QUANTIFYING AND COMMUNICATING UNCERTAINTY IN SEISMIC RISK ASSESSMENT

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Workshop on Risk Acceptance and Communication
Stanford University
March 26-27, 2007

Principles of risk-informed decision-making

- Achieve performance consistent with expectations and resources
- Target investments to achieve maximum benefits in risk reduction
- Balance allocation of risk mitigation efforts to competing hazards
- Understandable and acceptable decision process - transparency
- Formal methods for systematic treatment of uncertainty
    - Seismic source, attenuation and demand
    - Facility response
    - Damage, loss assessment and social impact

Seismic vulnerability and risk assessment

Need for improved practices

- New building and bridge systems
- Demands for performance beyond code minimums
- Perception of increasing risk for certain facilities
- Public awareness of performance and demands for safety
- Low-probability, high-consequence events are not well suited to trial-and-error management

Performance-Based Engineering

Premises

- Performance levels and objectives can be quantified
- Performance can be predicted analytically with sufficient confidence
- Uncertainties can be modeled
- Risk can be managed at an acceptable level

DOE-STD-1020-02

Natural phenomena hazards design and evaluation criteria

Cat.	Performance goal	Hazard (/yr)	Failure prob (/yr)
1	Occupant safety	2×10^{-3}	1×10^{-3}
2	Occupant safety, cont'd function	1×10^{-3}	5×10^{-4}
3	Occupant safety, cont'd function; hazard confinement	5×10^{-4}	1×10^{-4}
4	Occupant safety; cont'd function; high confidence of hazard confinement	1×10^{-4}	1×10^{-5}

See also *ASCE Standard 43-05, Seismic design criteria for nuclear facilities*

Sources of uncertainty in seismic risk assessment

- Seismic hazard
- Ground motions – synthetic or natural accelerograms
- Construction practices and in material and system properties for steel, concrete, masonry, timber construction -
- Structural and non-structural component modelling
- Quantitative definition of performance levels and limit states
- Damage and loss estimation for individual facilities
- Damage and loss aggregation for inventories
- Social impact and social vulnerability

Classification of uncertainties

- Inherent randomness (aleatoric)

  Uncertainty explicitly recognized by a stochastic model (irreducible)

- Knowledge-based (epistemic)

  Uncertainty in the model itself and in its descriptive parameters (reducible)

Comment: The distinction is somewhat arbitrary. What is important is that ***all*** sources of uncertainty are properly accounted for in the analysis and displayed as part of the decision framework.

Framework for risk assessment

LS: structural limit state (e.g., $\theta > \theta_{limit}$)
DS: damage state (relates structural response to loss metric)

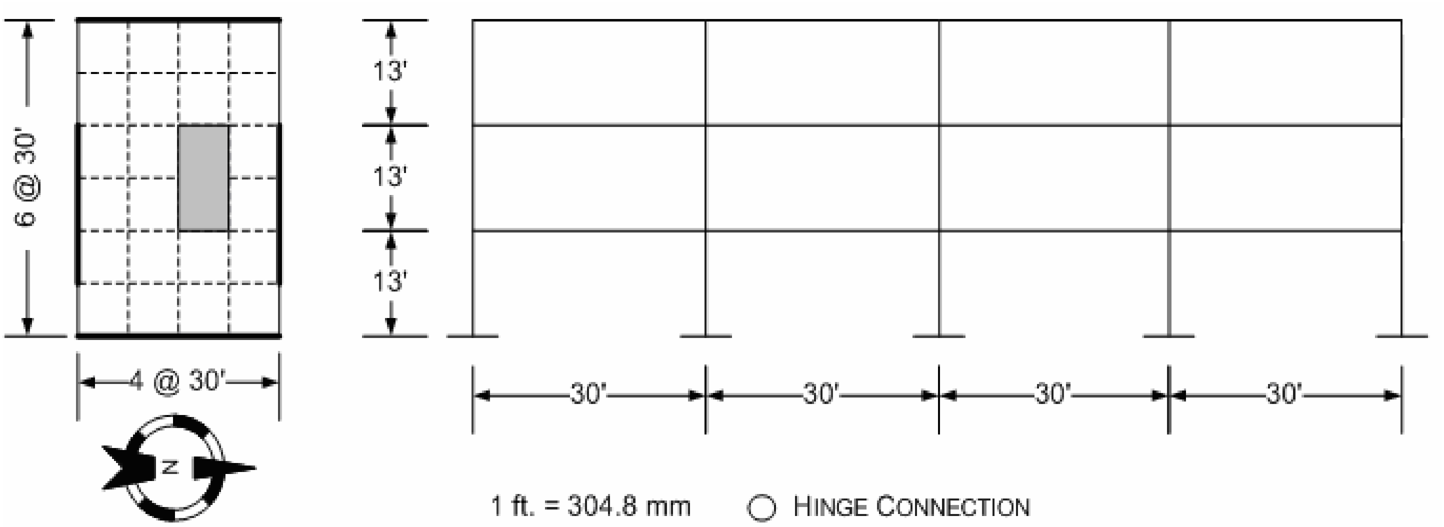
$$P[DS] = \Sigma_s \Sigma_{LS} P[DS=d|LS]\ P[LS|S_a = x]\ P[S_a = x]$$

