Behavior and Modeling of Existing Reinforced Concrete Columns

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with contributions from
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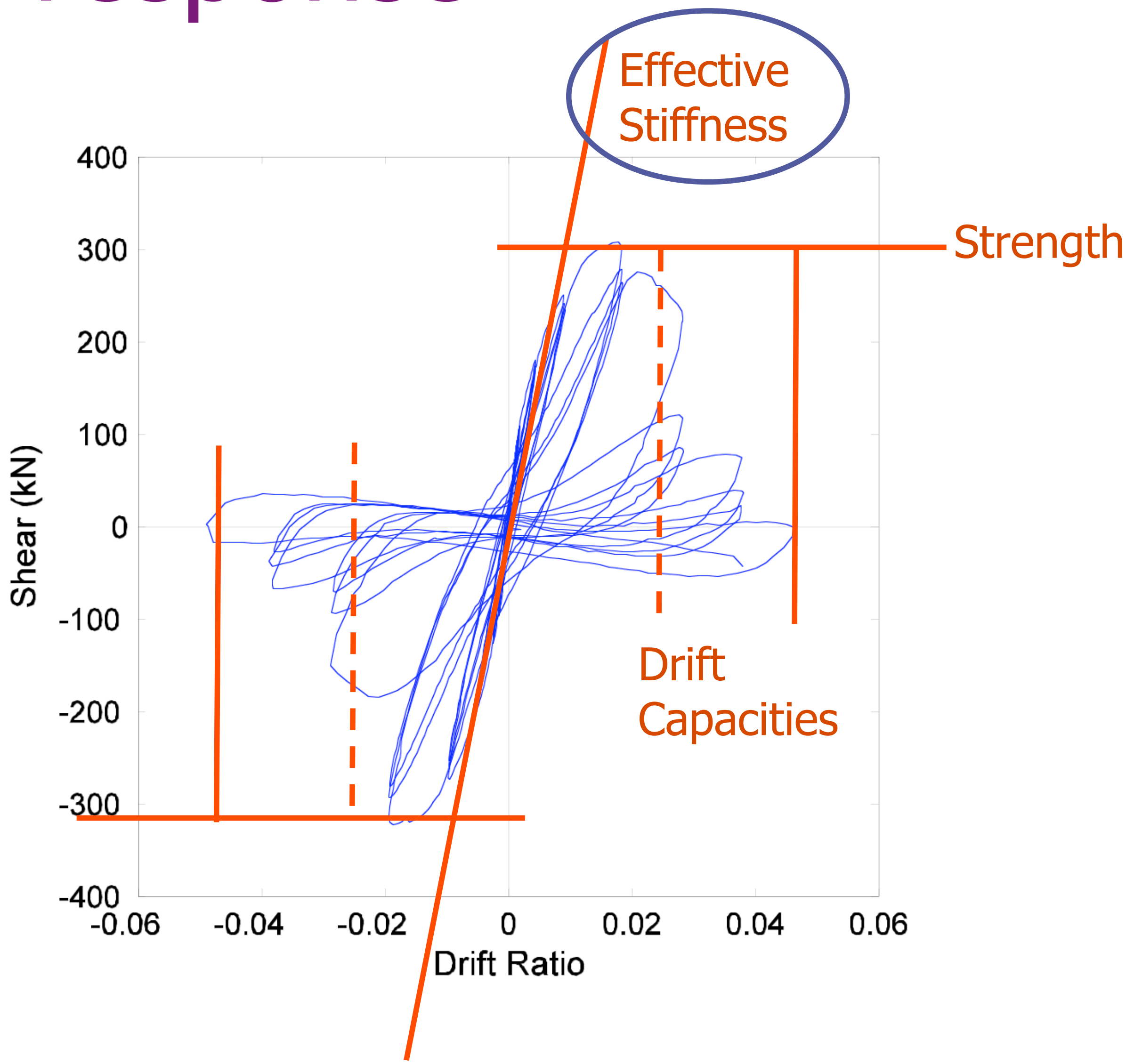
John Wallace, UCLA

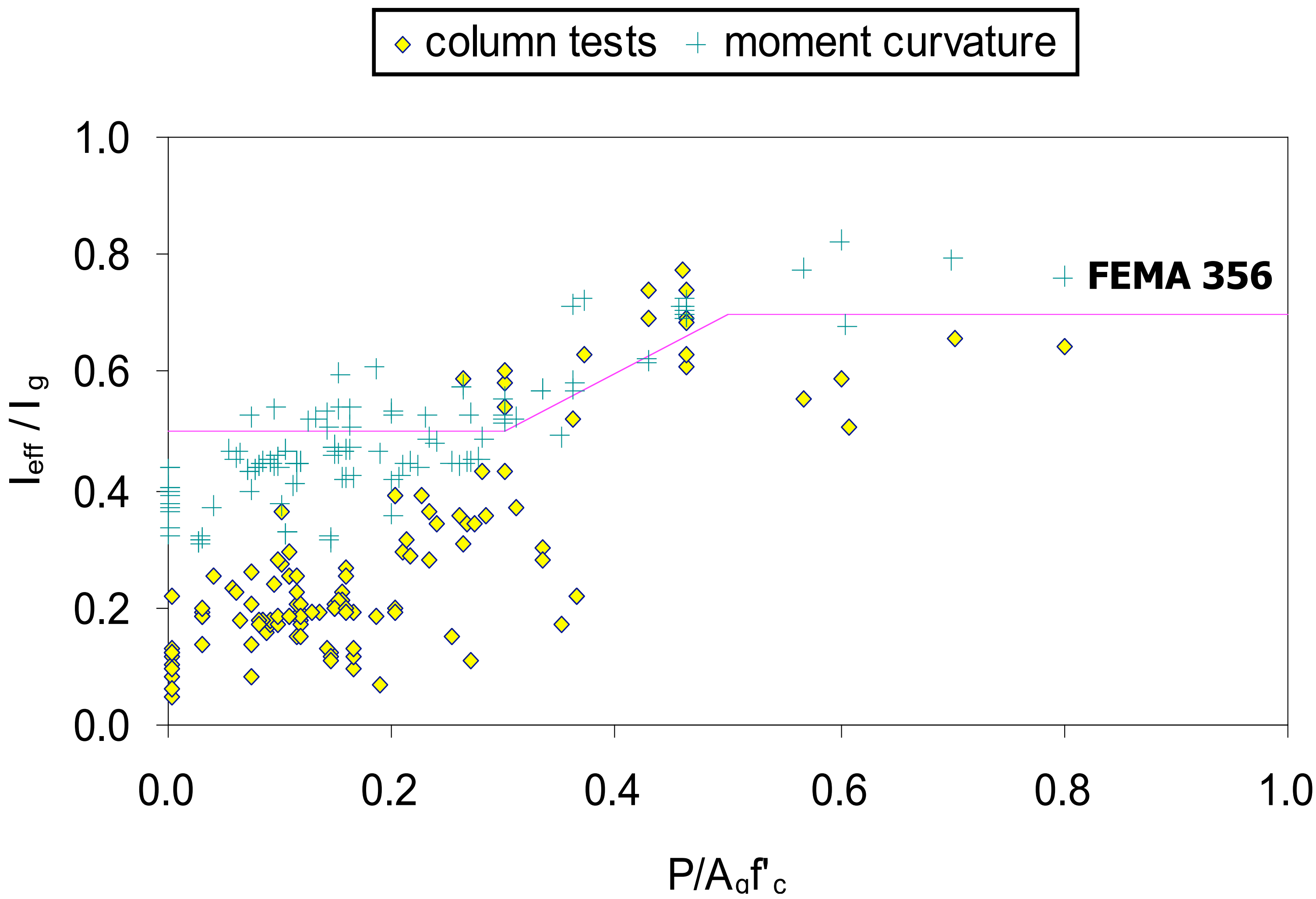
Questions?

- What is the stiffness of the column?
- What is the strength of the column?
- What failure mode is expected?
- What is the drift capacity…
  - at shear failure?
  - at axial failure?
- How can we account for uncertainty in the models?
- How can we model this behavior for the analysis of a structure?
- What is the influence of poor lap splices?

Column response

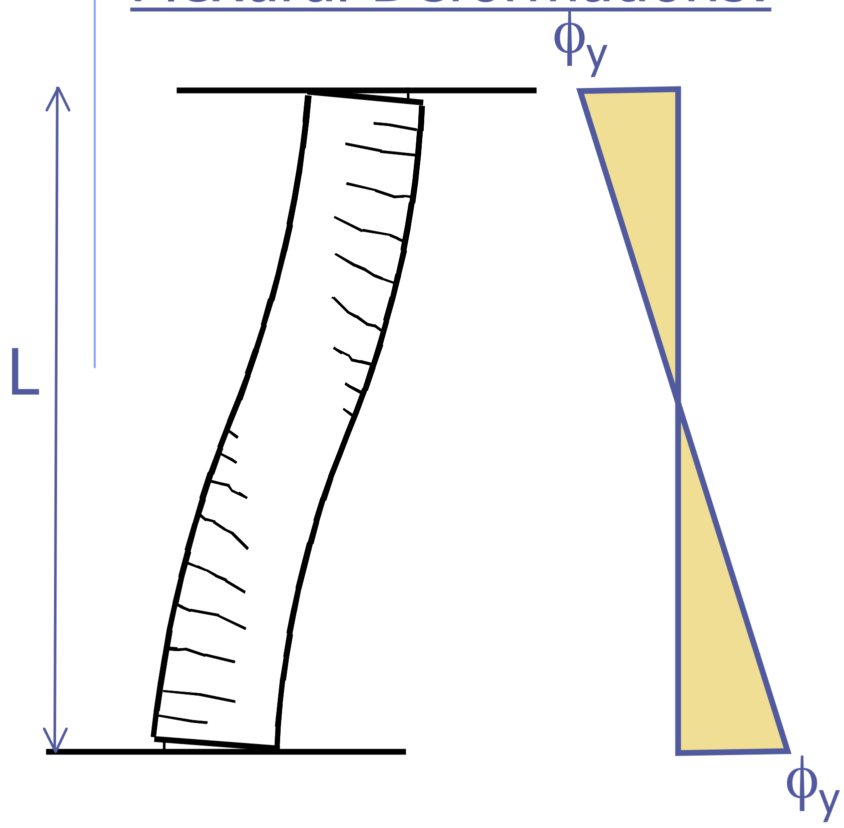


Effective stiffness



Effective stiffness

Flexural Deformations:

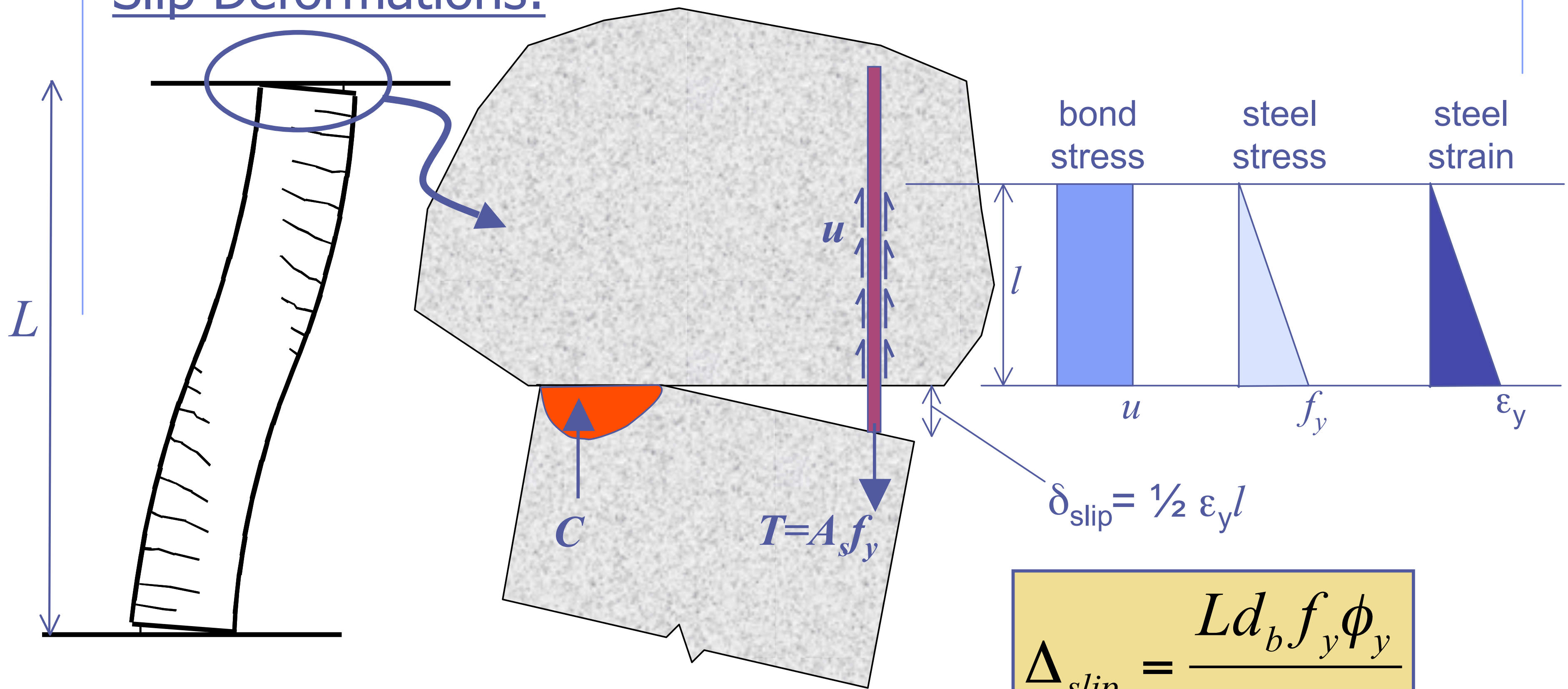


$$\Delta_{flex} = \frac{L^2}{6}\phi_y$$

Does not account for end rotations due to bar slip!

Effective stiffness

Slip Deformations:



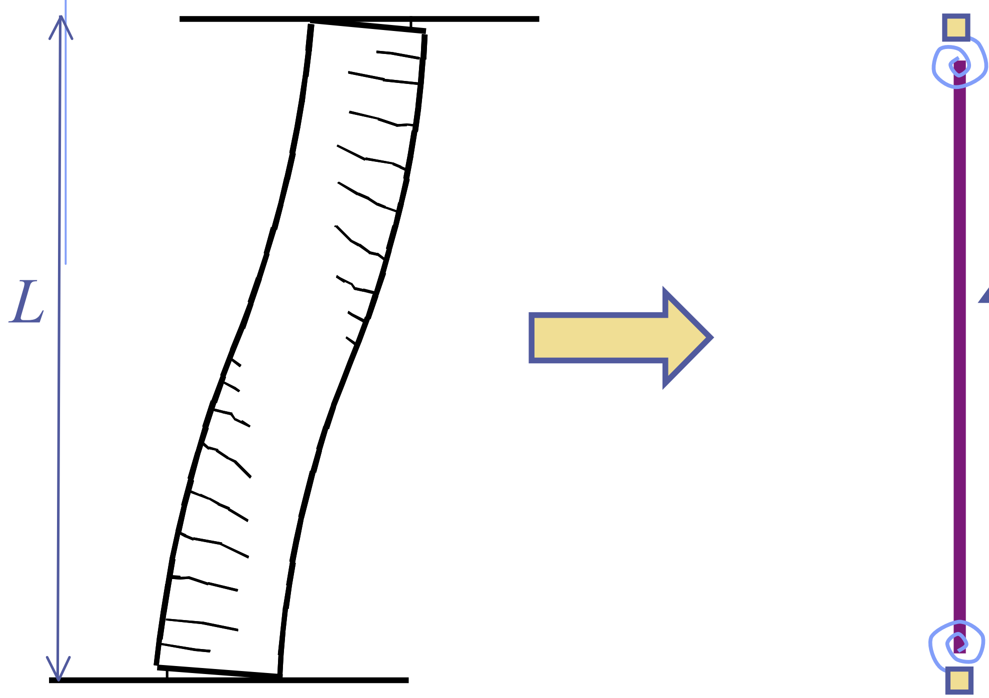
$$\Delta_{slip} = \frac{L d_b f_y \phi_y}{8u}$$

$$u \approx 6\sqrt{f'_c} - 12\sqrt{f'_c}$$

Effective stiffness

Modeling options:

Option 1 (with slip springs)



Stiffness based on moment-curvature analysis (or FEMA 356 recommendations)

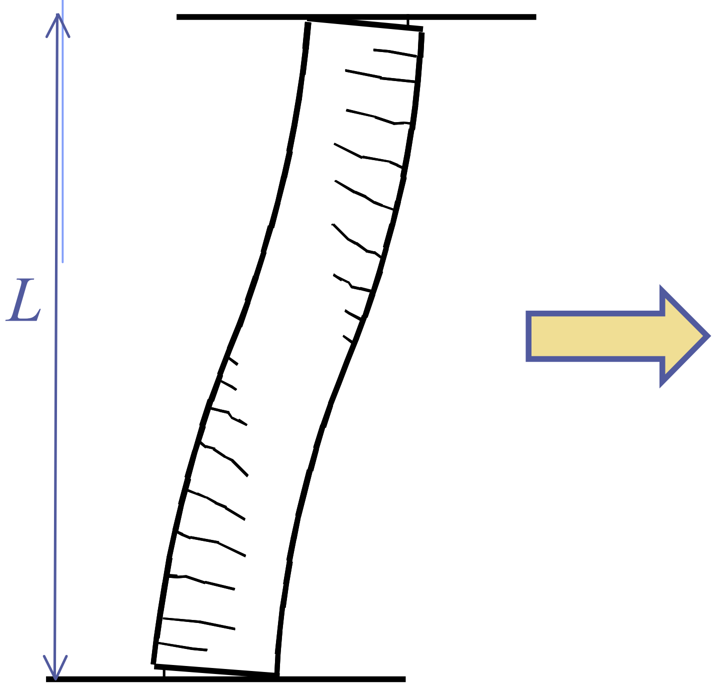
Slip springs:

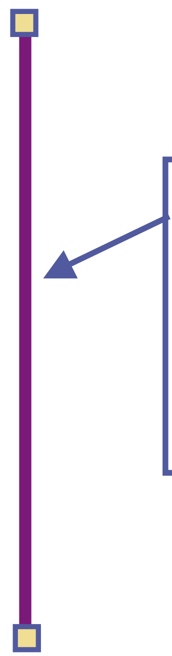
$$k_{slip} = \frac{8u}{d_b f_y} \frac{M_y}{\phi_y}$$

Effective stiffness

Modeling options:

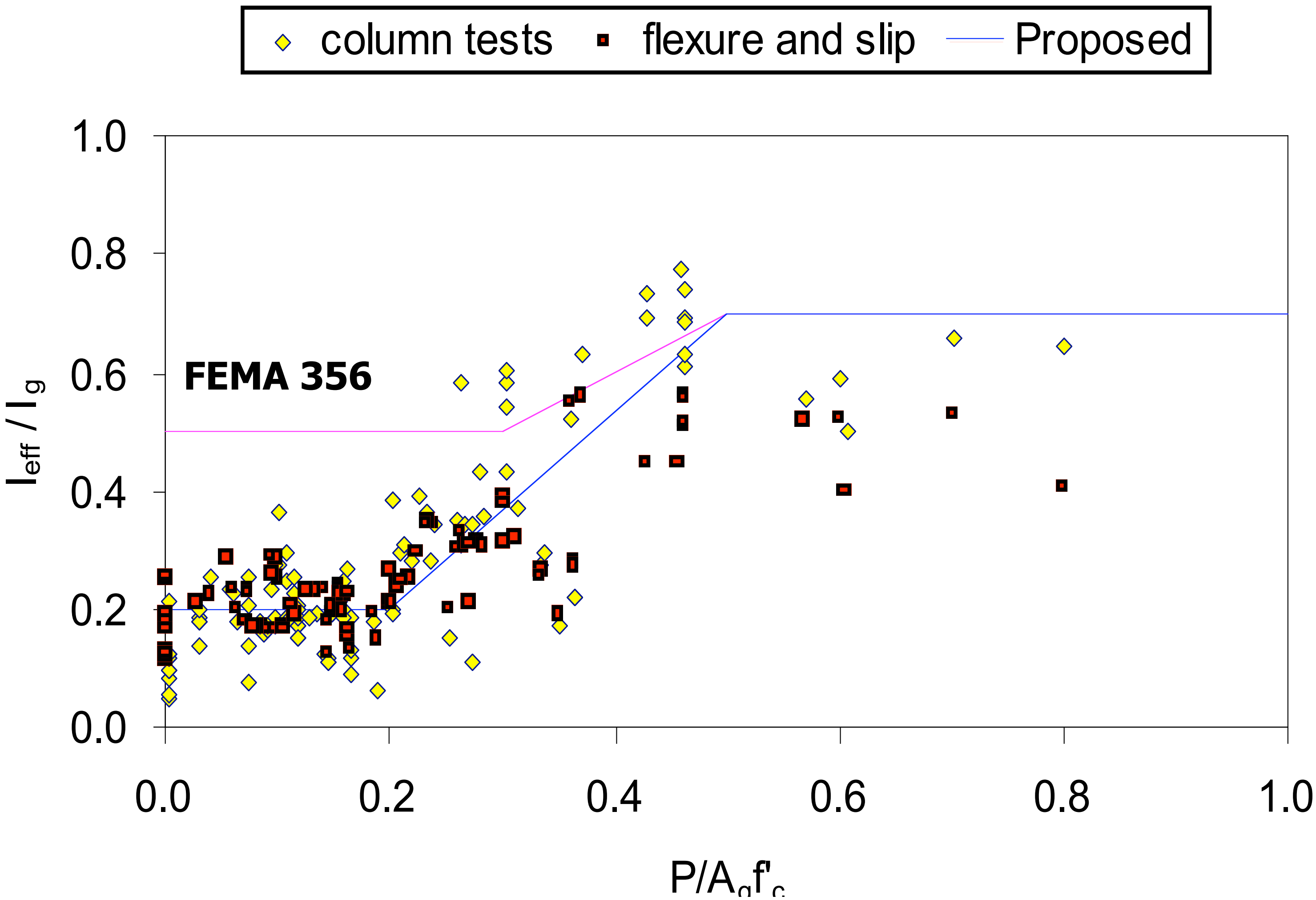
Option 2 (without slip springs):



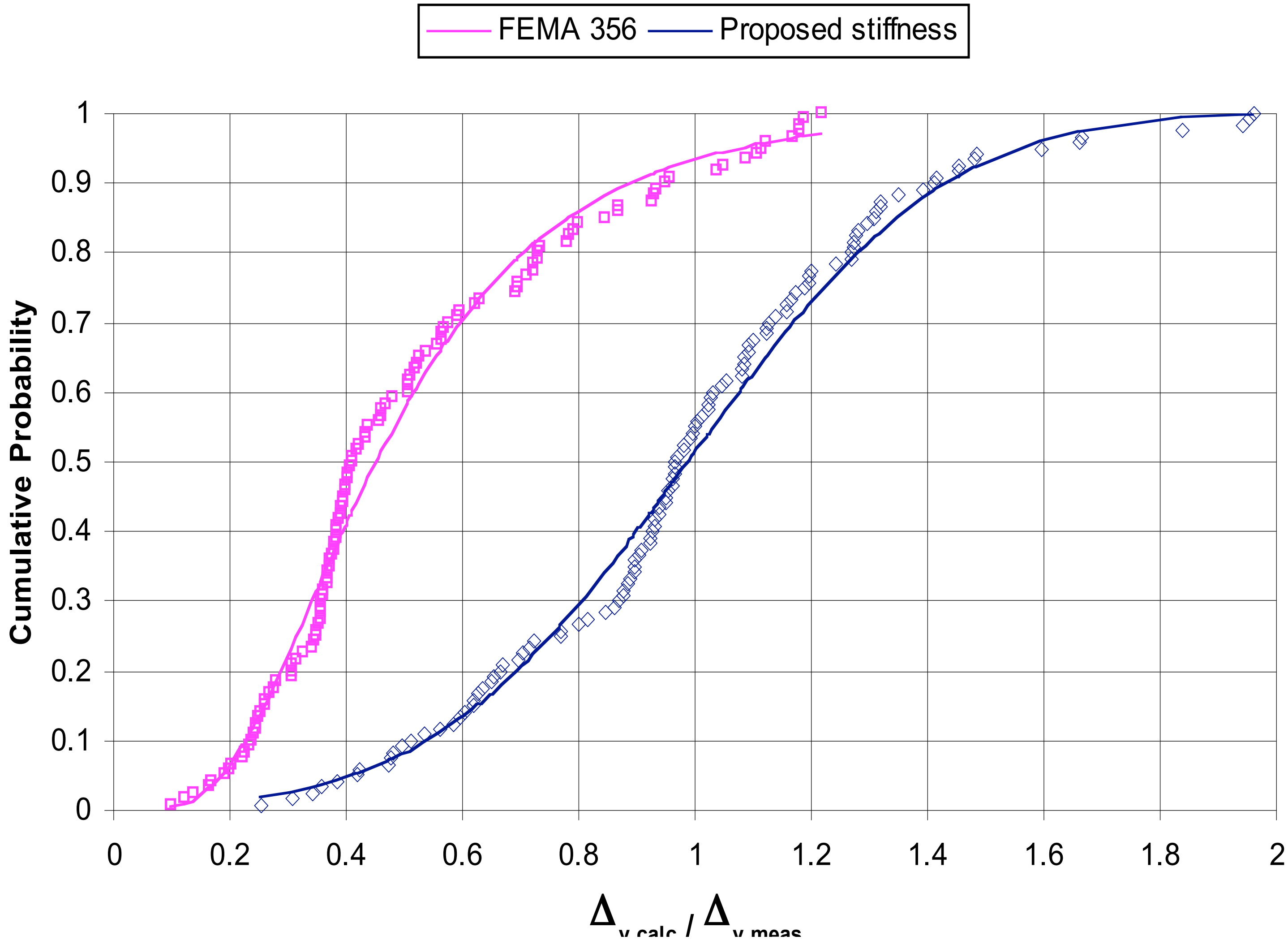


Use effective stiffness determined from column tests. More flexible than FEMA recommendations for low axial load.

