NORTHRIDGE 20
SYMPOSIUM

Reliability of Structural Systems

Uncertainty – Confidence - Judgment

Greg Deierlein, Stanford University

January 16-17, 2014 - University of California, Los Angeles

Milestones in Performance Evaluation

- SEAOC Vision 2000 (1995)
- Evaluation of Existing Buildings

  FEMA 273 (1997) & ATC – 40 (1996)
- FEMA/NIBS (HAZUS) Loss Estimation

  Building Specific Damage Functions (1997)
- SAC/FEMA 351 Evaluation and Upgrade (2000)

  Appendix A - Detailed Procedures for Performance Evaluation
- PEER Framework Equation (2000)
- Quantification of Building Collapse Safety
  - *FEMA P695 (2009) & IBC Risk Targeted Maps (2010)*
- Performance Based Design
  - *FEMA P58 (2012)*
  - *Tall Building Guidelines (PEER/TBI 2010, LATBSDC 2011)*
  - *BSSC PUC "Chapter 16" (2014)*

Milestones in Performance Evaluation

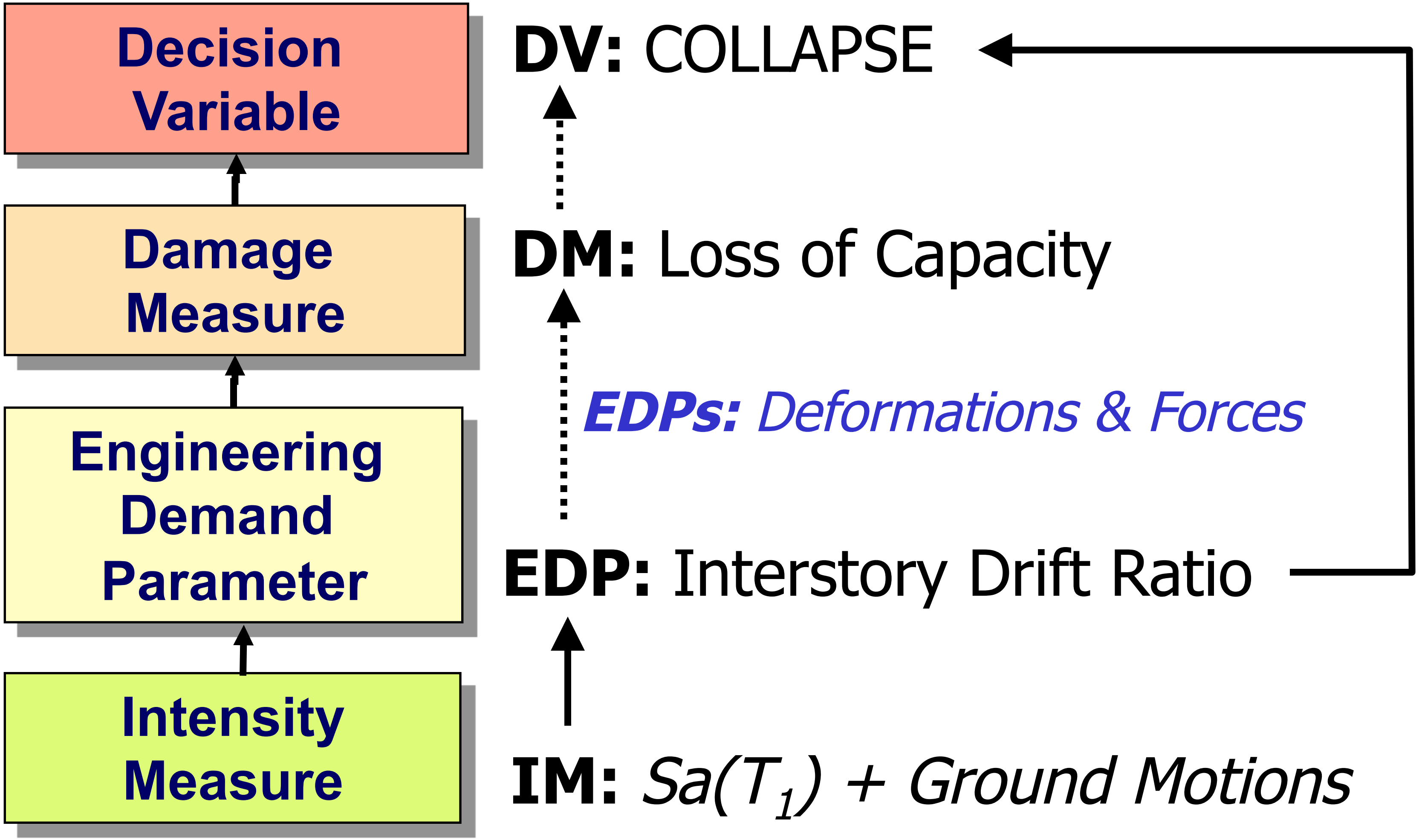
- SEAOC Vision 2000 (1995)
- Evaluation of Existing Buildings

  FEMA 273 (1997) & ATC – 40 (1996)
- FEMA/NIBS (HAZUS) Loss Estimation

  Building Specific Damage Functions (1997)
- SAC/FEMA 351 Evaluation and Upgrade (2000)

  Appendix A - Detailed Procedures for Performance Evaluation
- PEER Framework Equation (2000)
- Quantification of Building Collapse Safety
  - *FEMA P695 (2009) & IBC Risk Targeted Maps (2010)*
- Performance Based Design
  - *FEMA P58 (2012)*
  - *Tall Building Guidelines (PEER/TBI 2010, LATBSDC 2011)*
  - *BSSC PUC "Chapter 16" (2014)*

PBEE: Collapse (SAFETY) Assessment



Decision Variable

Damage Measure

Engineering Demand Parameter

Intensity Measure

DV: COLLAPSE

DM: Loss of Capacity

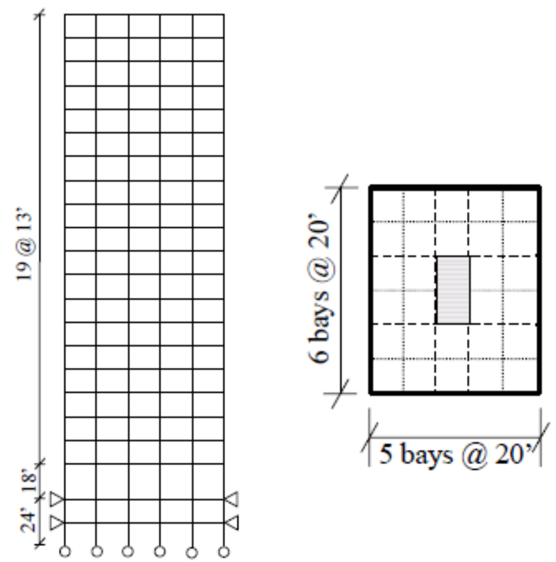
EDPs: *Deformations & Forces*

EDP: Interstory Drift Ratio

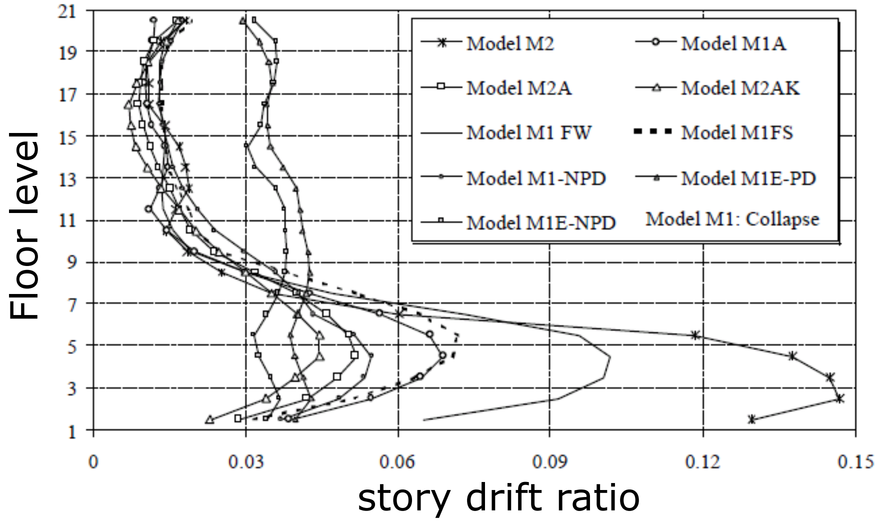
IM: $Sa(T_1)$ *+ Ground Motions*

SAC Research & Development on System Evaluation: 1995-2000

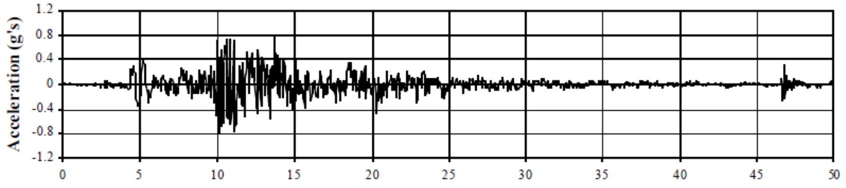
Systematic Application of NL Dynamic Analysis



