

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

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Tall Buildings in Regions of High Seismicity

One Rincon Hill - San Francisco



*Reinforced concrete
core walls for lateral
force resistance*

*Schematic of Lateral Force
Resisting System*



Damage in Tall Buildings in Recent Earthquakes

2010 M8.8 Chile Earthquake



Partial collapse of 21-story O'Higgins building, tallest in Concepcion, threatens the surrounding built environment. Courtesy of J. Restrepo.

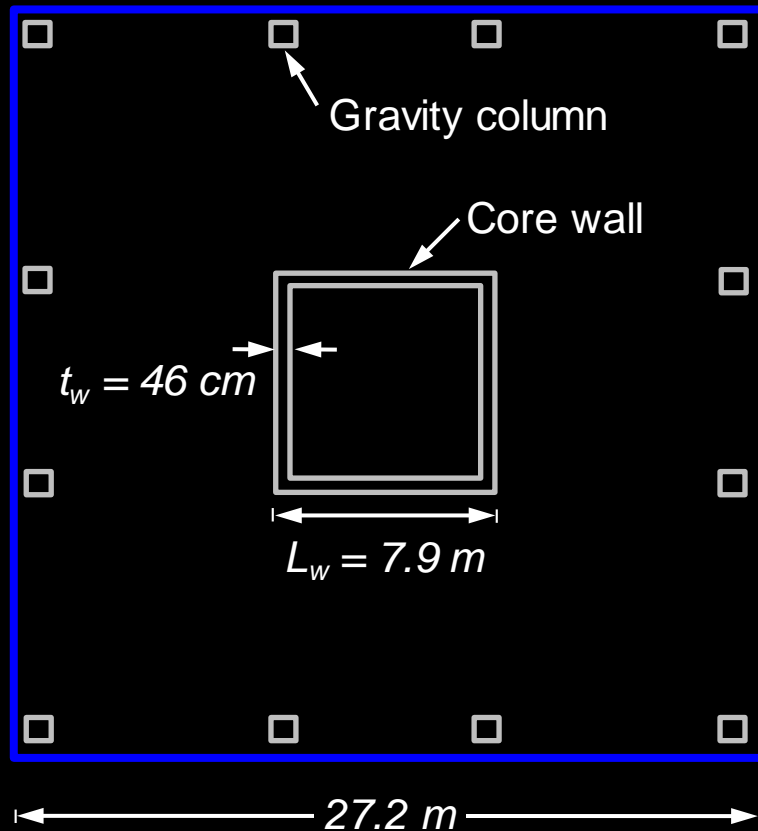
2011 M6.1 NZ Earthquake



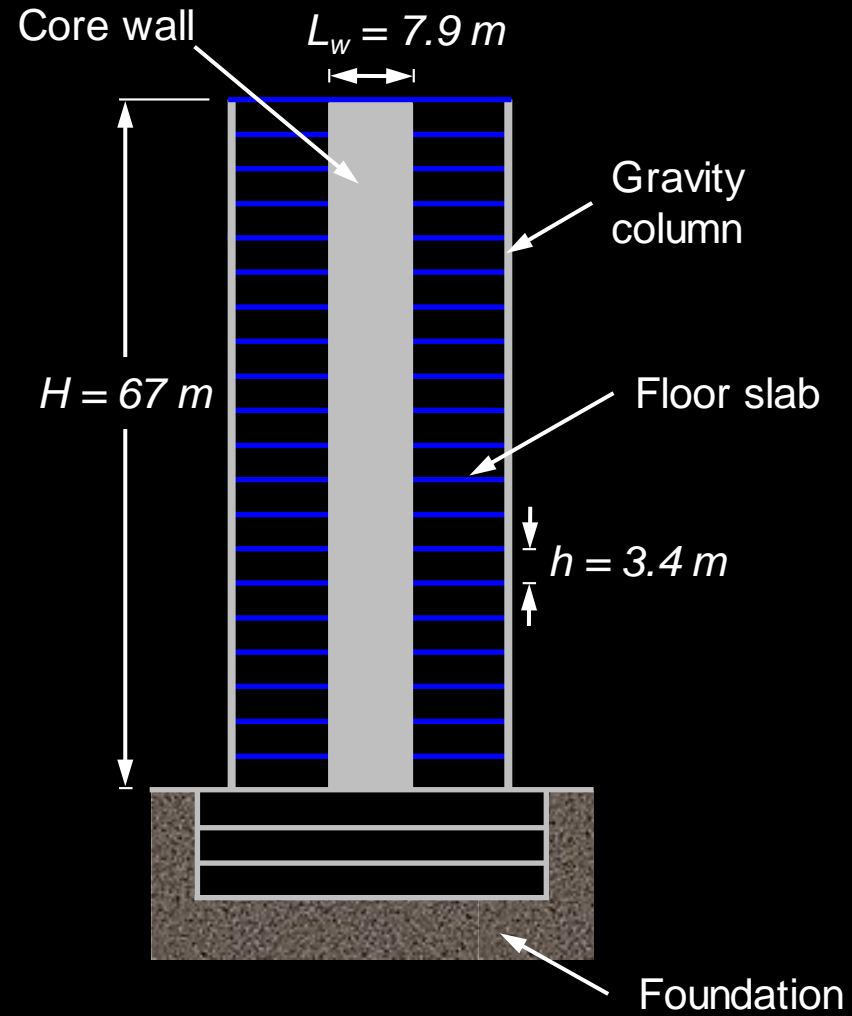