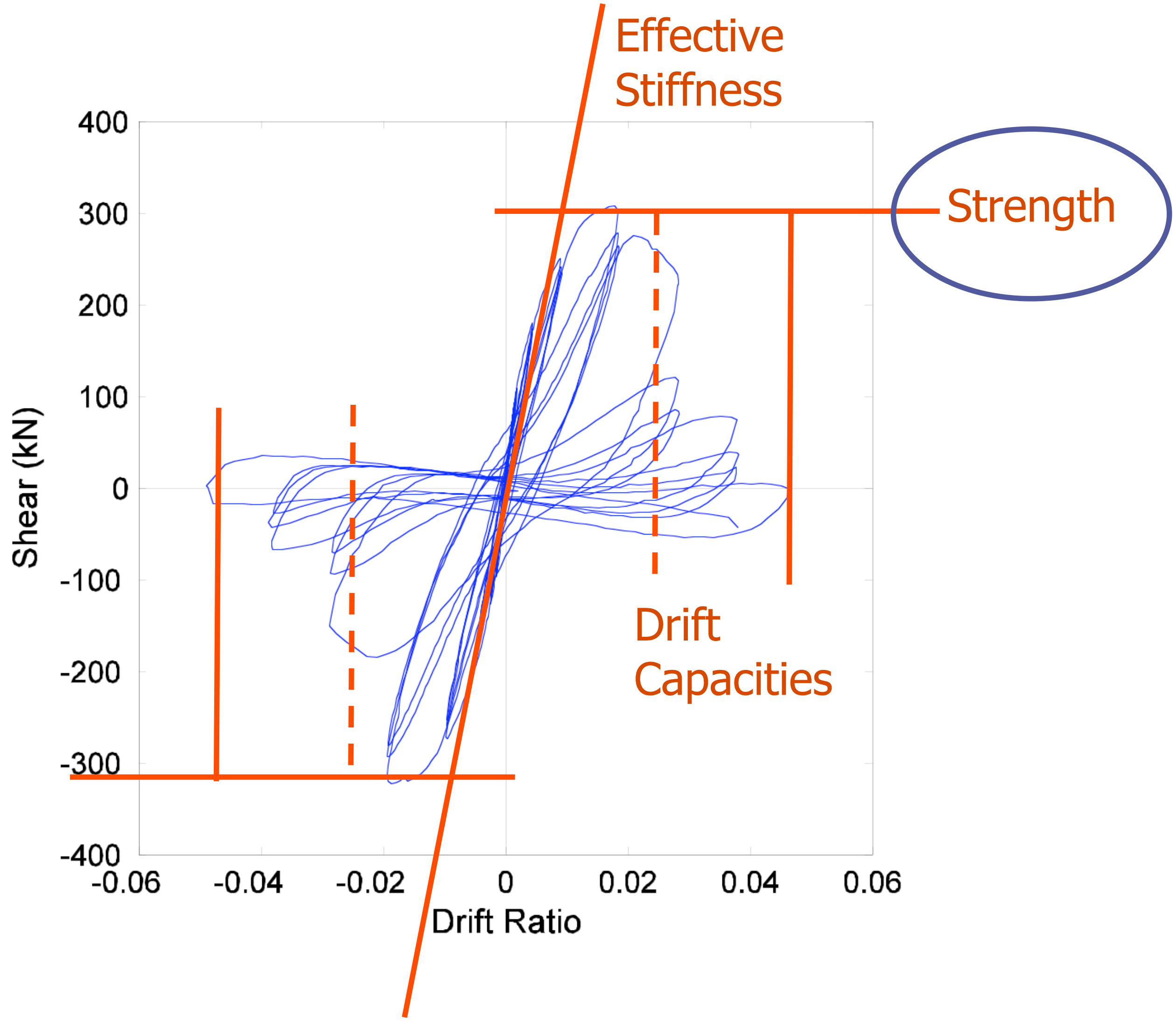
Effective stiffness



Yield displacement



Column response



Shear Strength

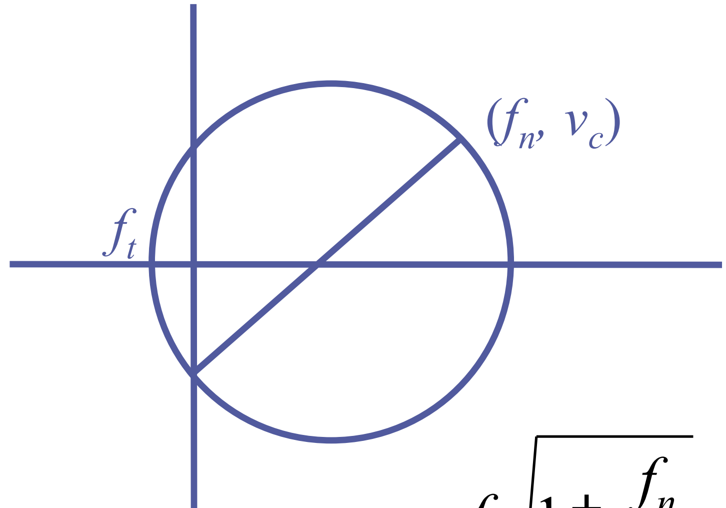
- Several models available to estimate shear strength:
  - Aschheim and Moehle (1992)
  - Priestley et al. (1994)
  - Konwinski et al. (1995)
  - FEMA 356 (Sezen and Moehle, 2004)
  - ACI 318-05
- All models (except ACI) degrade shear strength with increasing ductility demand.

Shear Strength

$$V_n = V_c + V_s$$

$$V_c = k\left(\frac{1}{a/d}\right)\left(6\sqrt{f_c'}\sqrt{1+\frac{P}{6\sqrt{f_c'}A_g}}\right)0.8A_g$$

$$V_s = k\frac{A_{sw}f_yd}{s}$$



$$v_c = f_t\sqrt{1+\frac{f_n}{f_t}}$$

- Based on principle tensile stress exceeding $f_t = 6\sqrt{f_c'}$

Sezen and Moehle, 2004

Shear Strength

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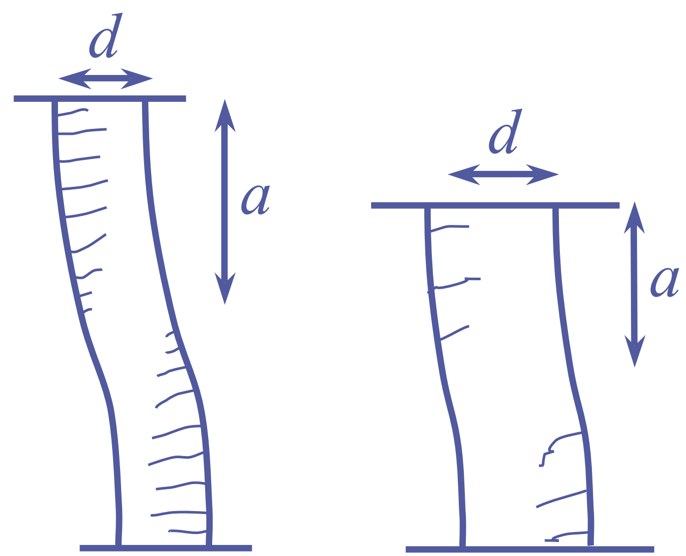

- Based on principle tensile stress exceeding $f_t = 6\sqrt{f_c'}$
- Accounts for degradation due to flexural and bond cracks

Sezen and Moehle, 2004

Shear Strength

$$V_n = V_c + V_s$$

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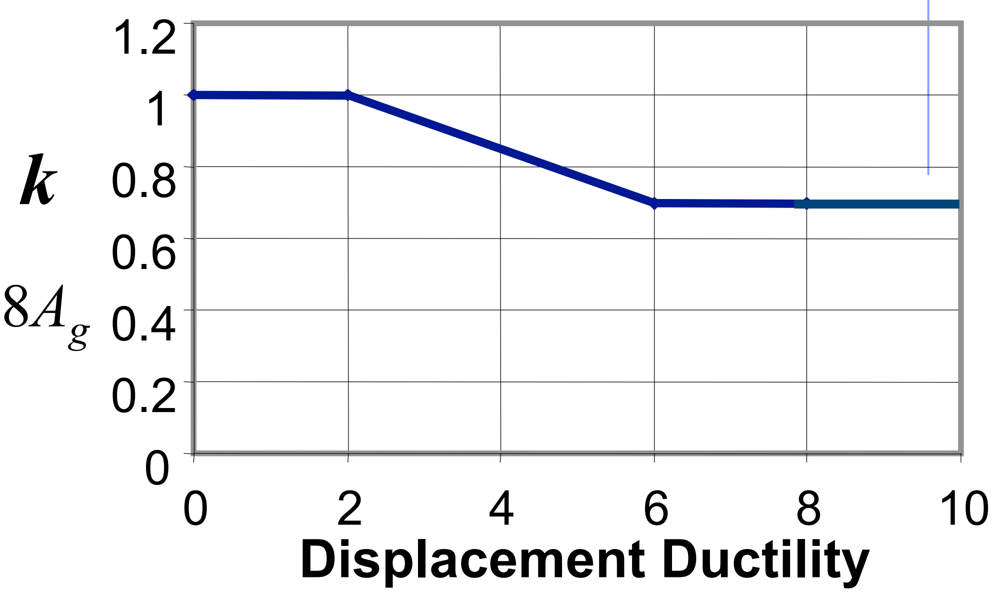
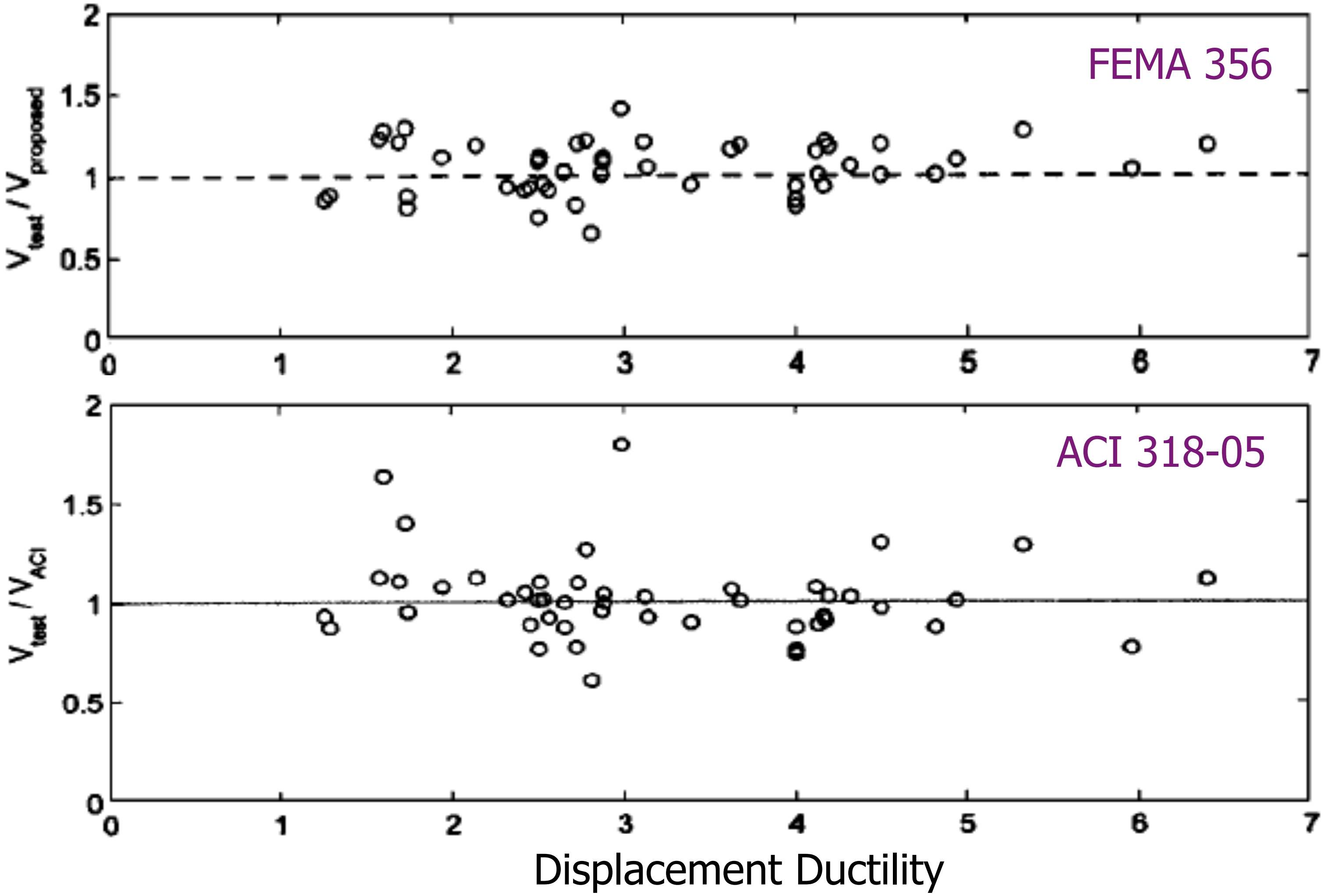


- Based on principle tensile stress exceeding $f_t = 6\sqrt{f_c'}$
- Accounts for degradation due to flexural and bond cracks
- Degrades both V_s and V_c based on ductility

