Computational and Experimental Investigation of Circular Bridge Columns of Different Sizes

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Outline

- Tasks
- Background
- Computational Model
- Physical Models and Calibration
- Conclusions and Future Tasks
Tasks

- Perform a literature review of tests and models for circular RC columns with confining media accounting for size effect.
- Develop a theoretical model for confined RC circular sections addressing the **size effect** in a rigorous manner.
- Develop a computational model with nonlinear **3D FEM** for confined RC circular sections.
- Calibrate the models using past tests of circular columns of different sizes.
- Compare the models to recent tests in Japan and UC-San Diego and upcoming tests at UC-Berkeley.
- Implement a **3D constitutive model** of confined RC sections, based on the 3D FE model, into **OpenSees**.
Background
Size Effect in RC

\( G_{fc} = \) Compressive fracture energy as a material property
- Energy released per area of crack propagation
- More research for estimating the tensile fracture energy
- Affected by max. aggregate size, aggregate content, aggregate fineness modulus, cement type, w/c, ... etc.
- Needs to be determined through testing or empirically, e.g.

- Mizuno, Nakamura, Higai (1999): \( G_{fc} = 8.8 \sqrt[3]{f'_c} \)
- Lertsrisakulrat, Watanabe, Matsuo, Niwa (2000): \( G_{fc} = 0.99 \sqrt[3]{f''c} \)

- Energy released within a plastic hinge of length \( L_p \):
  \[ G_{fc}/L_p = \int \sigma(\varepsilon) \cdot d\varepsilon \]
- Shows size dependence – inverse relationship between toughness and characteristic length
- Simplified assumption for pure axial compression but not straightforward for combined forces (P, V, M)
Computational Model
Confinement in RC Material (ConcreteBLE)

- Family of stress-strain curves $(\sigma_1, \varepsilon_1)$
- Parametrized by $\phi = \sigma_3 / f'_c$
- Softening conserves fracture energy, $G_{fc}$
- Enforces lateral strain compatibility with confining media
- Use of Leon-Pramono failure criterion

\[ \sigma_3 \approx \sigma_1 \]

\[ \sigma_{11} \]

\[ \varepsilon_{11} \]

Increasing confining stress

\[ G_{fc} / r_c \]

Lateral strain compatibility
Computational Model

Confinement in RC Section (RCFiber)

Strain compatibility enforced HERE

\[ \sigma_f = \sigma_{f_{\text{max}}} \sinh(A\theta)/\sinh(A\theta_c) \]

Depending on location of fiber in cross-section

\[ \frac{d^2\sigma_f}{d\theta^2} - A^2 \sigma_f = 0 \]

\[ A^2 = \left( R^2 G_a \right) \left( E_f t_f t_a \right) \]

Confining stress distribution for different values of bond parameter (A)
Computational Model

Cyclic Loading & Confinement in RC

- Unloading-reloading rules [Lokuge et al, 2004]
- Stress-strain relationship invariant in principal shear space
- Modified to account for variable confinement and hysteretic energy-based envelope reduction factor

Experimental [Lokuge et al, 2004] vs. simulated axial and lateral stress-strain response

Envelope experimental [Ahmad & Shah, 1982] validation for unconfined cylinders and confined with tie spacing = s
Physical Models and Calibration

Outline

- **UCB**
  - Columns made of pressurized grout
    - Cyclic testing w/ variable axial load
  - Scaled columns under hrz. & vl. motion
    - 2D seismic testing
  - 1/3-Scale of UCSD column
    - 1D seismic testing

- **UCSD**
  - Full-scale column
    - 1D seismic testing
Physical Models and Calibration
Modeling Assumptions

Each section has 4 “NonlinearBeamColumn” elements with 3 integration points

“Mass-Block”
- 25% of column height
- Standard fiber section with Concrete02
- Confinement by Mander, Park and Priestly (1988)
- Length scale increased 3x ($E_{eff}$ increased $3^3 = 81x$)
- Manual input of top mass weight and moment of inertia

“Plastic Hinge”
- 20% of column height
- RCFiber section with ConcreteBLE

“Elastic Section”
- 60% of column height
- Standard fiber section with Concrete02
- Confinement by Mander, Park and Priestly (1988)

“Plastic Hinge”
- 20% of column height
- RCFiber section with ConcreteBLE
Physical Models and Calibration Modeling Assumptions

Full Scale refers to 24’ tall, 4’ diameter, lateral hoops #5 @ 6.25”
Physical Models and Calibration
UCB – Scaled columns made of pressurized grout

