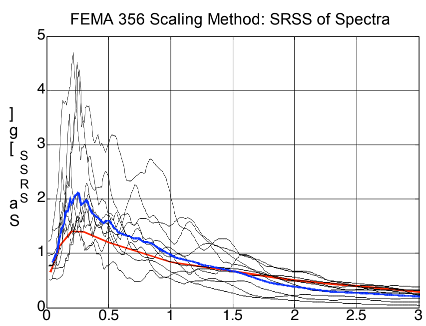
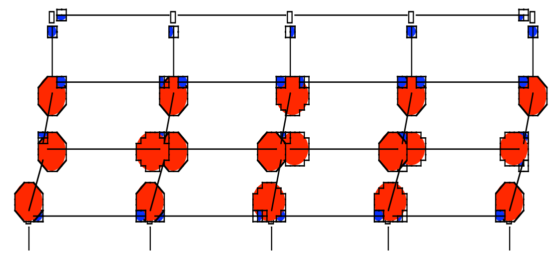
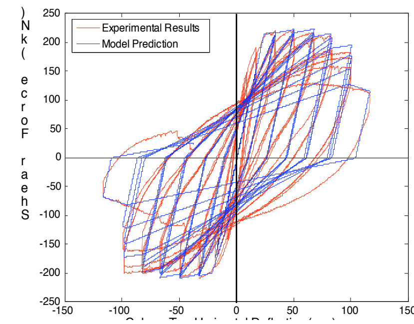
Performance Assessment Through Nonlinear Time History Analysis



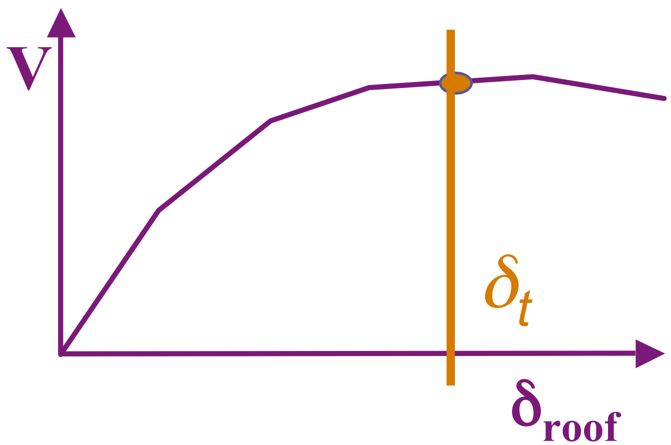




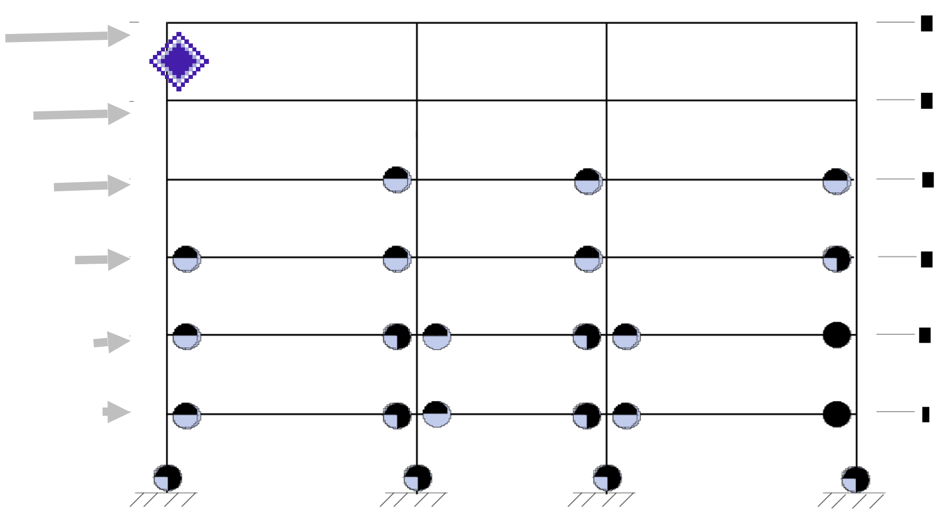
Greg Deierlein
Stanford University

with contributions by
Curt Haselton & Abbie Liel
Stanford University

PBEE Current "Best" Practice: FEMA 273/356



Global Pushover Response

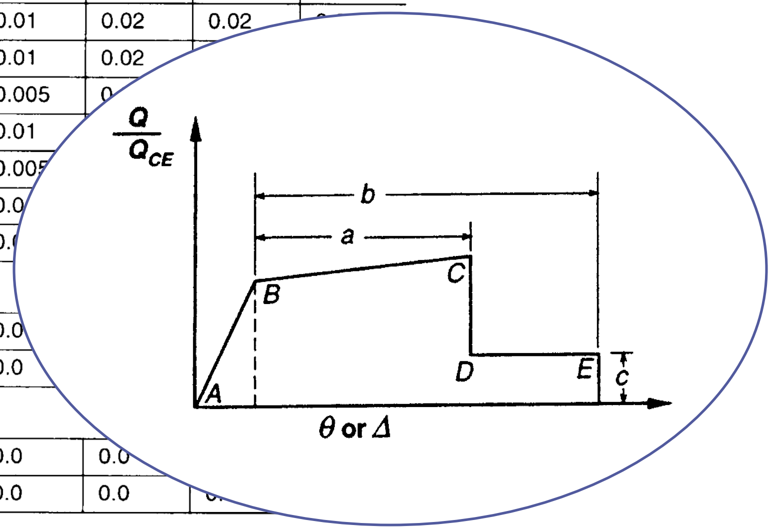


- **Nonlinear "Pushover Analysis"**
  - Modeling Assumptions
  - Force Distribution
  - Target Displacement (Sa)
- **Component Modeling Criteria**
  - "Backbone Curve"
- **Component Acceptance Criteria**
  - Force Controlled Elements
  - Deformation Controlled Elements

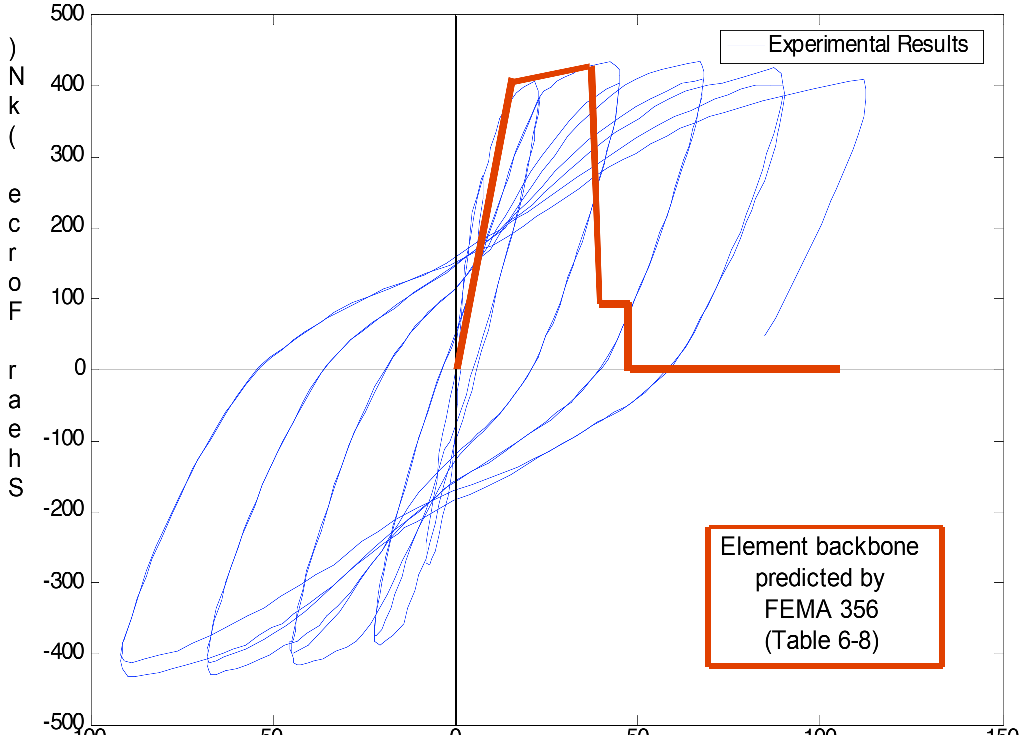
Example: Criteria for RC Beams (FEMA 273)

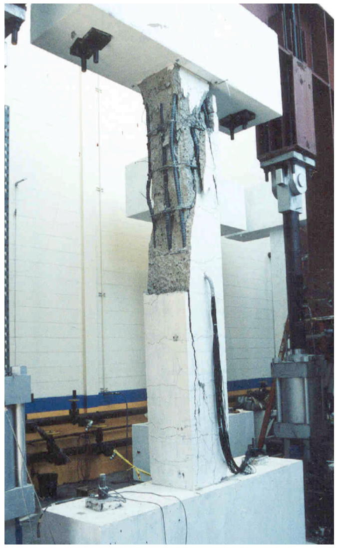
Table 6-6 — Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Beams

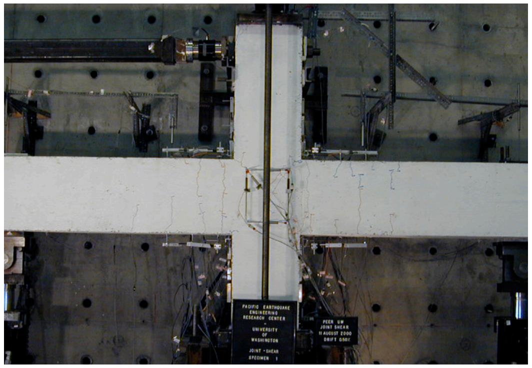
Conditions			Modeling Parameters[3]: Plastic Rotation Angle, radians		Modeling Parameters[3]: Residual Strength Ratio	Acceptance Criteria[3] — Plastic Rotation Angle, radians — Component Type: Primary — Performance Level			Secondary	
			a	b	c	IO	LS	CP	LS	CP
i. Beams controlled by flexure[1]										
$\frac{\rho - \rho'}{\rho_{bal}}$	Trans. Reinf.[2]	$\frac{V}{b_w d \sqrt{f'_c}}$								
≤ 0.0	C	≤ 3	0.025	0.05	0.2	0.005	0.02	0.025	0.02	0.05
≤ 0.0	C	≥ 6	0.02	0.04	0.2	0.005	0.01	0.02	0.02	[illegible]
≥ 0.5	C	≤ 3	0.02	0.03	0.2	0.005	0.01	0.02	[illegible]	[illegible]
≥ 0.5	C	≥ 6	0.015	0.02	0.2	0.005	0.005	[illegible]	[illegible]	[illegible]
≤ 0.0	NC	≤ 3	0.02	0.03	0.2	0.005	0.01	[illegible]	[illegible]	[illegible]
≤ 0.0	NC	≥ 6	0.01	0.015	0.2	0.0	0.005	[illegible]	[illegible]	[illegible]
≥ 0.5	NC	≤ 3	0.01	0.015	0.2	0.005	[illegible]	[illegible]	[illegible]	[illegible]
≥ 0.5	NC	≥ 6	0.005	0.01	0.2	0.0	[illegible]	[illegible]	[illegible]	[illegible]
ii. Beams controlled by shear[1]										
Stirrup spacing ≤ *d*/2			0.0	0.02	0.2	0.0	0.0	[illegible]	[illegible]	[illegible]
Stirrup spacing > *d*/2			0.0	0.01	0.2	0.0	0.0	[illegible]	[illegible]	[illegible]
iii. Beams controlled by inadequate development or splicing along the span[1]										
Stirrup spacing ≤ *d*/2			0.0	0.02	0.0	0.0	0.0	0.0	[illegible]	[illegible]
Stirrup spacing > *d*/2			0.0	0.01	0.0	0.0	0.0	0.0	[illegible]	[illegible]
iv. Beams controlled by inadequate embedment into beam-column joint[1]										
			0.015	0.03	0.2	0.01	0.01	0.015	0.02	0.03



Shortcomings of FEMA 273/356



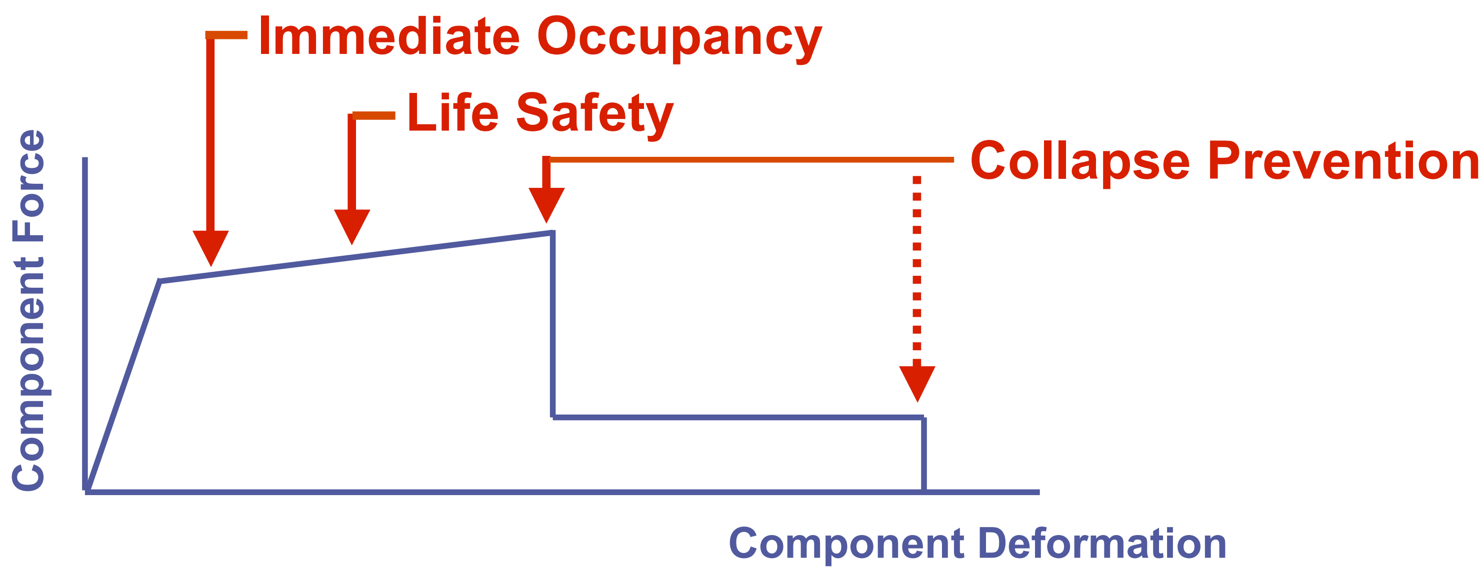




Component Backbone Curve:

- Overly Idealized
- Conservative
- Deterministic

Shortcomings of FEMA 273/356



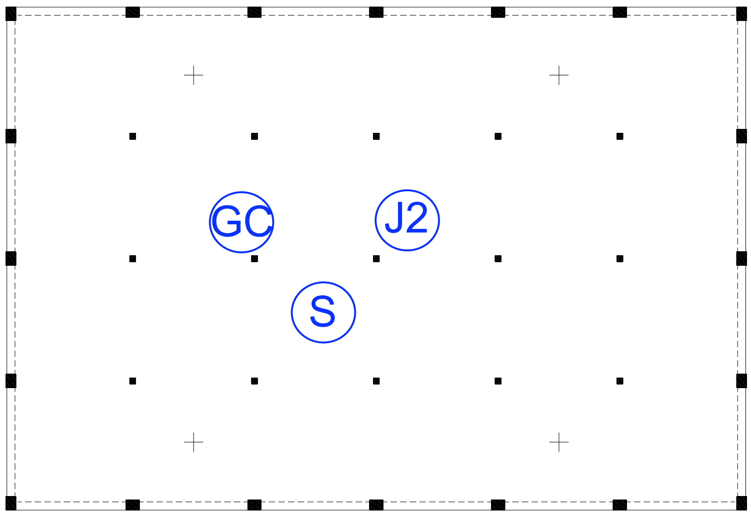
Component Backbone Curve

- Over-reliance on idealized (simplified) **local component demand** indices to predict **system response**
- Ambiguous relationships between **structural indices** and **building performance**
- Limited emphasis on static monotonic pushover approach

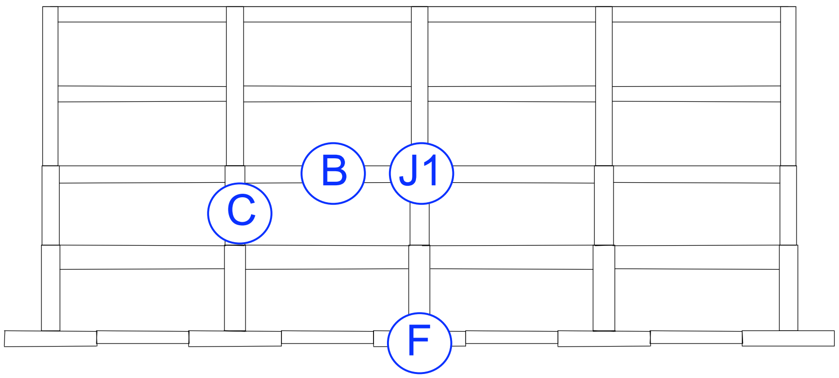
Assessment Using Improved NLTH Analysis

- Nonlinear Component and System Modeling
- FEMA 356 Concepts with NLTH Analysis
- Preview of Comprehensive Collapse Simulation

Structural System & Components



Floor Framing Plan



Perimeter Frame Elevation

Moment Frames

- Beams, Columns, B-C Joints, and Foundations

Gravity Frames

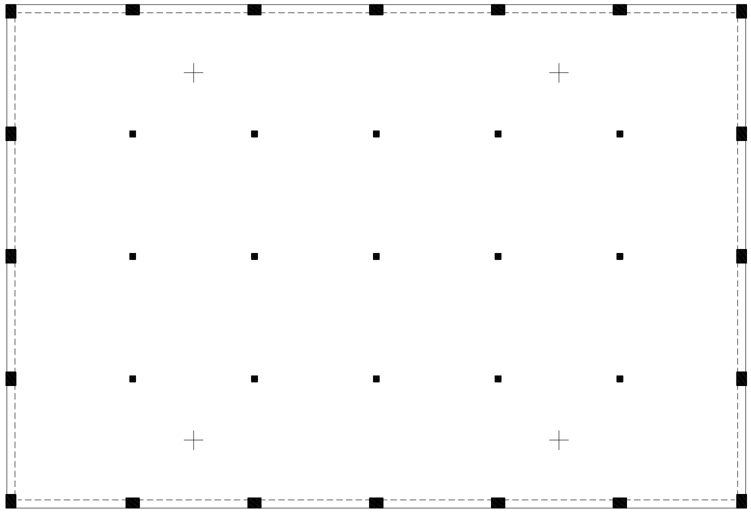
- Slab/beams, Gravity Columns, S-C Joints, and Foundations

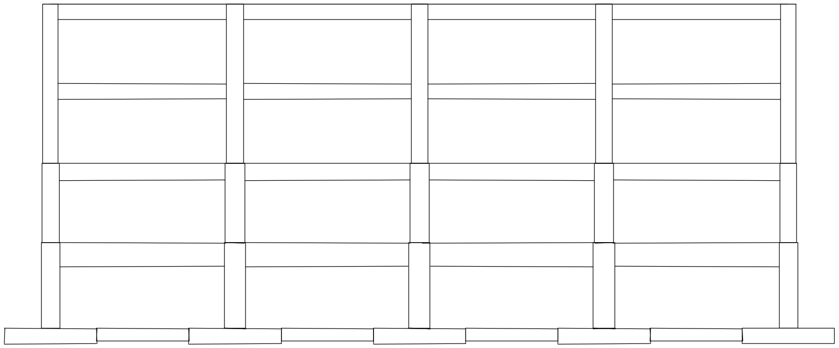
Shear Walls (not shown)

