Earthquake Resistant and Resilient Tall Buildings using Seismic Isolation and Rocking Core Walls

Vladimir Calugaru, Graduate Student Researcher
Marios Panagiotou, Assistant Professor

Department of Civil and Environmental Engineering
University of California, Berkeley
Tall Buildings in Regions of High Seismicity

One Rincon Hill - San Francisco

Schematic of Lateral Force Resisting System

Reinforced concrete core walls for lateral force resistance

Moehle (2007)
Damage in Tall Buildings in Recent Earthquakes

2010 M8.8 Chile Earthquake


2011 M6.1 NZ Earthquake

Grand Chancellor Hotel 26-story, tallest building in Christchurch Currently under demolition

http://en.wikipedia.org
20-story Building Layout

Plan View

- Gravity column
- Core wall
- \( t_w = 46 \text{ cm} \)
- \( L_w = 7.9 \text{ m} \)
- 27.2 m

Elevation

- Core wall
- Gravity column
- Floor slab
- \( H = 67 \text{ m} \)
- \( h = 3.4 \text{ m} \)
- Foundation
**Ground Motions**

Fixed-Base Buildings – Design of Core Walls

Extended Plasticity (EP)

- $\rho_l = 0.4\%$
- $\rho_l = 0.6\%$
- $\rho_l = 0.8\%$

Single Plastic Hinge (SPH)

- $H = 67 \text{ m}$
- $\rho_l = 2.4\%$
- $\rho_l = 0.8\%$

OPENSEES Numerical Model

- Force-based fiber section beam-column elements
- Lumped mass, $m$

- $T_1 = 1.88 \text{ sec}$
- $T_2 = 0.30 \text{ sec}$
- $T_v = 0.11 \text{ sec}$

- $T_1 = 1.83 \text{ sec}$
- $T_2 = 0.29 \text{ sec}$
- $T_v = 0.10 \text{ sec}$
Mean Results for 14 Near-Fault Ground Motions

- **Bending Moment**
- **Steel Strain**
- **Shear Force**
- **Total Acceleration**
- **Displacement**
- **Interstory Drift**

Extended Plasticity (EP) vs. Single Plastic Hinge (SPH)
**Fixed-Base Buildings:**

- Undergo significant inelastic deformations
- Develop large forces (bending moment and shear forces)
- Develop large floor accelerations
- Experience significant post-earthquake damage

**Use Seismic Isolation or / and Rocking Walls to:**

- Control deformations in one or two robust planes
- Reduce floor accelerations, and forces
- Reduce post-earthquake damage and make building adaptable
Isolated Tall Buildings

Thousand Tower
Kawasaki city, 41-story, base isolated

Shiodome Sumitomo Building
Tokyo, 25-story

Isolation layer at 40% of the height

Komuro et al. (2005)

Tsuneki et al. (2009)
Isolated Building Designs

Plan View Below Ground

- Elastomeric bearing
- Ø = 155 cm
- L_w = 7.9 m

Elevation

- H = 67 m
- \( \rho_l = 2.4\% \)
- Seismic Isolators

Dimensions:
- 27.2 m
- 30.5 m
Isolated Building Designs

- **Design 1**
  - 20 bearings
  - $T_1 = 3.9 \text{ sec}$
  - $T_2 = 1.2 \text{ sec}$
  - $T_v = 0.1 \text{ sec}$

- **Design 2**
  - 16 bearings
  - $T_1 = 4.6 \text{ sec}$
  - $T_2 = 1.3 \text{ sec}$
  - $T_v = 0.1 \text{ sec}$

**Diagram:**
- Lw = 7.9 m
- 67 m
- Elastomeric bearings
- Rigid elements
- Isolation bearings
- Elastic springs

$H$ and $3h$ indicate additional structural elements.
Mean Results for 14 Near-Fault Ground Motions

<table>
<thead>
<tr>
<th>$T_{1,BI}$ (sec)</th>
<th>3.9</th>
<th>4.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolator displacement [mean and (max) in cm]</td>
<td>59 (82)</td>
<td>77 (118)</td>
</tr>
</tbody>
</table>

- **Bending Moment**
- **Steel Strain**
- **Shear Force**
- **Total Acceleration**
- **Displacement**
- **Interstory Drift**
Seismic Isolation Design:

- **Reduced** floor accelerations, and base shear force by about 2 times
- **Increased** base moment demand and resulted in significant *inelastic* response at the base of the wall

Use **Rocking Core-Wall** to:

- Avoid the formation of a flexural plastic hinge and *reduce* damage in wall in comparison with *fixed-base* building
Rocking Core-Wall Building Design

Core wall $\rho=2.4\%$

Unbonded Steel

Viscous Dampers

Rocking plane

Building Elevation

Close-up Elevation of Rocking Plane Region

Unbonded steel

Bonded steel

Linear viscous damper
Mean Results for 14 Near-Fault Ground Motions

Rocking plane rotation: mean=1.7%, max=3.8%
Seismic Isolation:

- Reduced floor accelerations, and shear forces by about 2 times
- Increased base moment demand and resulted in significant inelastic response at the base of the wall

Rocking Core Wall:

- Reduced damage in core wall
- Forces and accelerations similar to fixed-base building
Base Isolation and Rocking Core Wall Building

Core wall

H = 67 m

Seismic isolators

Foundation

Unbonded steel

Viscous dampers

Seismic isolators

Elevation

Rocking Plane Close-up View

nonlinear trusses

contact springs

“Rigid” elements

“Rigid” elements

Isolation bearings, elastic springs

OPENSEES Model
Mean Results for 14 Near-Fault Ground Motions

Mean rocking plane rotation uplift = 2.6% (max = 5%)
Mean isolator displacement = 57 cm (max = 102 cm)
Effect of Viscous Dampers

<table>
<thead>
<tr>
<th>C</th>
<th>0</th>
<th>300</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplift (cm)</td>
<td>24 (49)</td>
<td>20 (42)</td>
<td>18 (38)</td>
</tr>
<tr>
<td>Isolator Disp. (cm)</td>
<td>60 (117)</td>
<td>57 (102)</td>
<td>56 (94)</td>
</tr>
</tbody>
</table>

- **Bending Moment**
- **Steel Strain**
- **Shear Force**
- **Total Acceleration**
- **Displacement**
- **Interstory Drift**
Conclusions

In comparison with the **fixed-base buildings:**

- The **base isolated building** reduced about 2 times base shear force and floor accelerations but resulted in significant inelastic response at the base of the wall.

- The **rocking wall building** prevented the formation of a flexural plastic hinge at the base of the wall without reducing forces and accelerations.

- The building with **base isolation and rocking core wall** had a superior performance reducing about 2 times base shear forces and floor accelerations while it prevented the formation of a plastic hinge at the base of the wall.
End

Kobe 1995 Earthquake
12-story building

Chile 2010 Earthquake
23-story O’Higgins 241 tower

EQE (1995)

EERI (2010)
Mean Results for High Frequency (Bin 1) Near-Fault Ground Motions

Bending Moment

Steel Strain

Shear Force

Total Acceleration

Displacement

Interstory Drift
Mean Results for Low Frequency (Bin 2) Near-Fault Ground Motions

**Bending Moment**

**Steel Strain**

**Shear Force**

**Total Acceleration**

**Displacement**

**Interstory Drift**
# Mean Peak Responses

<table>
<thead>
<tr>
<th>Peak Response. Mean of 14GM (Max of 14GM)</th>
<th>EP</th>
<th>SPH</th>
<th>BI</th>
<th>RW</th>
<th>BI+RW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear (V/W)</td>
<td>0.25 (0.38)</td>
<td>0.24 (0.41)</td>
<td>0.22 (0.31)</td>
<td>0.30 (0.54)</td>
<td>0.15 (0.20)</td>
</tr>
<tr>
<td>Roof acceleration (A/PGA)</td>
<td>1.35 (2.67)</td>
<td>1.42 (2.12)</td>
<td>0.80 (1.48)</td>
<td>1.52 (2.95)</td>
<td>1.00 (2.05)</td>
</tr>
<tr>
<td>Steel strain at wall base (%)</td>
<td>3.40 (5.25)</td>
<td>3.80 (6.29)</td>
<td>2.37 (5.42)</td>
<td>0.04 (0.07)</td>
<td>0.06 (0.12)</td>
</tr>
<tr>
<td>Steel strain anywhere along building height (%)</td>
<td>3.40 (5.25)</td>
<td>3.80 (6.29)</td>
<td>2.37 (5.42)</td>
<td>0.15 (0.28)</td>
<td>0.20 (0.69)</td>
</tr>
<tr>
<td>Concrete compression strain at wall base (%)</td>
<td>0.20 (0.26)</td>
<td>0.21 (0.28)</td>
<td>0.20 (0.28)</td>
<td>0.50 (0.98)</td>
<td>0.73 (1.42)</td>
</tr>
<tr>
<td>Wall uplift (cm)</td>
<td></td>
<td></td>
<td></td>
<td>13 (29)</td>
<td>20 (42)</td>
</tr>
<tr>
<td>Isolator displacement (cm)</td>
<td></td>
<td></td>
<td></td>
<td>59 (82)</td>
<td></td>
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Ground Motions


High Frequency (Bin 1) – LGP, RRS, SCS, TAK, TARZANA, TCU084, TCU129
Low Frequency (Bin 2) – DUZCE, ELCEN6, LCN, TABAS, TCU052, TCU075, TCU102

EXPLAIN BINs HERE
Unbonded Steel
Viscous Dampers
Post-tension tendon (PT)
Core wall
Rocking plane