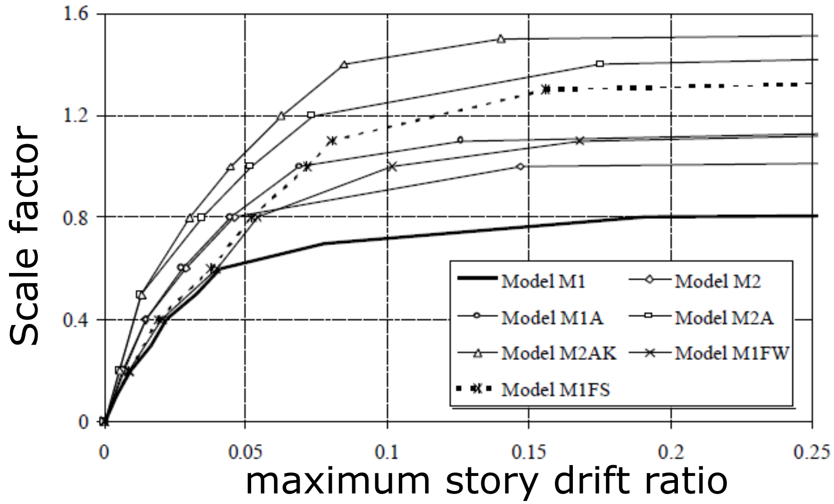
SAC LA 20-story



Drift @ MCE – Various Models



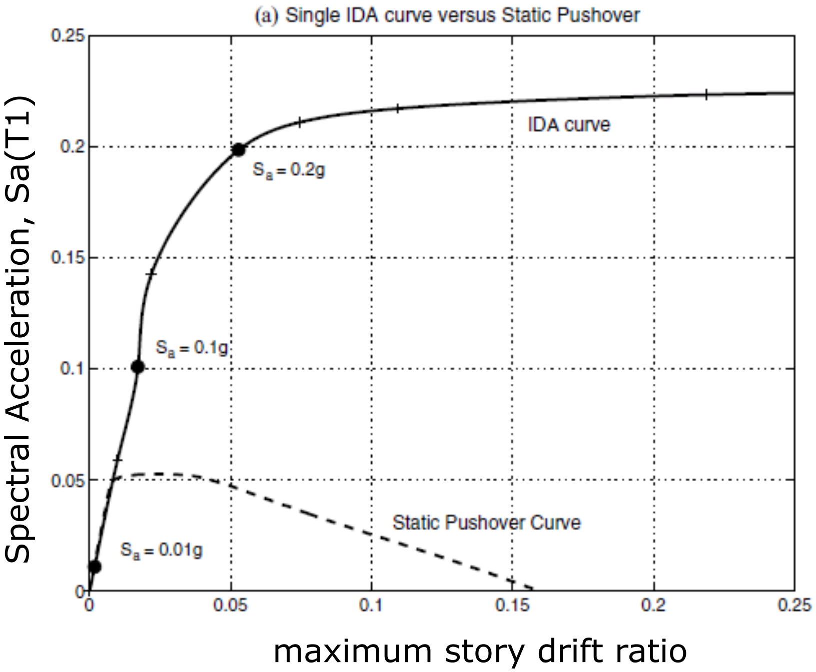
LA30 - Tabas Ground Motion

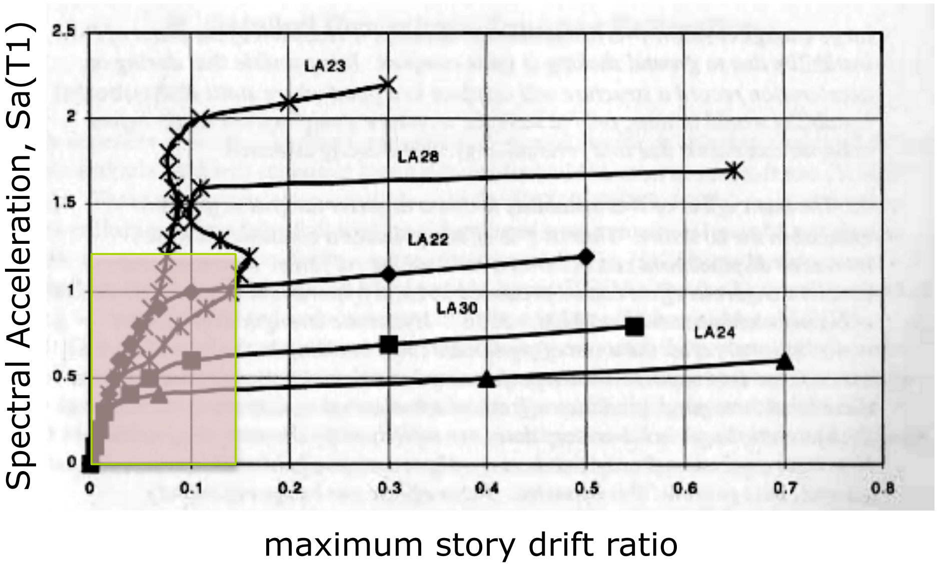


"Dynamic Pushover Analysis"

Gupta & Krawinkler, 1999

Incremental Dynamic Analysis (IDA)

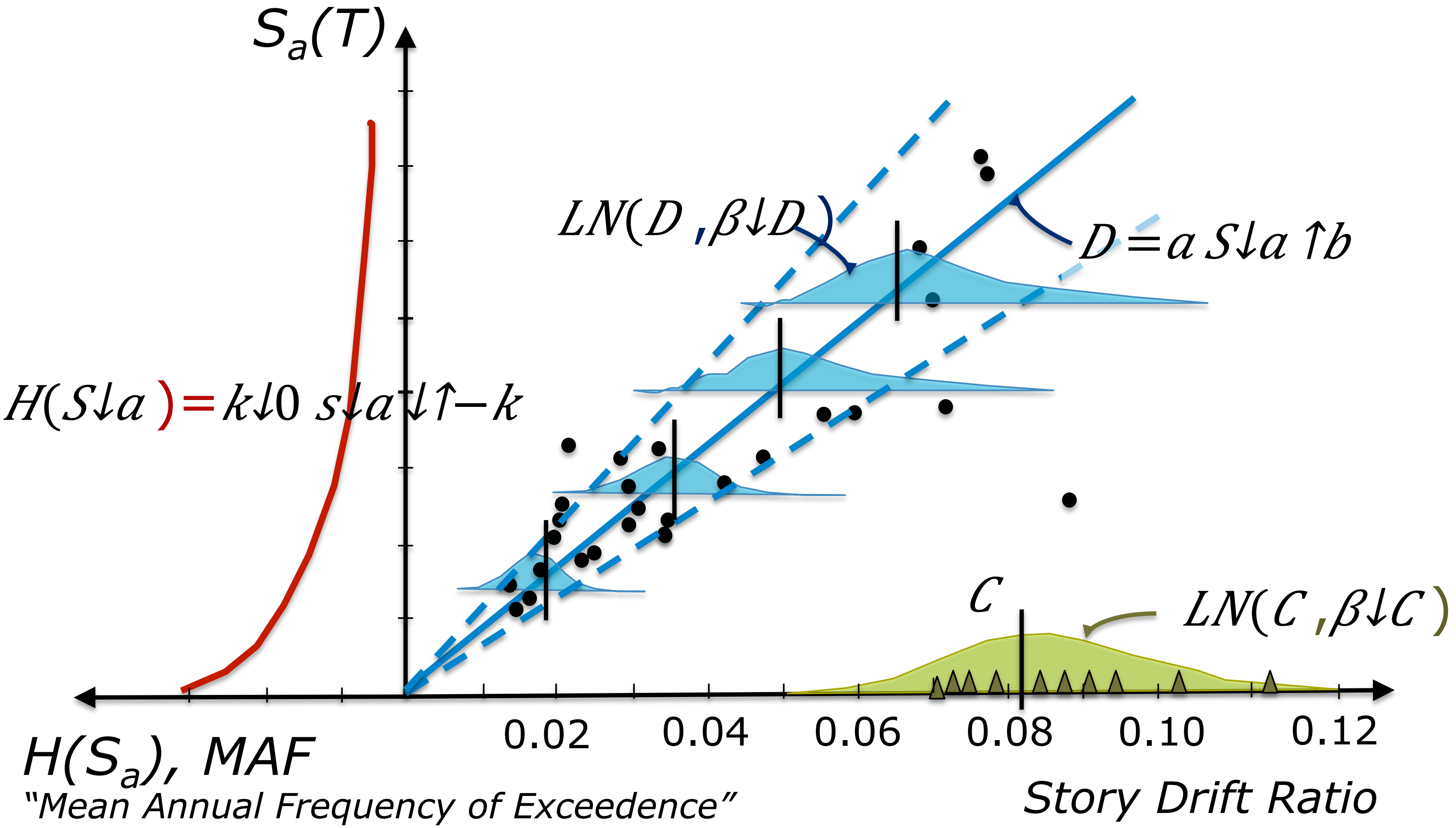




Static Pushover versus IDA
(Vamvastikos & Cornell, 2002)