or

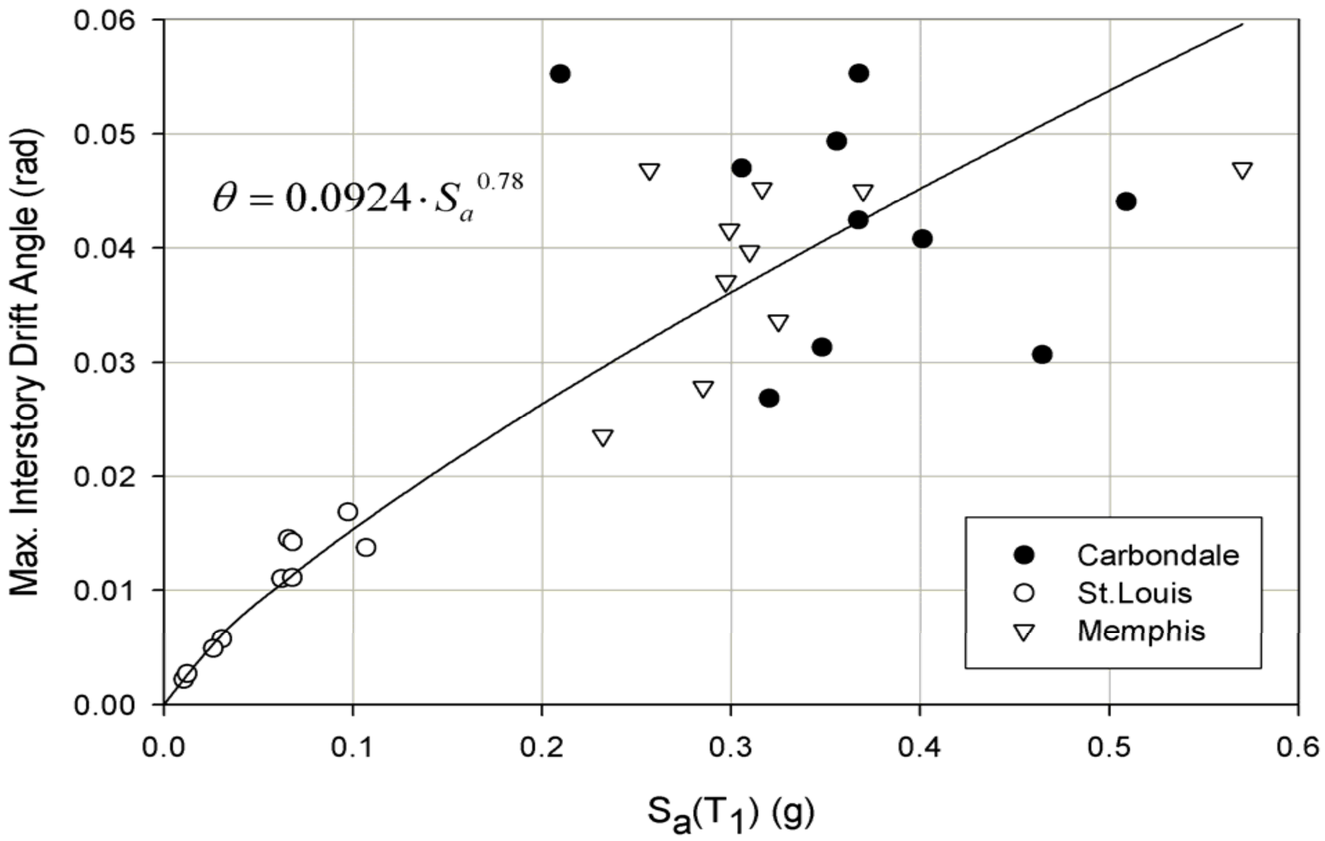
$$P[DS|Scenario] = \Sigma_{LS} \Sigma P[DS=d|LS]\ P[LS|Scenario]$$

