Modeling Guidelines for Nonlinear Analysis

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LATBSDC May 9, 2008

Guidelines for NL Analysis

- Part I – General Modeling Guidelines
  - Overview of Modeling Issues
  - Energy Dissipation and Damping
  - Deterioration and Modeling Options
- Part II – Properties of Structural Components
  - Structural Steel: Beams and Columns
  - Reinforced Concrete: Beam-Columns and Joints

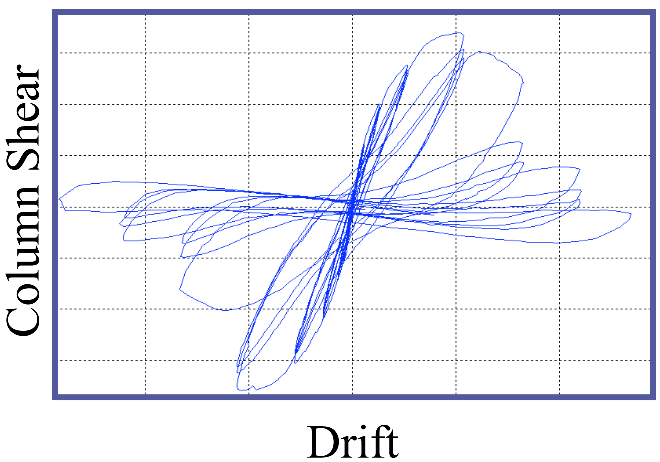
NL Analysis Considerations for Design

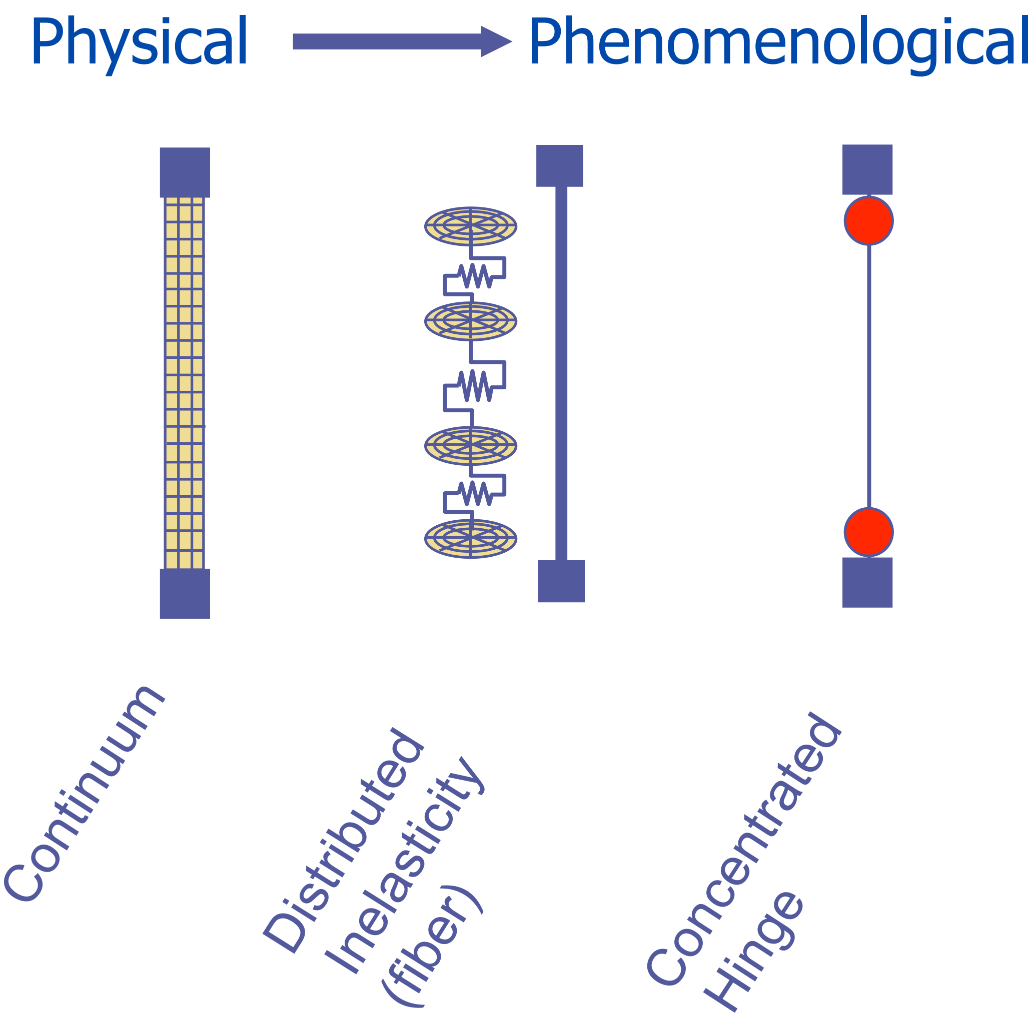
- Accurate Assessment of Building Performance
  - Structural Performance and Limit States
  - Non-structural and Contents Performance
- Evaluation of Serviceability Limit State
  - Limit State: limited yielding/cracking & permanent deformations
  - Modeling: effective (elastic) stiffness
- Evaluation of Safety (MCE) Limit State
  - Limit State: onset of severe degradation
  - Modeling: post-yield response and degradation (how much?)
- "Non-Modeled Effects"
  - contribution of gravity systems to lateral response
  - nonstructural components
  - certain energy dissipation, degradation, and failure modes

