Seismic Response of Tall Reinforced Concrete Wall Buildings

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1. (a) *Displacement*-based Seismic Design of RC Wall Buildings and
   (b) *Dual Plastic Hinge* Design of Tall RC Buildings

2. **Observations** from a Shake Table Test of a Full-Scale 7-Story Building Slice
1. How important is the interaction between the walls and elements framing to them (slab, gravity system) in RC wall buildings?

2. Are the effects of higher modes negligible, or should they be accounted for in design?

3. How well can current seismic design methods estimate structural and nonstructural component response for different hazard levels?
PART I

Displacement-based Seismic Design of RC Wall Buildings

Considering the effects of kinematic system overstrength and higher mode of response
Displacement-based Design for 2 Performance Levels

**Immediate Occupancy in frequent EQs**
- Minimize non structural damage
  - Interstory drift $\theta \leq 1\%$

**Collapse Prevention in rare EQs**
- Prevent bar buckling, fracture
  - $\varepsilon_s \leq 5\%, \varepsilon_c \leq 2\%$

For the predefined strains $\phi_u \approx 10\sim 15 \phi_y$

$\Delta_{io}$
- $\varepsilon_s$: Steel tensile strain
- $\varepsilon_c$: Concrete compr. strain

$\theta \leq 1\%$

$\Delta_u$
- Performance objectives are tunable!

\[ 1\% \]
Explicit Selection of **Mechanism of Inelastic Response** – Basic Mechanics

**Elastic Range:** \( \varphi_y \approx 2 \frac{\varepsilon_y}{L_w} \) \( \Delta_y = \frac{11}{40} \varphi_y H^2 \)

**Inelastic Range:** \( \varphi_p = 10 \sim 15 \varphi_y \) \( \Delta_p = \varphi_p L_p \left( \frac{H-L_p}{2} \right) \)

\( \Delta_u = \Delta_y + \Delta_p \)

Which is the \( \Delta_u \) corresponding to the **predefined objectives**?

\( \theta_p = \varphi_p L_p \)

\( \varphi_p \)

\( L_p \)

\( \Delta_u \)

\( L_p \)

Design to ensure **Elastic Response**

Enough Shear Strength

Detail to ensure **Inelastic Response**

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Displacement-based Design – First Mode

\[ V_{1b} = M_{e1} \left( \frac{2T}{T_D} \right)^2 \frac{\Delta_y}{1.4} \]

\[ M_{e1} \approx 0.7M \]

\[ h_{e1} \approx 0.7H \]

\[ T_D = \min (T_{io}, T_{cp}) \]

\[ K_D = \left( \frac{2T}{T_D} \right)^2 M_{e1} \]
Kinematic System Overstrength Framing Effects
**Kinematic System Overstrength**

**Framing Effects**

\[ V_f = \frac{2M_f}{L_f} \]

The additional lateral forces have to be resisted by the walls!

In a more “aggressive” design we can take advantage of increased OTM capacity.

\[ \Delta V_f \approx \frac{n}{\bar{a}} \sum_{i=1}^{\infty} \frac{2M_f}{h_i} + \frac{L_w}{L_f} \]
Displacement-based Design - Static Part

For a 7-Story Wall

and \( M_f = 2\%M_{bo} \), \( L_w = L_f \)

\[ \Delta V_f = V_{1b} \]

100% Increase of base shear due to frame action!
Dynamic Response – 2\textsuperscript{nd} Mode Effects

Lateral Forces due to:

System static flexural Overstrength + 2\textsuperscript{nd} Mode (elastic)
(Wall Overstrength + Framing)

\[ F_{10}^i = F_{wo}^i + \Delta V_f^i \]

\[ F^i = \sqrt{(F_{10}^i)^2 + (F_2^i)^2} \]

Modal Force Shape
Summary

Wall Overstrength

Wall Overstrength + Framing

Wall Overstrength + Framing + 2nd Mode
2nd Mode Effects - Design Cases of Cantilever Walls

ACI-318 Design
Potential plasticity into “elastic” regions?