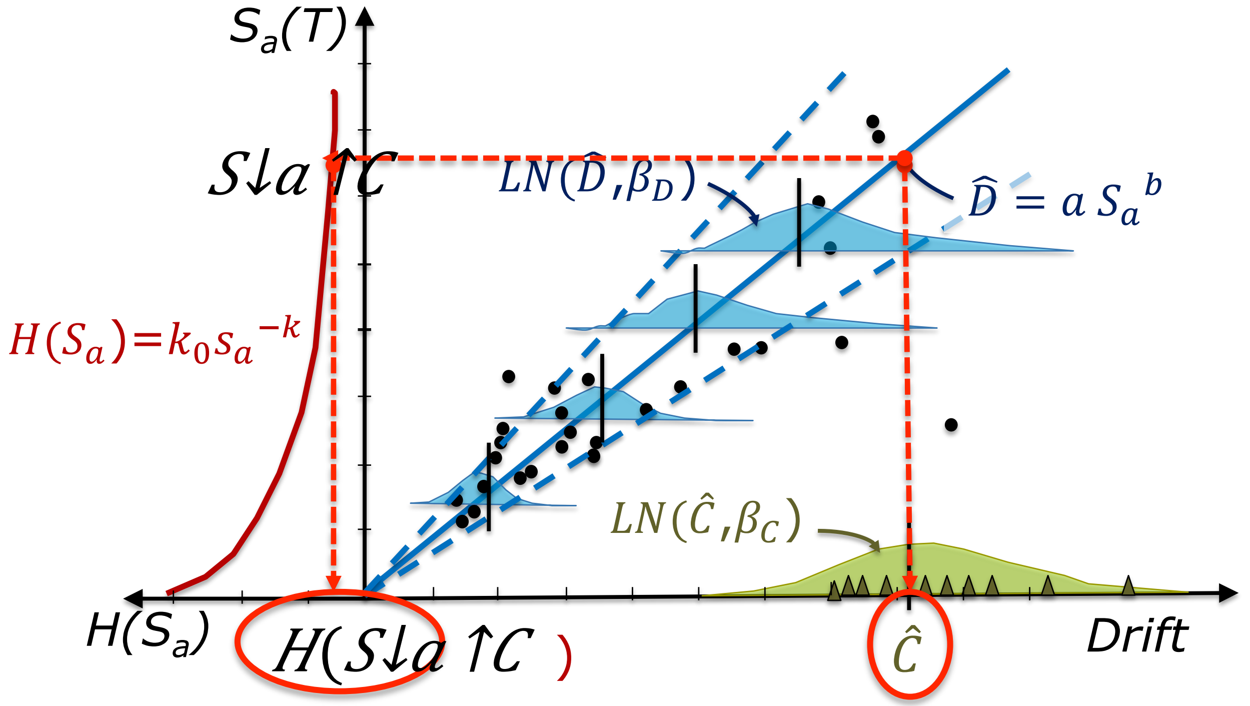
Representative IDA
(Appendix A - FEMA 351 2000)

Integration of Hazard, Demand and Capacity



Cornell, Jalayer, Hamburger, Foutch, 2002

Integration of Hazard, Demand and Capacity



P_{PL} - Mean Annual Frequency D > C:

$$P_{\mathrm{PL}} = \underbrace{H(s_a^{\hat{C}})}_{\text{Mean Annual Frequency Sa > Sa}^{C}} \underbrace{\exp\left[\frac{1}{2}\frac{k^2}{b^2}(\beta^2_{D|S_a} + \beta^2_C)\right]}_{\text{Variability in Sa, D, and C}}$$

Cornell, Jalayer, Hamburger, Foutch, 2002

Demand-Capacity Factor Design (DCFD)

$$\phi \hat{C} \geq \gamma \hat{D}^{P_o} \qquad \gamma = \exp\left[\frac{1}{2}\frac{k}{b}\beta^2_{D|S_a}\right] \quad \phi = \exp\left[-\frac{1}{2}\frac{k}{b}\beta^2_C\right]$$

Limit state with frequency of exceedence (P_o) equal to that of ground motion used to calculate the demand (D)

$$\lambda = \frac{\gamma \cdot \gamma_a \cdot D}{\phi \cdot C}$$

… ratio of factored D/C

λ- Confidence Factor: *Certainty in the probabilistic estimate that C > D at the specified return period, considering other sources of uncertainty.*

λ = 1 ~50 to 70% confidence
λ = 3/4 ~90% confidence

Cornell, Jalayer, Hamburger, Foutch, 2002

Demand-Capacity Factor Design (DCFD)

Collapse Drift Ratio Limit (Post-NR SMF):

$$D < \phi\lambda/\gamma\gamma_{a} \; C$$

Low-Rise: $D < 0.5*0.1 = \mathbf{0.05}$

High-Rise: $D < 0.35*0.085 = \mathbf{0.03}$

assuming 90% confidence that capacity will not be exceeded based on mean demands, D (at MCE)

Column Axial Force (Post-NR SMF):

$$C > \gamma\gamma_{a} /\phi\lambda \; D$$

High-Rise: $C < \mathbf{1.6\ D}$

Per default values in FEMA 351 (2000)

PEER to ATC 63: 2000 - 2009

PBEE – Probability Framework Equation

$$\nu(DV) = \iiint G\langle DV \mid DM \rangle \mid dG\langle DM \mid EDP \rangle \mid dG\langle EDP \mid IM \rangle \mid d\lambda(IM)$$

Impact

Performance (Loss) Models and Simulation

Hazard

IM – Intensity Measure

EDP – Engineering Demand Parameter

DM – Damage Measure

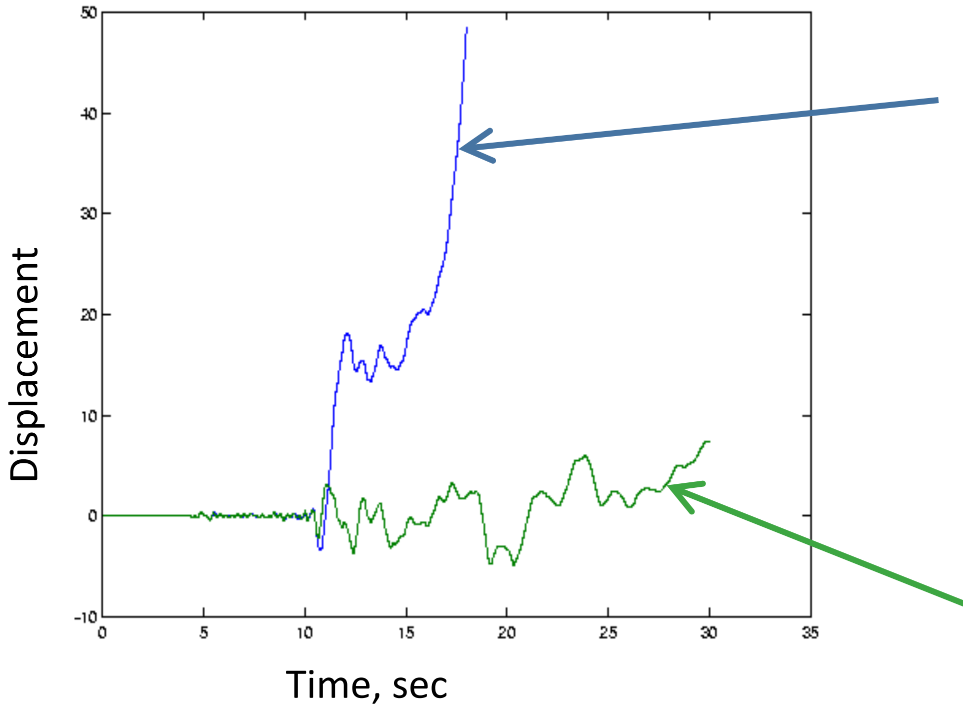
DV – Decision Variable

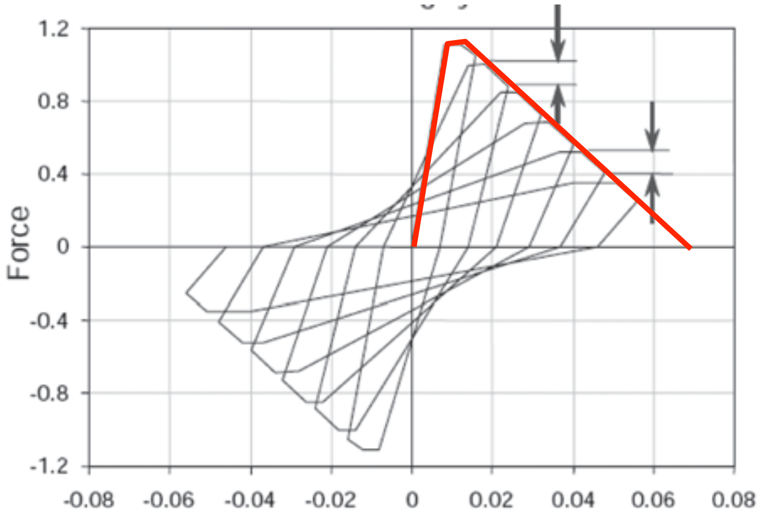
ν(DV) – Probabilistic Description of Decision Variable

