Performance Modeling Strategies for Modern Reinforced Concrete Bridge Columns

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Pacific Earthquake Engineering Research Center (PEER)
UW-PEER Structural Performance Database

- Nearly 500 Columns
  - spiral or circular hoop-reinforced columns (~180)
  - rectangular reinforced columns (~300)
- Column geometry, material properties, reinforcing details, loading
- Digital Force-Displacement Histories
- Observations of column damage
- http://nisee.berkeley.edu/spd
- User’s Manual (Berry and Eberhard, 2004)
Objective of Research

Develop, calibrate, and evaluate column modeling strategies that are capable of accurately modeling bridge column behavior under seismic loading.

- Global deformations
- Local deformations (strains and rotations)
- Progression of damage
Advanced Modeling Strategies

Distributed-Plasticity

Lumped-Plasticity

Force-Based Fiber Beam Column Element (Flexure)

Fiber Section at each integration point with Aggregated Elastic Shear

Zero Length Section (Bond Slip)

Elastic Portion of Beam (A, EI_{eff})

Fiber Section assigned to Plastic Hinge

L_f
Cross-Section Modeling
Cross-Section Modeling Components

- Concrete Material Model
- Reinforcing Steel Material Model
- Cross-Section Discretization Strategy
Concrete Material Model

Popovic’s Curve with Mander et. al. Constants and Added Tension Component *(Concrete04)*
Reinforcing Steel Material Models

Giufre-Menegotto-Pinto (Steel02)

Mohle and Kunnath (ReinforcingSteel)
Objective: Use as few fibers as possible to eliminate the effects of discretization
Cross-Section Fiber Discretization

Uniform (220 Fibers)

Confined
\[ n^r_c = 10 \]
\[ n^t_c = 20 \]

Unconfined
\[ n^r_u = 1 \]
\[ n^t_u = 20 \]
Reduced Fiber Discretization

Uniform (220 Fibers)

Nonuniform Strategies
Cross-Section Fiber Discretization

Uniform (220 Fibers)

Confined

- \( r_c = 10 \)
- \( t_c = 20 \)

Unconfined

- \( r_u = 1 \)
- \( t_u = 20 \)

Reduced (140 Fibers)

Confined

- \( r_{fine} = 5 \)
- \( t_{fine} = 20 \)
- \( r_{coarse} = 2 \)
- \( t_{coarse} = 10 \)

Unconfined

- \( r_u = 1 \)
- \( t_u = 20 \)
Modeling with Distributed-Plasticity Element
Model Components

- **Flexure Model (Force-Based Beam-Column)**
  - `nonlinearBeamColumn`
  - Fiber section
  - Popovics Curve (Mander constants)
  - Giufre-Menegotto-Pinto \((b)\)
  - Number of Integration Points \((Np)\)

- **Anchorage-Slip Model**
  - `zeroLengthSection`
  - Fiber section
  - Reinforcement tensile stress-deformation response from Lehman et. al. (1998) bond model \((\lambda)\)
  - Effective depth in compression \(d_{comp}\)

- **Shear Model**
  - `section Aggregator`
  - Elastic Shear \((\gamma)\)
Model Optimization

- **Objective:** Determine model parameters such that the error between measured and calculated global and local responses are minimized.

\[
E_{total} = \text{mean}(E_{push}) + \frac{\kappa_1}{2} \text{mean}(E_{strain}^{(0-D/2)}) + \frac{\alpha_2}{2} \text{mean}(E_{strain}^{(D/2-D)})
\]

\[
E_{push} = \frac{\sum (F_{meas} - F_{calc})^2}{\sqrt{\text{max}(F_{meas})}^2 n}
\]

\[
E_{strain} = \frac{\sum (\varepsilon_{meas} - \varepsilon_{calc})^2}{\sqrt{\text{max} (\varepsilon_{meas})}^2 n}
\]
### Optimized Model:

- Strain Hardening Ratio, $b = 0.01$
- Number of Integration Points, $N_p = 5$
- Bond-Strength Ratio, $\lambda = 0.875$
- Bond-Compression Depth, $d_{\text{comp}}$
- Shear Stiffness $\gamma = 0.4$

### Performance Metrics

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{total}}$</th>
<th>$E_{\text{push}}$</th>
<th>$E_{\text{strain}}^{(0-D/2)}$</th>
<th>$E_{\text{strain}}^{(D/2-D)}$</th>
<th>S.R.</th>
<th>M.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>14.89</td>
<td>6.73</td>
<td>7.78</td>
<td>14.4</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>cov (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>
Modeling with Lumped-Plasticity Element
Lumped-Plasticity Model

- Hinge Model Formulation:
  - \textit{beamwithHinges3}
  - Force Based Beam Column Element with Integration Scheme Proposed by Scott and Fenves, 2006.
  - Fiber Section