Issue: *Whether or not to consider the lateral resistance of the "gravity system" in the simulation. There gravity system can provide significant enhancement in a nonlinear*

PEER

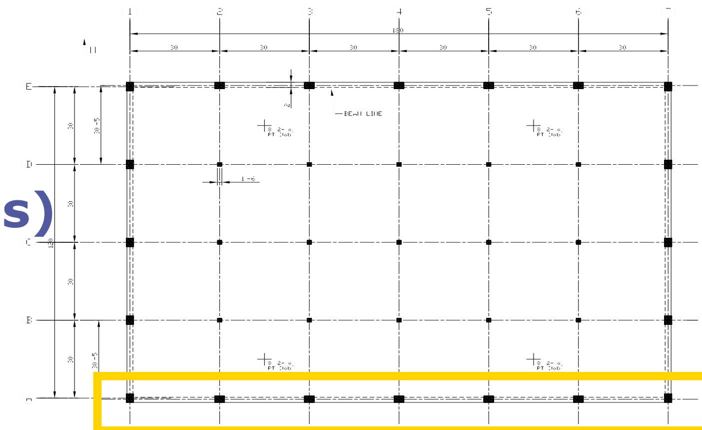
Deterioration Modes & Collapse Scenarios





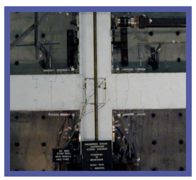
1. **Deterioration Modes of RC Elements**
   - Simulation vs. Fragility Models
2. **Building System Collapse Scenarios**
   - Sidesway Collapse (SC)
   - Loss in Vertical Load Carrying Capacity (LVCC)
3. **Likelihood of Collapse Scenarios**
   - Existing vs. New Construction
   - "Ordinary" versus "Special" seismic design

Simulation Model



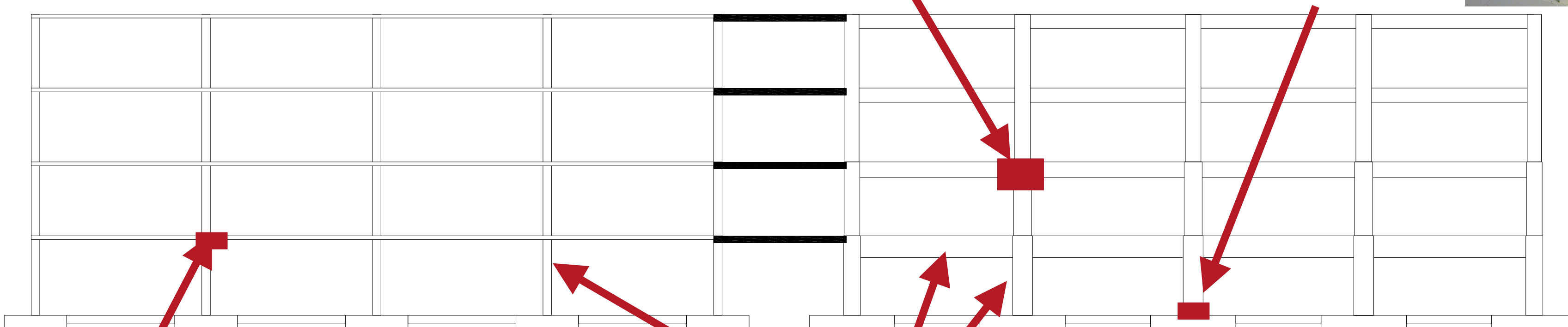
Gravity Frame(s)

Lateral Frame



Joints with both bond-slip springs and shear springs

Column bond-slip springs



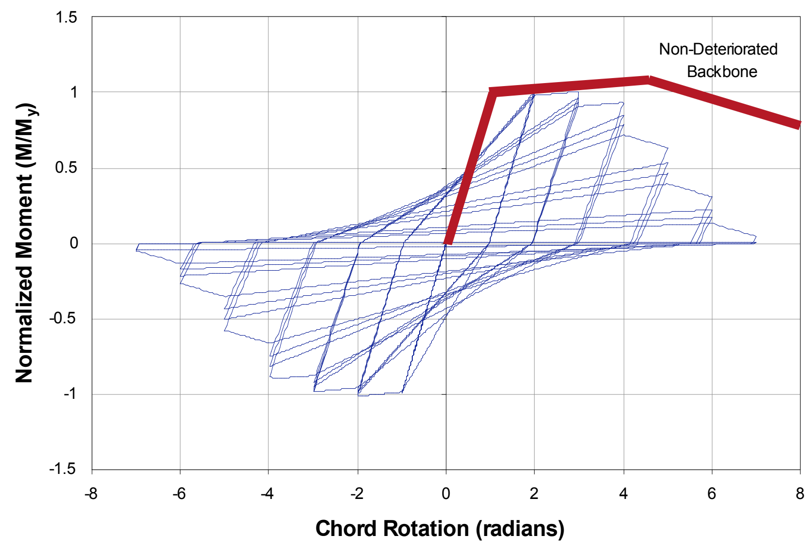
Gravity Frame(s)

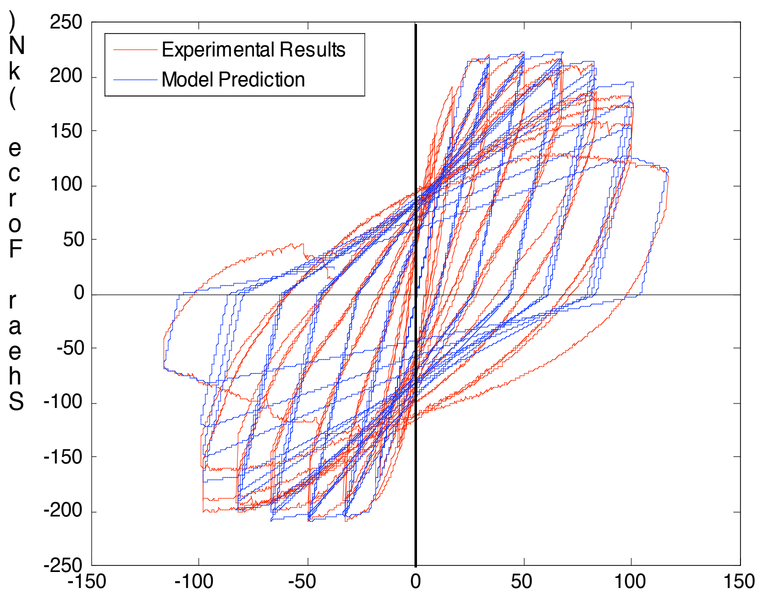
Lateral Frame

Lumped plasticity beam-columns

More realistic component simulation

OR OTHER COMPUTER CODES





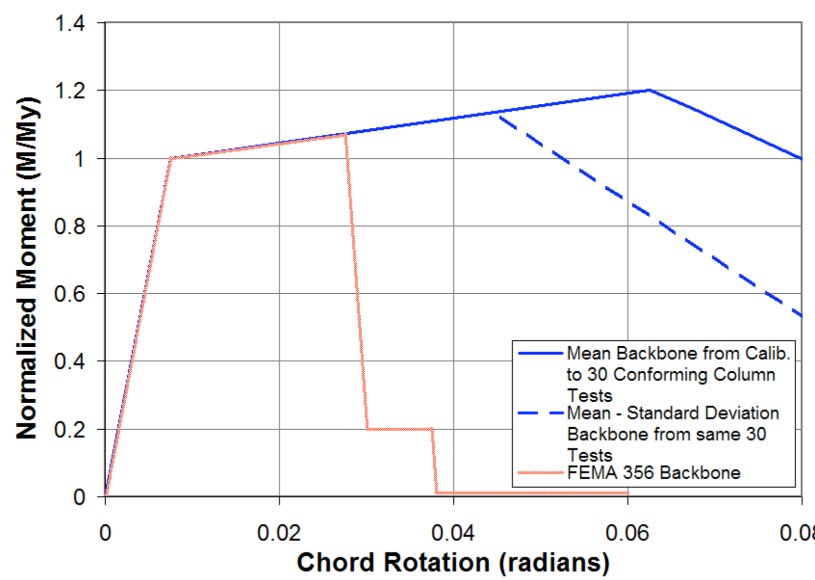
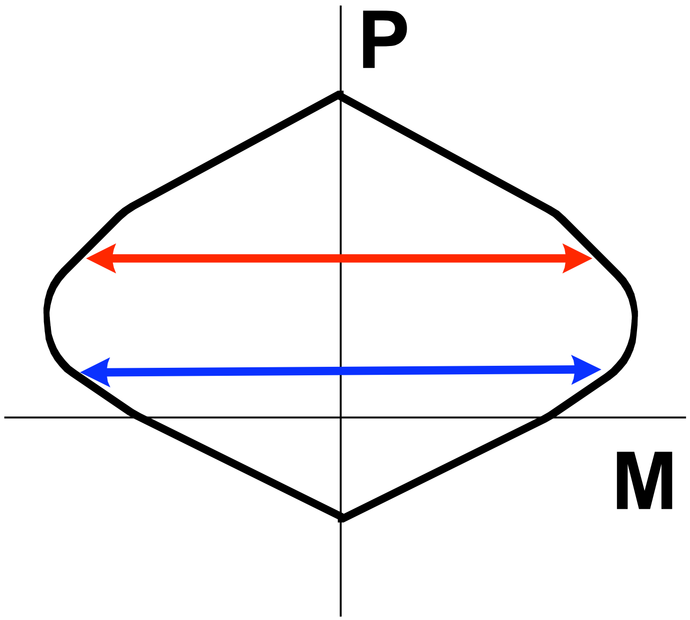
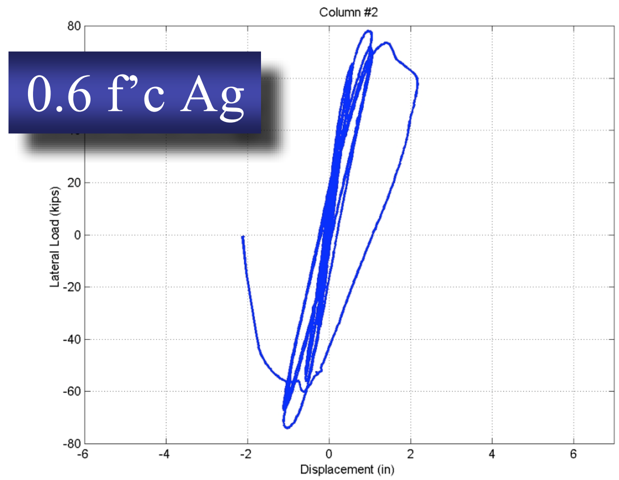
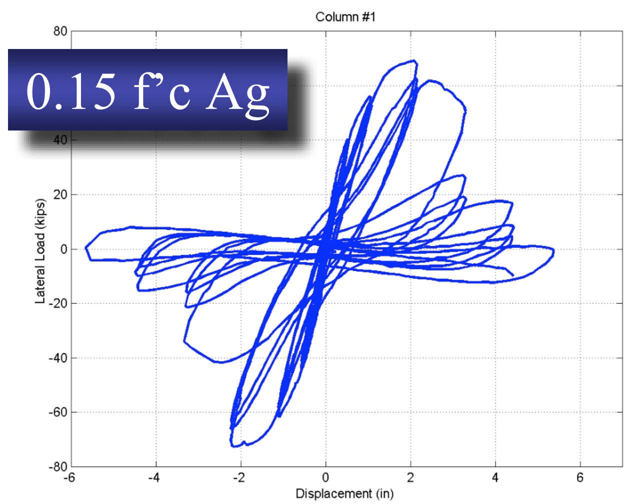


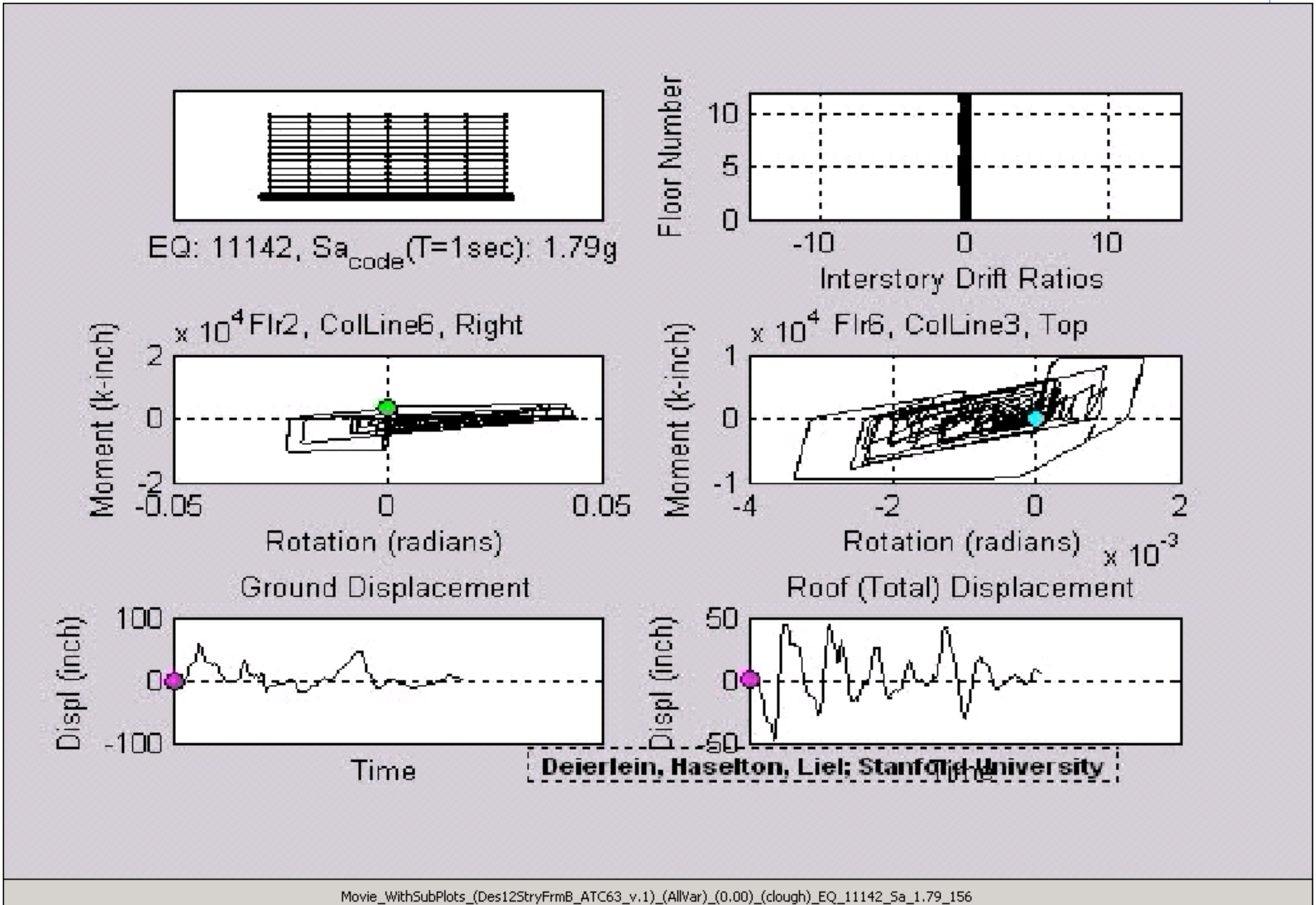
Illustration: Axial Load & Post-Peak Response





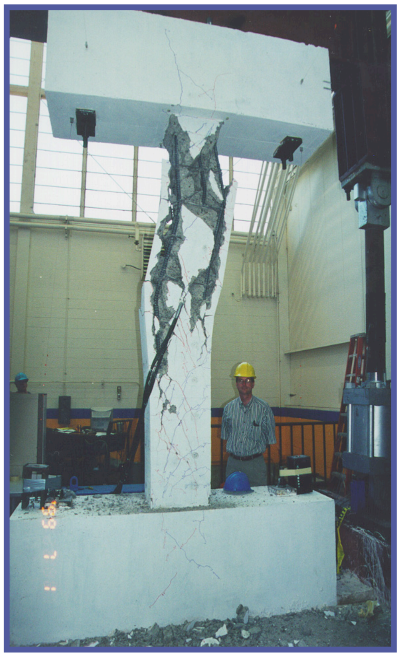


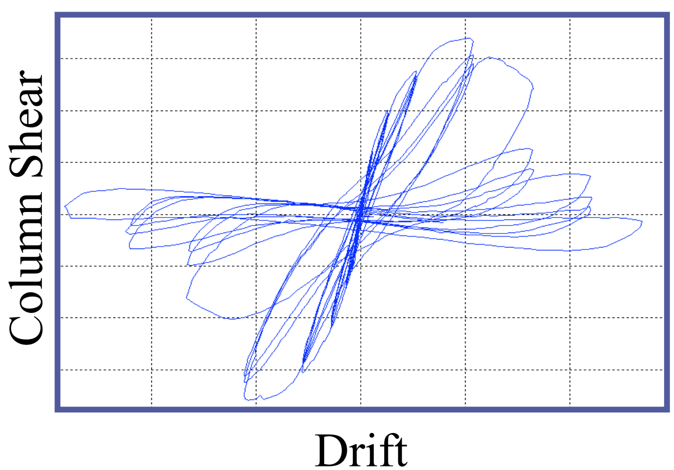
Key Parameter: $P/P_{balance}$

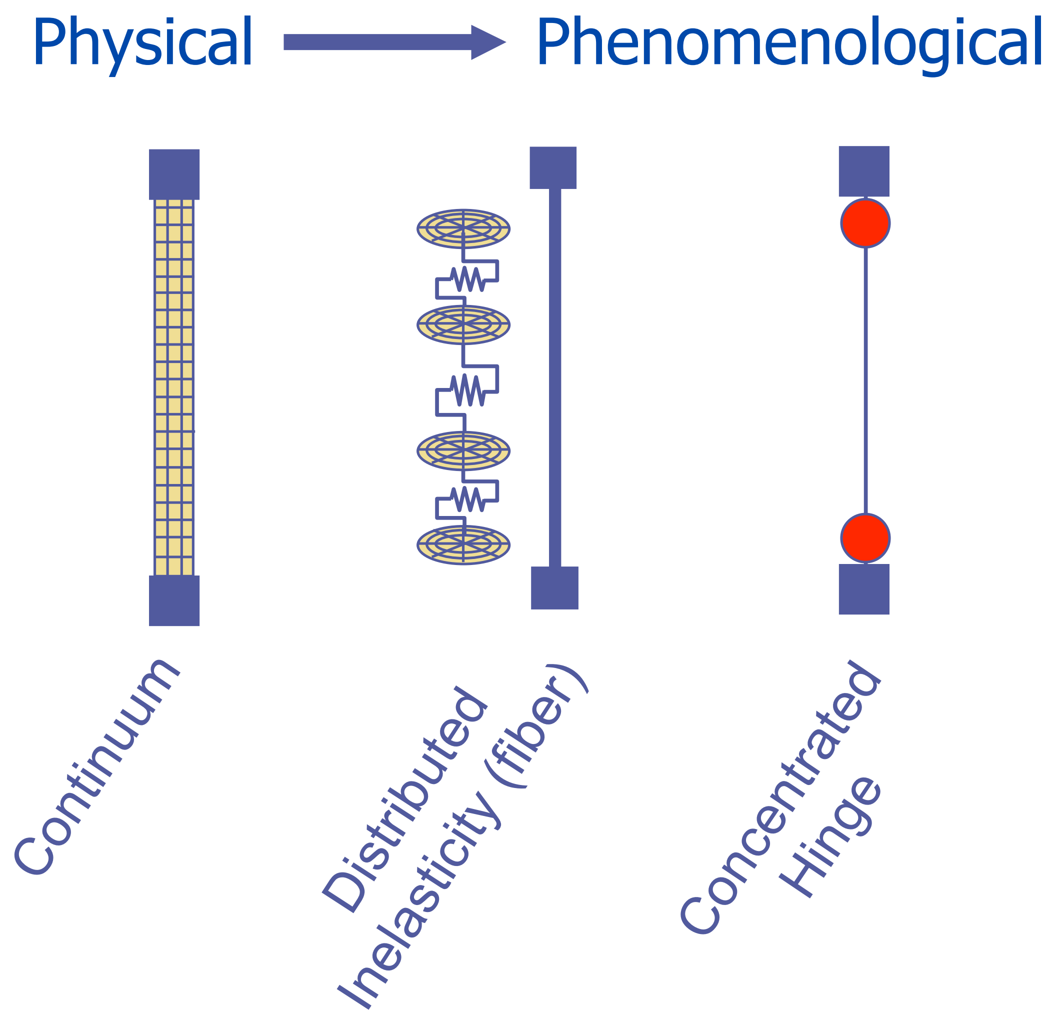


Ref. Haselton, Liel, Deierlein (12 story IMF system)

