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

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# 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

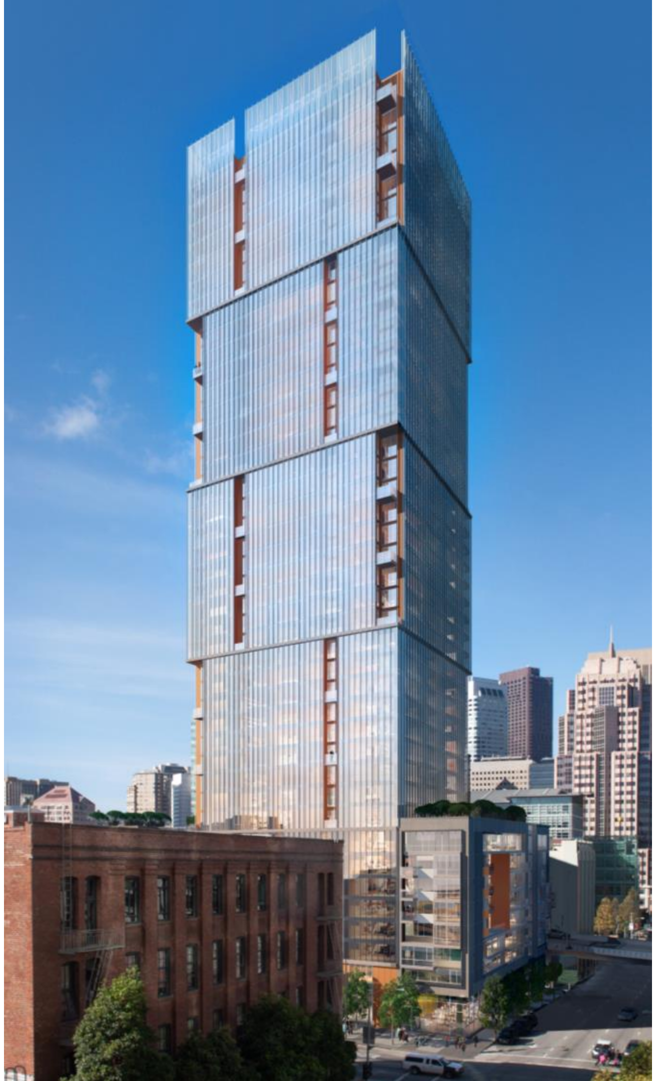
KEY PARAMETERS

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

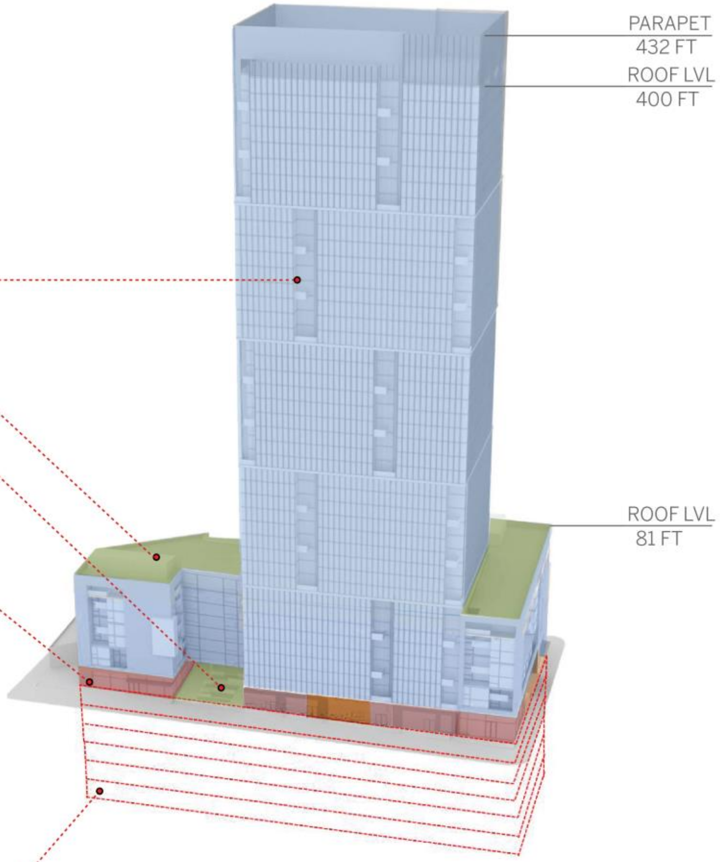
## FOLSOM BOULEVARD RETAIL

- **6,775 SQ FT** GROUND LEVEL RETAIL

## BELOW GRADE PARKING (6 LEVELS)

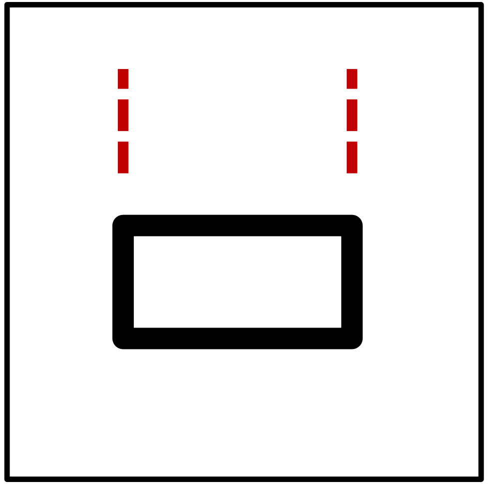
- BIKE PARKING AT B1: **206 (.38:1)**

- **APROX 286 STALLS (.52:1)** FROM B1 TO B6 COMPRISED OF:
    - **269** SELF PARK
    - **11** HC
    - **3** CAR SHARE STALLS
    - **3** CHARGING STATIONS

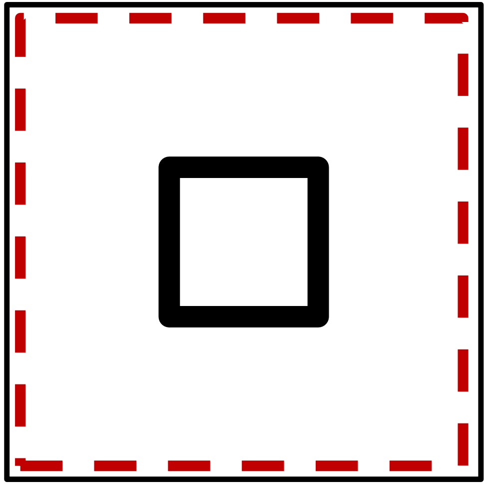


# SEISMIC SYSTEMS

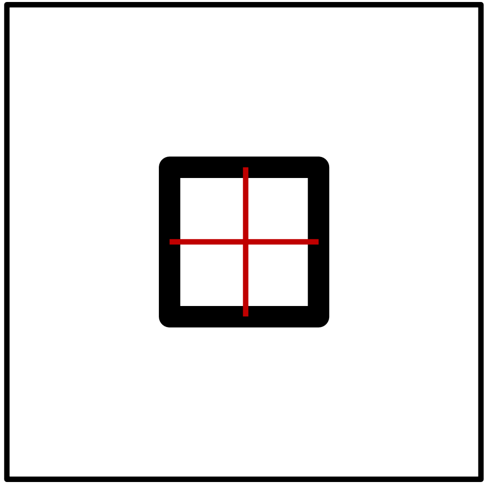
## CLARITY?



CORE + WALLS



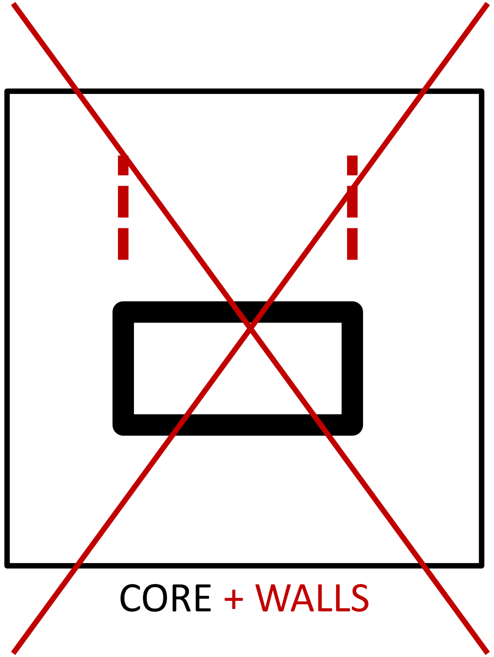
CORE + MOMENT FRAME



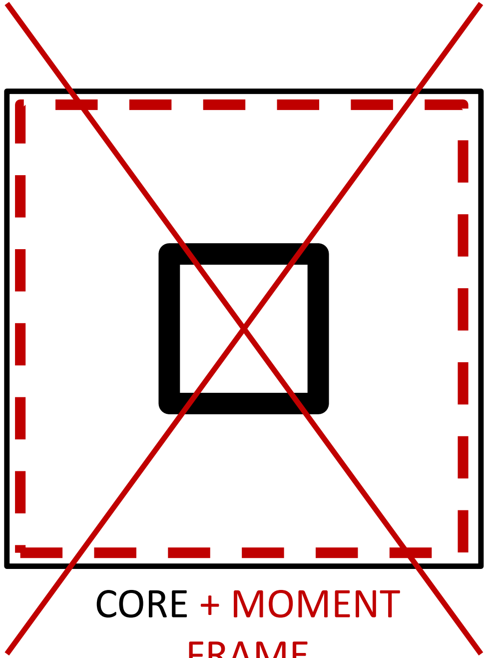
CORE + WEB

# SEISMIC SYSTEMS

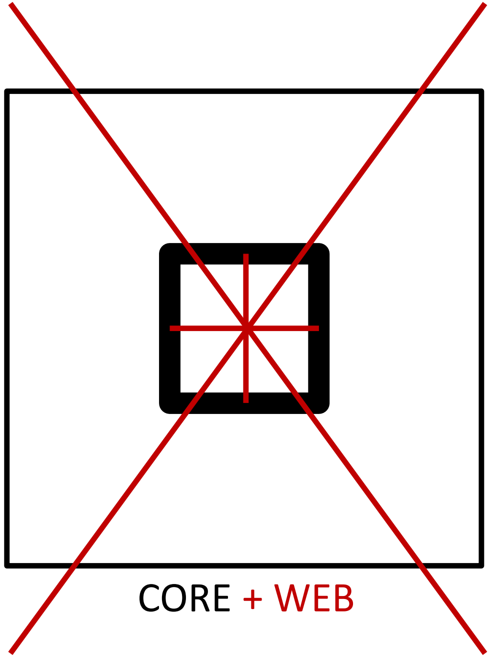
## CLARITY?



CORE + WALLS



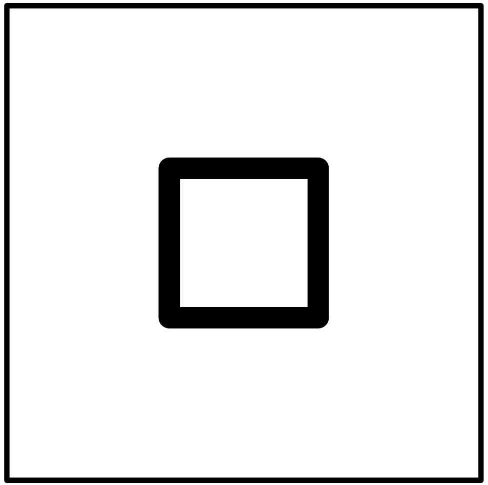
CORE + MOMENT FRAME



CORE + WEB

# SEISMIC SYSTEMS

## CLARITY



CORE

# TOWER PLAN

## TYPICAL – 12 UNITS

KEY PARAMETERS

Units

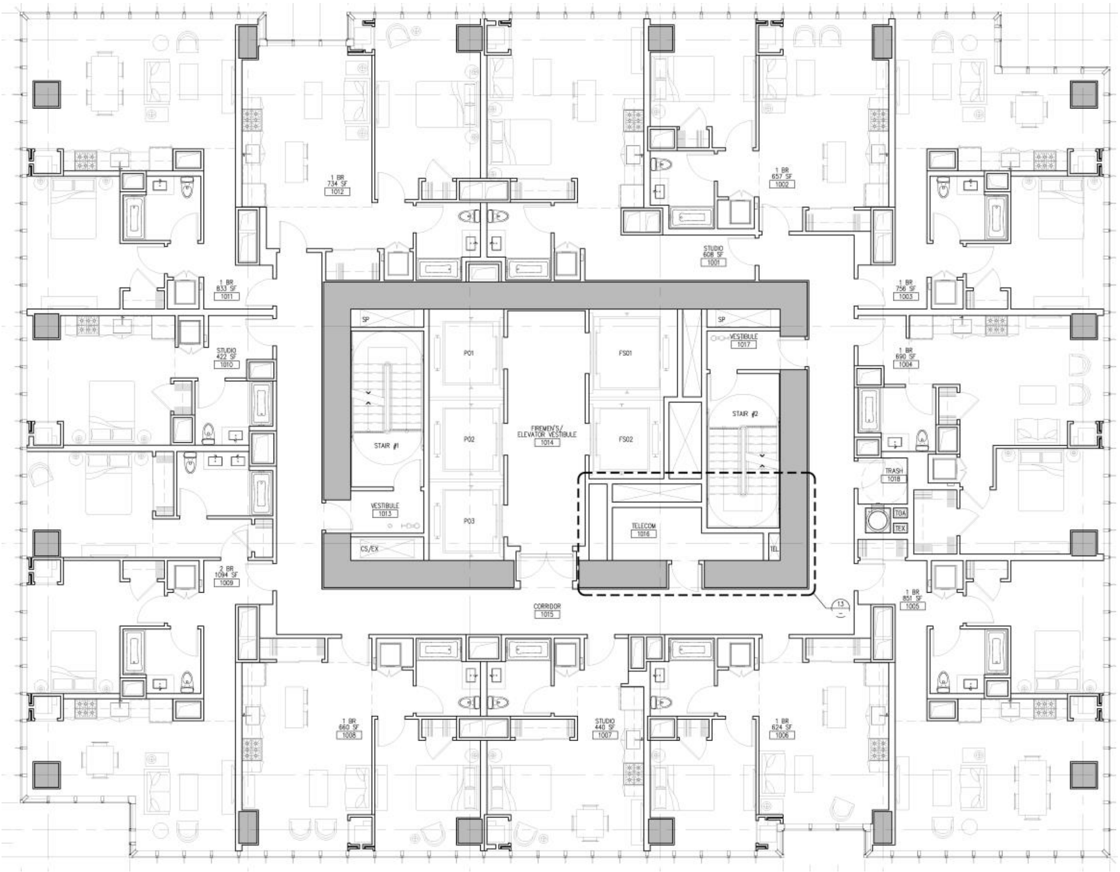
- All columns at demising walls
- Heat pumps at partitions

