EFFECT OF LATERAL LOADING PROTOCOLS ON SEISMIC PERFORMANCE OF RC COLUMNS

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Introduction-Motivation

• Many tests have been conducted previously on RC columns (ACI 369 database- PEER Data base) in order to:
  ▪ Investigate their behavior when subjected to gravity and seismic loadings
  ▪ Develop and improve design code provisions
  ▪ Generate and calibrate analytical models of RC columns

• However, there are shortcomings in the available test data.
Introduction-Motivation

• Specimen size: most tests are done at small scale.

• Levels of deformation: almost all current tests do not continue to large deformations.

• Loading Protocols
  ▪ Limited test data to show effects of loading history
  ▪ Limited test data for identical specimens under cyclic and monotonic loading
  ▪ Almost all current cyclic tests have symmetric cycles
Experimental Program

• Seven (7) full-scale RC columns were tested to better understand the effect of loading history collapse behavior.

• Specimens were representative of lower portion of a column bent in a double-curvature at the ground floor of a high-rise building.

• All specimens were designed according to seismic provisions in chapter 21 of the ACI 318-11 code.
Experimental Program

- Two types of specimens:

<table>
<thead>
<tr>
<th>Section</th>
<th>SF</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P/f'_c A_g$</td>
<td>0.3 (0.28)</td>
<td>0.15 (0.14-0.16)</td>
</tr>
<tr>
<td>Specimens</td>
<td>SP5</td>
<td>SP1, SP2, SP3, SP4, SP6, SP7</td>
</tr>
</tbody>
</table>
Experimental Program

Effect of Laterlal Loading Protocols on Seismic Performance of RC Columns
Experimental Program

Monotonic

Symmetric Cyclic (ACI 374-05)

Cyclic then Monotonic Push # 1

Cyclic then Monotonic Push # 2

Near-Collapse

Bi-axial
Effect of Loading Protocols

- Effect of axial load level \( \rightarrow \) SP5
- Effect of biaxial loading \( \rightarrow \) SP7
- Effect of Cycling \( \rightarrow \) SP2 also vs. SP3, SP4, and SP6.
Test Observations

- Progression of Damage
  - Flexural cracks on SE and NW faces
  - Shear-flexural cracks on SW and NE faces
  - Yielding of longitudinal bars
  - Spalling of cover concrete
  - Bar buckling and fracture

δ = 2.2%  δ = 3.5%  δ = 6.9%
Damage Index Models

• Noncumulative
  ▪ Lybas & Sozen (1977)
  \[ DR = \frac{K_o}{K_m} \]
  ▪ Roufaiel & Meyer (1987)
  \[ FDR^+ = \frac{K_m - K_o}{K_f - K_o^+} \]

• Cumulative
  ▪ Stephens & Yao (1987)
  \[ D_i = \left( \frac{\Delta \delta_{pi}^+}{\Delta \delta_f} \right)^{1-br} \]
  \[ D = \sum_{i=1}^{n} D_i \]
  ▪ Kratzig & Meskouris (1987)
  \[ D^+ = \sum E_{pi}^+ + \sum E_i^+ \]
  \[ D = D^+ + D^- - D^+ D^- \]

• Combined
  ▪ Park & Ang (1985)
  \[ D = \frac{\Delta m}{\Delta u} + \beta \int dE \]
  \[ \frac{1}{F_y \Delta u} \]
Calculated Damage Indices

(1) Lybas & Sozen
(2) Roufaiel & Meyer
(3) Stephens & Yao
(4) Kratzig & Meskouris
(5) Park & Ang
## Correlation with Observed Damage

<table>
<thead>
<tr>
<th>Cat.</th>
<th>Damage State</th>
<th>Description of the Observed Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Negligible</td>
<td>None or minor hairline flexural or flexural-shear cracks</td>
</tr>
<tr>
<td>II</td>
<td>Light</td>
<td>Widespread cracking throughout - initiation of cover spalling</td>
</tr>
<tr>
<td>III</td>
<td>Moderate</td>
<td>Widespread cracks &gt; 1/8 in. wide and cover spalling around the corners</td>
</tr>
<tr>
<td>IV</td>
<td>Severe</td>
<td>Extensive wide cracking and cover spalling throughout and/or single bar exposure</td>
</tr>
<tr>
<td>V</td>
<td>Failure</td>
<td>Extensive cover spalling and bar exposure, buckling/fracture of longitudinal bars</td>
</tr>
</tbody>
</table>

### Damage State Description

- **I (Negligible)**: None or minor hairline flexural or flexural-shear cracks
- **II (Light)**: Widespread cracking throughout - initiation of cover spalling
- **III (Moderate)**: Widespread cracks > 1/8 in. wide and cover spalling around the corners
- **IV (Severe)**: Extensive wide cracking and cover spalling throughout and/or single bar exposure
- **V (Failure)**: Extensive cover spalling and bar exposure, buckling/fracture of longitudinal bars

### Diagrams

- **Lybas-Sozen**: Graph showing damage index for different categories.
- **Stephens-Yao**: Graph showing damage index for different categories.
- **Park-Ang**: Graph showing damage index for different categories.

### Effect of Laterlal Loading Protocols on Seismic Performance of RC Columns

[Graphs and data points indicating the correlation between lateral loading protocols and observed damage states.]

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Conclusions

• Drift capacity (after either 20% or 50% strength degradation) was highly dependent on loading protocol.

• Among all specimens, SP5 (under larger axial load ratio), SP7 (under biaxial loading), and SP2 (under larger number of cycles) exhibited the smallest drift capacity.

• Columns will exhibit more damage during cyclic biaxial loading protocol as compared to uniaxial loading conditions.

• SP5, which had a similar loading protocol to that of SP2, but under a larger axial load ratio, experienced more damage.

• The model proposed by Park can directly include the effect of biaxial loading.
Thank You