EC-8 Design
Single Plastic Hinge (SPH)

Capacity Design (CD)
Elastic response

Dual Plastic Hinge (DPH)
2 potential plastic hinges

Boundary elements
Plastic hinge at base

CD
Design and analysis of 10-, 20- and 40-story cantilever walls for 3 near-fault records
Bending Moment Envelopes – Comparison of designs

Reduction of mid-height moment demand with DPH

Large mid-height moment demand with SPH

Level vs. $M_i / (Wt)$ for 10-story, 20-story, and 40-story structures.
Curvature Ductility Envelopes - Comparison of designs

Large $\mu_\phi$ demand in unexpected regions with ACI design

Control of inelastic response in two regions with DPH design
PART II

Observations from the UCSD Full-Scale 7-Story Building Slice Shake Table Test
Test Structure

- **7-story building slice with cantilever wall as the lateral force resisting system**
- **Tallest** building structure ever tested on a shake table
- **Single** axis of input ground motion in the plane of the wall

**Phase 1 Testing:**
- 12ft long rectangular wall

**Phase 2 Testing:**
- 14ft-8in long T-wall
Objective

- Verify the seismic performance of medium rise RC wall buildings designed with displacement-based method (DbD)

- **ASCE-7: Force-based Design**
  - Site Class C less than 2 km from fault
  - \( R = 5 \)

  \( V = 0.28 \ W \) \( (T=0.63 \ \text{sec}) \)

- **Displacement-based Design**

  \( V = 0.15 \ W \) \( (T_e=1.05 \ \text{sec}) \)

**Period \( T \) and \( R \) unknown until the end of the design**
Acceleration Response Spectra
damping=5%

Uncracked Period
$T = 0.51 \text{ sec}$

Cracked Period before EQ4
$T = 0.88 \text{ sec}$
EQ4: Roof Drift Ratio 2.1%, PGA = 0.93g
EQ4: Level 1 – Plastic Hinge Region
EQ4: max Steel Tensile Strain $\varepsilon_s = 2.7\%$
Experimental Response – Observations

1. The performance objectives were met for significantly reduced (50%) design seismic forces

2. Kinematic system overstrength increased the system moment capacity and the corresponding developed shear forces

3. Higher mode effects, additionally increased shear forces and floor accelerations
Observation 2. Kinematic System Overstrength

Hysteretic Response - Phase I
Observ. 2&3. **System Overstrength & Higher Modes**

**Shear Force Envelope - Phase I**

- **Design Shear Strength**
  - \( V_n = 325 \text{ kips} \)
  - \( V_n = 360 \text{ kips} \)

**From First Mode Forces**

**+ Section Overstrength**

**+ Kinematic Overstrength**

**+ Higher Modes**

- EQ1
- EQ2
- EQ3
- EQ4
Observation 3. Kinematic System Overstrength

Framing between web wall - slab – gravity columns

(a) Elevation

(b) Side view
Observation 3. **Kinematic System Overstrength**

**Framing between web wall – slotted slab – flange wall**

(a) Elevation

(b) Free body diagram of slotted slab
Plan of 7-Story Prototype Building

8 @ 28 ft = 224 ft

Rectangle of Test Structure

Residential Unit

Shear Wall (Transverse)
Conclusions

1. The 7-story building test verified the Db seismic design approach indicating the important effects of system overstrength and higher modes of response.

2. The dual plastic hinge design concept can improve the performance and construction efficiency of tall RC wall buildings.
Relation of **Linear** and **Nonlinear** Displacement Demand

**SDOF - Statistical Results**

\[ R = \frac{F_e}{F_y} \quad \mu = \frac{\Delta_i}{\Delta_y} \]

\[ C_\mu = \frac{\mu}{R} = \frac{\Delta_i}{\Delta_e} \]

**Excitation**

\[ F \]

\[ M_e \]

\[ K_e, T_e \]

\[ \Delta_i \]

\[ \Delta_y \]

**Displacement, \Delta**

**Period, T**

**C_\mu**

90th percentile

median
Dual Plastic Hinge Design Concept

- Design based on ACI-318 may result in unintended concentration of inelastic deformations higher up in the walls.

- Design according to EC-8 may result in large moment demand and high reinf. steel ratios on the upper part of the building which is supposed to remain elastic.

- The dual plastic hinge design can reduce the mid-height moment demand and control the inelastic response.
Test Regime

- **Testing at the NEES@UCSD Large High-Performance Outdoor Shake Table between October 2005 and May 2006**

- **Structure tested under increased intensity historical earthquake records and with low-intensity white noise in between**

- **600 Sensors for measuring the dynamic response**
Phase I - EQ4 - 6th Floor – Inner Hinge
Dynamic Response – 2nd Mode Effect

\[ F_1 = \frac{(0.7M) \alpha_1}{0.7H} \]

\[ M_{bo} \]

\[ T_2 \approx \frac{T_1}{5} \]

\[ F_2 = (0.2M)*S\alpha_2 \]

Dimensionless Response

\[ a_m: \text{modal acceleration} \]

\[ H \]

\[ \frac{h}{H} \]

Lateral Force

Shear Force

Bending Moment

\[ F_m / a_m \]

\[ V_m / (W\alpha_m) \]

\[ M_m / (W\alpha_m) \]
Observation 1. *Strain Performance Objectives Met*

**Levels 1 and 2 - Tensile Strain Envelope**

![Chart showing tensile strain envelope for different levels and strains](chart)

