Performance of Existing Reinforced Concrete Columns under Bidirectional Shear & Axial Loading

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Research Background & Project Objectives
Design of Test Setup
RC Column Specimen Material & Geometry
Capacity Models
  - Flexural, Shear and Axial Capacity
  - Moment – Curvature Response of Column
Deformation Components
  - Lateral Deformation – Shear Failure
  - Axial Deformation
  - Residual Column Capacity & Damage Progression
Fabrication of RC Column Specimens
  - Sensitivity Analysis
Ongoing
Acknowledgments
Mechanisms leading to the collapse of existing, pre-seismic code RC frames are *NOT* well documented.

Shake table tests are currently being conducted at PEER-UCB to observe & identify the failure components & load redistribution processes in RC bridge columns & in RC building frames under seismic & gravity loading.

Identifying mechanisms causing shear failure in RC columns can be used to develop performance-based seismic design - strengthen future & existing structures against earthquake loading

Column shear failure & its effect on the degradation of axial capacity in a pre-seismic code RC column is the focus of this project.
Project Objectives

PERSONAL:

■ To independently conduct research & gain extensive laboratory experience in the field of structural – earthquake engineering

■ Opportunity to work with researchers on cutting-edge research and learn about ongoing studies in seismic design and retrofitting

■ Opportunity to learn and apply theories of seismic design & analysis to RC columns under seismic and gravity loads

RESEARCH:

■ Identify lateral & axial deformation components leading to RC column failure

■ Compute flexural, shear and axial capacity models of RC column

■ Design experimental setup allowing bidirectional loading of RC column for specific loading requirements & under budget

■ Fabricate RC column specimens based on design specs

■ Analyze the effect of bidirectional loading on the shear and axial failure of RC column and compare to predictive capacity models
Simplified Model of RC Column

- One-third scale of existing, pre-seismic ACI code designed RC Column
- $\frac{1}{2}$ of RC column used in analysis
- Free end of column idealized as hinge connection with a fixed end at base of column
Simplified Model of RC Column (cont.)

RC Col’n

\[ M = 0 \] (hinge)

\[ M = M_{\text{MAX}} \] (fixed)

RC Col’n
Design of Test Setup

Gravity Load
= 10 kips

Actuator / Seismic Load = 8.3 kips

RC Col’n

HINGE

FIXED
Design of Test Setup (cont.)

- **Concrete Floor**: 9"x8" flanged beam 70 lb/ft. S=61.5 cu. in.
- **TEST APPARATUS**: base plate 2 in. thickness, 15 in. width and 3 ft. length.
- **ACTUATOR POSITION**: 2'-9" 8" x 4'-7" 8"
- **Lead ingot**: 14 bars, 110 lb/bar, total wt. 1540 lb.
- **H-structure safety frame**: 3"x2" angle iron welded construction.
- **ANCHOR BOLTS**: 1/2" concrete anchor bolts (??2 places??)
- **C-SECTION C-C**: 4" (add spacing if needed)
- **Concrete Floor**: 42.25" x 15 in. width and 3 ft. length
- **Base plate**: 2 in. thickness
RC Column Material & Geometry
RC Column Material & Geometry (cont.)

- 90 DEGREE HOOKS
- ALTERNATE LOCATION OF HOOKS
- CLEAR COVER = 3/4" OVER LONGITUDINAL BAR
- 1/4" DIAMETER TIES @ 4" O.C.
- 8 #3
- Section A-A
**Capacity Models of RC Column**

**Specimen: Axial Capacity**

Axial Capacity of *undamaged* RC column:

\[
P_N = 0.85 f'_C (A_g - A_{SL}) + f_{YL} A_{SL}
\]

..where \( f'_C \) concrete compressive strength, \( A_g \) is the gross concrete area, \( A_{SL} \) is the longitudinal reinforcement area, \( f_{YL} \) is yield strength of longitudinal steel

\[
P_N = 0.85 \times (3 \text{ksi}) \times [36 \text{in}^2 - 0.884 \text{in}^2] + (70 \text{ksi}) \times (0.884 \text{in}^2)
\]

\[
P_N = 151.43 \text{ kips}
\]
Capacity Models of RC Column

Specimen: Flexural Capacity

\[ \varepsilon_{cu} = 0.003 \]

\[ \varepsilon_{S1} = -0.00207 \]

\[ \varepsilon_{S2} \]

\[ \varepsilon_{S3} \]

\[ \frac{.85f'_c}{\varepsilon_{S3}} \]

\[ \frac{a}{\varepsilon_{S2}} \]

\[ \frac{h}{2} \]

\[ T_{S1} \]

\[ T_{S2} \]

\[ T_{S3} \]

\[ C_C \]

\[ P_N \]

\[ M_N \]

\[ \Sigma M_{h/2} = 0 \]