(e.g., Mean Annual Frequency of Collapse)

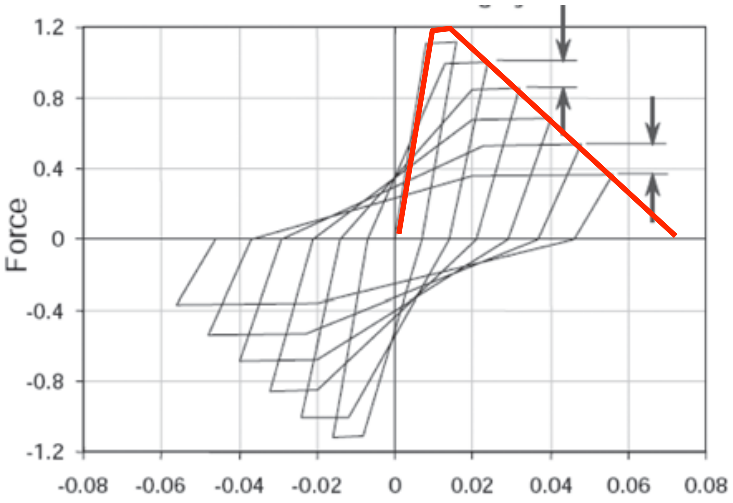
Systematic Application of NL Dynamic Analysis