<http://en.wikipedia.org>

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

20-story Building Layout



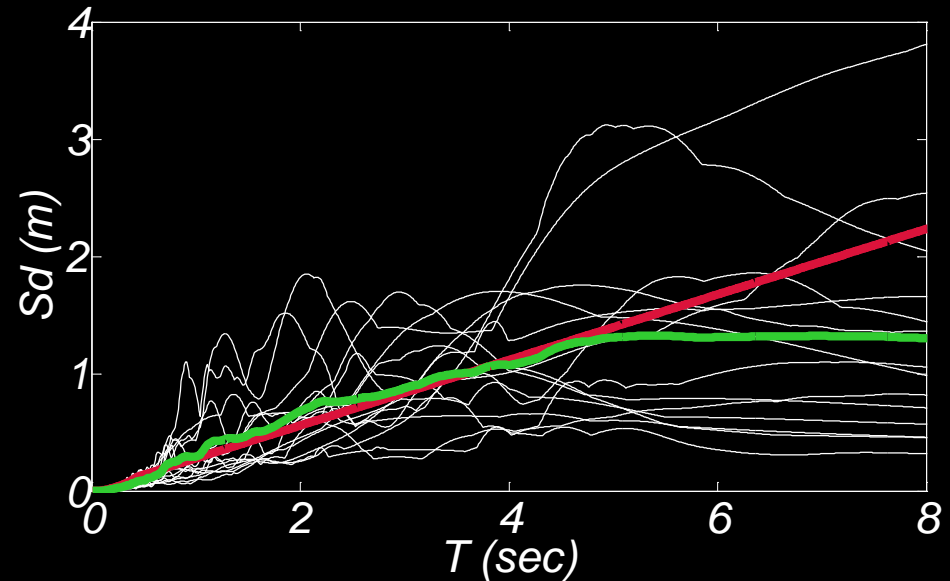
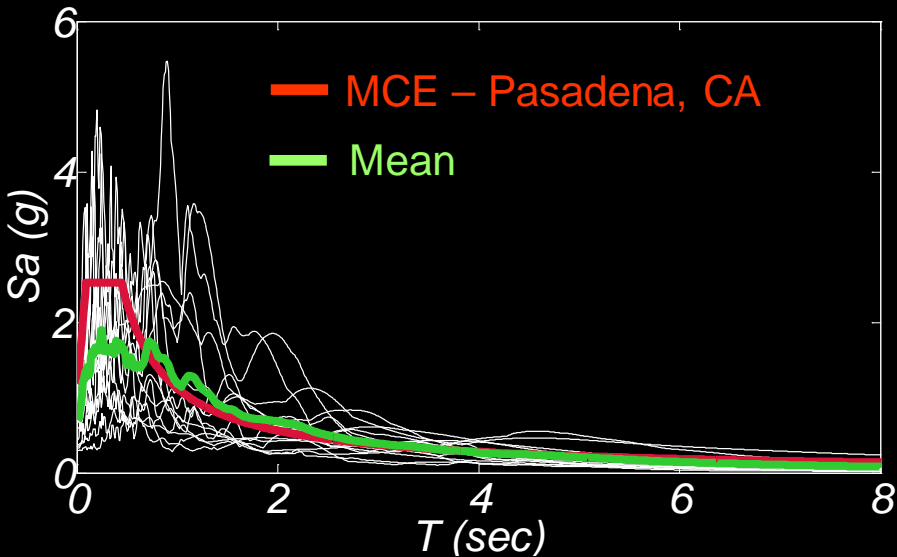
Plan View



Elevation

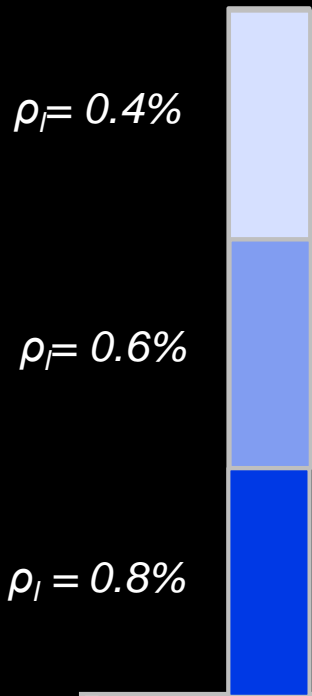
Ground Motions

14 **strong pulse-type near-fault** ground motions from the Tabas (1978), Imperial Valley (1979), Loma Prieta (1989), Landers (1992), Northridge (1994), Kobe (1995), Chi-Chi (1999), and Duzce (1999) earthquakes.



Fixed-Base Buildings – Design of Core Walls

Extended
Plasticity (EP)



$H = 67\text{ m}$

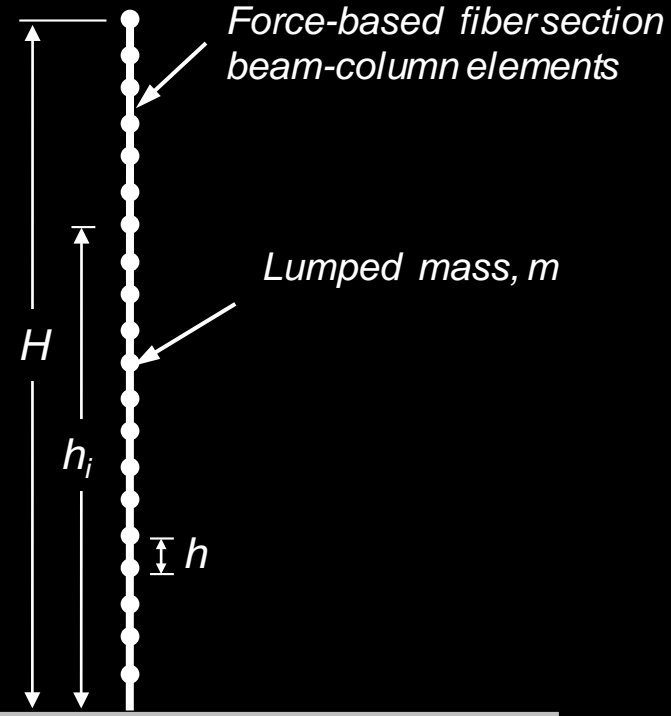
Single Plastic
Hinge (SPH)



