Effect of Load History on Performance Limit States of Bridge Columns

Research Assistants:
Chad Goodnight
Yuhao Feng

Principal Investigators:
Dr. Mervyn Kowalsky
Dr. James Nau

North Carolina State University
Constructed Facilities Laboratory
11 April 2011
Project Scope

1. Determine if strain limits are affected by seismic load history.

2. Investigate the impact of load history on the relationship between strain and displacement.

3. Develop recommendations for strain limits for displacement-based seismic design.
Outline

- Load History Characteristics
- Peak Cycle Strain Comparison
- Review of Anti-Buckling Recommendations
- Review of Berry-Eberhard Buckling Model
- Impact of Variables within B-E Model
- Proposed Column Detailing for Tests 13-18
- Preliminary Plans for Remaining Specimens
Three Cycle Set Load History
El Centro 1940

Load History for Test 4
Load History for Test 5 and 6
Chile 2010

Load History for Test 8
Chichi 1999

Load History for Test 10
Kobe 1995

Load History for Test 11
Load History for Test 12

First Yield Displacement
Ductility One Displacement
1.25*Japan 2011 Load History - Test 12
Outline

- Load History Characteristics
- **Peak Cycle Strain Comparison**
- Review of Anti-Buckling Recommendations
- Review of Berry-Eberhard Buckling Model
- Impact of Variables within B-E Model
- Proposed Column Detailing for Tests 13-18
- Preliminary Plans for Remaining Specimens
Tensile Strain and Displacement

- CUMBIA
- Kobe - 3.86 sec: Ductility 10
- Chichi - 17.31 sec: Ductility 8.9
- Chile 2010 - 26.34 sec: Ductility 8.7
- Japan 2011 - 68.62 sec: Ductility 9.9
- Three Cycle Set - Ductility 8 +1

Largest Tensile Gage Length for Peak Displacement Cycles
Compressive Strain and Displacement

Largest Compressive Gage Length for Peak Displacement Cycles

- CUMBIA
- Kobe - 3.86 sec: Ductility 10
- Chichi - 17.31 sec: Ductility 8.9
- Chile 2010 - 26.34 sec: Ductility 8.7
- Japan 2011 - 68.62 sec: Ductility 9.9
- Three Cycle Set - Ductility 8 +1

Displacement (in)
Vertical Curvature Profiles

- Kobe - 3.86 sec: Ductility 10
- Chichi - 17.31 sec: Ductility 8.9
- Chile 2010 - 26.34 sec: Ductility 8.7
- Japan 2011 - 68.62 sec: Ductility 9.9
- Three Cycle Set - Ductility 8 +1
Increase in Extent of Plasticity and Linear Distribution of Curvature
Increase in Extent of Plasticity and Linear Distribution of Curvature
Summary of Tests 7-12

- Strain-Displacement Relationship
- Correlation with Moment Curvature Analysis
- Tension Based and Compression Based Buckling
- Strain to Cause Buckling for Tension Based
- Significance of Strain Accumulation
Outline

- Load History Characteristics
- Peak Cycle Strain Comparison
- Review of Anti-Buckling Recommendations
- Review of Berry-Eberhard Model
- Impact of Variables within B-E Model
- Proposed Column Detailing for Tests 13-18
- Preliminary Plans for Remaining Specimens
Equation 5.50 from “Seismic Design and Retrofit of Bridges” regarding buckling of longitudinal reinforcement between layers of transverse reinforcement.

For \( \frac{f_u}{f_y} = 1.5 \), \( s_{max} = 6 \times d_{bl} \).

\[
s \leq \left[ 3 + 6 \left( \frac{f_u}{f_y} - 1 \right) \right] d_{bl}
\]

\[
s_{max} = \left[ 3 + 6 \left( \frac{94.8ksi}{68ksi} - 1 \right) \right] 0.75in = 4.02in
\]
Equation 5.53 from “Seismic Design and Retrofit of Bridges” regarding buckling of longitudinal reinforcement over multiple layers of transverse reinforcement.