Central Core

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

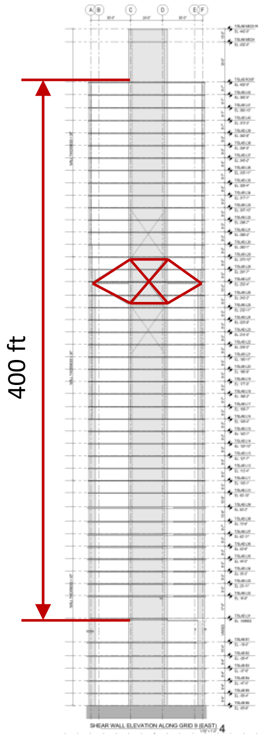
Framing

- Units coordinated with PT layout
- Repetitive edge of slab



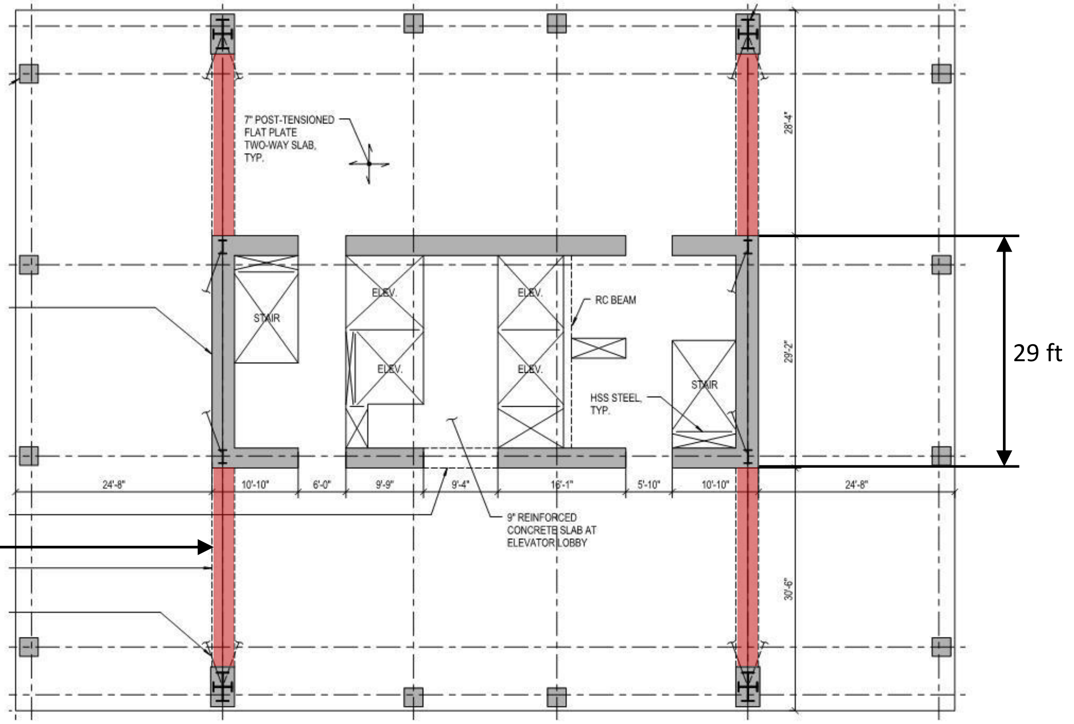
# TOWER PLAN

## SCHEMATIC DESIGN



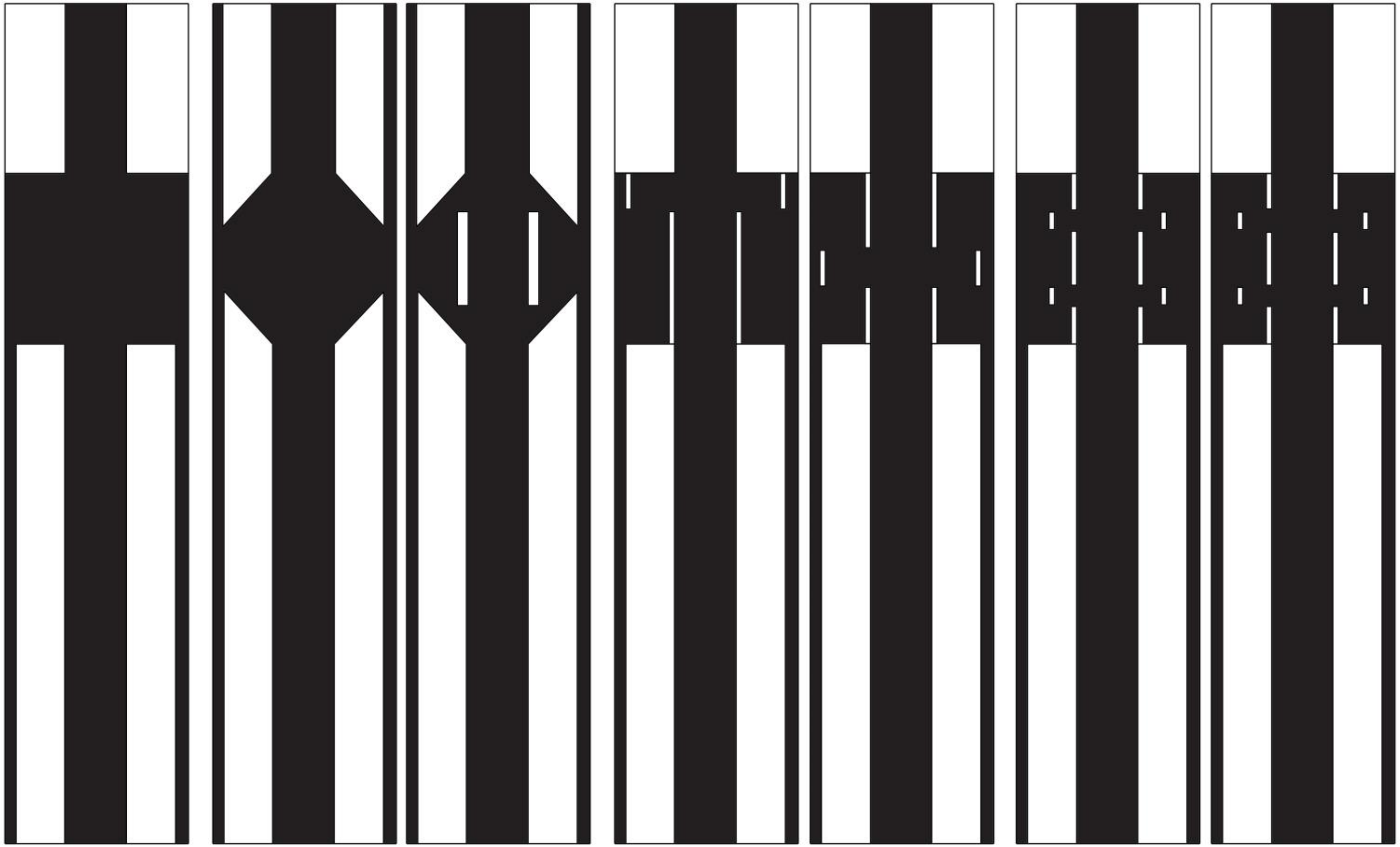

Aspect Ratio: 14 : 1

Outriggers



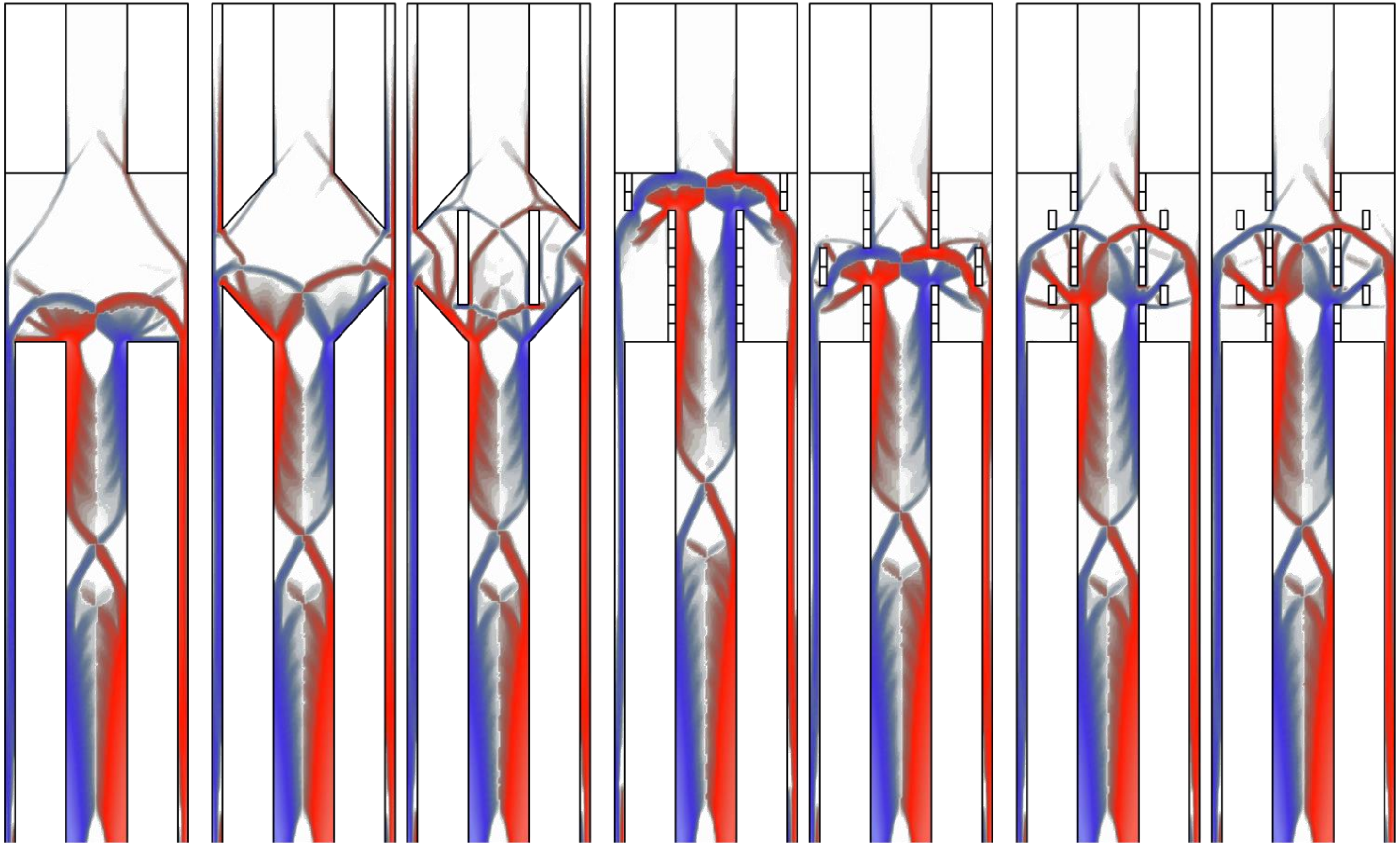
# OPTIMIZATION

## DESIGN DOMAIN



# OPTIMIZATION

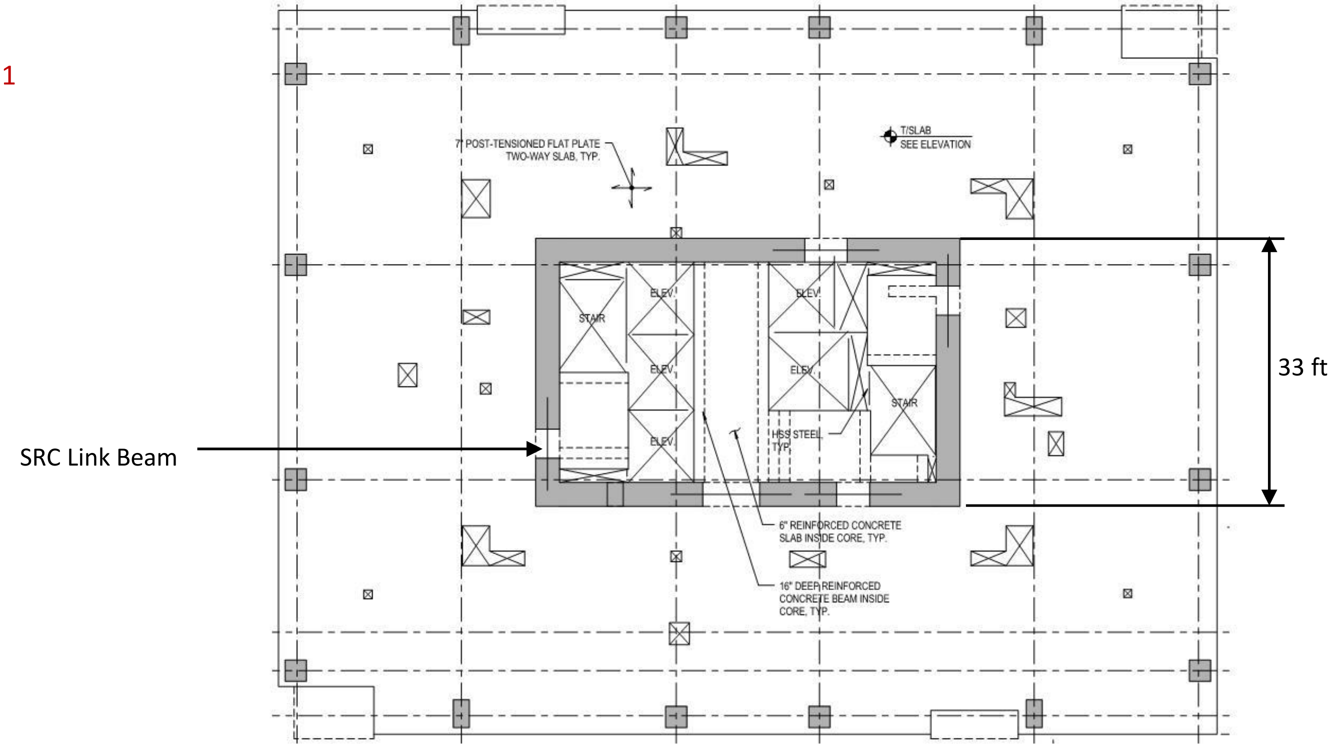
## FLOW



# TOWER PLAN

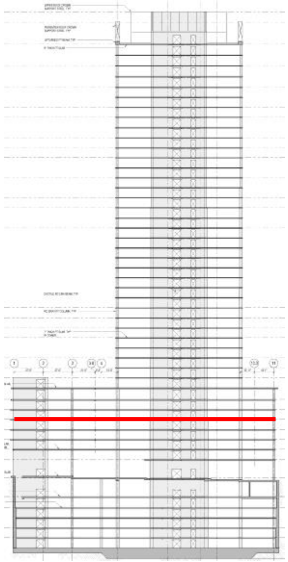
## DETAILED DESIGN

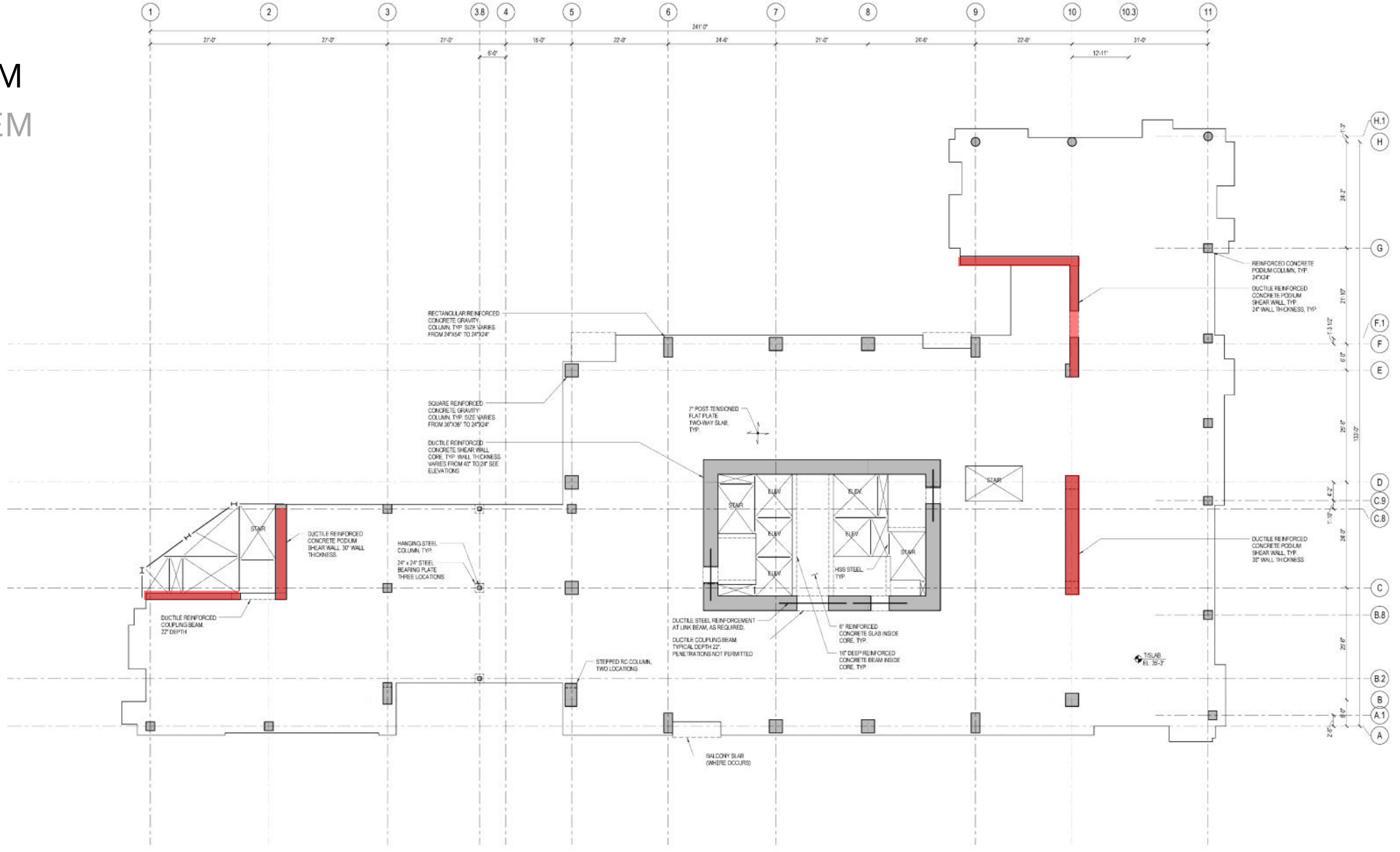
Core to Height Aspect Ratio: 12 : 1



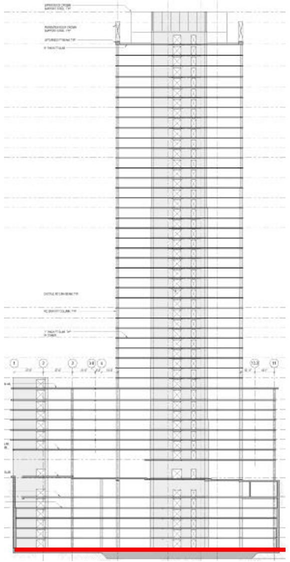
# TYPICAL PODIUM

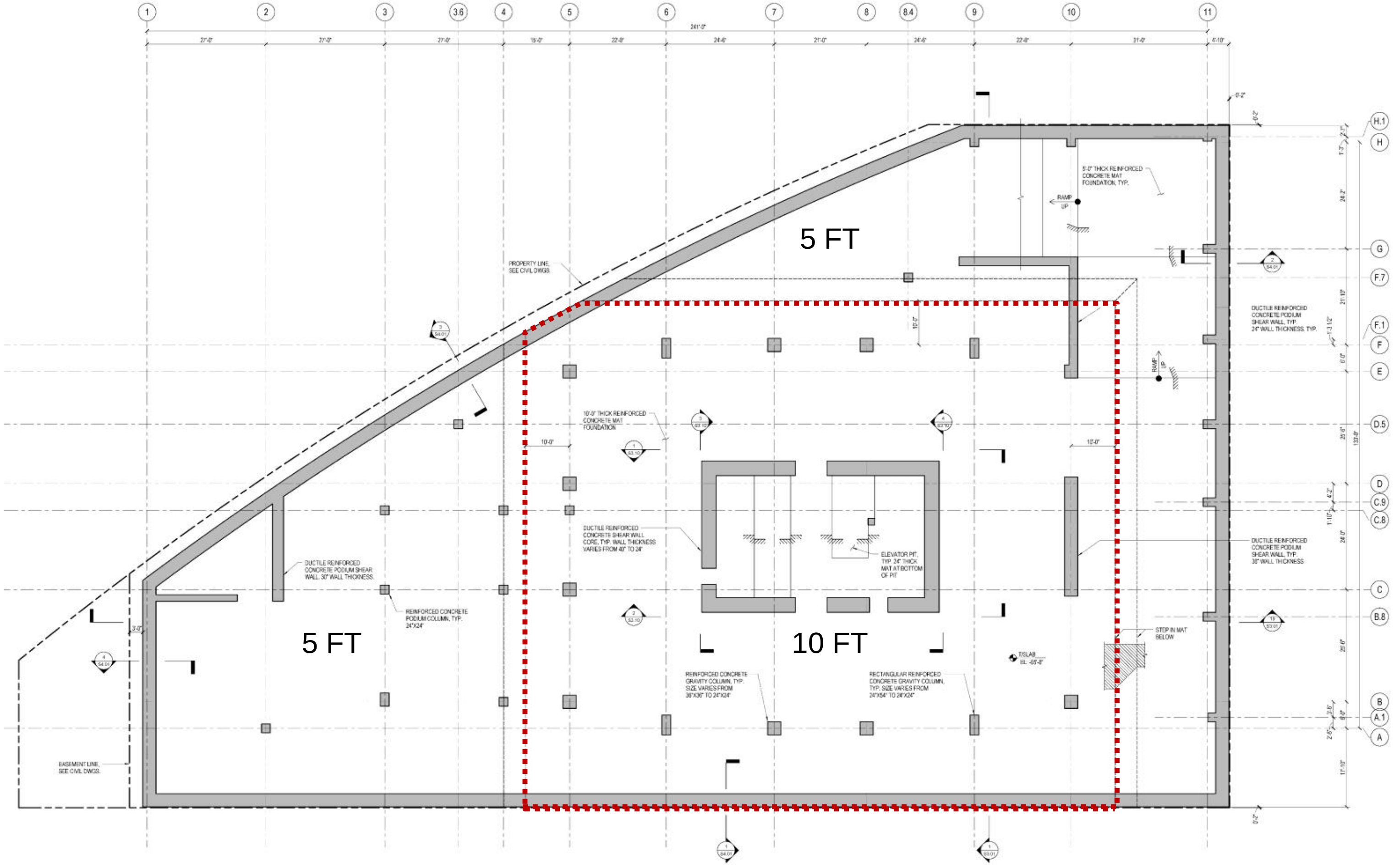
## LATERAL SYSTEM





# FOUNDATION




5 FT
5 FT
10 FT
PROPERTY LINE, SEE CIVIL DWGS.
EASEMENT LINE, SEE CIVIL DWGS.
STEP IN MAT BELOW

# TOWER PLAN

## CONSTRUCTION DOCUMENTS

### KEY PARAMETERS

Aspect Ratio: 12 : 1

