PROPORTIONING STRENGTH TO LIMIT BUILDING MOVEMENTS OF SLENDER CORE-ONLY TOWERS

MARK SARKISIAN
ERIC LONG
DAVID SHOOK
FRANCESCO RANAUDO

SOM
AGENDA

1. Clarity of structural system is important for slender/ductile seismic systems.
2. Nonlinear analysis as a design tool early in the design. DD stage with appropriate rebar assumptions.
3. Expanded use of NLRHA results for the design of the following elements.
   • Boundary zone type and extents
   • Panel zone ties extents
   • Panel zones above/below openings using section cuts
4. Torsion under high levels of ductility may not be well accounted for in linear response spectrum analysis.
FOLSOM STREET
SAN FRANCISCO’S
NEW MAIN STREET.

500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
500 FOLSOM
TRANSBAY BLOCK 9

KEY PARAMETERS

Tower
  Height: 400 ft
  Floors: 43

Podium
  Height: 85 ft
  Floors: 8

Basement
  Depth: -76 ft (b/mat)
  Floors: 6

Gross Area: 700,00 sqft
PROJECT OVERVIEW

RESIDENTIAL PROJECT
- 545 TOTAL UNITS, INCLUDING 3 TOWNHOUSES ON CLEMENTINA
- 436 MARKET RATE UNITS
- 109 AFFORDABLE UNITS (20% OF TOTAL)

OPEN SPACE
- 9,330 SQ FT AT L9 LANSCAPED TERRACE
- 2,915 SQ FT AT GROUND LEVEL

FOLSOM BOULEVARD RETAIL
- 6,775 SQ FT GROUND LEVEL RETAIL

BELOW GRADE PARKING (6 LEVELS)
- BIKE PARKING AT B1: 206 (38:1)
- APROX 286 STALLS (52:1) FROM B1 TO B6 COMPRISED OF:
  - 269 SELF PARK
  - 11 HC
  - 3 CAR SHARE STALLS
  - 3 CHARGING STATIONS
SEISMIC SYSTEMS
CLARITY?

CORE + WALLS

CORE + MOMENT FRAME

CORE + WEB
SEISMIC SYSTEMS

CLARITY?

CORE + WALLS

CORE + MOMENT FRAME

CORE + WEB
SEISMIC SYSTEMS
CLARITY

CORE
TOWER PLAN
TYPICAL – 12 UNITS

KEY PARAMETERS

Units
- All columns at demising walls
- Heat pumps at partitions

Central Core
- Clear central core configuration
- Coordinated with all MEP trades in schematic design

Framing
- Units coordinated with PT layout
- Repetitive edge of slab
TOWER PLAN

SCHEMATIC DESIGN

Aspect Ratio: 14 : 1

Outriggers

400 ft

29 ft

500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
OPTIMIZATION

DESIGN DOMAIN
OPTIMIZATION

FLOW
Core to Height Aspect Ratio: 12 : 1
TYPICAL PODIUM
LATERAL SYSTEM

500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
**TOWER PLAN**

**CONSTRUCTION DOCUMENTS**

**KEY PARAMETERS**

**Slabs**
- Avg span: 28 ft
- Thickness: 7 in
- Strength: 6,000 psi

**Shear Walls**
- Thickness: 30” – 24”
- Strength: 8,000 psi

**Link Beams**
- Depth: 22”, 18”
- Diagonally reinforced

*Aspect Ratio: 12 : 1*
TOWER CORE

ELEVATIONS
## BUILDING CHARACTERISTICS

### Modal Summary

Well defined modes between translation and torsion

<table>
<thead>
<tr>
<th>Mode</th>
<th>Period [s]</th>
<th>UX</th>
<th>UY</th>
<th>RZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.8</td>
<td>0.00</td>
<td>0.38</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>4.3</td>
<td>0.38</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>2.6</td>
<td>0.01</td>
<td>0.00</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>0.00</td>
<td>0.15</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>0.11</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>0.06</td>
<td>0.00</td>
<td>0.09</td>
</tr>
</tbody>
</table>
DESIGN SUMMARY
LINEAR CODE-BASED DESIGN

Design Level Earthquake (DBE)

Detailed ETABS model w/site-specific response spectrum loading

Drift and global code checks satisfied

All components satisfy code prescribed strength checks – shear walls, link beams, gravity columns, etc

Service and MCE Level Earthquake (SLE & MCE_R)

Detailed ETABS model w/site-specific response spectrum loading

Drift and global code checks satisfied (0.5% & 3%)

All components satisfy code prescribed strength checks based on design criteria
PERFORMANCE BASED DESIGN
GROUND MOTIONS - COMPASS

- Ground motion evaluation

ROT100 Response Spectrum, Short Period
NONLINEAR MODELING

DETAILED APPROACH

Link Beam Modeling: w/RC Slab

Wall Fiber Arrangement

Deformation Gages
PROPORTIONING

REINFORCEMENT LEVEL ASSESSMENTS

Compare of axial-moment demands of response spectrum and nonlinear time history analysis.