\[
\rho_s \geq \frac{0.0052 \cdot \rho_i \cdot D}{d_{bl}} \cdot \frac{f_y}{f_{yh}}
\]

\[
\rho_{s,\text{min}} = \frac{0.0052 \cdot 0.0156 \cdot 24\text{in}}{0.75\text{in}} \cdot \frac{68\text{ksi}}{74.1\text{ksi}} = 0.24\%
\]
In the Berry–Eberhard model, the plastic rotation \( \theta_p = \phi_p L_p \) at the onset of bar buckling is defined as:

\[
\theta_{p,bb} = C_0 \left( 1 + C_1 \rho_{eff} \right) \left( 1 + C_2 \frac{P}{Agf_c'} \right)^{-1} \left( 1 + C_3 \frac{L}{D} + C_4 \frac{f_{ydbl}}{D} \right)
\]

- Rectangular Sections
  \( C_0 = 0.019 \) \( C_1 = 1.650 \) \( C_2 = 1.797 \) \( C_3 = 0.012 \) \( C_4 = 0.072 \)

- Circular Sections
  \( C_0 = 0.006 \) \( C_1 = 7.190 \) \( C_2 = 3.129 \) \( C_3 = 0.651 \) \( C_4 = 0.227 \)

Where \( \rho_{eff} = \frac{f_{yh}}{f_c'} \rho_s \) and buckling occurs when the plastic rotation in the member reaches \( \theta_{p,bb} \). The variable \( f_{yh} \) is the transverse steel yield stress and the distance \( L \) is measured from the column base to the point of contraflexure.
Outline

• Load History Characteristics
• Peak Cycle Strain Comparison
• Review of Anti-Buckling Recommendations
• Review of Berry-Eberhard Model
• Impact of Variables within B-E Model
• Proposed Column Detailing for Tests 13-18
• Preliminary Plans for Remaining Specimens
Past Tests Utilized #3 at 2” on center
Transverse Steel and B.E. Model

Past Tests Utilized #3 at 2” on center
Transverse Steel and B.E. Model

Past Tests Utilized #3 at 2” on center
Tests 6-12 around 6.2%
Axial Load Ratio and the B.E. Model

Tests 6-12 around 6.2%
Axial Load Ratio and the B.E. Model

Tests 6-12 around 6.2%
Past Tests with a 16 #6 Bars – 0.75in diameter
Cantilever Aspect Ratio and the B.E. Model

Past Tests $L/D = 4$
Outline

- Load History Characteristics
- Peak Cycle Strain Comparison
- Review of Anti-Buckling Recommendations
- Review of Berry-Eberhard Buckling Model
- Impact of Variables within B-E Model
- Proposed Column Detailing for Tests 13-18
- Preliminary Plans for Remaining Specimens
Specimens 13-18

Transverse Steel Columns

- #3 spiral at 1.5"
  - $\rho_s = 1.3\%$, $\mu_{\Delta B.E.} = 10.23$

- #4 spiral at 2.75"
  - $\rho_s = 1.3\%$, $\mu_{\Delta B.E.} = 10.05$

- #3 spiral at 2.75"
  - $\rho_s = 0.7\%$, $\mu_{\Delta B.E.} = 7.99$

- #3 spiral at 4”, $\rho_s = 0.5\%$
  - $s_{\text{max}}$ for buckling between layers of transverse steel

Past Test Utilized #3 Spiral at 2”

Three Cycle Set

Earthquake Load History

Earthquake Load History

Three Cycle Set

Three Cycle Set

Three Cycle Set

Three Cycle Set
Preliminary Plan for Remaining Specimens

Axial Load Columns

- **5% Axial Load Ratio**
  \( \mu_{\Delta B.E.} = 9.35 \)

- **10% Axial Load Ratio**
  \( \mu_{\Delta B.E.} = 8.11 \)

- **15% Axial Load Ratio**
  \( \mu_{\Delta B.E.} = 7.16 \)

- **20% Axial Load Ratio**
  \( \mu_{\Delta B.E.} = 6.48 \)

- **Three Cycle Set**
  - **Earthquake Load History**

- **Earthquake Load History**

- **Test 5% Axial Load Ratio and Replace with EQ Load History**

**Tests 6-12 around 6.2%**
References