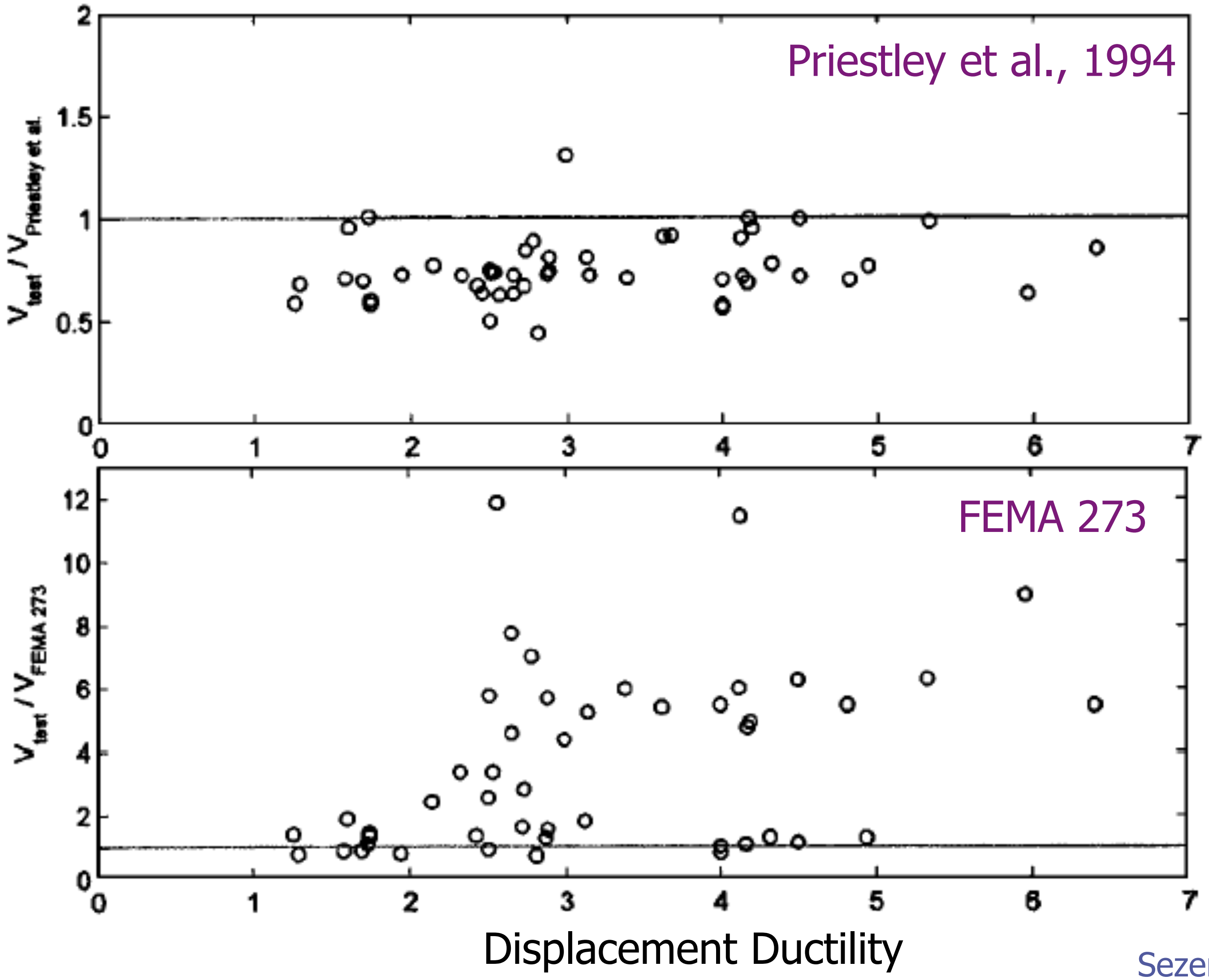
Sezen and Moehle, 2004

Shear Strength



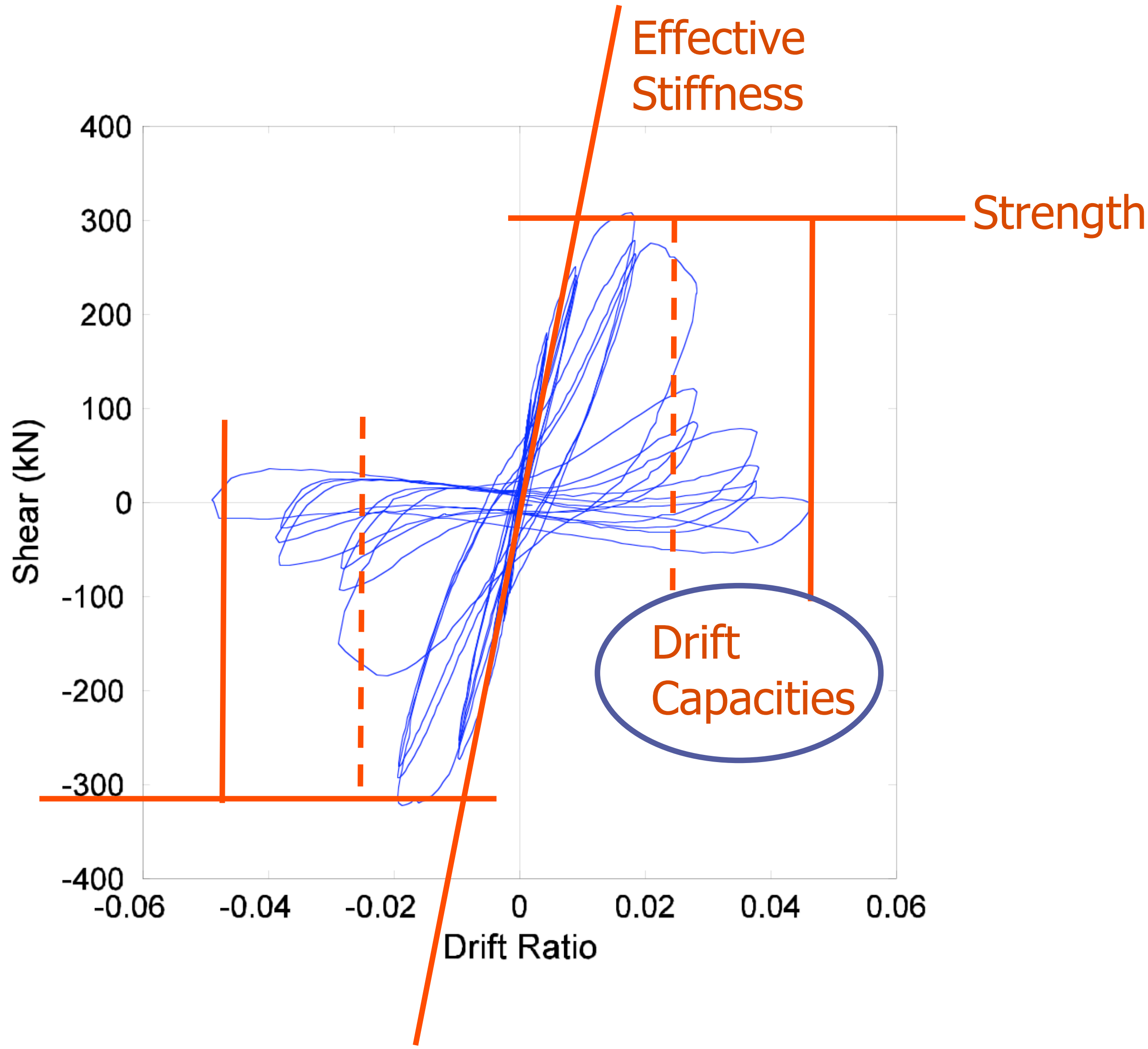
Sezen and Moehle, 2004

Shear Strength

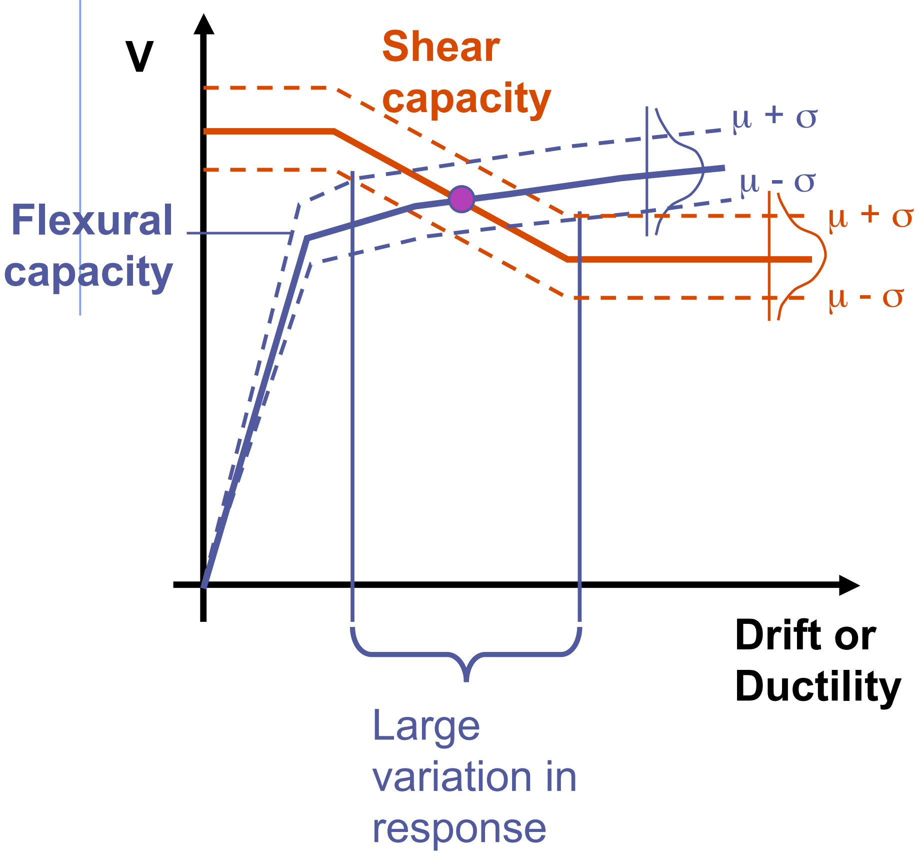


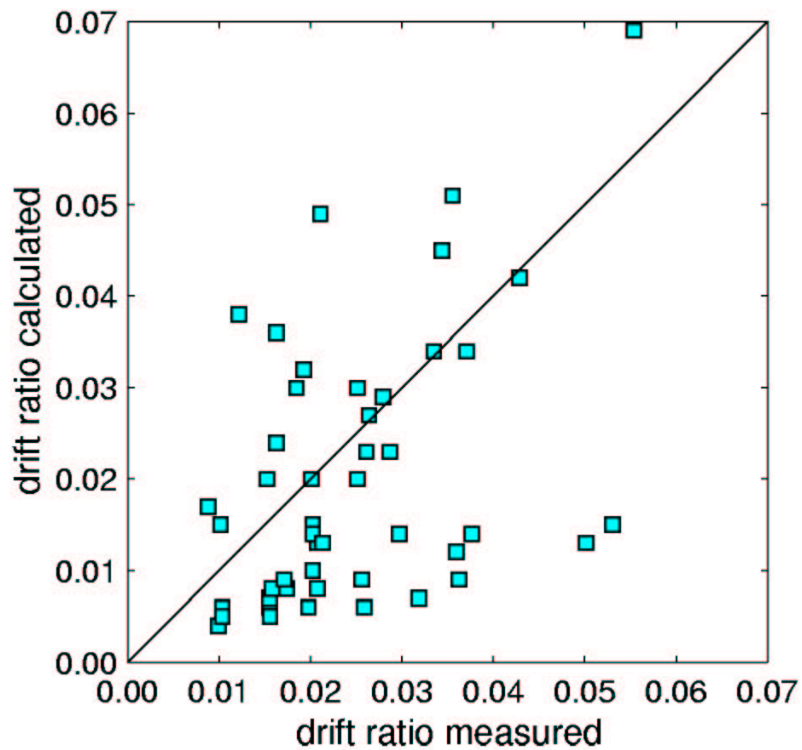
Sezen and Moehle, 2004

Column response



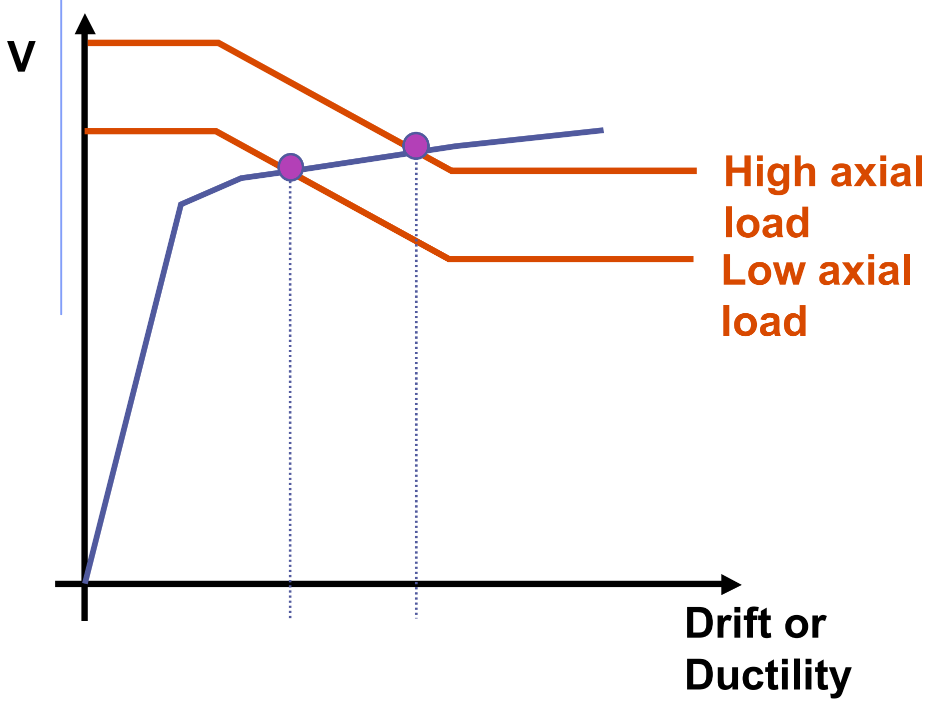
Shear Failure

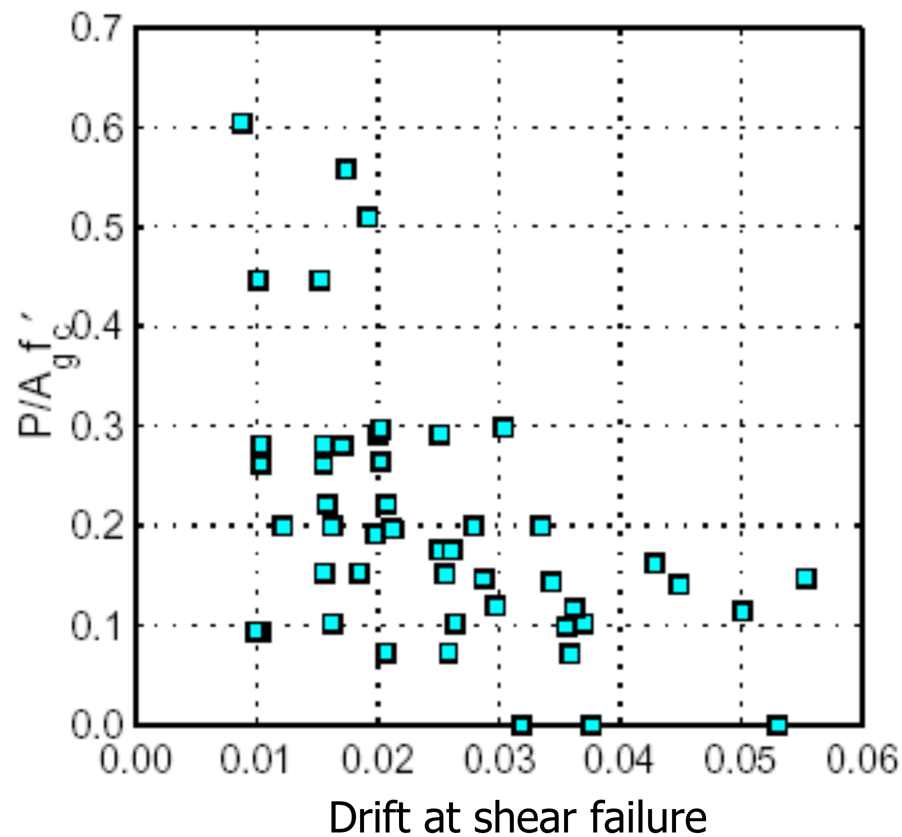




Elwood and Moehle, 2005a

Shear Failure



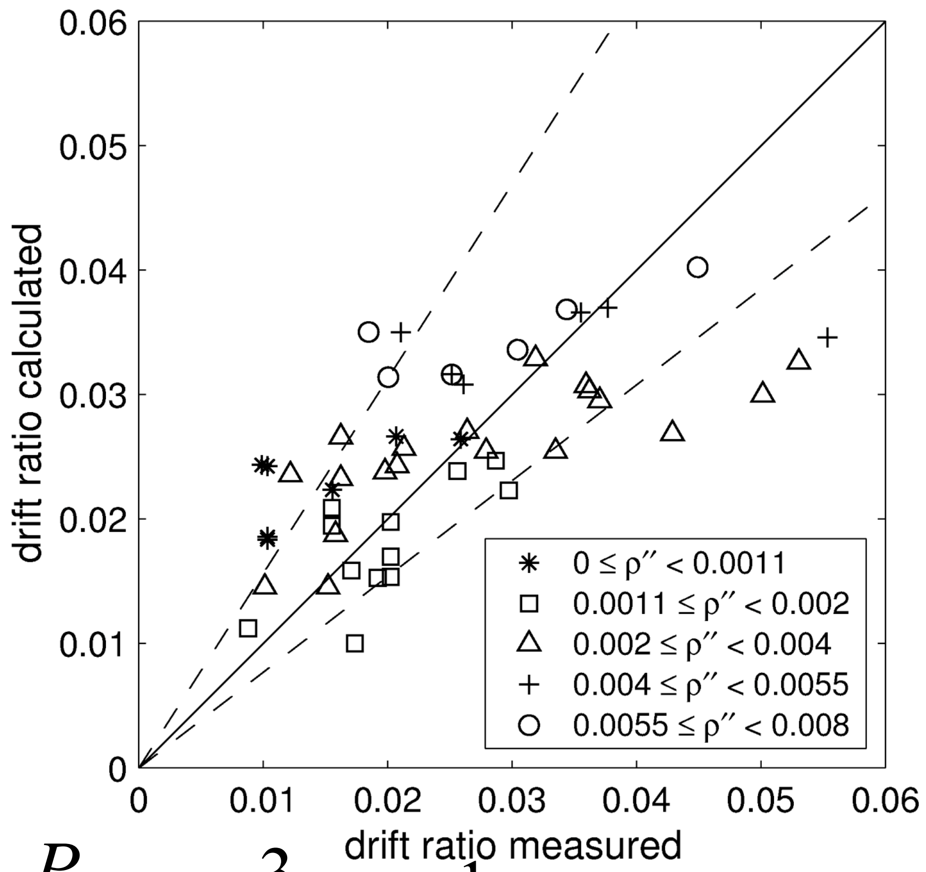


Elwood and Moehle, 2005a

Drift at Shear Failure Model

Drift capacity depends on:

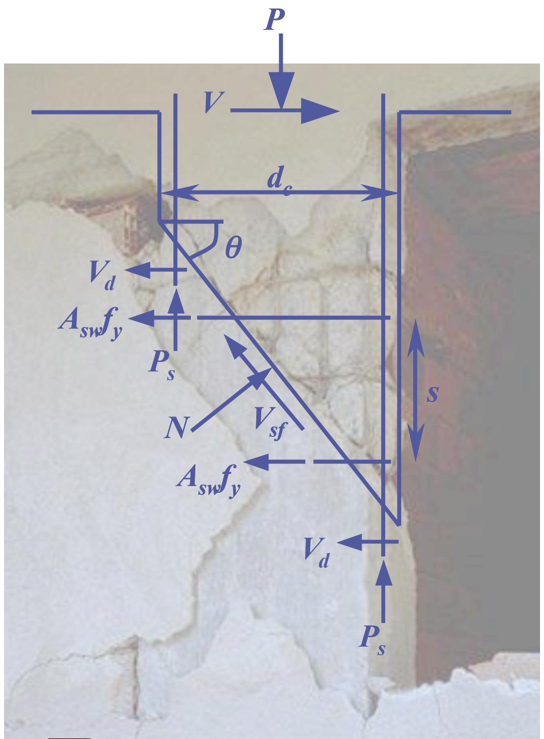
- amount of transverse reinforcement
- shear stress
- axial load



$$\frac{\Delta_s}{L} = 4\rho'' - \frac{1}{500}\frac{v}{\sqrt{f'_c}} - \frac{1}{40}\frac{P}{A_g f'_c} + \frac{3}{100} \geq \frac{1}{100}$$

Elwood and Moehle, 2005a

Drift at Axial Failure Model



Simplifying Assumptions

- *V* assumed to be zero since shear failure has occurred
- Dowel action of longitudinal bars (V_d) ignored
- Compression capacity of longitudinal bars (P_s) ignored

$$\sum F_y \rightarrow P = N\cos\theta + V_{sf}\sin\theta$$

$$\sum F_x \rightarrow N\sin\theta = V_{sf}\cos\theta + \frac{A_{st} f_y d_c \tan\theta}{s}$$

$$\textit{Classic Shear-Friction} \longrightarrow V_{sf} = N\mu$$

$$P = \frac{A_{st} f_y d_c}{s}\tan\theta\left(\frac{\cos\theta + \mu\sin\theta}{\sin\theta - \mu\cos\theta}\right)$$

Elwood and Moehle, 2005b

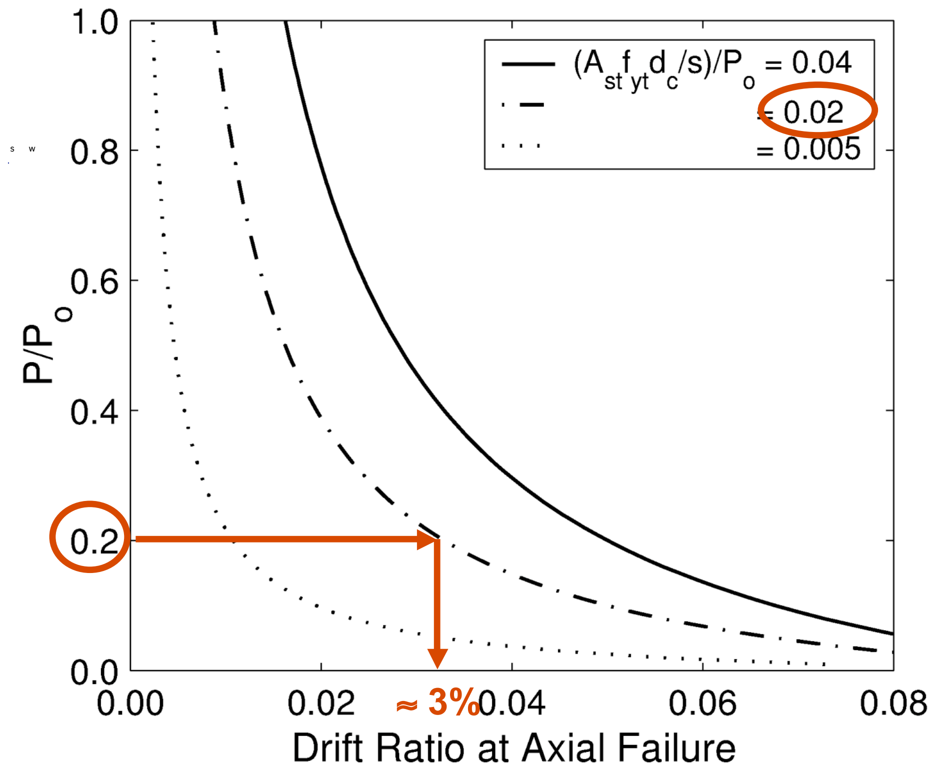
Drift at Axial Failure Model

- Relationships combine to give a design chart for determining drift capacities.

$$P = \frac{A_{st} f_y d_c}{s} \tan\theta \left(\frac{\cos\theta + \mu \sin\theta}{\sin\theta - \mu \cos\theta} \right)$$

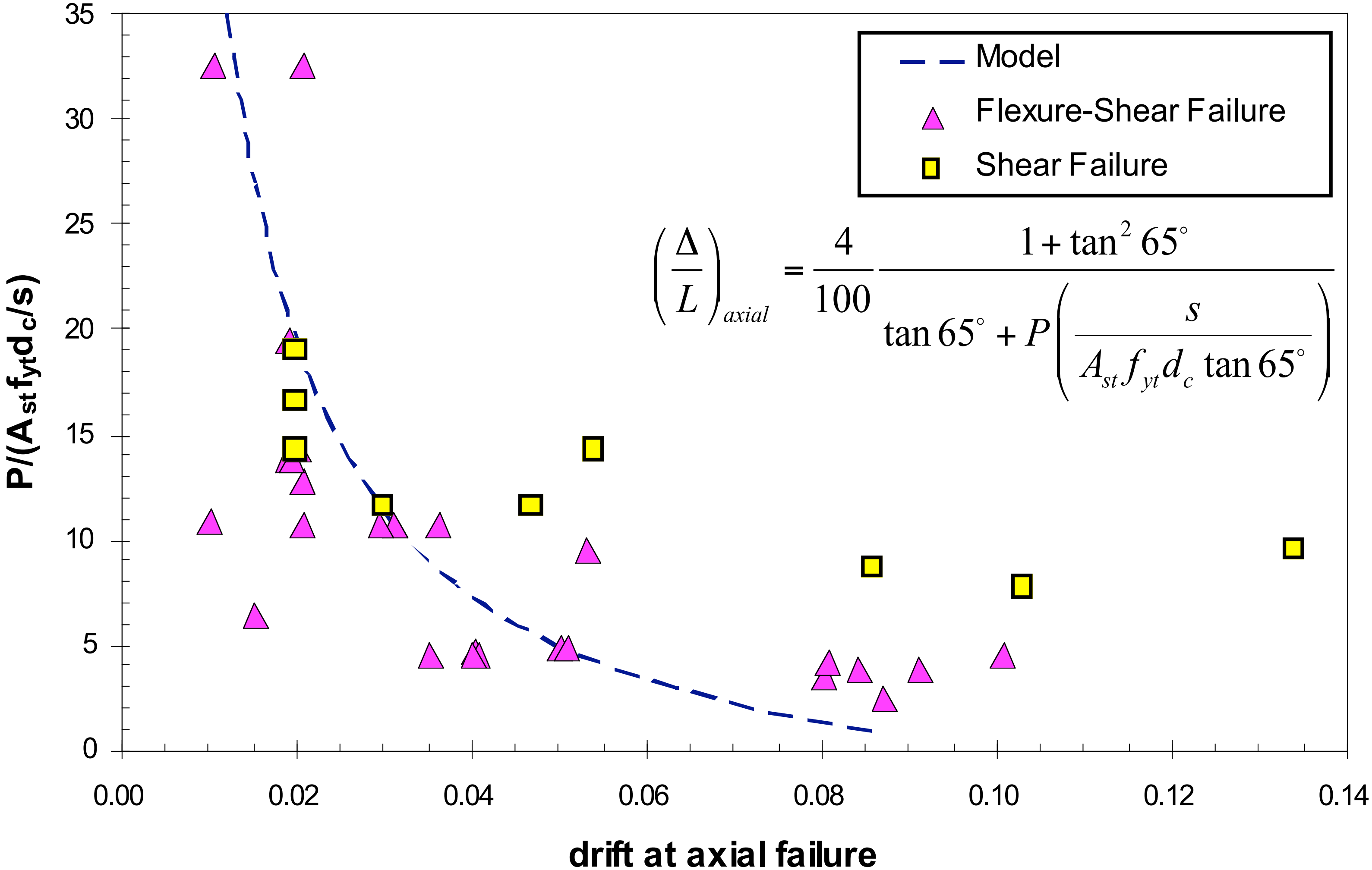
$$\theta \approx 65^o$$

μ *vs. Drift at axial failure*



Elwood and Moehle, 2005b

Drift at Axial Failure Model



Elwood and Moehle, 2005b

Drift models for flexural failures

- Flexural strength will degrade for columns with $V_p << V_o$ due to spalling, bar buckling, concrete crushing, etc.
- Several drift models have been developed:
  - Drift at onset of cover spalling:

$$\frac{\Delta_{spall}}{L} = 1.6(1 - \frac{P}{A_g f_c'})(1 + \frac{L}{10D})$$

(Berry and Eberhard, 2004)

  - Drift at bar-buckling:

$$\frac{\Delta_{bb}}{L} = 3.25(1 + k_e \frac{\rho_{vol} f_{yt}}{f_c'} \frac{d_b}{D})(1 - \frac{P}{A_g f_c'})(1 + \frac{L}{10D})$$

(Berry and Eberhard, 2005)

k_e: 50 for rectangular columns, 150 for spiral-reinforced columns

  - Drift at 20% reduction in flexural capacity:

$$\frac{\Delta_f}{L} = 0.049 + 0.716\rho_l + 0.120\frac{\rho'' f_{yt}}{f_c'} - 0.042\frac{s}{d} - 0.070\frac{P}{A_g f_c'}$$

(Zhu, 2005)