Used $R = 3.0$ for initial deformation-controlled action design ($R = 2$ for force-controlled)

Determined more appropriate $R$ factors for deformation-controlled action design of slender cores

- Modest/Low yielding: $R = 5.0$
- Higher yielding (hinge): $R = 7.5$
Create Plastic Hinge
Original design using RS analysis

Reinforcement design using NLRH results
(~ 500'000 $)
LINK BEAM
2% REBAR SCHEME

B4 COUPLING BEAM ROTATIONS - C1-SP

B3 COUPLING BEAM ROTATIONS - C1-SP

500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
LINK BEAM
1% REBAR SCHEME

S00 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
LINK BEAM ROTATIONS
0.8% REBAR SCHEME + INCREASE LK STRENGTH
STRAIN DEMANDS
2% REBAR SCHEME

-1.5% -1.0% -0.5% 0.0% 0.5% 1.0%


B01 B02 B03 B04 B05

WEST WALL
PIER 3
- OUTER
INNER
PIER 2
INNER
PIER 1
INNER
OUTER

WEST WALL
PIER 3
- OUTER
INNER
PIER 2
INNER
PIER 1
INNER
OUTER

Applicable Limit
UNCONFINED
Applicable Limit
CONFINED

A - CHICHI36
B - DUZCE
C - LOMAP
D - LANDERS
E - CHYO24
F - TCU065
G - DENALI
H - CAPEMEND FFS
I - CAPEMEND LFS
J - DARFIELD CNH
K - DARFIELD HORC
C1-SP Mean

500 FOLSOM – P
SKIDMORE, OWI
STRAIN DEMANDS

1% REBAR SCHEME
STRAIN DEMANDS
0.8% REBAR SCHEME + INCREASE LK STRENGTH
STRAIN DEMANDS
CONFINEMENT BASED ON NLRHA

Ordinary (6” or 8” tie spacing)

Special (4” or 5” tie spacing)

Compressive Strain Limits
- Unconfined Limit = 0.003/2”/1.5” = 0.001
- Ordinary Limit = 0.004/2” = 0.002
- Special Limit = 0.013/2” = 0.006

*Reduction in limit by 2 per Wallace, 2007
**Reduction in limit by 1.5 due to force-controlled action

Tensile Strain Limits
- Unrestrained bar limit = 1x yield
- 8” spacing bar restraint = 2x yield
- 6” spacing bar restraint = 10x yield

Fig. R18.10.6.4.2—Summary of boundary element requirements for special walls.
STRAIN DEMANDS
APPLIED TO CORE

- $\varepsilon_t \leq 1x$ yield
- $1x$ yield $< \varepsilon_t \leq 2x$ yield
- $2x$ yield $< \varepsilon_t$

Non-boundary
- $1x$ yield $< \varepsilon_t \leq 2x$ yield
- $2x$ yield $< \varepsilon_t$

Diagram:
- Roof
- Coupling
- Top of Podium
- "Plastic Hinge"
- Ground Level
- Low Yielding
- Basement
- No Yielding
STRAIN DEMANDS
APPLIED TO CORE

Panel Ties

Select areas with special BZ

Ordinary 6" Typ

Ordinary 8" Typ

Level 13

Level B2

500 FOLSOM – PROPORTIONING SLENDER TOWERS
SKIDMORE, OWINGS & MERRILL LLP
Design Load Cases

1. 1.5 times the average of short period ground motions
2. 1.5 times the average of long period ground motions
3. 1.0 times peak responses from short period ground motions E & F
4. 1.0 times peak responses from long period ground motions E & G
FOUNDATION DESIGN
BASED ON NLRHA
FOUNDATION DESIGN
BASED ON NLRHA

For long and short period suites obtain:
1. Global MX and MY
2. Core MX and MY
3. Shear X and Y

Four variable diaphragm loads at variable height:
1. Match global MX and MY
2. Observe core MX and MY
3. Match shear X and Y

Comparison of ETABS/PERFORM3D
Global Moment Mx 1.0
Global Moment My 1.0
Core Moment Mx 1.0
Core Moment My 1.0
Shear X 1.0
Shear Y 1.0
AGENDA

1. Clarity of structural system is important for slender/ductile seismic systems.

2. Nonlinear analysis as a design tool early in the design. DD stage with appropriate rebar assumptions.

3. Expanded use of NLRHA results for the design of the following elements.
   - Boundary zone type and extents
   - Panel zone ties extents
   - Panel zones above/below openings using section cuts

4. Torsion under high levels of ductility may not be well accounted for in linear response spectrum analysis.