Beam-Column Modeling Alternatives

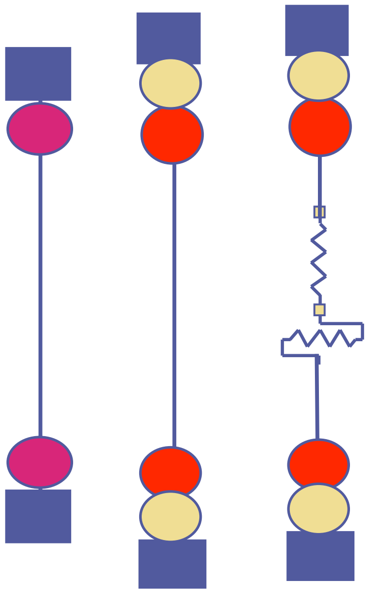






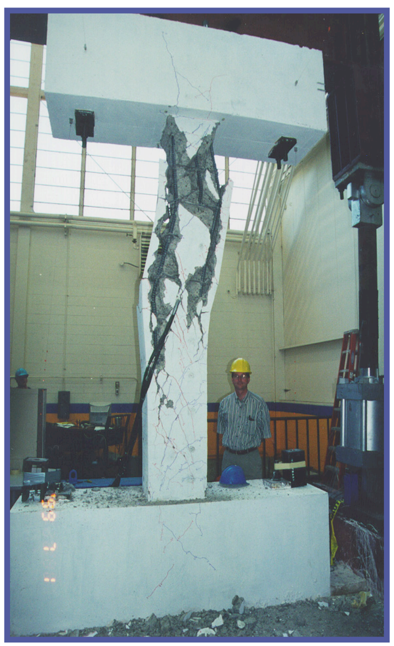
Beam-Column Model Considerations

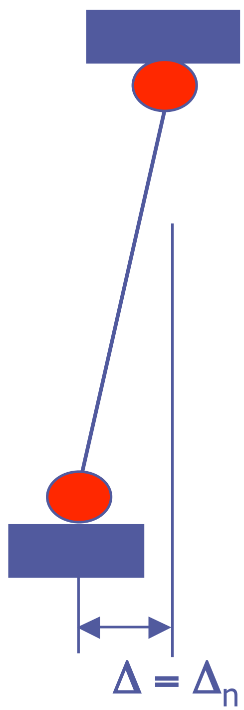
- Flexural Deformations
  - concrete cracking/tension stiffening
  - reinforcing bar yielding
  - concrete crushing
- Shear Deformations
  - uncracked, cracked
- Anchorage Bond Slip
  - pre and post-yield
- Critical Failure Modes and Deterioration
  - lateral tie fracture … concrete crushing, rebar buckling
  - longitudinal bar buckling/fracture
  - PMV interaction



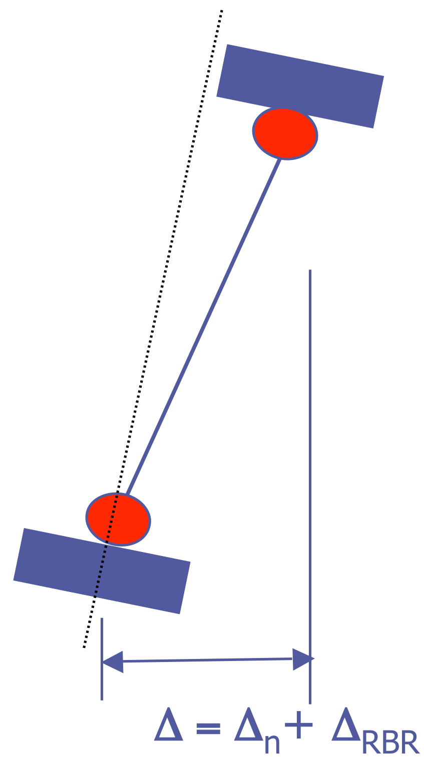
Beam-Column Model Considerations, cont'd

- Definition of Displacements and Deformations
  - Total Δ = Distortional (or "Natural") Δ + Rigid Body Δ
  - Total Δ = *Clear* Story Drift
  - Damage is typically associated with distortional deformations



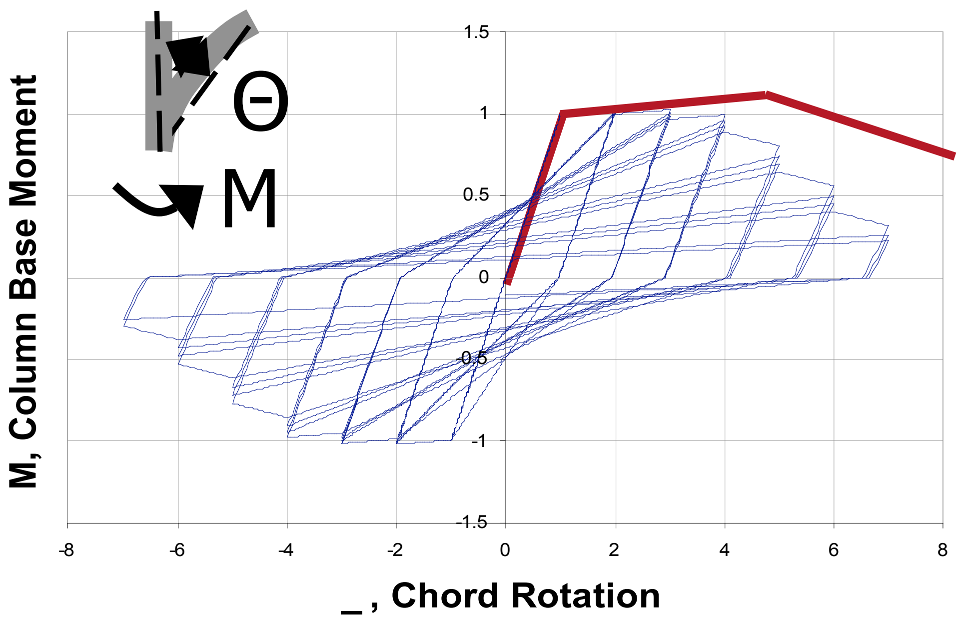


Drift from Experiment



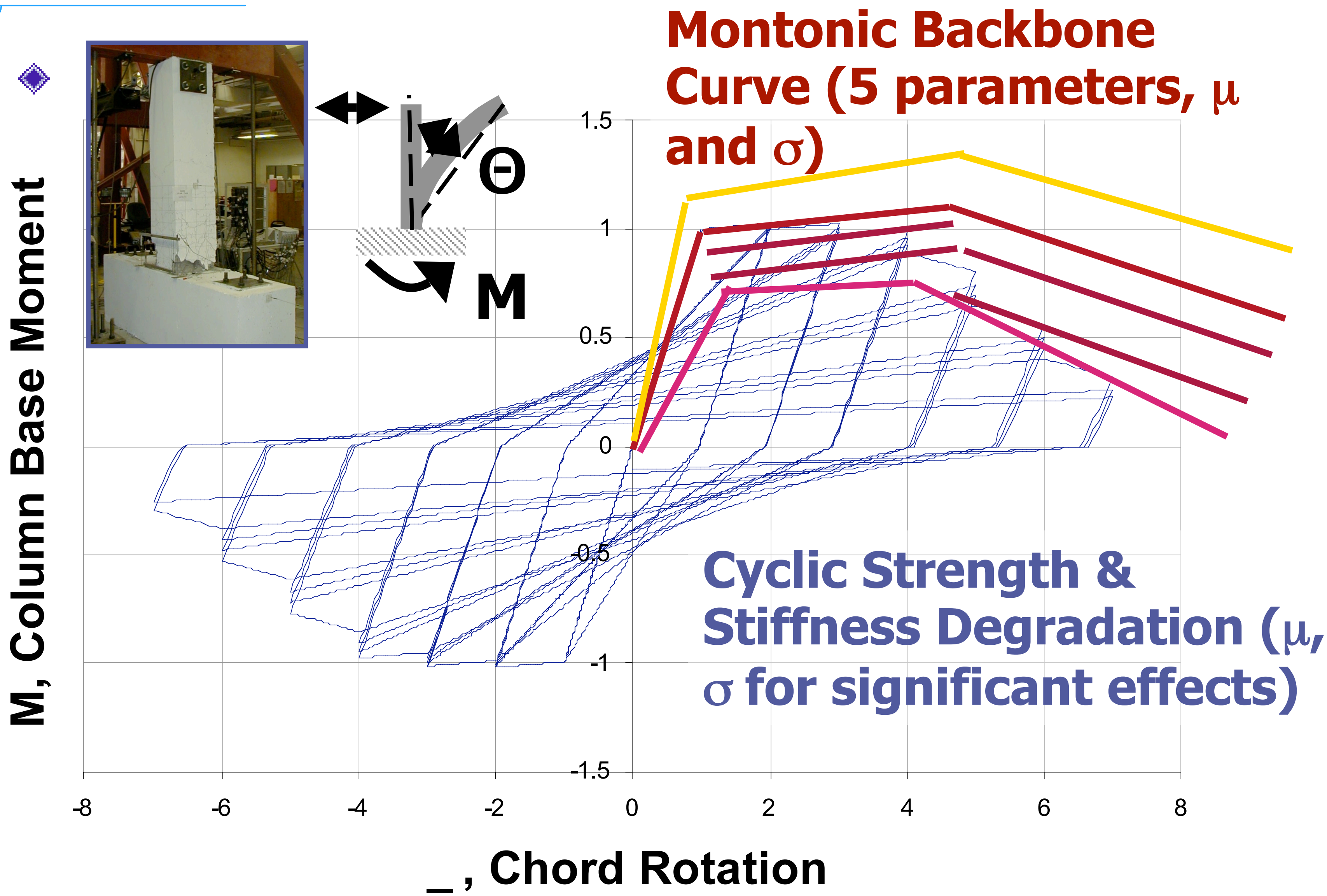
Drift from Frame Analysis

Standardized Inelastic Component Models



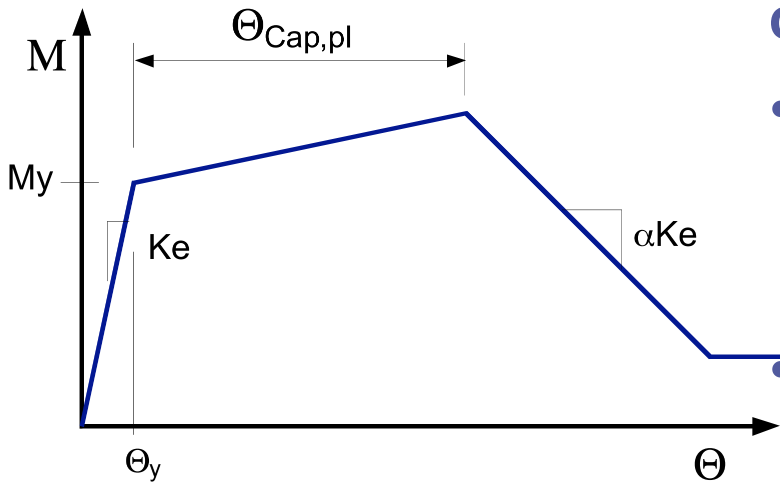
- Model Input
  - Physical Design Parameters (material, configuration, geometry, details, …)
  - Calculated/calibrated backbone parameters (***mean and COVs*** for anchor points and hysteretic response parameters)
- Model Output: Engineering Demand Parameters (e.g., $\Theta_{plastic}$)

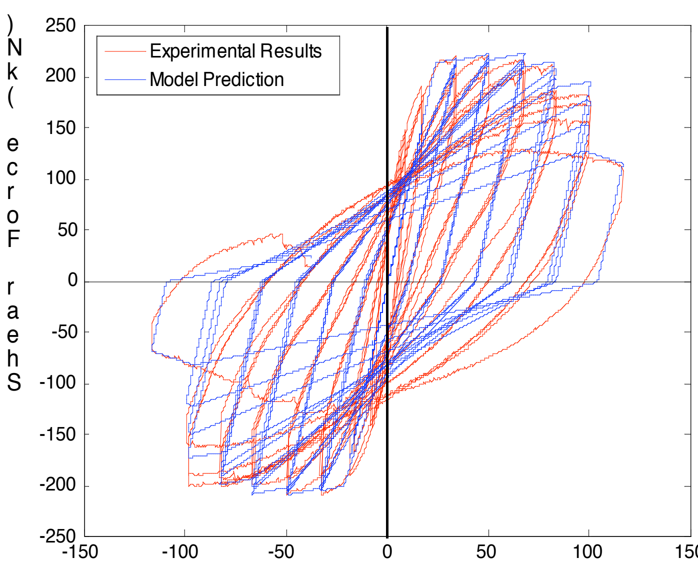
Element Models for Collapse Analyses



PEER

RC Beam-Column Simulation Model Calibration





OVERVIEW OF CALIBRATION EFFORT

- Basic Hysteretic Model

  5 parameter backbone curve

  2 (x4) hysteretic parameters

- Previous RC Behavioral Studies

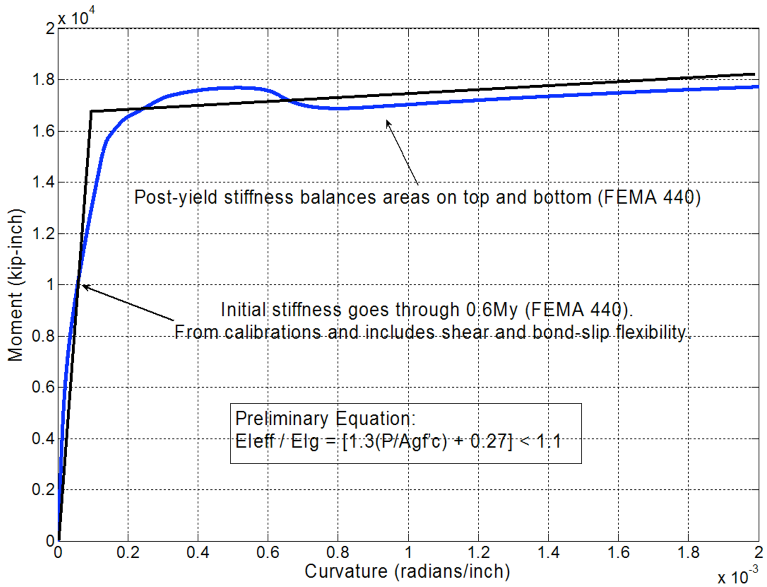
  -Fardis et al. (Θcap, Θu)

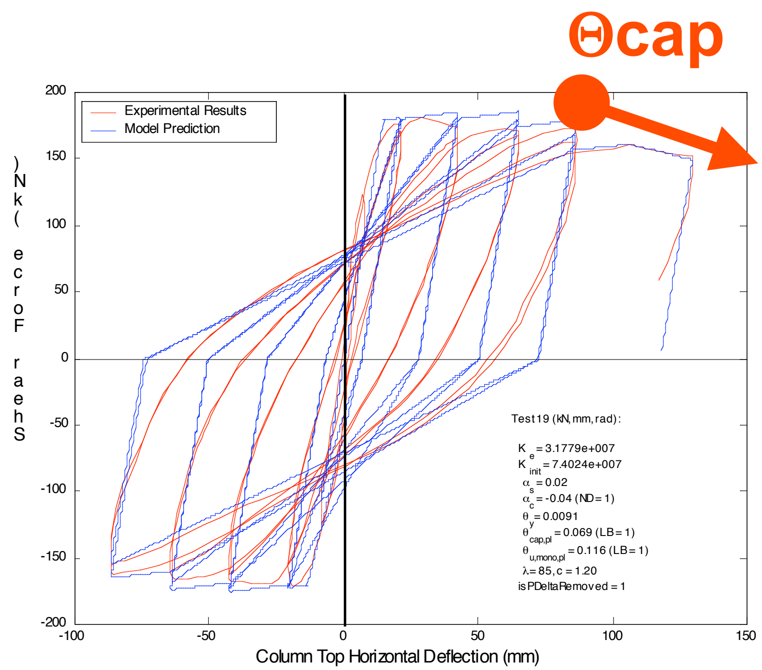
  -Eberhard et al. (EDP criteria for spalling and bar buckling)

- Current effort: Systematic calibration to 226 flexurally dominated columns

- **Goal:** *Validated model to be vetted through consensus process*

RC Beam-Column Parameters





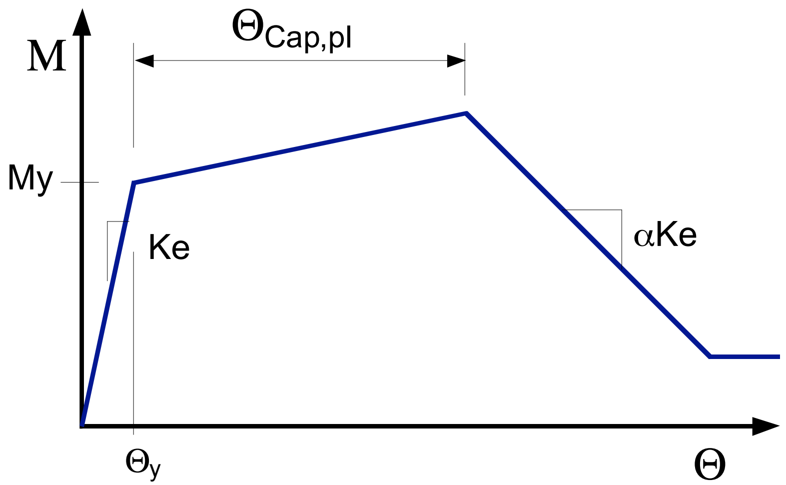
Semi-Empirical -- calibrated from tests, fiber analyses, and basic mechanics:

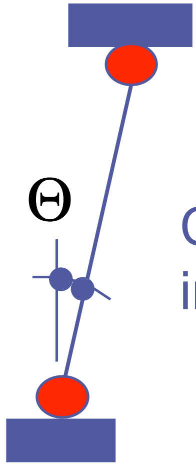
- Secant Stiffness (EI_{eff})
- Yield Strength (My)
- Hardening Stiffness

Empirical - calibrated from tests:

- Capping (peak) point
- Post-peak unloading (strain softening) stiffness
- Hysteretic stiffness/strength degradation

Column Models (sample data)