How to apply models…

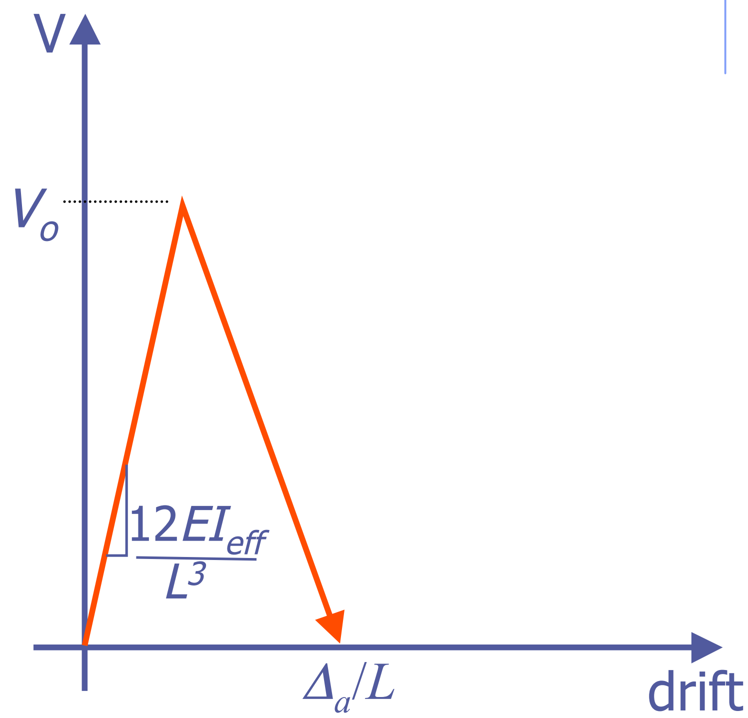
- First classify columns based on shear strength:
  - $V_p/V_o > 1.0$ → shear failure
  - $1.0 \geq V_p/V_o \geq 0.6$ → flexure-shear failure
  - $V_p/V_o < 0.6$ → flexure failure

$$\text{where} \quad V_o = \frac{6\sqrt{f_c'}}{a/d}\sqrt{1+\frac{P}{6\sqrt{f_c'}A_g}}\,0.8A_g + \frac{A_{st}f_{yt}d}{s}$$

$$V_p = \frac{2M_p}{L}$$

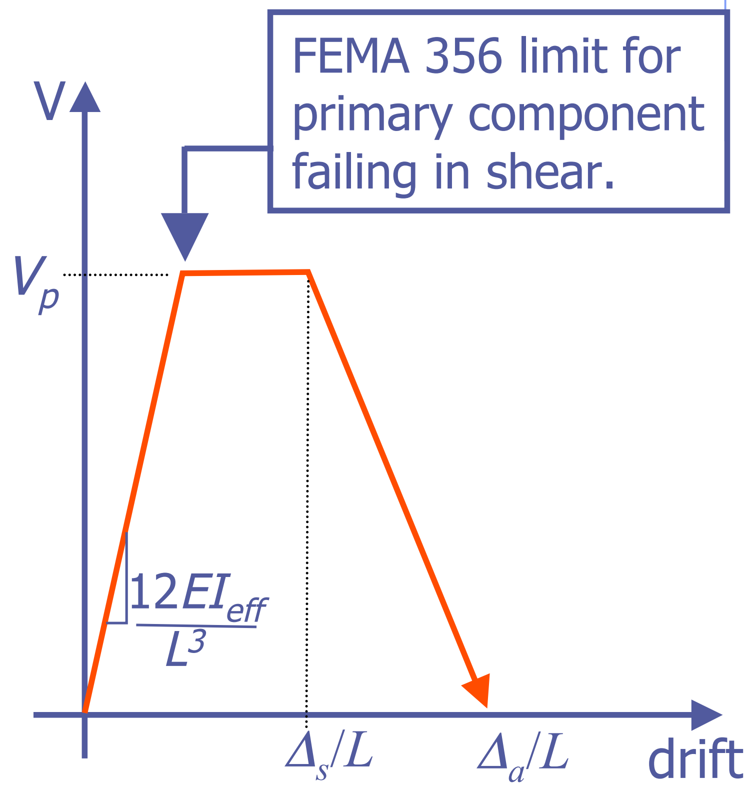
How to apply models…

- Shear failure
  - Force-controlled
  - Define drift at shear failure using effective stiffness and V_o.
    - May be conservative if $V_p \approx V_o$
  - Use drift at axial failure model to estimate Δ_a/L
    - Very little data available for drift at axial failure for this failure mode, but model provides conservative estimate in most cases.
  - Do not use as primary component if $V > V_o$



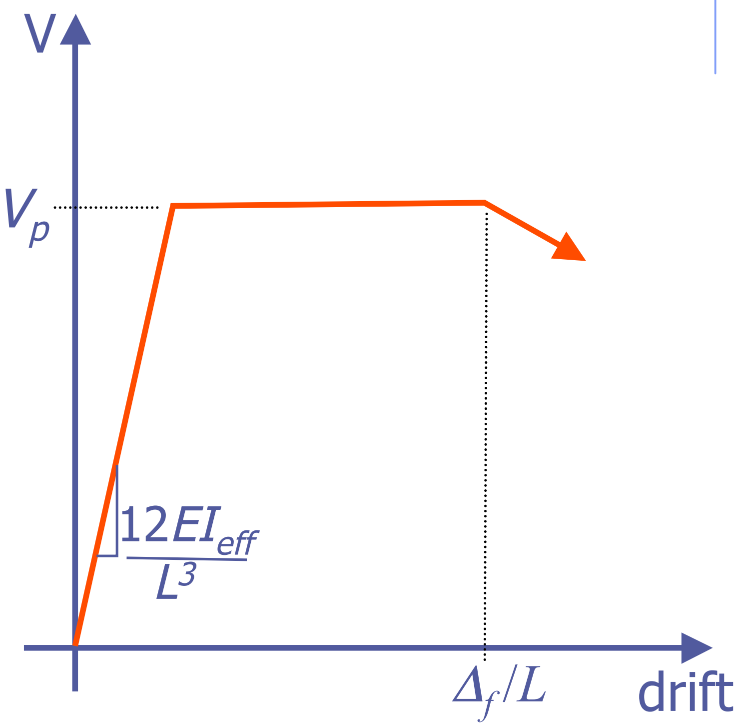
How to apply models…

- Flexure-Shear failure
  - Deformation-controlled
  - Max shear controlled by $2M_p/L$
  - Use drift at shear failure model to estimate Δ_s/L
  - Use drift at axial failure model to estimate Δ_a/L
  - Do not use as primary component if drift demand > Δ_s/L



How to apply models…

- Flexure failure
  - Deformation-controlled
  - Max shear controlled by $2M_p/L$
  - Use model for drift at 20% reduction in flexural capacity to estimate Δ_f/L
  - Do not use as primary component if drift demand > Δ_f/L
  - For low axial loads, axial failure not expected prior to P-delta collapse.
  - For axial loads above the balance point and light transverse reinforcement, column may collapse after spalling of cover.



Points to remember

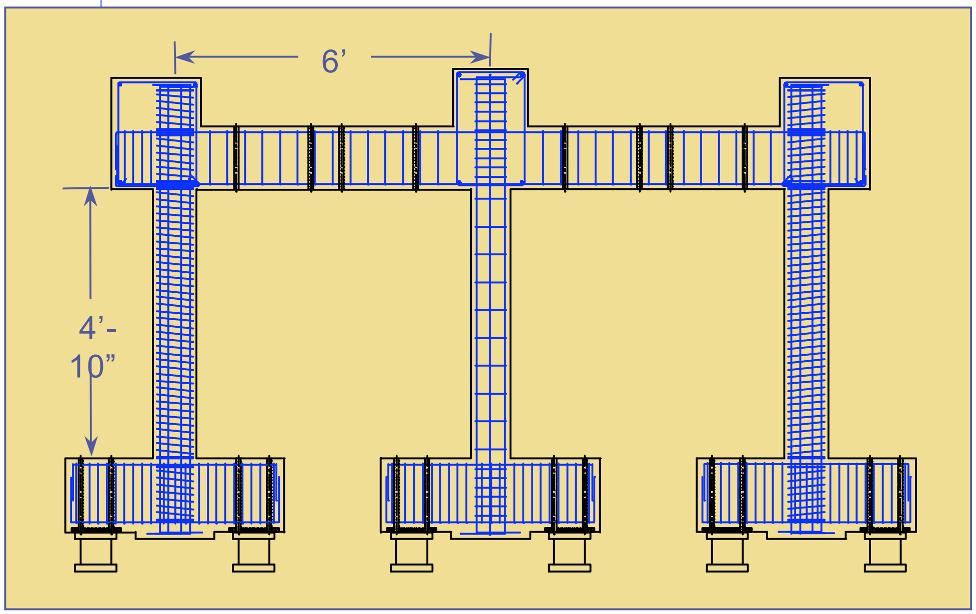
- Models provide an estimate of the **mean** response.
  - 50% of columns may fail at drifts less than predicted by the models.

Drift Model	Mean $\Delta_{meas}/\Delta_{calc}$	CoV $\Delta_{meas}/\Delta_{calc}$
Shear Failure	0.97	0.34
Axial Failure	1.01	0.39
Flexural Failure	1.03	0.27
Spalling	0.97	0.43
Bar Buckling	1.00	0.26

Points to remember

- Shear and axial failure models based on database of columns experiencing:
  - flexure-shear failures
  - uni-directional lateral loads
- All models except bar buckling and spalling only based on database of rectangular columns.
- Use caution when applying outside the range of test data used to develop the models!
- Shear and axial failure models are not coupled.
  - If calculated drift at axial failure is less than the calculated drift at shear failure, assume axial failure occurs immediately after shear failure.

Application of Drift Models – Shake Table Tests



Characteristics

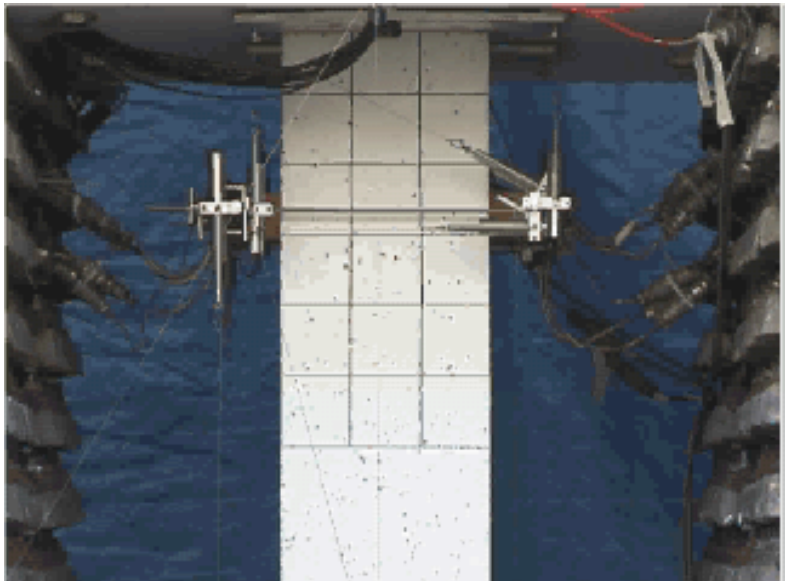
- Half-scale, three column planar frame
- Specimen 1:
  - Low axial load ($P = 0.10f'_cA_g$)
- Specimen 2:
  - Moderate axial load ($P = 0.24f'_cA_g$)

Objective

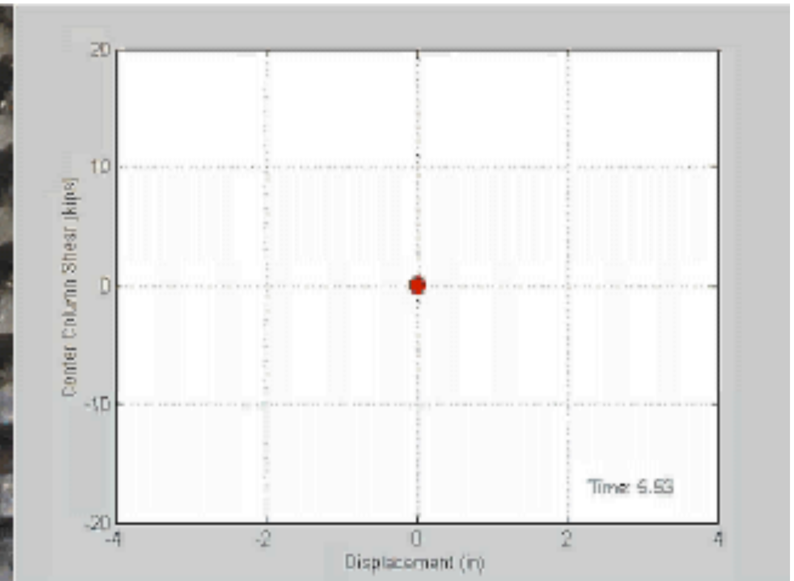
- To observe the process of dynamic shear and axial load failures when an alternative load path is provided for load redistribution

Specimen #1 – Low Axial Load

Top of Column - Total Displ.



Center Column Hysteresis

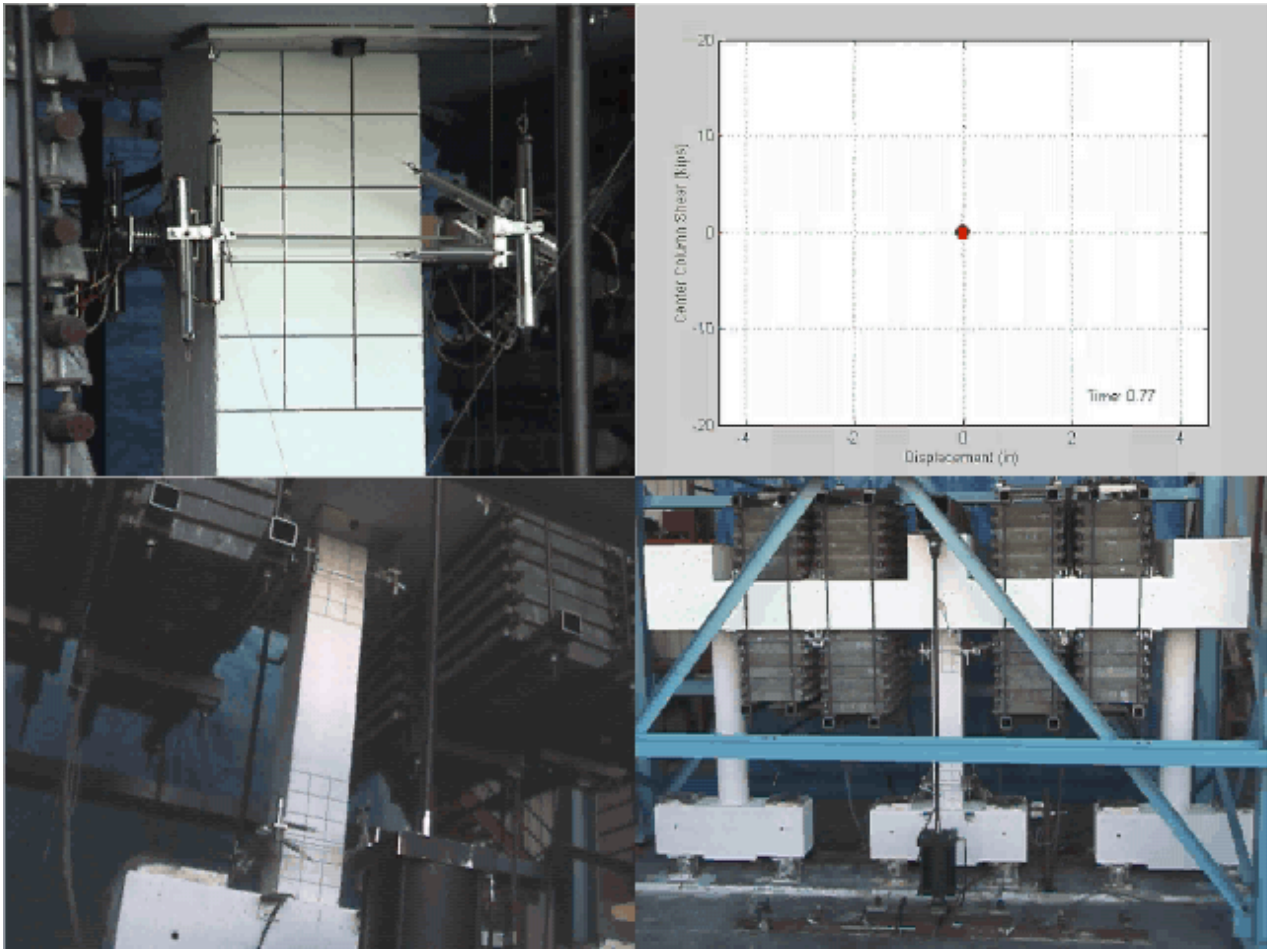


Center Column - Relative Displ.

Full Frame - Total Displ.

Specimen #2 – Moderate Axial Load

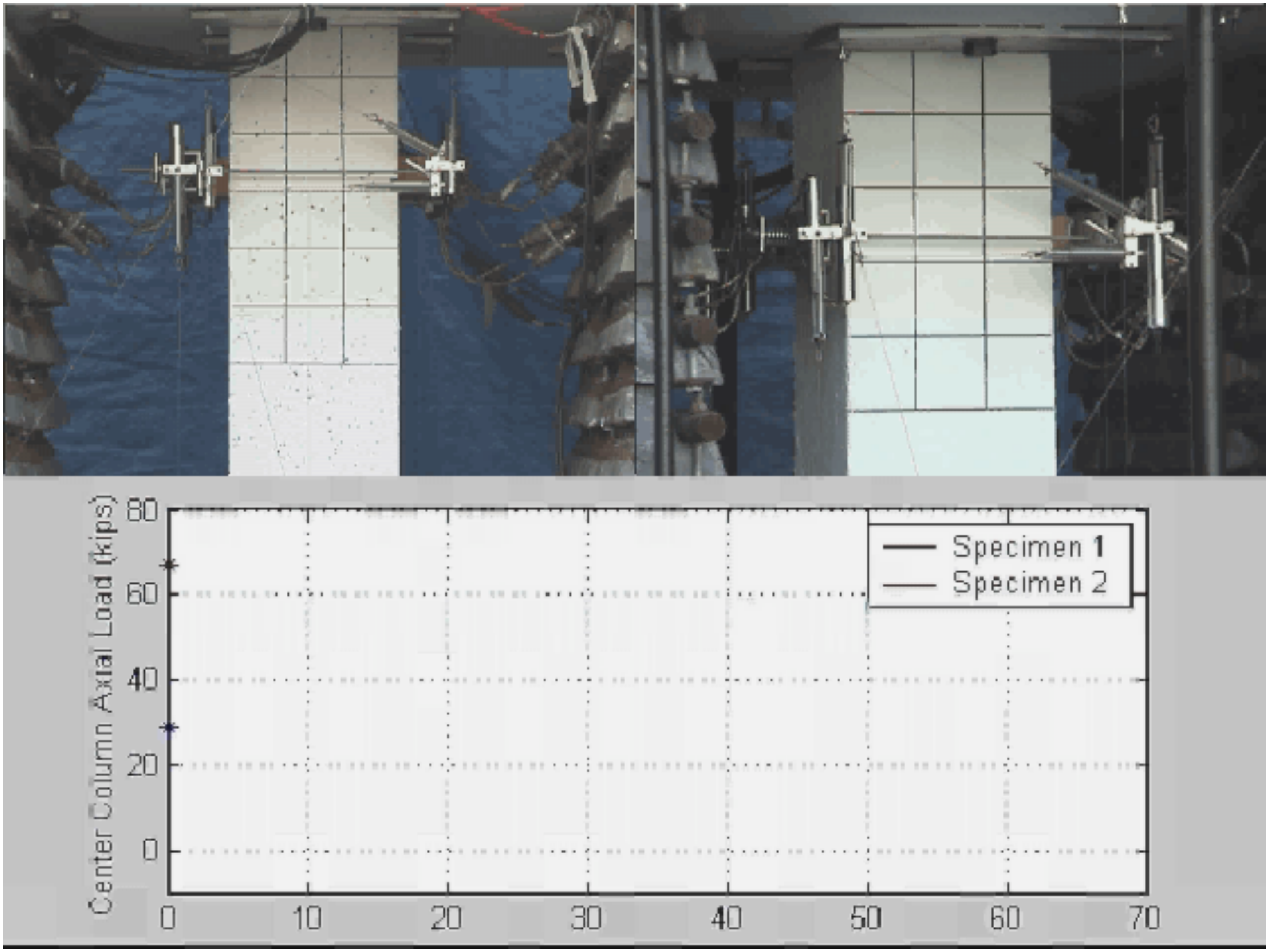
Top of Column - Total Displ. Center Column Hysteresis



Center Column - Relative Displ. Full Frame - Total Displ.

