System Performance Assessment
Quantifying Building Code Advancements

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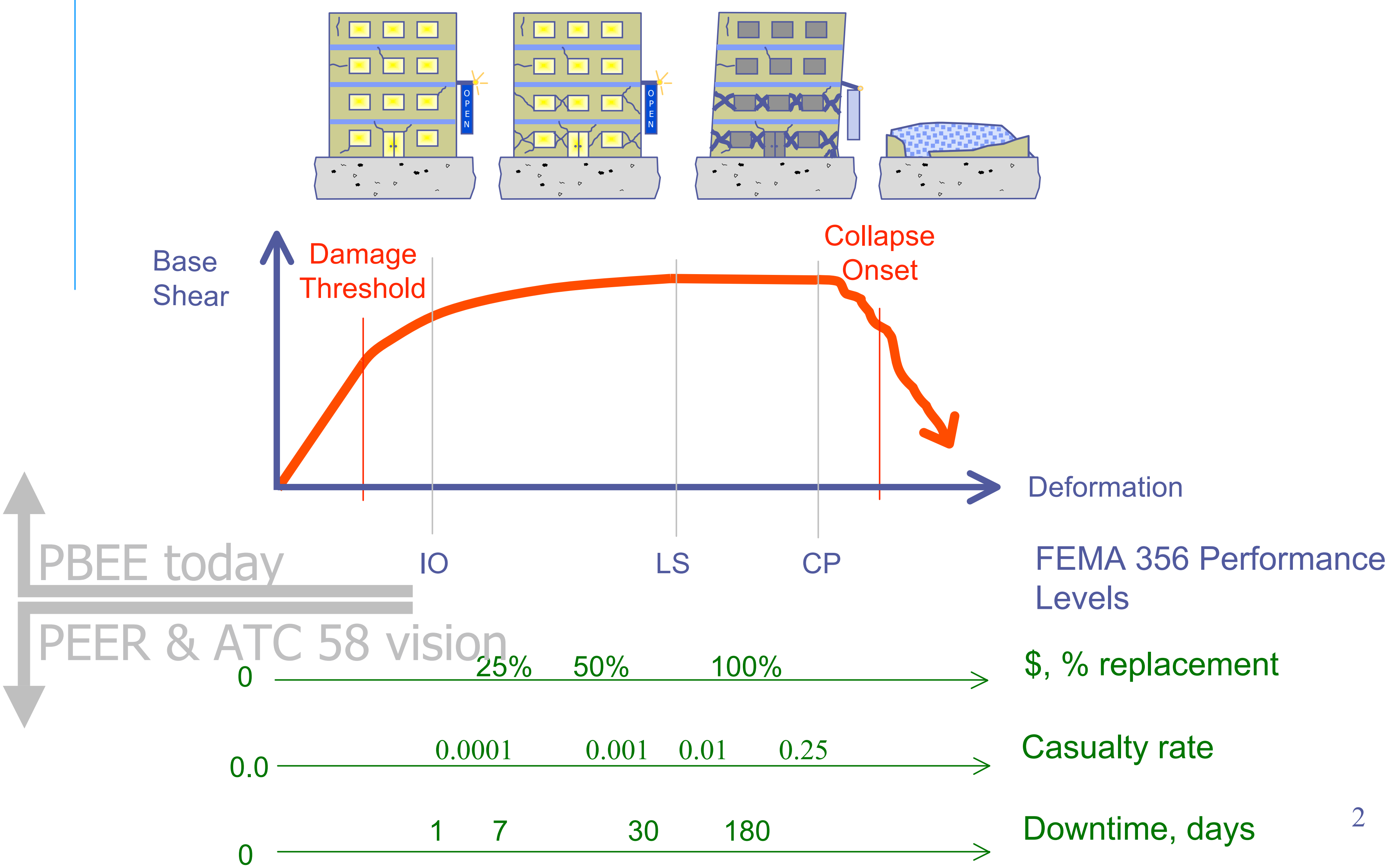
Performance-Based Earthquake Engineering



PBEE: Collapse (SAFETY) Assessment

Decision Variable — **DV:** COLLAPSE

Damage Measure — **DM:** Loss of Vertical Carrying Capacity (LVCC)

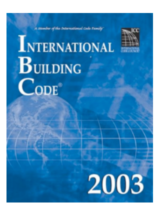
EDPs: Deformations & Forces

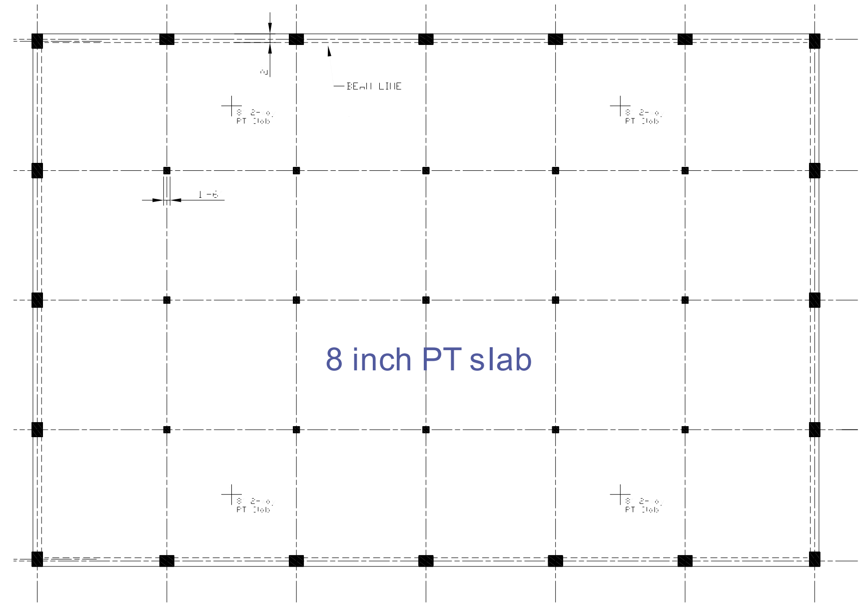
Engineering Demand Parameter — **EDP:** Interstory Drift Ratio

Intensity Measure — **IM:** *$Sa(T_1)$ + Ground Motions*

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)