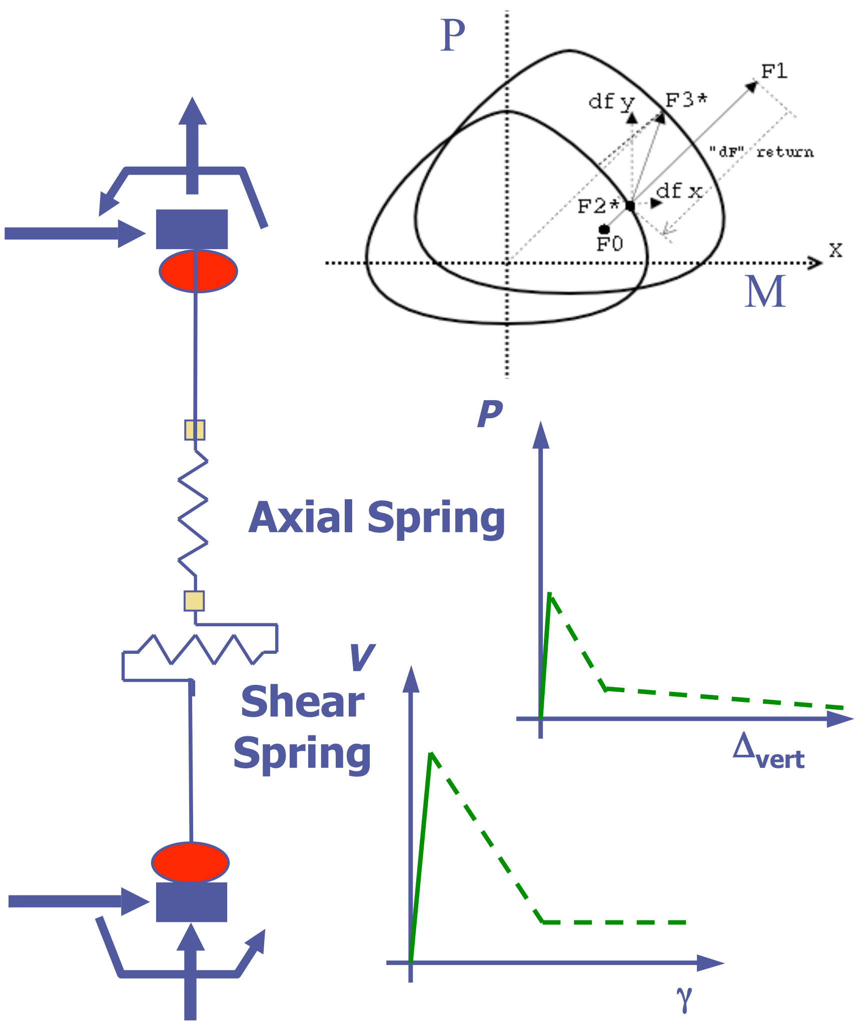


Cap rotation includes bond slip

COMPONENT	$\Theta_{cap,pl}$ (RAD)	COV	α	COV
Beam - Conforming	0.07	60%	-0.05	60%
Beam - Nonconforming	0.02 to 0.05	"	-0.15	"
Column – conform, low axial	0.04 to 0.05	"	-0.05	"
Column – nonconf, low axial	0.02	"	-0.15	"
Column – nonconf, med. axial	0.01	"	-0.15	"

PEER

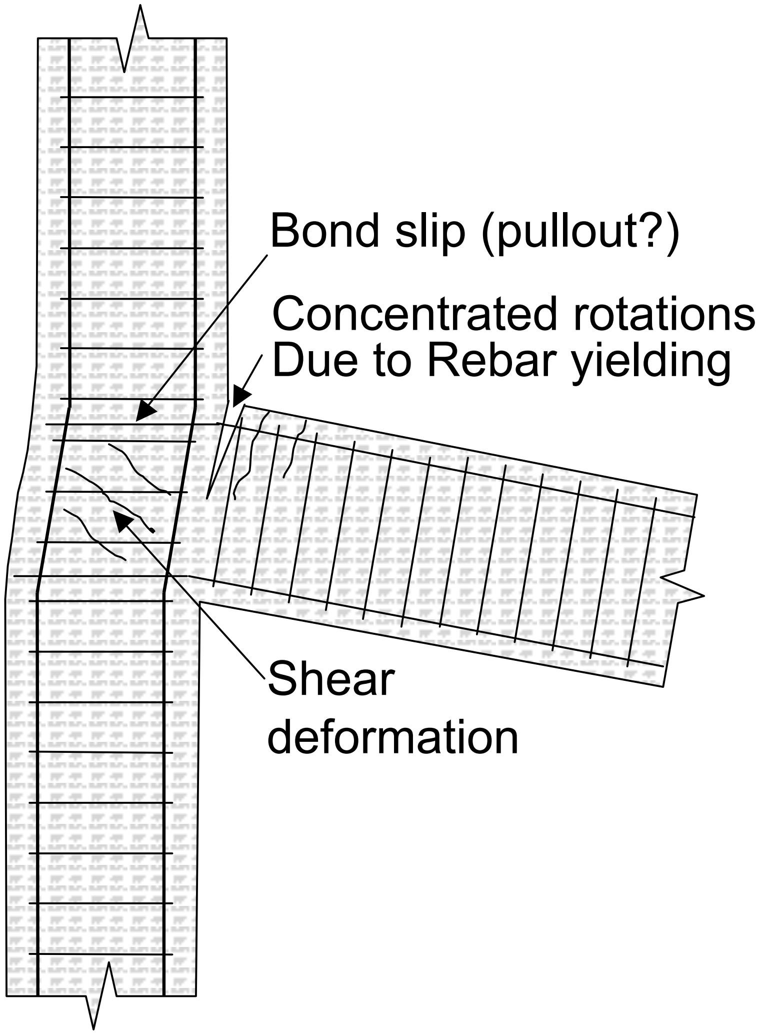
Phenomenological P-M-V Hinge Element

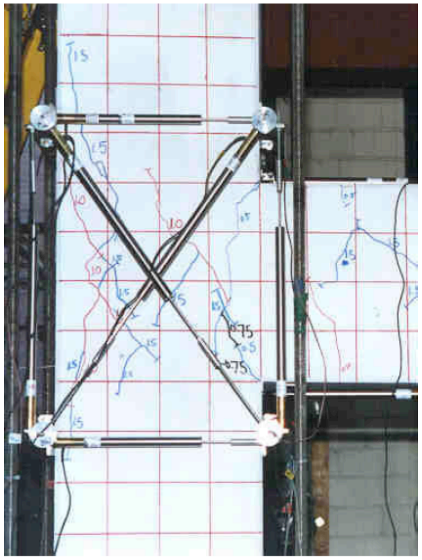


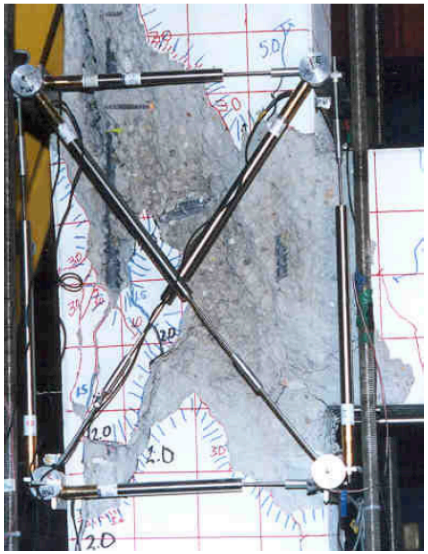
Desired Model Features:

- direct modeling of P-M interaction through limit surface (strength, post-peak softening, hysteretic degradation)
- **DIRECT SIMULATION** (as opposed to limit state check) of column shear failure and axial failure (LVCC)
- More transparent modeling of flexibility introduced by bond slip and shear deformations.

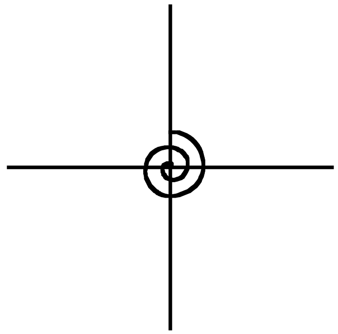
Beam-Column Joint Models



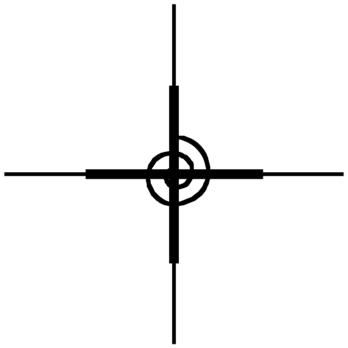




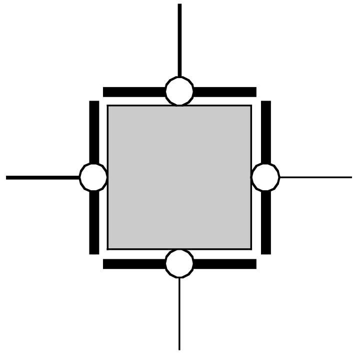
Alternative Joint Models



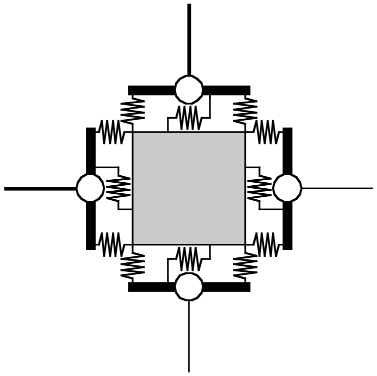
Single spring joint



Single Spring joint with rigid zones

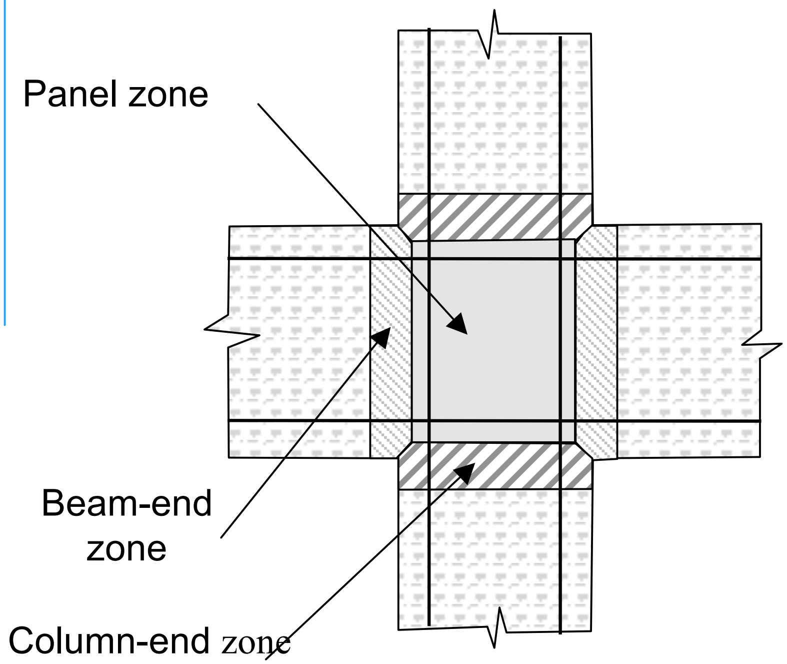


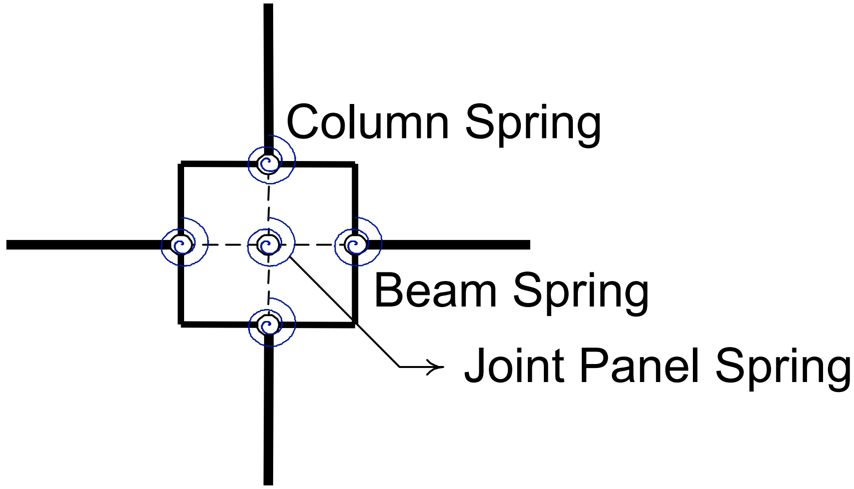
Continuum model



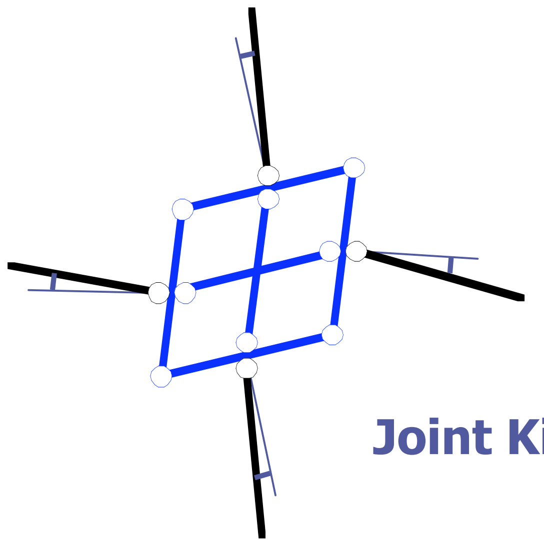
Multi spring super element

Idealized Joint Model



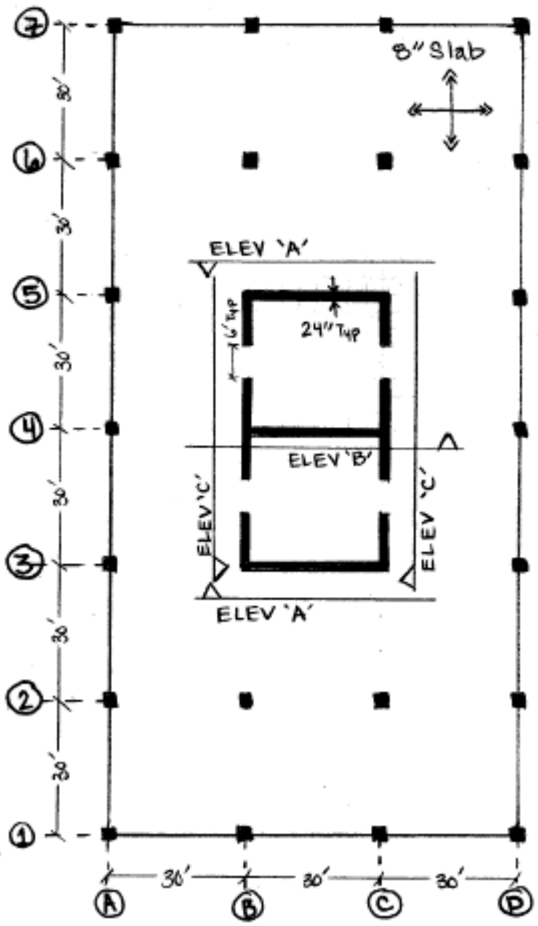


Component Springs



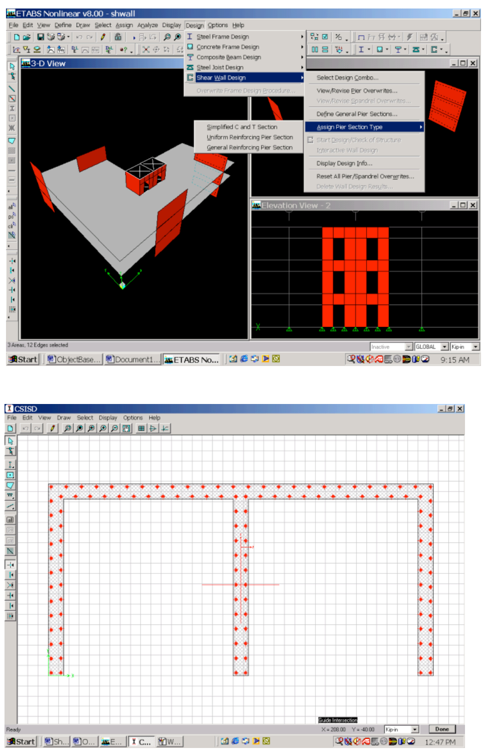
Joint Kinematics

Shear Wall Systems – Behavior Modes

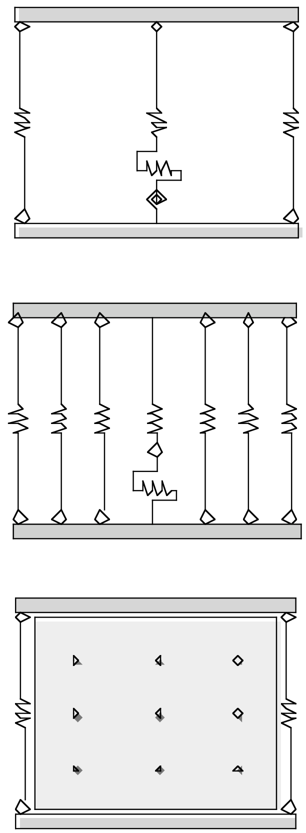


- Flexural Behavior
  - concrete cracking/tension stiffening
  - reinforcing bar yielding
  - concrete crushing
  - tie rupture – rebar buckling/fracture
- Shear Behavior
  - uncracked, cracked
  - shear failure
- Anchorage Bond Slip (base only)
  - pre and post-yield
- Coupling Beams
- Foundations
- System Compatibility
  - slab/column & slab/wall
  - column deformation

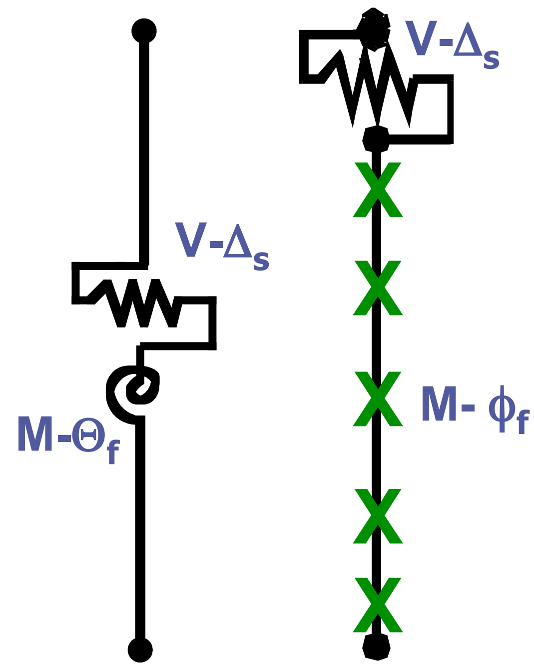
Idealization of RC Walls



Continuum



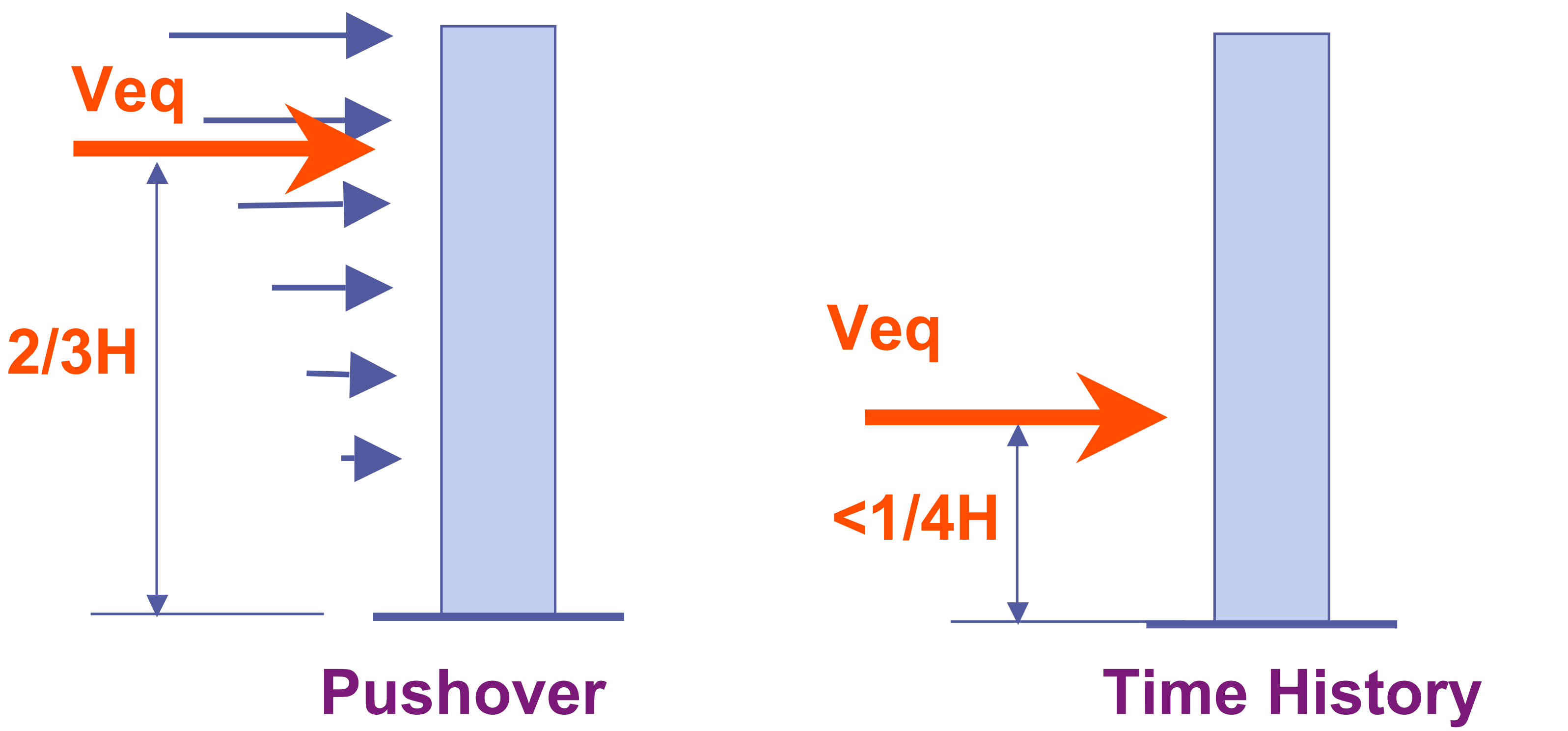
Multi-Spring



Concentrated Spring

Shear Wall Modeling and Behavior

- Squat (short) walls versus tall flexural walls
- Inelastic Time History versus Equivalent Static Loading
  - surprising variations in flexural and shear demands
  - shears can be much higher than predicted by pushover analysis (e.g., Krawinkler & Zareian)



