Structural Response of Bent Caps in Reinforced Concrete Box-Girder Bridges

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Sponsor:

Western Bridge Engineers Seminar, Reno, NV, Sep. 9-11, 2015
Motivation

Bent Cap Response

- Bent caps damage in past events
  - e.g. San Fernando 1971, Whittier 1987, Chi-Chi 1999

- Post-event repair is not feasible
  - $$$ + long down time

- Why accurate bent cap response important?
  - Modeling and analysis
  - Optimized design (new bridges)
  - Retrofit design (old bridges)
Problem Statement

1. What is box-girder slab contribution to bent cap? *strain-based effective slab width approach*

2. How can bent cap capacity accurately estimated? *slab reinforcement inclusion*

3. Could column over-design migrate damage to bent cap? *informed retrofit decisions*
Methodology

Stage 1: Pre-test analyses:
- FE analyses of prototype bridge
- FE analyses of test specimen

Stage 2: Experimental program (2 large-scale specimens):
- Quasi-static testing of SP1 (as-built & repaired)
- Hybrid Simulation testing of SP2 (retrofitted)

Stage 3: Post-test analyses:
- FE model calibration/parametric study
- Design implications
Prototype Bridge

Adopted from Caltrans Academy Bridge

(Typical RC box-girder bridge in CA)
Specimen Design & Test Setup

- Design acc. to AASHTO, Caltrans SDC, and ACI-318
- Two Specimens tested in an inverted position at UC Berkeley Structures Laboratory
- Gravity & lateral loads applied at the column top

Summary of specimen reinforcement

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column</td>
<td>16 #6 longitudinal bars</td>
</tr>
<tr>
<td></td>
<td>#3 spiral at 2-1/2 in.</td>
</tr>
<tr>
<td>Cap beam</td>
<td>8 #5 negative reinforcement</td>
</tr>
<tr>
<td></td>
<td>8 #5 positive reinforcement</td>
</tr>
<tr>
<td></td>
<td>#3 stirrups 4 branches at 5 in. spacing</td>
</tr>
<tr>
<td>Box-girder</td>
<td>#3 in transverse dir. at 4 in. spacing</td>
</tr>
<tr>
<td></td>
<td>#3 in longitudinal dir. at 2-1/2 in. spacing</td>
</tr>
<tr>
<td></td>
<td>#3 single branch tie at 4 in. spacing</td>
</tr>
</tbody>
</table>
Pre-test FEA: OpenSees

- **Objectives:**
  - Choose GMs with most severe effect on bent cap beam
  - Select final GMs for loading protocol
- Prelim. nonlinear time history analysis of prototype w/ & w/o vl. excitation
- > 80 ground motions (GMs) from PEER NGA database (Criteria: Magnitude > 6 & Distance to fault < 20 km)

### Summary of critical GMs causing bent cap beam failure

<table>
<thead>
<tr>
<th>GM</th>
<th>Earthquake</th>
<th>Year</th>
<th>Magnitude</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Nahanni- Canada</td>
<td>1985</td>
<td>6.76</td>
<td>Site 1</td>
</tr>
<tr>
<td>#2</td>
<td>Loma Prieta</td>
<td>1989</td>
<td>6.93</td>
<td>LGPC</td>
</tr>
<tr>
<td>#3</td>
<td>Northridge-01</td>
<td>1994</td>
<td>6.69</td>
<td>Rinaldi</td>
</tr>
<tr>
<td>#4</td>
<td>Kobe- Japan</td>
<td>1995</td>
<td>6.90</td>
<td>Takarazuka</td>
</tr>
<tr>
<td>#5</td>
<td>Chi-Chi- Taiwan</td>
<td>1999</td>
<td>7.62</td>
<td>TCU068</td>
</tr>
</tbody>
</table>
Pre-test FEA: DIANA

- **Objectives:**
  - Behavior & mode of failure
  - Setup design & instrumentation
- **Pushover Analysis**
  - Vertical & lateral direction
  - Different constant gravity load
    - (0% → 23% column axial capacity)
- **Time-history Analysis**

**Concrete Material Model**

- Total Strain-Based Crack Model
- Constant Compression
- Linear Tension Softening

- Embedded Reinforcement Mesh
- Reinforcement mesh
- Concrete mesh using brick solid elements
Pre-test FEA: DIANA

Pushover Analysis

- Only Cap Beam fails (mode 3)
- Only Column fails (mode 1)
- Both cap beam and column fail (mode 2)

Satisfy SDC requirements

Do not satisfy SDC requirements

Gravity Load

Equivalent Vertical EQ

Constant Gravity Load

Displacement Pushover

Mode 1

Mode 2

Mode 3
Experimental Program

- **Objectives:**
  - Global subassemblage behavior (*force, disp., stiffness*)
  - Local Bent cap & column behavior (*moment, curvature, strains*)
  - Box-girder behavior (*effective slab width*)