Key Considerations for Idealized Models

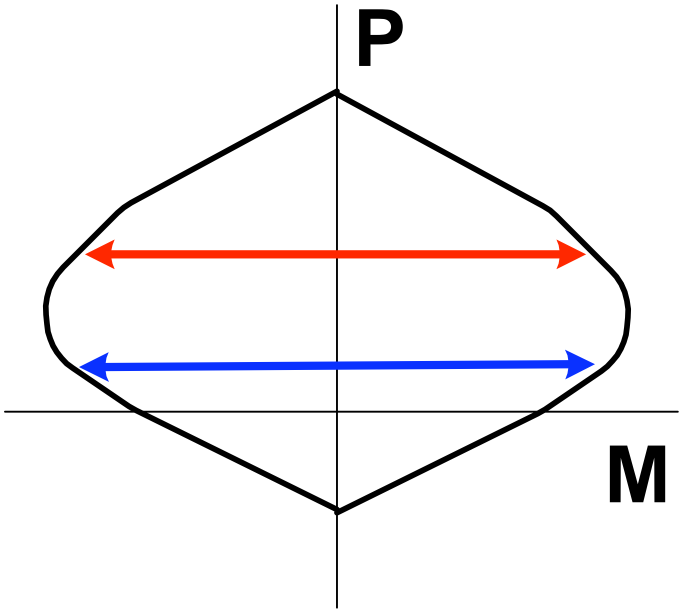
- How faithfully do models capture *significant* behavioral effects
  - Pre-yield (initial) stiffness
  - Strength and failure modes
  - Post-yield deformations and deterioration
- Practicality and reliability for design practice
  - Relationship to "codified" standards for strength and deformation capacity
  - Transparent and easy to verify
- Ability to Represent Variability in Response
  - Randomness in input parameters (e.g., f'c, Fy)
  - Epistemic model uncertainties

Model Idealizations

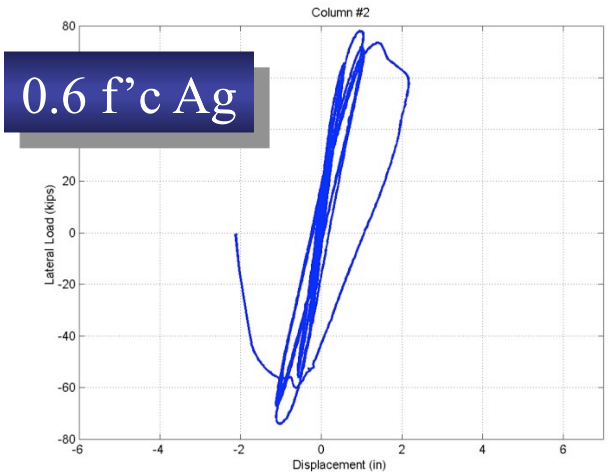


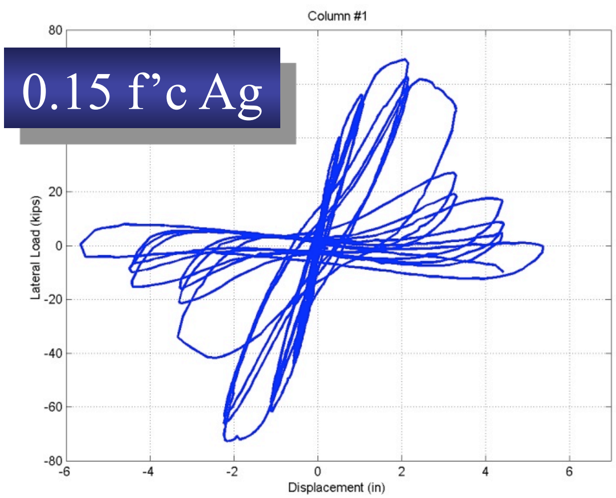


Axial Load & Post-Peak Response in RC Columns



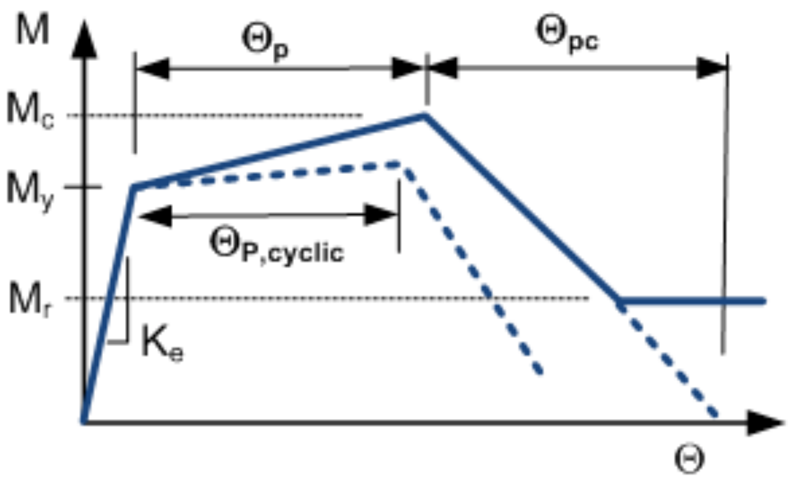
Key Parameter: $P/P_{balance}$





Tests by: Moehle & Sezen

Example: RC Column Hinge Model

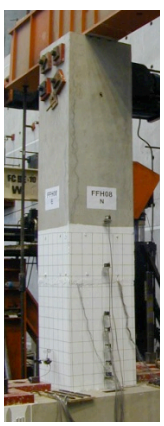


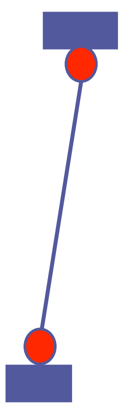
Key Parameters:

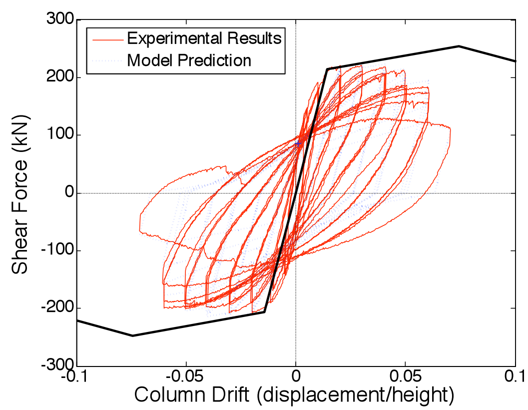
- strength
- initial stiffness
- post-yield stiffness
- plastic rotation (capping) capacity
- post-capping slope
- cyclic deterioration rate

Advantages:

- Compatible with design models and standards for stiffness, strength and deformation capacity
- Easy to calibrate and validate backbone and hysteresis parameters to test data
- Ability to empirically model complex failure modes and deterioration (e.g., rebar buckling and fracture)



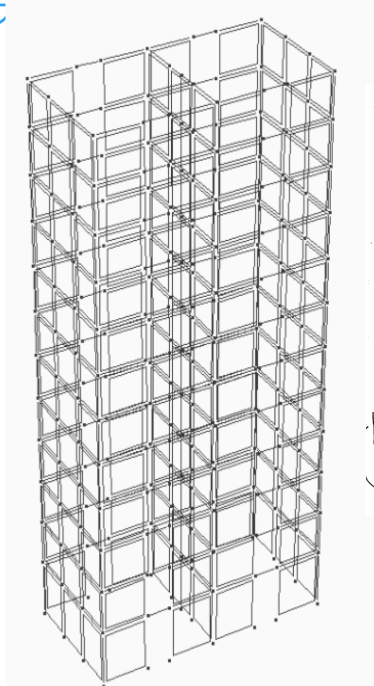


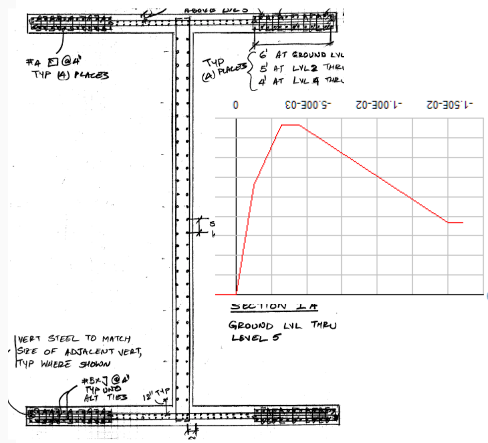


Disadvantages:

- Difficult to capture multi-component force interaction (P-M, Mx-My, P-M-V)

Example: RC Shear Wall "Fiber Model"





Key Parameters:

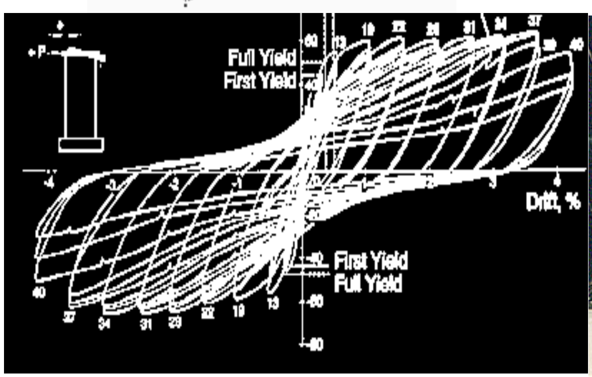
- stress-strain properties of steel and concrete fibers (quasi-uniaxial)
- quasi-elastic shear stiffness

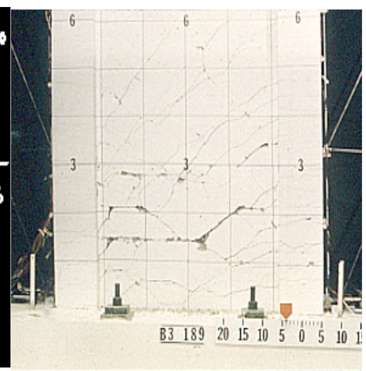
Advantages:

- captures inelastic flexural (P-Mx-My) response out to reasonable deformations
- Reasonable model for quasi-elastic shear deformations and shear lag

Disadvantages:

- Challenges in modeling
  - bond-slip and tension-stiffening
  - degradation due to reinforcing bar buckling and fracture
  - inelastic shear deformations
  - effect of wall openings
- Difficult to model variability in wall response