$\rho_l = 2.4\%$

$\rho_l = 0.8\%$

OPENSEES
Numerical Model



$T_1 = 1.88\text{ sec}$

$T_2 = 0.30\text{ sec}$

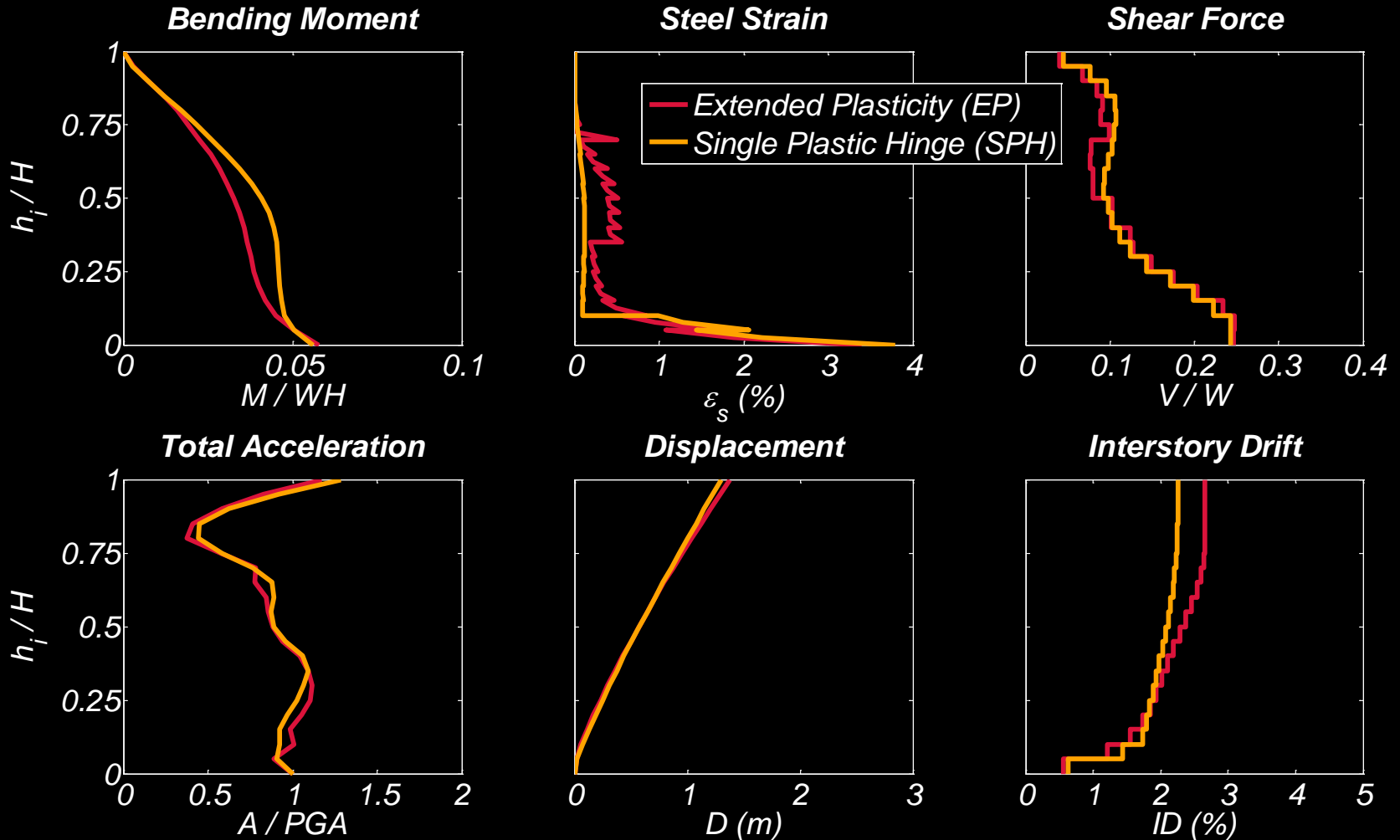
$T_v = 0.11\text{ sec}$

$T_1 = 1.83\text{ sec}$

$T_2 = 0.29\text{ sec}$

$T_v = 0.10\text{ sec}$

Mean Results for 14 Near-Fault Ground Motions