Slabs

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

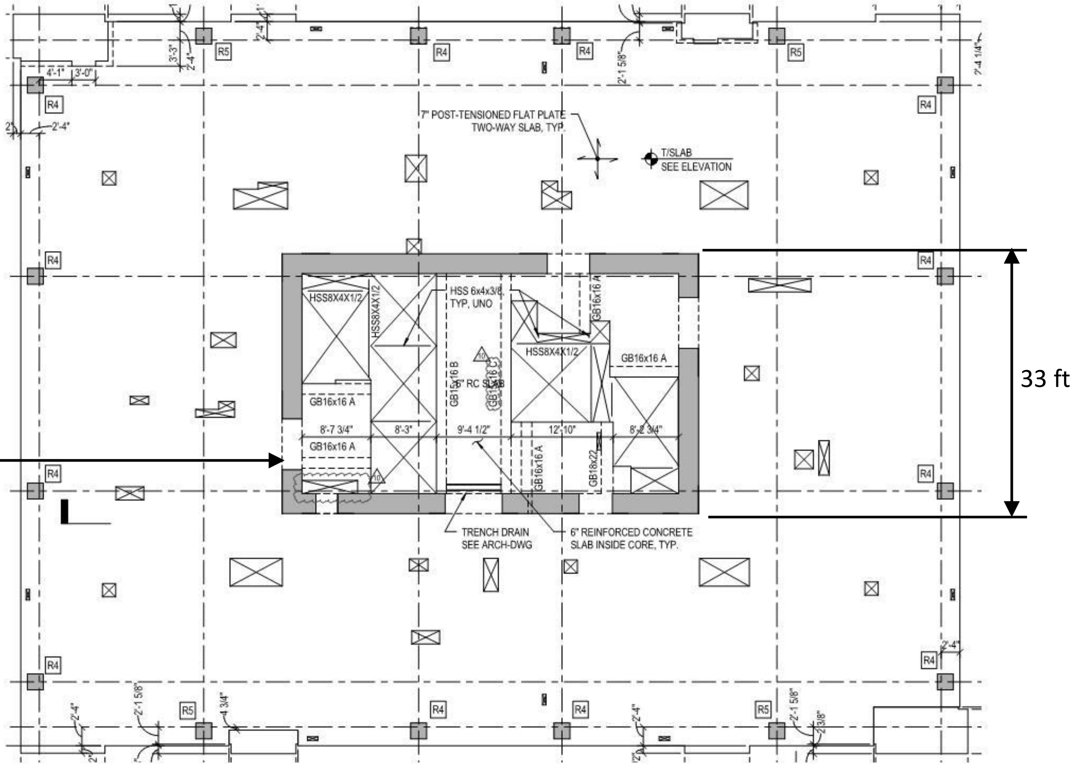
Shear Walls

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

Link Beams

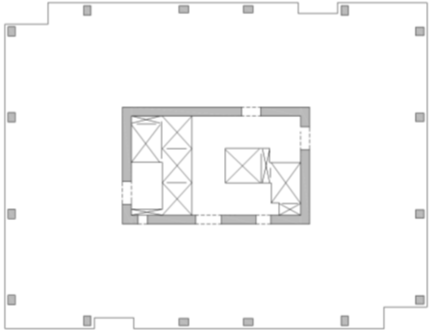
- Depth: 22”, 18”
- Diagonally reinforced

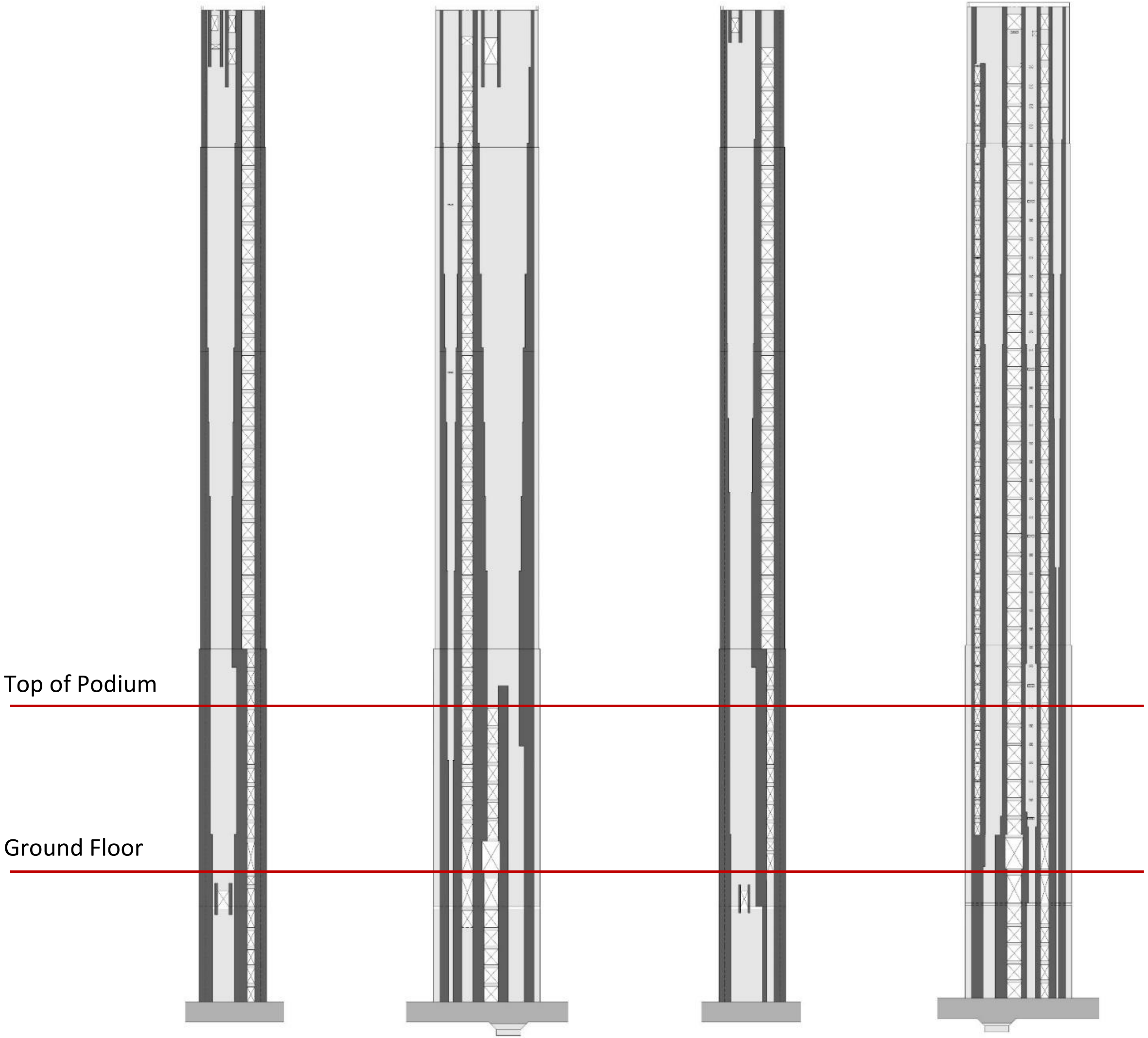
Longer, diagonally reinforced link beam



# TOWER CORE

## ELEVATIONS





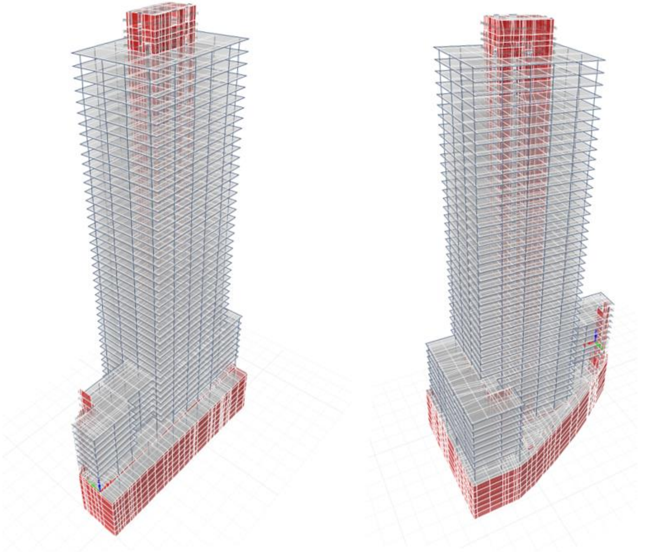
# DESIGN SUMMARY

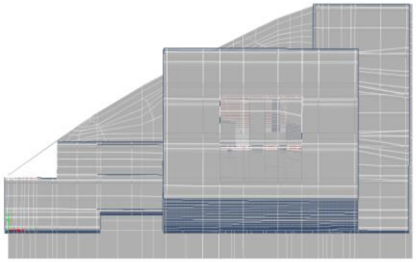
## BUILDING CHARACTERISTICS

### Modal Summary

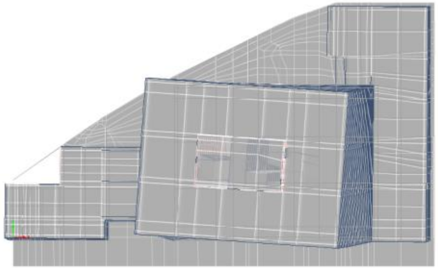
Well defined modes between translation and torsion

| Mode | Period [s] | UX | UY | RZ |
|---|---|---|---|---|
| 1 | 5.8 | 0.00 | 0.38 | 0.00 |
| 2 | 4.3 | 0.38 | 0.00 | 0.01 |
| 3 | 2.6 | 0.01 | 0.00 | 0.18 |
| 4 | 1.2 | 0.00 | 0.15 | 0.00 |
| 5 | 1.0 | 0.11 | 0.00 | 0.03 |
| 6 | 0.8 | 0.06 | 0.00 | 0.09 |