@Balanced Failure (Z=-1)

\[ -T_{S3} \cdot (h/2)-d_{S3} - C_C \cdot (h/2)-(a/2) + M_N - T_{S1} \cdot [d_{S1}-(h/2)] \]

\[ M_N = T_{S3} \cdot (h/2)-d_{S3} + C_C \cdot (h/2)-(a/2) + T_{S1} \cdot [d_{S1}-(h/2)] \]

..so, \[ M_N = 153.3 \text{ kip-in} \]
Capacity Models of RC Column

Specimen: Shear Capacity

- Total shear capacity of an RC column depends on the shear capacity of the concrete, $V_C$, and the shear capacity carried by the transverse reinforcement, $V_{ST}$ in the column.

$$V_N = (V_C + V_{ST}) = 2*[1+(P/2000*Ag)]*\sqrt{f'_C}*b_W*d + \left[\frac{4*A_{ST}*f_{YT}*d}{s}\right]$$

..where $A_{ST}$ is the transverse reinforcement area, $f_{YT}$ is yield strength of transverse reinforcement, $d$ is distance from compression fiber to farthest tensile reinforcement, $s$ is transverse reinforcement spacing, $b_W$ is the width of column x-section, $P$ is axial load.

$$V_N = 2*[1+(10,000lb/(2000*35.12in^2))]*\sqrt{(3000psi)*(6in)(5.145in)} + \left(\frac{0.01228in^2)(70,000psi)(5.145in)}{s}\right)$$

$$V_N = 8.283 \text{ kips}$$
The flexural and axial capacity model for RC columns is used to derive an interaction diagram which relates the axial load column capacity with its moment capacity at any given time.
Moment-Curvature Response of Shear-Critical RC Column under Axial & Lateral (Shear) Loading

The flexural and axial capacity model for RC columns is used to derive an interaction diagram which relates the axial load column capacity with its moment capacity at any given time.

\[ M_Y = V_Y \cdot \theta \]
Deformation Components: Lateral Deflection

\[ \Delta_{flex} = \frac{L^2}{6} \phi_y \]

\[ \Delta_{FL} = \frac{(39\text{in})^2}{6} \times (7.6 \times 10^{-4} \text{in}^{-1}) = 0.19266 \text{ in} \]
Deformation Components: 
*Lateral* Deflection

- Flexure
Deformation Components: Lateral Deflection

- Bar (Bond) Slip

\[ \Delta_{SL} = \frac{(39\text{in})(0.375\text{in})(70,000\text{psi})(7.6\times10^{-4}\text{in}^{-1})}{8\times6\sqrt{3000\text{psi}}} \]

\[ \Delta_{SL} = \frac{Ld_bf_y\Phi_y}{8u} \]
Deformation Components: *Lateral* Deflection

\[ \Delta_{\text{shear}} = \frac{2M_y}{GA_y} \]

\[ \Delta_{SH} = \frac{[2(113,000\text{lb-in})]}{(1.53 \times 10^6)(29.26\text{in}^2)} = 0.005048 \text{ in.} \]
Deformation Components: *Lateral* Deflection

- Shear
Lateral Yield Deformation of RC column:

Lateral yield deformation (prior to shear failure) of longitudinal reinforcement in RC column results from 3 components acting in series:

Flexure, Bar (Bond) Slip, Shear

\[(\Delta_{LAT})_Y = \Delta_Y = (\Delta_{FL} + \Delta_{SL} + \Delta_{SH})\]

\[(\Delta_{LAT})_Y = \Delta_Y = (0.19266 \text{ in}) + (0.29594 \text{ in}) + (0.005048 \text{ in}) = 0.49365 \text{ in.}\]
Deformation Components: 
Shear → Axial Failure

*After* yielding of longitudinal reinforcement, column sustains gravity and lateral (shear) loads until shear demand on column *exceeds* ultimate shear capacity of column ($V > V_U$) – shear failure occurs.

*After* shear failure occurs in column, gravity loads are supported by shear-friction forces along shear failure plane – ($\Delta_{LAT}$)$_{AX}$ occurs.

Figure 3-4. Free-body diagram of column after shear failure.
Deformation Components:
Shear $\rightarrow$ Axial Failure (cont.)

Figure 3-4. Free-body diagram of column after shear failure
Deformation Components:  
Shear $\rightarrow$ Axial Failure (cont.)