Types of strength degradation





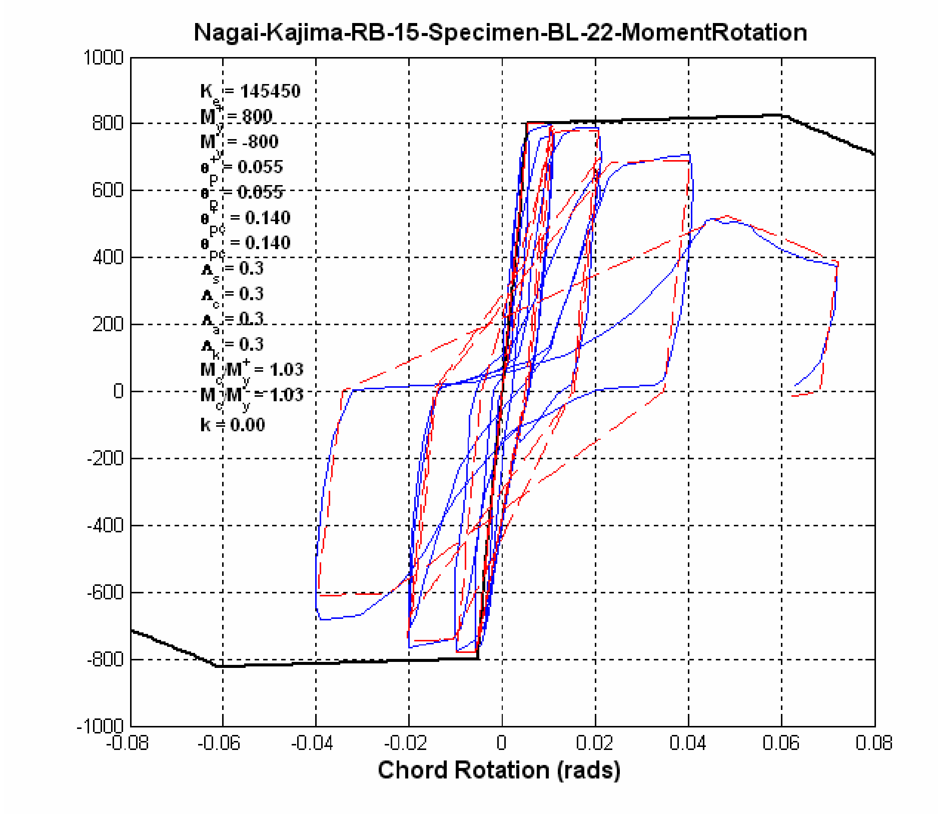
In-cycle strength degradation



Cyclic strength degradation

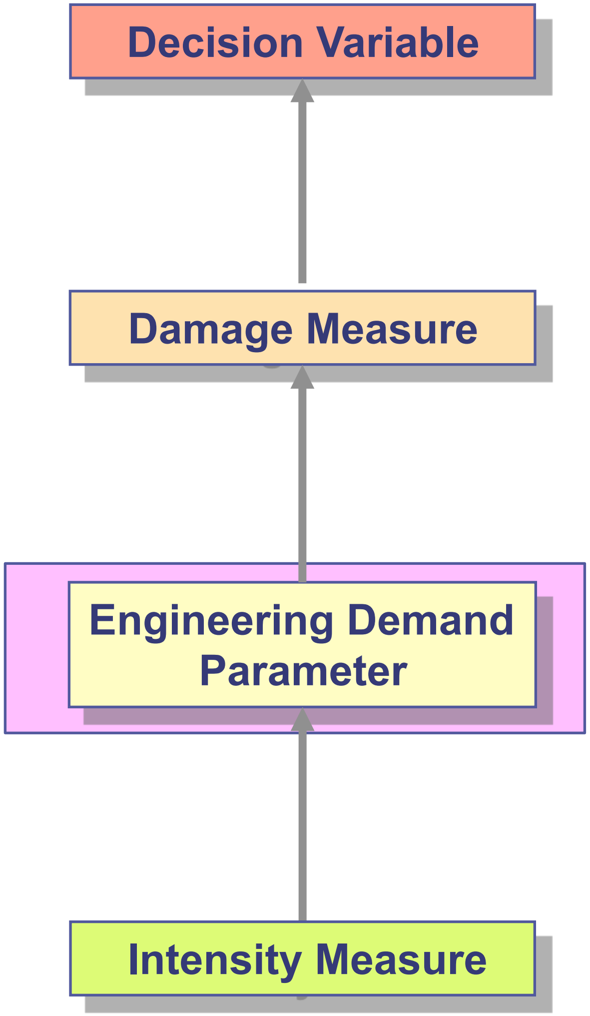
Michael Scott, PEER, 2003; FEMA 440

Modeling Strength Degradation



Importance of Modeling

Strength and Stiffness Degradation



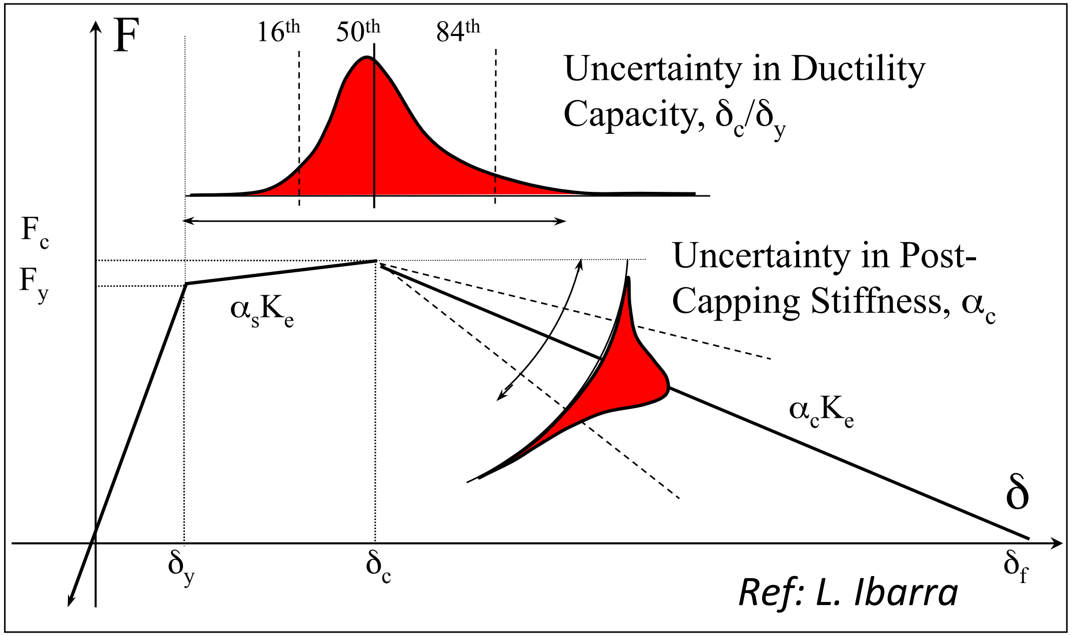
Decision Variable

Damage Measure

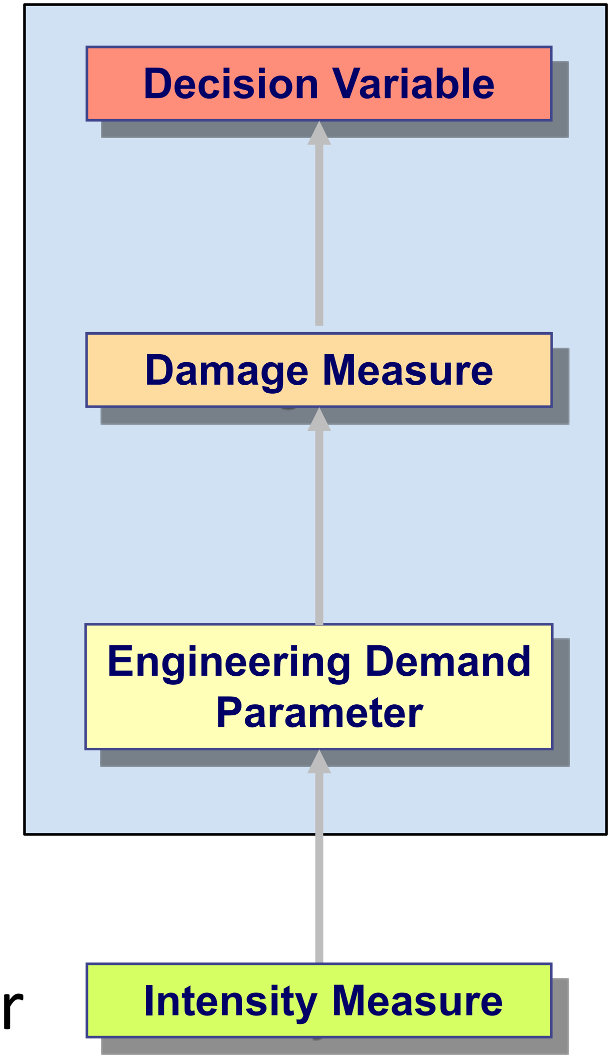
Engineering Demand Parameter

Intensity Measure

Characterization of Modeling Uncertainties



Ref: L. Ibarra



Decision Variable

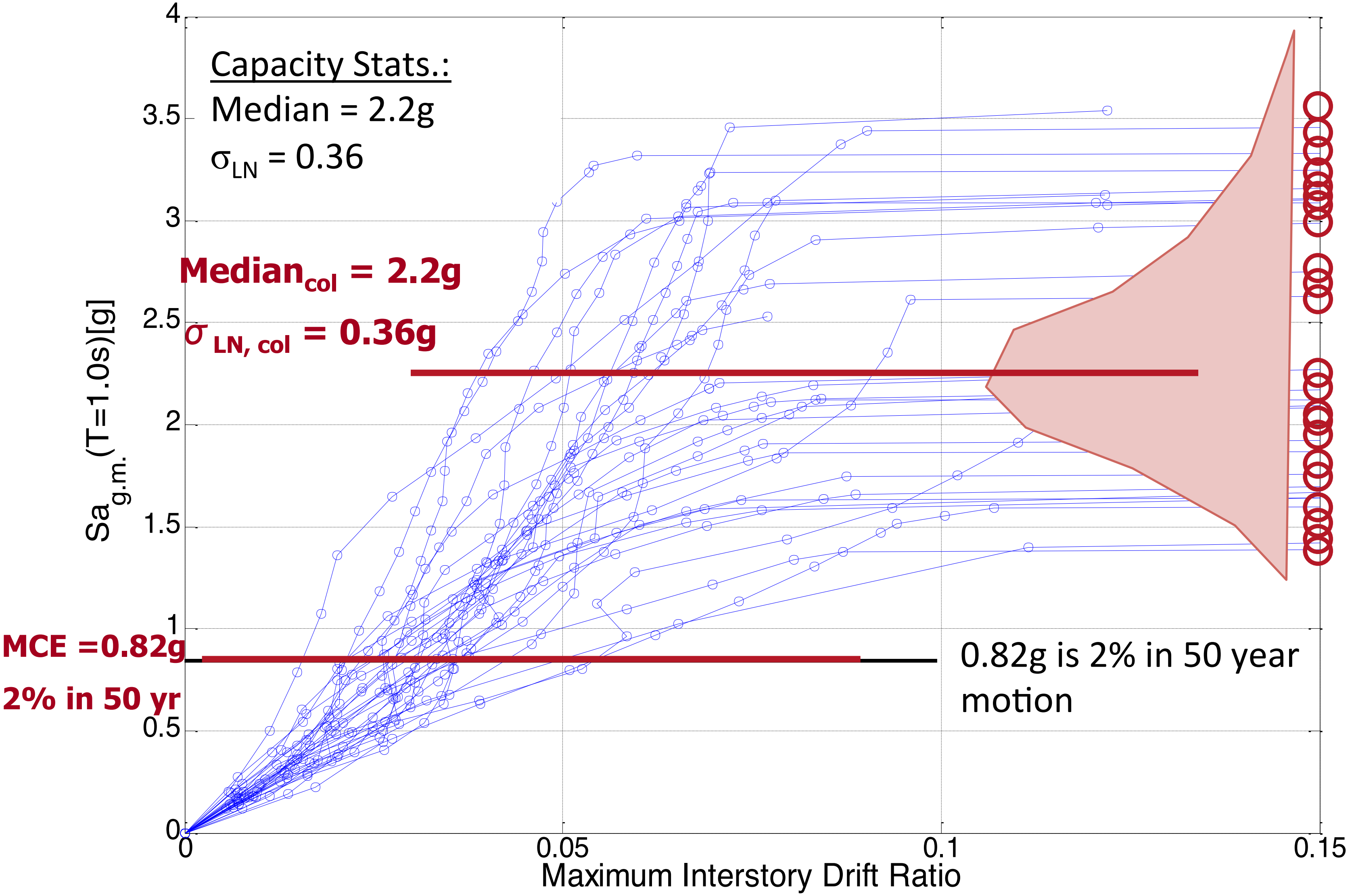
Damage Measure

Engineering Demand Parameter

Intensity Measure

- *Aleatory* (inherent) variability in materials and response
- *Epistemic* (lack of knowledge) uncertainty in our models of behavior

