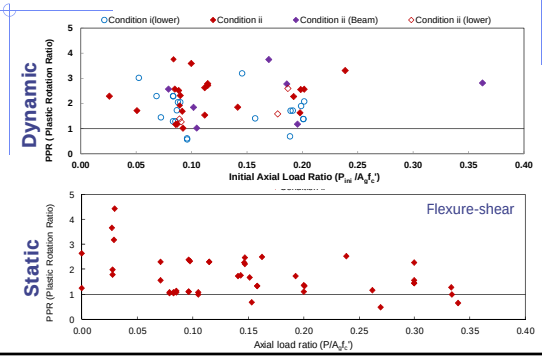


ASCE 41 Backbone Model

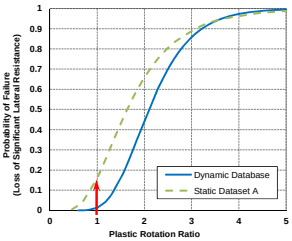


Plastic Rotation Ratio = $\frac{\delta_s - \delta_y}{a}$

Lateral load failure – "a-value"



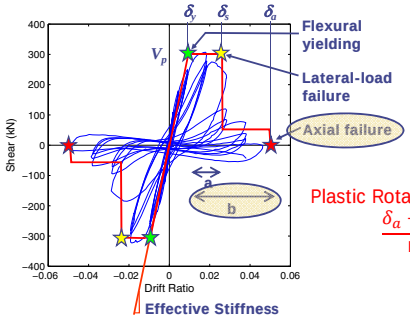
Lateral load failure – "a-value"



Flexure-shear columns

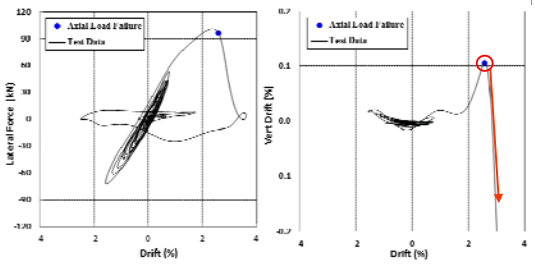
- ✓ Target probability of failure from ASCE 41 Supplement 1 = 15%
- ✓ Lower probability of failure for Dynamic database compared with target and Static database.

ASCE 41 Backbone Model

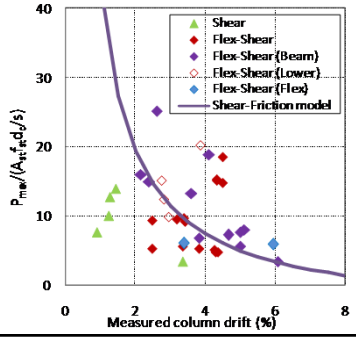


Plastic Rotation Ratio = $\frac{\delta_a - \delta_y}{b}$

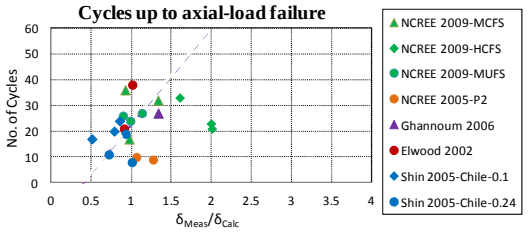
Axial Failure



Axial failure

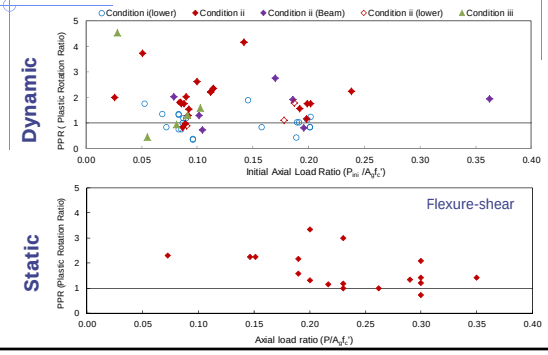


Axial Failure
– *effect of cycles*

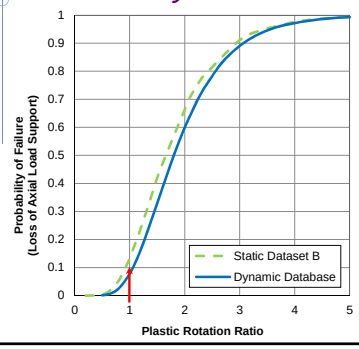


- ✓ Only consider cycles over $0.3V_{max}$
- ✓ No clear relationship with number of cycles

Axial failure
– *Plastic Rotation Ratio*



Axial failure
– *Probability of failure*



- ✓ Similar probability of failure for Dynamic database compared with Static database.

Conclusion (1/3)

- ASCE 41 overestimates stiffness of columns with low axial loads.
  - Consistent with static tests.
- Influence of cycles → not conclusive
  - Requires further study.

Conclusion (2/3)

- ASCE 41 classification results in most columns considered as pure shear failures -*too conservative*.
- Recommendation:
  - Transition to V_s=0 from s=0.75d to s=d;
  - Change upper limit on Condition ii (flexure-shear columns) from V_p/V_0 =1.0 to V_p/V_0=1.1.
    - or incorporate V_p/V_o in calculation of a – see Ghannoum

Conclusion (3/3)

- Flexure-shear critical columns:

$$\delta_{s\ dynamic} > \delta_{s\ static}$$

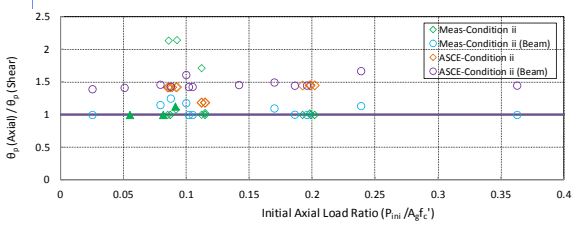
$$\delta_{a\ dynamic} \approx \delta_{a\ static}$$

$$(\delta_a - \delta_s)_{dynamic} < (\delta_a - \delta_s)_{static}$$

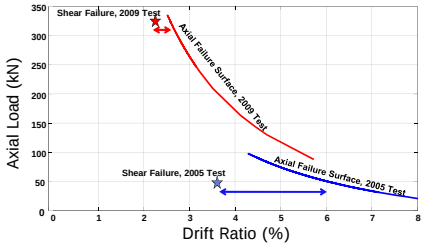
→ Shake table tests suggest assessment of drift at shear failure is conservative BUT… …limited reserve after shear failure.

Thank you!

Questions?



2005 vs 2009 tests?



- If drifts at shear and axial failure are very close, predicted response very sensitive to failure drift estimate.