- **Two identical specimens → Repair & Retrofit?**

<table>
<thead>
<tr>
<th>Test Set</th>
<th>Status</th>
<th>Type</th>
<th>Direction</th>
<th>Gravity</th>
<th>Different Scale Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1-1</td>
<td>As-built</td>
<td>Cyclic</td>
<td>Bidirectional</td>
<td>5%</td>
<td>0.25µ, 0.35µ, 0.50µ, 0.70µ, 1.0µ</td>
</tr>
<tr>
<td>SP1-2</td>
<td>As-built</td>
<td>Cyclic</td>
<td>Bidirectional</td>
<td>10%</td>
<td>1.4µ, 2.0µ, 2.8µ, 4.0µ, 5.6µ, 8.0µ</td>
</tr>
<tr>
<td>SP1-3</td>
<td>Repaired</td>
<td>Cyclic</td>
<td>Bidirectional</td>
<td>10%</td>
<td>1.4µ, 2.0µ, 2.8µ, 4.0µ, 5.6µ</td>
</tr>
<tr>
<td>SP1-4</td>
<td>Repaired</td>
<td>HS Trials</td>
<td>Bidirectional</td>
<td>0%</td>
<td>20%, 50% Rinaldi Ground Motion (GM)</td>
</tr>
<tr>
<td>SP1-5</td>
<td>Repaired</td>
<td>HS Trials</td>
<td>Bidirectional</td>
<td>10%</td>
<td>50%, 80%, 100% Rinaldi GM</td>
</tr>
<tr>
<td>SP2-1</td>
<td>Retrofitted</td>
<td>HS</td>
<td>Bidirectional</td>
<td>10%</td>
<td>25%, 50%, 75%, 100% Rinaldi GM</td>
</tr>
<tr>
<td>SP2-2</td>
<td>Retrofitted</td>
<td>HS</td>
<td>Transverse</td>
<td>15%</td>
<td>125%, 150%, 175%, 200% Rinaldi GM</td>
</tr>
</tbody>
</table>
Cyclic Tests: As-built SP1
Cyclic Tests: As-built SP1

Bidirectional Cyclic Loading Protocol

Cross-loading adopted from FEMA 461
Cyclic Tests: As-built SP1

Bidirectional Cyclic Loading Protocol

Cross-loading adopted from FEMA 461
Cyclic Tests: As-built SP1

Crack Propagation, Cover Spalling & Rebar Rupture in Column Plastic Hinge Region
Cyclic Tests: As-built SP1

Global Behavior

Subassemblage Force-Displacement Relationship
Cyclic Tests: As-built SP1

Local Behavior

- Yielding of rebars & hairline cracks
- **NO** spalling or PH formation

- Rupture of rebars
- Cover spalling & PH formation
Cyclic Tests: As-built SP1

Effective Slab Width

Procedure for estimating effective width from strain distribution

Experimental data

- Extend tails to zero

Calculate shaded area (A)

- \( B_{\text{eff}} = \frac{A}{\varepsilon_{\text{min}}} \) or \( B_{\text{eff}} = \frac{A}{\varepsilon_{\text{mean}}} \)
Cyclic Tests: As-built SP1

Strain Distribution & Effective Slab Width during TRANSVERSE Loading

**Section B**

- Drift = 1.4 % ($\mu = 1.00$)
- Drift = 2.7 % ($\mu = 1.96$)
- Drift = 5.3 % ($\mu = 3.84$)
- Drift = 10.5 % ($\mu = 7.57$)

**Section D**

- Drift = 1.4 % ($\mu = 1.00$)
- Drift = 2.7 % ($\mu = 1.96$)
- Drift = 5.3 % ($\mu = 3.84$)
- Drift = 10.5 % ($\mu = 7.57$)

**Experimental Value (using $\varepsilon_{\text{mean}}$)**

**Experimental Value (using $\varepsilon_{\text{min}}$)**

**Caltrans Value**
Cyclic Tests: Repaired SP1
HS Tests: Background

WHAT is Hybrid Simulation?

Analytical Simulation + Experimental Simulation = Hybrid Simulation (HS)

TYPES?

Slow Hybrid Simulation vs. Real-time Hybrid Simulation
HS Tests: Background

WHY Hybrid Simulation?

More convenient & feasible than shaking table tests

✓ Mass modeling
✓ Larger structures
✓ Observing the damage progression
✓ Modeling physical boundary conditions

Shaking Table VS. Hybrid Model
HS Tests: Hybrid System

- Slow HS Test Components:
  - **Physical Substructure:** specimen subassemblage
  - **Computational Substructure:** MDOF mass & damping

- How HS works?

\[ M \ddot{U}_{i+1} + C \dot{U}_{i+1} + P_r(U_{i+1}) = P_{i+1} \]

- Communication Loop?