Viscous Damping with NLTH Analysis

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{\ddot{x}_g\} + [P]$$

Raleigh Damping:

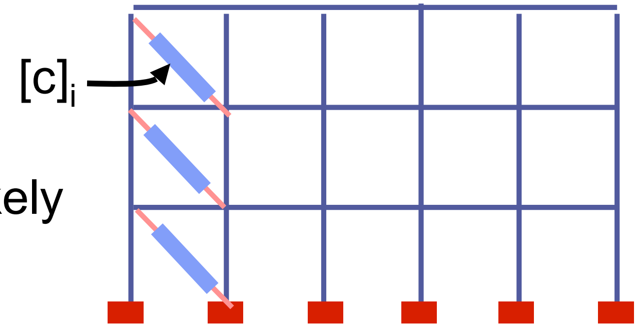
$$[C] = \alpha[M] + \beta[K]; \quad \zeta_n = \frac{\alpha}{2}\frac{1}{\omega_n} + \frac{\beta}{2}\omega_n$$

- For inelastic analysis, viscous damping should be on the order of $\zeta_n = 5\%$.
- Need to be careful how $[K]$ is specified, i.e., $[K_e]$ versus $[K_t]$, since the choice will lead to variations in [C] during the analysis (see Bernal).

Explicit Damping Elements (preferred?):

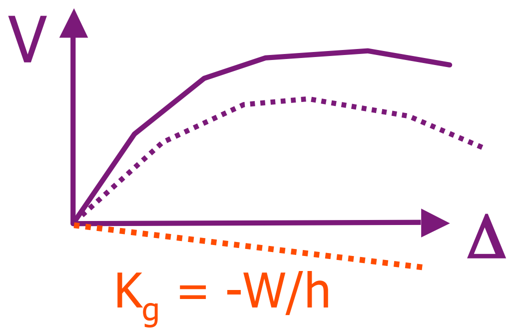
$$[C] = \sum [c]_i$$

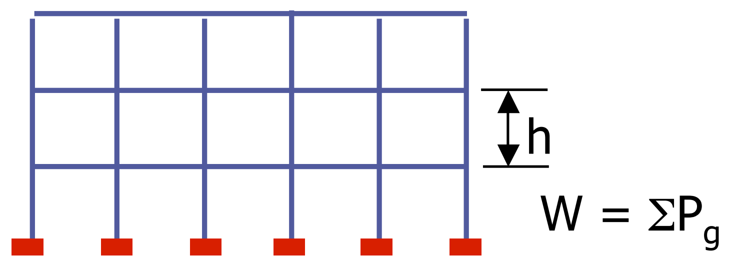
$[c]_i$ configured to represent likely sources of viscous and other incidental damping.



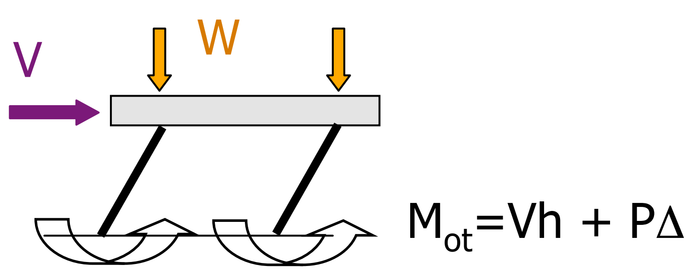
Geometric Nonlinear (P-Δ) Effects

- Negative stiffness effect of P-Δ:



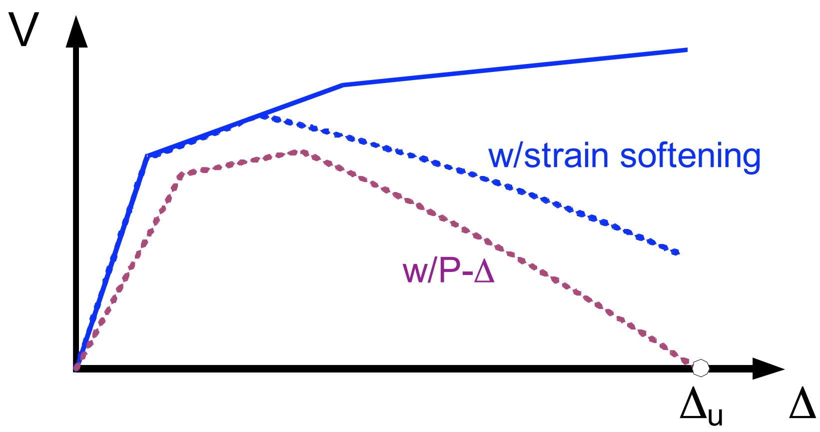


- Increases internal forces associated with overturning:

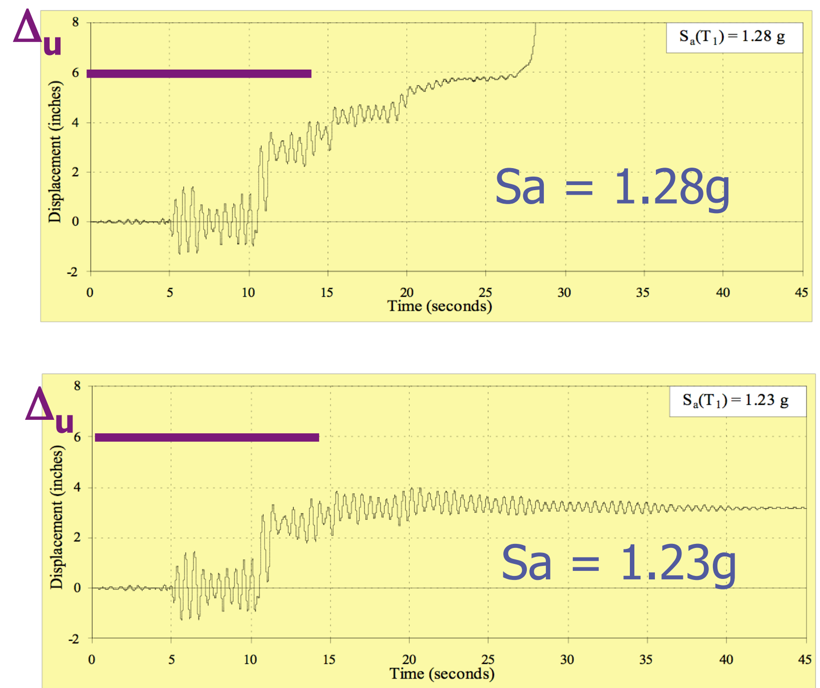


- Key Points
  - "W" should represent the seismic mass that is being stabilized by the lateral system (not just the tributary gravity load)
  - "Linear P-Δ" formulations accurate for drift ratios up to about 5-10%; beyond this large rotation (e.g., "co-rotational") formulations should be used to track response.

Dynamic Sidesway Collapse



Static Pushover Analysis
(Critical Story)



NLTH Analysis Results

- For structural systems governed by *sidesway collapse,* evidence suggests that the dynamic drift capacity is about 2/3 of the static pushover limit (Δ_u) --- provided that the static analysis represents strength degradation due to strain (displacement) softening and P-Δ effects.
- Collapse point can be very sensitive to ground motion intensity level and other effects.

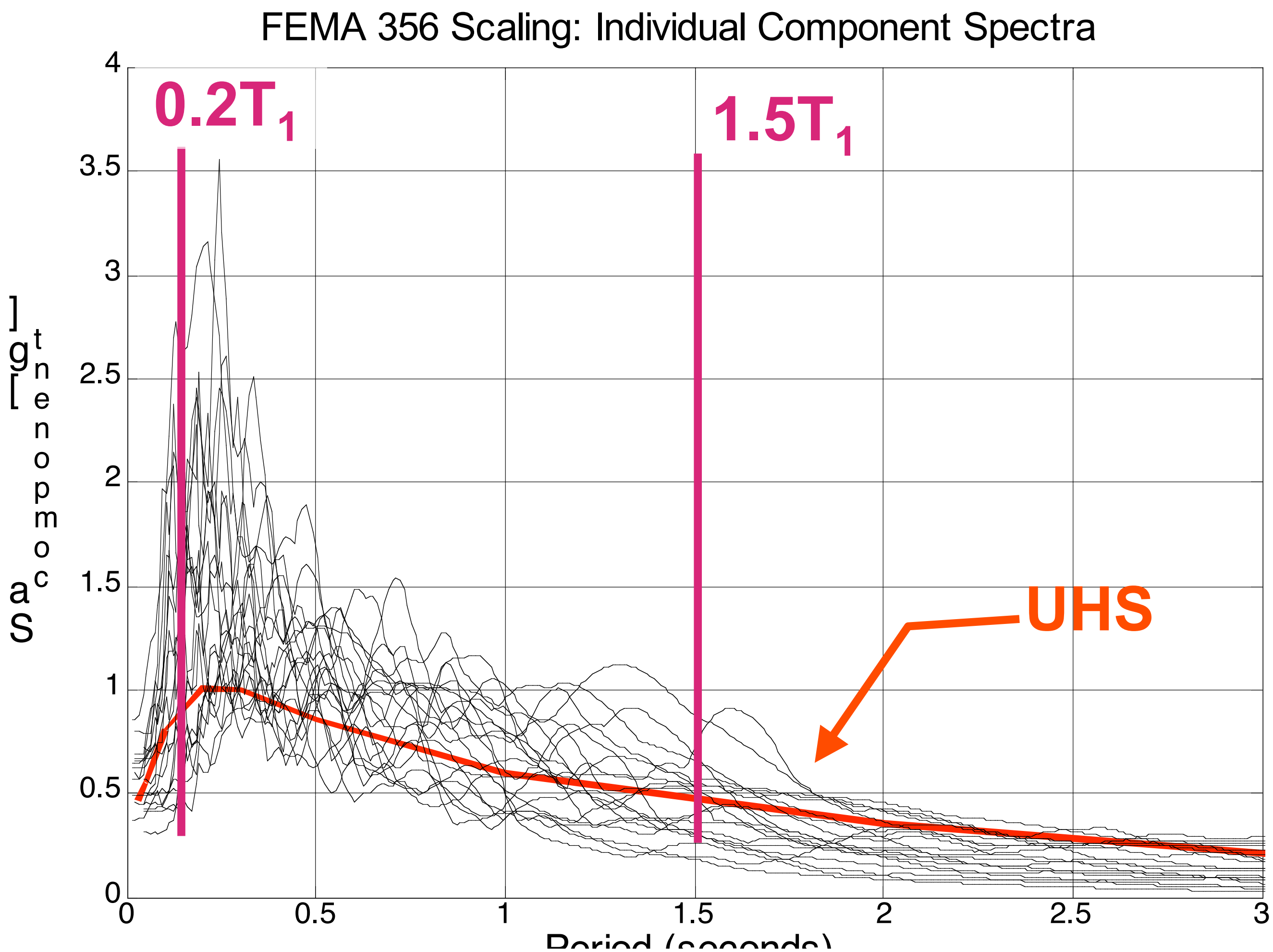
Assessment Using Improved NLTH Analysis

- Nonlinear Component and System Modeling
- FEMA 356 Concepts with NLTH Analysis
- Preview of Comprehensive Collapse Simulation

FEMA 356 with NL Time History Analysis

- NL Analysis Model
  - modeling assumptions (role of component backbone curves?)
- Selection of GM
  - match M, R and fault type/mechanism
  - records from at least 3 events
  - synthetics OK if necessary
- Scaling of GM to UHS to “design EQ”
  - 5% damped spectra from SRSS of two orthogonal components
  - Scale such that SRSS spectra > 1.4 UHS for periods between $0.2T_1$ and $1.5T_1$

Ex. – Ground Motion Scaling to 10/50 Hazard



20 components for 10 pairs of EQ Records

FEMA 356 with NL Time History Analysis

- Acceptance Critera
  - Demand Parameters < Component Criteria
    - e.g., $\Theta_p < \Theta_{p,limit}$
  - Evaluation based on either:
    - Maximum demand from results of 3 records
    - Average demand from results of >7 records

Concerns:

- statistical rationale for acceptance criteria ?

- implementation (which 3 records) ?

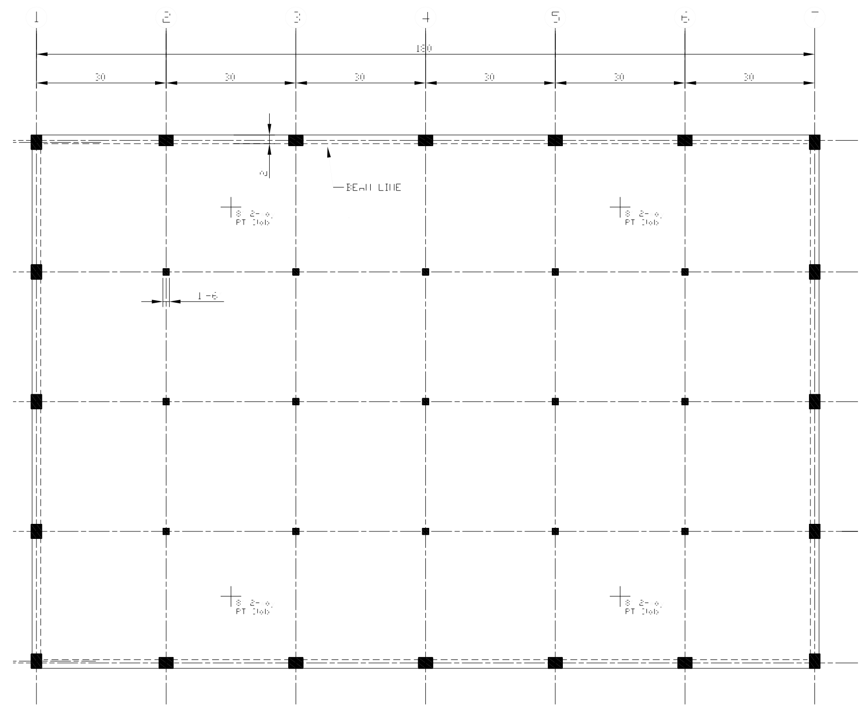
"Enhanced FEMA 356"

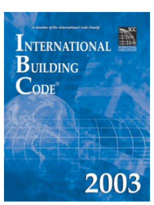
- Realistic Inelastic Model
- Nonlinear Time History Analysis
- 20 ground motions (10 pairs) with their geometric mean scaled to hazard at Sa(T1)
- Statistical evaluation of deformation demands to input ground motions
- Probabilistic assessment of component acceptance criteria to test data

$$Probability[\Theta_p > \Theta_{p,limit\text{-}state}] = X$$

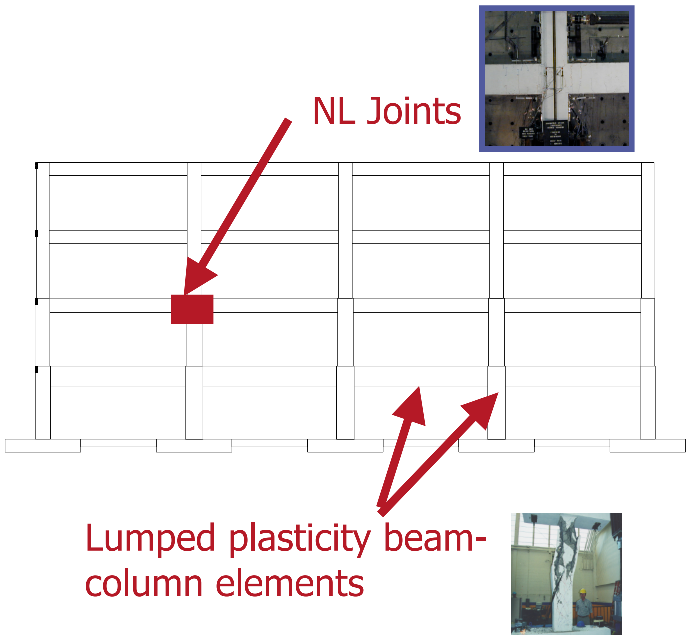
Illustration – 4 Story SMF Building

- Office occupancy
- Los Angeles Basin
- Design Code: 2003 IBC / 2002 ACI / ASCE7-02
- Perimeter Frame System
- Maximum considered EQ demands:
  - $S_s = 1.5g$; $S_1 = 0.9g$
  - $S_{a(2\% \text{ in } 50 \text{ yr})} = 0.82g$
- Design V/W of 0.094g
- Maximum inelastic design drift of 1.9% (2% limit)



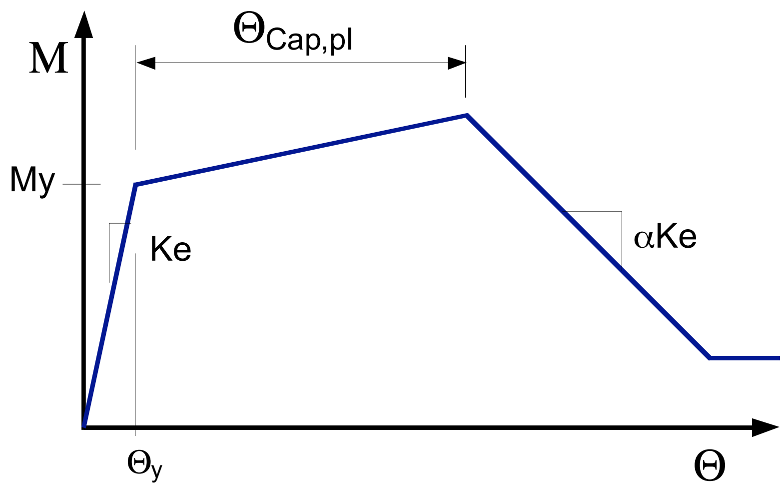


RC Beam & Column Component Models



OpenSees Model

- Lumped plasticity beams, columns, and joints with strength/stiffness degradation
- Geometric NL (P-Δ)
- 20 ground motions (10 pairs)