Axial Load Comparison

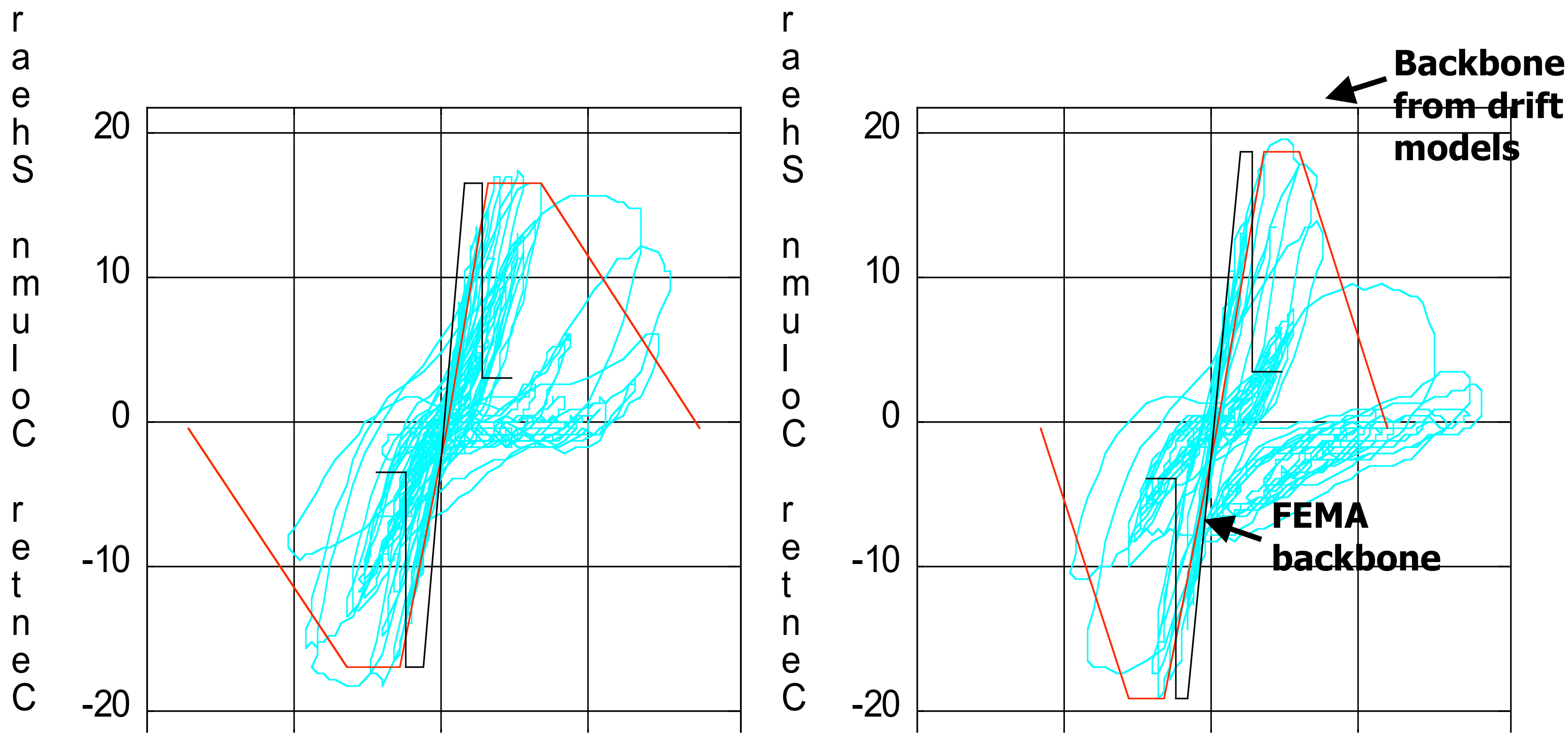
Low Axial Load (Spec 1) Moderate Axial Load (Spec 2)



Center Column Axial Load Time History

Application of Drift Models – Shake Table Tests

$P = 0.10f'_c A_g$ **$P = 0.24f'_c A_g$**



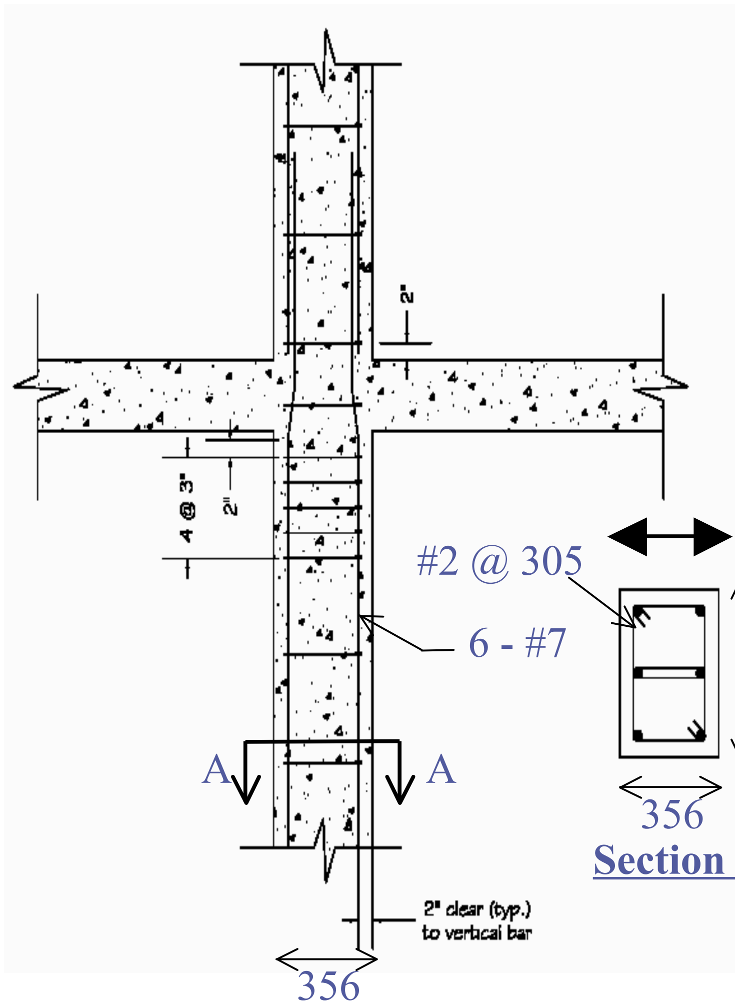
Elwood and Moehle, 2003

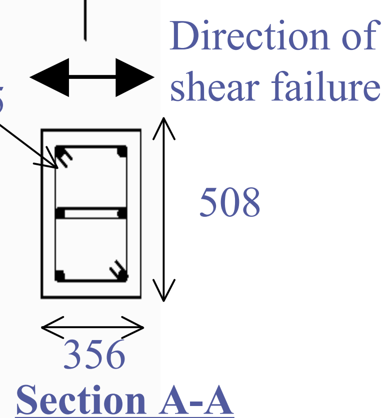
Application of Drift Models – Van Nuys, Holiday Inn

- 7-story reinforced concrete frame building (1965)
- Damaged during San Fernando and Northridge Earthquakes

Did columns sustain axial load failures?

Application of Drift Models – Van Nuys, Holiday Inn





Column C4 Properties:

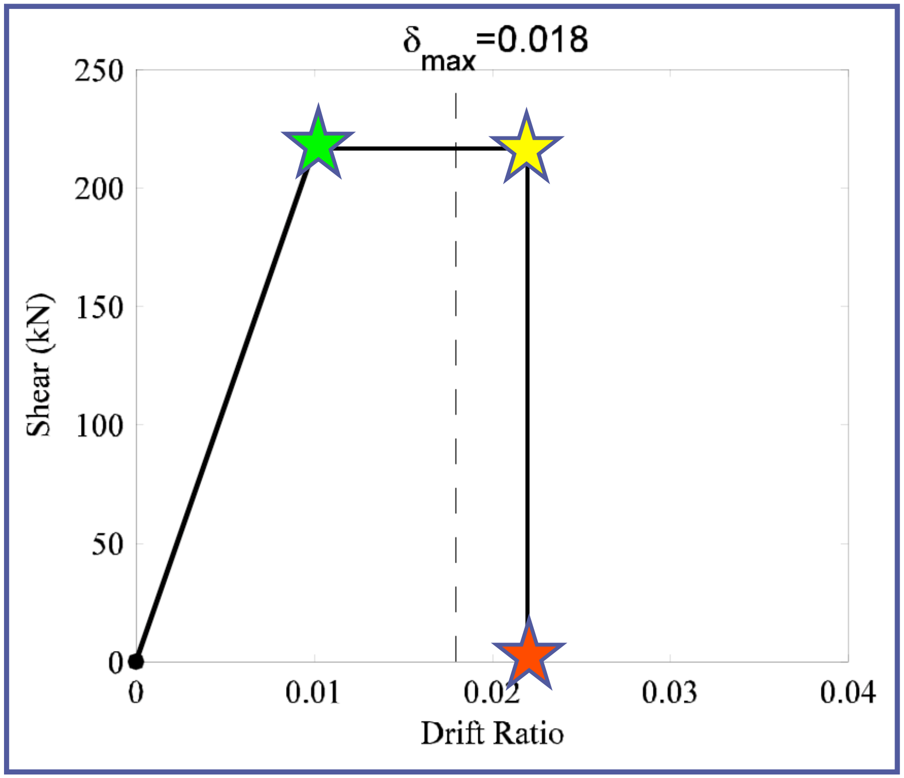
$f_{y\ long}$ =	496 MPa
$f_{y\ trans}$ =	345 MPa
f'_c =	28 MPa
P =	$0.13\ A_g f'_c$
L =	2.08 m

Application of Drift Models – Van Nuys, Holiday Inn

Fourth story column:

Max. interstory drift ≥ 0.018

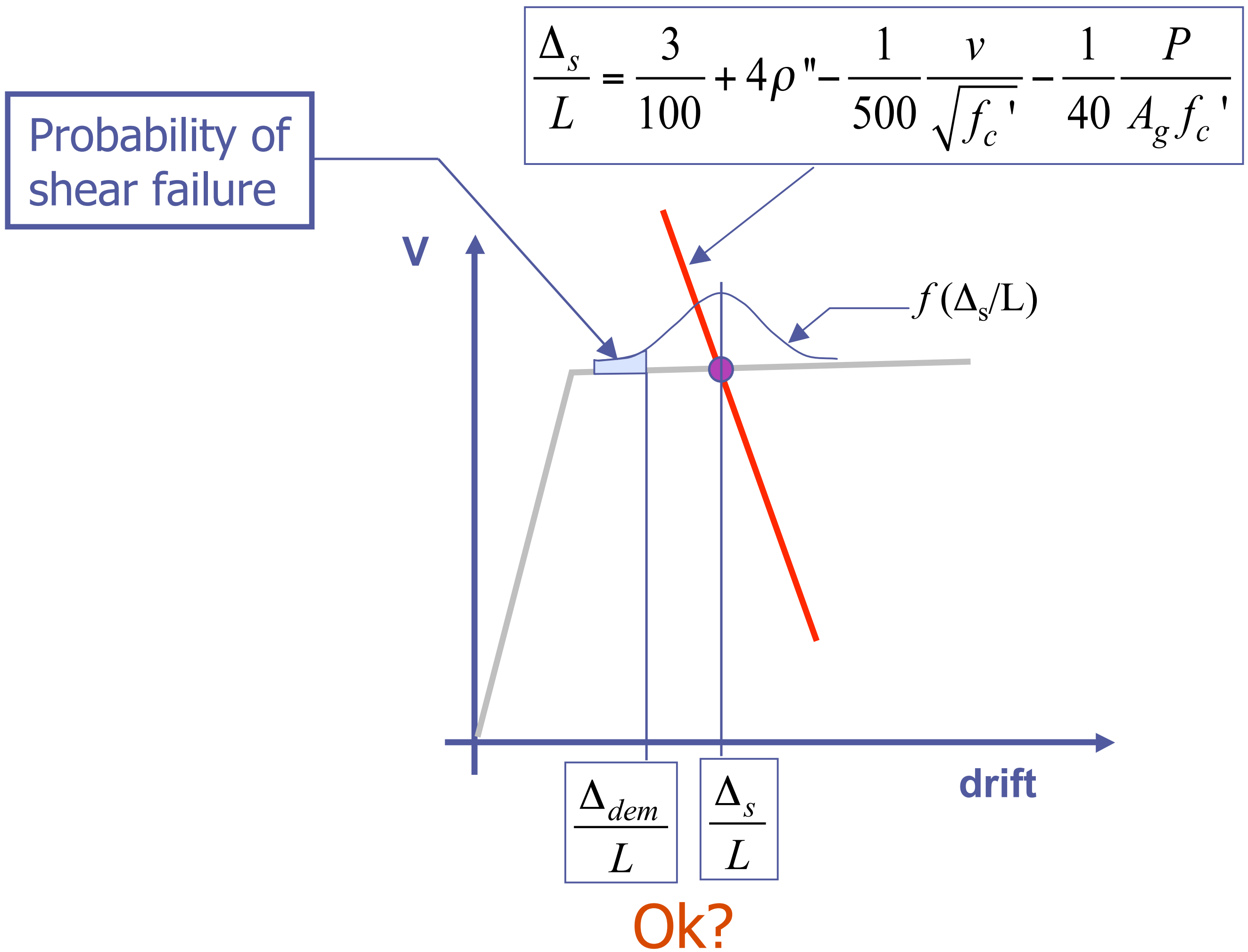
Interpolated from recorded motions on third and sixth floors → Lower Bound



Axial load failure expected to follow rapidly after shear failure.

Elwood and Moehle, 2004

Need for probabilistic model



Probabilistic Drift Capacity Models

- Median prediction of drift at shear failure:

$$\left(\frac{\Delta_s}{L}\right)_{median} = 2.02\rho'' - 0.025\frac{s}{d} + 0.013\frac{a}{d} - 0.031\frac{P}{A_g f_c'}$$

- Median prediction of drift at flexural failure:

$$\left(\frac{\Delta_f}{L}\right)_{median} = 0.049 + 0.716\rho_l + 0.120\frac{\rho'' f_{yt}}{f_c'} - 0.042\frac{s}{d} - 0.070\frac{P}{A_g f_c'}$$

- Median prediction of drift at axial failure:

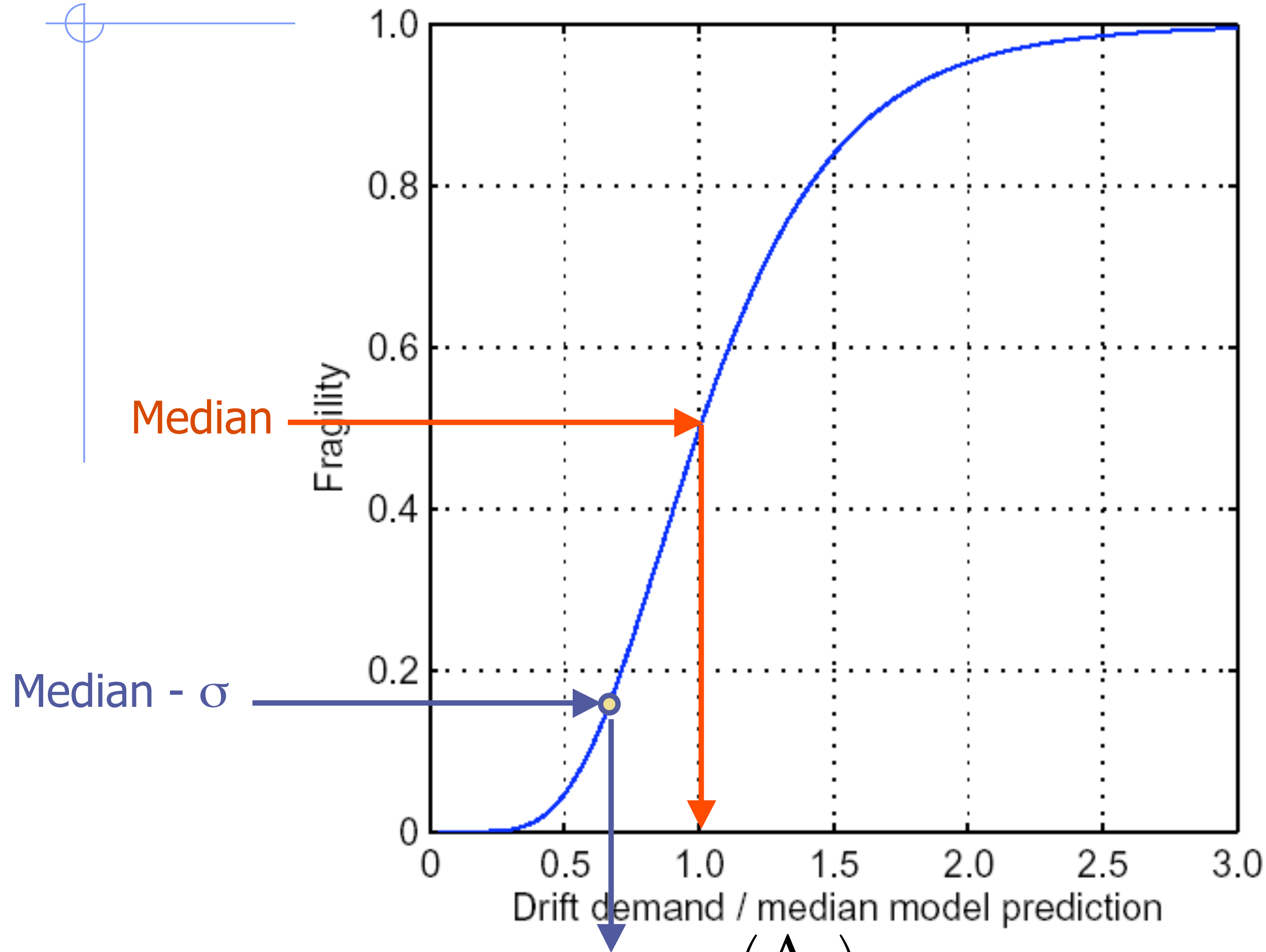
$$\left(\frac{\Delta_a}{L}\right)_{median} = 0.184\exp\left(-1.45\mu\right)$$

$$\mu = \frac{\dfrac{P}{A_{st} f_y d_c / s} - 1}{\dfrac{P}{A_{st} f_y d_c / s}\dfrac{1}{\tan\theta} + \tan\theta}$$

Now have distributions on coefficients, capturing uncertainty in model!!

