Decision Analysis for Seismic Retrofit of Structures

Ryan J. Williams
Paolo Gardoni
Joseph M. Bracci
Texas A&M University

Risk Acceptance and Risk Communication
March 26-27, 2007
Stanford, California, USA
Problem statement and motivation

- The latest IBC provisions would require (if adopted) buildings in Mid-America to be designed for similar seismic events as in California.
- If so, buildings in parts of Mid-America would be significantly overdesigned for less intense earthquakes.

Objectives

- Investigate how building location affects the annual probability of attaining or exceeding specified performance levels.

- Develop a framework to determine the economic feasibility of seismic retrofitting.

- Study the effects that achievable loss reduction, investment return period, and retrofitting cost have on the economic feasibility of seismic retrofitting.
  - Compare Mid-America with California.
Outline

• Annual probability of failure of an example building
• Framework to compute the Estimated Annual Loss
• Parametric study on Estimated Annual Loss (achievable loss reduction, investment return period and retrofitting cost)
• Impact of retrofit: A case study
• Conclusions
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Consider a typical gravity-load designed building prone to “soft-story” failure mechanism.

Plan and elevation views of the example 2-story RC building (Ramamoorthy et al., 2006)

Design details (Ramamoorthy et al., 2006)

This represents typical low-rise construction in Mid-America.
Identical example buildings are studied in Memphis, TN and San Francisco, CA.

Building location is therefore the primary factor affecting retrofit feasibility.

The seismic hazard can be used to compute the annual probability of attaining or exceeding a performance level.

The annual probability of attaining or exceeding a performance level is given by:

\[
P_f = \int_{S_a} F(S_a) f(S_a) dS_a
\]

The corresponding generalized reliability index is:

\[
\beta = \Phi^{-1} \left( 1 - P_f \right)
\]

Where:

- \( S_a \) = Spectral acceleration
- \( F(S_a) \) = Fragility
- \( f(S_a) \) = Annual probability density of \( S_a \) at building site

*FEMA-356 Performance Levels*

Ramamoorthy et al. (2006)
Should stakeholders retrofit their buildings?

<table>
<thead>
<tr>
<th>Annual Probability $P_f$</th>
<th>Memphis</th>
<th>San Francisco</th>
</tr>
</thead>
<tbody>
<tr>
<td>IO</td>
<td>0.00590</td>
<td>0.06438</td>
</tr>
<tr>
<td>LS</td>
<td>0.00469</td>
<td>0.04693</td>
</tr>
<tr>
<td>CP</td>
<td>0.00375</td>
<td>0.03514</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Reliability Index $\beta$</th>
<th>Memphis</th>
<th>San Francisco</th>
</tr>
</thead>
<tbody>
<tr>
<td>IO</td>
<td>2.52</td>
<td>1.52</td>
</tr>
<tr>
<td>LS</td>
<td>2.60</td>
<td>1.68</td>
</tr>
<tr>
<td>CP</td>
<td>2.67</td>
<td>1.81</td>
</tr>
</tbody>
</table>

The annual probabilities are ~10 bigger in San Francisco (SF) than in Memphis.

Reliability in Memphis is within the commonly acceptable range.

Stakeholders also need to consider the improvements in the reliability provided by a retrofitting strategy and its expected economic benefit.
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The Estimated Annual Loss can be used to determine the economic benefit of a retrofitting strategy.

