Hybrid Precast Concrete Shear Walls for Seismic Regions

Yahya C. (Gino) Kurama, Ph.D., P.E.
Brian J. Smith, Ph.D., P.E.
University of Notre Dame
Civil & Environmental Engineering & Earth Sciences

PTI Convention
Norfolk, Virginia

May 6, 2014
Hybrid Precast Shear Walls

• Precast Concrete Wall Panels with Horizontal Joints
• During Large Earthquake, Gap Opens at Base Joint
  • High Strength Unbonded Post-Tensioning Strands Provides Re-Centering Force
  • Mild (E.D.) Steel Bars Provide Energy Dissipation
Market Need & Research Objectives

• Code Approval of Hybrid Wall System
  — Categorized as “Non-Emulative” Structure
  — Requires Experimental Validation
  — ACI ITG-5.1 Provides Validation Criteria
  — ACI ITG-5.2 Provides Roadmap for Wall Design

• Research Objectives
  — Develop Experimental, Analytical, and Design Validations to Allow for Code Adoption of Hybrid Precast Walls
  — Develop Design Procedure Document for Moderate and High Seismic Regions
Prototype Building & Wall

- Six Test Specimens
- Design Based on Prototype Parking Garage Building
- Seismic Category D in Los Angeles, CA 90045
  - $S_S = 1.500$; $S_1 = 0.640$; $C_S = 0.167$; $R = 6.0$; $C_D = 5.0$
- Base Moment for Full-Scale Wall ~20,000-kip-ft
- Structures Designed with Minimal Over-strength/Over-detailing

Plan View

Courtesy of Consulting Engineers Group (CEG), Texas
Experimental Program

- 0.4 Scaled Test with Two Wall Panels
- Specimen Design Parameters:
  \[ \Delta_{wd} = 0.54\% - 0.87\%; \quad \Delta_{wm} = 2.30\% \]
  \[ (H_w / L_w = 2.25) \]

ACI Required Drift History

\[ \Delta_{wm} = \text{Validation-Level Drift} = 2.3\% \]

\[ \Delta_{wm} = 0.90\% \leq 0.80(H_w / L_w) + 0.5 \leq 3.0\% \]
Specimen HW3 - Reinforcement Details

Casting Performed at High Concrete - Springboro, OH Plant
Specimen HW4 - Reinforcement Details

Base Panel

Additional Reinforcement Around Panel Perforations

Block-Out for Panel Perforation
Hysteretic Behavior of Validated Hybrid Walls

HW3: Solid Wall

HW4: Perforated Wall
Damage State of Specimen HW3

\[ \Delta_w = +2.95\% \]
Outline

• Introduction & Objectives
• Experimental Program
• Seismic Design Approach
• Analytical Investigation
• Summary and Acknowledgements
Performance Objectives

• Design-Level Drift
  - Gap Opening at Base Joint
  - Yielding of E.D. Bars
  - PT Steel Linear-Elastic
  - Minor Concrete Cracking
  - Cover Concrete on Verge of Spalling

• Maximum-Level Drift
  - No Significant Gap Opening at Upper Joints
  - No Significant Residual Vertical Wall Uplift Upon Unloading
  - No Significant Slip at Joints
  - No Fracture of E.D. Bars
  - No Fracture or Significant Yielding of PT Steel
  - Confined Core Concrete on Verge of Crushing
Design-Level Drift, $\Delta_{wd}$

Cross-Section

Elevation View of FBD

\[ f_{sd} \approx f_{sy} \]

\[ f_{pd} \approx 1.1f_{pi} = 0.6f_{pu} \]

\[ \Delta_{wd} \]

\[ \frac{A_p}{2} f_{pd} \]

\[ \frac{A_s}{2} f_{sd} \]

\[ 0.85f'_c \]

\[ c_d \]

\[ a_d \]

\[ z_d \]

\[ L_{w}/2 \]

\[ L_{w} \]

\[ \beta c_d \]
Maximum-Level Drift, $\Delta_{wm}$

Cross-Section

- Determine Probable Base Moment Strength
- Design Confinement Steel at the Toes
- Satisfy Maximum PT and E.D. Steel Strain Limits to Prevent Fracture

Cross-Section Formulas:

- $\Delta_{wm}$
- $N_w$, $M_{wm}$
- $A_p f_{pm}$, $A_s f_{sm}$
- $\gamma_m f_{cc}'$
- $a_m / 2$
- $z_m$, $c_m$
- $L_w / 2$
- $a_m = \beta_m c_m$

Maximum-Level Drift Limits:

- $\varepsilon_{sm} \leq 0.85 \varepsilon_{su}$
- $\varepsilon_{pm} \leq 1\%$
Estimation of Steel Strains

\[ \delta_p = \Delta_w \left( \frac{L_w}{2} + e_p - c \right) \]

\[ \varepsilon_p = \frac{f_{pi}}{E_p} + \frac{\delta_p}{l_p} \]

- \( \Delta_w \): initial strain
- \( \Delta_w \): strain due to gap
Outline

• Introduction & Objectives
• Experimental Program
• Seismic Design Approach
• Analytical Investigation
• Summary and Acknowledgements
Fiber Element Model

- DRAIN-2DX Program
- Concrete Wall Panels
  - Fiber Beam-Column Elements
- Unbonded PT Steel
  - Truss Elements
- E.D. Steel
  - Truss Elements
Lateral Load versus Deflection Behavior

Measured

Analytical
Gap Opening Displacements

Measured

Analytical

\( \Delta_w = 2.30\% \)

\[ \text{Gap Opening Disp. at Wall Ends (in.)} \]

\[ \text{Drift, } \Delta_w (\%) \]

\( \Delta_w = 2.30\% \)

\[ \text{Gap Opening Disp. at Wall Ends (in.)} \]

\[ \text{Drift, } \Delta_w (\%) \]
PT Steel Stresses

Measured

Analytical

Normalized PT Stress

Drift, $\Delta_w$ (%)

Initial

Final

HW3 (North Tendon)

Normalized PT Stress

Drift, $\Delta_w$ (%)

Initial

Final

HW3 (North Tendon)

Normalized PT Stress

Drift, $\Delta_w$ (%)

Initial

Final

HW3 (South Tendon)

Normalized PT Stress

Drift, $\Delta_w$ (%)

Initial

Final

HW3 (South Tendon)
MCE Level Dynamic Peak Drift Demands

\[ \Delta_{wm} = 2.30\% \] Reasonable for Validation-Level Drift

Unscaled MCE

Scaled MCE
Factors that Affect PT Strain Demands

Factors that affect $\epsilon_p$:
- Wall drift demand, $\Delta_w$
- Wall length, $L_w$
- PT tendon eccentricity, $e_p$
- Initial stress, $f_{pi}$
- Unbonded length, $l_p$

$$\delta_p = \Delta_w \left( \frac{L_w}{2} + e_p \cdot c \right)$$

$$\epsilon_p = \frac{f_{pi}}{E_p} + \frac{\delta_p}{l_p}$$
Effect of PT Eccentricity and Initial Stress

Max. PT steel strain, $\varepsilon_p$ (%)

- $f_{pi} = 0.70f_{pu}$
- $f_{pi} = 0.55f_{pu}$

PT strain limit

Validated design
Summary

• Tested Six 0.4-Scaled Specimens
  - Developed Validation Evidence for Hybrid Walls as Special RC Shear Walls in Seismic Regions
Implications for Unbonded Post-Tensioning

- Large PT Strain Demands Under Extreme Loading
- Strand-Anchorage Systems up to 2% Strain Capacity May be Needed for Seismic Regions

![Graph showing strain vs. eccentricity](image)
Acknowledgements

• **Sponsors**
  - The Charles Pankow Foundation
  - PCI Research & Development Committee
  - High Concrete Group, LLC
  - The Consulting Engineers Group – Texas
  - PCI Central Region
  - University of Notre Dame

• **Advisory Panel**
  - Walt Korkosz - The Consulting Engineers Group, Inc.
  - Ken Baur - High Concrete Group, LLC
  - Neil Hawkins - Univ. of Illinois Urbana-Champaign
  - Dave Dieter - Mid-State Precast, LP

• **Industry Support**
  - Dayton Superior Corp.
  - ECCO Manufacturing
  - Enerpac Precision
  - SURE-LOCK
  - Essve Tech, Inc.
  - Prestress Supply, Inc.
  - Sumiden Wire Products Corp.
  - Summit Engineered Products
  - Ambassador Steel Corp.
Questions?

WEBSITE: hybridwalls.nd.edu