$P[S_a = x]$ = Seismic intensity
$P[LS|S_a = x]$, $P[LS|Scenario]$ = system response, capacity
$P[DS|LS]$ = Damage state probability

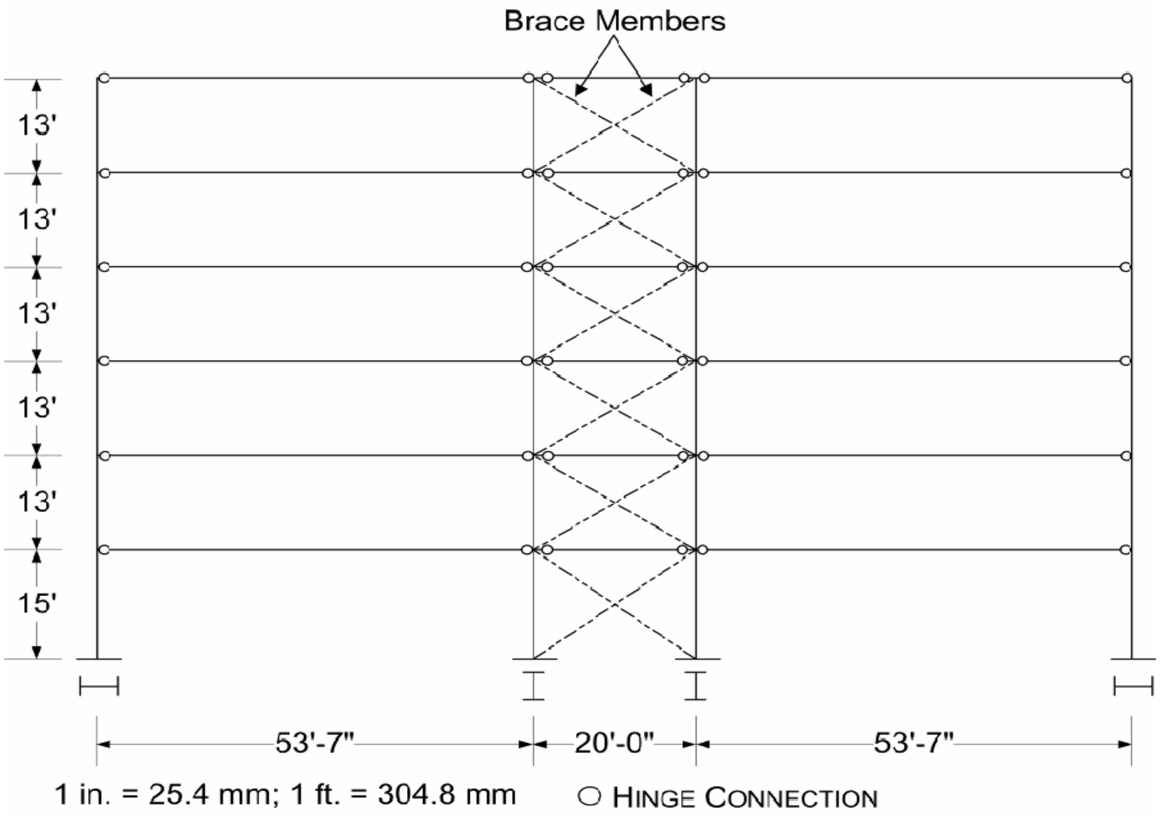
Three-story steel moment frame in CEUS



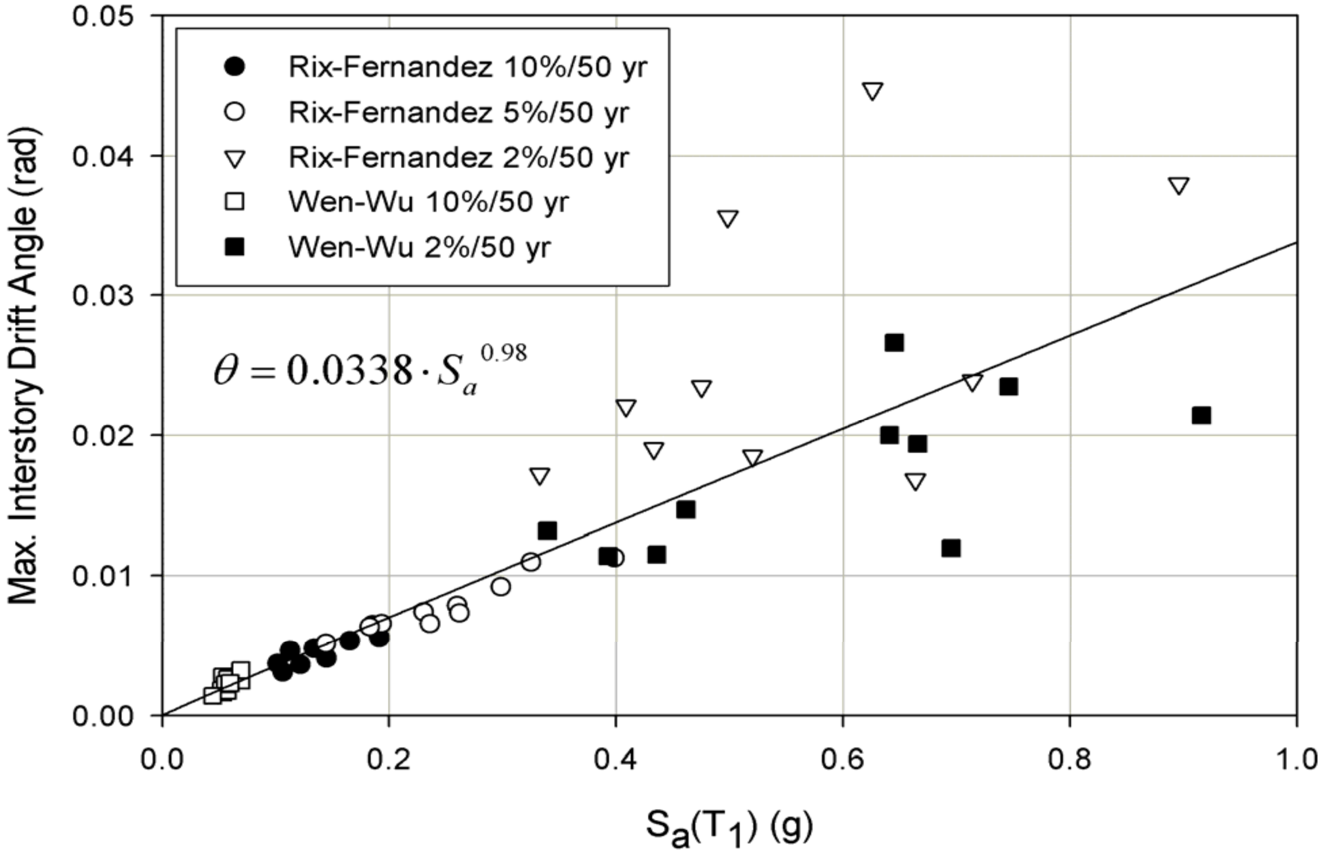
Seismic demand on 3-story moment frame



Six-story steel braced frame in CEUS



Seismic demand on 6-story braced frame



Modeling seismic demand

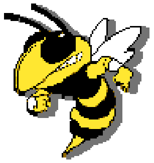
- Intensity: S_a
- Structural response: $\theta = a\, S_a^{\,b}\, \varepsilon$

  $m_\theta = a\, S_a^{\,b}$ (median)

  ε models scatter about the median

  Lognormal model for θ (aleatoric)