Typical Perimeter Frame Members

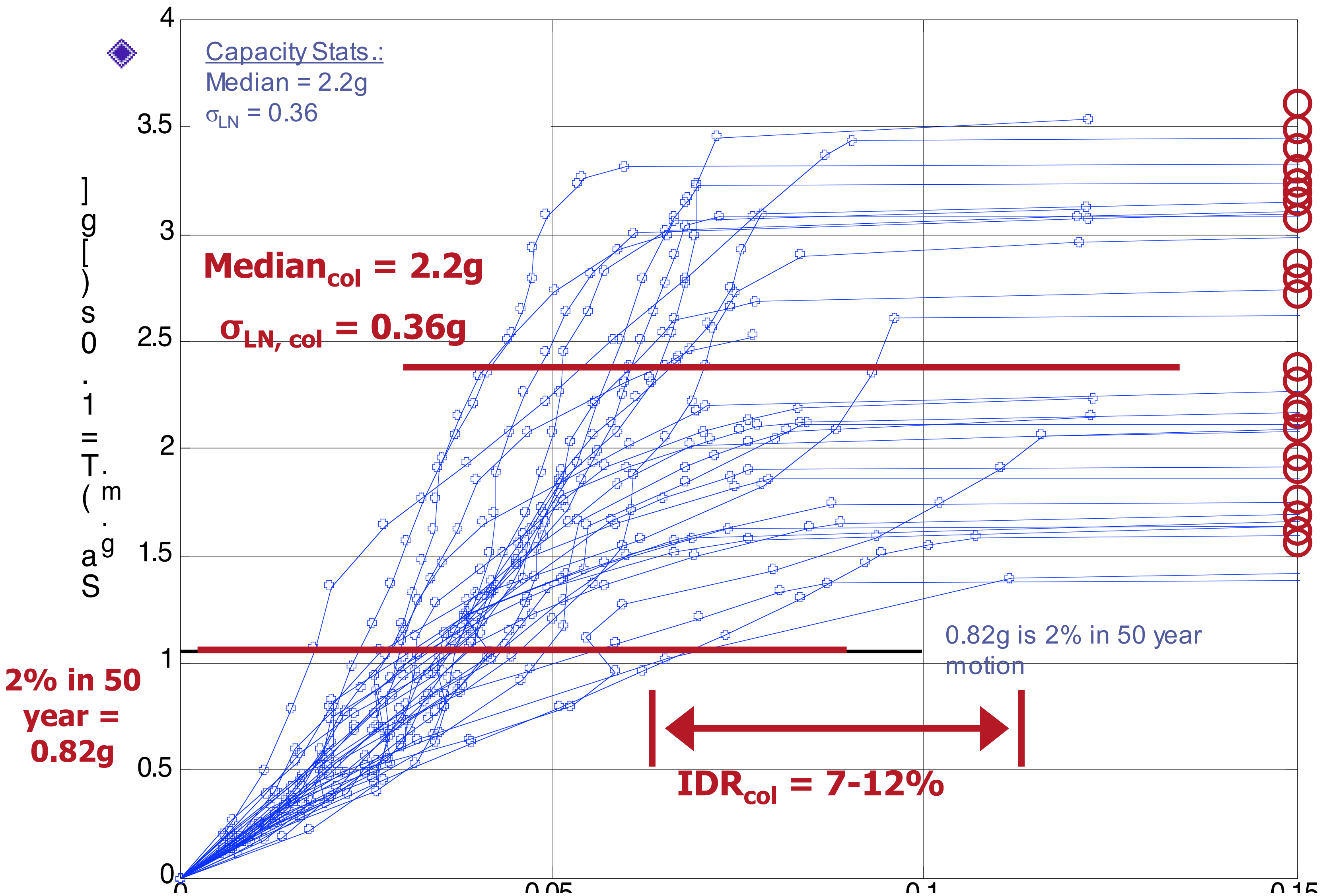
Beams: 32" to 40" deep

Columns: 24"x28" to 30"x40"

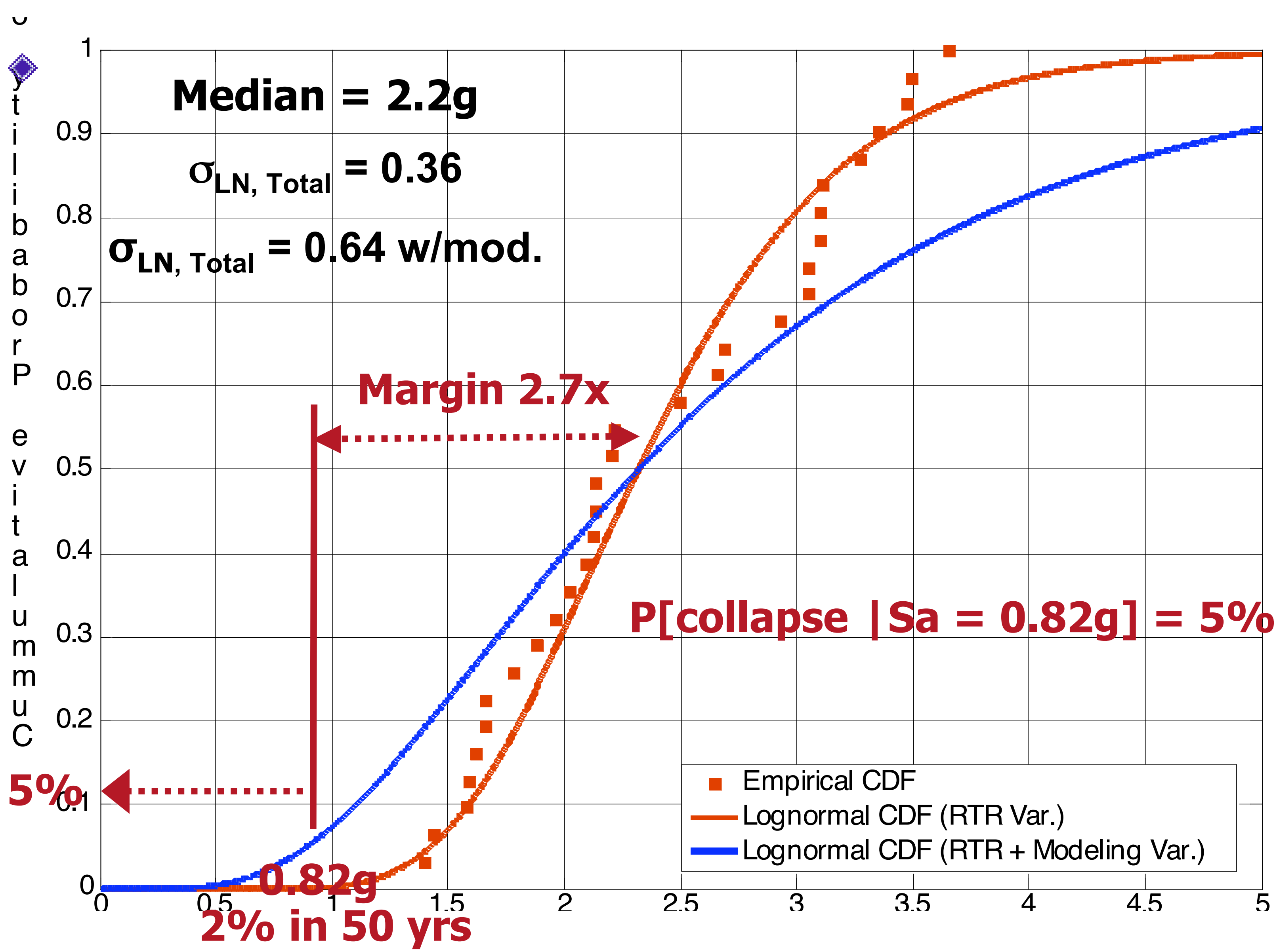
Governing Design Parameters

- Beams: minimum strength
- Column size: joint strength
- Column strength: SCWB
- Drift: just meets limit