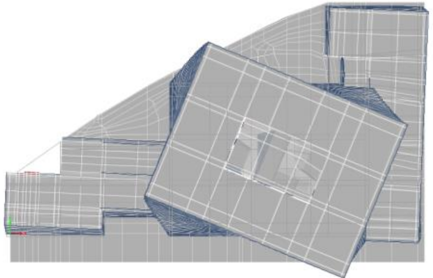




Mode 1



Mode 2



Mode 3

# DESIGN SUMMARY

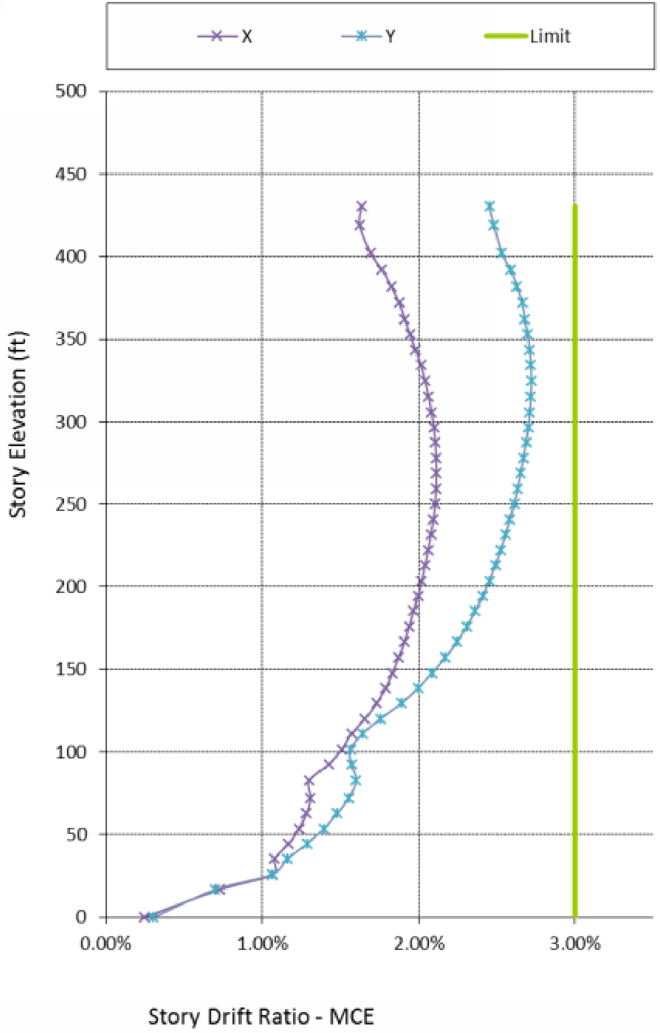
## LINEAR CODE-BASED DESIGN

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 & $MCE_R$)

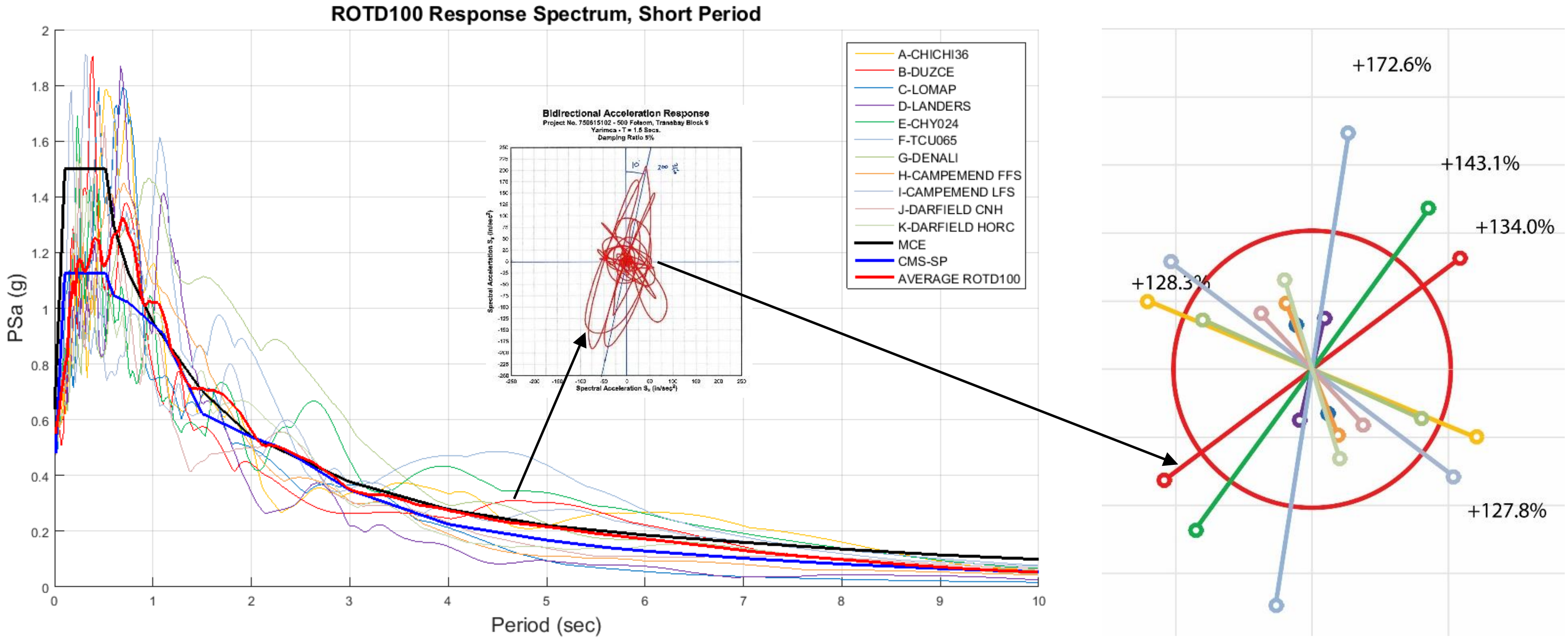
- Detailed ETABS model w/site-specific response spectrum loading
- Drift and global code checks satisfied (0.5% & 3%)
- All components satisfy code prescribed strength checks based on design criteria



# PERFORMANCE BASED DESIGN

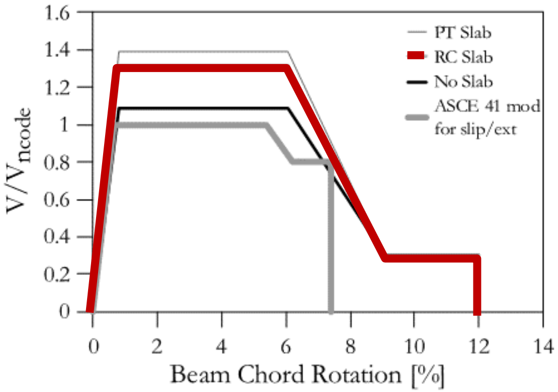
## GROUND MOTIONS - COMPASS

- Ground motion evaluation

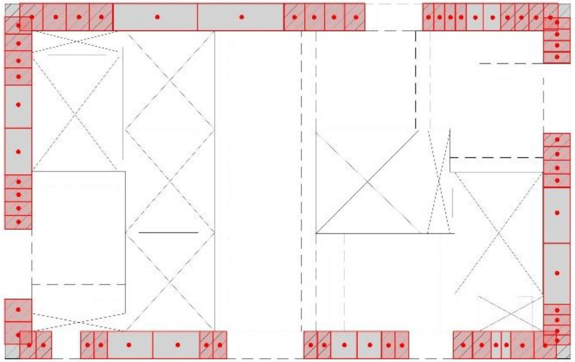


# NONLINEAR MODELING

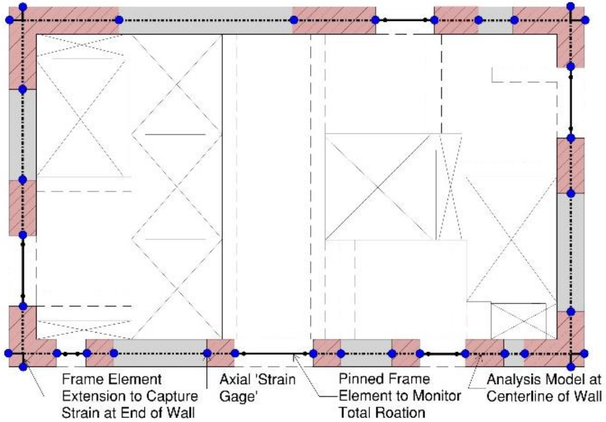
## DETAILED APPROACH



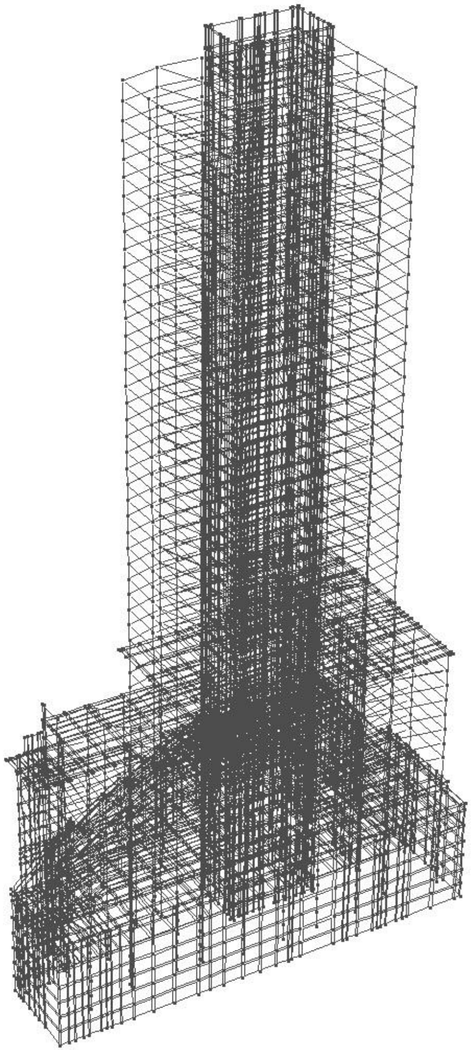

Link Beam Modeling: w/RC Slab



Wall Fiber Arrangement




Deformation Gages



# PROPORTIONING

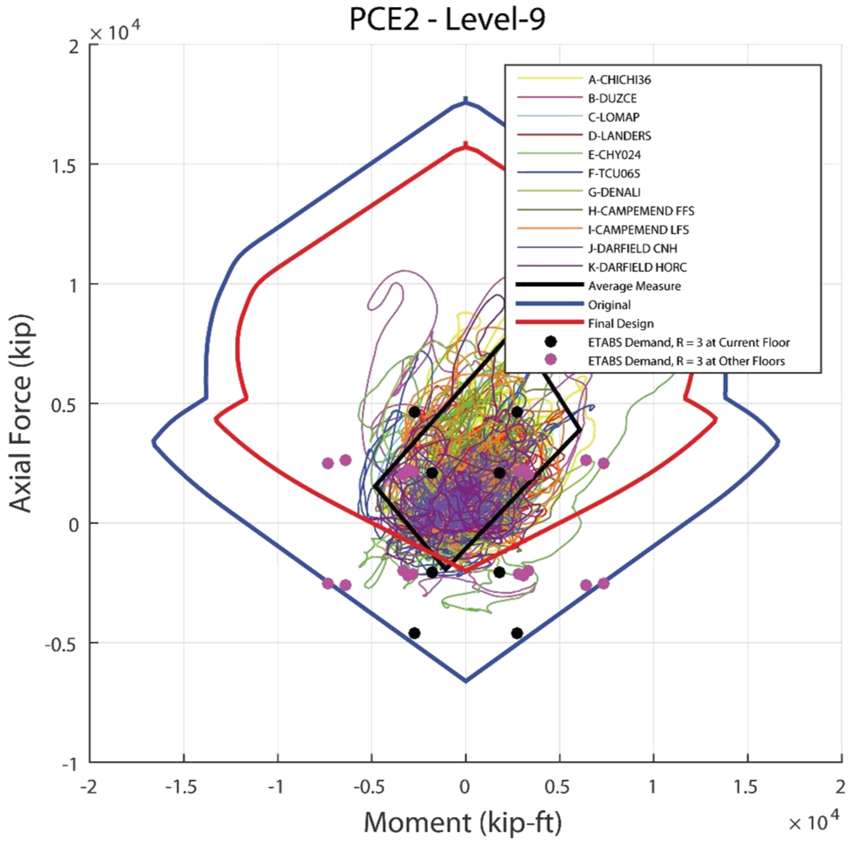
## REINFORCEMENT LEVEL ASSESSMENTS

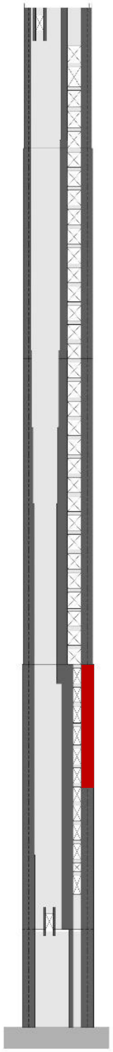
Compare of axial-moment demands of response spectrum and nonlinear time history analysis.