Zhu, 2005

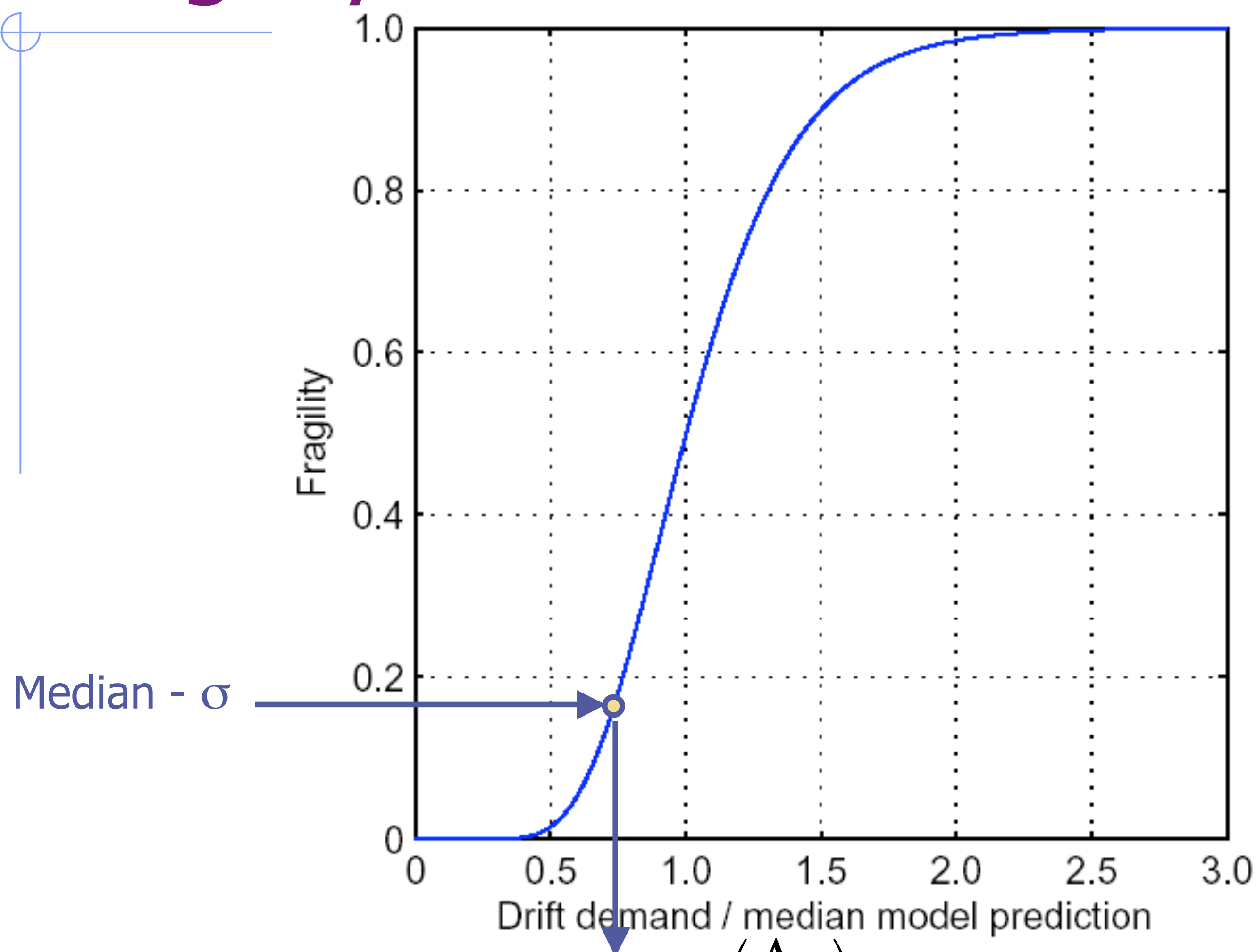
Fragility curves – Shear Failure



$$\text{Drift limit} = 0.64 \times \left(\frac{\Delta_s}{L} \right)_{median}$$

Zhu, 2005

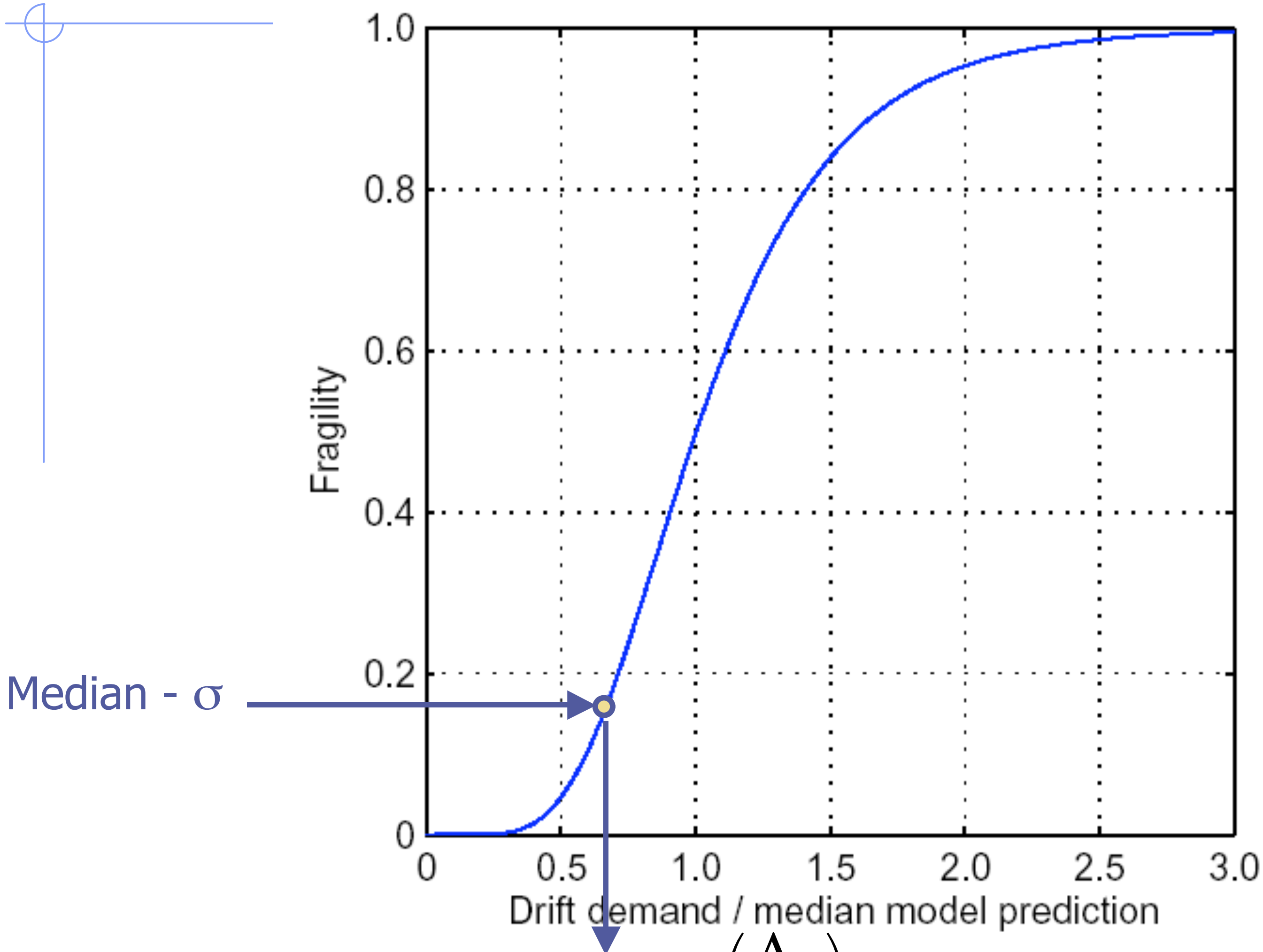
Fragility curves – Flexural Failure



Drift limit $= 0.72 \times \left(\frac{\Delta_f}{L} \right)_{median}$

Zhu, 2005

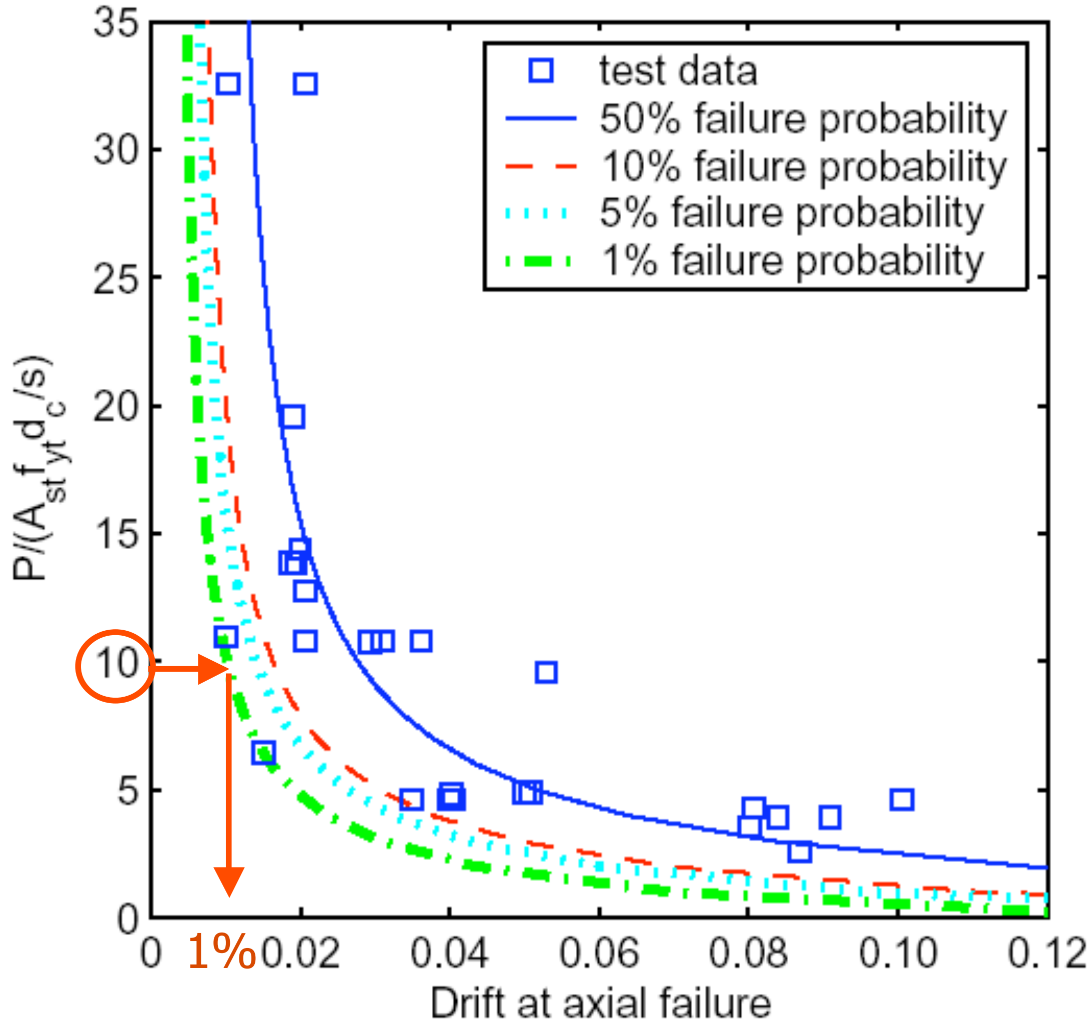
Fragility curves – Axial Failure



$$\text{Drift limit} = 0.64 \times \left(\frac{\Delta_a}{L}\right)_{median}$$

Zhu, 2005

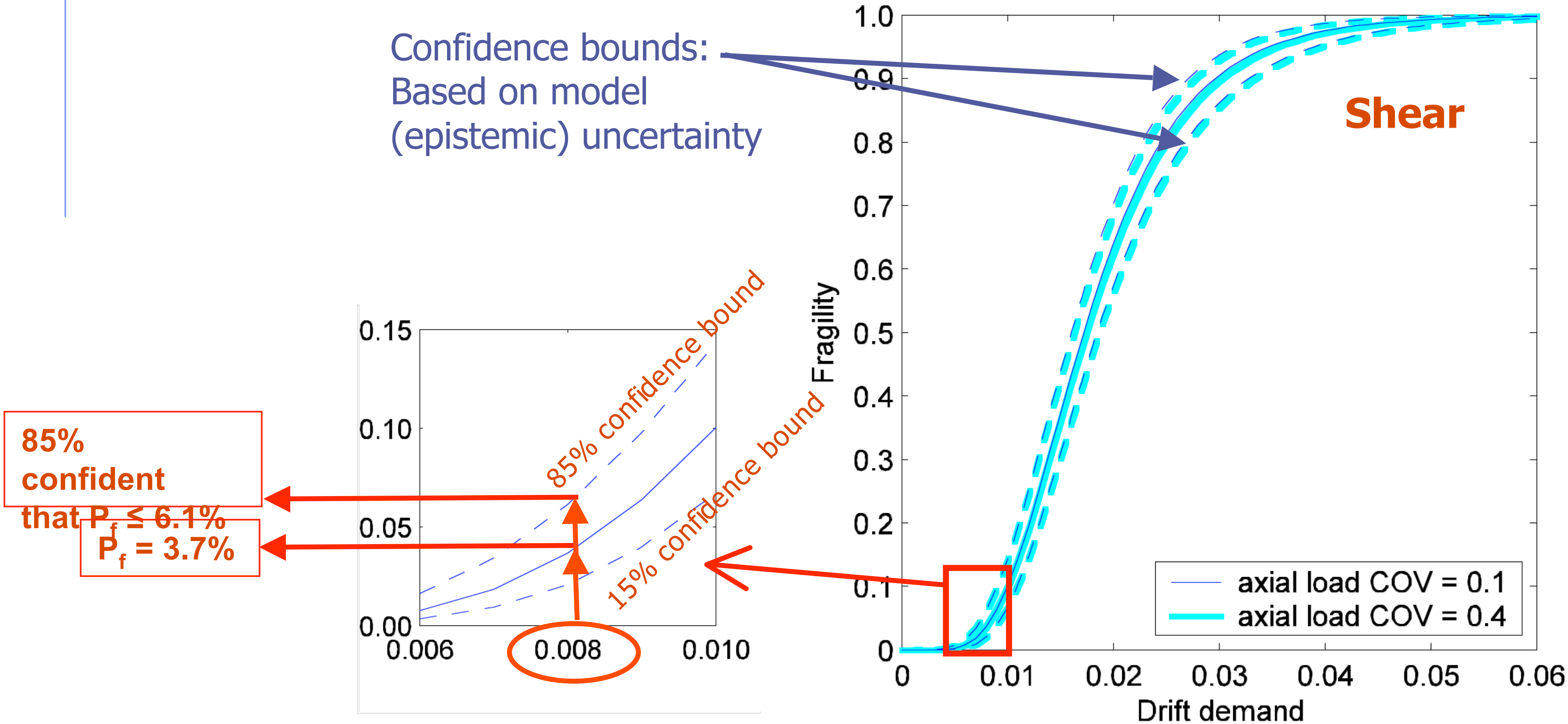
Probabilistic model for drift at axial failure



Zhu, 2005

Application of Probabilistic Drift Capacity Model

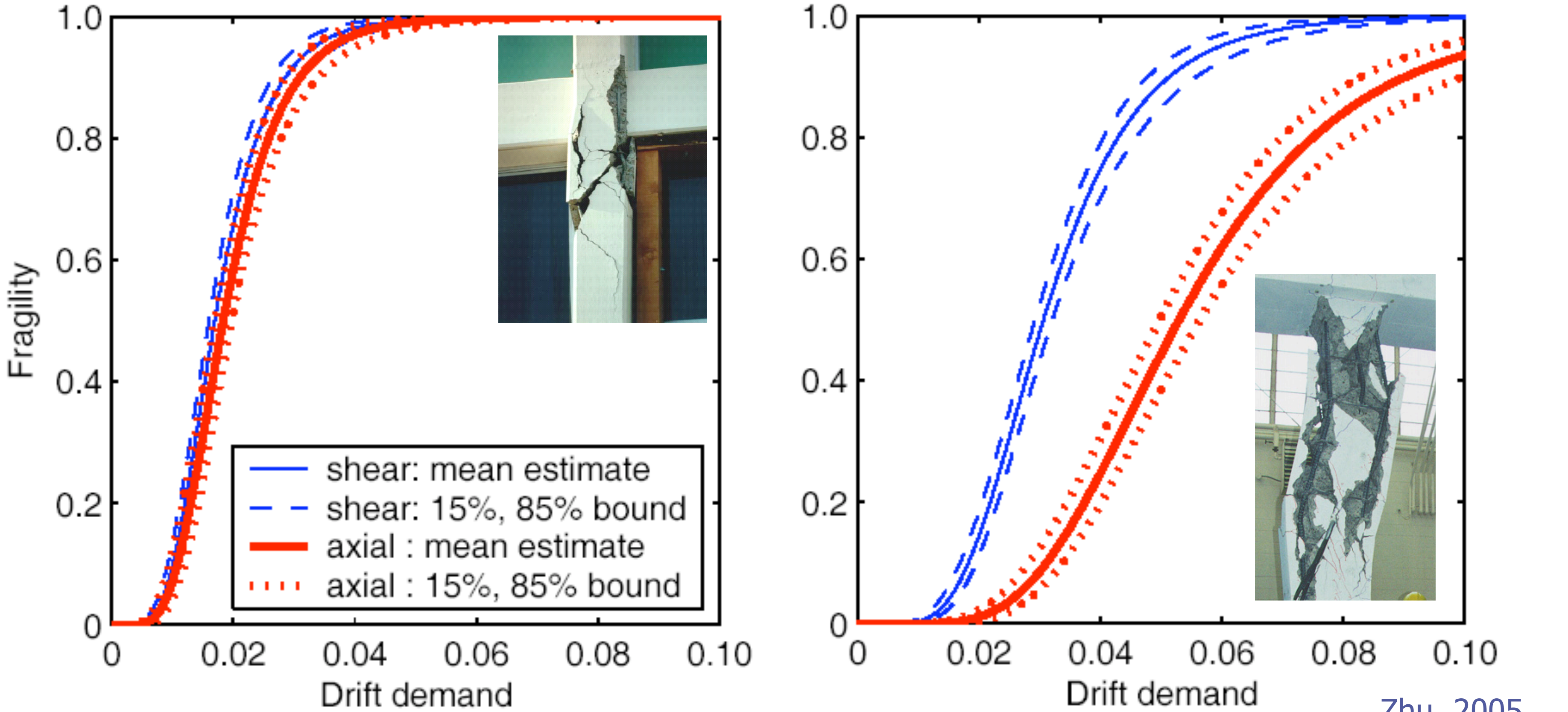
- The probabilistic drift capacity model is used to develop a fragility estimate for column from Van Nuys, Holiday Inn.



Zhu et al., 2006

Application of Probabilistic Drift Capacity Model

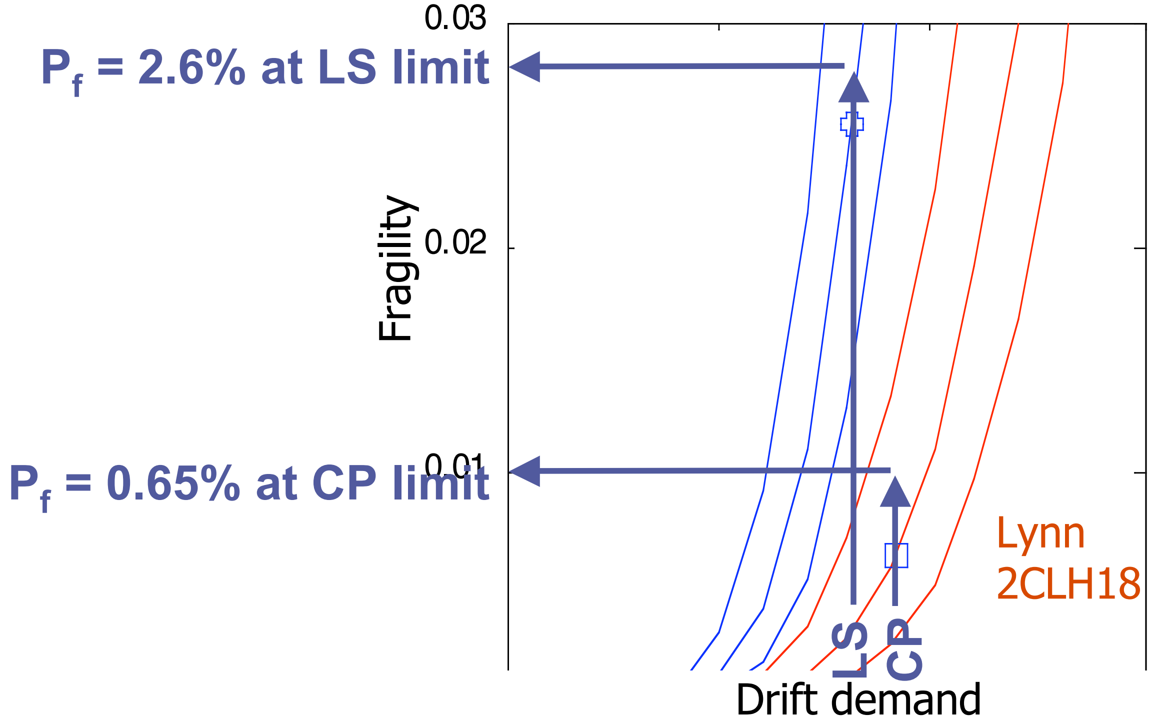
- The relation between the fragility curves of shear failure and axial failure gives useful information regarding the column axial load capacity after shear failure.



Zhu, 2005

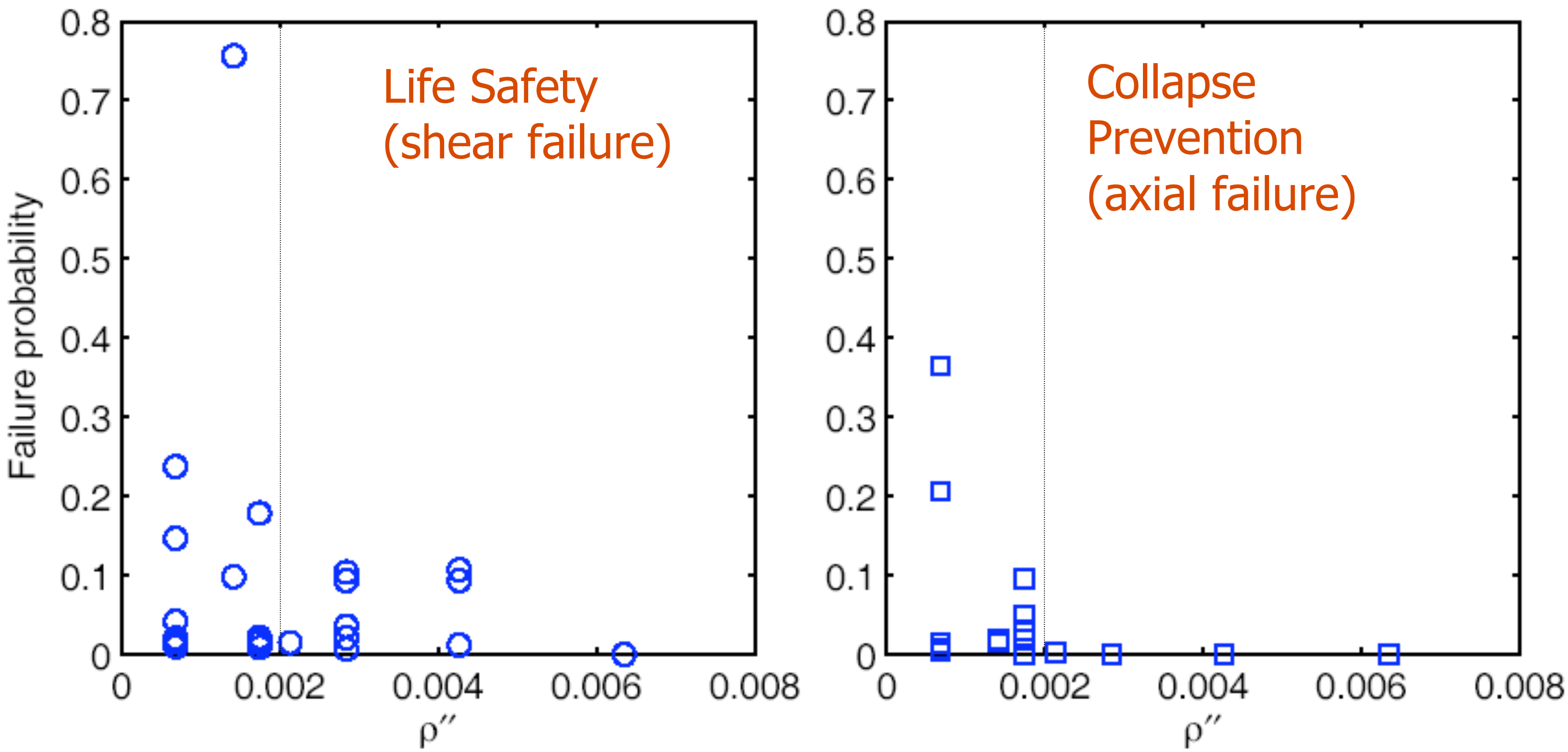
Assessment of FEMA 356

- Probabilistic models can be used to assess the probability of failure implied by drift limits in FEMA 356.
  - "Shear-controlled" response
  - Δ_s/L model compared with LS criteria for secondary components
  - Δ_a/L model compared with CP criteria for secondary components



Zhu, 2005

Assessment of FEMA 356

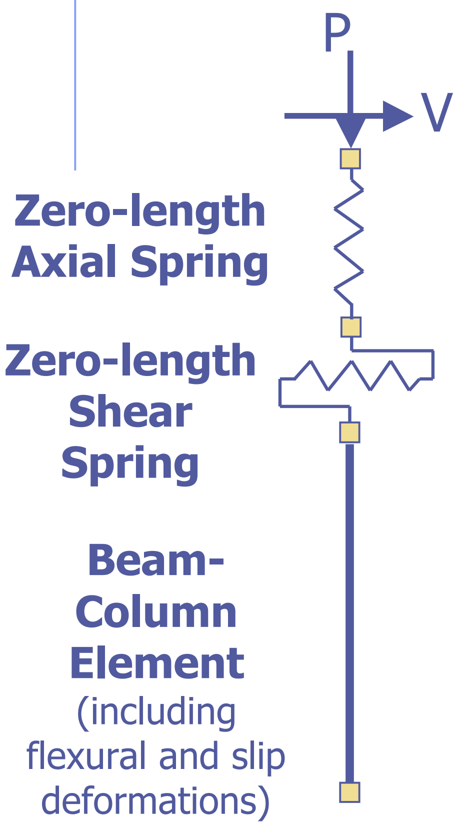


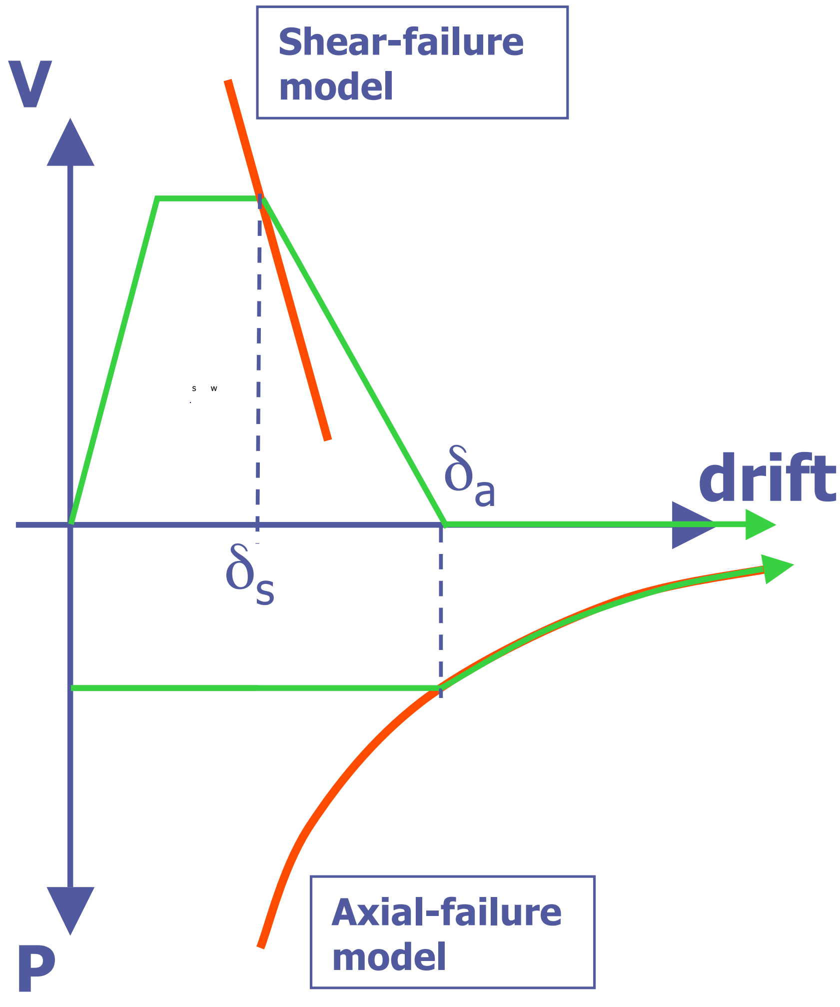
Level of safety provided is not consistent for all columns.

Is this level of safety appropriate?

