Impact of Complex System Behavior on Seismic Assessment of RC Bridges

Amr S. Elnashai
Department of Civil and Environmental Engineering

Based on the PhD Work of Thomas Frankie, Advised by Kuchma, Spencer and Elnashai
Part of NEES NSF Project CABER .... Lead Institution UNR
Motivation

• Earthquakes pose risk to society due to vulnerability of infrastructure, including bridges
  - Life safety
  - Direct economic loss
  - Other disruptions

• Technical Challenge: Unknown vulnerability of bridges with complex geometry and loading
Motivation

- Fragility relationships representing vulnerability are used in impact assessment
- Current fragilities developed with various assumptions and simplifications made
- Additional Challenge: Influence on the accuracy and reliability of impact assessments is not known
Research Objectives

- Develop experimentally-based fragility relationships that display the impact of the following parameters on vulnerability of RC bridges
  - Complex geometry (namely curvature)
  - Combined loading
  - Modeling assumptions
- Evaluate the results and discuss implications of findings in context of structural response and impact assessment
Experimental Hybrid Simulation

MUST-SIM Facility
NEES Multi-Axial Full-Scale Sub-Structures Testing and Simulation
Experimental Hybrid Simulation

Hybrid Testing of Curved 4-Span Bridge Under Complex Earthquake Motions

NEESR-SG-0530737
Bridge and Pier Features

- Modified from NCHRP design example
- 400 ft length, R=600 ft
- Spans 75-150 ft
- Pier lengths 28.5, 37.5, 22.5
- Tested at 1/3, 1/20, and 1/3 scale
Earthquake Record Applied

- Cracking – 0.08(MCE)
- Yielding – 0.3(MCE)
- Design Level – 1.0(MCE)
- Failure – 2.0(MCE)
Quality of Test

- Loading Units
- 6DOF Control Algorithm
- Deformation Correction
- Small Scale Justification
Quality of Data

- **Traditional – 166 Channels**
  - 152 Strain Gages
  - 6 String Potentiometers
  - 8 LVDTs

- **Krypton – 200 Channels**
  - 2 Krypton Cameras

- **Cameras**
  - 12 High Resolution Still Cameras
  - 2 High Resolution Video Cameras
  - 4 Telepresence Cameras

- **Control Instrumentation**
  - 18 Linear Potentiometers
  - 6 Degree of Freedom compensation of deformations
Data Processing/Visualization
Data Processing/Visualization
Data Processing/Visualization
Data Processing/Visualization

- Step x displacement (in)
- Pier 1

<table>
<thead>
<tr>
<th>Loads</th>
<th>Def.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx</td>
<td>Dx</td>
</tr>
<tr>
<td>Fy</td>
<td>Dy</td>
</tr>
<tr>
<td>Fz</td>
<td>Dz</td>
</tr>
<tr>
<td>Mx</td>
<td>Rx</td>
</tr>
<tr>
<td>My</td>
<td>Ry</td>
</tr>
<tr>
<td>Mz</td>
<td>Rz</td>
</tr>
</tbody>
</table>

Notes: Small Scale spalling on face D. Significant spalling on face D of both 1:3 scale piers. Significant torsional cracking on faces B to C for Pier 1.
Preliminary Observations

- Pier 1 is flexurally dominant
- Pier 2 is flexure-shear
- Extensive hinge formation leads to softening and period elongation
- Period elongation shifts the dynamic response during application of final seismic level
- Stiffness degradation caused greater deformation response demands than seen in analytical model
- Pier response is single curvature in transverse direction
Preliminary Observations

- In-plane stiffness of the deck creates restraints that push the piers into double curvature in the longitudinal direction.
- Transverse drifts at yield are 2%, 1%, and 3%.
- Ultimate drifts reached are 5.5%, 3.3%, and 6.7%.
- Application of vertical load creates non-negligible rotations/moments at top interface of the pier.
- Torsional loading contributes significantly to formation and propagation of cracks for both piers, regardless of flexural or shear dominance.
Model Calibration – Overview

- Objectives
  - Develop agreement between results and data set throughout record
  - Identify disparity and account for assumptions or inaccurate model parameters
  - Utilize global and local response relationships

- Priorities
  - Global displacement response at each pier
  - Reactions at base of piers
Preliminary Comparison of Results

Pier 1 $D_x$

- Expt
- Anly

Time (s) vs. Disp (in)

Pier 1 $F_x$

- Expt
- Anly

Time (s) vs. Force (lbs)

Pier 1 Transverse Hysteresis

Disp (in) vs. Force (lbs)
Preliminary Comparison of Results

Pier 1 Ry

Expt  | Anly
--- | ---
Rotation (deg)

Time (s)

Pier 1 My

Expt  | Anly
--- | ---
Moment (in-lbs)

Time (s)

Pier 1 OOP Rotational Hysteresis

Expt  | Anly
--- | ---
Rotation (deg)

Moment (in-lbs)
Preliminary Comparison of Results
Preliminary Comparison of Results

![Graphs showing comparisons between experimental (Expt) and analytical (Anly) results for Pier 1.](image)
Model Calibration – Methods

- Rotational Hinge Model
  - Derive relationship from experimental data
  - Comparison of corrected response readings and non-contact measurement
Model Calibration – Methods