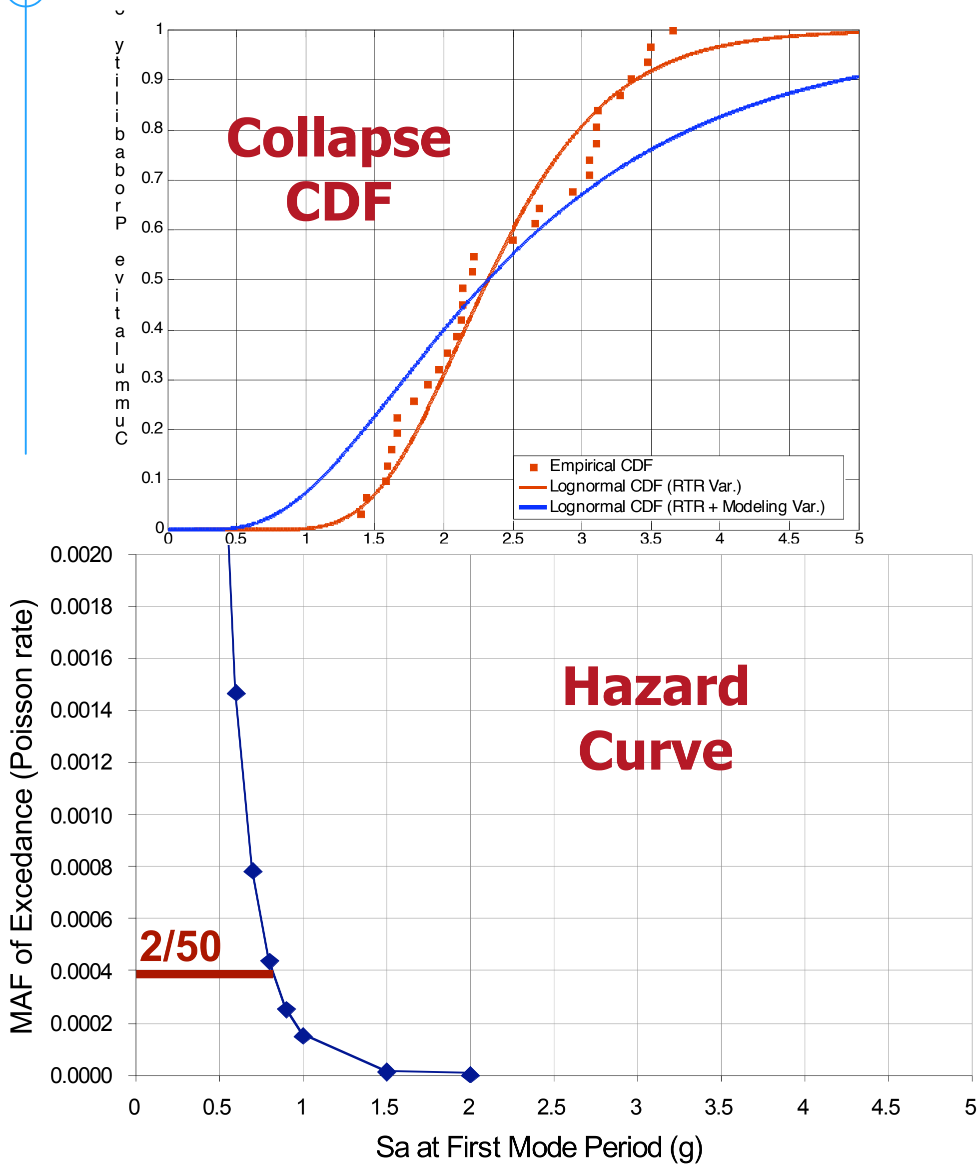
Incremental Dynamic Analysis – Collapse



Collapse Capacity – with Modeling Uncert.



Mean Annual Frequency of Collapse



Collapse Performance

- Margin: $S_{a,collapse}$ = 2.7 MCE
- Probability of collapse under design MCE = 5%
- MAF_{col} = 1.0 x 10^{-4} (about ¼ of the MCE 2% in 50 year ground motion)

Comparison of Alternative Risks

- Mean Annual Frequency (MAF) of "Serious Events"

  EQ Collapse (Conform. RC Buildings): 1×10^{-4}

  Strength Limit State (Gravity Loads)[2]: 7×10^{-4}

  Flashover Fire in Office Building[1]: 1×10^{-6}

  EQ damage to Nuclear Power Plant: 1×10^{-5}

- Fatality Rate in Collapsed Buildings[3]: 10% to 20%

- Causes of Death (lifetime probability in US)

Heart disease	2000×10^{-4} (20% chance)
Fire or smoke (residential)	9×10^{-4}
Air travel accident	0.5×10^{-4}
Tornado	0.2×10^{-4}
Snake or Bee Bite/Sting	0.1×10^{-4}
Earthquake	0.08×10^{-4}

REF: 1) Ellingwood and Corotis (1991); 2) Ellingwood and Tekie (1999); Krawinkler et al (2005).

Discussion Topics

- Selection and Scaling of Ground Motions
- Effect of Building Code Design Provisions on Building Collapse Performance
  - 2003 Design Variants
  - 1967 vs. 2003 Design

Ground Motion Hazard Characterization

Current Best ***Seismology*** Practice*:

- *Disaggregate PSHA* at Sa1 at p_o, say, 2% in 50 years, by M and R: $f_{M,R|Sa}$. [Perhaps: Repeat for several levels, $Sa1_1$, $Sa1_2$, …]

- [For Each Level] *Select Sample of Records*: from a “bin” near mean M and R. Same faulting style, hanging/foot wall, soil type, …

- *Scale* the records to the UHS in some way, e.g., to the $S_a(T_1)$.

*DOE, NRC, PEER, … e.g., see R.K. McGuire: “... Closing the Loop”(BSSA, 1996+/-); Kramer (Text book; 1996 +/-); Stewart et al. (PEER Report, 2002)

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Additional Factors To Consider

- Elastic versus Inelastic Structural Response
  - softening and period lengthening
  - cumulative damage effects
- Availability of records to represent extreme ground motions (e.g., 2% in 50 year)
  - Coastal CA – many records, can require large scaling
  - Central & Eastern US – few recorded events
- Record features not captured by M-R selection and UHS (Sa) scaling

PEER research indicates that ***spectral shape*** is key consideration in record selection & scaling

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Dissaggregation of Seismic Hazard

Van Nuys (119.47°W; 34.22 N)