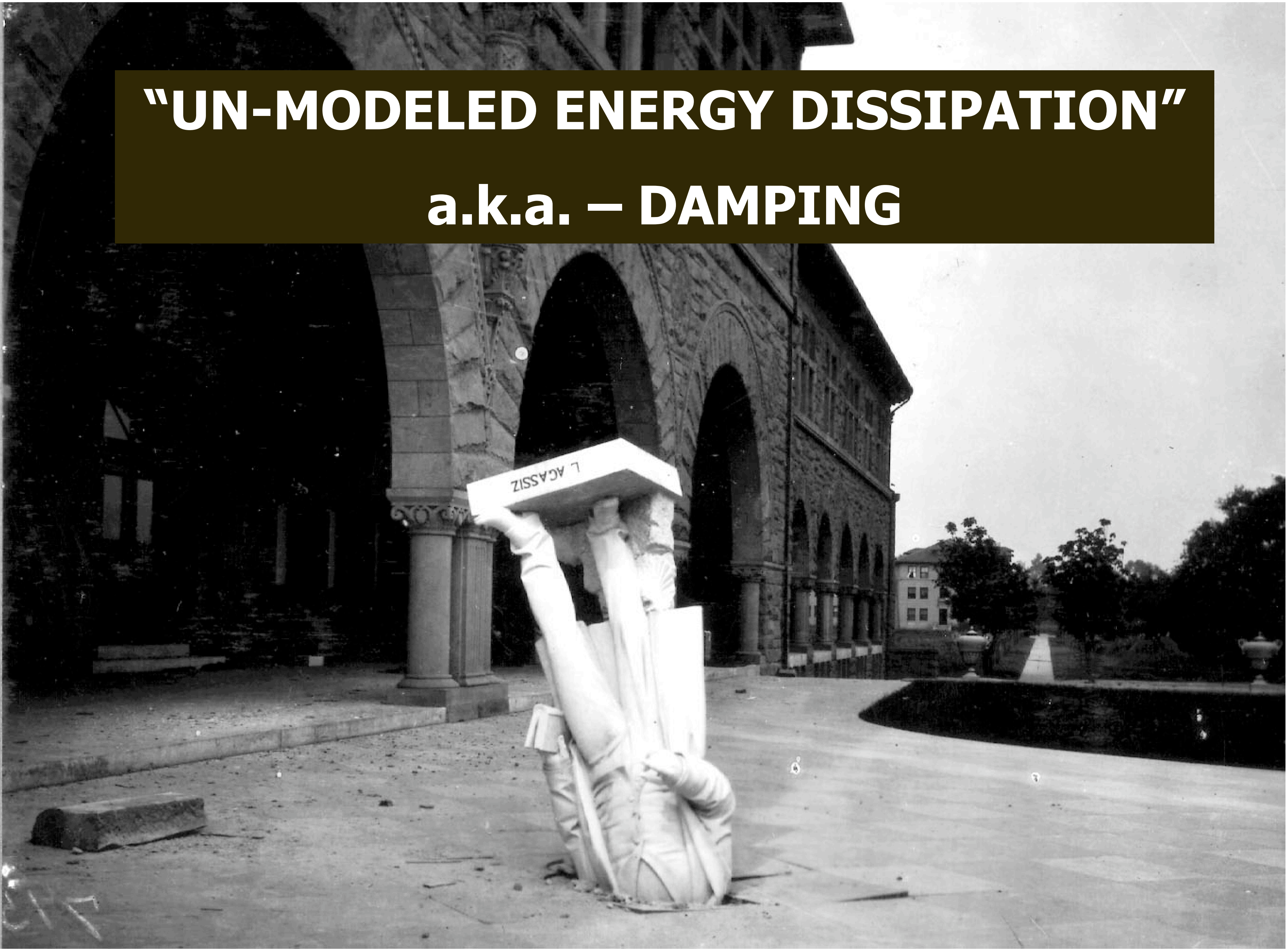
Flexurally dominated response

Key Considerations for Model Calibration

- Identification and quantification of key behavioral indices
  - Model Type – Physical versus Phenomenological
  - Stress-strain or force-deformation
  - Modeled versus Un-Modeled Behavior (deterioration)
  - Availability of data or other supporting evidence
- Robust statistical characterization
  - Unbiased, statistically neutral, mean response prediction
  - Variability in input and response parameters
- Acceptance Criteria
  - Definition of engineering demand parameters and damage measures
  - Establishment of component limit states (serviceability and safety)

“UN-MODELED ENERGY DISSIPATION”

a.k.a. – DAMPING



Viscous Damping with NLTH Analysis

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

Raleigh (proportional) Damping:

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

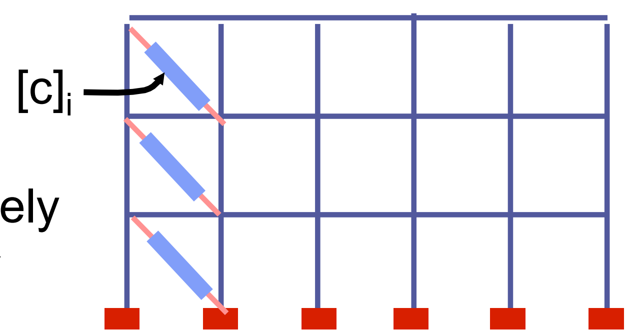
Modal Damping:

$$[C]=[\Phi]^{T(-1)}\begin{bmatrix} c_1 & & \\ & c_2 & \\ & & \cdots \end{bmatrix}[\Phi]^{(-1)}$$

Explicit Damping Elements

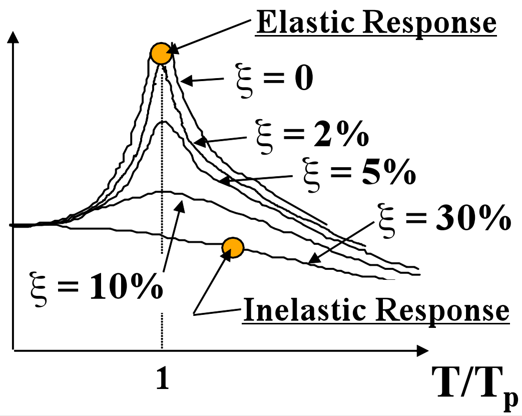
$$[C]=\sum[c]_i$$

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



Modeling of Damping in NLTH Analysis

Definition: reduction in dynamic building response due to energy dissipation of structural and nonstructural components of the building, its foundation, and the underlying soil/rock materials



Complicating Factors: The interpretation and representation of damping is complicated by –

- relationship of ***mathematical representation of damping*** to the physical sources of damping, e.g.,
  - (1) artificial distinctions between energy dissipation of structural components that is modeled by nonlinear hysteretic response versus equivalent viscous damping,
  - (2) modification of input motions to account for reduction in response due to SSI effects
- ***amplitude dependency*** (displacement, velocity, acceleration) of damping effects and its effect on building performance for different overall intensity of building response, and (b) different effects for alternative vibration modes.

Physical Sources of Damping

- SUPERSTRUCTURE – STRUCTURAL:
  - **Primary Structural Components** whose nonlinear behavior may be explicitly modeled in the analysis (e.g., walls, beams, columns, b/c joints)
  - **"Secondary" Structural Components** that contribute to response but whose energy absorbing characteristics may not be modeled explicitly (e.g., energy dissipation provided gravity framing, deformations to floor slab at slab-wall connections, etc).
- SUPERSTRUCTURE – "NONSTRUCTURAL"
  - **Exterior Cladding** – a likely source of considerable damping, depending on the material, method of attachment, expansion joints.
  - **Interior Wall Partitions and Finishes** (issues – materials, method of attachment of finishes to structural walls/braces/columns, method of attachment of partitions to slabs, "density" of partitions – i.e., open office versus partitioned residential)
  - **Mech/Electrica**l - piping, electrical conduit, HVAC risers, elevator rails and cables, stairs, etc.