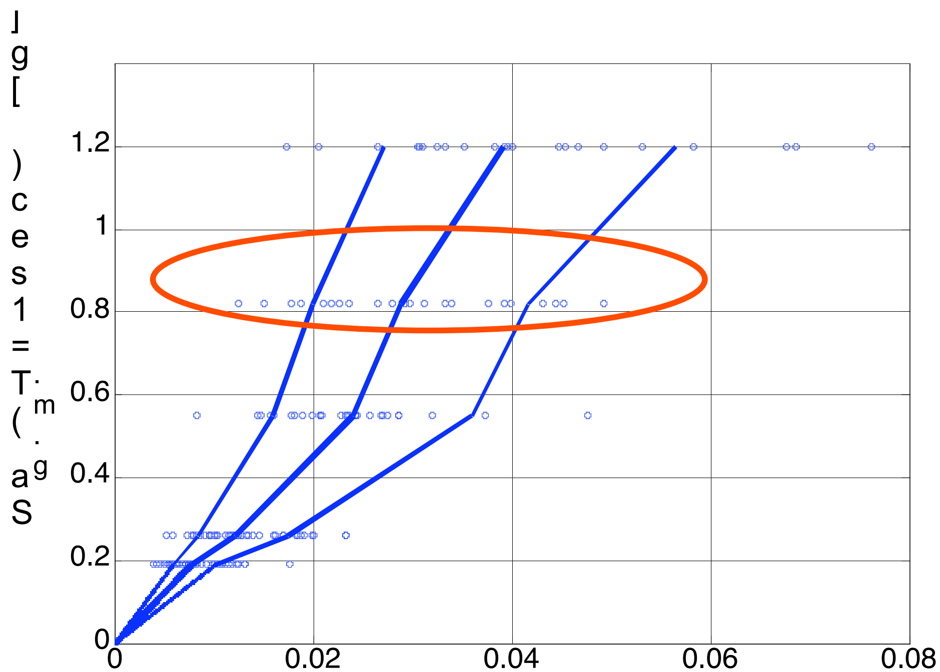


$\Theta_{pl,cap}$ of conforming members:

- **Columns (low axial)**
  Mean = 0.050 rad
  COV = 40%
- **Beams**
  Mean = 0.065 rad
  COV = 40%

PEER

Peak Interstory Drift Demands



At 2% in 50 year (MCE) Sa:

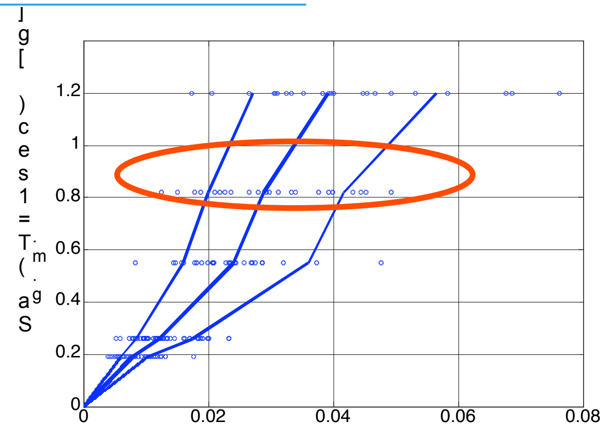
IDRmax = 0.016 to 0.050

Mean IDR_{max} = 0.028

COV = 37%

- 20 time history analyses at each of 5 hazard levels
- peak inter-story drift ratio from each time history analysis
- ground motions are scaled to hazard spectra over the region $0.2T_1$ to $1.5T_1$.

Probabilistic Measures of Drift Demand



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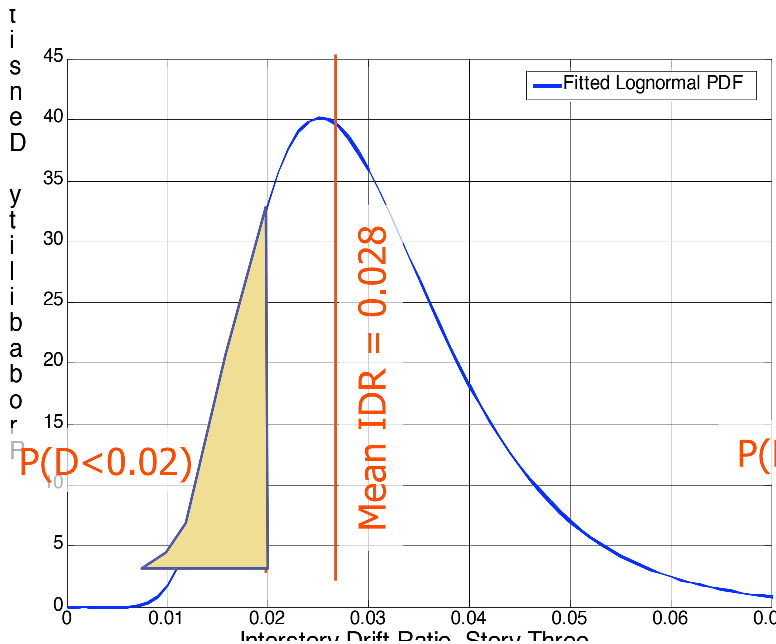
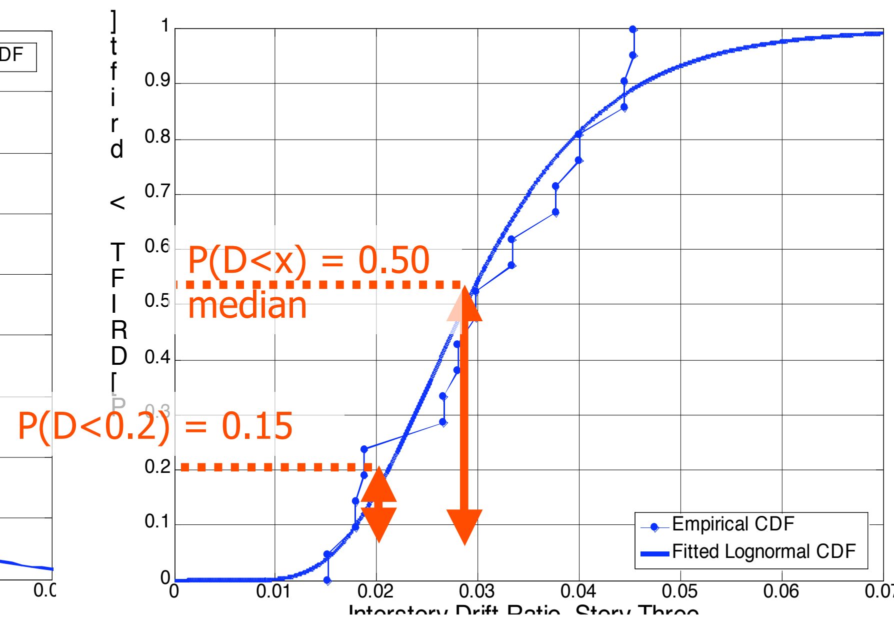
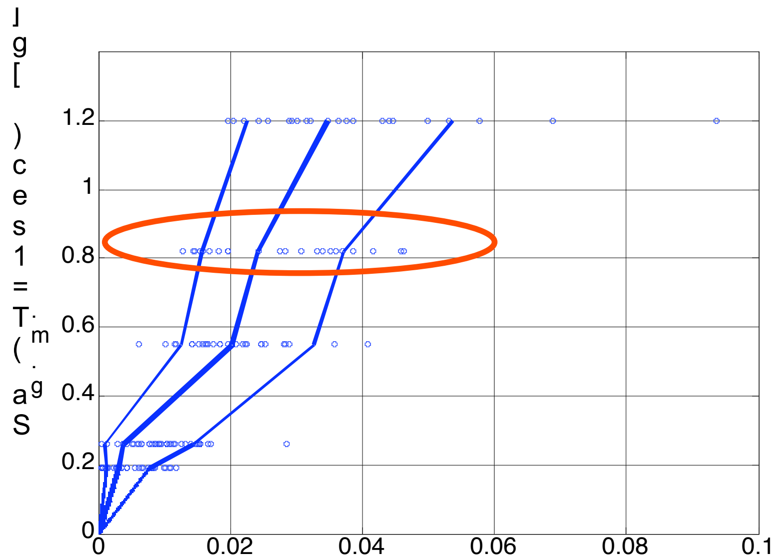


PDF (probability density function)



CDF (cumulative density function)

Beam and Column Plastic Rotation Demands



At 2% in 50 year (MCE) Sa:

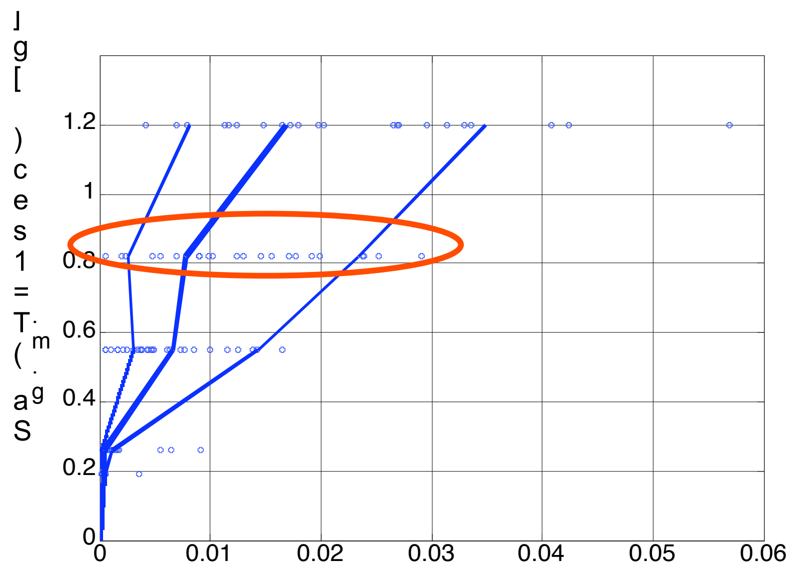
Beams:

$\Theta_{p,max}$ = 0.012 to 0.045

Mean $\Theta_{p,max}$ = 0.025

COV = 43%

(vs. FEMA 356 Θ_{cp} < 0.025)



Columns:

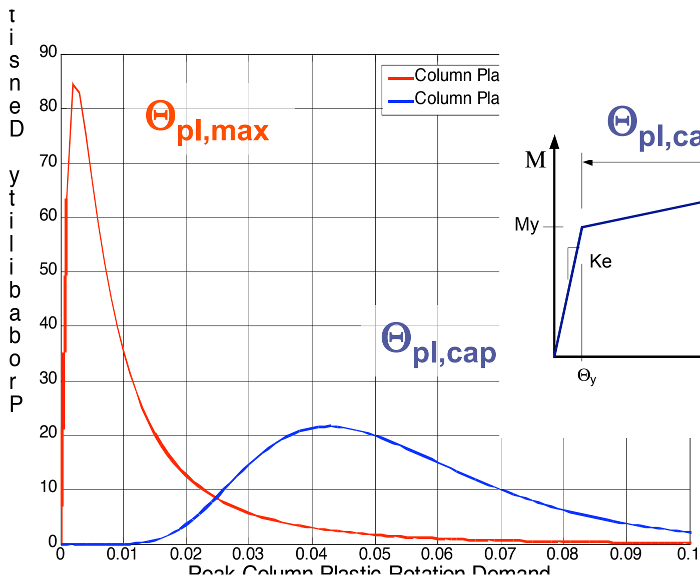
$\Theta_{p,max}$ = 0 to 0.03

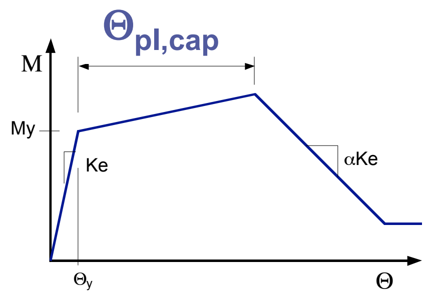
Mean $\Theta_{p,max}$ = 0.010

COV = 110%

(vs. FEMA 356 Θ_{cp} < 0.020)

Probabilistic Limit State Assessment





	Demand ($\Theta_{pl,max}$)		Capacity ($\Theta_{pl,cap}$)	
	μ	σ_{ln}	μ	σ_{ln}
Beams	0.025	0.43	0.065	0.40
Col's	0.010	1.10	0.050	0.40

$$P[D \geq C] = 1 - \Phi\left(\frac{0 - \mu_{\ln,z}}{\sigma_{\ln,z}}\right)$$

where: $$\mu_{\ln,z} = \mu_{\ln,D} - \mu_{\ln,C}$$

$$\sigma^2_{\ln,z} = \sigma^2_{\ln,D} + \sigma^2_{\ln,C}$$

Φ (standard normal table)

Component Limit State Checks:

Beams *P[D>C] = 5.6%*

Columns *P[D>C] = 5.6%*

(just a coincidence that they turn out the same)

Comments

- Advantages

  -More transparent and rigorous assessment of component limit state criteria

  -Framework to incorporate available test data (outside the scope of FEMA 356)

- Limitations and Issues

  - Requires judgment to select appropriate limit states and the probabilistic acceptance criteria, i.e., *P[D>C] at some hazard level*

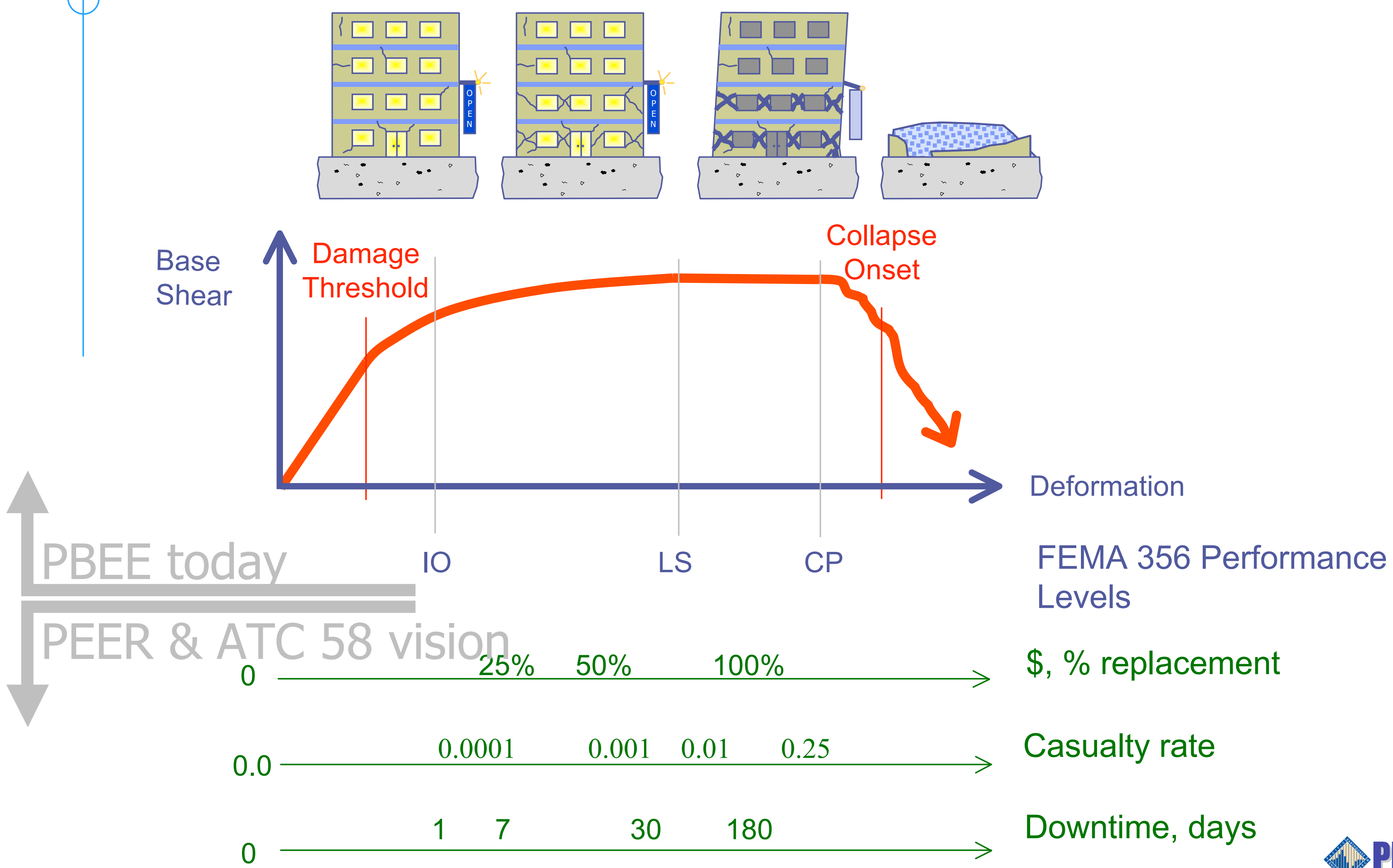
  -Still limited by assumptions between component and system performance.

  - Does not incorporate variability and uncertainties in structural system behavior.

Assessment Using Improved NLTH Analysis

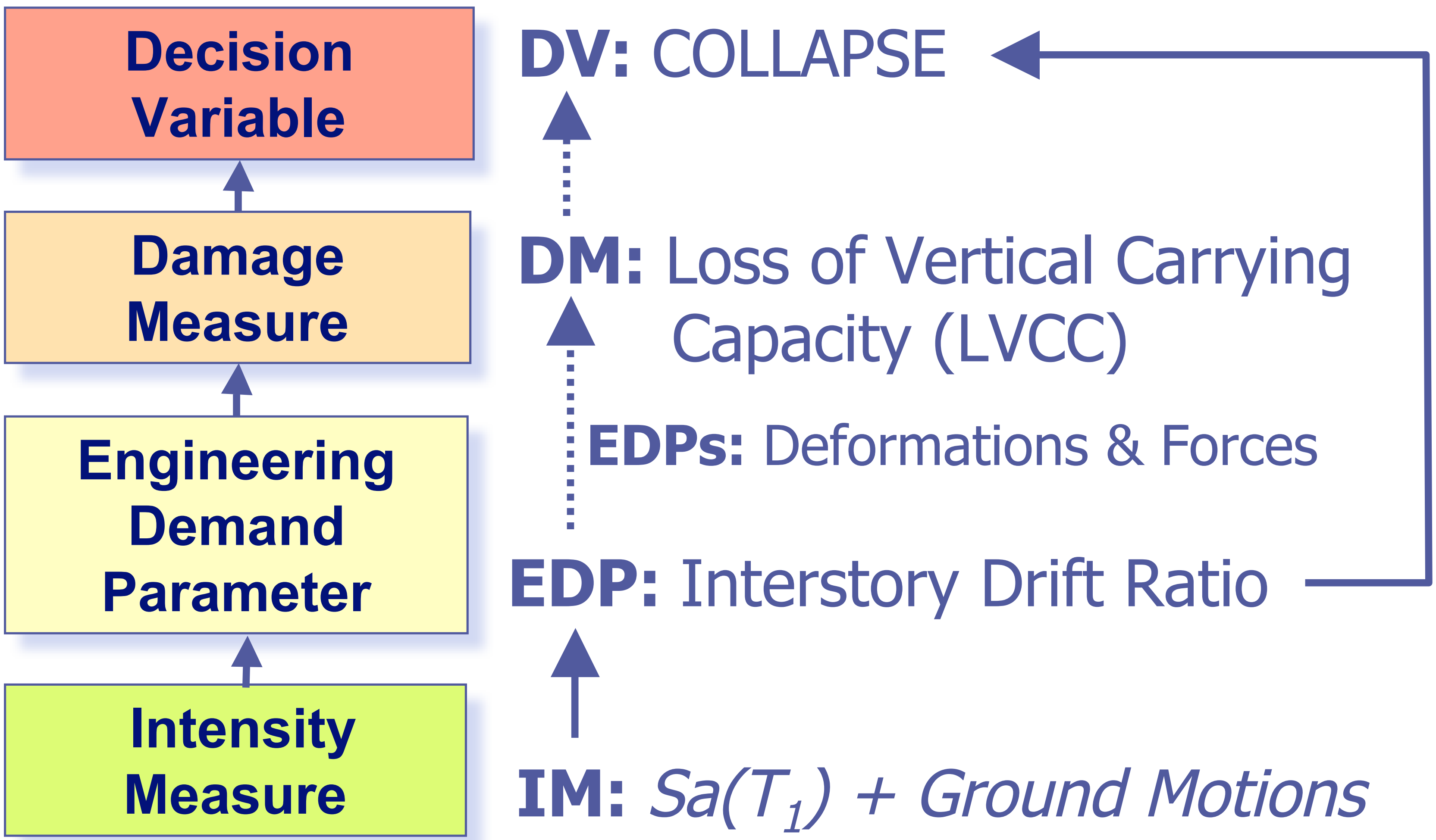
- Nonlinear Component and System Modeling
- FEMA 356 Concepts with NLTH Analysis
- Preview of Comprehensive Collapse Simulation