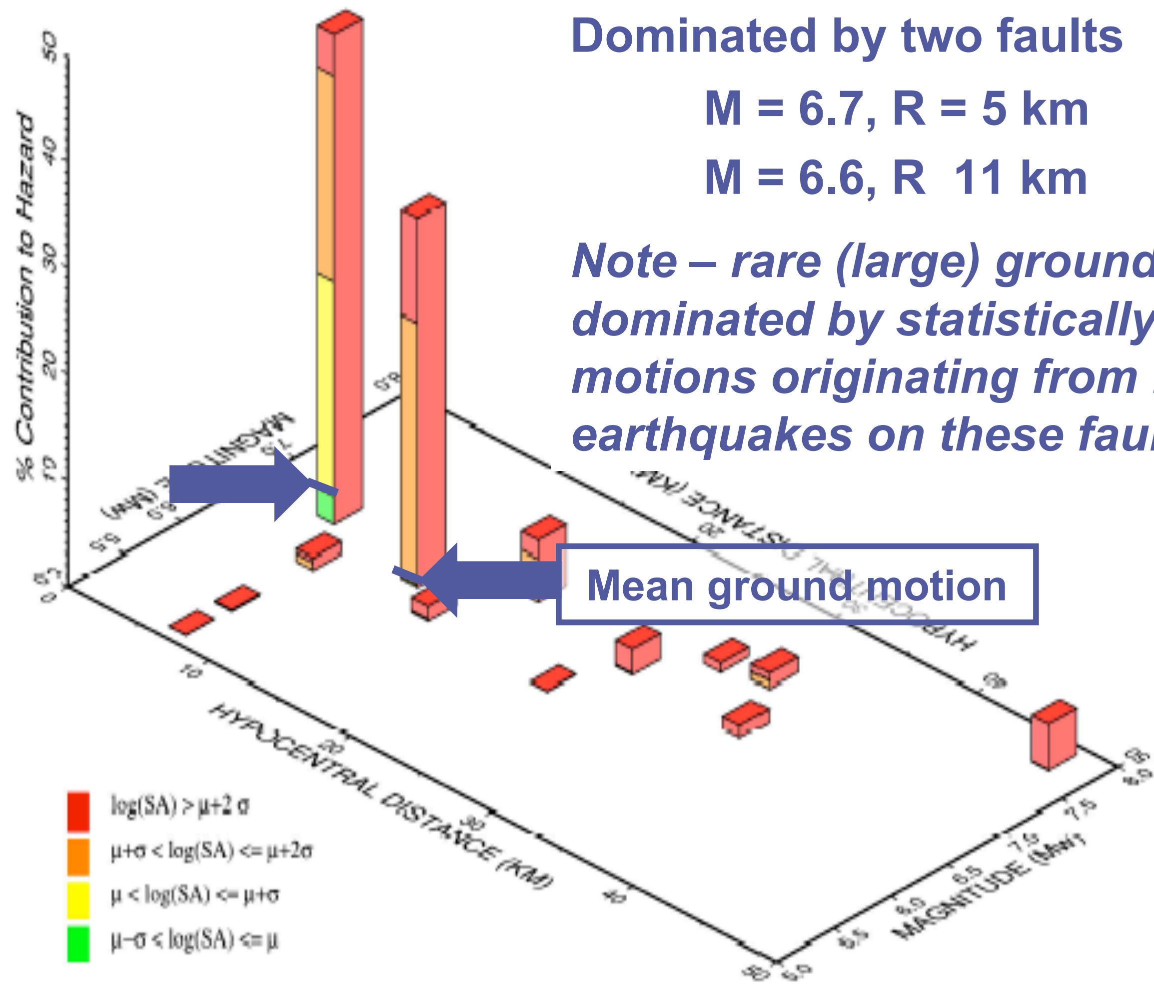
10% in 50 Year Hazard: $S_{a(T=1s)}$ = 0.48g

Dominated by two faults

M = 6.7, R = 5 km

M = 6.6, R 11 km

Note – rare (large) ground motion hazard dominated by statistically extreme motions originating from NOT so extreme earthquakes on these faults.



The 2% in 50 year ground motion

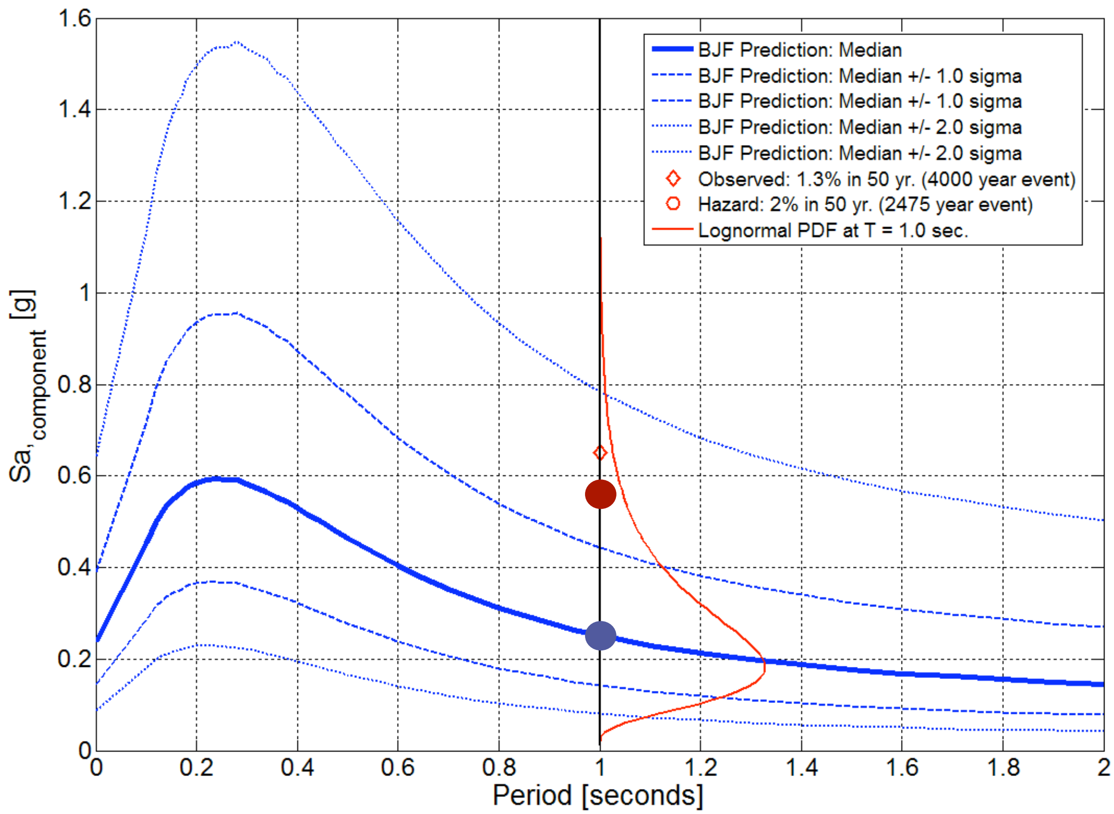
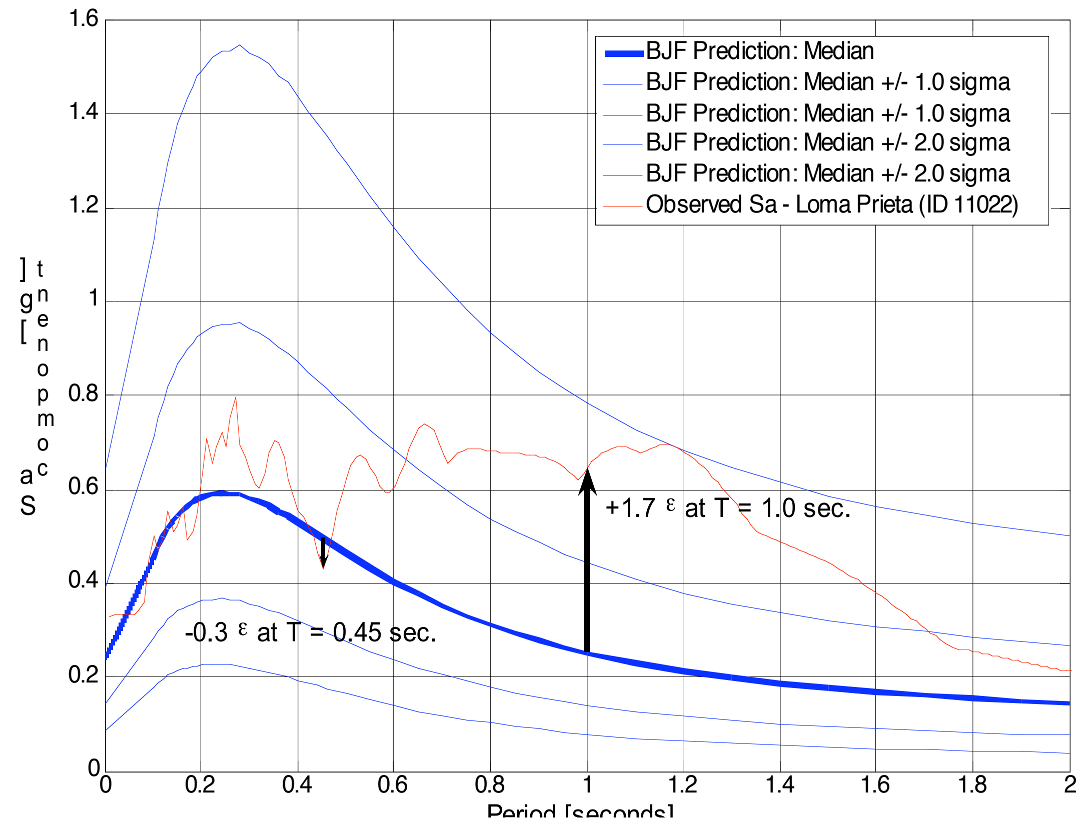