◆ SUBSTRUCTURE – FOUNDATION & SITE

- soil-foundation interface (e.g, soil yielding and gapping))
- radiation damping

Current/Recent Practice for NLTHA

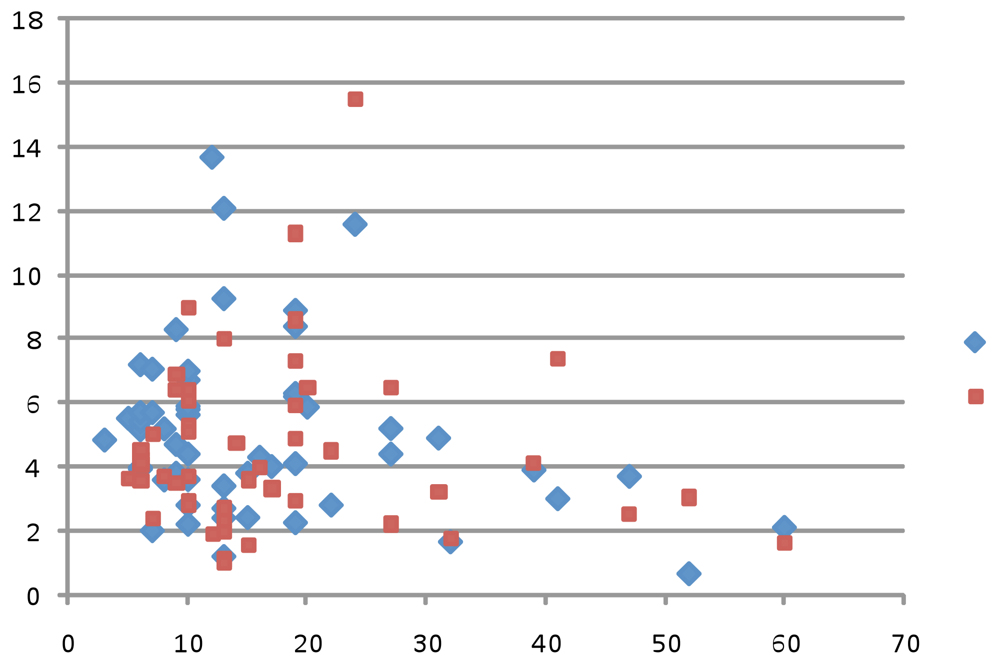
- Assume that energy dissipation at large deformations is primarily accounted for by hysteretic response
- Raleigh (proportional) damping is usually expressed as a percentage of critical damping (for first few modes) to reflect other sources of "un-modeled" energy dissipation:
  - SF AB83 (2007): ≤ 5%
  - LA Alternative Procedure (2005) – not specified
  - SAC Joint Venture (1995): 2%
  - ATC 63 (2007): 5%
  - LATBDC (1989):

    Design EQ – 5% to 10%

    MCE EQ – 7.5% to 12%

Geared to elastic analysis. Too high for NL analysis!!

Recorded Strong Motion Data (US)



REF: Chopra/Goel

Observations:

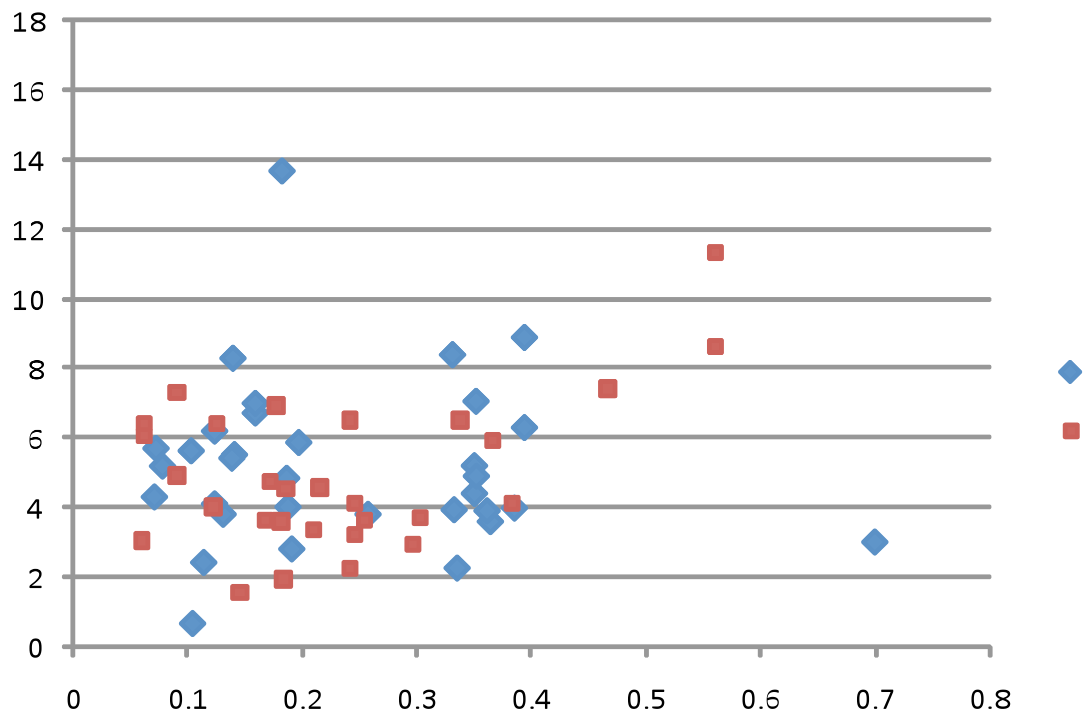
1.Damping in the range of 2% to 8% of critical

2.Reduction in damping with increasing height

Possible Explanations:

- proportionally less soil/foundation damping
- proportionally less nonstructural damping
- smaller excitation (amplitude) in measured earthquakes

Recorded Strong Motion Data (US)