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

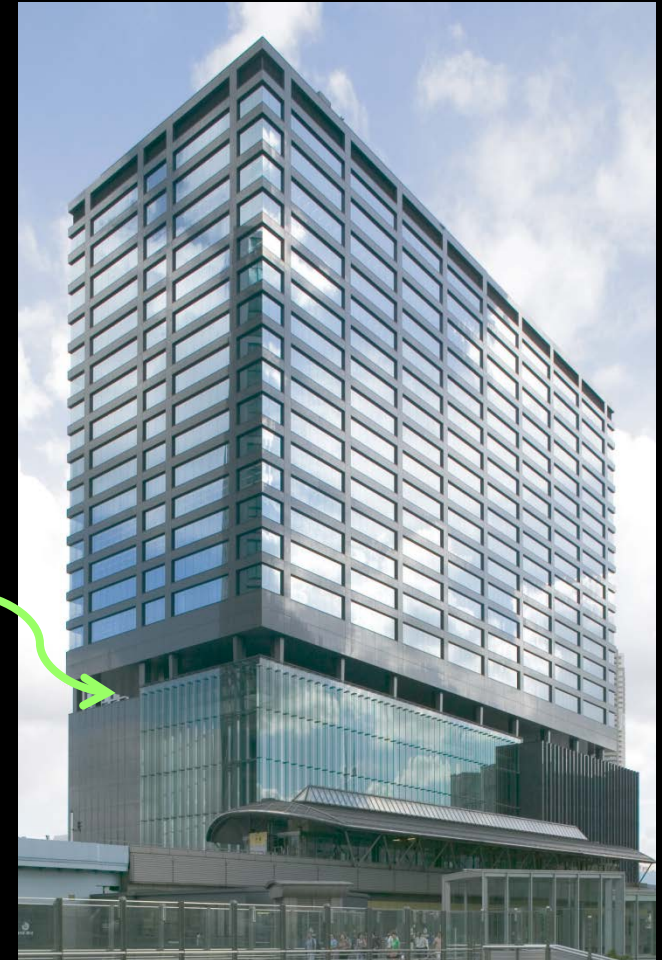
Kawasaki city, 41-story, base isolated



Komuro et al. (2005)

Shiodome Sumitomo Building

Tokyo, 25-story

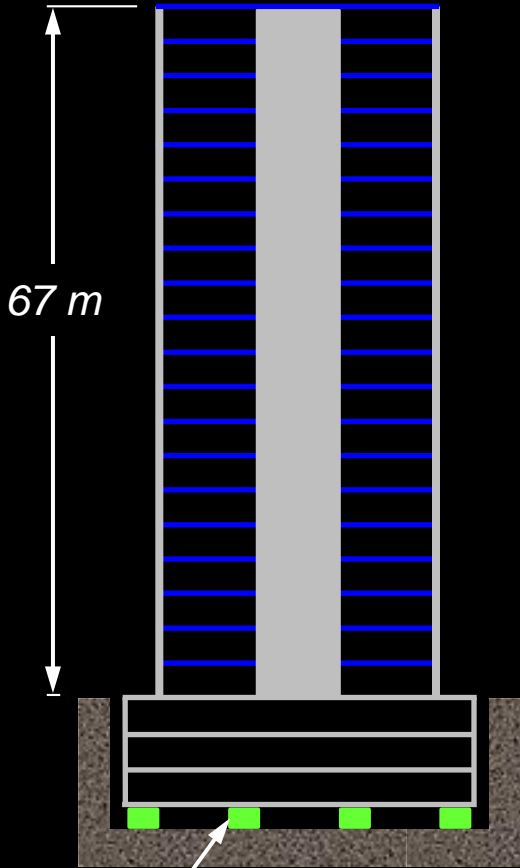


*Isolation layer at
40% of the height*

Tsuneki et al. (2009)