- Elastic Section Properties
  - Elastic Area, \( A \)
  - Effective Section Stiffness, \( E_{I_{eff}} \)

- Calculated Plastic-Hinge Length
  - \( L_p \)
Section Stiffness Calibration

<table>
<thead>
<tr>
<th>Stiffness Ratio Stats</th>
<th>$EI_{eff} = \alpha_g^{calc} E_c I_g$</th>
<th>$\alpha_{sec}^{calc} EI_{sec}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>cov (%)</td>
<td>19</td>
<td>16</td>
</tr>
</tbody>
</table>

$$\alpha_g^{calc} = 0.1 + 0.034 \frac{L}{D} + 1.35 \frac{P}{A_g f_{ct}} \leq 1.0$$

$$\alpha_{sec}^{calc} = 0.45 + 0.087 \frac{L}{D} \leq 1.0$$
Plastic-Hinge Length Calibration

\[ L_p = 0.05L + 0.1 \frac{f_y d_b}{\sqrt{f_c'}} \leq \frac{L}{4} \]

\[ \epsilon_{bb}^{calc} = 0.046 + 0.25 \rho_{eff} \leq 0.15 \]

<table>
<thead>
<tr>
<th>Plastic-Hinge Length</th>
<th>Pushover Accuracy</th>
<th>Damage Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[E_{total}]</td>
<td>[E_{push}]</td>
</tr>
<tr>
<td><strong>Selected Optimal</strong></td>
<td>mean</td>
<td>mean</td>
</tr>
<tr>
<td>[0.05L + 0.1 \frac{f_y d_b}{\sqrt{f_c'}} \leq L/4]</td>
<td>8.32</td>
<td>8.08</td>
</tr>
<tr>
<td><strong>Priestley et al. (1996)</strong></td>
<td>mean</td>
<td>mean</td>
</tr>
<tr>
<td>[0.08L + 0.022 f_y d_b \leq 0.044 f_y d_b]</td>
<td>8.87</td>
<td>8.32</td>
</tr>
<tr>
<td><strong>Mattock (1967)</strong></td>
<td>mean</td>
<td>mean</td>
</tr>
<tr>
<td>[0.05L + 0.5D]</td>
<td>8.96</td>
<td>8.41</td>
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</tbody>
</table>
Cyclic Response
Cyclic Material Response

- Cyclic response of the fiber-column model depends on the cyclic response of the material models.

**Reinforcing Steel**

- Giufre-Menegotto-Pinto (with Bauschinger Effect)
- Steel02

**Confined and Unconfined Concrete**

- Karsan and Jirsa with Added Tension Component
- Concrete04

- **Current Methodologies**
  - Do not account for cyclic degradation steel
  - Do not account for imperfect crack closure
## Evaluation of Response

<table>
<thead>
<tr>
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<th>Lumped-Plasticity</th>
<th>Distributed-Plasticity</th>
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<tbody>
<tr>
<td>$E_{\text{force}}$ (%)</td>
<td>$E_{\text{force}}$ (%)</td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>16.13</td>
<td>15.66</td>
</tr>
<tr>
<td>min</td>
<td>6.63</td>
<td>6.47</td>
</tr>
<tr>
<td>max</td>
<td>44.71</td>
<td>46.05</td>
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</tbody>
</table>

### Graph

Lehman No.415

- **Force (KN)**
- **$\Delta/\Delta_y$**
- **Measured**
- **OpenSees**
Kunnath and Mohle

Steel Material Model

- Cyclic degradation according to Coffin and Manson Fatigue.
- Model parameters:
  - Ductility Constant, $C_f$
  - Strength Reduction Constant, $C_d$
Preliminary Study with Kunnath Steel Model

- Ductility Constant, $C_f=0.4$
- Strength Reduction Constant, $C_d=0.4$

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<th>Kunnath and Mohle</th>
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<tr>
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<td>16.13</td>
<td>11.98</td>
</tr>
<tr>
<td>min</td>
<td>6.63</td>
<td>5.15</td>
</tr>
<tr>
<td>max</td>
<td>44.71</td>
<td>29.45</td>
</tr>
</tbody>
</table>

Giufre-Menegotto-Pinto (with Bauschinger Effect)  Kunnath and Mohle (2006)
Continuing Work
Imperfect Crack Closure
Prediction of Flexural Damage

- Drift Ratio Equations
- Distributed-Plasticity Modeling Strategy
- Lumped-Plasticity Modeling Strategy

Key Statistics  Fragility Curves  Design Recommendations
Evaluation of Modeling-Strategies for Complex Loading

• Bridge Bent (Purdue, 2006)
• Unidirectional and Bi-directional Shake Table (Hachem, 2003)
Thank you