Performance-Based Earthquake Engineering

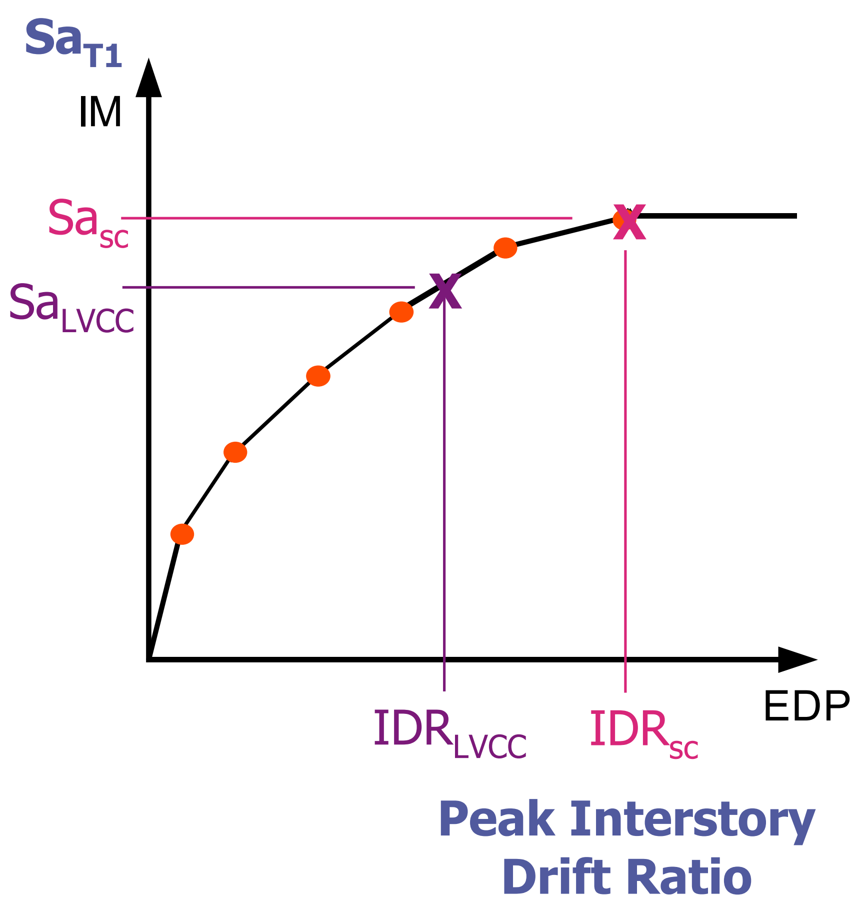


PEER

PBEE COLLAPSE (SAFETY) Assessment

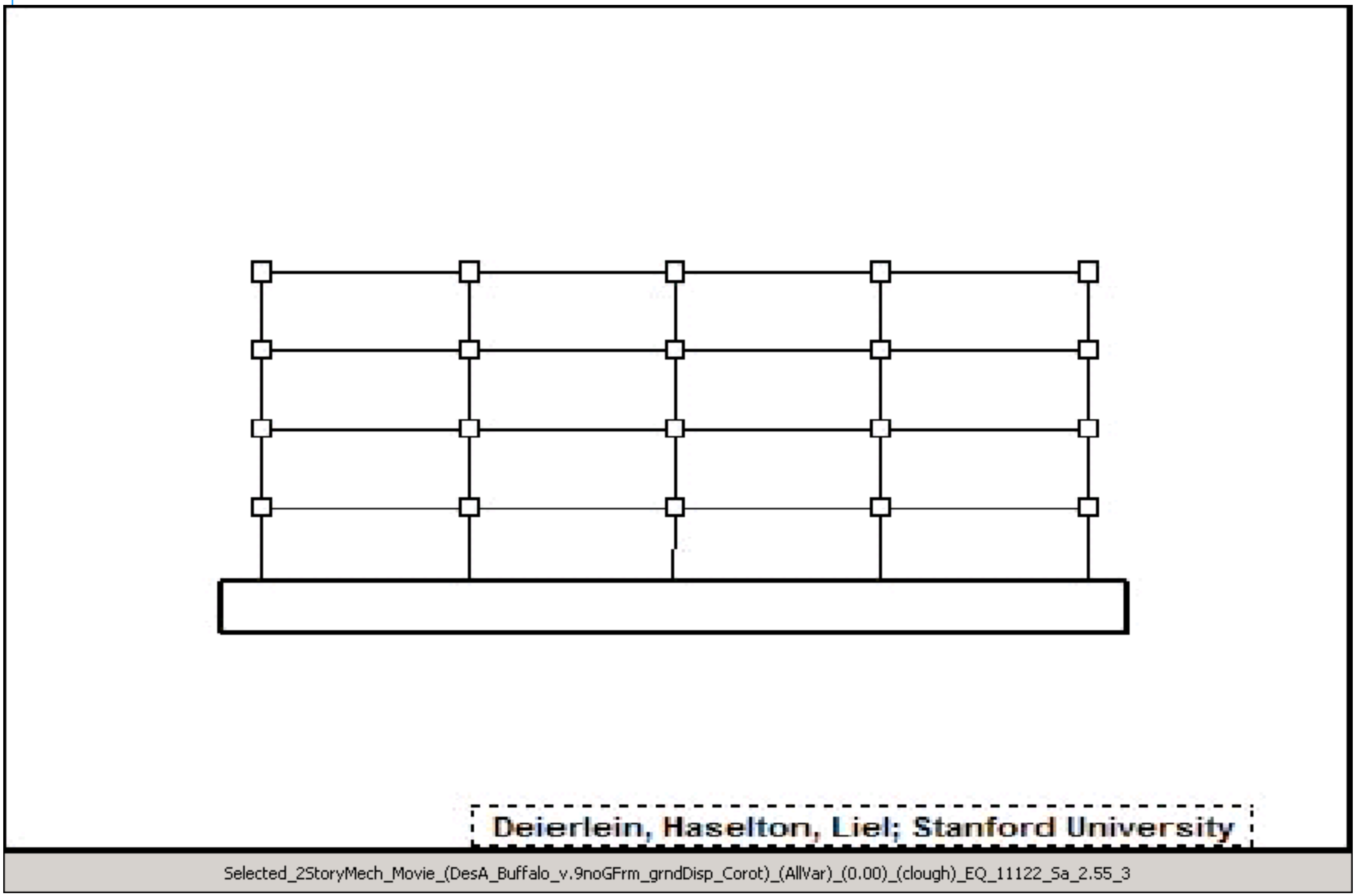


Incremental Dynamic Analysis Concept

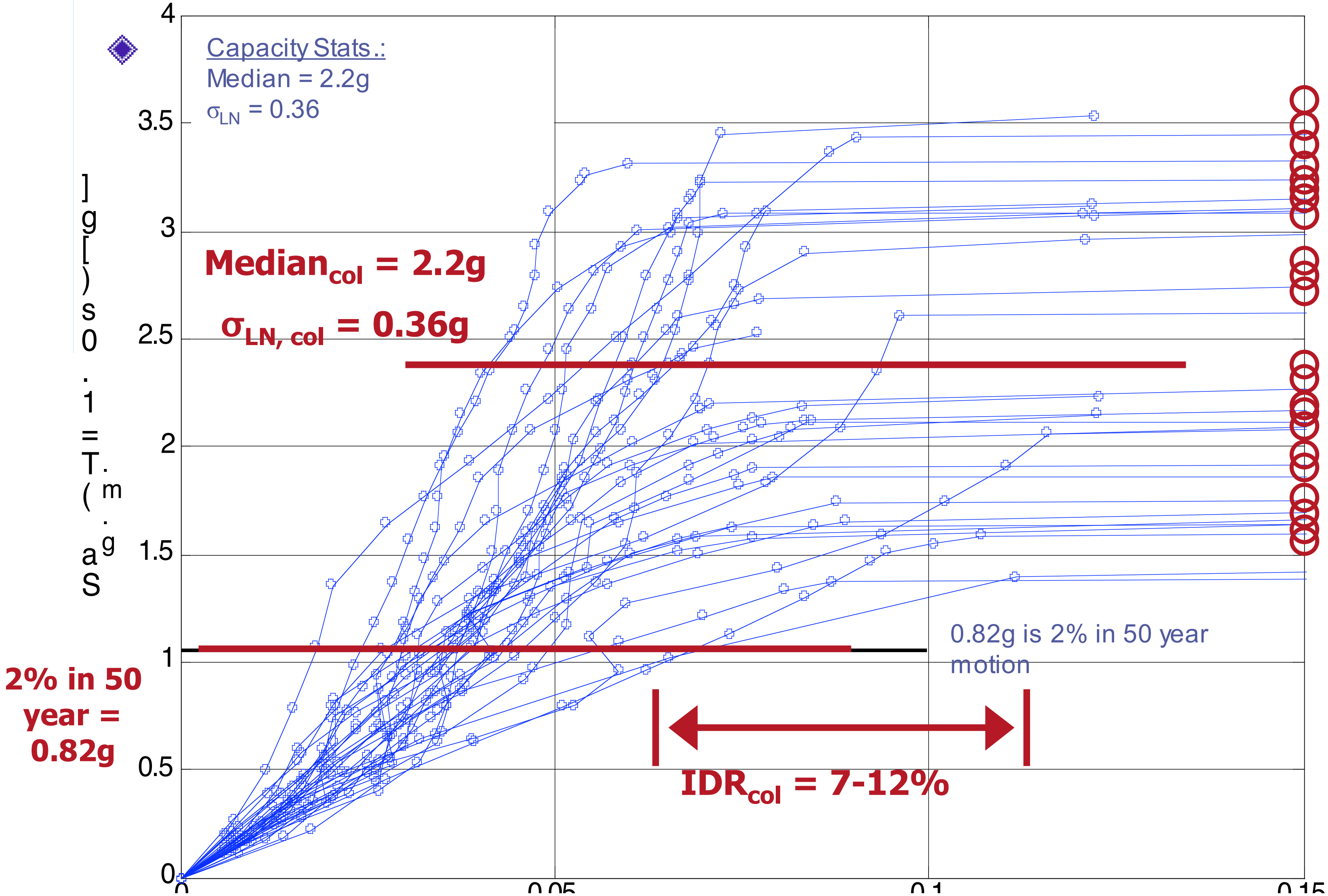


1. Given: Inelastic Analysis Model
2. Select and scale earthquake ground motion to specified earthquake intensity (IM)
3. Perform nonlinear time history analysis
4. Record and plot engineering demand parameter (EDP)
5. Repeat steps 2-5 until system collapse is observed through analysis
6. Perform check for local LVCC conditions that are not simulated in analysis

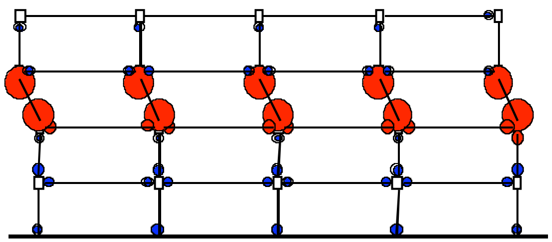
Sidesway Collapse Simulation – 4 Story SMF