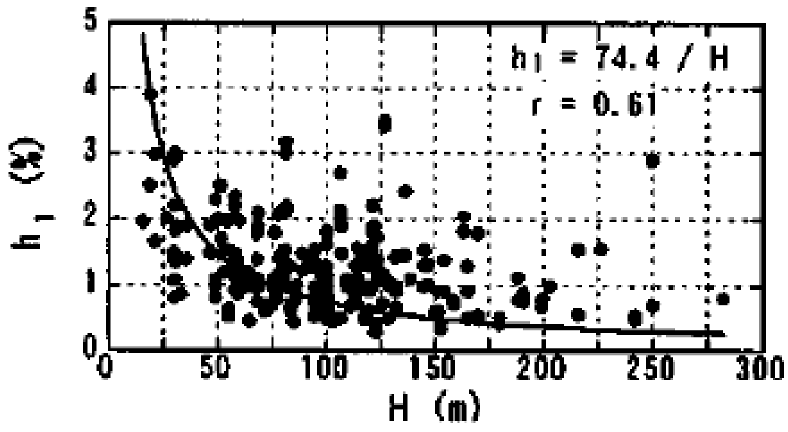


REF: Chopra/Goel

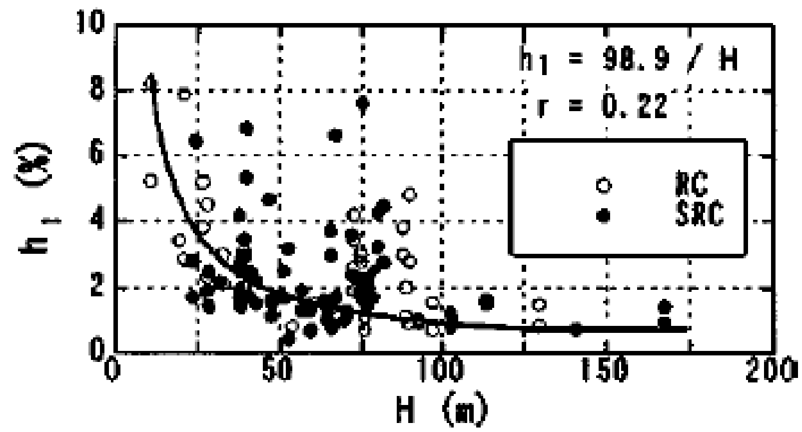
Observations:

1. Modest trend for increase in % Critical Damping with increasing roof drift demand.
2. Interstory drift ratios may vary considerably between cases and may reveal stronger trends

Recorded Motion Data (Japan)



(a) Steel-framed Buildings



(b) RC/SRC Buildings

REF: Satake, 2003

Observations:

1.Data from shaking tests, strong motion and a few ambient

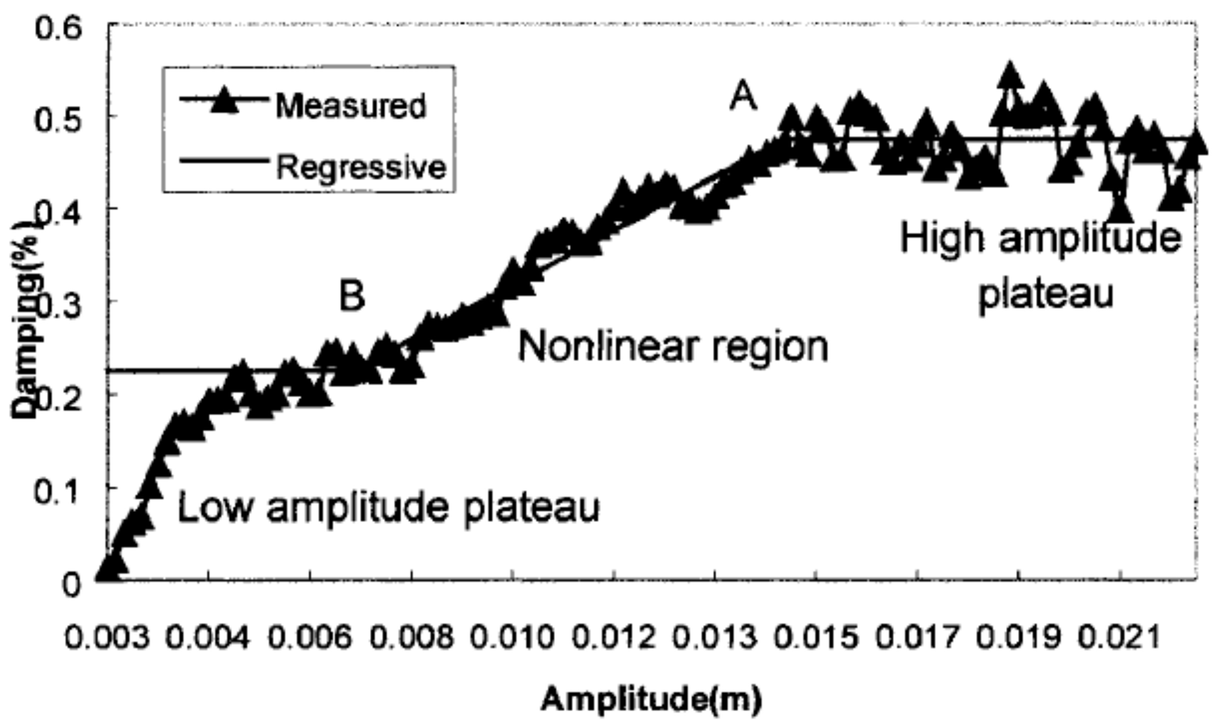
2.Damping ranges:

- Steel-Framed Buildings: 0.5% to 3%
- RC and SRC Buildings: 0.5% to 8%

3.Decreasing damping with building height (suggested trend 1/height)

- Satake et al. hypothesize soil/foundation effects as a major factor

Measured Wind-Induced Damping



- Fair number of tall building measurements that demonstrate amplitude dependence of damping. However, measured response is limited to very low acceleration and displacement amplitudes with correspondingly small damping values.

- The plot above is a typical example, where damping during wind events is typically around 0.5% to 1% of critical.

