Aftershock Seismic Vulnerability and Time-dependent Risk Assessment of Bridges

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Research team

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Motivation

• Caltrans uses the following table to relate bridge seismic damage to post-earthquake functionality and repair priorities

<table>
<thead>
<tr>
<th>Bridge system damage states</th>
<th>BSST-0</th>
<th>BSST-1</th>
<th>BSST-2</th>
<th>BSST-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOR</td>
<td>Low</td>
<td>Medium</td>
<td>Medium-High</td>
<td>High</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ShakeCast Inspection Priority levels</th>
<th>Low</th>
<th>Medium</th>
<th>Medium-High</th>
<th>High</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Likely Immediate Post-Event Traffic State</th>
<th>Open to normal public traffic – No Restrictions</th>
<th>Open to Limited public traffic – speed/weight/lane restrictions</th>
<th>Emergency vehicles only – speed/weight/lane restrictions</th>
<th>Closed (until shored/braced) – potential for collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Operation Implications</td>
<td>Very unlikely</td>
<td>Unlikely Likely</td>
<td>Likely Very Likely</td>
<td>Very likely Very Likely - Detour</td>
</tr>
<tr>
<td>Is closure/detour needed? &amp; Are traffic restrictions needed?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Emergency Repair Implications | Very unlikely | Unlikely | Likely | Very likely |
| Is shoring/bracing needed? & Is roadway leveling needed? | | | | |

<table>
<thead>
<tr>
<th>Component Damage Range</th>
<th>CDT-0 to 1</th>
<th>CDT-1 to 2</th>
<th>CDT-2 to 3</th>
<th>Above CDT-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary components</td>
<td>CDT-0</td>
<td>CDT-1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Secondary components</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Aftershock Vulnerability and Time dependent Risk Assessment of Bridges

Motivation

• The extent to which ‘residual structural capacity’ and ‘time-dependent aftershock hazard and risk’ inform these damage-functionality and inspection priority relationships is unclear.

Goals / Overall Objective

• Conduct aftershock seismic vulnerability and time-dependent risk assessment of typical California bridges.

• Evaluate the effect of seismic design philosophy on the time-dependent risk.

• Use results from vulnerability and risk assessments to inform decisions regarding the appropriateness and timing of inspections and post-event closure (partial and complete).
Steps involved in proposed framework

- Select mainshock-aftershock ground motions
- Create structural models of bridge structures
- Conduct mainshock and mainshock-aftershock fragility analysis
- Quantify time-dependent hazard (APSHA) and risk (Markov Chain Models) assessment
- Establish time-dependent risk and functionality/inspection relationships
Past studies have reported non-negligible differences in frequency content of mainshock (MS) and aftershock (AS) records.

Therefore, MS-AS sequences in response history analysis.
Mainshock-aftershock ground motions for bridge-specific risk analysis

- Selected based on high-seismicity zones in California
- Set of 34 record-pairs from Class 1 and Class 2 events in PEER-NGA West2 database
  - $5.8 \leq M_{w,MS} \leq 7.6$
  - $4.0 \leq M_{w,AS} \leq 6.5$
  - $\varepsilon \sim 1.3$
Mainshock-aftershock ground motions for network risk analysis

- Set of 33 record-pairs
- Selected based on a hypothetical scenario event
  - $M_{W,MS} = 7.3$
  - $6.2 \leq M_{W,AS} \leq 7.1$
More than 24,000 bridges in California

Mangalathu (2017): based on design philosophy, bridges in California can be grouped into three

- Era 11 (constructed before 1970)
- Era 22 (Between 1970-1990)
- Era 33 (Constructed post 1990)
Selected Bridge Cases

**Aftershock Fragility Analysis**

- **Aftershock fragility**: A conditional probability that determines the likelihood that a damaged structure will meet or exceed a specified level of damage, given an aftershock intensity measure and an initial damage state associated with the mainshock. 
  
  [mainshock-damage-dependent aftershock fragility]
Main shock and Aftershock fragilities of a bridge designed in Era 11
A Probabilistic Framework for Quantifying MS and MS-AS Seismic Risk

\[ \Pi^k = \begin{bmatrix} p_{11}^k & p_{12}^k & \cdots & p_{1r}^k \\ 0 & p_{22}^k & \cdots & p_{2r}^k \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & p_{rr}^k \end{bmatrix} \]

\[ P_{ij}^k = \left( P_{i,j}[EDP > edp_j|IM] - P_{i,j+1}[EDP > edp_{j+1}|IM] \right) d\lambda_{IM}^k(\text{im}) \]

- \( i \): damage state under 1\(^{st} \) event
- \( j \): damage state 2\(^{nd} \) event

Probability of transition between limit states at time step \( k \) after mainshock

APSHA curve at time step \( k \) after mainshock
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Complete Limit State Probability under Aftershocks for different mainshock limit states and Bridge E3

20% reduction in $S_{a_{median}}$

$P[\text{Complete} | DS_{MS}]$

$S_{a} (g)$

Intact
Slight
Extensive

0 0.5 1 1.5 2 2.5
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Aftershock Transition Probability conditioned on different limit states under mainshock

![Graph showing transition probability over time for different eras.
- Era 1
- Era 2
- Era 3

- All motor vehicle accidents: 0.6% in 50 years
- Daily $P_{MS}[Complete]$
  - 0.23% in 50 years
  - 0.12% in 50 years
  - 0.03% in 50 years]
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Service–life probability of Complete damage state under MS and MS-AS scenarios

- Only mainshock
- Mainshock-aftershock
- Era 1
- Era 2
- Era 3
Conclusions

- Performed aftershock probabilistic seismic hazard analysis (APSHA) to quantify time-dependent post-mainshock hazard.

- Implemented Markov Chain Model that integrates time-dependent hazard curves and mainshock-damage-dependent-fragilities to quantify time-dependent risk.

- Suggested a time-dependent risk outcomes to inform bridge functionality and inspection priorities.