Zhu, 2005

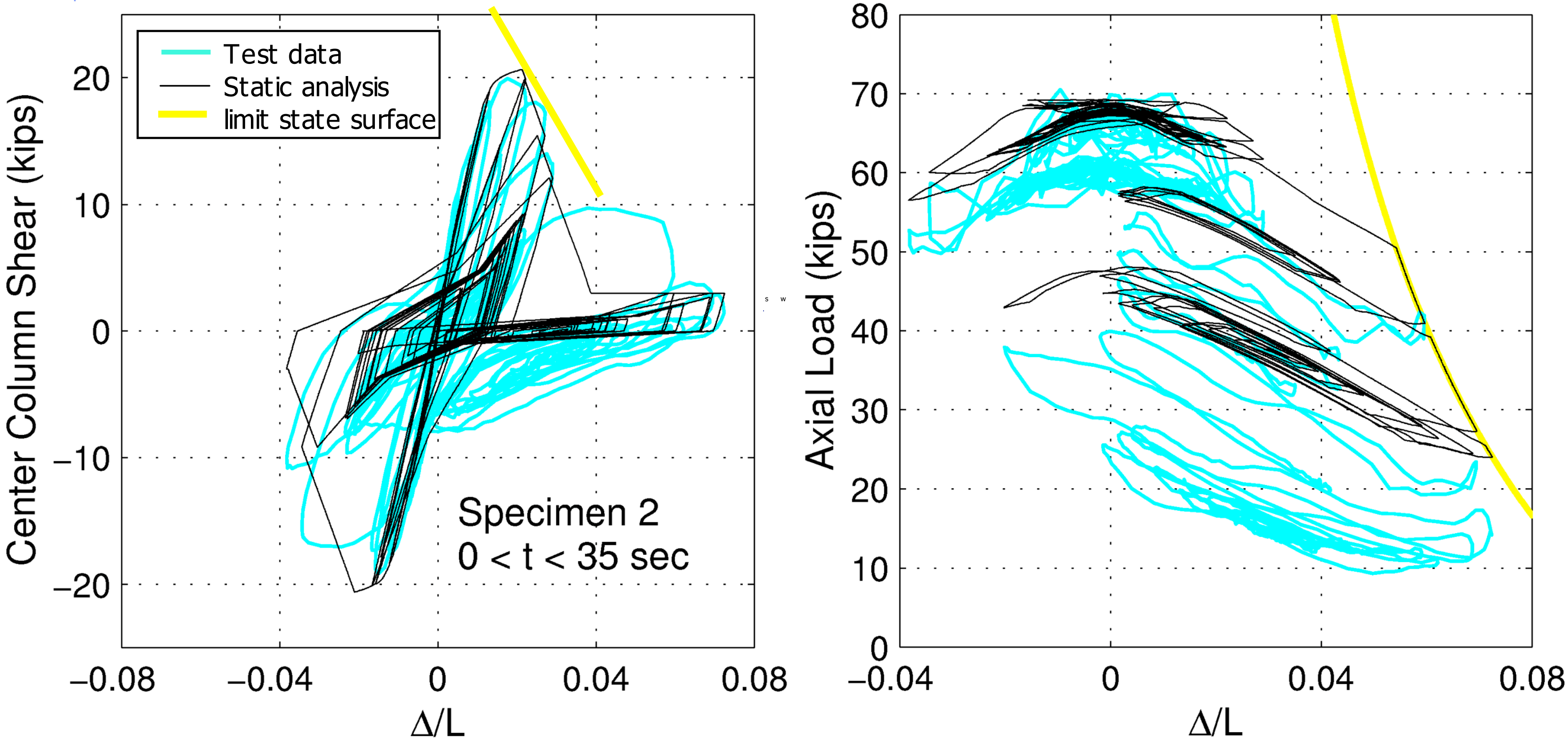
Analytical Model for Shear-Critical Columns





Elwood, 2004

Analytical Model for Shear-Critical Columns



Elwood, 2004

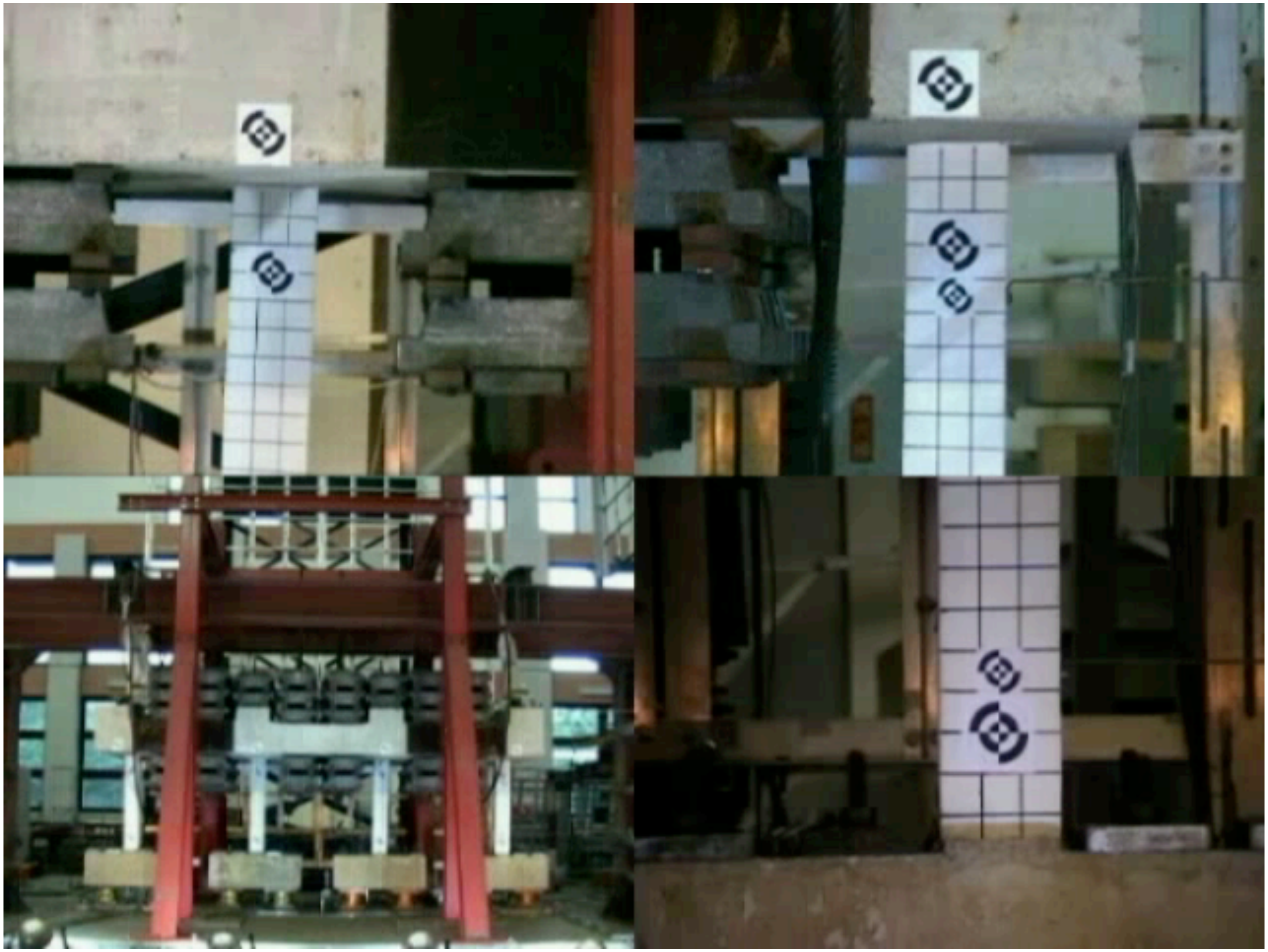
Benchmark Shake Table Tests

NCREE, Taiwan, 2005

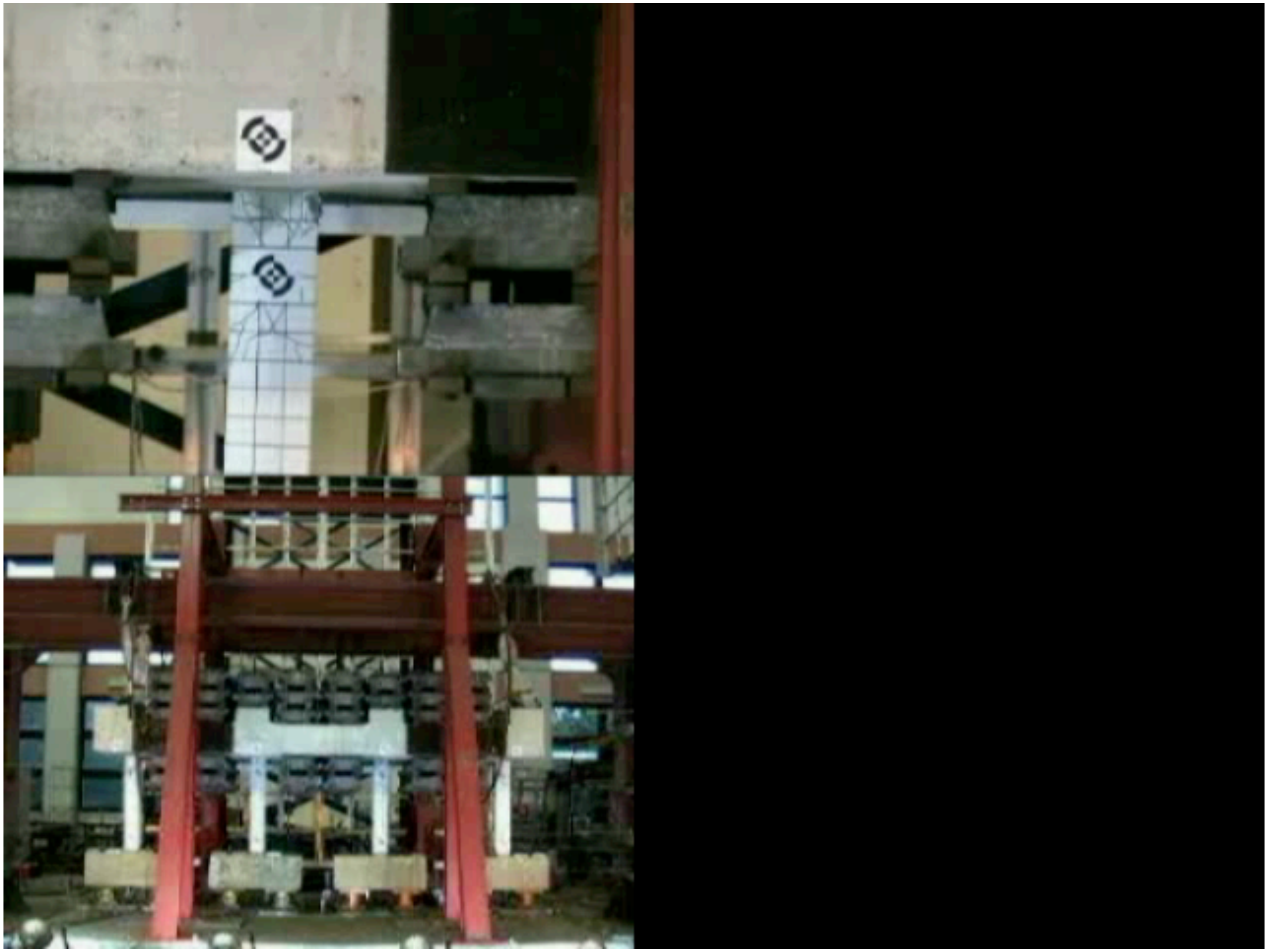
E-Defence, Japan, 2006

PEER, 2006

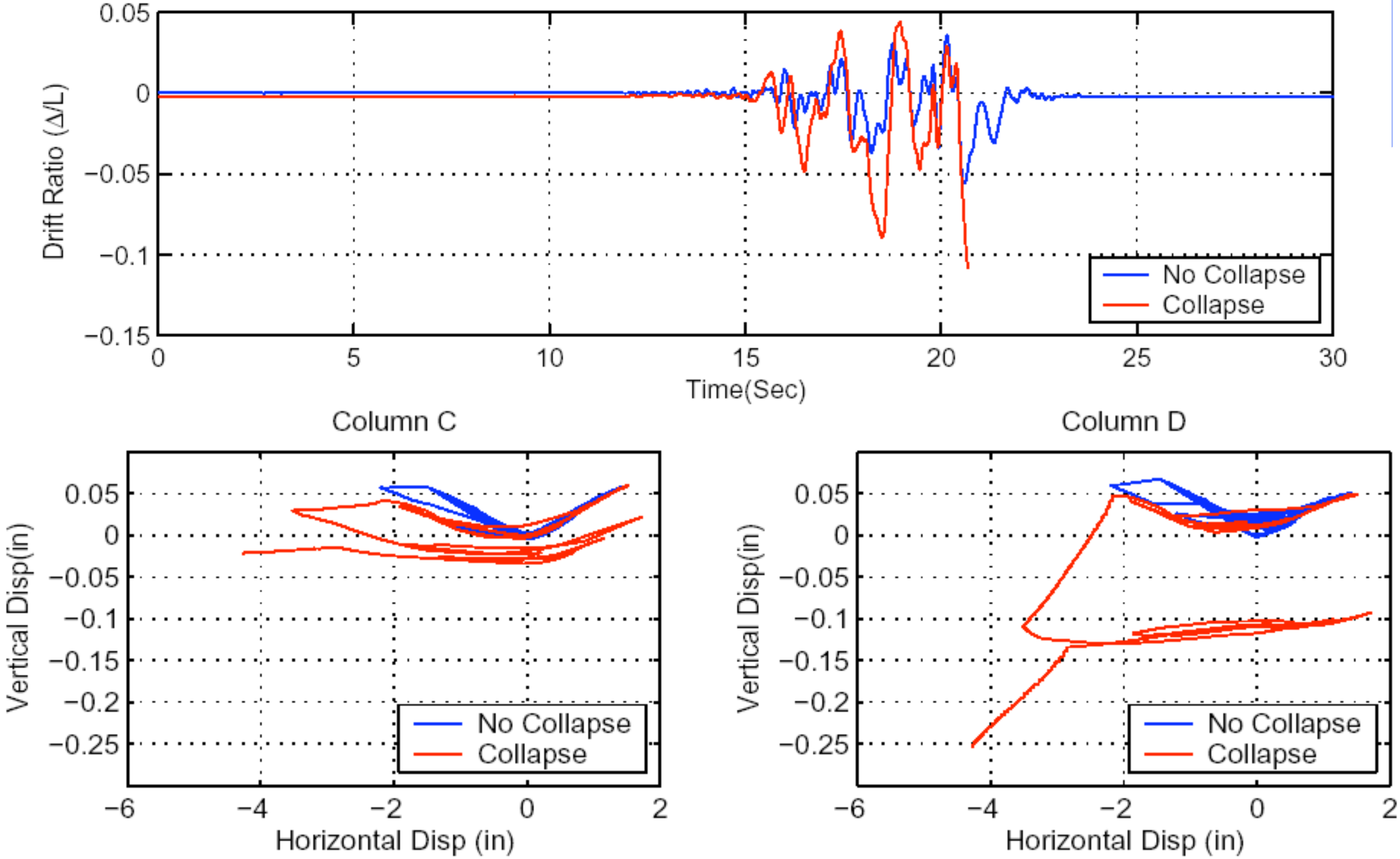
NCREE Shake Table Test 1



NCREE Shake Table Test 2

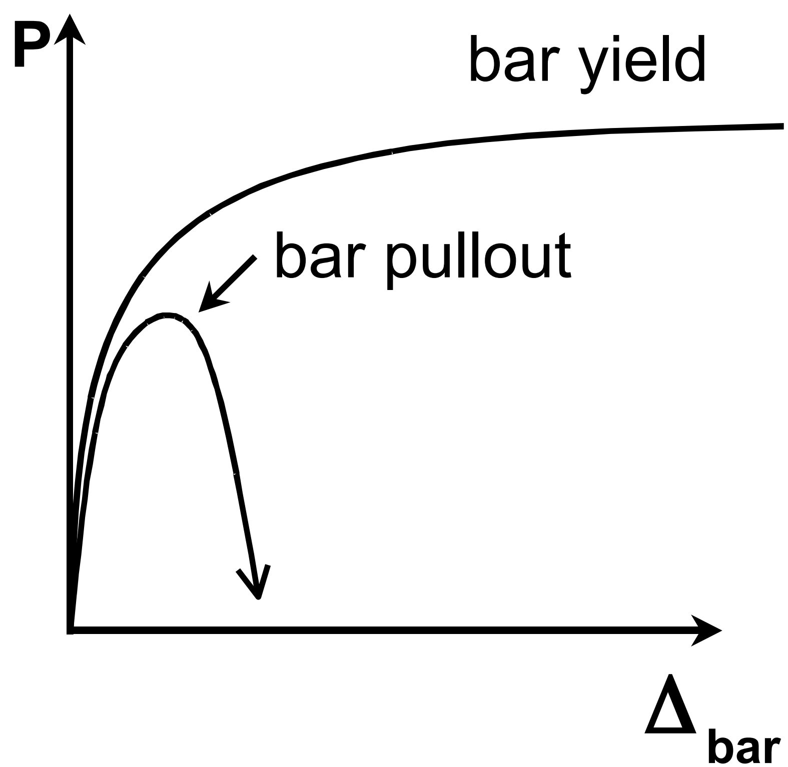


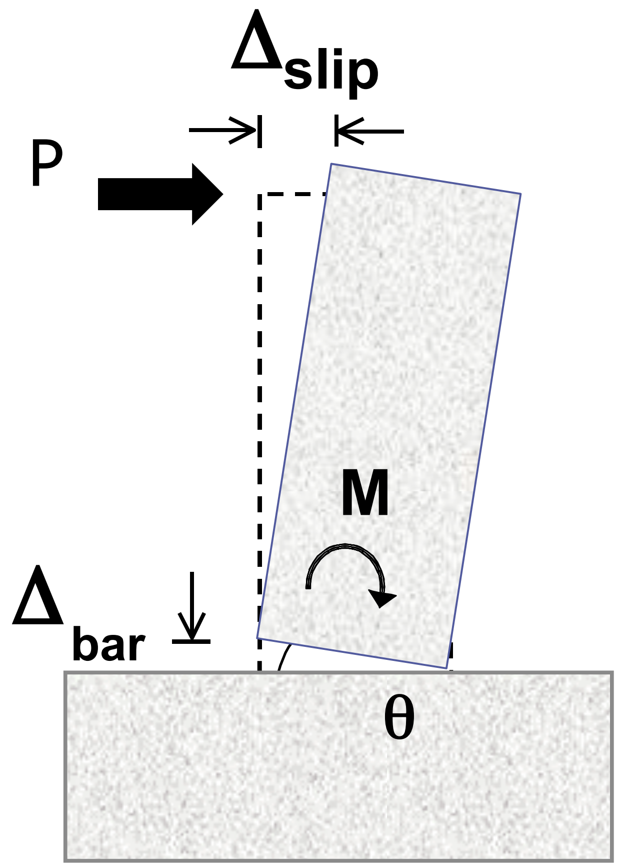
Analysis using OpenSees



Lap Splice Failures

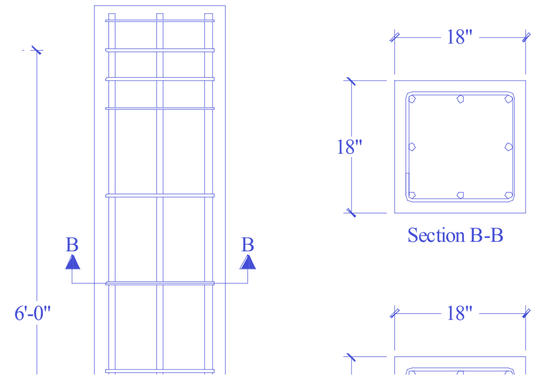
Effect of poor lap splices





Melek and Wallace (2004)

- **Six Full-Scale Specimens**
  - **18 in. square column**
  - **8 – #8 longitudinal bars**
  - **#3 ties with 90° hooks**
  - **$20d_b$ lap splice**
- **Tested with Lateral and Axial Load**
  - **Lateral Load**
    - **Standard Loading History**
    - **Near Field Loading History**
  - **Axial Load**
    - **Constant**



Melek and Wallace (2004)

Test Matrix

Specimen	Splice $20d_b$	Axial Load $\% A_g f'_c$	Shear $(V_u @ M_{EXP})/V_n$	Load History	Hoop Spacing (inch)	Column Height
S10MI	YES	10	0.67	STD	12	6'- 0"
S20MI	YES	20	0.70	STD	12	6'- 0"
S30MI	YES	30	0.78	STD	12	6'- 0"
S20HI	YES	10	0.82	STD	12	5'- 6"
S20HIN	YES	20	0.81	NEAR	12	5'- 6"
S30XI	YES	30	0.93	STD	12	5' - 0"

[illegible]

[illegible] (12-1) ACI-318-99

Melek and Wallace (2004)

Experimental Results

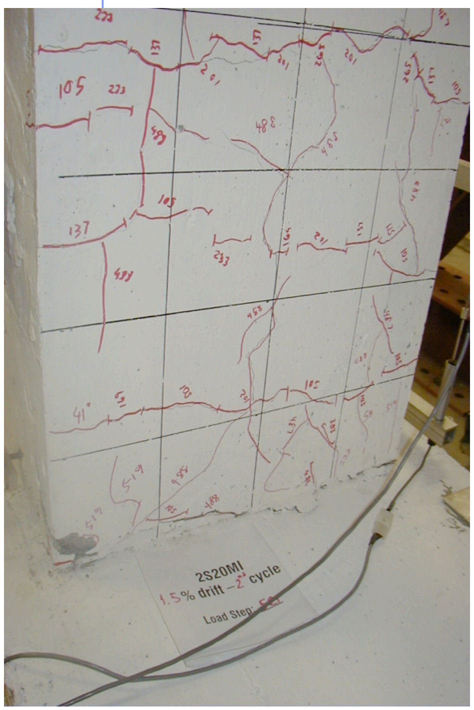
Specimen	Maximum Lateral Load (kips)	Lateral Strength Degradation at	Type of Failure	Applied Axial Load (kips)	Axial Capacity Lost?
S10MI	45.56	1.50% Drift	Bond Det.	120	No
S20MI	52.49	1.28% Drift	Bond Det.	240	Yes @ 7% Drift
S30MI	64.14	1.45% Drift	Bond Det.	360	Yes @ 5% Drift
S20HI	55.53*	1.33% Drift	Bond Det.	240	Yes @ 7% Drift
S20HIN	55.10*	1.00% Drift	Bond Det.	240	No
S30XI	63.82*	1.50% Drift	Bond Det.	360	Yes @ 5% Drift

*normalized

Melek and Wallace (2004)

Observed Damage

Specimen: S20MI



1.5% Drift
Splice Deterioration
(F_{ult}=53 kips)

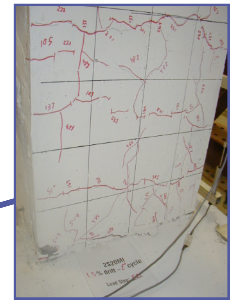
3% Drift

5% Drift

7% Drift
Axial Load
Capacity Lost

Melek and Wallace (2004)