Measured Wind-Induced Damping

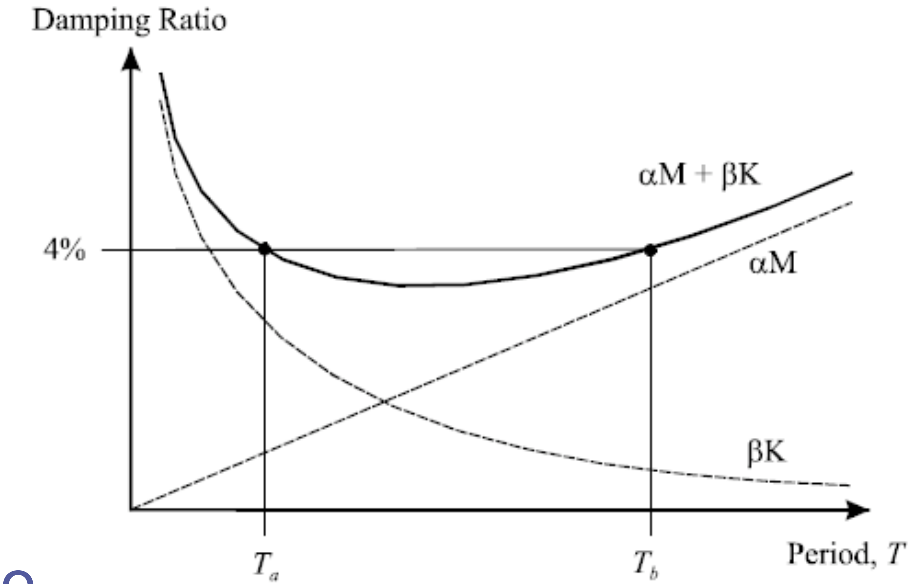
Building Description	*Damping (% critical)*	*Reference*
57 story steel-framed office building	0.8%	Kijewski-Correa et al. (2007), case B1
73 story reinforced-concrete shear wall with outrigger frames	0.8% - 1.2%	Kijewski-Correa et al. (2007), case S1
>50 story steel perimeter tube system	0.9%	Kijewski-Correa et al. (2007), case C1
>50 story reinforced-concrete shear wall with frames	1.4%	Kijewski-Correa et al. (2007), case C2
>50 story steel framed tube system	1.0%	Kijewski-Correa et al. (2007), case C2
79 story Di Wang building, reinforced-concrete core with outriggers	0.4%	Li et al. (2002)
70 story Bank of China, composite braced frame	0.5%	Li et al. (2000)
78 story Central Plaza building, reinforced concrete shear wall	0.5%	Li et al. (2003)
63 story reinforced concrete shear wall	0.3%	Li et al. (2004)

Damping ratios under wind-induced (storm) vibrations of tall buildings range from 0.5% to 1.4% of critical

Considerations for Raleigh Damping

$$[C] = \alpha[M] + \beta[K]$$

$$\zeta_n = \frac{\alpha}{2}\frac{1}{\omega_n} + \frac{\beta}{2}\omega_n$$



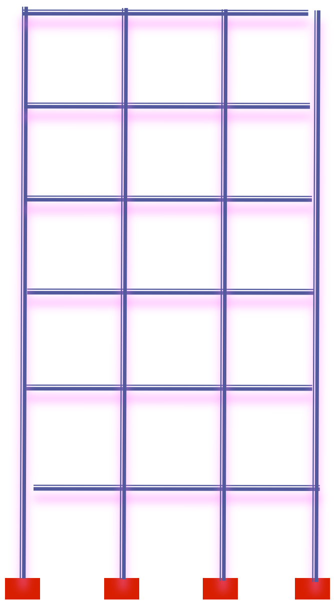
1. Target Damping Ratio
2. Specified Period Range
3. Definition of Stiffness
   - Initial or Tangent Stiffness, Ko or Kt
   - Basis for Ko
4. Other variations:
   - Mass or Stiffness Only
   - Damping parameters (a, b) vary during analysis

Definition of Stiffness

$$[C] = \alpha[M] + \beta[K]$$

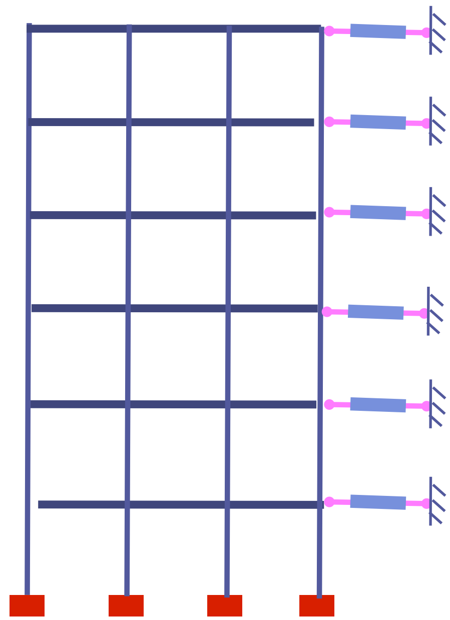
1. Justification for using Ko
   - damping mechanisms do not change during loading
   - Ko or Kt is not a major factor, *aM* dominates first mode damping
   - use of Ko is simpler and more robust
2. Justification for using Kt
   - Maintains original damping ratios as the system as the structure softens and velocities increase (avoids over-damping)
   - safeguards against equilibrium problems with "ill-conditioned" stiffnesses of yielding/cracking elements
   - numerical studies suggest better correlation with tests
3. Definition of Basis Stiffness, Ko
   - "gap" elements/materials, such as cracked concrete in fiber-type formulations, can lead to large initial [C]
   - rigid-plastic hinges (or similar) can lead to local force imbalance