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

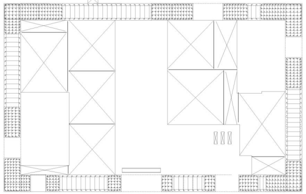
- Modest/Low yielding R = 5.0
- Higher yielding (hinge) R = 7.5



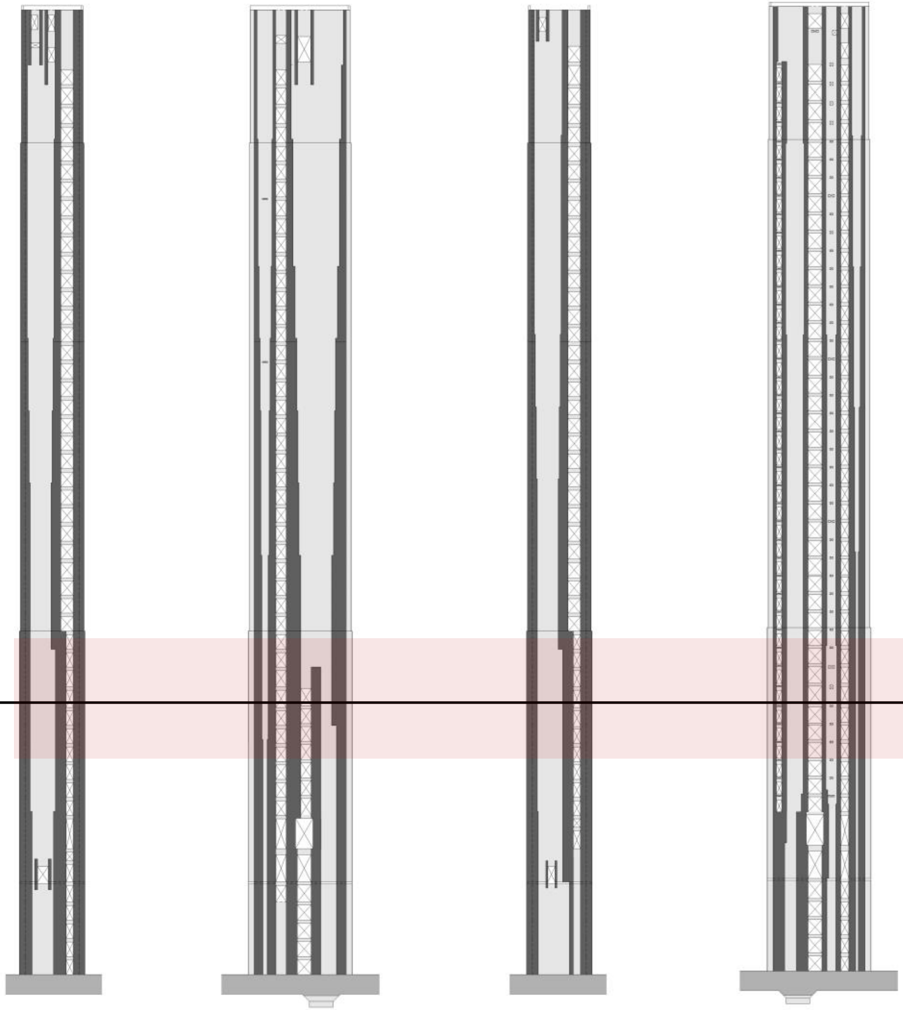
CORE

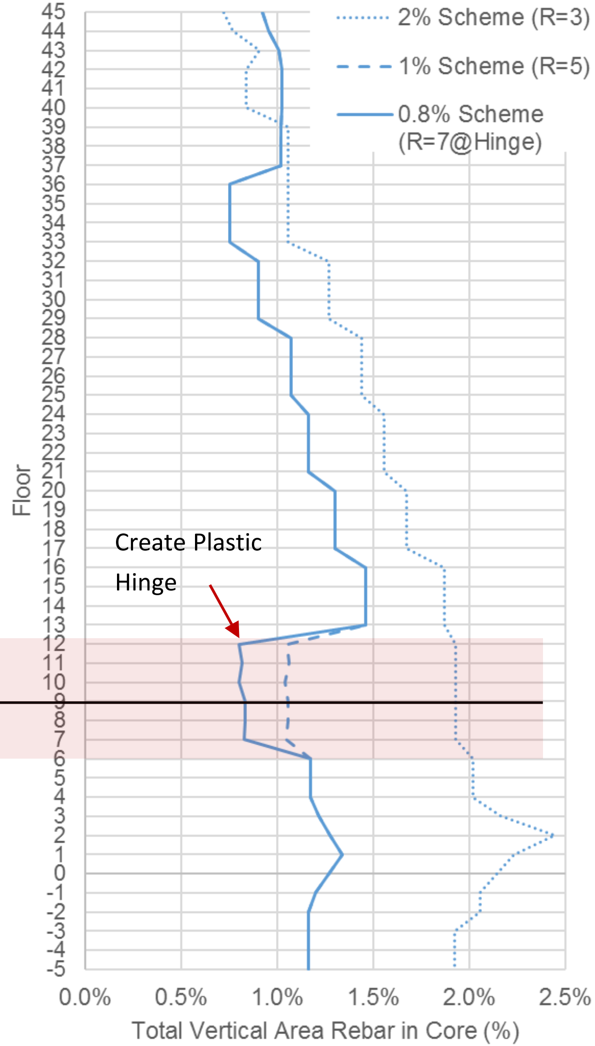
HINGE



LEVEL 9

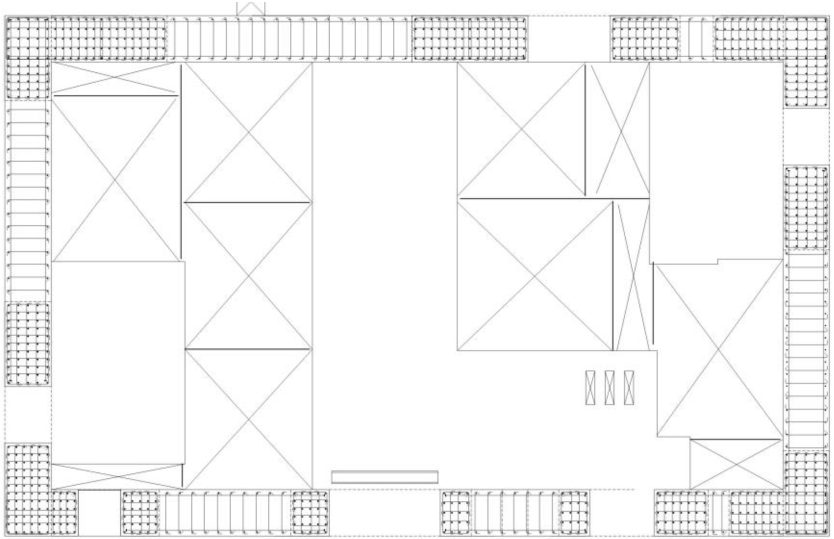
TOP OF PODIUM



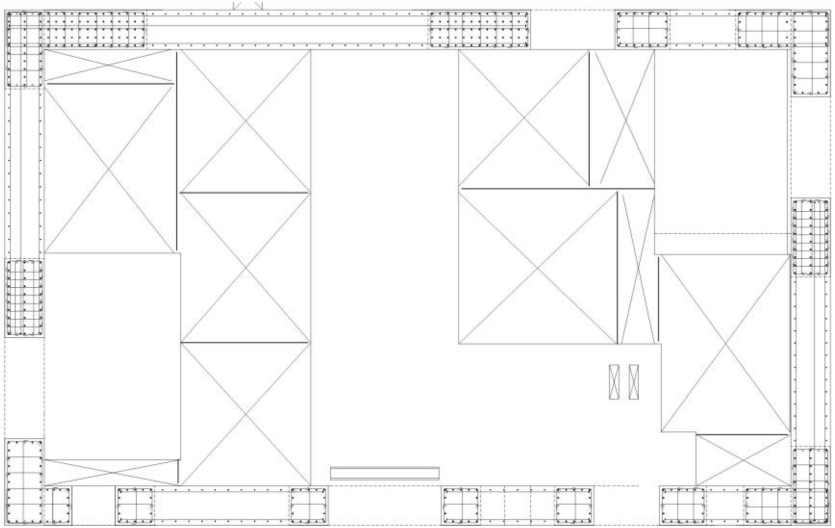


# CORE

## HINGE



Original design using RS analysis

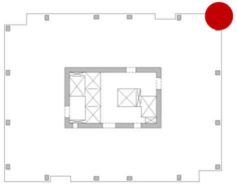


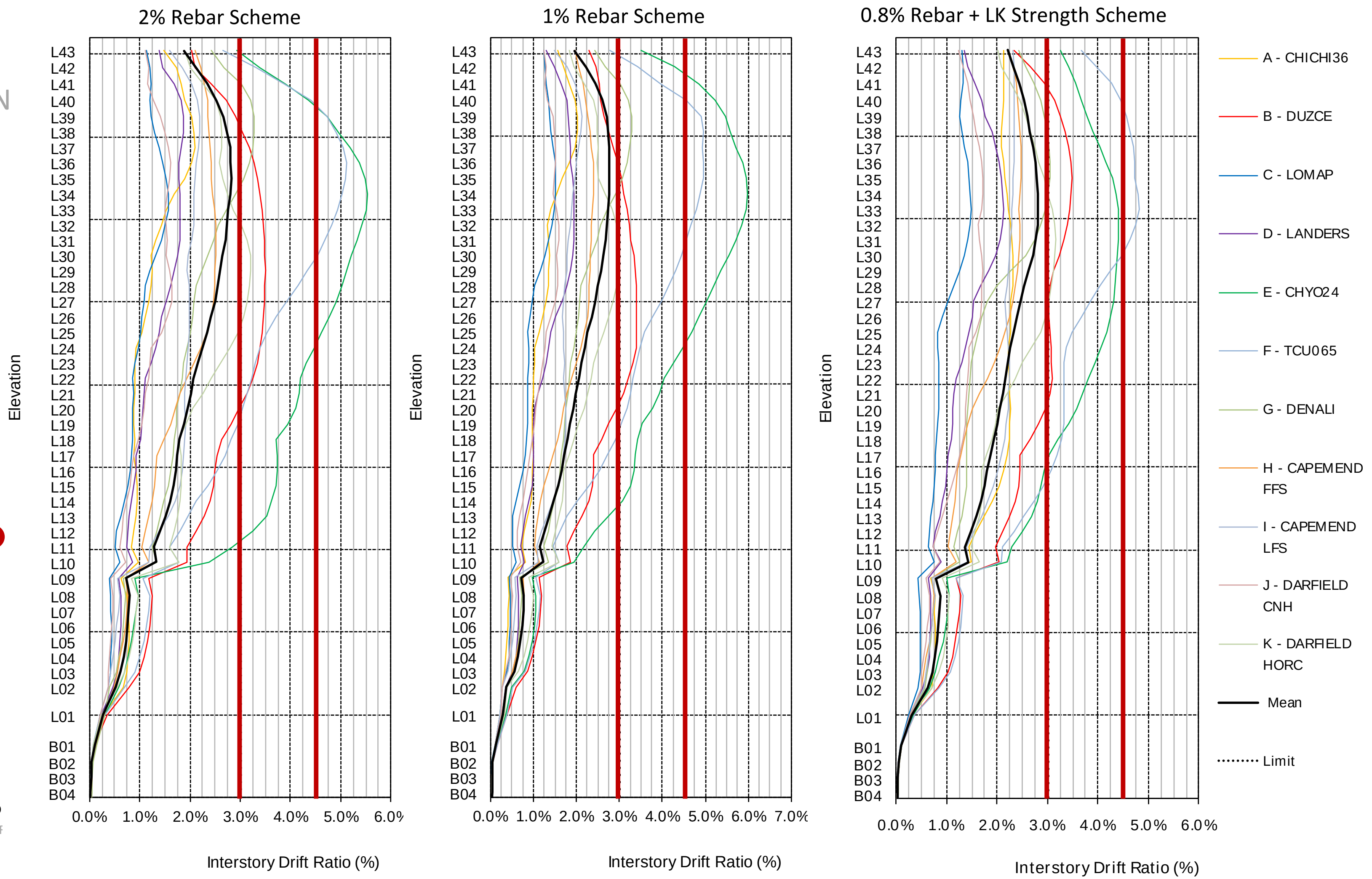
Reinforcement design using NLRH results

(~ 500’000 $)