Illustration:

- Site dominated by single event (M 6.9, R 14 km) with a return period of 200 years (MAF 25% in 50 yr)
- Sa(T) from Boore-Joyner (BJ) attenuation function
- Sa (25/50) -- median of BJ. At T=1 sec., Sa = 0.28g
- Sa (2/50) -- +1.5σ of BJ. At T=1 sec., Sa = 0.56g.

Mean Annual Freq. = (Probability of Sa > Sa*, given EQ) x (MAF of EQ)

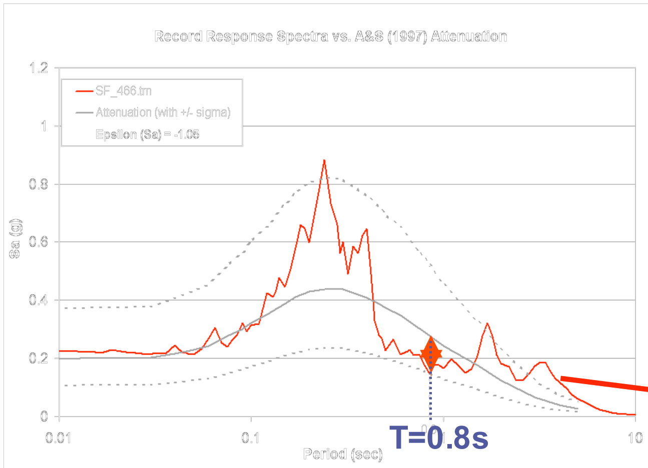
Ground motion selection (+ε effect)



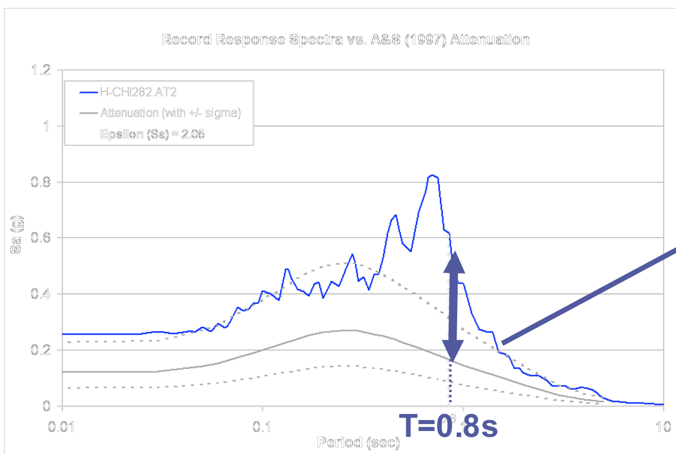
Consider the Loma Prieta (11022 record):

- Close match to characteristic event [M 6.9, R 14, Sa(T=1) = 0.65g]
- Epsilon: +1.7 at T=1 sec; -0.3 at T = 0.45 sec
- General trend for +epsilon records to peak at the +e periods and drop off elsewhere

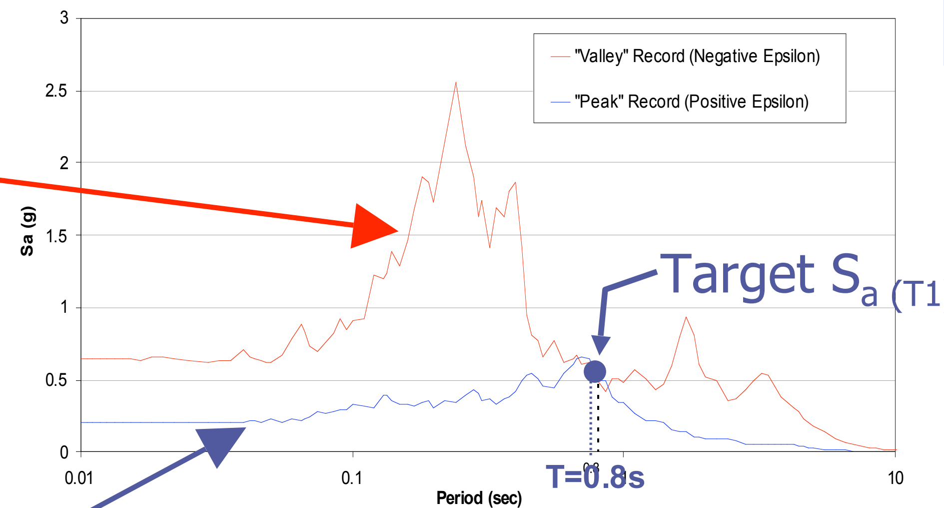
Choosing/Scaling Records for Large GM



"Negative ε" G.M.



"Positive ε" G.M.



Lesson: Do not scale "negative ε" motions to a spectral hazard that is statistically the result of "positive ε" motions.