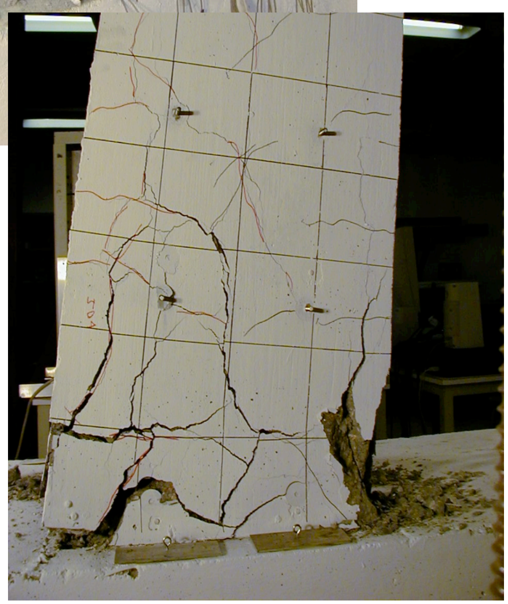
S10MI – S20MI – S30MI



Melek and Wallace (2004)

S20MI – S20HI – S20HIN

Axial Load Capacity



S20MI, S20HI, S30MI, S30XI

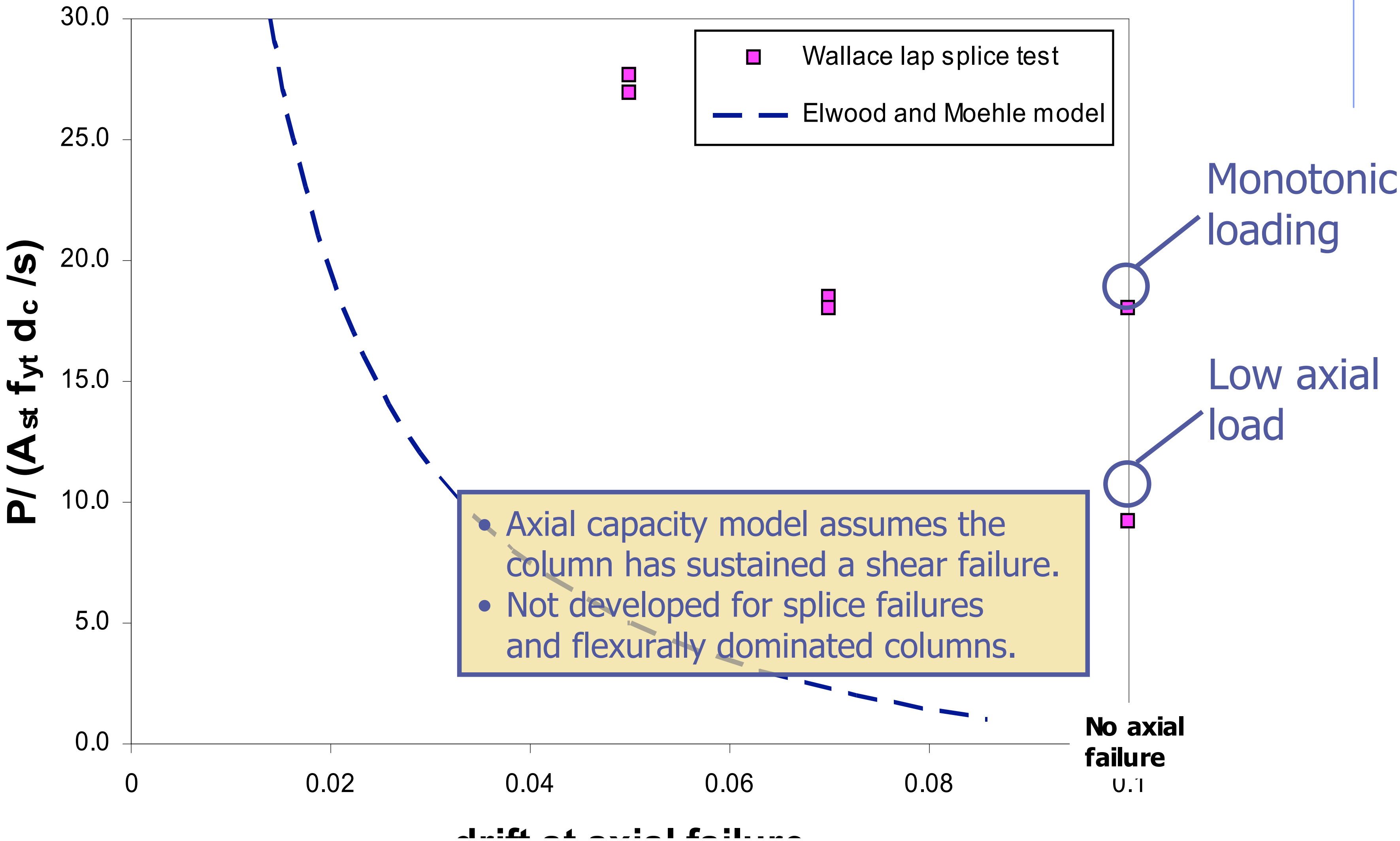
- Axial load capacity lost due to buckling of longitudinal bars
- 90° ties at 4” and 16” above pedestal opened up
- Concrete cover lost

S20HIN – Axial Load Capacity Maintained

- Near Fault Displacement History (Less cycles)
- Concrete cover intact

Melek and Wallace (2004)

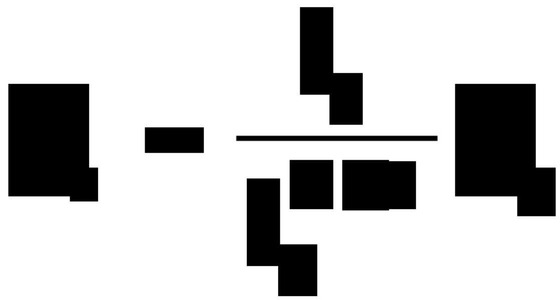
Axial load capacity



- Axial capacity model assumes the column has sustained a shear failure.
- Not developed for splice failures and flexurally dominated columns.

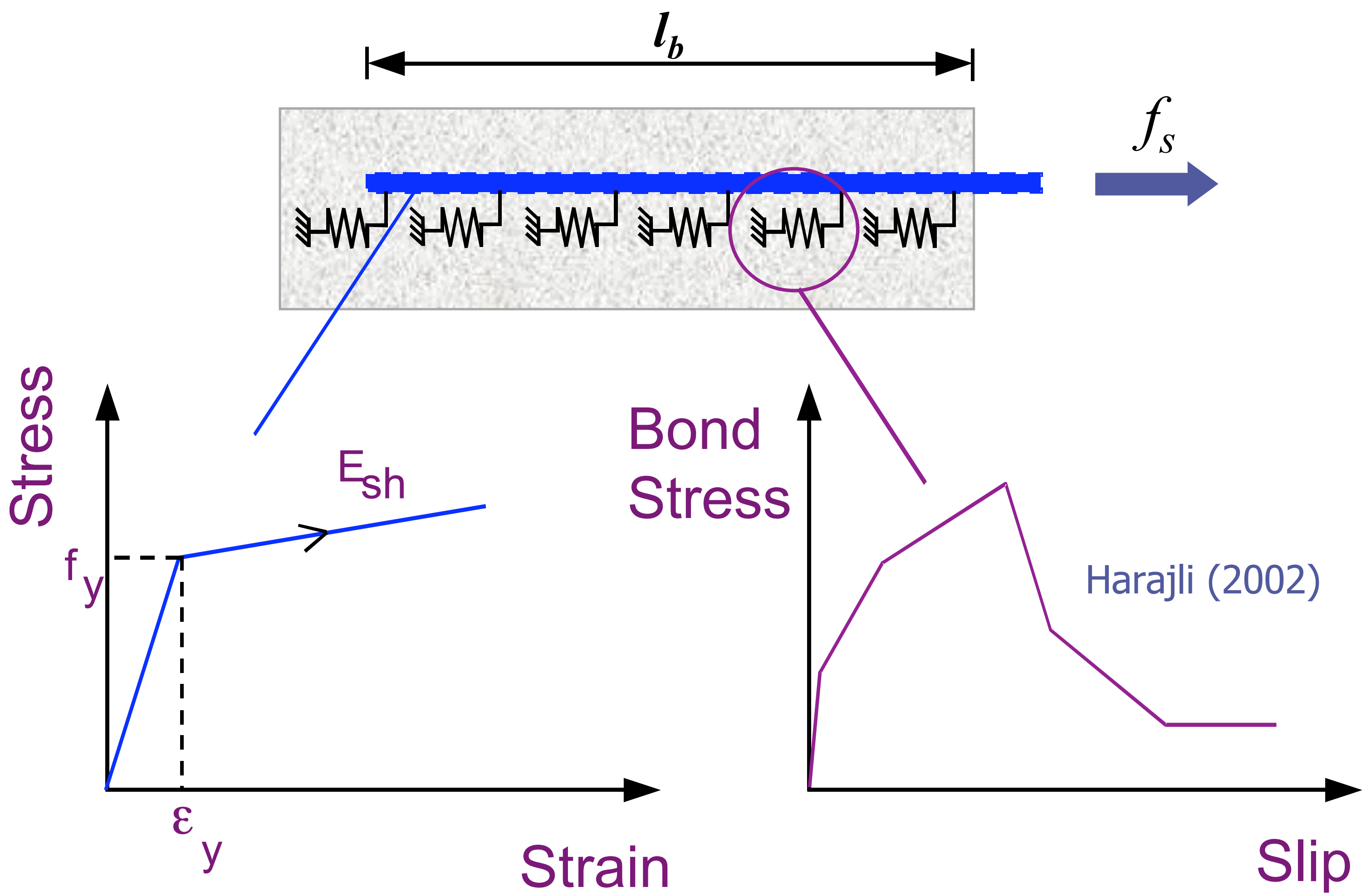
FEMA 356 lap splice provisions

- Adjust yield stress based on lap splice length:



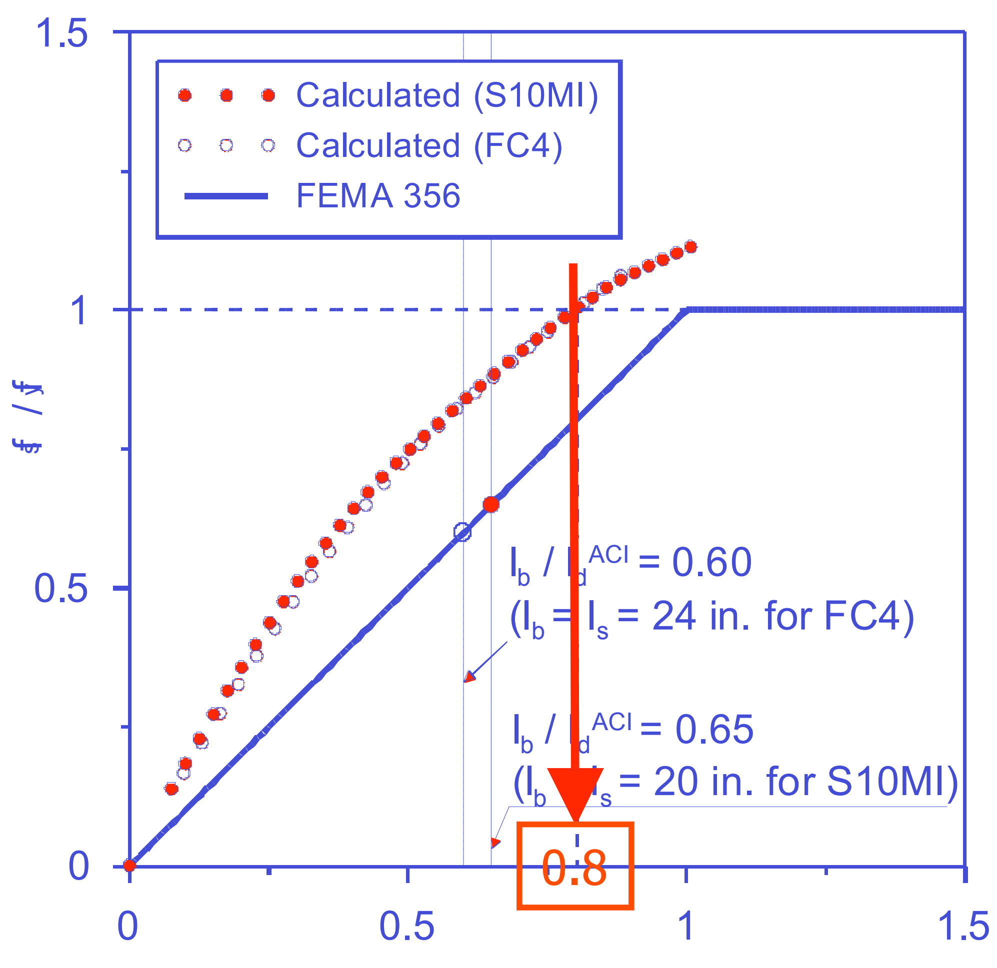
- Cho and Pinchiera (2005) evaluated provisions using detailed bar analysis calibrated to test data.

Spring model for anchored bar



(Cho and Pincheira, 2005)

FEMA 356 lap splice provisions



FEMA 356 under-predicts steel stress.

(Cho and Pincheira, 2005)

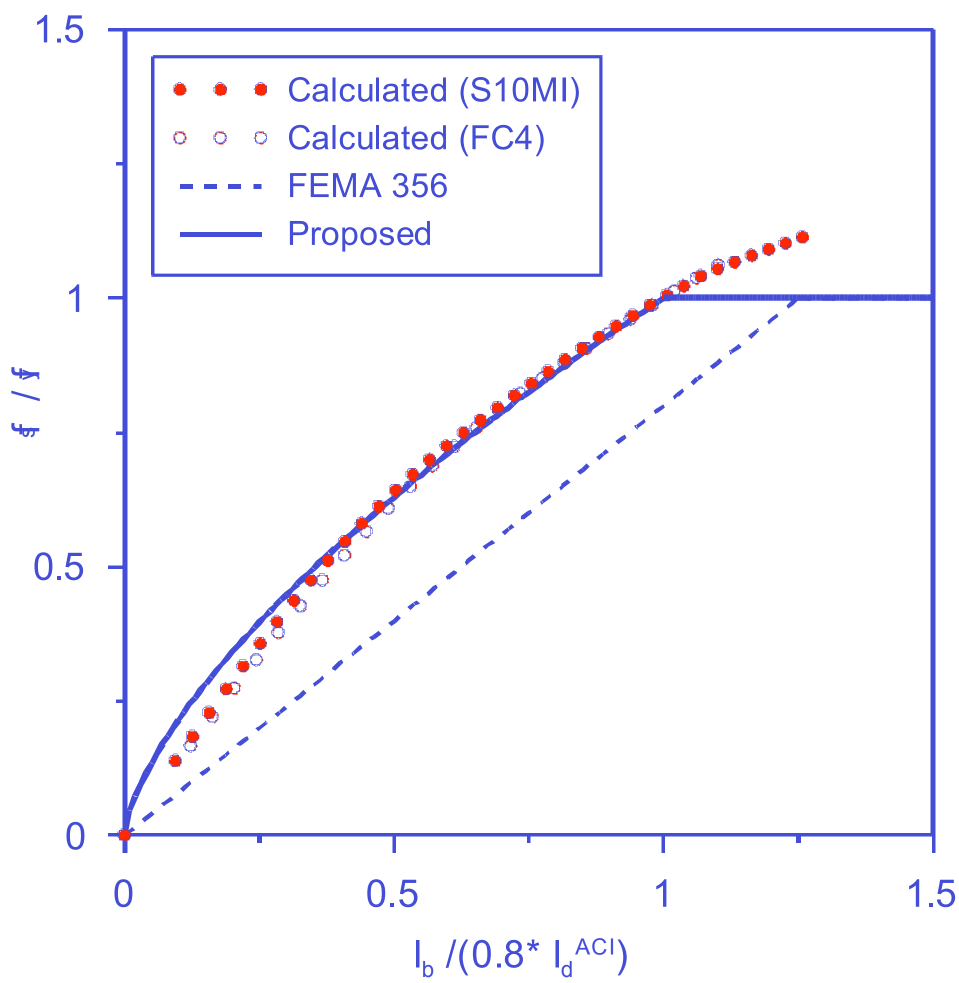
Modified Equation
(Cho and Pincheira, 2005)

[illegible]

[illegible]

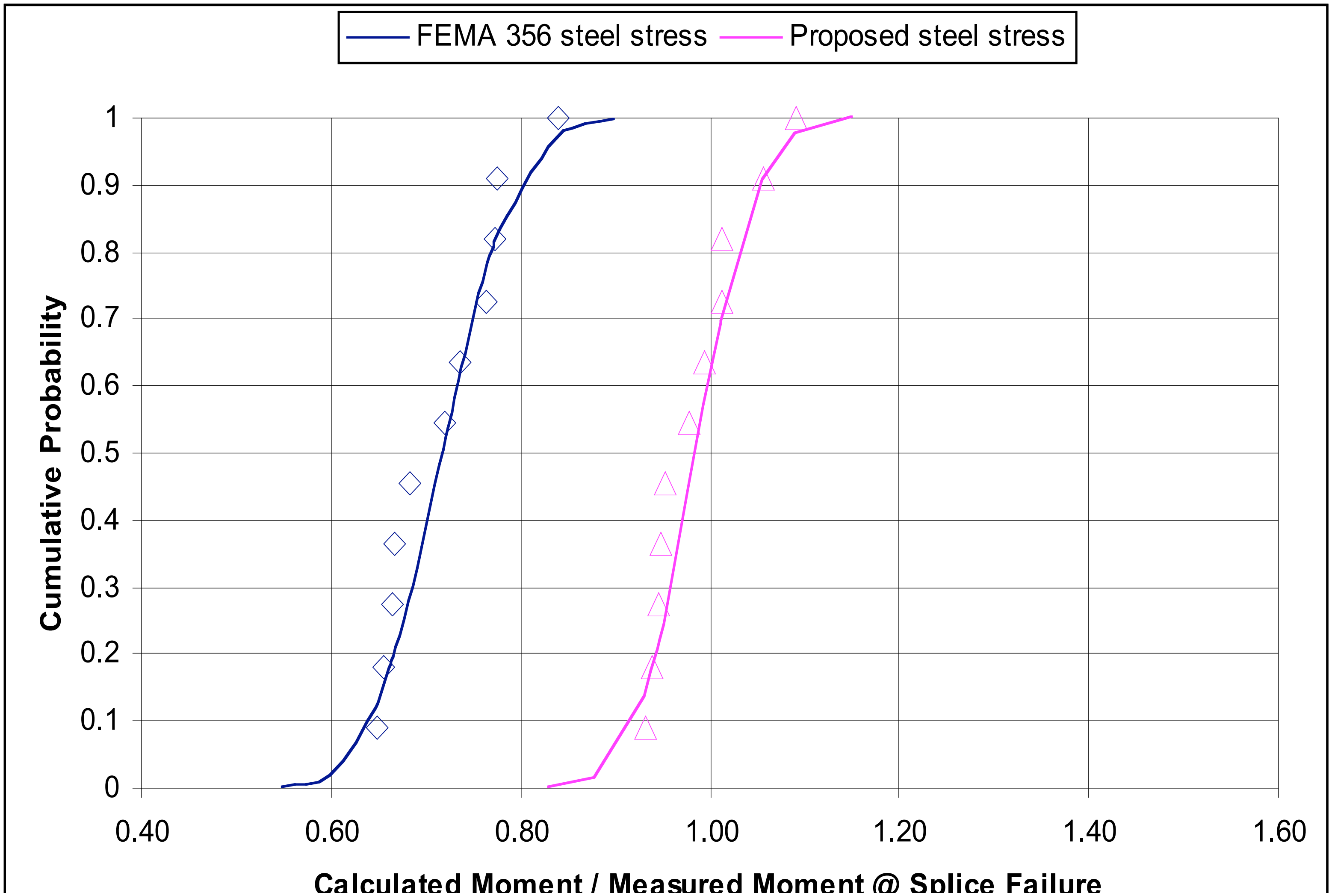
(Cho and Pincheira, 2005)

Modified Equation (Cho and Pincheira, 2005)



(Cho and Pincheira, 2005)

Modified Steel Stress Equation (Cho and Pincheira, 2005)



References

- Berry, M., Parrish, M., and Eberhard, M., (2004) "PEER Structural Performance Database User's Manual," (**www.ce.washington.edu/~peera1**), Pacific Earthquake Engineering Research Center, University of California, Berkeley.
- Berry, M., and Eberhard, M., (2004) "Performance Models for Flexural Damage in Reinforced Concrete Columns," PEER report 2003/18, Berkeley: Pacific Earthquake Engineering Research Center, University of California.
- Berry, M., and Eberhard, M., (2005) "Practical Performance Model for Bar Buckling", *Journal of Structural Engineering*, ASCE, Vol. 131, No. 7, pp. 1060-1070.
- Cho, J-Y, and Pincheira, J. A., (2004) "Nonlinear Modeling of RC Columns with Short Lap Splices," Proceedings of 13th World Conference on Earthquake Engineering, Vancouver, B. C., Canada.
- Elwood, K.J., and Moehle, J.P., (2005a) "Drift Capacity of Reinforced Concrete Columns with Light Transverse Reinforcement", *Earthquake Spectra*, Earthquake Engineering Research Institute, vol. 21, no. 1, pp. 71-89.
- Elwood, K.J., and Moehle, J.P., (2005b) "Axial Capacity Model for Shear-Damaged Columns", *ACI Structural Journal*, American Concrete Institute, vol. 102, no. 4, pp. 578-587.
- Elwood, K.J., (2004) "Modelling failures in existing reinforced concrete columns", *Canadian Journal of Civil Engineering*, vol. 31, no. 5, pp. 846-859.
- Elwood, K.J., and Moehle, J.P., (2004) "Evaluation of Existing Reinforced Concrete Columns", Proceedings of the Thirteenth World Conference on Earthquake Engineering, Vancouver, BC, Canada, August 2004, 15 pages.
- Elwood, K. J. and Moehle, J.P., (2003) "Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames", PEER report 2003/01, Berkeley: Pacific Earthquake Engineering Research Center, University of California, 346 pages.
- Melek, M., and Wallace, J. W., (2004) "Cyclic Behavior of Columns with Short Lap Splices," ACI Structural Journal, V. 101, No. 6, pp. 802-811.
- Priestley, M.J.N., Verma, R., and Xiao, Y., (1994) "Seismic Shear Strength of Reinforced Concrete Columns," Journal of Structural Engineering, Vol. 120, No. 8, pp. 2310-2329.
- Sezen, H., and Moehle, J.P., (2004) "Shear Strength Model for Lightly Reinforced Concrete Columns," *Journal of Structural Engineering*, Vol. 130, No. 11, pp. 1692-1703.
- Zhu, L. (2005) "Probabilistic Drift Capacity Models for Reinforced Concrete Columns", MASc Thesis, Department of Civil Engineering, University of British Columbia.
- Zhu, L., Elwood, K.J., Haukaas T. and Gardoni, P., (2005) "Application of a Probabilistic Drift Capacity Model for Shear-Critical Columns," Journal of the American Concrete Institute (ACI), Special Publication.