# DRIFTS

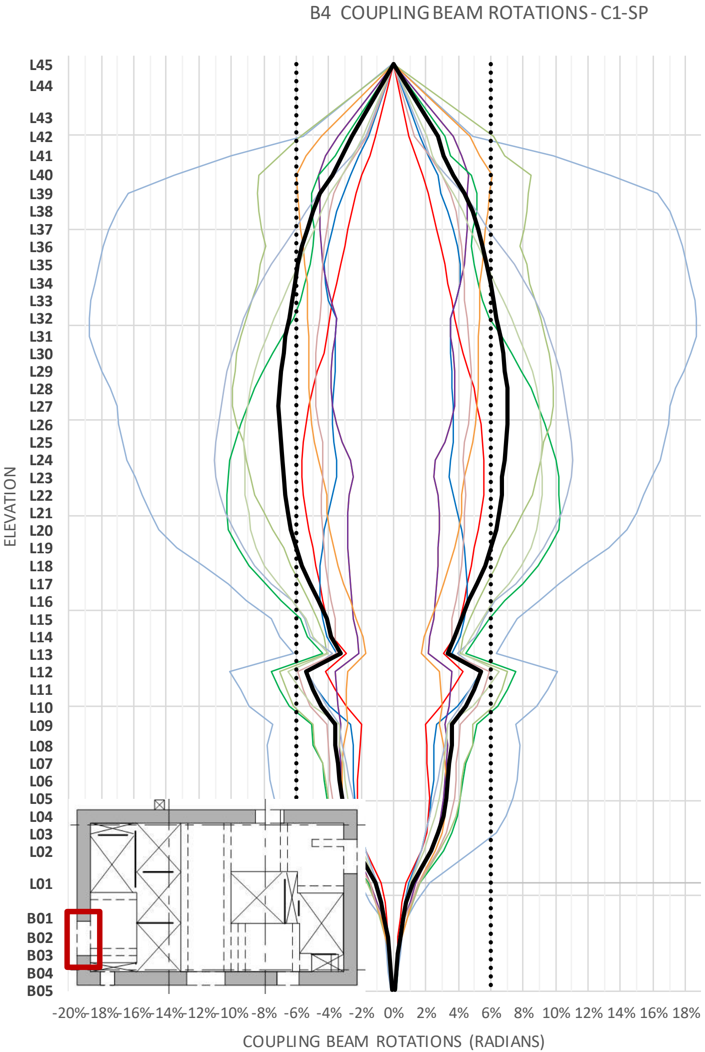
## Y-DIRECTION

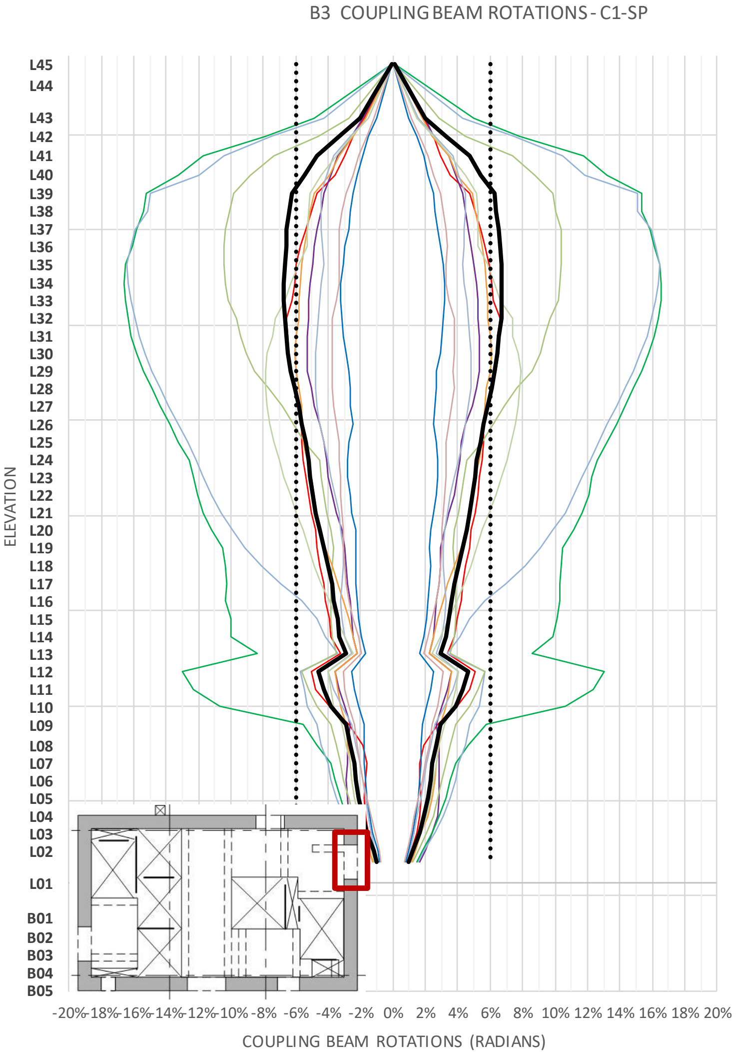




# LINK BEAM

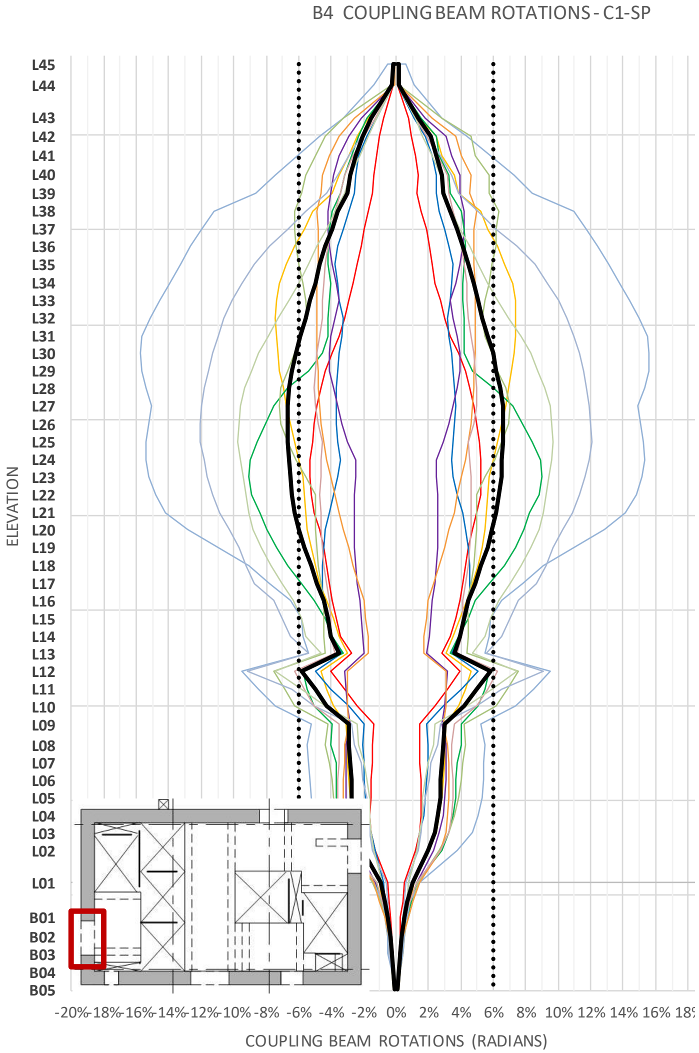
## 2% REBAR SCHEME

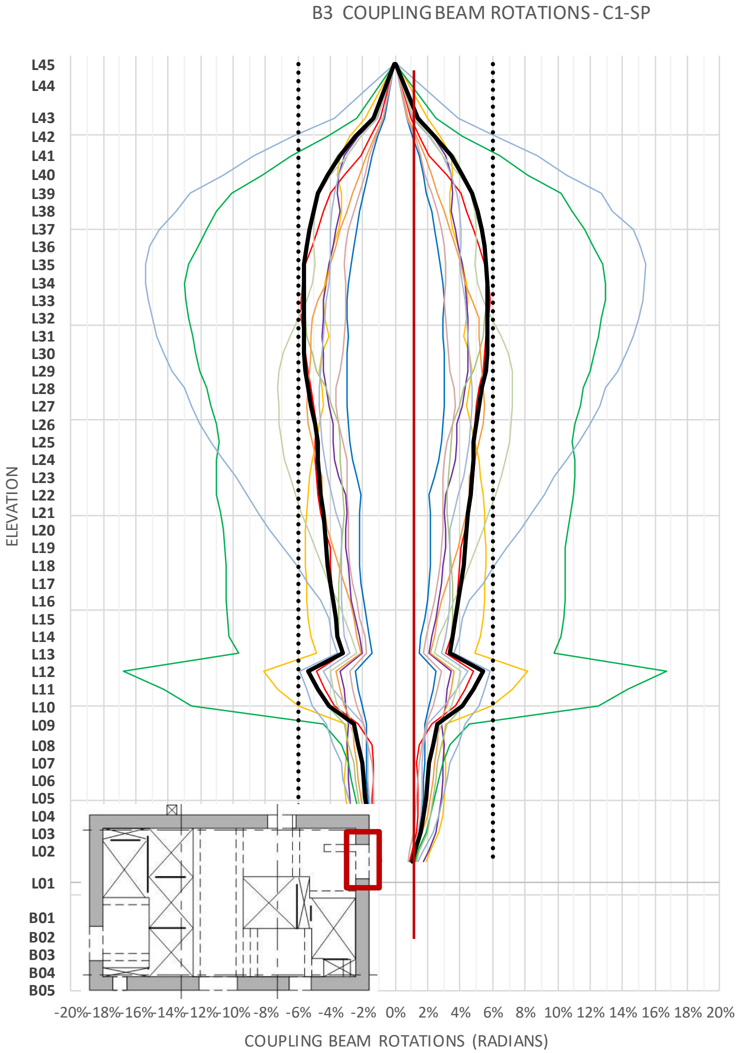


# LINK BEAM

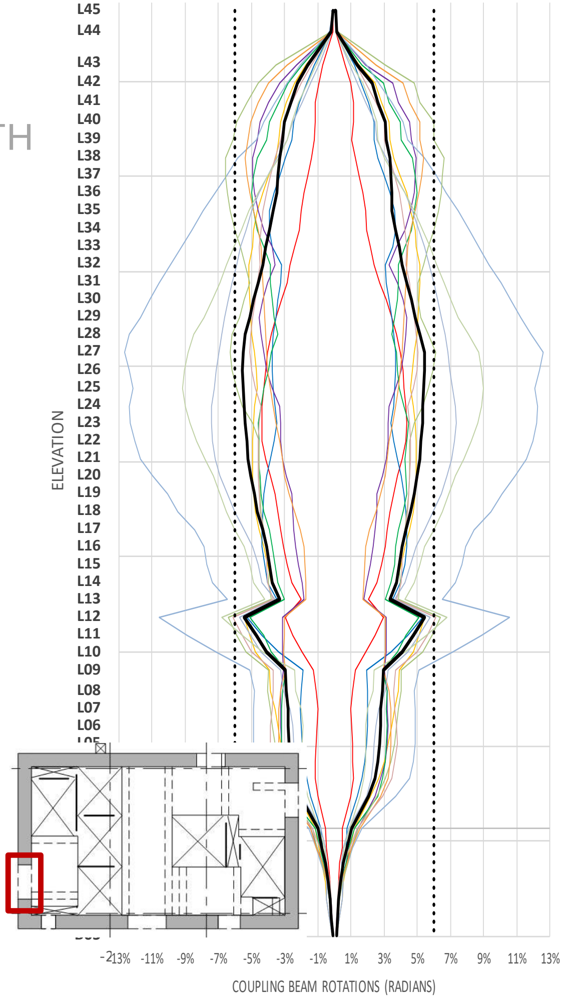
## 1% REBAR SCHEME

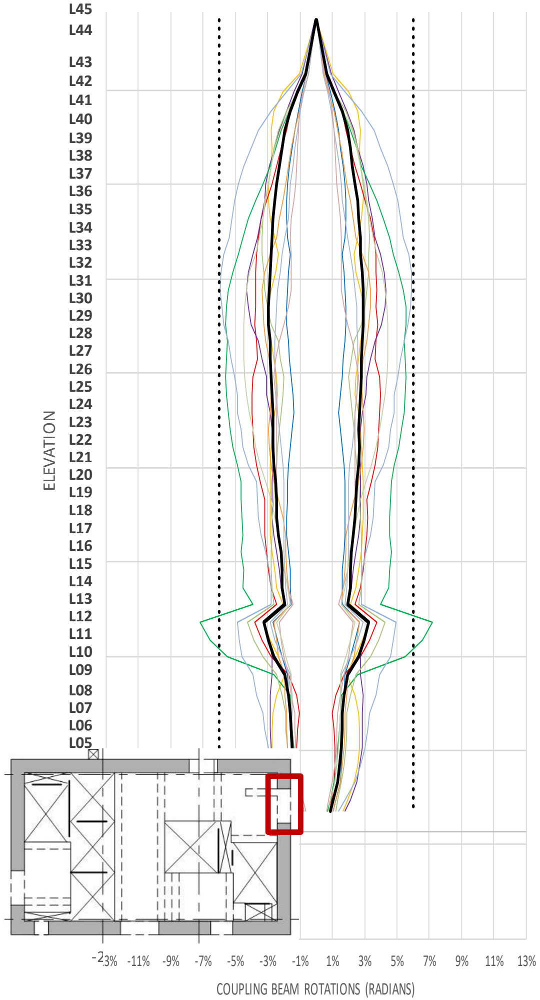


# LINK BEAM ROTATIONS

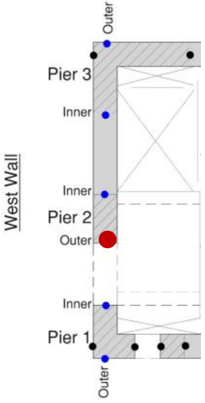
## 0.8% REBAR SCHEME + INCREASE LK STRENGTH