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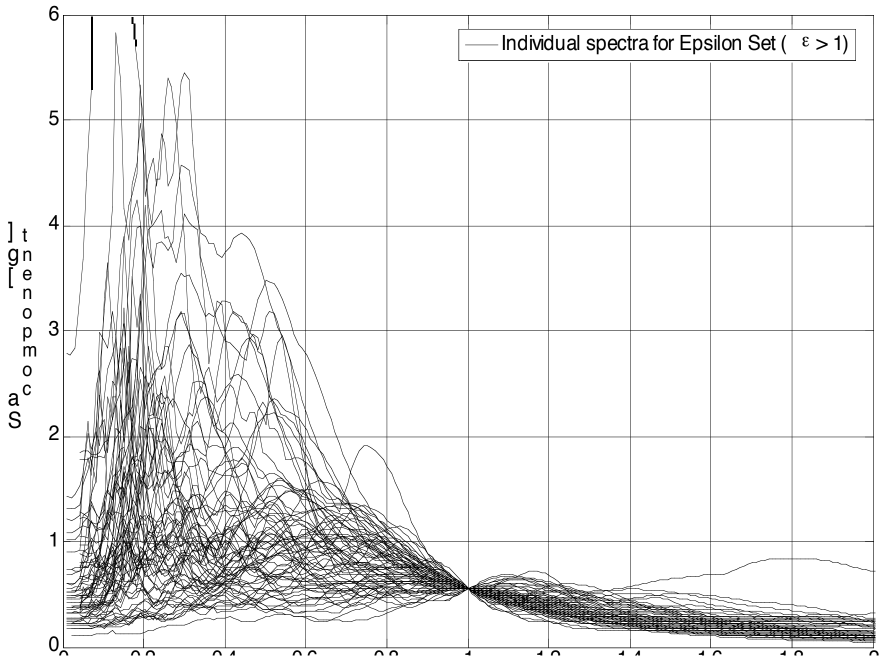
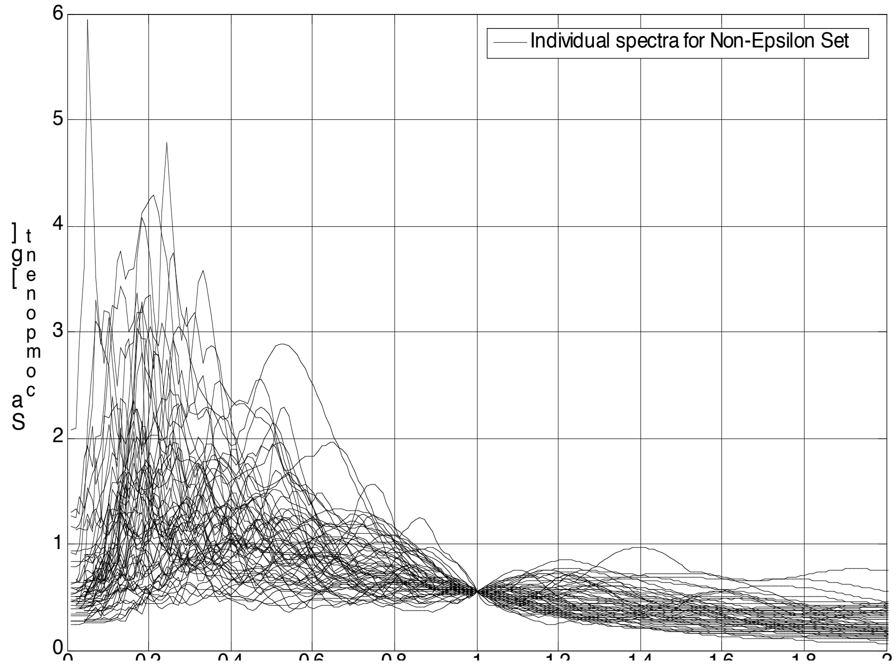
Ground motion selection (+ε effect)

Two bins of 35 record pairs of representative earthquake ground motions, scaled to Sa = 0.56g at T=1 sec





Positive Epsilon Records

Epsilon Neutral Records

(default)

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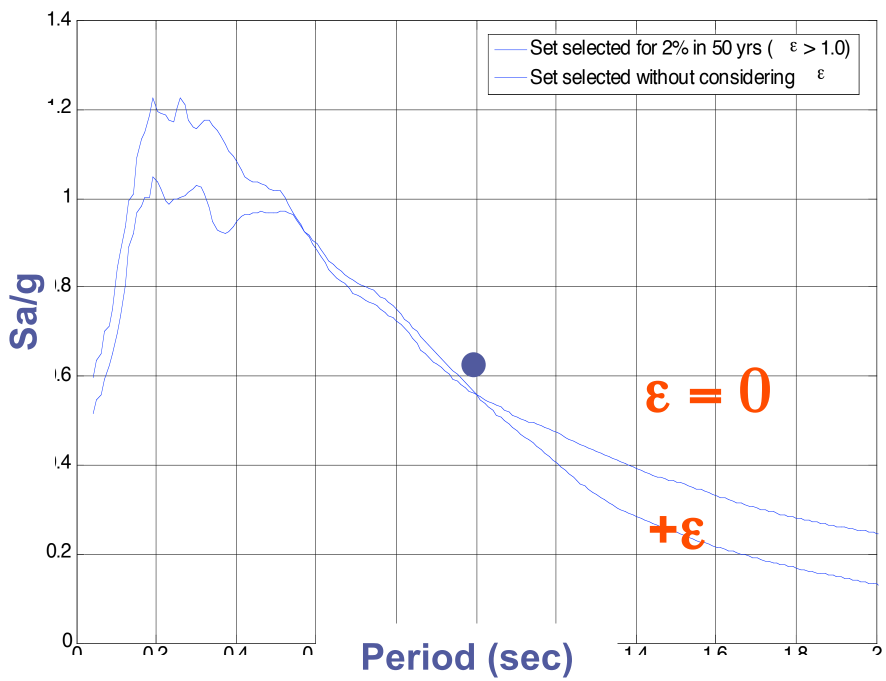
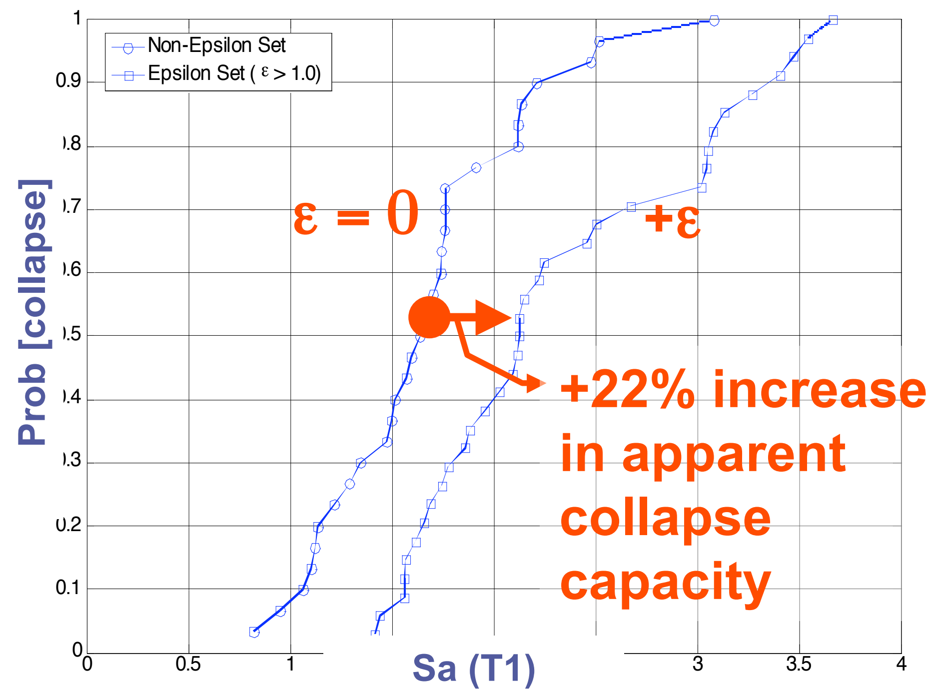
Ground Motion Selection (+ε effect)



Average Response Spectra

(from bins of +ε and epsilon neutral records)



Building Collapse Fragility

(case study 4-story building from NL dynamic analyses)

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Summary – Selection/Scaling Method I

- Earthquake Hazard Curve (MAF vs. IM)
  - Intensity Measure = $S_{a(T1)}$
- Ground Motion Record Selection
  - Strong records, matching characteristic M-R, fault & site effects
  - For collapse analyses, use $+\varepsilon$ records (western US)
- Scale record pairs by IM = $S_{a(T1)}$
- Drawbacks and Limitations
  - Does not address near-fault (R < ?) with directivity
  - Epsilon is site and period dependent
  - Cases with significant higher modes or long periods have not been fully investigated.