![Main components of HS system](image)
HS Tests: Retrofitted SP2

Retrofit Procedure
HS Tests: Retrofitted SP2

HS Test In-progress
Retrofitted SP2 Damage after HS Tests
Bent cap concrete crushing in compression
HS Tests: Retrofitted SP2

- Retrofit increased overall SYSTEM capacity by ~25%
- Increased demand from column + higher gravity (15%) → bent cap failure

Force-displacement relationship (transverse)

Bent cap moment-curvature relationship
HS Tests: Retrofitted SP2

Effective Slab Width

Overall mean values for effective slab width from SP1 cyclic & SP2 HS tests

Strain distribution from transverse-only up to 200% (left) & bidirectional up to 100% (right) at Section B
Post-test FEA

- Calibrate FE model
  - using SP1 experiments
- Extensive parametric study
  - e.g. different beam designs
- Section Analysis

Bent cap beam capacity [kip-in]
using section analysis

<table>
<thead>
<tr>
<th>Section Analysis</th>
<th>12(t_s)</th>
<th>w/o slab rft.</th>
<th>4504</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/ slab rft.</td>
<td>5977</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18(t_s)</td>
<td>w/o slab rft.</td>
<td>4566</td>
</tr>
<tr>
<td></td>
<td>w/ slab rft.</td>
<td>6855</td>
<td></td>
</tr>
</tbody>
</table>

SP2 HS Tests 6535

Bent cap beam moment history

Final FE Calibrated Model

Force-displacement relationship (transverse dir.)
Design Implications

- Design example using Academy Bridge Prototype
- 3 column design scenarios ($\rho_{long.}$ ~ 1.4%, 2.6%, 3.5%)
- 3 configurations for bent cap for capacity check:
  - 12\(t_s\) w/o slab rft
  - 12\(t_s\) w/ slab rft
  - 18\(t_s\) w/ slab rft

<table>
<thead>
<tr>
<th>Column Cross-section</th>
<th>Diameter</th>
<th>6 ft</th>
<th>6 ft</th>
<th>6 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long. Rft.</td>
<td>26 #14</td>
<td>26 #18</td>
<td>36 #18</td>
<td></td>
</tr>
<tr>
<td>Rft. Ratio</td>
<td>1.44%</td>
<td>2.56%</td>
<td>3.53%</td>
<td></td>
</tr>
<tr>
<td>Hoops</td>
<td>#8 @ 5 in.</td>
<td>#8 @ 5 in.</td>
<td>#8 @ 5 in.</td>
<td></td>
</tr>
<tr>
<td>Ultimate Moment $M_p$ [kip-ft]</td>
<td>14,510</td>
<td>21,140</td>
<td>26,200</td>
<td></td>
</tr>
<tr>
<td>Overstrength Moment $M_o$ [kip-ft]</td>
<td>17,410</td>
<td>25,370</td>
<td>31,440</td>
<td></td>
</tr>
<tr>
<td>Cap Beam $M_{+ve}$ Demand [kip-ft]</td>
<td>14,970</td>
<td>21,820</td>
<td>27,040</td>
<td></td>
</tr>
<tr>
<td>Cap Beam $M_{-ve}$ Demand [kip-ft]</td>
<td>15,670</td>
<td>22,830</td>
<td>28,300</td>
<td></td>
</tr>
</tbody>
</table>

Amplified demands due to higher column capacity (design requirements or retrofit decision)
Design Implications

Section analysis for moment-curvature (e.g. results of negative moment side)

Caltrans & AASHTO Seismic Capacity Check ➔ Revised design required if NOT satisfied!

<table>
<thead>
<tr>
<th>Case</th>
<th>Column Design</th>
<th>Moment Demand [kip-ft]</th>
<th>12t_s w/o slab rft</th>
<th>12t_s w/ slab rft</th>
<th>18t_s w/ slab rft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Capacity</td>
<td>Satisfy Capacity Check?</td>
<td>Capacity</td>
</tr>
<tr>
<td>1</td>
<td>1.44%</td>
<td>15,670</td>
<td>20,270</td>
<td>YES</td>
<td>26,170</td>
</tr>
<tr>
<td>2</td>
<td>2.58%</td>
<td>22,830</td>
<td>NO</td>
<td></td>
<td>YES</td>
</tr>
<tr>
<td>3</td>
<td>3.50%</td>
<td>28,300</td>
<td>NO</td>
<td></td>
<td>NO</td>
</tr>
</tbody>
</table>
Conclusions

• $12t_s$ code value conservative & revised effective slab width of $18t_s$ recommended to account for box-girder contributions;

• Transverse deck & soffit slab reinforcement within effective width should be included in bent cap capacity estimation;

• Overdesigned column retrofit may migrate damage to bent cap and/or superstructure;

• Accurate bent cap effective width & capacity check crucial for economical design & informed repair/retrofit decisions.
Thank You! Questions?