Residual Axial Capacity (after shear failure) of damaged RC column:

$$P_N = \tan \theta \times \left[ \frac{(A_{ST} \times f_{YT} \times d_C)}{s} \right] \times \frac{(1 + \mu \tan \theta)}{(\tan \theta - \mu)}$$

..where $f_{YT}$ is yield strength of transverse reinforcement, $d_C$ is distance b/w extreme longitudinal reinforcement, $s$ is transverse reinforcement spacing, $\theta$ is critical crack angle, $\mu$ is effective friction coefficient, $A_{ST}$ is transverse reinforcement area

$$P_N = \left[ \frac{\tan 65(0.01228 \text{in}^2)(70 \text{ksi})(4.5417 \text{in})}{(4 \text{in})} \right] \times \left[ \frac{(1 + (8.28 \text{kip/10kip}) \times \tan 65)}{(\tan 65 - (8.28 \text{kip/10kip}))} \right]$$
$$= 4.4 \text{ kips}$$

When gravity loads exceed shear-friction forces, axial failure occurs in column (column loses ALL shear capacity) $\rightarrow$ total collapse of structure
Deformation Components:
Shear $\rightarrow$ Axial Failure (cont.)

Axial Failure of Column

Total Collapse of Column
Progression of damage in a shear-critical RC column can be quantified using an empirical drift capacity model based on the column’s lateral displacement (i.e. ‘drift’)

**Drift Ratio at Yielding of Longitudinal Reinforcement**

\[
\left( \frac{\Delta}{L} \right)_{axial} = \frac{4}{100} \frac{1 + (\tan \theta)^2}{\tan \theta + P \frac{s}{A_{sy} f_{ytl} d_c \tan \theta}}
\]

\((\Delta/L)_Y = 0.00494\)

**Drift Ratio at Shear Failure**

\[
\frac{\Delta_s}{L} = \frac{3}{100} + 4 \rho'' - \frac{1}{500} \sqrt{\frac{v}{f_c'}} - \frac{1}{40} \frac{P}{A_g f_c'} \geq \frac{1}{100} \text{ (psi units)}
\]

\((\Delta/L)_{SH} = 0.026248\)

**Drift Ratio at Axial Failure**

\[
\frac{\Delta_y}{L} = \frac{\Delta_{flex} + \Delta_{slip} + \Delta_{shear}}{L}
\]

\((\Delta/L)_{AX} = 0.035183\)
Damage Progression in Column – EPP Backbone Model

Elastic-Perfectly-Plastic (EPP) backbone model approximates the shear load vs. lateral displacement behavior of shear-critical RC columns via a ‘shear-failure surface’

EPP backbone model utilizes the calculated column drift ratios at yielding, shear & axial failure, as well as the yield moment derived from the column moment-curvature response to generate the column’s ‘shear failure surface’ under lateral and gravity loading.
Shear-Critical RC column *Shear Hysteretic (force-displacement) Response* w/ EPP shear-drift backbone

\[ \Delta_Y \]

\[ \Delta_{AX} \]

\[ \Delta_{SH} \]
Fabrication of RC Column Specimens

Column Forms –
plywood, 2x4’s

6”

2'-4 5/8”

RC Col’n

1'-1 5/8”

1'-10”
Steel Cages / Longitudinal & Transverse Reinforcement

- 60 Grade #3 & #5 rebar, tie wires, 1/8” diameter stirrups
Fabrication of RC Column Specimens (cont.)

- Casting of Column Specimens
  - $f_c' = 3 \text{ ksi}$
Sensitivity of RC Column Moment Capacity to Increasing 28-day Compressive Strength of Concrete.
Sensitivity Analysis

Sensitivity of RC Column Axial Load Capacity to Increasing 28-day Compressive Strength of Concrete.

**Graph:**
- **Y-axis:** Nominal Axial Load Capacity, \( P_n \) (kips)
- **X-axis:** Concrete Compressive Strength, \( f_{c'} \) (ksi)
- Trend line indicates that the axial load capacity increases with increasing concrete strength.
- The line is labeled as \( f_y \) constant.

**Observation:**
- As the concrete compressive strength increases, the axial load capacity also increases linearly.
-Ongoing-

My Research Objectives to be completed:

- Fabrication of experimental setup
- Testing of RC column specimens
- Comparing observed RC column hysteretic response under axial & shear loading w/ that response predicted by capacity models

Overall Research Objectives to be completed:

- Using results to calibrate existing OpenSees analytical model that is based on RC structure deformation components & capacity models
- Using revised OpenSees analytical model to predict hysteretic response of existing RC building structure (composed of several column-beam components) to seismic & gravity loading
- Fabrication & testing of large-scale RC building frame
- Additional verification studies of OpenSees analytical model
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