Components to Damping Matrix



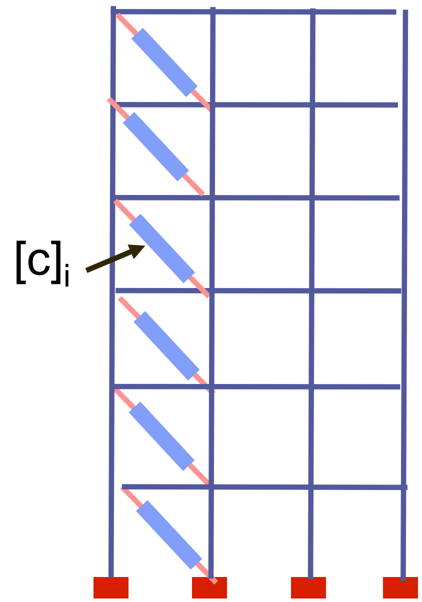
$b[K]$

Stiffness



$a[M]$

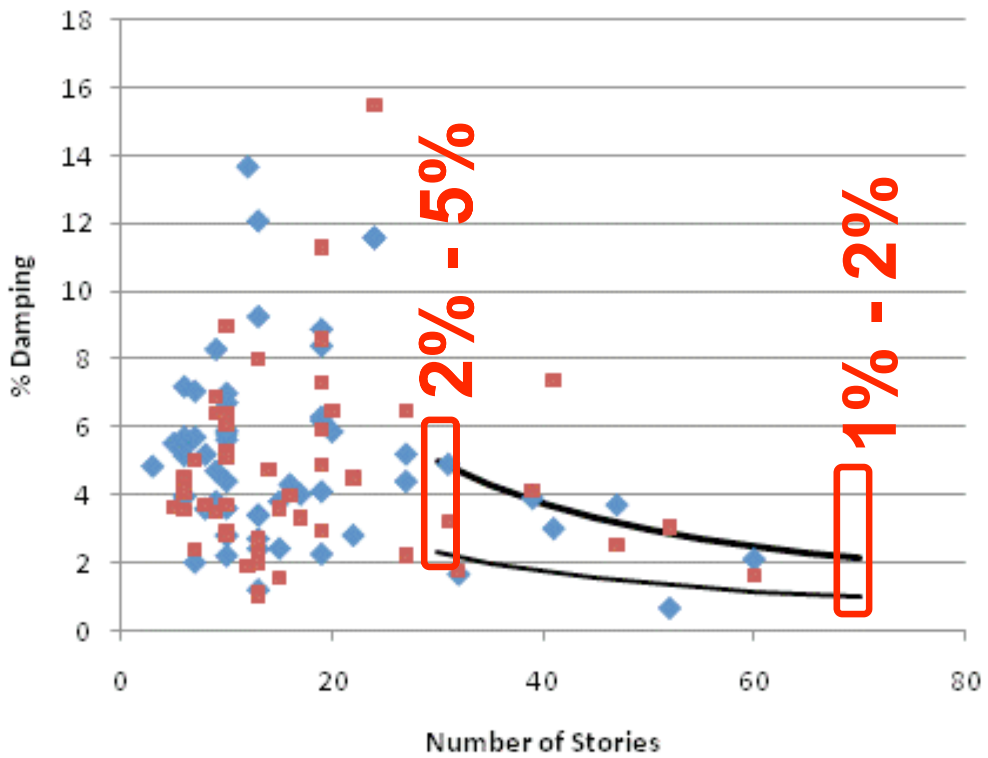
Mass



$\sum [c]_i$

Discrete

Damping Recommendations



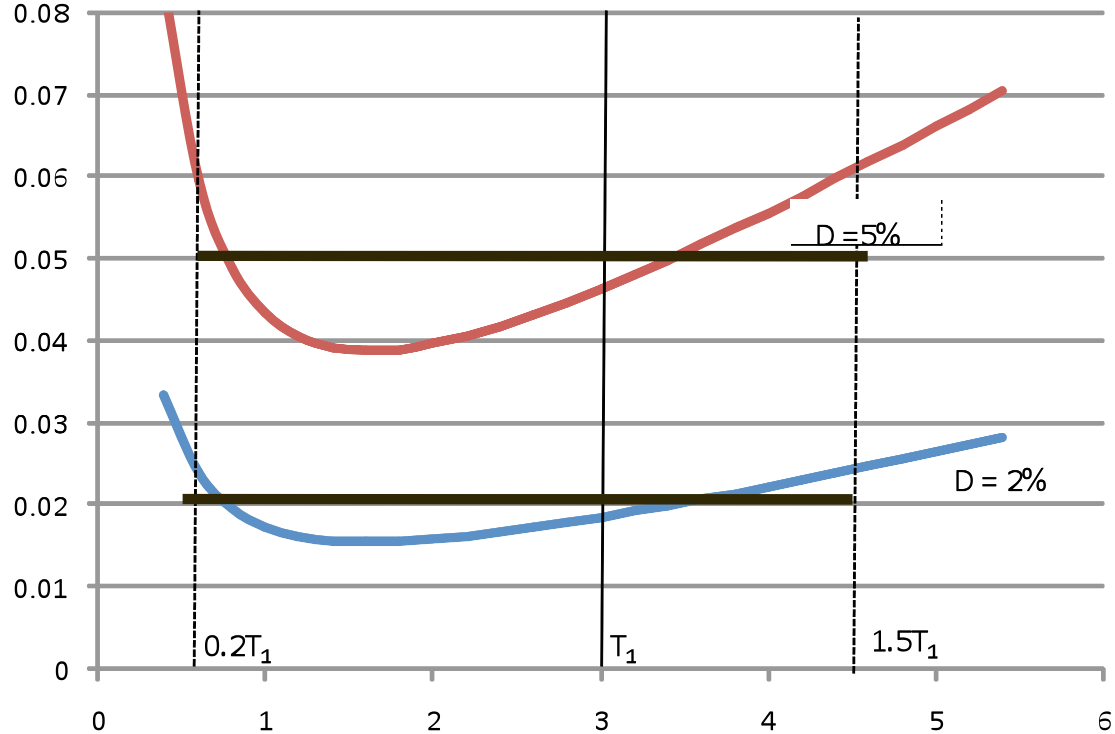
Damping = a/N

N = # stories

a: 70 to 80 steel
80 to 100 RC
130 dual sys.

Target Damping (Percentage of Critical)

Damping Recommendations (Raleigh)



- Period Range: 0.2To to 1.5To
- Hall's method for setting a & b to control error over period range
- Use Kt or reduced (effective) Ko

Damping: Suggested Future Study

1. Measurements/Evaluation of Damping
   - Laboratory shake table tests
   - Instrumented buildings
   - Understand how "un-modeled energy dissipation" changes during inelastic loading?
2. Examine sensitivity of tall building (40+ stories) response to assumed damping models
   - damping in higher modes (deformations, internal forces)
   - Significance at serviceability and safety (MCE) levels
3. Clarify numerical and implementation issues
   - Initial versus tangent stiffness
   - Raleigh vs. Modal vs. Discrete damping
   - Influence of hysteretic model properties (e.g., degradation in unloading/reloading stiffness)