- No coarse aggregate
- Comparison with conventional mix design
- Cyclic Loading

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material</th>
<th>Longitudinal Reinforcement</th>
<th>Spiral Transverse Reinforcement</th>
<th>Axial Load [Kips]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grout</td>
<td>(6)#6</td>
<td>#4@3&quot;</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>Concrete</td>
<td>(6)#6</td>
<td>#4@3&quot;</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>Grout</td>
<td>(6)#6</td>
<td>#4@3&quot;</td>
<td>300.0</td>
</tr>
<tr>
<td>4</td>
<td>Concrete</td>
<td>(6)#6</td>
<td>#4@3&quot;</td>
<td>300.0</td>
</tr>
<tr>
<td>5</td>
<td>Grout</td>
<td>(6)#6</td>
<td>#4@2&quot;</td>
<td>300.0</td>
</tr>
</tbody>
</table>
Physical Models and Calibration

UCB – Scaled columns made of pressurized grout

- Grout specimen 1 - no added axial load
- Modeling - linear geometric transformation

![Lateral Cyclic Push Over](image-url)

- Base Shear [kips] vs. Disp [in]
- Actual (black) and simulation (green) curves
Physical Models and Calibration
UCB – Scaled columns made of pressurized grout

- Grout specimen 3 - 300 kip axial load
- Modeling – corotational geometric geometric transformation

![Lateral Cyclic Push Over](image)

- Actual
- Simulation
Physical Models and Calibration
UCSD – Full-scale column

- PI: Prof. Jose Restrepo
- Unidirectional
- Full scale - 24’ height  4’ diameter
Physical Models and Calibration
UCSD – Full-scale column

Comparison of:

- Experimental Response
- Concrete02 with Standard Fiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation
Physical Models and Calibration
UCSD – Full-scale column

Experimental Response

Concrete02 + Fiber

ConcreteBLE + RCFiber

Drift [%]

Base Shear [kips]

Tip Shear [kips]

Base Moment [kip-ft]

Curvature [1/1000in]

EQ1

Drift [%]

Base Shear [kips]

Tip Shear [kips]

Base Moment [kip-ft]

Curvature [1/1000in]

EQ1

Drift [%]

Base Shear [kips]

Tip Shear [kips]

Base Moment [kip-ft]

Curvature [1/1000in]

EQ1

Drift [%]

Base Shear [kips]

Tip Shear [kips]

Base Moment [kip-ft]

Curvature [1/1000in]

EQ1
Physical Models and Calibration
UCSD – Full-scale column

Experimental Response

Concrete02 + Fiber

ConcreteBLE + RCFiber
Physical Models and Calibration

UCSD – Full-scale column

Experimental Response | Concrete02 + Fiber | ConcreteBLE + RCFiber

Drift [%] | Base Shear [kips] | Drift [%] | Base Shear [kips] | Drift [%] | Base Shear [kips]

Physical Models and Calibration
UCSD – Full-scale column

Experimental Response | Concrete02 + Fiber | ConcreteBLE + RCFiber
---|---|---
**EQ5**

- **Tip Shear [kips]** vs. **Drift [%]**
- **Base Moment [kip-ft]** vs. **Curvature [1/1000in]**

- **Base Shear [kips]** vs. **Drift [%]**
- **Base Moment [kip-ft]** vs. **Curvature [1/1000in]**
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

- Unidirectional
- 1/3 scale - 8’ height 16” diameter
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>UCSD</th>
<th>UC Berkeley</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Height, $H_{Column}$ (in.)</td>
<td>Between footing and column top</td>
<td>288</td>
<td>96</td>
<td>$S = \frac{288}{96} = 3$</td>
</tr>
<tr>
<td>Column Diameter, $D_{Column}$ (in.)</td>
<td>Include clear cover</td>
<td>48</td>
<td>16</td>
<td>$S = \frac{48}{16} = 3$</td>
</tr>
<tr>
<td>Axial Load Ratio, $\rho_{Axial}$ (%)</td>
<td>$\rho_{axial} = \frac{P_{axial}}{\left(A_gf'_c\right)}$</td>
<td>5.34%</td>
<td>5.51%</td>
<td>$S = \frac{5.34}{5.51} = 0.97$</td>
</tr>
<tr>
<td>Superstructure Mass, $M_{Super}$ (kips)</td>
<td>$M_{topblock} + M_{beams} + M_{lead blocks}$</td>
<td>521.9</td>
<td>62.585</td>
<td>$S^2 = \frac{521.9}{62.585} = 8.34, S = 2.9$</td>
</tr>
<tr>
<td>Longitudinal Steel Ratio, $\rho_L$ (%)</td>
<td>$\rho_L = \frac{A_{st}}{A_g}$</td>
<td>1.55</td>
<td>1.59</td>
<td>$S = \frac{1.55}{1.59} = 0.98$</td>
</tr>
<tr>
<td>Volumetric Transverse Steel Ratio $\rho_T$ (%)</td>
<td>$\rho_T = \frac{4A_T}{D_{core}S}$</td>
<td>0.953</td>
<td>0.976</td>
<td>$S = \frac{0.953}{0.976} = 0.98$</td>
</tr>
<tr>
<td>Longitudinal Rebar Area, $A_b$ (in$^2$)</td>
<td>UCSD = #11, UC Berkeley = #4</td>
<td>1.56</td>
<td>0.20</td>
<td>$S^2 = \frac{1.56}{0.20} = 7.8, S = 2.8$</td>
</tr>
<tr>
<td>Transverse Reinforcement Area $A_T$ (in$^2$)</td>
<td>UCSD = 2#5, UC Berkeley = 2#2</td>
<td>0.62</td>
<td>0.098</td>
<td>$S^2 = \frac{0.62}{0.098} = 6.33, S = 2.5$</td>
</tr>
<tr>
<td>Transverse Reinforcement Spacing $s$ (in.)</td>
<td>Considering effect of both Segregation and Buckling</td>
<td>6</td>
<td>2.75</td>
<td>$S = \frac{6.0}{2.75} = 2.2$</td>
</tr>
<tr>
<td>Center of Mass Elevation, $y_{CM}$ (in.)</td>
<td>Measured above Footing Top</td>
<td>288</td>
<td>102</td>
<td>$S = \frac{288}{102} = 2.8$</td>
</tr>
<tr>
<td>Moment of Inertia, $I$ (kips-in-sec$^2$)</td>
<td>*See Calculations</td>
<td>8778</td>
<td>223</td>
<td>$S^4 = \frac{8778}{223} = 39.4, S = 2.5$</td>
</tr>
</tbody>
</table>
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Comparison of:

- Concrete02 with Standard Fiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation, Length Scaled by 1/3
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Concrete02 + Fiber

ConcreteBLE + RCFiber (1/3)

ConcreteBLE + RCFiber

Drift [%]

Base Shear [kips]

Curvature [1/1000in]

Base Moment [kip-ft]
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Concrete02 + Fiber
ConcreteBLE + RCFiber (1/3)
ConcreteBLE + RCFiber

EQ3

<table>
<thead>
<tr>
<th>Drift [%]</th>
<th>Base Shear [kips]</th>
<th>Curvature [1/1000in]</th>
<th>Base Moment [kip-ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Concrete02 + Fiber
ConcreteBLE + RCFiber (1/3)
ConcreteBLE + RCFiber
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Concrete02 + Fiber

ConcreteBLE + RCFiber (1/3)

ConcreteBLE + RCFiber

EQ4 Drift [%]

EQ4 Drift [%]

EQ4 Drift [%]

EQ4 Curvature [1/1000in]

EQ4 Curvature [1/1000in]

EQ4 Curvature [1/1000in]

EQ4 Base Moment [kip-ft]

EQ4 Base Moment [kip-ft]

EQ4 Base Moment [kip-ft]
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Concrete02 + Fiber
ConcreteBLE + RCFiber (1/3)
ConcreteBLE + RCFiber

Drift [%]
Base Shear [kips]

EQ5

Drift [%]
Base Shear [kips]

EQ5

Drift [%]
Base Shear [kips]

EQ5

Curvature [1/1000in]
Base Moment [kip-ft]

EQ5

Curvature [1/1000in]
Base Moment [kip-ft]

EQ5

Curvature [1/1000in]
Base Moment [kip-ft]
Physical Models and Calibration
UCB – Scaled columns under hrz. & vl. motion

Two specimens (SP1, SP2)
- ¼-scale Plumas Arboga Overhead (Prototype)
- Aspect Ratio = 3.5 : D=20”, h=70”
- Axial Load Ratio = 6.8%
- 2D excitation = X+Z, Northridge EQ
- ρ_Y =0.55% (SP1), 0.36% (SP2)
Physical Models and Calibration
UCB – Scaled columns under hrz. & vl. motion

Sample Test Results

Moment-Curvature at h=10” and 60”
70% Northridge EQ (1-7 and 2-7)

SP1

Moment-Curvature at h=10” and 60”
125% Northridge EQ (1-9 and 2-9)

SP1

SP2
Conclusions and Future Tasks

- Accounting for concrete softening behavior and real-time confining pressures give a more realistic response.
- Results from scaled specimens in physical testing show more relative energy dissipation than larger prototypes.
- Size effect should be accounted for in modeling.
- The new material and fiber section models consider explicit parameters that depend on the size of the modeled column. Further calibration is still needed.
- Damage models should be calibrated and implemented for different mix designs and confinement conditions.
Conclusions and Future Tasks

- Complete physical testing of the 1/3-model (concrete casting is taking place TODAY!)
- Further calibration of the material and fiber section models is underway
- Comparison between findings and code provisions (e.g. ACI, AASHTO, CALTRANS)
- Release ConcreteBLE material, RCFiber section and Damage models in the next version of OpenSees