Performance-Based Earthquake Engineering

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EERI 2005 Distinguished Lecture
Contributors

PEER

- Ross Boulanger, Yousef Bozorgnia, Mary Comerio, Greg Deierlein, Ahmed Elgamal, Helmut Krawinkler, Peter May

Example building

- ATC 58 Project Team Participants: Robert Bachman, Craig Comartin, Ron Hamburger, Gee Hecksher, Andrew Whittaker
- Rutherford & Chekene; Simpson Gumpertz & Heger
- Armen der Kiureghian, Kevin Mackie, Boza Stojadinovic, Tony Yang
Performance-based engineering

Design for the achievement of specified results rather than adherence to particular technologies or prescribed means.  (after May 2004)

If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.  (after Hammurabi 1780 BC)
Prescriptive design approach

- Linear analysis model
- Prescribed strength
- Prescriptive details
- Shortcomings:
  - focus on aesthetics, functionality during normal service, and up front costs
  - emphasis on satisfying criteria, with performance as an undefined byproduct of design
Why shift to a performance basis?

- Reduce code complexity
- Allow intent of building regulations to be understood
  - improve design outcomes
  - promote innovation with materials, systems, design approaches
- Allow design to be tailored to individual buildings and uses
- Reduce cost of facilities
- Easier export of products and expertise
Performance-based design approach

- Base Shear
- Damage threshold
- Collapse onset
- Deformation

Performance Levels:
- IO
- LS
- CP

Frequency of Design Ground Shaking Level:
- Infrequent
- Rare
- Very rare

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Three styles of decision-making

- **Prescriptive design**
  - *focus on up-front costs*

- **Performance design**
  - *optimized performance*

- **Investment-based design**
  - *consideration of trade-offs*
Performance measures for decision-making

- Base
- Shear
- Damage threshold
- Collapsed onset

Performance Levels
- IO
- LS
- CP

- $, % replacement

- Casualty rate

- Downtime, days

Holmes, 2001
Framework for PBEE

\[ v(DV) = \int \int \int G(DV \mid DM) \, dG(DM \mid EDP) \, dG(EDP \mid IM) \, d\lambda(IM) \]

- **Decision Variable**
- **Damage Measure**
- **Engineering Demand Parameter**
- **Intensity Measure**
- **Loss Functions**
- **Fragility Functions**
- **Response Simulations**
- **PSHA**

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A PBEE implementation challenge

To conduct a PBEE study on a real building using real earthquake professionals and a realistic budget and timeframe.
Conceptual damage calculation
Conceptual damage calculation
Conceptual damage calculation

EDP = story drift
Conceptual repair quantities calculation

Performance Group $i$

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Conceptual repair quantities calculation

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Conceptual repair cost calculation

Quantity $i$ (e.g., running feet of wallboard partition)

Total repair cost

Total cost = $\sum C_i Q_i$

(plus contractor's OH and profit (~12%) and general project costs (design, admin etc, at 20-50%).
Conceptual repair cost calculation

Hazard level

Total Cost

Annual frequency of exceedance
A PBEE implementation challenge

To conduct a PBEE study on a real building using real earthquake professionals and a realistic budget and timeframe.
Simplified building plan
Lateral-force-resisting systems

(a) Special moment frame

(b) Eccentric braced frame

(c) Special concentric braced frame

(d) Buckling-restrained braced frame
Equal-hazard spectra with average fault rupture directivity effects

5% Damping

Return periods of 72 years, 475 years, 975 years and 2475 years
1-second spectral accelerations

475-year Return Period Ground Motion

% Contributions

Magnitude

Distance, km

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Suites of ground motions

Ground motion: LP-lex1

Fault Normal

Fault Parallel
Ground motion scaling procedure

Scaled to $S_{a,T1}$
Nonlinear dynamic analysis
Summary of responses

Seismic hazard level: 10% in 50 years

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<th>Filename</th>
<th>$\Delta u_{\text{max}}$</th>
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$\Delta u_{\text{max}}$ = maximum inter-story drift at the $i^{th}$ floor as a ratio of the story height.  
$\Delta u_{\text{max}}$ = maximum roof drift as a ratio of the total building height.  
$\Delta u_{\text{res}}$ = residue inter-story drift at the $i^{th}$ floor as a ratio of the story height.  
$\Delta u_{\text{res}}$ = residue roof drift as a ratio of the total building height.  
$V_{\text{res}}$ = maximum floor velocity with respect to the ground.  
$A_{\text{res}}$ = maximum absolute floor acceleration.
Response simulation

- Lots of nonlinear dynamic analyses
- Simulation of the results

Floor Peak Relative Displacements for 10 EDP Realizations
Determination of damage states

\[ P(DS \geq DS_i) \]