- $P[LS|S_a = x] = P[\theta > \theta_{limit}|S_a = x]$



Performance objectives

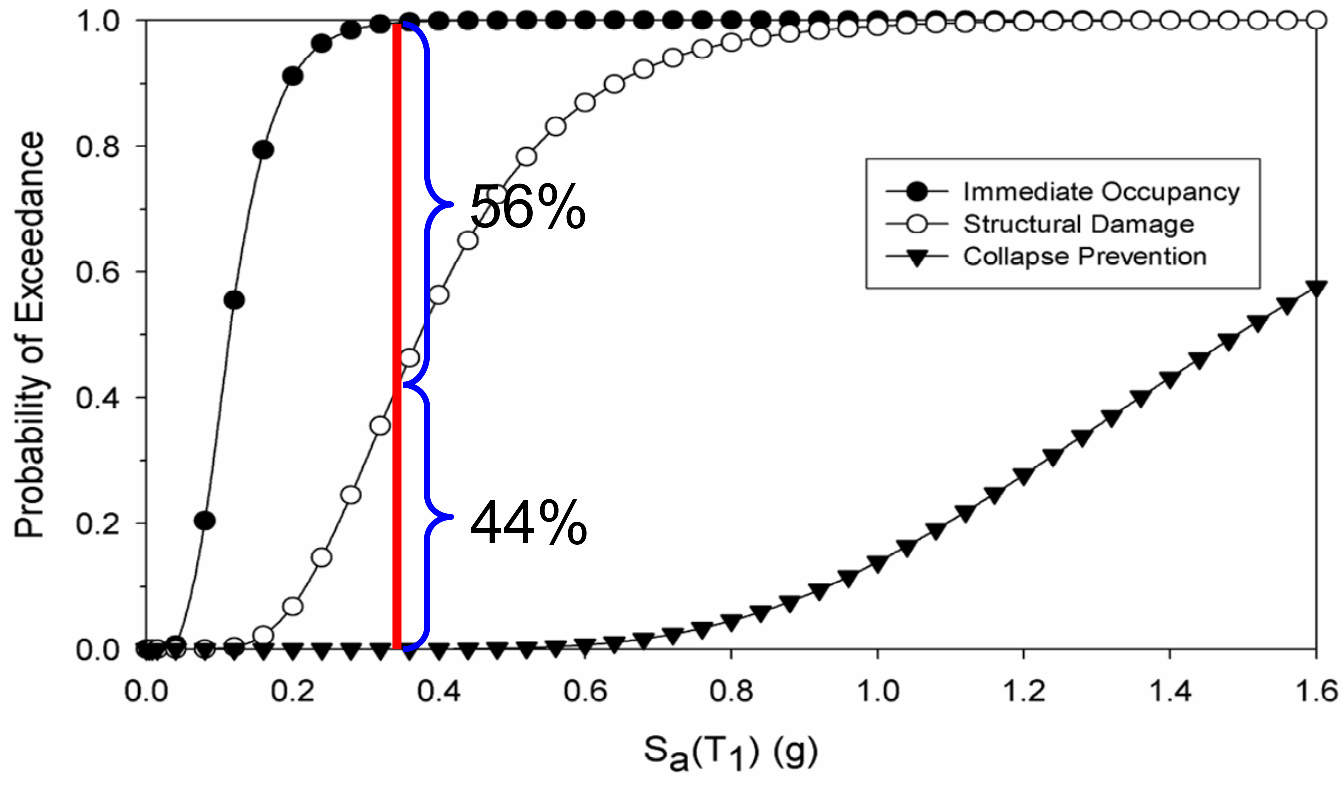
- Immediate occupancy (IO) – damage to nonstructural components occurs beyond elastic range (ISD 0.5% to 1.0% for steel frame buildings)

- Structural damage (SD) - damage occurs at an ISD 1% - 2%. (Drifts associated with "life safety" cannot be computed reliably)

- Collapse prevention (CP) – excessive P-Δ effects develop even in well-designed frames at approximately 5% - 8% ISD. (ISDs beyond this level cannot be computed reliably with software currently being used for this purpose.)

Seismic fragilities based on interstory drift

(Six-story braced frame – Memphis, TN)



Limit state probability – point estimate

(Six-story braced frame – Memphis, TN)