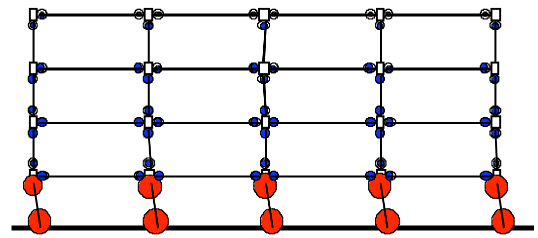
Incremental Dynamic Analysis – Collapse



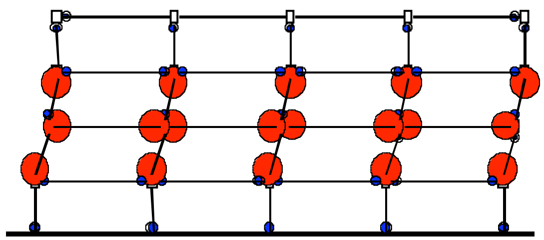
Sidesway Collapse Modes



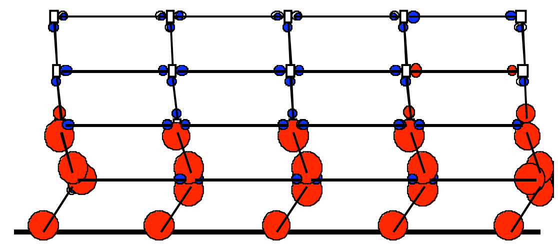
40% of collapses



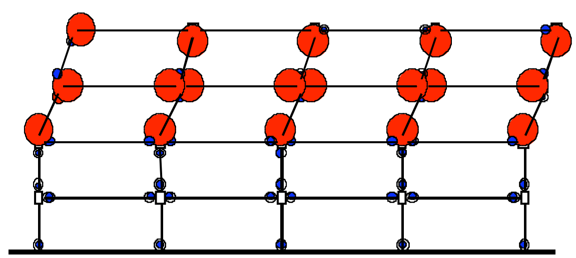
27% of collapses



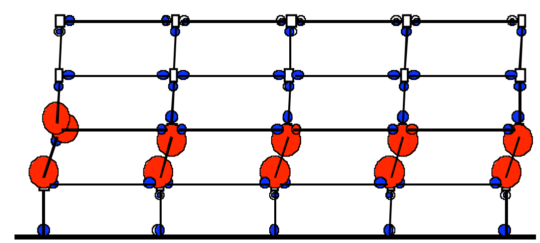
17% of collapses



12% of collapses

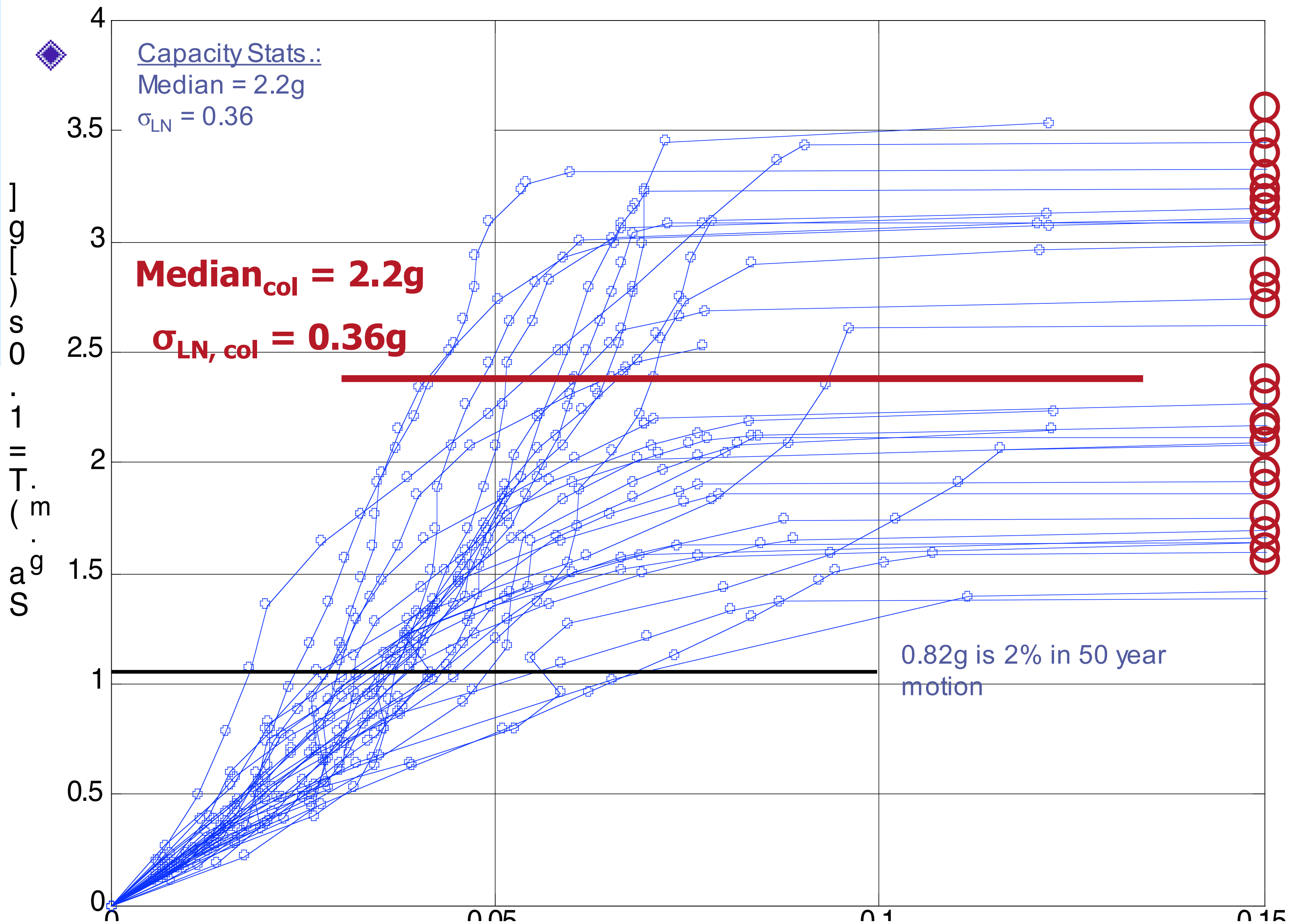


5% of collapses

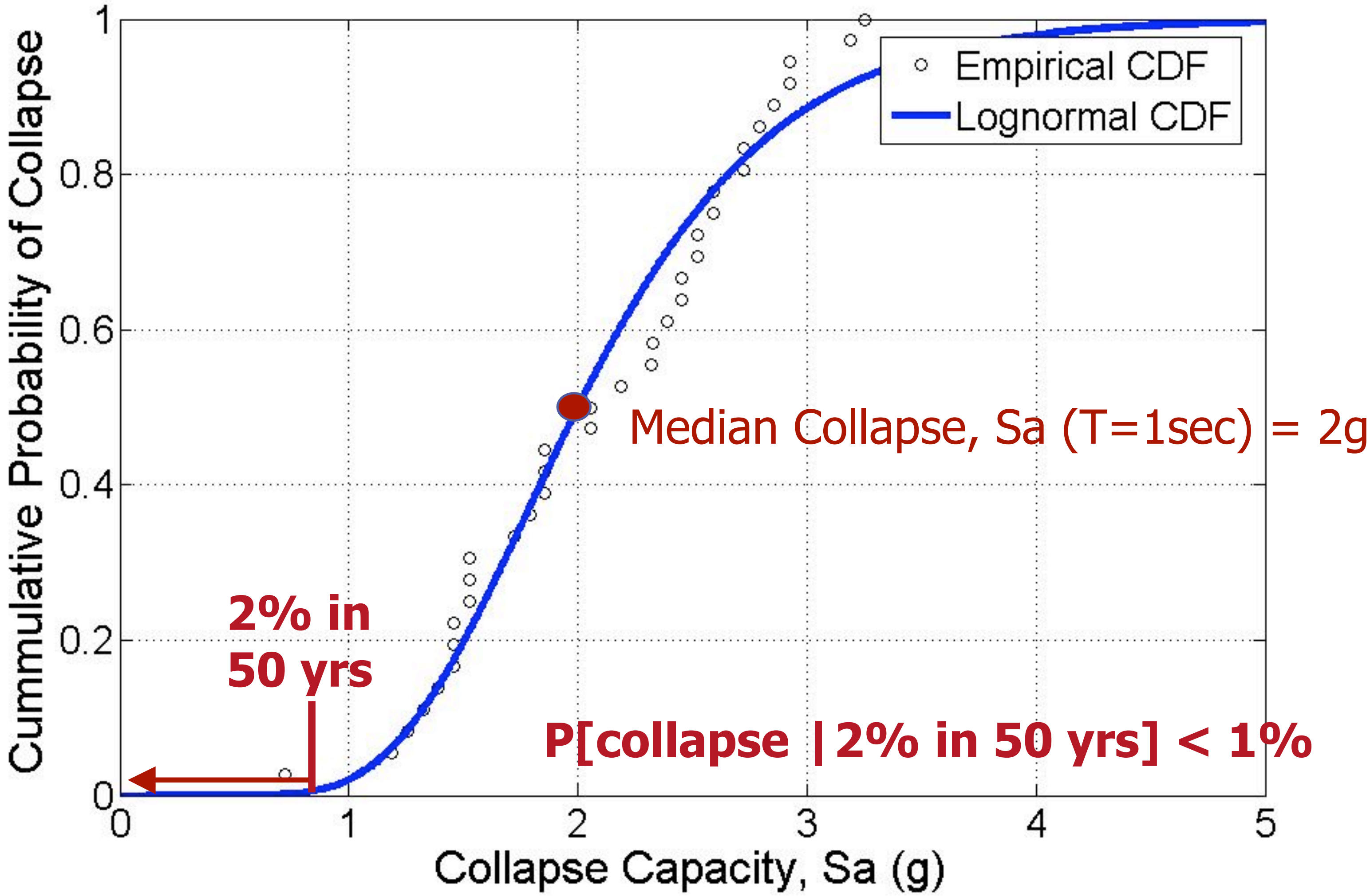


2% of collapses

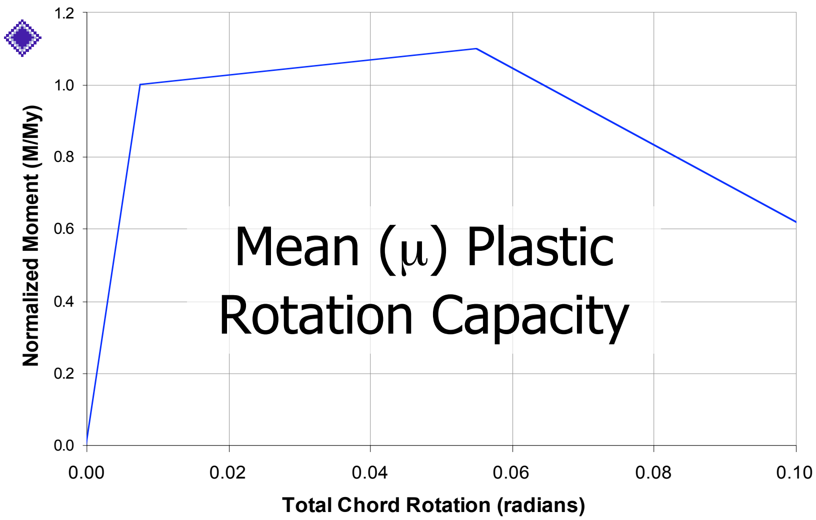
Incremental Dynamic Analysis – Collapse

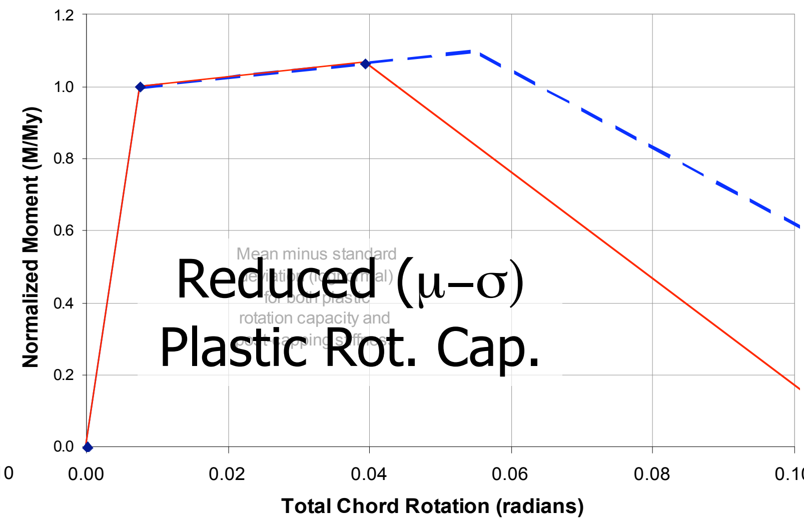


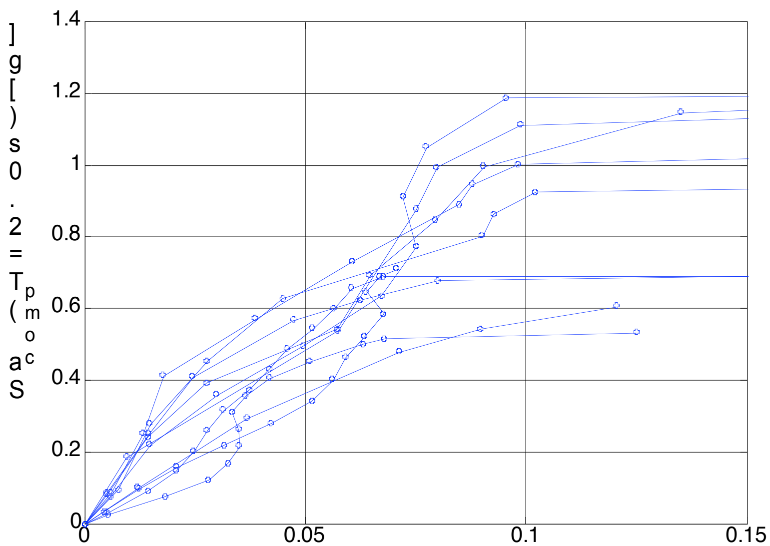
Collapse Capacity – Empirical and Lognormal Fit

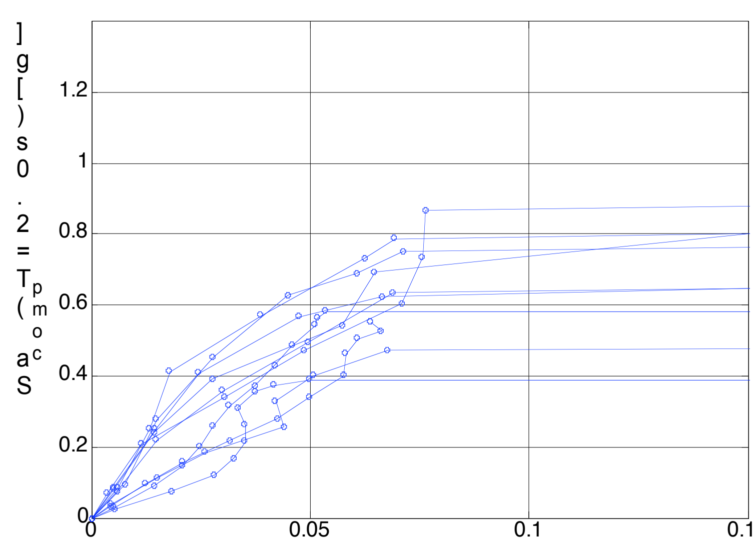


Uncertainty – Plastic Rotation Capacity

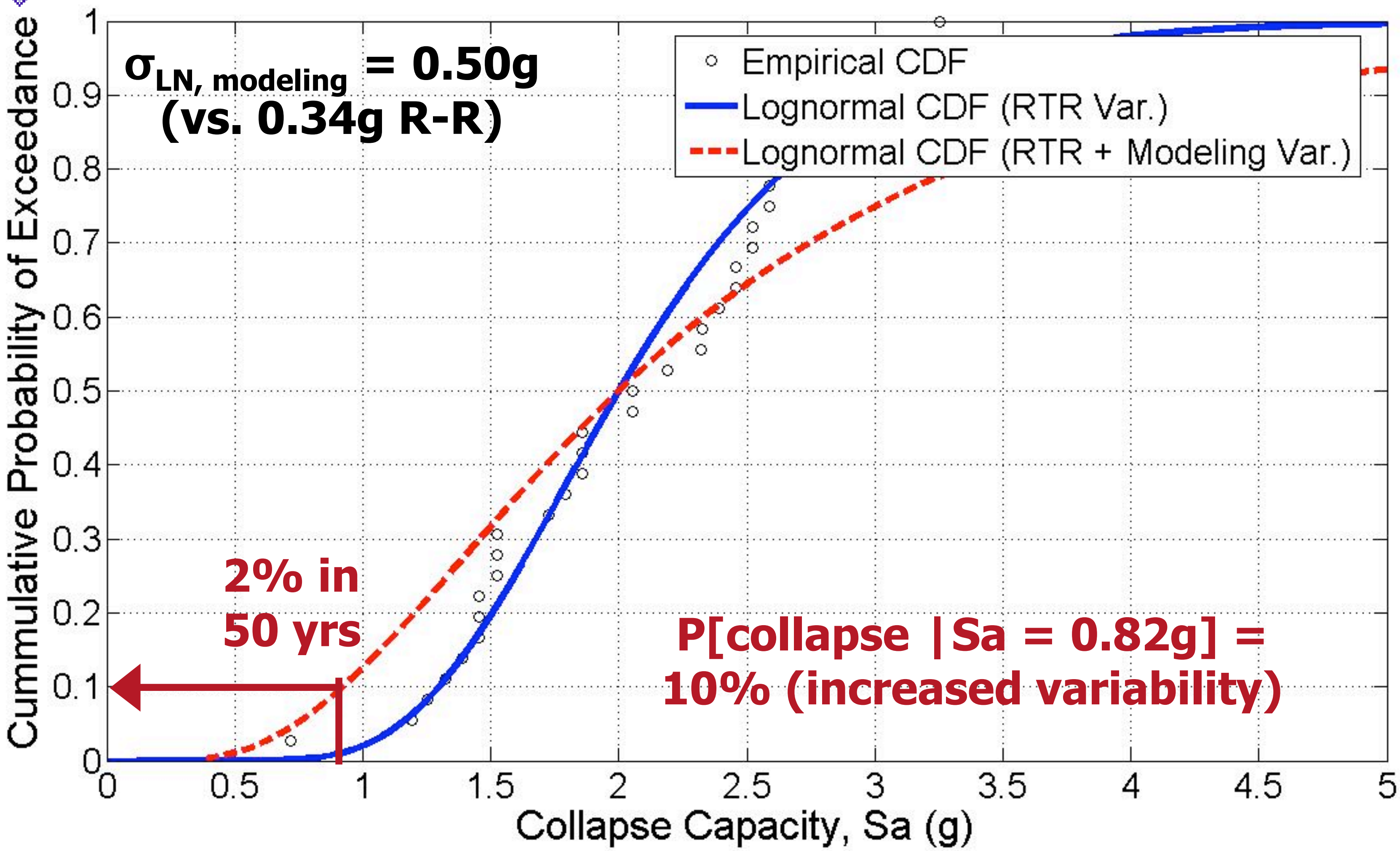








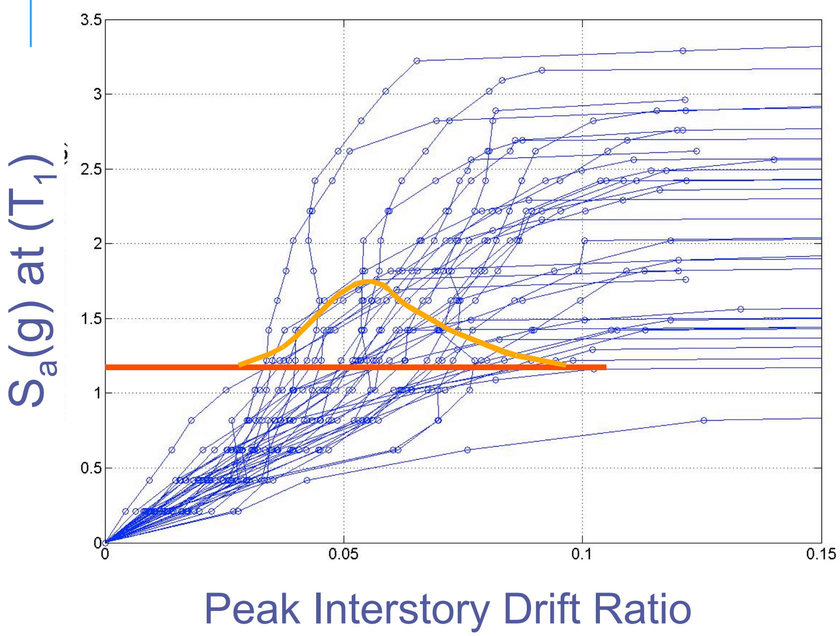
Collapse Capacity – with Modeling Uncert.

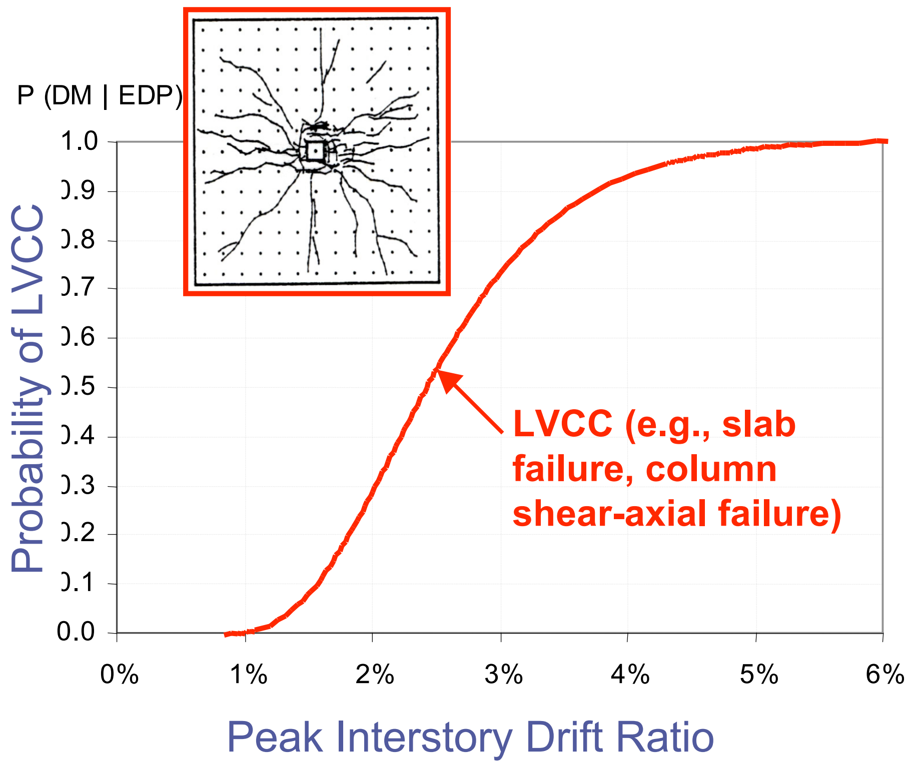


Combined Sidesway and Vertical (LVCC) Collapse

$$P[C \mid IM = im] = P[C_{SIM} \mid IM = im] + P[C_{DM} \mid NC_{SIM}, IM = im] \cdot P[NC_{SIM} \mid IM = im]$$

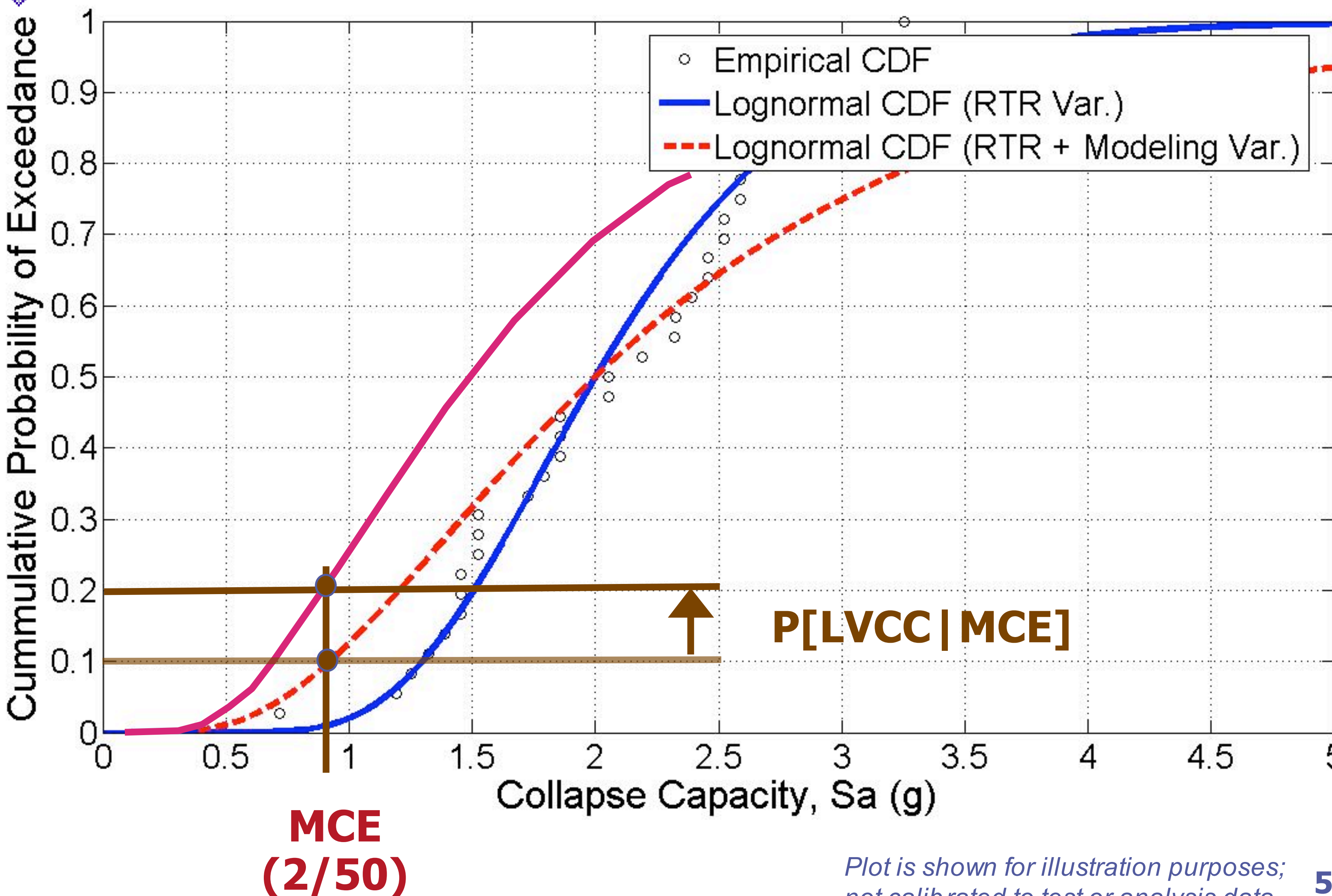
Total Collapse Probability = **Sidesway Collapse Probability at IM_i** + **Probability of LVCC (given drift ratio)** X **Probability of no SS Collapse at IM_i**





Plot is shown for illustration purposes; not calibrated to test data.

Collapse Capacity – Simulation + LVCC



Plot is shown for illustration purposes; not calibrated to test or analysis data.

Concluding Remarks

- Benefits of Assessment by NLTH Analysis
  - More explicit simulation of cyclic and dynamic effects
  - Transparent and extendable to innovative systems and materials
- Challenges with NLTH Analysis
  - Calibration/Validation of Hysteretic Component Models
  - Selection and Scaling of Input Ground Motions
  - Computational hurdles (convergence, runtime, post-processing)
- Standardization of Structural Component Models & Criteria
  - Simulation & fragility models
  - Statistically "neutral" models i.e., *mean* and *COV*
  - Important role for material standards organizations (e.g., ACI)
- Future Vision -- Explicit Assessment of Collapse Risk

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