- Joint models in Zeus-NL
  - Zero-length 3D element
  - Uncoupled Axial, Shear, Moments
- Various available joint force-disp curves
  - Hysteretic shear and flexural models
  - Each under constant or variable axial force
  - Can be defined in each DOF
Model Calibration – Methods

- **Yield Penetration Model**
  - At plastic hinge zones adjacent to footing or cap
  - Additional ductility
  - Express as increase of $H_e$
    - *Add* $L_{pj}$ *to each end in model*
    - *Increases flexibility of column*

\[ L_{pj} = 0.15 f_y d_{bl} \]

(Priestley and Park, 1987)
Model Calibration – Methods

- Pier 1 response primarily flexural
- Pier 2 response contains more shear contribution
  - Shear spring model
- Other considerations
  - Ultimate capacity
  - Material properties
  - Damping
  - Torsional model
Calibration Procedure

- Calibrate first 10 second response
- Save for developing fragility curves at serviceability limit state

- Run 0-20 sec
- Focus on calibrating from 10-20 sec
- Save for developing fragility curves at next limit state

- 0-30 sec: repeat
- 0-40 sec: repeat
Selection of Records

• Natural records at three hazard levels
• 10 records each (Wen & Wu, 2001) representing
  – 75 year return period
  – 475 year return period
  – 2500 year return period
• Multi-directional (N-S, E-W, V)
Selection of Records

- Not focusing on specific structure or location
  - Not selecting records to fit a specific response spectra
  - Distribution of site conditions according to incidence rates

Total Analyses per “case”:
Records x Limit States x Scaling Levels = 30(No. Scaling Levels)
Matrix of Cases

- Parameters varied for
  - 2 Bridge geometries
  - 2 Modeling considerations
  - 4 Load and boundary conditions
- 16 total “cases”

<table>
<thead>
<tr>
<th>Calibration Parameter</th>
<th>Bridge Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Straight</td>
</tr>
<tr>
<td>Un-Calibrated</td>
<td>2D-L/2D-T/MD/3D</td>
</tr>
<tr>
<td>Calibrated</td>
<td>2D-L/2D-T/MD/3D</td>
</tr>
</tbody>
</table>
Damage classifications

- Mapping local strains to global deformations for cases
- Limit state thresholds based off of this assessment
  - 3 Limit states threshold values yield 4 damage classifications
    - None - Slight
    - Slight - Moderate
    - Moderate - Heavy
    - Heavy – Collapse
- Still, how to assess overall bridge damage?
- Component-by-component methods
  - Appropriate for detailed assessment (i.e. retrofit)
  - Alternative means desired for fragility analysis
Seismic Damage Assessment

- Consider pier displacement ductility ratio $\mu_d = \frac{\Delta}{\Delta_y}$
  - First yield ($\mu_d = 1$)
  - Peak load/moment capacity
  - Ultimate displacement limit or loss of load capacity
- Has been shown to represent overall damage to bridge (Hwang, Liu, & Chiu, 2001)
- Alternative: damage index composed of ($\mu_d$, $\mu_\theta$, energy dissipation, hinge capacity)
### Limit State Definitions

<table>
<thead>
<tr>
<th>Earthquake Scaling</th>
<th>None-Slight</th>
<th>Slight-Moderate</th>
<th>Moderate-Heavy</th>
<th>Heavy-Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08 MCE</td>
<td>0.3 MCE</td>
<td>1.0 MCE</td>
<td>2.0 MCE</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Record Portion</th>
<th>0-10 sec</th>
<th>10-20 sec</th>
<th>20-30 sec</th>
<th>30-40 sec</th>
</tr>
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<tr>
<th>Structural Parameters</th>
<th>Cracking</th>
<th>Yielding</th>
<th>Peak load</th>
<th>Loss of load capacity</th>
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| Societal Limit State Definition | Serviceability | Moderate Down-Time | Economic Loss | Life Safety |

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<thead>
<tr>
<th>Earthquake Scaling</th>
<th>LS1</th>
<th>LS2</th>
<th>LS3</th>
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<tbody>
<tr>
<td>75 year return</td>
<td>475 year return</td>
<td>2500 year return</td>
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<th>Yielding/peak loads</th>
<th>Ultimate displacement or Loss of load capacity</th>
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Simulating Complex Response

- Can we account for these factors in a straightforward fashion?
- Application of modification factors to statistical results
  - Geometric Design Factor (GDF) for complex geometry
  - Complex Load Factor (CLF) for 3D effects
  - Modeling Effect Factor (MEF) for purely analytically-based sources

Can we simulate effects of curvature on vulnerability through applying a geometric design factor to results obtained from analysis of a straight bridge? What about accounting for 3D loading effects using relationships developed under a 2D approach?

- Likely need to have more cases tested or modeled
Conclusions – (of the ongoing study)

• Motivation for developing experimentally-based vulnerability relationships given
• Literature review reveals need for assessing effects of complex geometry and loading on system response
• High-fidelity hybrid 3D hybrid simulation has been performed
• Initial analytical model is developed
• Data analysis has identified potential methods/tools for model calibration
• Test matrix for cases to analyze has been prepared
• Method for structural performance assessment has been proposed