Collapse IDA – Median Structural Model



Capacity Stats.:
Median = 2.2g
σ_{LN} = 0.36

Median$_{col}$ = 2.2g

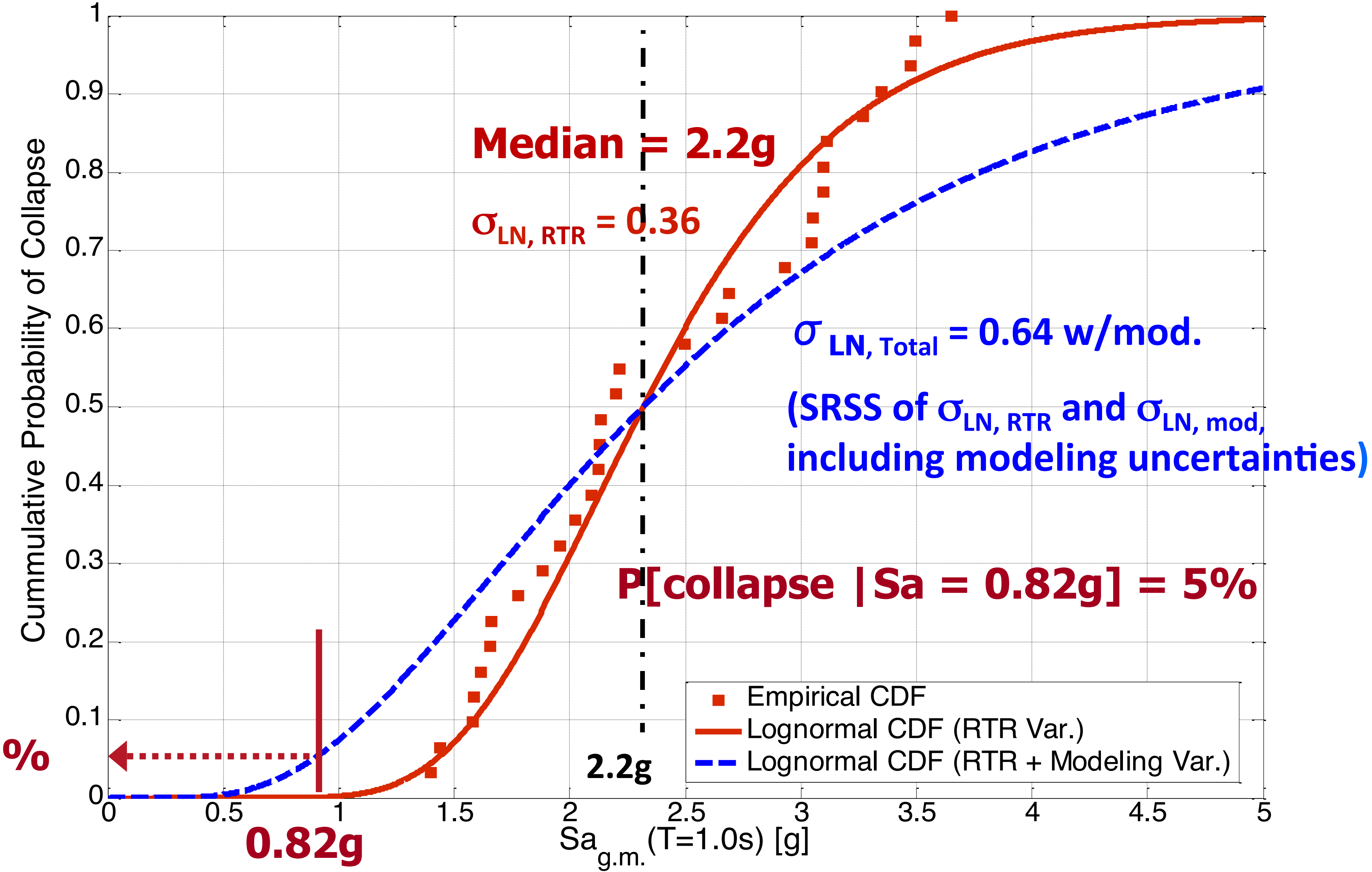
$\sigma_{LN, col}$ = 0.36g

MCE =0.82g

2% in 50 yr

0.82g is 2% in 50 year motion

Collapse Fragility Curve



Median = 2.2g

$\sigma_{LN, RTR}$ = 0.36

$\sigma_{LN, Total}$ = 0.64 w/mod.

(SRSS of $\sigma_{LN, RTR}$ and $\sigma_{LN, mod}$, including modeling uncertainties)

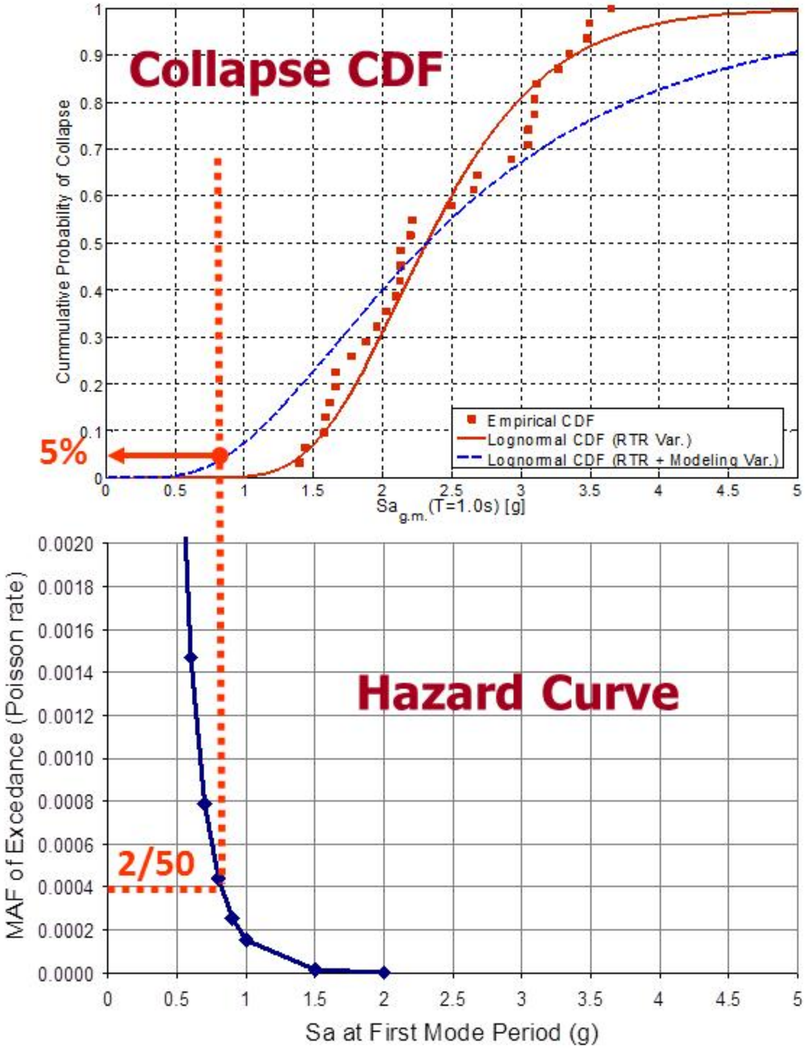
P[collapse |Sa = 0.82g] = 5%

2.2g

5%

0.82g
MCE Intensity
(2% in 50 yrs)

Integration of Collapse Fragility with Hazard Curve



Calculated Collapse Safety

- 5% Probability of collapse under "Maximum Considered Earthquake"
- MAF_{col} = 1.0 x 10^{-4} collapse/yr

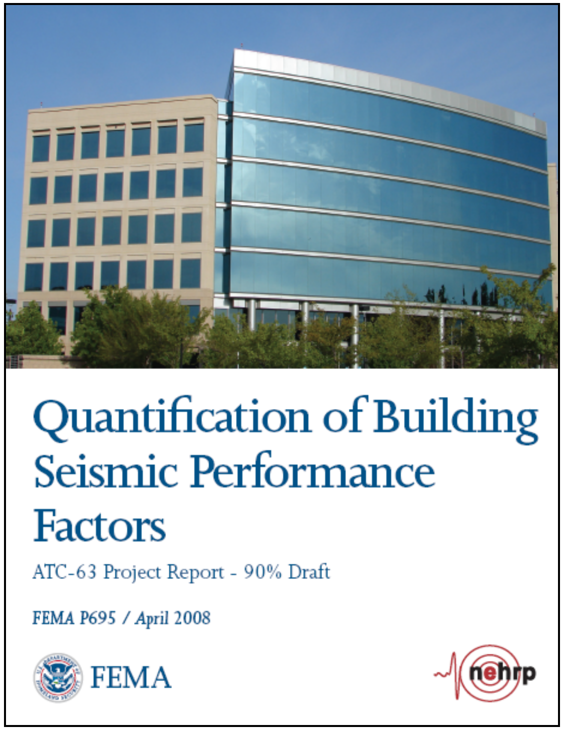
OR

0.5% Probability in 50 years

Question: Is this acceptable?

Perhaps, but the practical value may be in providing consistency among materials and systems.

FEMA P695 (ATC-63) Assessment Methodology



Quantification of Building Seismic Performance Factors

ATC-63 Project Report - 90% Draft

FEMA P695 / April 2008

FEMA

nehrp

Purpose – Provide a rational basis for determining building system seismic performance factors that, when properly implemented in design, will result in:

> *the equivalent safety against collapse in an earthquake, comparable to the inherent safety intended by current seismic codes, for buildings having different seismic systems.*

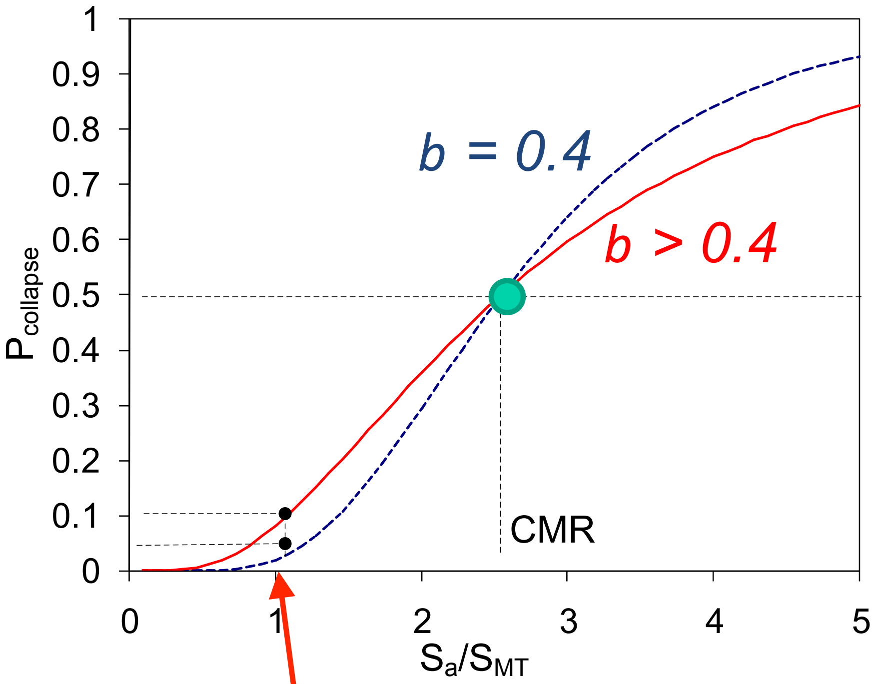
Recommended Use –

- ✓ to set minimum acceptable design criteria for standard code-approved seismic-force-resisting systems, and
- ✓ to provide guidance in selection of appropriate design criteria for other systems