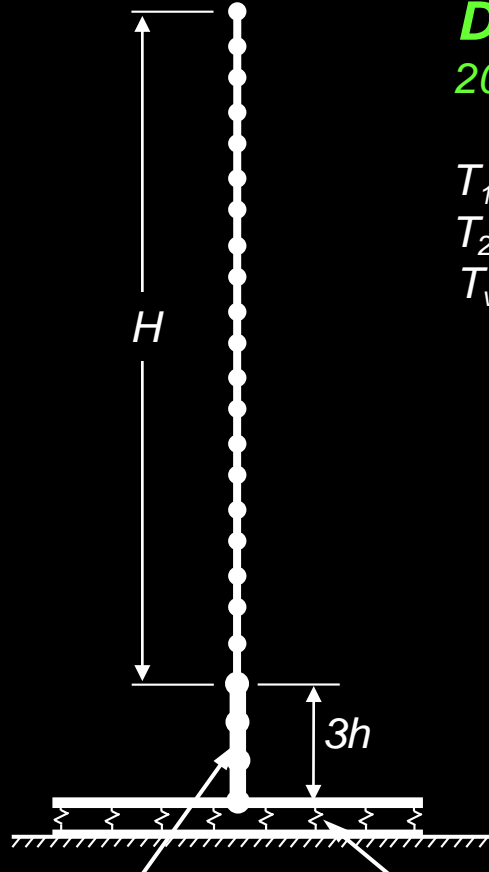
Isolated Building Designs

$L_w = 7.9 \text{ m}$



67 m

Elastomeric bearings



H

3h

Rigid elements

Isolation bearings
elastic springs

Design 1
20 bearings

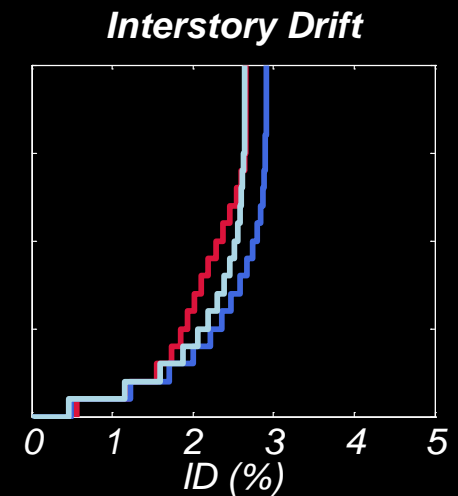
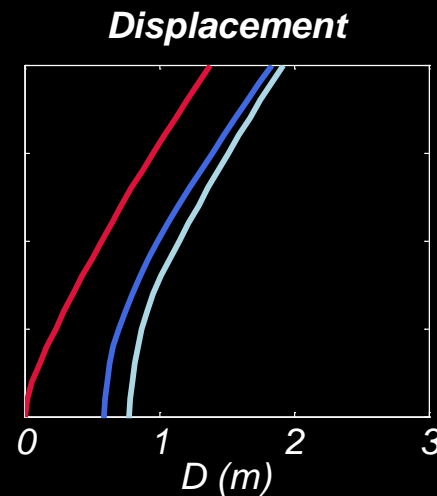
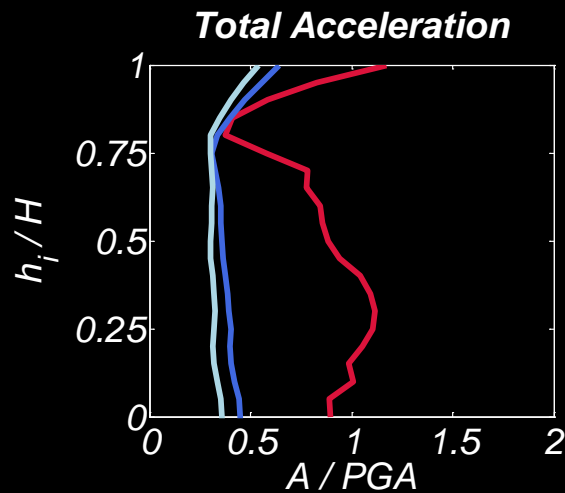
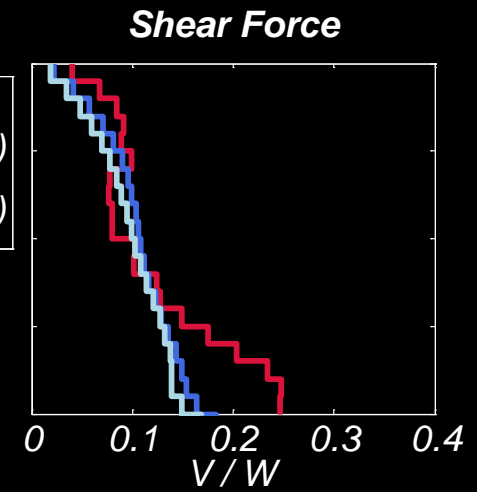
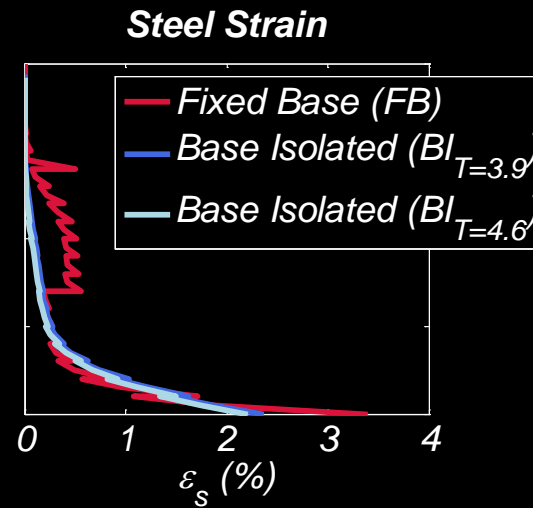
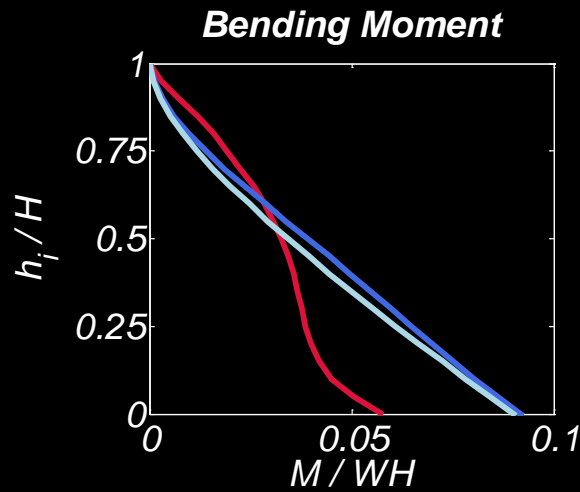
$T_1 = 3.9 \text{ sec}$
 $T_2 = 1.2 \text{ sec}$
 $T_v = 0.1 \text{ sec}$

Design 2
16 bearings

$T_1 = 4.6 \text{ sec}$
 $T_2 = 1.3 \text{ sec}$
 $T_v = 0.1 \text{ sec}$

Mean Results for 14 Near-Fault Ground Motions

$T_{1,BI}$ (sec)	3.9	4.6
Isolator displacement [mean and (max) in cm]	59 (82)	77 (118)