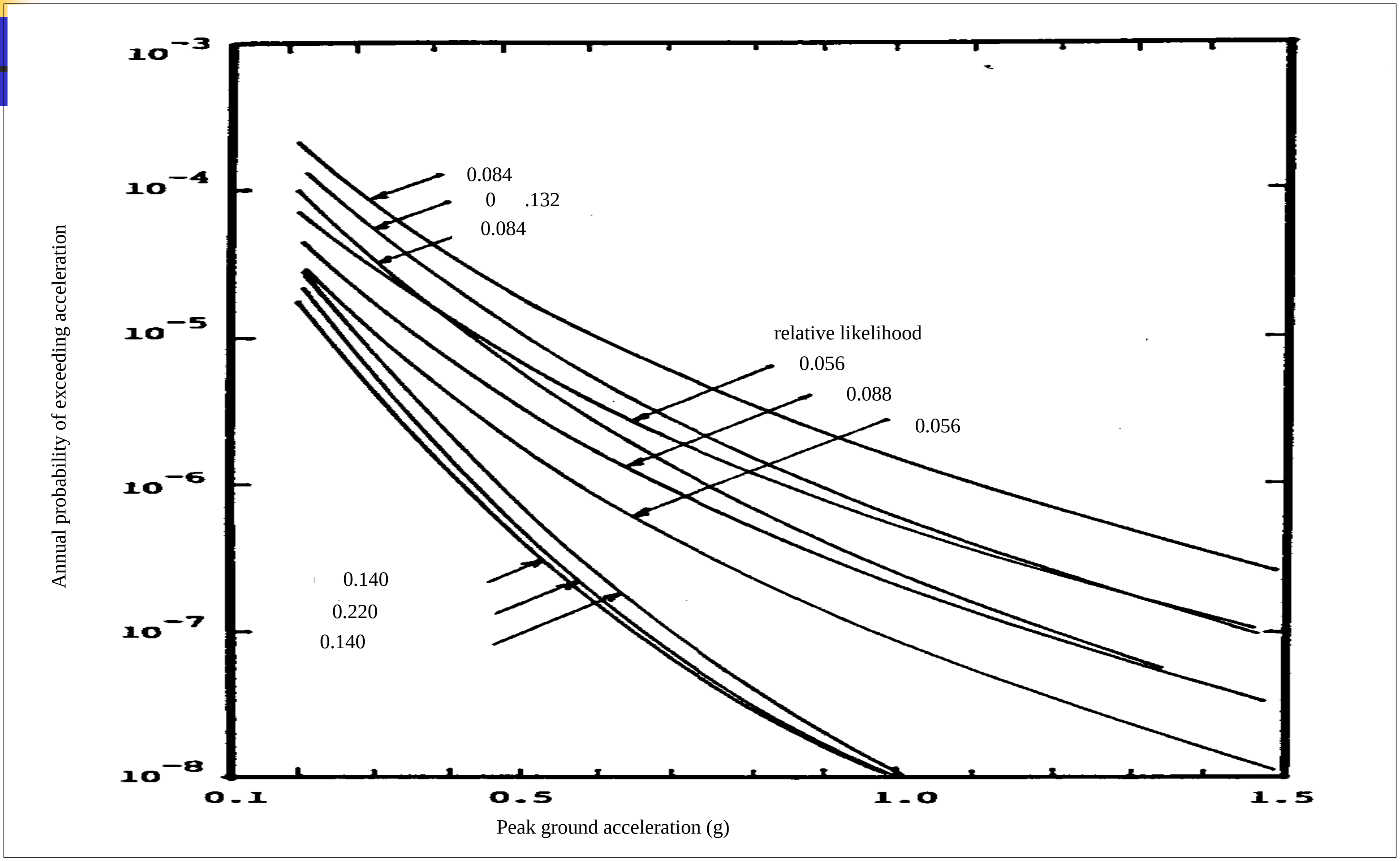
- Structural fragility: $F_R(x) = \Phi[\ln(x/m_R)/\beta_R]$
- Demand (hazard): $\ln H_Q(x) \approx k_o - k \ln x$
- Limit state probability (reflects aleatoric uncertainty):

$$P_{LS} \approx k_o[(m_{\theta C}/a)^{1/b}]^{-k} \exp[\ \tfrac{1}{2}((k\beta_{\theta C}/b)^2]$$