Alternative Selection/Scaling Methods

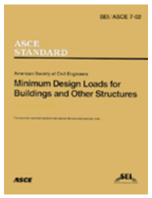
- FEMA 356
  - Record selection based on M-R, site, etc.
  - Scaling of SRSS of 2 components to hazard spectra over period range from $0.2T_1$ to $1.5T_1$
- SAC Steel Project
  - Record selection based on M-R, site, etc.
  - Scaling to hazard spectra based on scaling factors weighted based on *Sa* at **multiple periods** (T = 0.5 to 4 sec.)
- Others … *inelastic spectra*?

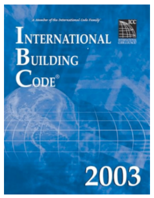
Discussion Topics

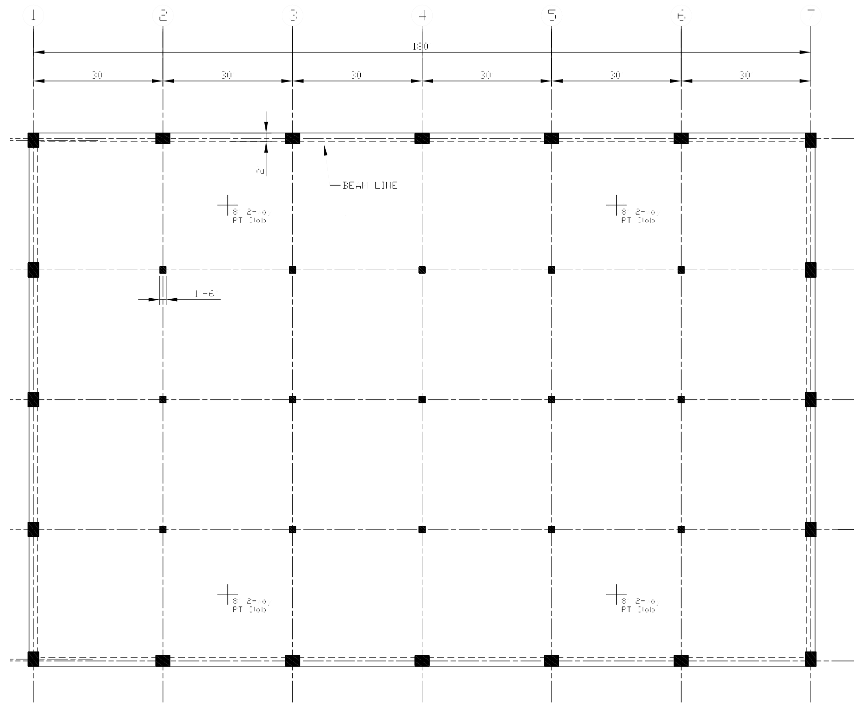
- Selection and Scaling of Ground Motions
- Effect of Building Code Design Provisions on Building Collapse Performance
  - 2003 Design Variants
  - 1967 vs. 2003 Design

4-Story Benchmark Building Design

- Office occupancy
- Los Angeles Basin
- Design Codes
  - 2003 IBC /2002 ACI
- Maximum considered EQ demands:
  - $S_s = 1.5g; S_1 = 0.9g$
  - $Sa_{2/50}(T_1) = 0.82g$
- Design V/W of 0.094g
- Maximum inelastic design drift of 1.9% (2% limit)





Design Variants:

Perimeter vs Space Frame

"Median" vs. Code Minimum

IBC 2003 vs. UBC 1997

Collapse Performance of Design Variants

Building Model	Median Collapse		Uncertainty Measure (s_{ln})		Collapse Performance	
	$Sa_{collapse}$	Margin	RTR	Total	P[C/ $Sa_{2/50}$]	MAF x 10^{-4}
Perimeter Frame, Rep., w/gravity frame	2.2g	2.7	0.36	0.62	4%	1.0
Perimeter Frame, Rep.	2.0g	2.4	0.34	0.60	5%	1.2
Perimeter Frame, MIN. Design w/gravity frame	2.1g	2.6	0.31	0.59	5%	1.1
Perimeter Frame, Rep.Design, w/o SCWB, w/gravity frame	1.0g	1.2	0.39	0.63	40%	22.0
Perimeter Frame, Rep.Design, w/o SCWB	0.7g	0.9	0.45	0.67	55%	49.0
Space Frame, w/T-beam	1.9g	2.3	0.38	0.63	11%	3.1
Space Frame	2.0g	2.4	0.32	0.59	6%	1.4
Space Frame, SCWB from 1997 UBC	1.9g	2.3	0.34	0.60	8%	1.8

Collapse Performance of Design Variants

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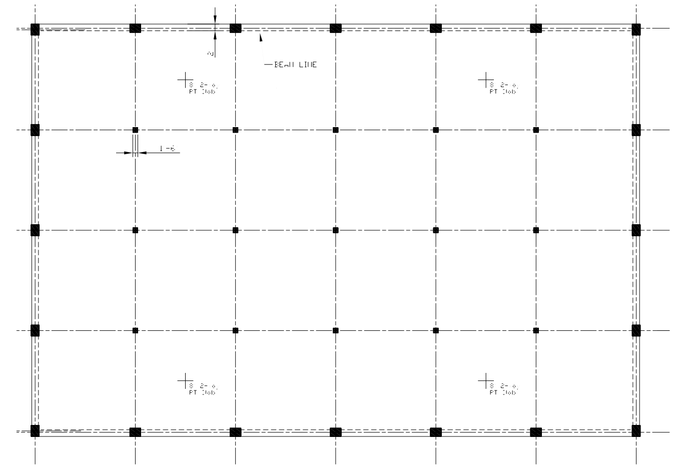
1967 and 2003 Design Comparisons



1967 Design

- Space Frame
- 1967 UBC, Zone 4
- Design V/W: 0.068 g
- Member sizes
  - Col. 20x20 to 24x24
  - Beam depth 20 to 26
- No SCWB, no joint check, non-conforming ties

2003 Design

- Perimeter Frame
- 2003 UBC/2002 ACI
- Design V/W: 0.094 g
- Member sizes
  - Col. 24x28 to 30x40
  - Beam depth 32 to 42
- Fully conforming design