**Estimated Annual Loss, \( EAL \)**

\[
EAL = V \int_{S_a=0}^{\infty} y(S_a)v(S_a) dS_a
\]

- \( V \) = the value of the facility and any additional value associated with it
- \( y(S_a) \) = total damage factor (mean repair cost of a facility as a fraction of \( V \))
- \( v(S_a) \) = average annual frequency of experiencing ground motion intensity \( S_a \)

**Economic Benefit, \( B \)**

\[
B = (EAL - EAL_{r}) \left( \frac{1 - e^{-\rho T}}{\rho} \right)
\]

Indicates \( EAL \) after retrofit

- \( \rho \) = discount rate
- \( T \) = investment return period
The total damage factor, \( y(S_a) \), represents the mean repair cost of a facility as a fraction of \( V \).

\[
y(S_a) = \sum_{k=1}^{4} \left( \mu_{L_k} \times P_{k|S_a} \right) \quad \text{(Bai et al., 2006)}
\]

Mean of the Damage Factor (structural damage as a percentage of \( V \)) associated to each damage state, \( k \)

\[
\text{Probability of being in each damage state for given } S_a
\]

Data for Example Building

| Performance Level | Damage State   | Probability, \( P_{k|IM} (S_a = 0.488g) \) |
|-------------------|----------------|---------------------------------------------|
| PL1: IO           | Insignificant (I) | 0.063                                       |
| PL2: LS           | Moderate (M)     | 0.094                                       |
| PL3: CP           | Heavy (H)        | 0.256                                       |
|                   | Complete (C)     | 0.587                                       |

\( S_a = 0.488g \)

\( EAL \) in Memphis = \textbf{0.4\% of } V \ vs. \( EAL \) in San Francisco = \textbf{4.0\% of } V

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Retrofit feasibility is studied considering investment return period, reduction in $EAL$, and retrofit cost.

As a rule of thumb, the budget for a retrofit that reduces $EAL$ by any given percentage is 10 times greater in San Francisco than in Memphis.
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Retrofitted fragility curves are used for a case study

Retrofitted column-to-beam strength ratio of 1.8 is used to deter the “soft-story” failure mechanism

(Ramamoorthy et al., 2006)

Maximum allowable retrofit cost for a 5-year return period is nearly 12 times greater for the example building if in San Francisco than if in Memphis.
Should stakeholders retrofit their buildings?

<table>
<thead>
<tr>
<th></th>
<th>Memphis Original</th>
<th>Memphis Retrofit</th>
<th>San Francisco Original</th>
<th>San Francisco Retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Probability $P_f$</td>
<td>IO 0.00590</td>
<td>0.00390</td>
<td>0.06438</td>
<td>0.03720</td>
</tr>
<tr>
<td></td>
<td>LS 0.00469</td>
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<td>0.04693</td>
<td>0.01922</td>
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<tr>
<td></td>
<td>CP 0.00375</td>
<td>0.00125</td>
<td>0.03514</td>
<td>0.00773</td>
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<tr>
<td>Annual Reliability Index $\beta$</td>
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<td>2.66</td>
<td>1.52</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>LS 2.60</td>
<td>2.82</td>
<td>1.68</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>CP 2.67</td>
<td>3.02</td>
<td>1.81</td>
<td>2.42</td>
</tr>
</tbody>
</table>

The reliability in Memphis of the original (unretrofitted) case-study building is still higher than that of the retrofitted building in San Francisco.
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- The annual probability of exceeding a specified performance level for a gravity-load designed building in San Francisco is about 10 times greater than if the same building is located in Memphis.

- Using 2/3 of the 2% earthquake intensity for the design basis of structures will not create uniform reliability (or probability of failure) on an annual basis throughout the US. It will only ensure that buildings throughout the US will not collapse under the 2% Maximum Credible Earthquake (MCE). However, for less intense earthquakes, buildings in parts of Mid-America will be significantly overdesigned as compared to California.

- The retrofit of gravity-load designed buildings might not be financially viable in Mid-America.

- In Mid-America, the indirect value (higher importance use, expensive contents, human lives, etc.) will have to be significantly greater than the direct structural value for the retrofit to be economically feasible, which may be the case for emergency headquarters, hospitals, etc.
Thank you
Appendix
Retrofit feasibility is studied considering investment return period, reduction in $EAL$, and retrofit cost.
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Appendix

(a) Memphis, TN

(b) San Francisco, CA