Interstory drift, %
Tables of performance groups, damage states, quantities, and unit costs

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Summary repair costs

$P(\text{Total Repair Cost} \leq \$C)$

$C$ (dollar)

- 95% in 50 yrs
- 90% in 50 yrs
- 75% in 50 yrs
- 50% in 50 yrs
- 10% in 50 yrs
- 5% in 50 yrs

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Summary repair costs
Various expressions of costs

(a) Expected cost for M7 scenario

$1.2M

(b) 90% confidence cost does not exceed threshold for 975-yr return period hazard level

$2.0M

(c) Mean cumulative annual total cost of damage

$50,000

(d) Contributions to total cost for scenario

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The language of PBEE

- Recognize the range of stakeholders
  - public versus private
  - large and small firms
  - single facilities versus inventories
  - single versus distributed facilities
  - essential versus nonessential facilities
  - facilities providing lifeline support

- Develop language and measures for specific stakeholder
The language of PBEE

Expression of seismic hazard
- mean annual rate of exceedance
- return period
- probability of exceedance in 20-50 years
- scenario that has a reasonable probability of occurring over 20-50 years

Expression of risk
- Ranges of losses versus confidence intervals
- Maximum probable loss
- Risk of financial ruin
Some uses of PBEE

Should the owner retrofit a facility to reduce earthquake losses?

Existing structure

A = net present value of annual losses

Retrofitted structure

B = retrofit cost + net present value of annual losses
Design enhancements beyond life safety

Estimated Losses after Life-Safety Retrofits only

Net present value of loss

Cost of enhancements

Estimated seismic losses

Net Benefit

Life Safety Retrofit

Enhancement Option

Design Performance Levels
Some uses of PBEE

- Business owner

  90% confidence that my business will not be financially ruined by capital losses exceeding $1M over the next 30 years
Some uses of PBEE

Essential facilities

For a hospital...
10% chance of being unable to accept new patients for more than a week after an earthquake in the next 50 years
Some uses of PBEE

- Improve reliability aspects of FEMA 356

For standard occupancy building…
90% confidence that a building will not collapse for ground shaking representative of 2500-year return period hazard level
Some uses of PBEE

- Clearer specification of code intent
  For standard occupancy building…
  not more than 0.0002 chance per year of a single life loss (considering the entire hazard)

- and code provisions the better accomplish the intent
A performance code format

Objectives

- Safeguard people from earthquakes

Functional statements

- Avoid building collapse

Performance requirements

- Mean annual rate of one or more lives lost in building collapse = 0.0002

Deemed to satisfy

Verification methods

- Prescriptive code or recognized PBEE methodology

*after Meecham 2005, Australian Building Code 1995*
Regulation of PBEE

💎 Regulation of performance standards not new
   - US drinking water standard of 1914

💎 Qualitative versus quantitative approach

   - Qualitative: performance at least equivalent to that obtained using prescriptive code requirements
   - Quantitative: the number of lives lost in a single building for 475-year event

💎 Open question: How tight should controls be to ensure consistency and accountability, versus how much discretion should be granted in promoting flexibility?
PBEE regulations/guidelines

UBC 1946

This code …“is dedicated to the development of better building construction and greater safety to the public, through the elimination of needless red tape, favoritism and local politics by uniformity in building laws; to the granting of full justice to all building materials on the fair basis of the true merits of each material; and to the development of a sound economic basis for the future growth of cities through unbiased and equitable dealing with structural design and fire hazards.”
PBEE regulations/guidelines

- **UBC 1946**
- **SEAOC Blue Book - 1967**

- Resist minor earthquakes without damage;
- Resist moderate earthquakes without structural damage, but with some nonstructural damage;
- Resist major earthquakes … without collapse, but with some structural as well as nonstructural damage.
PBEE regulations/guidelines

- UBC 1946
- SEAOC Blue Book - 1967
- ATC 3-06 - 1978
- FEMA 273/356 - 1997
- SAC (steel moment frames) - 1999
- ATC 58 - ongoing
Pattern of Diffusion of Technological Innovations

(hypothetical example)

Proportion Adopted

Late Adopters

Rapid Diffusion

Early Adopters

Time -- Years

May 2002
Adoption of PBEE

Attributes
- relative advantage
- compatibility
- complexity
- trialability
- observability

Promoting its effective use
- engaging early adopters
- FEMA 356, ATC 58, …
Performance-based engineering

Design for the achievement of specified results rather than adherence to particular technologies or prescribed means.
Performance-based earthquake engineering

An approach for managing seismic risk, whereby

earthquake professionals quantify seismic risk in terms that are meaningful to the decision-makers

decision-makers thereby make informed decisions that define a rational course of action for the earthquake professionals