FEMA P695 (ATC 63) - Consideration of Uncertainties

FOUR CONTRIBUTORS:

1. record-to-record
2. design requirements
3. quality of test data
4. analysis model quality



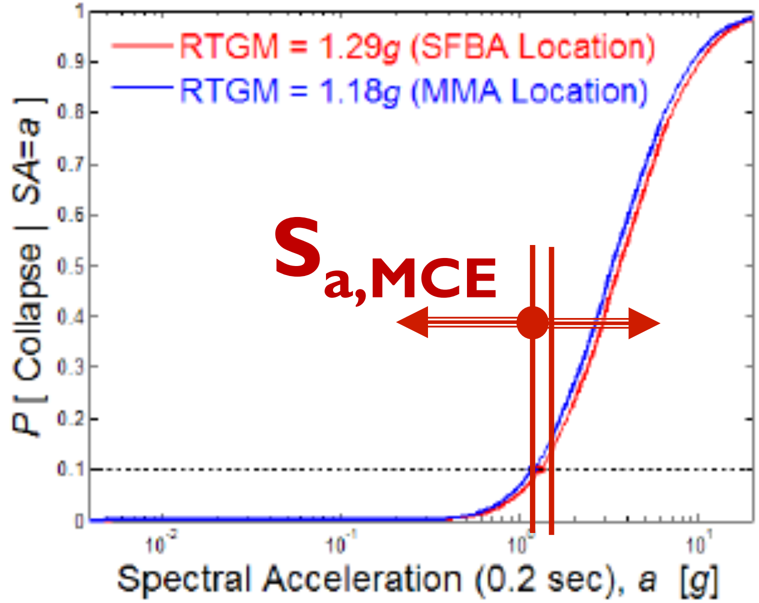
< 10% probability of collapse at MCE

$$\beta_{TOT} = \sqrt{\beta_{RTR}^2 + \beta_{DR}^2 + \beta_{TD}^2 + \beta_{MDL}^2}$$

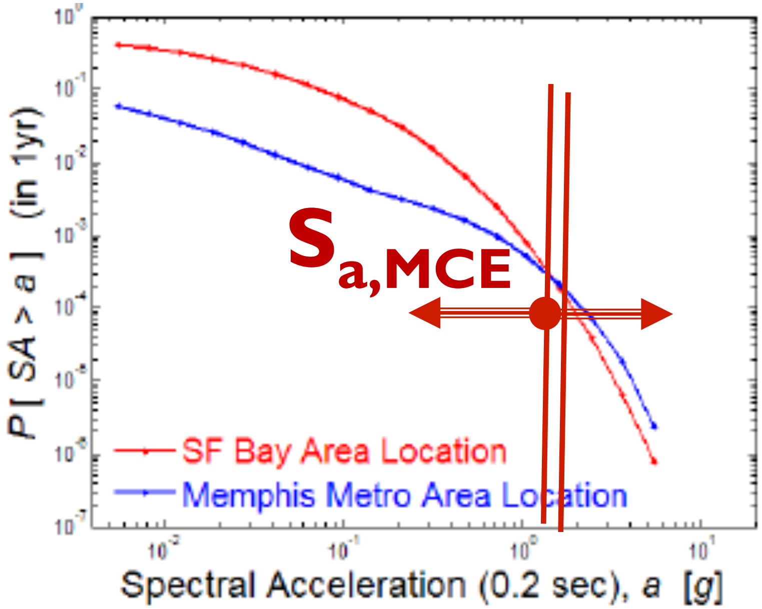
$$\beta_{TOT} \cong 0.5 \textit{ to } 0.9$$

Greater uncertainties will require larger median collapse margins to satisfy maximum collapse probability at MCE

Risk Targeted MCE Design Maps (ASCE 7-10)



Generic Collapse Fragility (β= 0.8)



Seismic Hazard Curve

$$P[Collapse] = \int_{0}^{\infty} \frac{\mathrm{d}P[Collapse|SA = a]}{\mathrm{d}a} P[SA > a]\,\mathrm{d}a$$

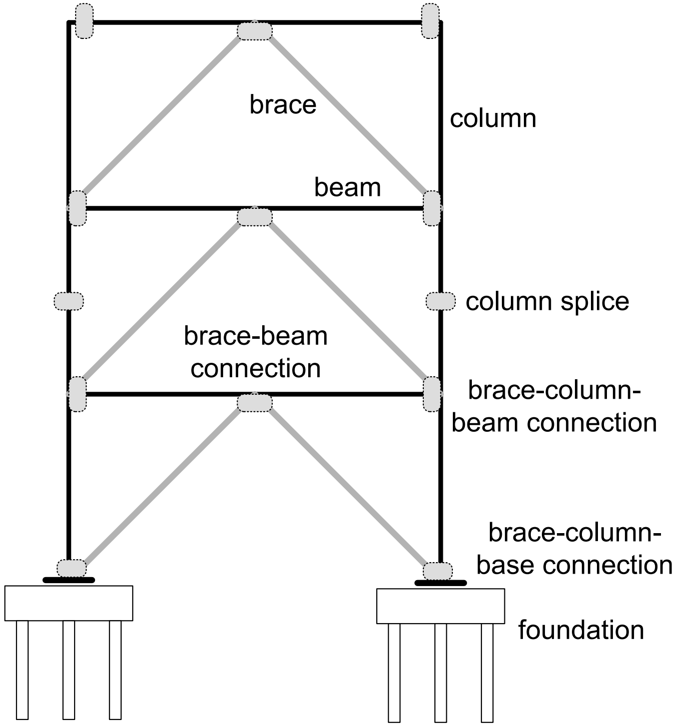
Set $S_{a,MCE}$ to obtain target of 1% P[collapse] in 50 yr

Except in near-fault regions!

Luco et al., 2007

Capacity design of force-controlled components …

Reliability of Capacity-Designed Components



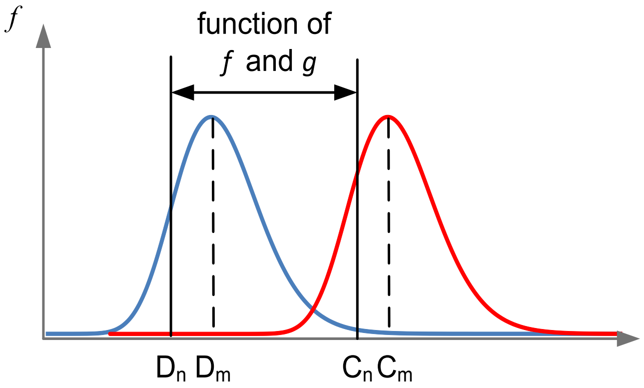
$$\phi C_n \geq \gamma D_n$$

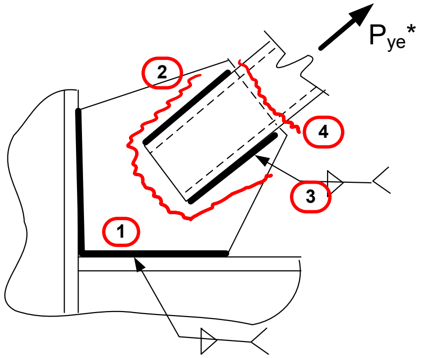
- Connections
- Columns
- Collectors
- Other “Non-Ductile” Elements

$$\frac{\gamma}{\phi} = \frac{D_m}{D_n}\frac{C_n}{C_m}\exp\left(\underline{\beta_{R,Ha}}\sqrt{V_C^2 + V_D^2 - 2\rho V_C V_D}\right)$$

Target Reliability (probability D>C)

Establishing Target Reliability – $\beta_{R,Ha}$





$$\gamma D_n = \phi C_n$$

Determine an appropriate target reliability index, $\beta_{R,Ha}$, or P(D>C), considering the following:

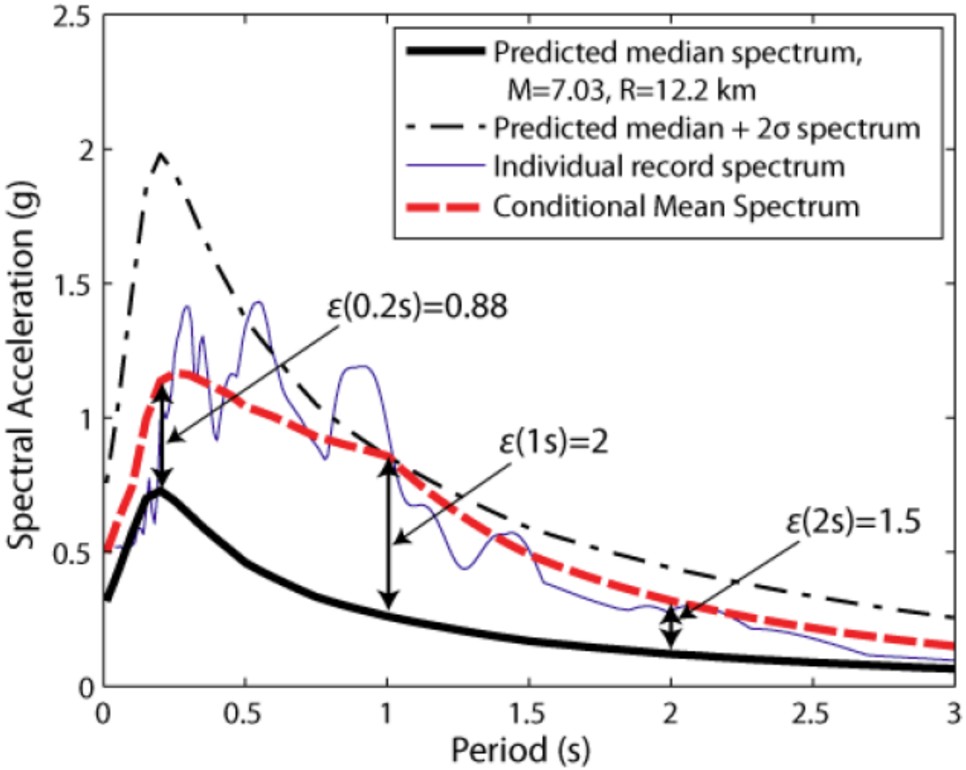
1) The likelihood of a large enough earthquake to yield the structure, i.e., $MAF(Sa > Sa_{y,\exp})$

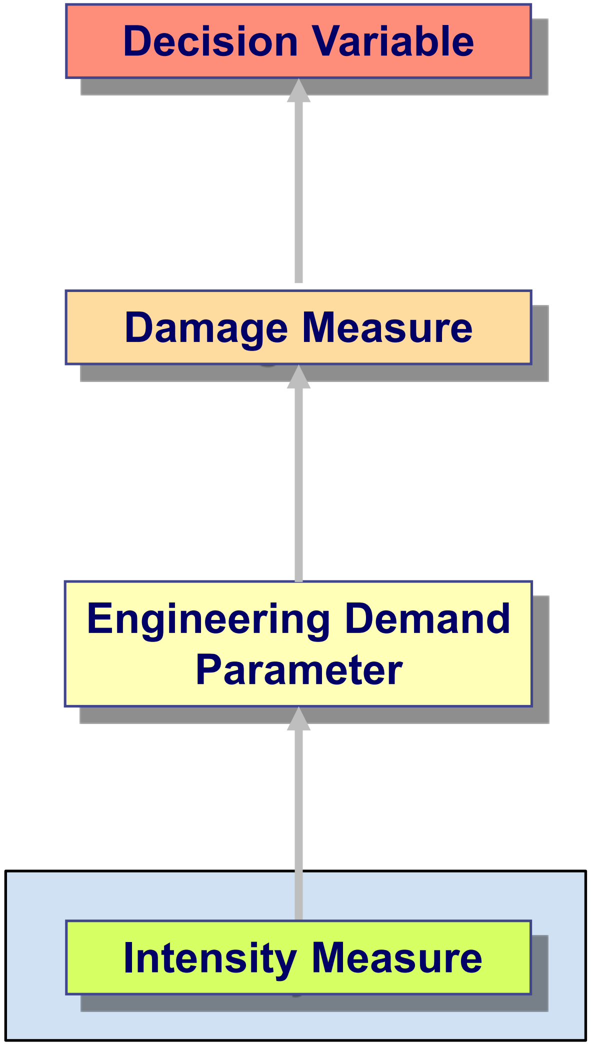
2) The increased risk of structural collapse due to failure of the component, i.e., $P\left(Coll_{D>C} \middle| D > C\right)$

3) Limiting the total probability of collapse, including component failure, to an acceptably low value, e.g., 1% in 50 years

Keep in Mind the Bigger Picture …

Characterization of Ground Motion Hazard





Decision Variable

Damage Measure

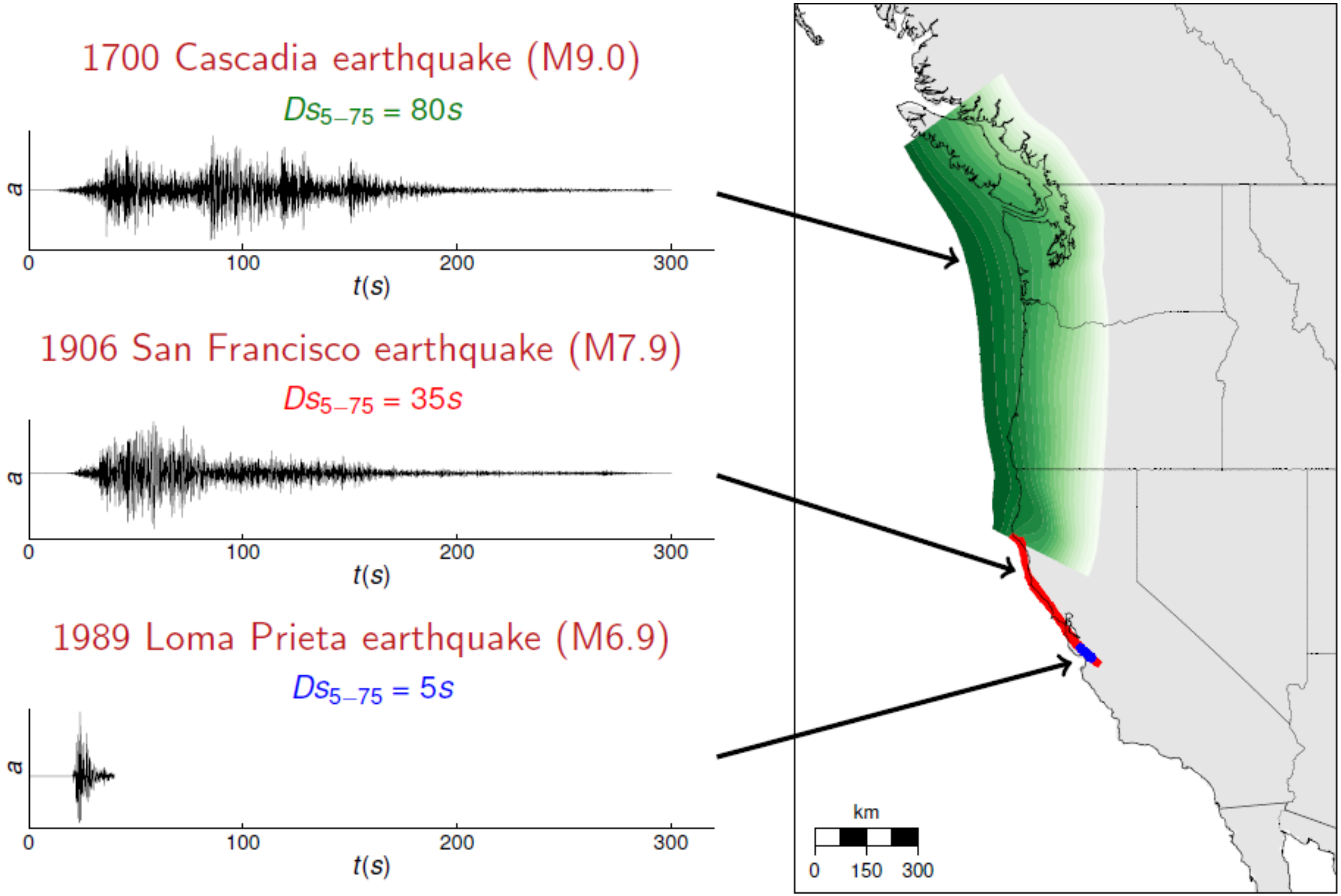
Engineering Demand Parameter

Intensity Measure

- Intensity: Sa(T1)
- Spectral Shape (conditional spectra)
- Other – duration, pulses, …

Baker, Cornell et al. (2006-present)

Significance of GM duration in design and assessment?



Chandramohan, Baker & Deierlein (2013)

Reliability?

Absolute "confidence" in risk estimates will continue to remain elusive … but a ***probabilistic framework*** is essential to integrate the uncertainties in hazard, analyses, and capacities for meaningful design decision making to ensure safe and cost-effective structures.