- **EQ1**, **EQ2**, **EQ3**, and **EQ4**
- Typical Layout of Longitudinal Reinforcement
- First Floor Slab
- Construction Joint
- Wall Base

*Note: The chart illustrates the tensile strain envelope for different levels and shows the performance met for objects.*
Effect of Higher Modes – Numerical Example

How can we handle the large bending moment demand?
**Effect of Higher Modes – Numerical Example**

- Analysis of 4 Cantiliver Wall Buildings with Sylmar OV Record
- ASCE-7 design with MRSA (R=5)
- Plastic hinge extends to about 10% of building’s height H

<table>
<thead>
<tr>
<th>Number of Stories</th>
<th>First Mode Period $T_1$ (sec)</th>
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<tbody>
<tr>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>14</td>
<td>1.3</td>
</tr>
<tr>
<td>20</td>
<td>1.9</td>
</tr>
<tr>
<td>40</td>
<td>3.9</td>
</tr>
</tbody>
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![Graph showing Sa(g) vs. T (sec) with 5% damping](image)

- Elastic
  - 40 story $T_1 = 3.9$ sec
- Plastic Hinge
  - 0.1H
  - 39

![Building height H](image)
Stiffness in RC structures is Strength dependent

Realistic Approximation

- Moment, $M$
- Curvature, $\varphi$

- $M_{y1}$
- $M_{y2}$
- $E_{I_{e1}}$
- $E_{I_{e2}}$

- $\varepsilon_y$: Steel yield strain

Myth

- Moment, $M$
- Curvature, $\varphi$

- $\varphi_{y1}$
- $\varphi_{y2}$

- $E_{I}$

- $\varepsilon_y$: Steel yield strain

$\phi_y \approx \frac{\varepsilon_y}{L_w / 2}$

RC Wall – Cross Section
Stiffness in RC structures is Strength dependent

For large curvature ductility $\mu_\varphi = \varphi_u / \varphi_y$:
- Uncracked stiffness $EI_t$ is immaterial
- Demand ($\varphi_u$) depends on effective stiffness $EI_e$

Effective stiffness $EI_e$ and period $T_e$ unknown till the end of the design ($M_y$)

$\phi_y \approx \frac{\varepsilon_y}{L_w / 2}$

$\varepsilon_y$ : Steel yield strain

RC Wall – Cross Section
UCSD 7-Story Building Slice - 3%g RMS WN Test
Force-based Design

Force reduction factor $R$, and Structural Period $T$ (Stiffness) are chosen in advance!

Design only for Collapse Prevention Performance Objective
How about Immediate Occupancy?

Base Shear: $V = MS_a / R$

$M$: 100% of seismic mass

$S_a (g)$

$T$ (sec)

Base Shear Force, $V$

Displacement, $\Delta$

Elastic Response $R=1$

$R=2$

$R=3$

$R=5$
Phase I - Summary Detailing – Web Wall

- Aiming at **Construction Optimization**:
  - Plastic hinge detailing on level 1 (Electrowelded Baugrid)
  - 1 Reinforcement curtain on levels 2-7

**Web Wall – Level 1**

- 8#5 @ 4in.
- 13#4 @ 10in.
- 12 ft.
- $\rho_l = 0.65\%$  $\rho_t = 0.31\%$  $\rho_v = 1.36\%$

**Web Wall – Levels 2-7**

- 4#7 @ 4in.
- 11#4 @ 10in.
- 6 in.
- $\rho_l = 0.87\%$  $\rho_t = 0.4\%$  $\rho_v = 0$
Wall Reinforcement Level 1
Observ. 3&4. **System Overstrength & Higher Modes**

**Instant of max measured Base Shear**
Observ. 3&4. **System Overstrength & Higher Modes**

**Acceleration Profile at max Base Shear - Phase I**

- Resultant Lateral Seismic Force
- \( h_{eff} \)
- \( H \)
- \( V \)
- \( h_{eff} \)
- \( M = V^* h_{eff} \)
Summary Detailing – T Wall – Level 1

- 6#4 @ 12 in.
- 8#5 @ 4 in.
- 13#4 @ 10 in.
- #4@8 in. (H)
- #3@4 in. (H)
- #4@12 in. (H)

Dimensions:
- 16 ft.
- 14 ft. - 8 in.
- 8 in.
Summary Detailing – T-Wall – Level 2-7

6#4@ 12 in.

4#7 @ 4in.  11#4 @ 10in.  #4@8 in. (H)

6 in.

16 ft.  14 ft.- 8 in.

2#6 @ 12 in.

#4@12 in. (H)
Interstory Drift Envelopes – Comparison of designs

- Reduced interstory drifts with DPH in comparison with ACI