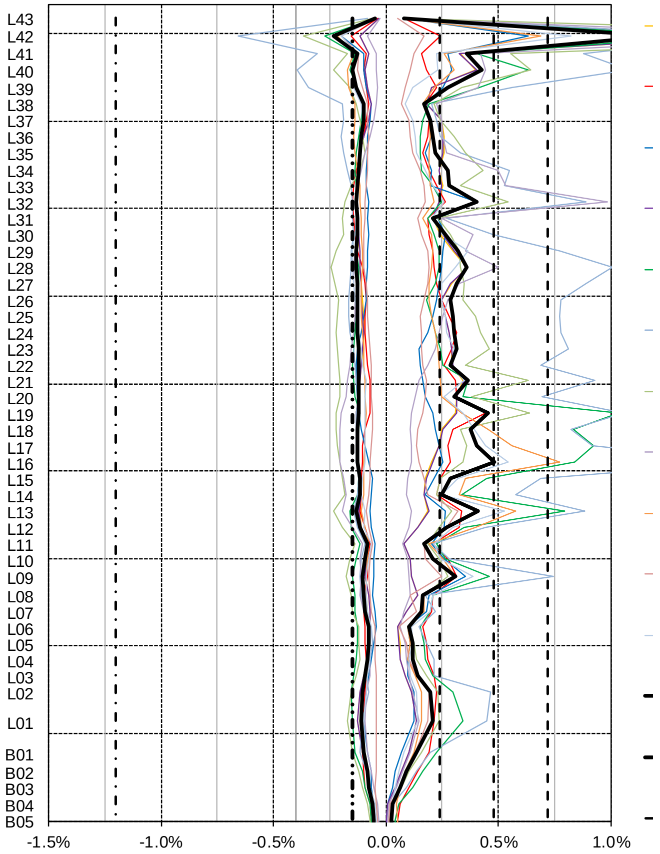


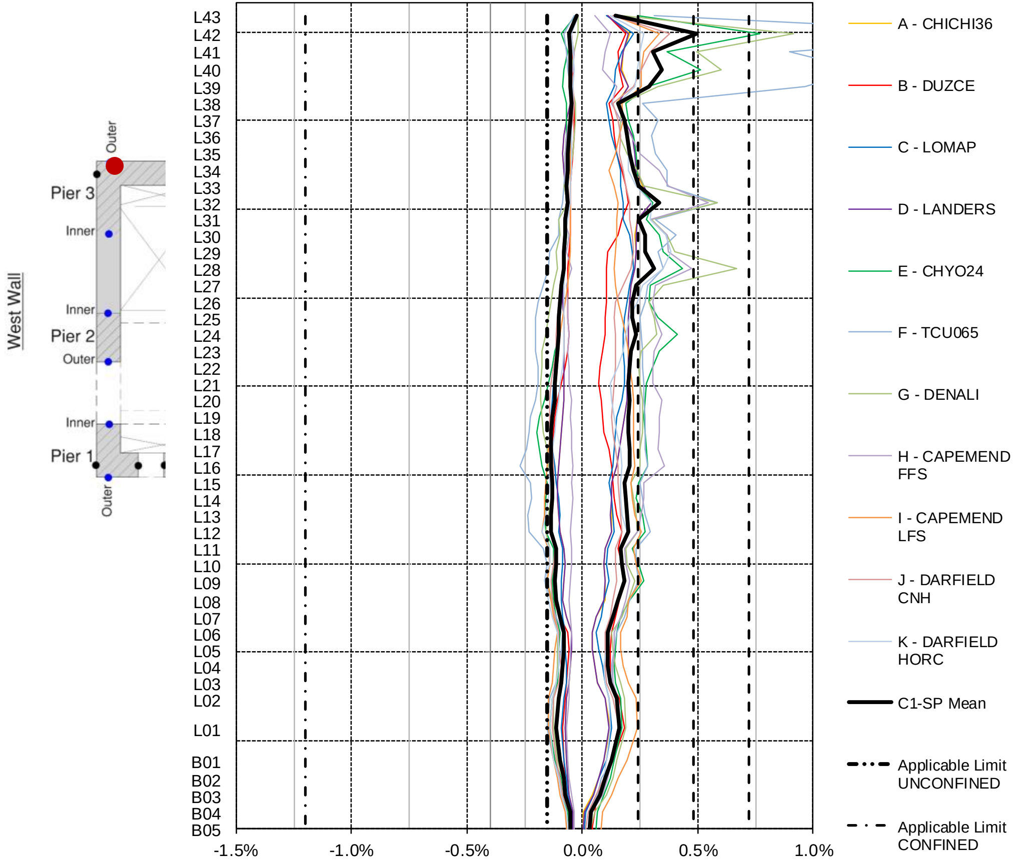



# STRAIN DEMANDS

## 2% REBAR SCHEME

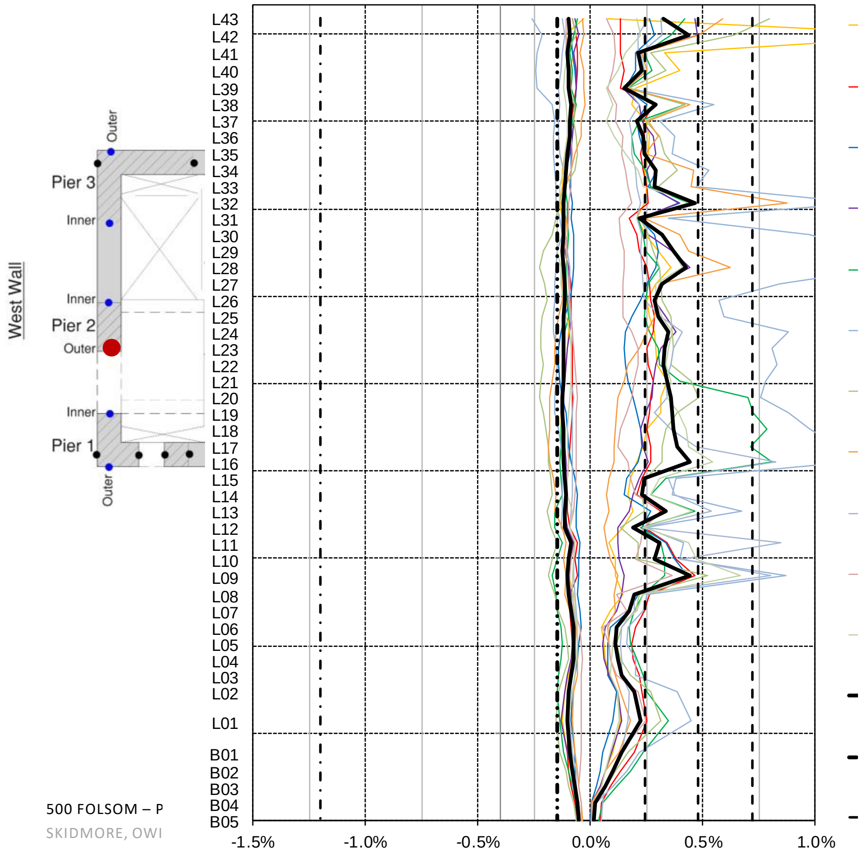


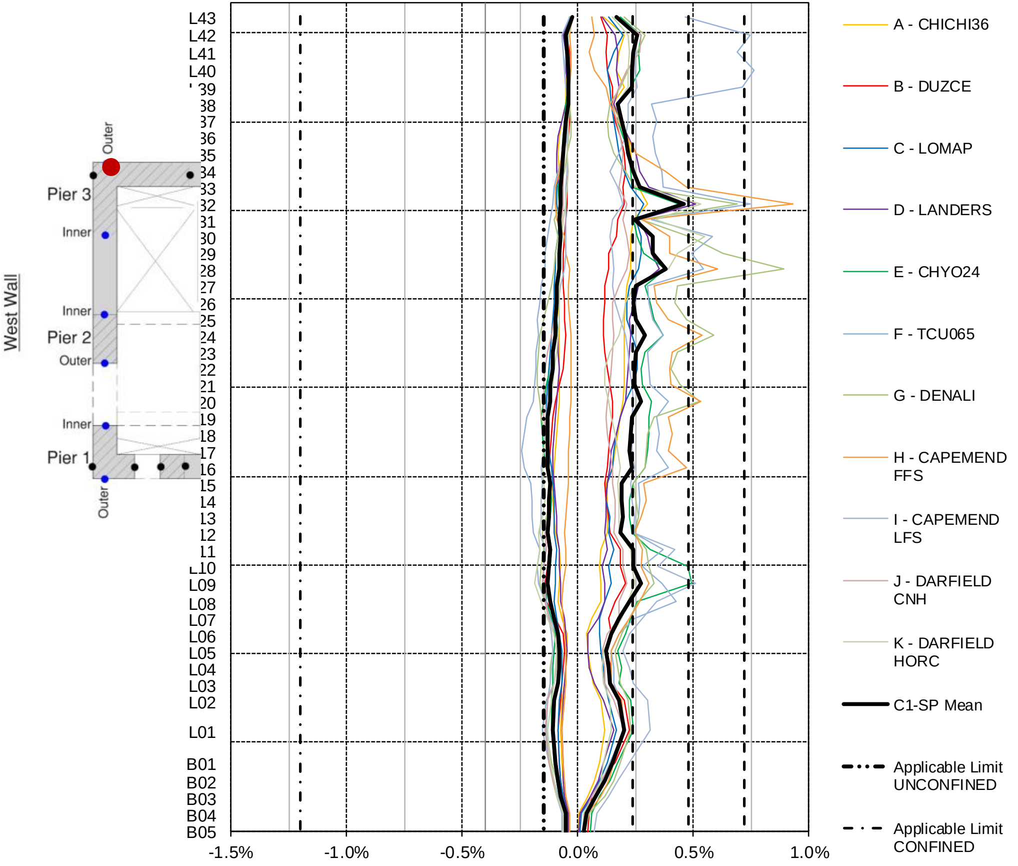



# STRAIN DEMANDS

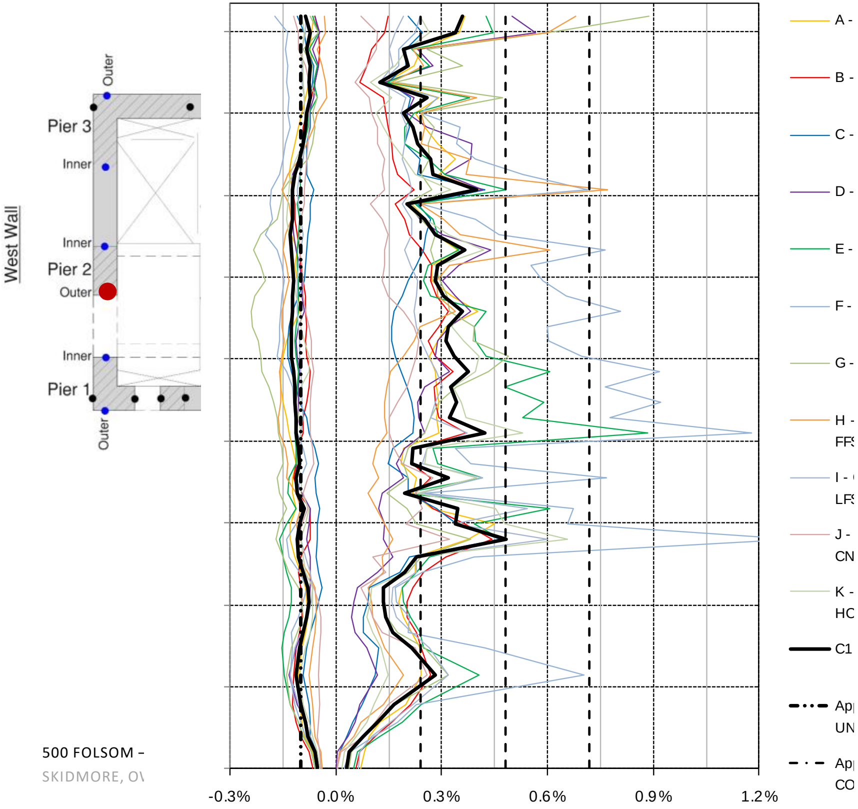
## 1% REBAR SCHEME

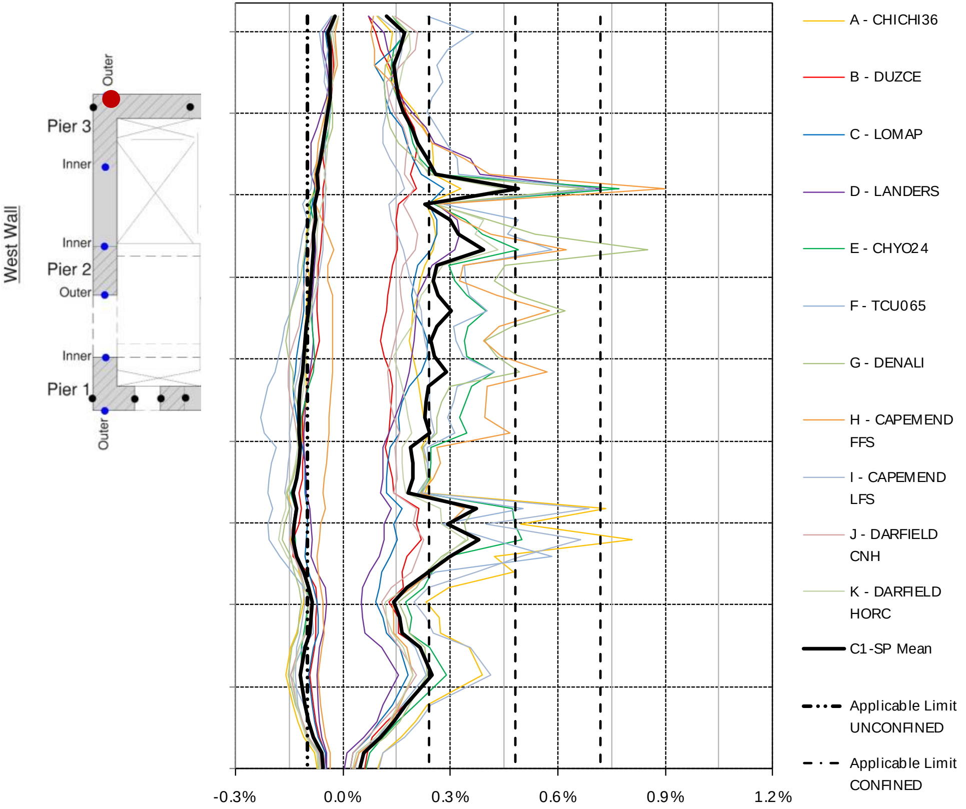


# STRAIN DEMANDS

## 0.8% REBAR SCHEME + INCREASE LK STRENGTH



# STRAIN DEMANDS

## CONFINEMENT BASED ON NLRHA

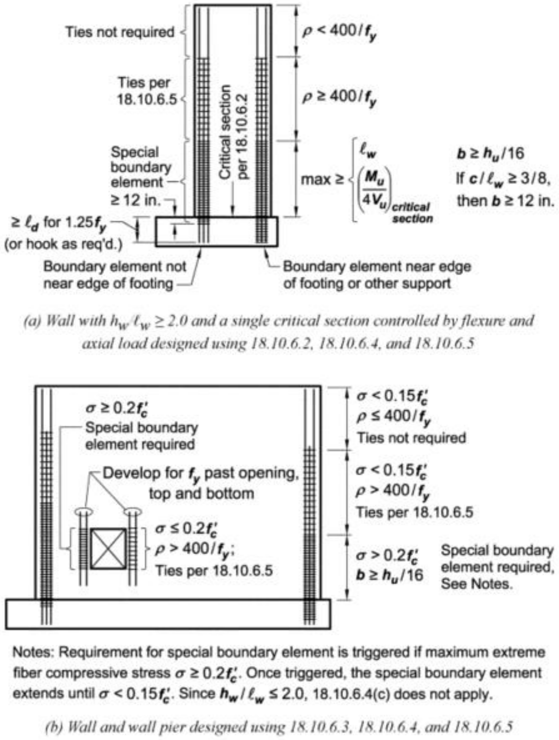
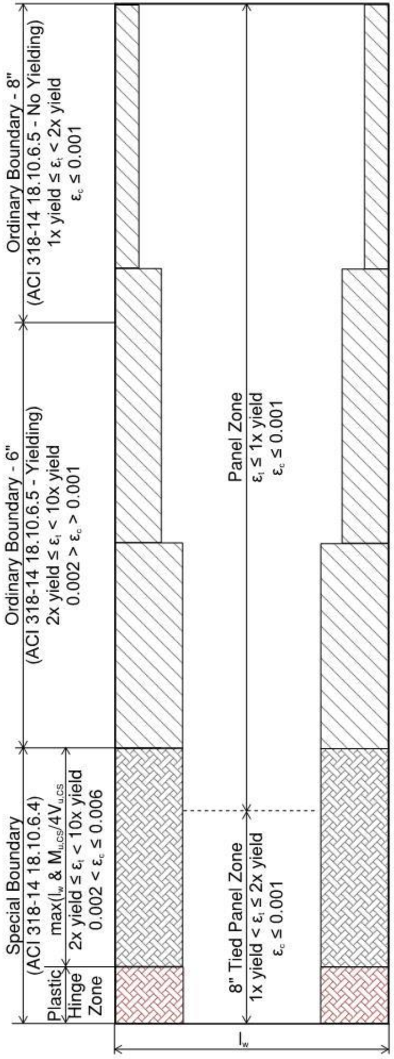
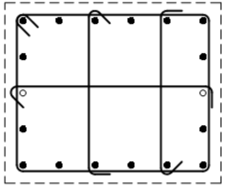
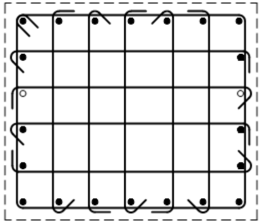



***Fig. R18.10.6.4.2**—Summary of boundary element requirements for special walls.*



Ordinary (6” or 8” tie spacing)



Special (4” or 5” tie spacing)

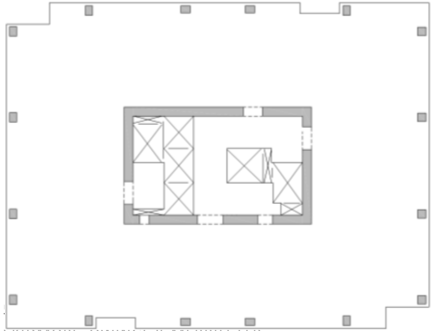
<u>Compressive Strain Limits</u>
Unconfined Limit = 0.003/2*/1.5** = 0.001
Ordinary Limit = 0.004/2* = 0.002
Special Limit = 0.013/2* = 0.006
*Reduction in limit by 2 per Wallace, 2007
**Reduction in limit by 1.5 due to force-controlled action