Comparison of 1967 vs. 2003 Designs

Column Hinge Backbone Parameters

$\Theta_{p,cap}$: *1967 = 0.02 rad (COV 50%)*

2003 = 0.06 rad

K_c/K_e: *1967 = -0.22 (COV 60%)*

2003 = -0.08

FEMA 356 Θ_p *limits:*

1967 = 0.006 rad

2003 = 0.015 rad

Static Pushover Response

Ω_u : *1967 = 2.4*

2003 = 2.7

Δ_u: *1967 = 1.5% roof drift ratio*

2003 = 5.0%

FEMA 356 demand at MCE*:*

1967 = 1.9% drift; Θ_p = 0.016 rad

2003 = 1.6% drift; Θ_p = 0.007 rad

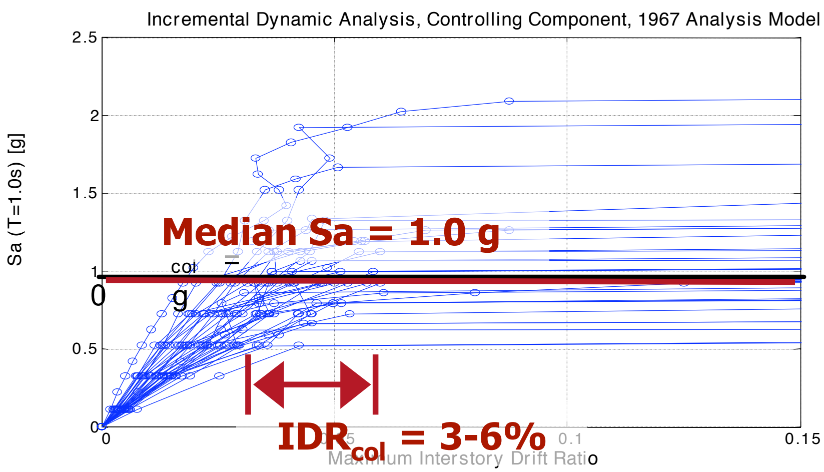
Possible Failure Modes

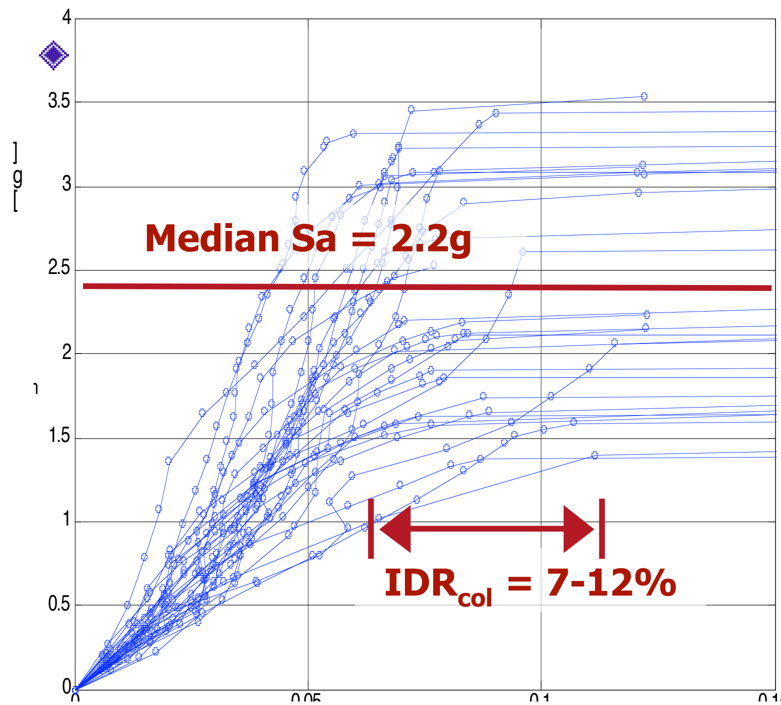
Sidesway
Collapse

Vertical
Collapse

Possible Failure Modes, cont'd

Incremental Dynamic Analysis – Sidesway Collapse





1967 Design

Strength: Median Sa = 1.0g, COV = 30%

Deformation: IDR_{max} = 3 to 6%

2003 Design

Strength: Median Sa = 2.2g, COV = 36%

Deformation: IDR_{max} = 3 to 6%

1967 Sidesway and Vertical Collapse

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

From Elwood/Moehle & Aslani/Miranda:

- Column Shear Failure:

  Column IDR = 0.02 (mean)

  Frame IDR = 0.03

- Column Axial Failure:

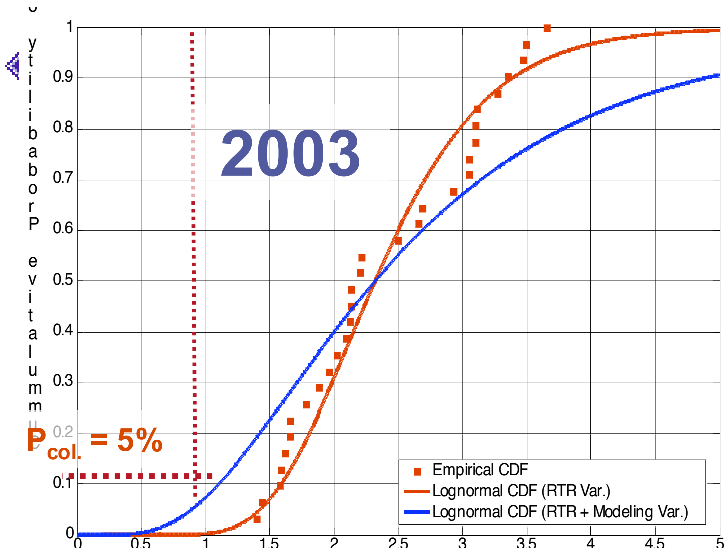
  Column IDR = 0.045 (mean)

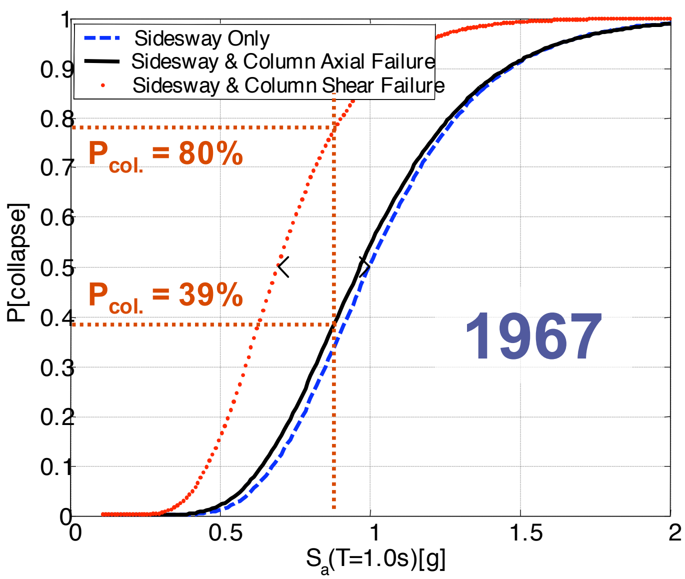
  Frame IDR = 0.06

Shear failure reduces median capacity by about 35%

Recall – Sidesway collapse occurs at peak drift ratios of 0.03 to 0.06.

Comparison of 1967 vs. 2003 Designs





Building	Collapse Risk	
	$P_{col.}$/MCE	$MAF_{collapse}$
2003	5%	1 x 10^{-4}
1967_{LVCC}	39%	18 x 10^{-4}
1967_{shear}	80%	46 x 10^{-4}

1967_{LVCC} – reflects combined probability of sidesway collapse and axial collapse of columns following shear failure.

1967_{shear} – reflects combined probability of sidesway collapse and shear failure of columns (not necessarily axial collapse).

Example – Van Nuys Hotel damage in 1994

Column Shear Failure, but no collapse

Concluding Remarks

- Integrative Assessment Framework
  - Transparent, Scientific, Modular, Extendable
  - Explicit Performance Metrics
- Standardization of Structural Component Models & Criteria
  - Simulation models & LVCC models
  - Statistically "neutral", i.e., μ & σ
  - Important role for material standards organizations (e.g., ACI, AIJ)
- Validation of System Response Simulation
- More Consistent Safety (Collapse Risk) in Buildings
  - Developing consensus on "codified" approaches
  - Applying to evaluate code provisions (e.g., ATC-63)
  - Applying in new performance-based standards (e.g., ATC-58)
- Developing Stakeholder (public) Awareness & Appreciation

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