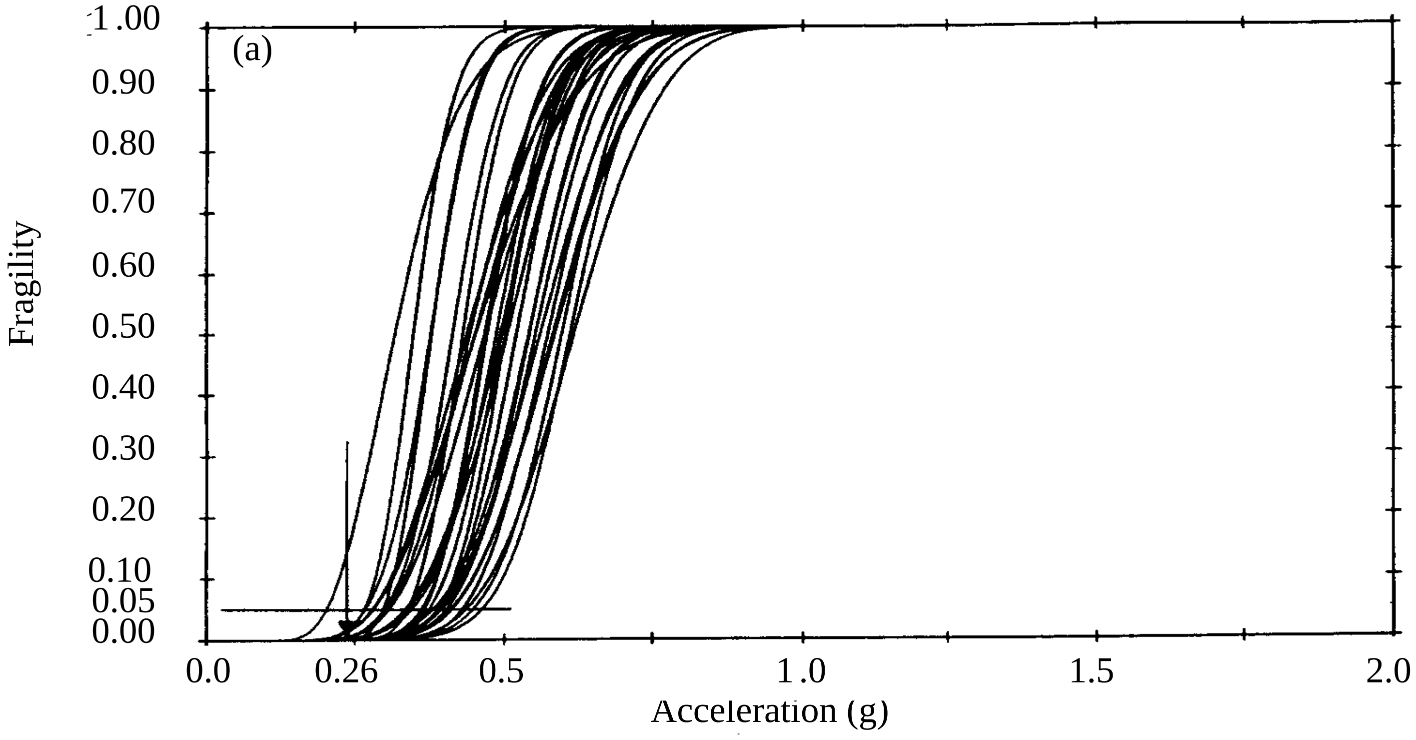
Memphis, TN: $k_o = 1.48 \times 10^{-4}$, $k = 1.0$ and $\beta_{\theta C} = 0.36$ (typ)

If $m_{\theta C} = 0.015$ rad, $P_{SD} = 3.8 \times 10^{-4}$/yr

Epistemic uncertainty in seismic hazard due to alternate source hypotheses (β_{UH})



Epistemic uncertainty in fragility due to structural behavior modeling (β_{UC})