Force-based beam-column elements, fiber section
"Rigid" elements
PT – elastic corotational truss element
Lumped mass
Unbonded Steel, truss elements
Linear viscous damper
Contact springs
"Rigid" elements

Building Elevation
OpenSees Model

Rocking Plane Detail
Rocking Plane Close-up View

Seismic fluid viscous dampers for large highway bridge, 1.5 million pounds output force.

http://www.taylordevices.com
Base of Rocking Wall Detail

- Core wall
- Post-tension tendon (PT)
- Unbonded Steel
- Viscous Dampers
- Rocking plane

Building Elevation

- Unbonded steel
- Bonded steel
- Linear viscous damper
Base Isolation and Rocking Core Wall (BI+RW) Building

- Core wall
- Post-tension tendon (PT)
- Unbonded Steel
- Viscous Dampers
- Rocking plane
- Seismic Isolators

Force-based beam-column elements, fiber section

- "Rigid" element
- Contact springs
- Linear viscous damper
- Unbonded Steel, truss elements
- "Rigid" elements
- Lumped mass
- PT – elastic corotational truss element

Building Elevation

OpenSees Model

Rocking Plane Close-up View

Isolation bearings, elastic springs
Isolation bearings, elastic springs

Rocking Plane
Close-up View

“Rigid” element
Contact springs
Linear viscous damper
Unbonded Steel, truss elements
“Rigid” elements

Isolation bearings, elastic springs
Rocking Core Wall (RW) Building

- Core wall: $L_w = 7.9 \text{ m}$
- Foundation

Elevation (no PT)

Elevation (with PT)

- Post-tension tendon (PT)
- Unbonded Steel
- Viscous Dampers
Base Isolation and Rocking Core Wall (BI+RW) Building

- Core wall
  - $L_w = 26 \text{ ft (7.9 m)}$

- Gravity column

- Floor slab
  - $h = 11 \text{ ft (3.4 m)}$

- Seismic Isolators

- Foundation

- Unbonded Steel Viscous Dampers

- Post-tension tendon (PT)

- Elevation (no PT)

- Elevation (with PT)
EP Response Envelopes for 14 ground motions

Bending Moment

Steel Strain

Shear Force

Total Acceleration

Displacement

Interstory Drift
RW Response Envelopes for 14 ground motions
BI+RW Response Envelopes for 14 ground motions

No PT

Bending Moment

Steel Strain

Shear Force

Total Acceleration

Displacement

Interstory Drift

- DUZCE
- ELCEN6
- LCN
- LGP
- RRS
- SCS
- TABAS
- TAK
- TARZANA
- TCU052
- TCU075
- TCU084
- TCU102
- TCU129

- $h_i/H$
- $\varepsilon_s$ (%)
- $V/W$
- $D$ (m)
- $ID$ (%)
BI+RW Response Envelopes for 14 ground motions

0.4% PT 30ksi prestress

Bending Moment

Steel Strain

Shear Force

Total Acceleration

Displacement

Interstory Drift

DUZCE
ELCEN6
LCN
LGP
RRS
SCS
TABAS
TAK
TARZANA
TCU052
TCU075
TCU084
TCU102
TCU129

A / PGA

M / WH

εs (%)

V / W

D (m)

ID (%)
Seismic Isolator Design

20-story

- $D_L = 8\text{ in}$
- $t_R = 12\text{ in}$
- $D_R = 40\text{ in}$

- $K_{\text{hor}} = 28\text{ kip/in}$
- $K_{\text{ver}} = 12100\text{ kip/in}$
- $F_y = 106\text{ kip}$

40-story

- $D_L = 8\text{ in}$
- $t_R = 20\text{ in}$
- $D_R = 60\text{ in}$

- $K_{\text{hor}} = 23\text{ kip/in}$
- $K_{\text{ver}} = 17400\text{ kip/in}$
- $F_y = 146\text{ kip}$
Isolated Building Designs

- Building height: $H = 67 \text{ m}$
- Width: $L_w = 7.9 \text{ m}$

**Seismic Isolators**

- Isolation bearings: $H_{bearing} = 32 \text{ cm}$
- $T_1 = 3.9 \text{ sec}$
- $T_2 = 1.2 \text{ sec}$
- $T_v = 0.1 \text{ sec}$
- $W_1 = 0.91W_t$
- $h_{1,eff} = 35.8 \text{ m}$
- $Sa(T_1) = 0.29 \text{ g}$
- $Sd(T_1) = 1.08 \text{ m}$

- Isolation bearings: $H_{bearing} = 47 \text{ cm}$
- $T_1 = 4.6 \text{ sec}$
- $T_2 = 1.3 \text{ sec}$
- $T_v = 0.1 \text{ sec}$
- $W_1 = 0.92W_t$
- $h_{1,eff} = 36.7 \text{ m}$
- $Sa(T_1) = 0.24 \text{ g}$
- $Sd(T_1) = 1.26 \text{ m}$