Toward Probabilistic Performance-based Seismic Design of Concrete Bridges

Bozidar Stojadinovic
Kevin Mackie

University of California, Berkeley

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PEER PBD Framework
Why a demand model?

1.) Quantitative Performance Based Earthquake Engineering tool for designers of bridges

What is probability of $y$, given $x$?

Intensity Measure: $x$  
Demand Measure: $y$
2.) How do design parameters affect performance?
The Big Picture

General Probabilistic Seismic Demand Analysis

Earthquake → Structure → Analysis Method → Demand Model (PSDM)
What is a PSDM?

PSDM = Probabilistic Seismic Demand Model

Relationship of seismic Intensity Measures (IM) to structural Engineering Demand Parameters (EDP)
Probabilistic Seismic Demand Analysis

- Define motions (IM)
- Define class of structures (EDP)
- Define analysis model
- Nonlinear analysis

- Design parameter sensitivity
- Ground motion bin sensitivity
- Residual dependence (M, R)
Demand: Bridge Classes

- Single bent
- 2-bent
- 3-bent
- Stand-alone
- Single-column bents
- 3-bent stand-alone
Seismicity: Ground Motions & IMs

• Period Independent Intensity Measures (in this study)
  • Arias intensity
  • PGA, PGV, PGD

• Period Dependent Intensity Measures
  • $S_a, S_v, S_d$
  • $S_d,_{inelastic}$
  • Spectral combinations (Cordova, 2000)

\[
S_{a_C} = S_a(T_1) \sqrt{\frac{S_a(2T_1)}{S_a(T_1)}}
\]
Demand: EDPs

- Local EDPs
  - Steel stress & strain
  - Concrete stress & strain
- Intermediate EDPs
  - Column curvature ductility
  - Maximum column moment
  - Plastic rotation
  - Hysteretic energy

- Global EDPs
  - Displacement ductility
  - Drift ratio
  - Residual displacement index

Single column/bent highway overpasses in California
OpenSees Bridge Model

- Elastic deck
- Fiber RC column
- Ground level
- Soil springs
- Abutment springs and gaps

- Mode 1 - Longitudinal
- Mode 2 - Transverse
- Mode 3 - Vertical
Bridge Design Parameters

Single-column, single-bent bridges
**Bridge Design Parameters**

Range of design parameter variations

- **L** span length 60-180 ft
- **L/H** span to column height ratio 1.2-3.5
- **$r_{s,\text{long}}$** column longitudinal reinforcement 1-4%
- **$D_{c/Ds}$** column to superstructure dimensions 0.67-1.33

- **$r_{s,\text{trans}}$** column transverse reinforcement 0.4-1.2%
- **Wt** additional superstructure weight 10-150%
- **$K_{\text{soil}}$** soil stiffness USGS A-D
- **Abut** abutment mass/stiffness models various
Analysis Method

Probabilistic Seismic Demand Analysis (PSDA)

Incremental Dynamic Analysis (IDA)
Demand Model Criteria

Practical
- Definition: Makes engineering sense
  - Practical: column drift
  - Not practical: steel stress

Effective
- Definition: linear or mult-linear median relationship

Efficient
- Definition: low variability

Sufficient
- Definition: No conditional dependence on M, R
  - \( P[EDP|IM,M,R] = P[EDP|IM] \)
  - Can also be applied to strong motion duration
Resulting Demand Models

Intensity Measure vs Demand Measure (IDA) - Eq1(-), Eq2(-.), Eq3(--), Eq4(:)

Drift Ratio Longitudinal

\[ \frac{D_c}{D_s} (4i) = 0.67, 0.75, 1, 1.3 \]

Intensity Measure vs Demand Measure (Parameters)

\[ \beta = 0.33, 0.32, 0.36, 0.36 \]

PSDA

IDA
In the context of IDA-PSDA Median Comparison, the focus is on the relationship between Sa_T1 and Drift ratio (linear), with a 8x10 IDA matrix. The graph illustrates the intensity measure vs demand measure (parameters) for PSDA solid and IDA dashed lines. The Superstructure depth to column diameter ratio (Dc/Ds) is visualized with various drift ratios: Dc/Ds (8ij)=0.67, Dc/Ds (8ij)=0.75, Dc/Ds (8ij)=1, and Dc/Ds (8ij)=1.3. This data pertains to 1-bent bridge with abutments.
- IDA 4x20 under-predicts dispersion
- IDA 8x10 approaches real dispersion
Design Parameter Sensitivity

Superstructure depth to column diameter ratio ($D_c/D_s$)

Decreasing column height increases drift (decreases max. displ.)
Design Parameter Sensitivity

Column longitudinal steel ratio ($\bar{r}_s$)

Increasing steel increases column moment demand

1-bent bridge with abutments
Sensitivity with Optimal IMs

SaT1-Drift sensitivity to Dc/Ds design parameter

Intensity Measure vs Demand Measure (Parameters)

\[
\begin{array}{c|ccccc}
\text{Drift Ratio Longitudinal} & 0.40 & 0.29 & 0.24 & 0.15 \\
\hline
\text{Dc/Ds=}0.67 & & & & \\
\text{Dc/Ds=}0.75 & & & & \\
\text{Dc/Ds=}1 & & & & \\
\text{Dc/Ds=}1.3 & & & & \\
\end{array}
\]

Arias

\[
\begin{array}{ccccc}
0.41 & 0.37 & 0.34 & 0.31 \\
\end{array}
\]

Sa(T1)

\[
\begin{array}{ccccc}
0.40 & 0.29 & 0.24 & 0.15 \\
\end{array}
\]
Sensitivity with Optimal IMs

Sa(Cordova)-Drift sensitivity to Dc/Ds design parameter

Intensity Measure vs Demand Measure (Parameters)

Dc/Ds=0.67
Dc/Ds=0.75
Dc/Ds=1
Dc/Ds=1.3

Arias
Sa(T1)
SaC

<table>
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<tr>
<th>Parameter</th>
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<td>0.29</td>
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</tbody>
</table>
Sufficiency

Distance (R) dependence

Residual Dependence (semilog scale)

c \( (E^{-2}) = 0.04, -0.11, 0.15, 0.63 \)

L2 = 1080
L2 = 1440
L2 = 2160
L2 = 2520
Demand fragility

![Demand fragility curve](image)
Demand Fragility
PSDM Extensions

Structural Demand Hazard Curves

Average Structural Demand Hazard Curve

**Drift Ratio Longitudinal**

- $Dc/Ds=0.67$
- $Dc/Ds=0.75$
- $Dc/Ds=1$
- $Dc/Ds=1.3$
PSDM Extensions

Functional EDPs

- Maximum post-earthquake functionality (traffic load, eg)
- Fragility functions: Probability of exceeding a given damage state
Conclusions

• PEER PBD framework is completely general with a probabilistic basis
• Demand models can be represented by:
  – PSDA
  – IDA
  – Demand fragility
• Criteria for acceptance of a demand model
  – Practical, efficient, effective, sufficient
• Damage fragility easily incorporated using capacity models
Thank You!

• Questions?

• For more information contact:
  – Kevin Mackie: mackie@ce.berkeley.edu
  – Boza Stojadinovic: boza@ce.berkeley.edu
• Visit http://millerbird.ce.berkeley.edu

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