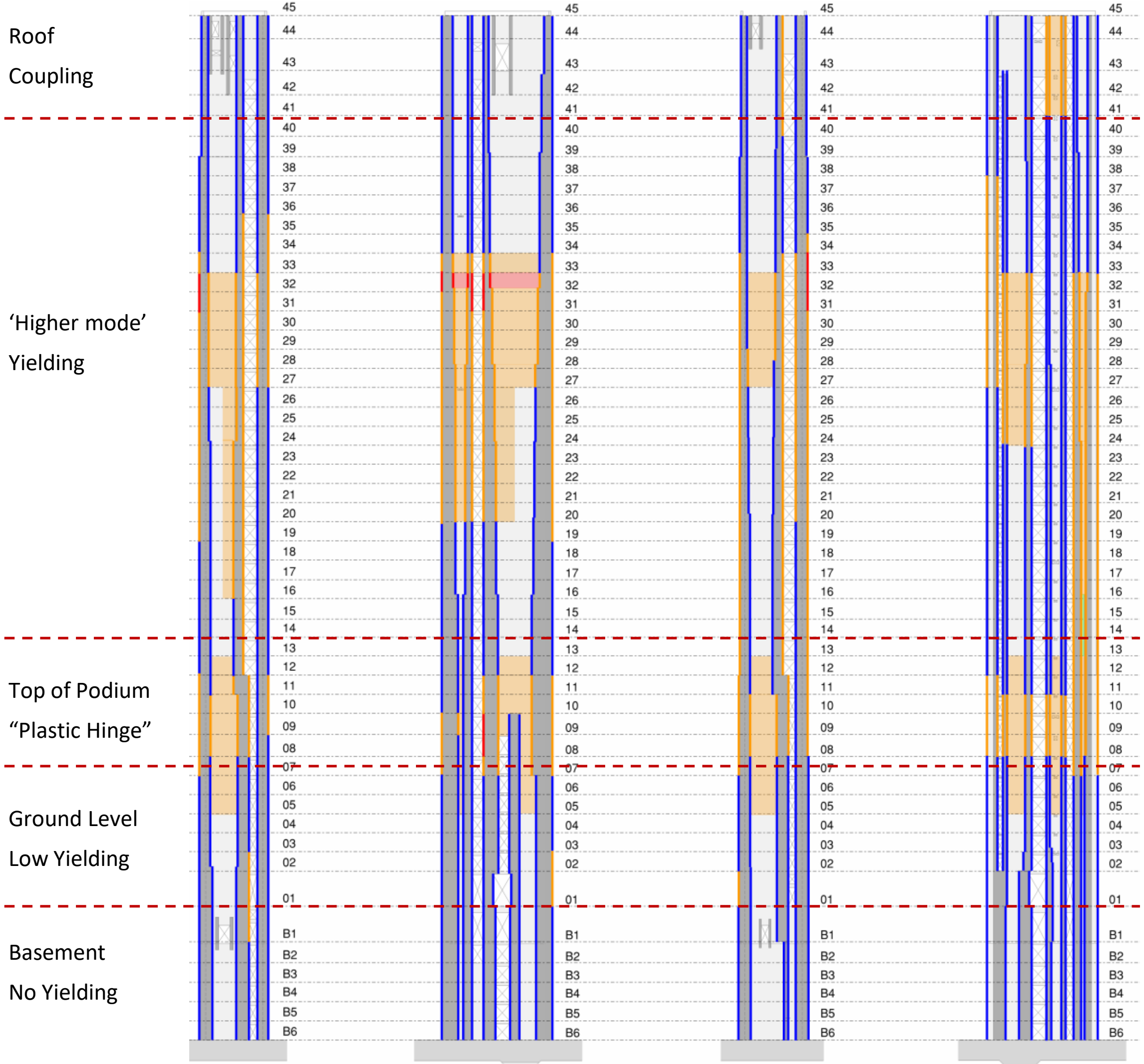
<u>Tensile Strain Limits</u>
Unrestrained bar limit = 1x yield
8" spacing bar restraint = 2x yield
6" spacing bar restraint = 10x yield

# STRAIN DEMANDS

## APPLIED TO CORE

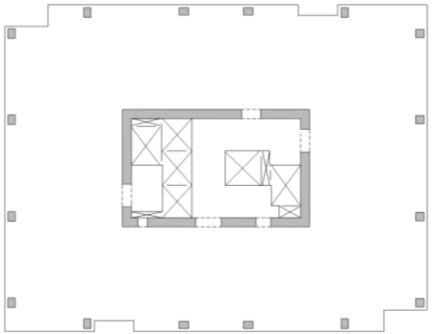
- $\varepsilon_t \leq$ 1x yield (blue)
- 1x yield $< \varepsilon_t \leq$ 2x yield (orange line)
- 2x yield $< \varepsilon_t$ (red line)
- Non-boundary 1x yield $< \varepsilon_t \leq$ 2x yield (orange fill)
- Non-boundary 2x yield $< \varepsilon_t$ (red fill)

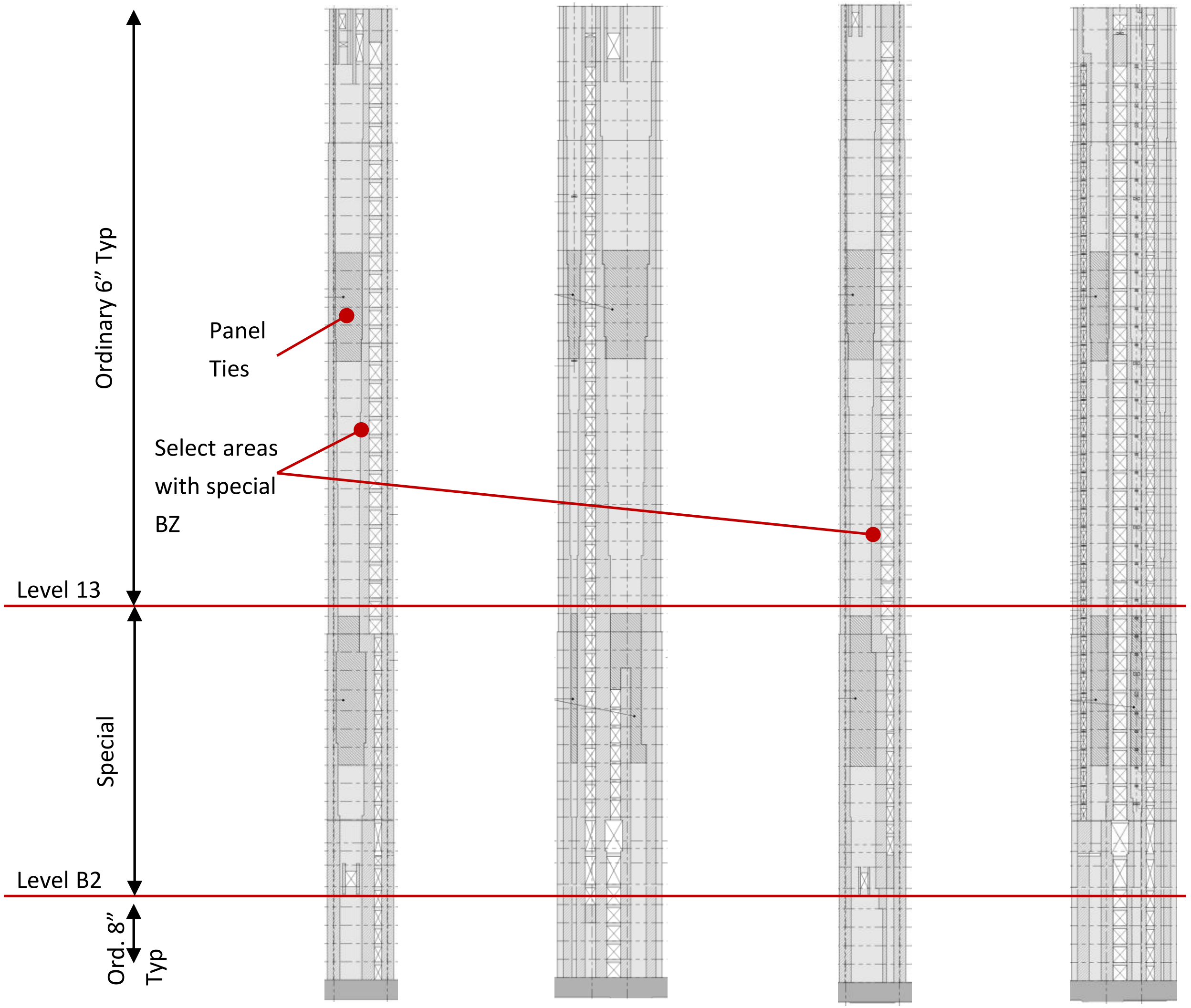




# STRAIN DEMANDS

## APPLIED TO CORE





# PANEL ZONES ABOVE/BELOW BAY OF LINK BEAMS

## NIST GCR 14-917-25

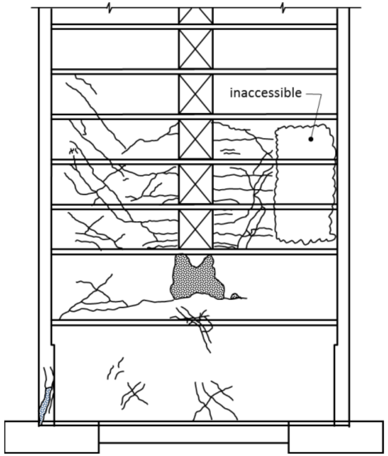



Figure C-1 Damage map from a building in Northern California damaged in the 1989 Loma Prieta earthquake (image courtesy of Jack Moehle).

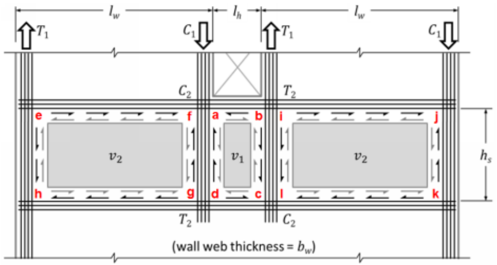
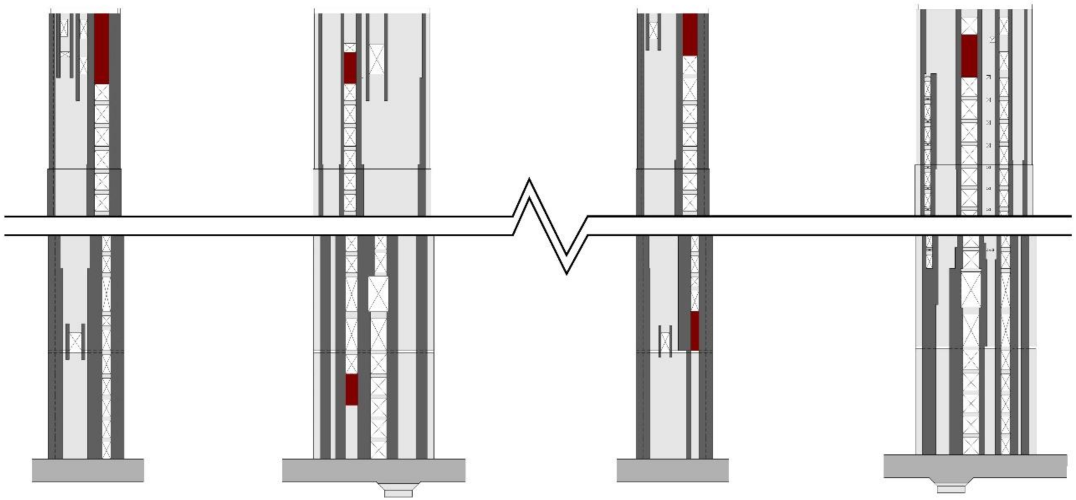



Figure C-11 Idealized resolution of basement wall forces beneath coupled walls.

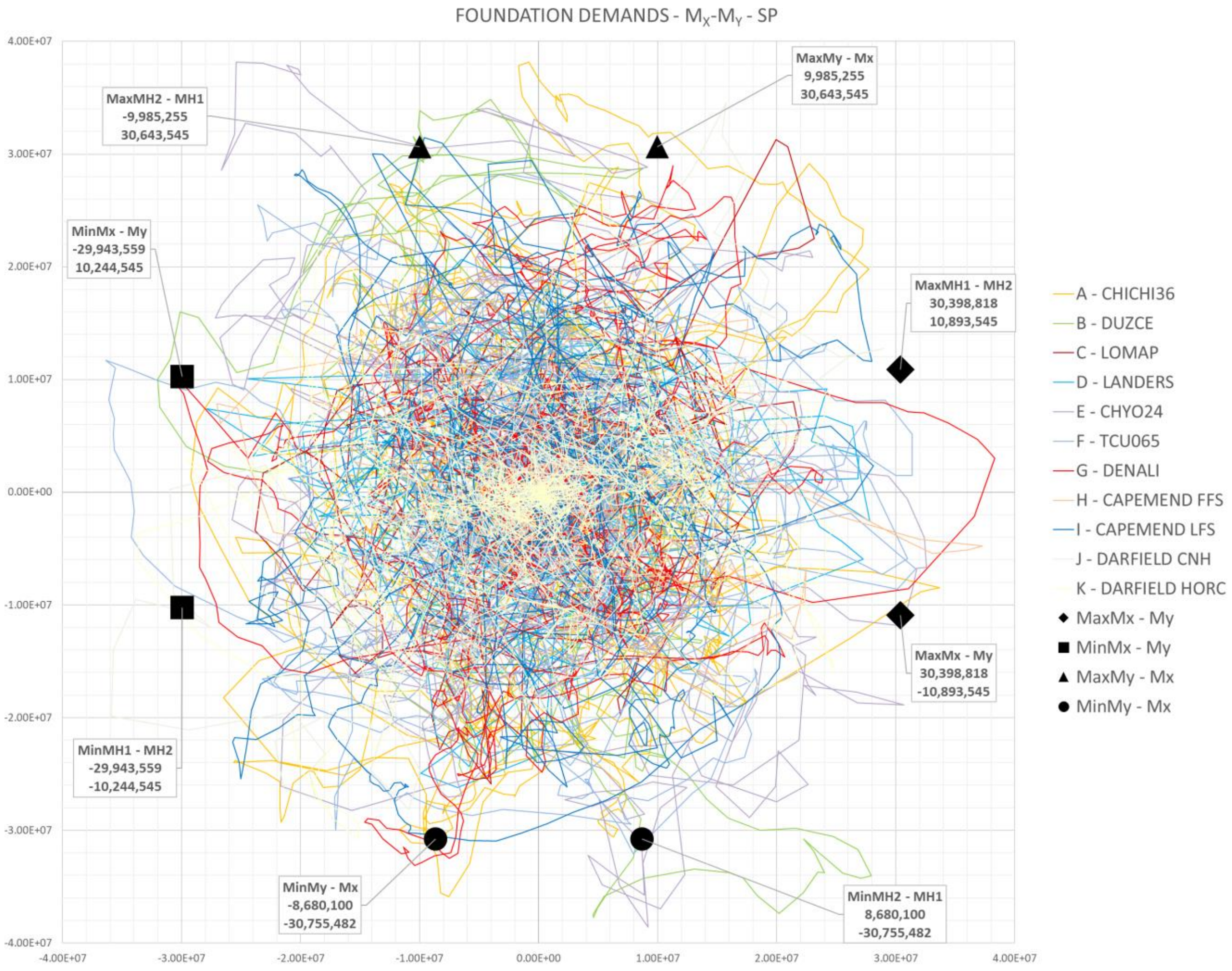


Design Load Cases

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

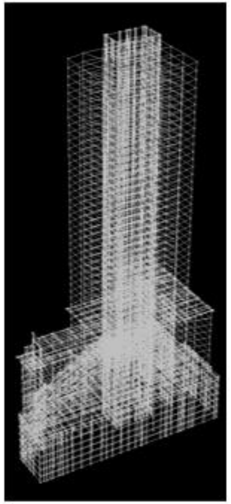
# FOUNDATION DESIGN

## BASED ON NLRHA



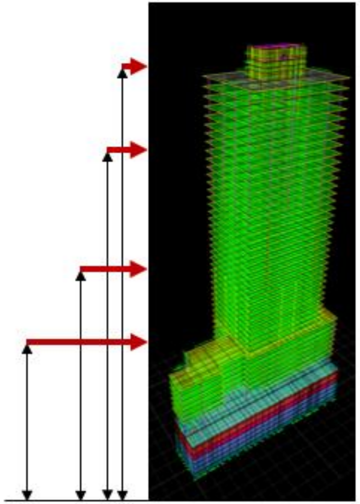
# FOUNDATION DESIGN

## BASED ON NLRHA



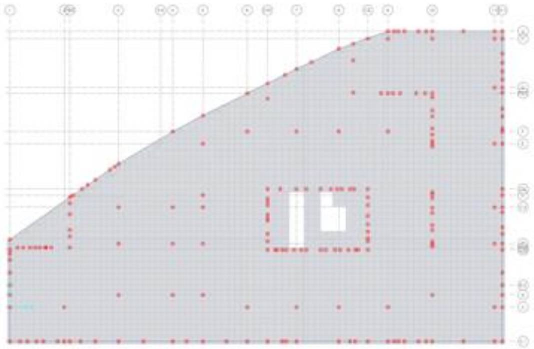
For long and short period suites obtain:

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.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