Encoding epistemic uncertainty

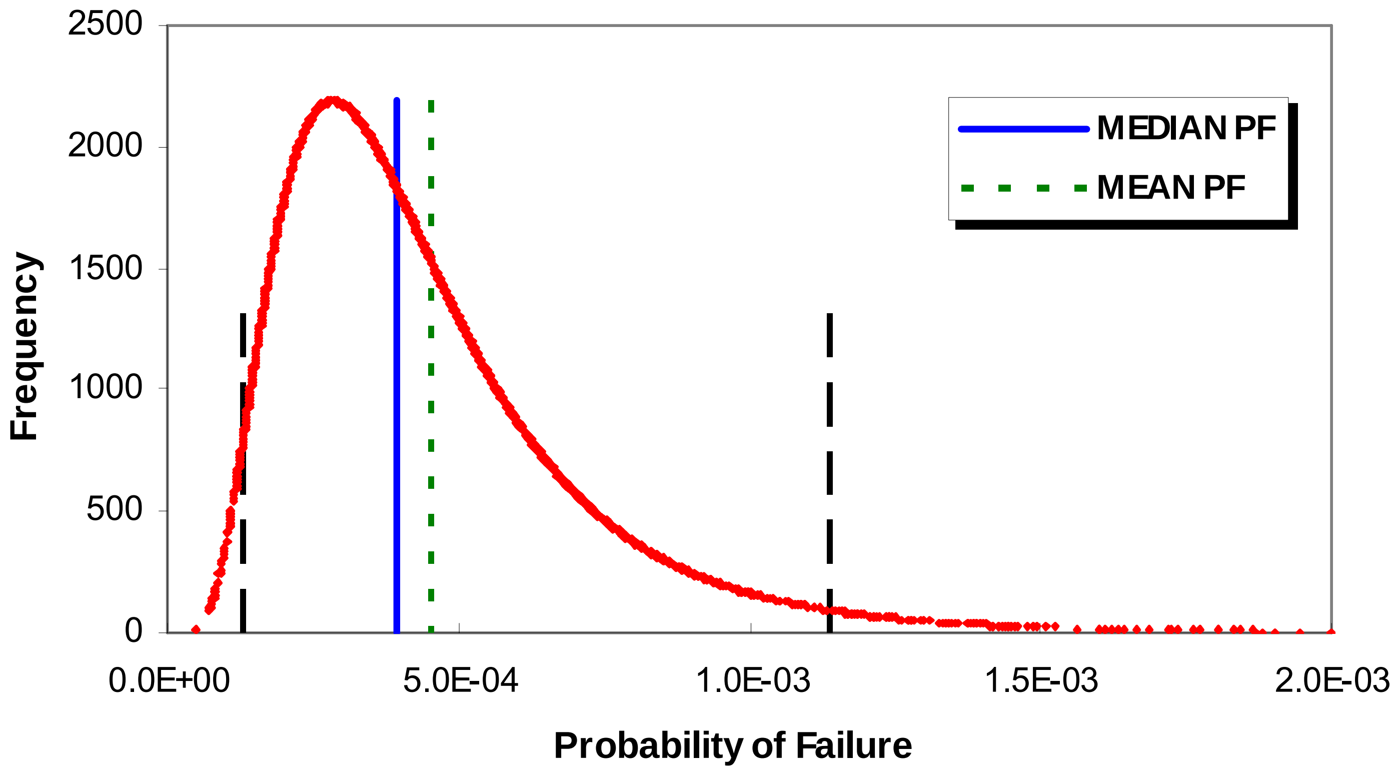
Assume that

- Median capacity can be estimated to within ±30% with "certainty" (90% confidence)
  - ….implies $\beta_{UR} \approx 0.20$

- Ratio of 85th to 15th percentiles of seismic hazard typically is about 3
  - ….implies $\beta_{UH} \approx 0.50$

Frequency distribution of P_{SD} for braced frame

Epistemic uncertainty in risk



Interval estimates of limit state probabilities (x 10^4) for 6-story braced frame

Fractile

	2.5%	50%	Mean	97.5%
IO	4.4	13	15	36
SD	1.3	3.8	4.4	11.0
CP	0.34	0.96	1.1	2.7

Confidence in risk assessment

If the onset of the structural damage state of the six-story frame is defined by $m_{\theta C}$ = 0.015 rad from NTHA:

- A “*point estimate*” of P_{SD} is:

  4.4×10^{-4} (mean)

  3.8×10^{-4} (median) (Reflects aleatoric uncertainty)

- PSD_{SD} is *between 1.3 and 11.0 x* 10^{-4}*/yr with 95% confidence* (Reflects epistemic uncertainty)

Research and implementation issues

- Mapping earthquake-induced demand to damage states
- Relating damage states to losses or other decision variables
  - Losses to engineered systems
  - Losses to non-engineered facilities
  - Damage to building contents
  - Impact on social fabric
- Risk validation
- Risk aggregation
- Risk communication
  - Metrics of acceptable risk
    - Annual probability of loss
    - Expected annual losses
    - Lifetime losses
  - Risk perception differences among stakeholders
  - Value engineering; investment in risk reduction

Acknowledgement

Research supported, in part, by the Mid-America Earthquake Center at the University of Illinois, funded by the National Science Foundation Grant No. EEC-9701785.

Thank you!