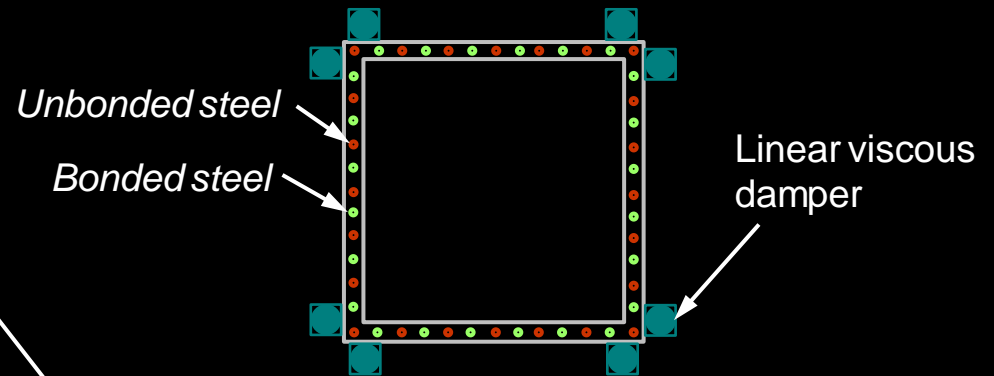
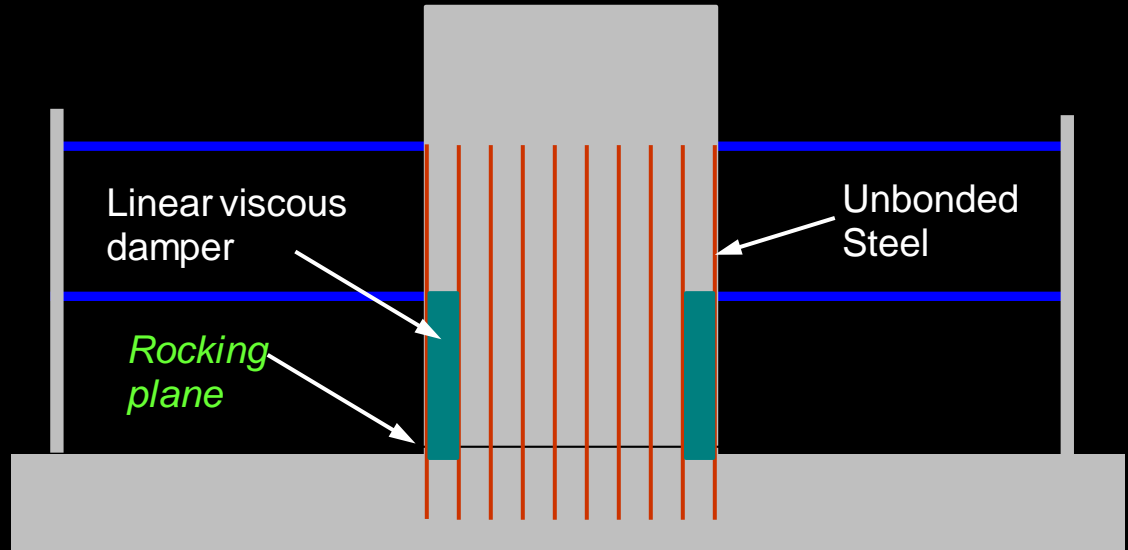
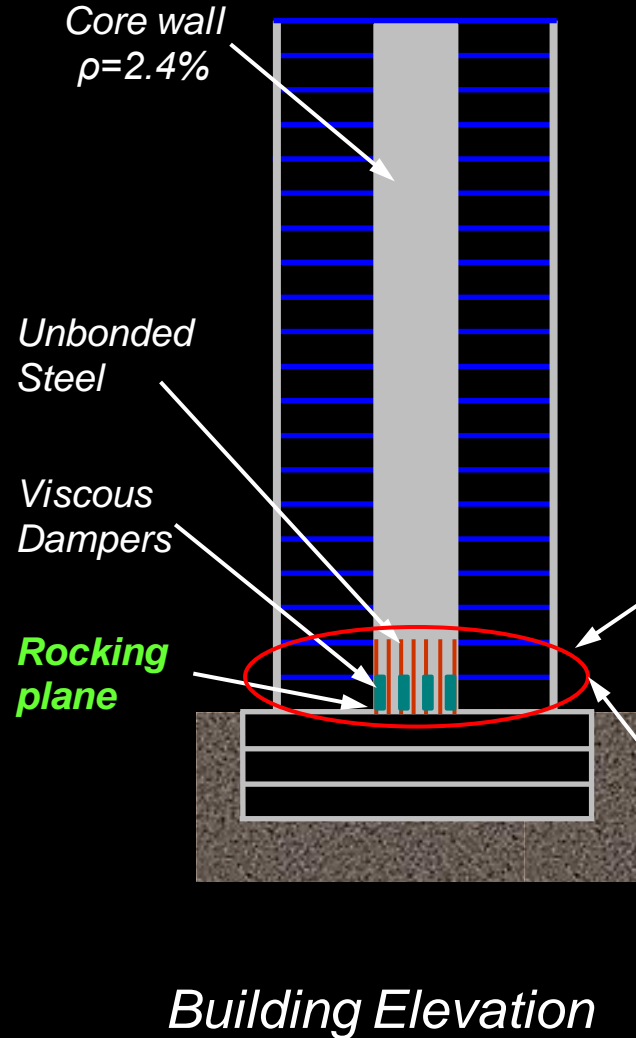
Seismic Isolation Design:

- **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

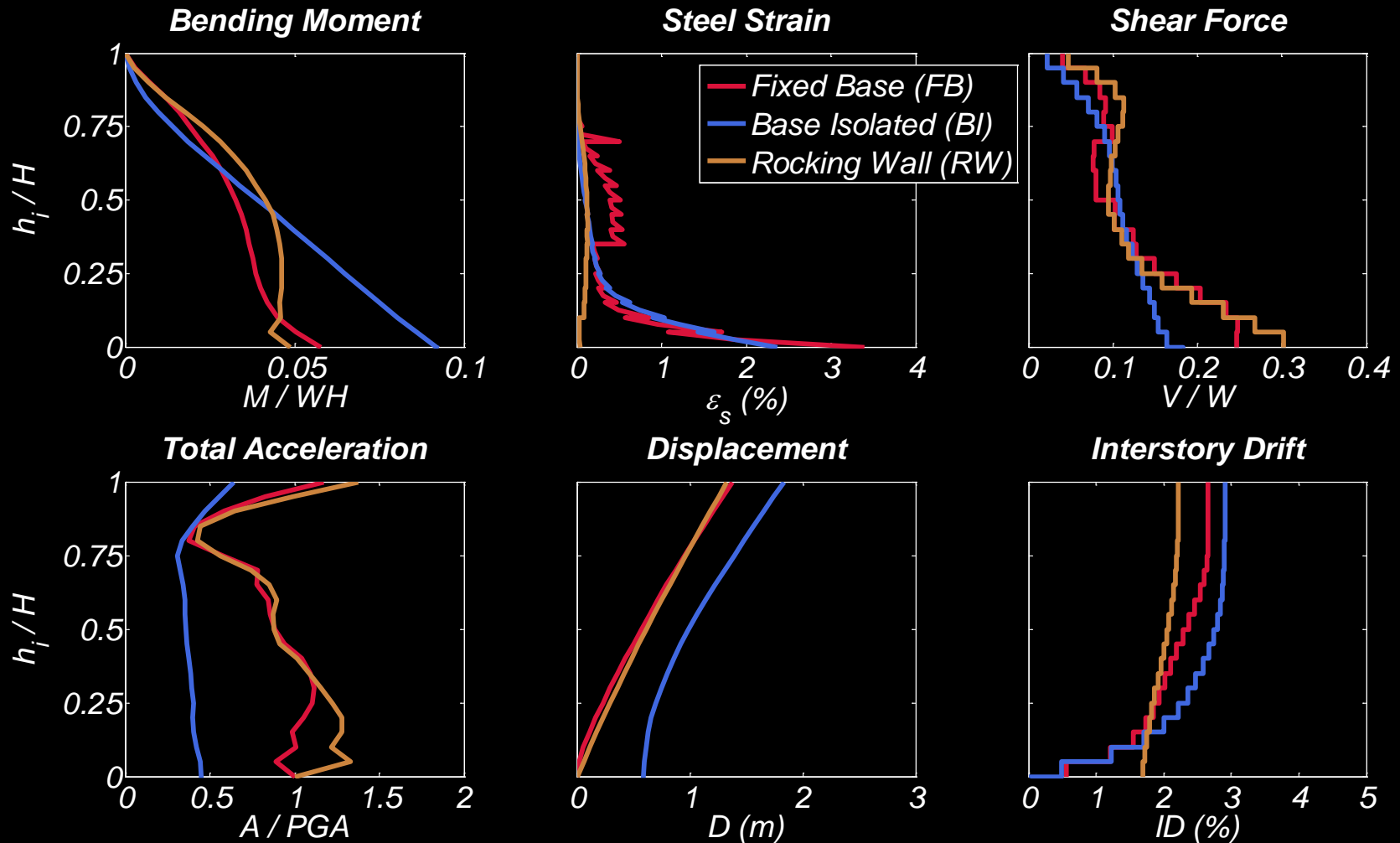
Rocking Core-Wall Building Design



Core-Wall Section and Viscous Dampers

Mean Results for 14 Near-Fault Ground Motions

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



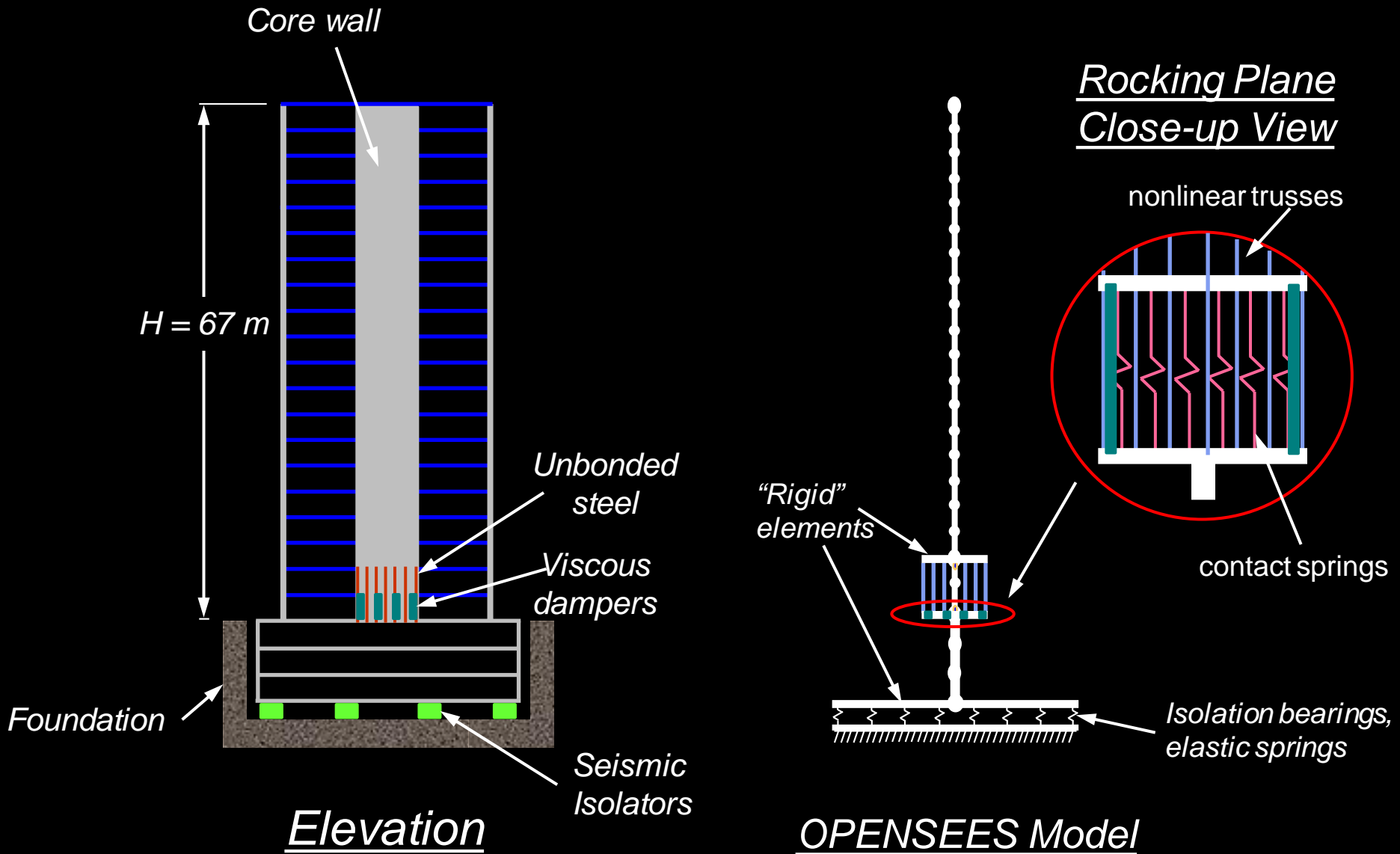
Seismic Isolation:

- **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

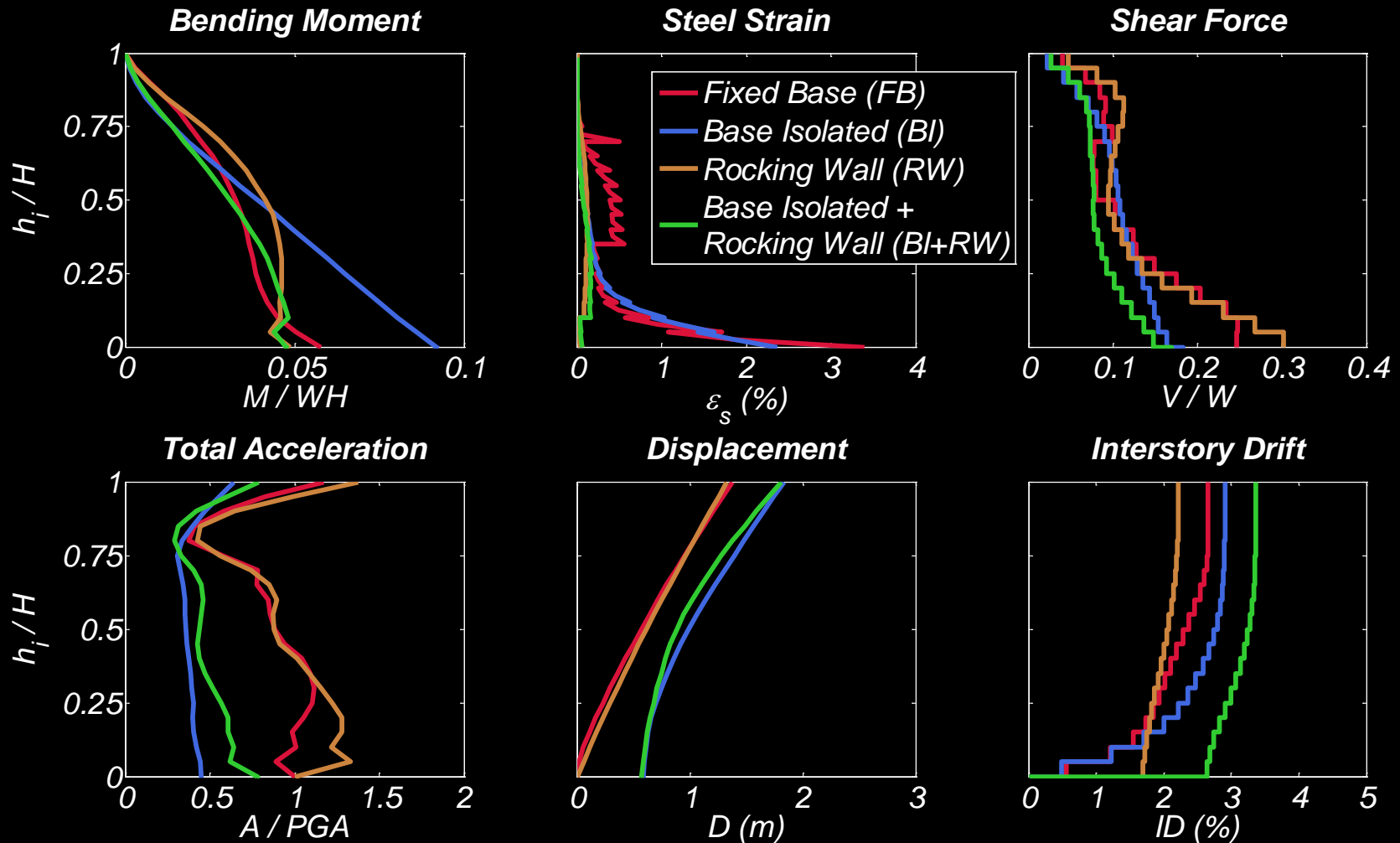
Base Isolation and Rocking Core Wall Building



Mean Results for 14 Near-Fault Ground Motions

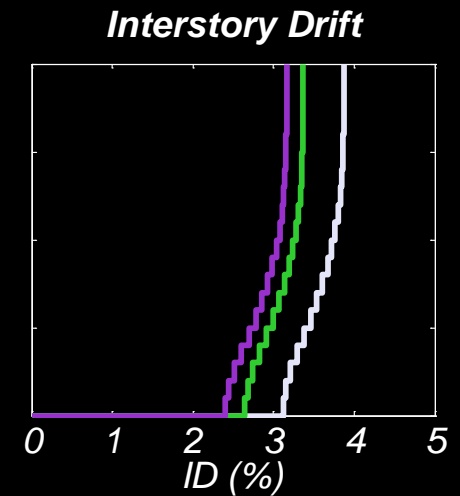
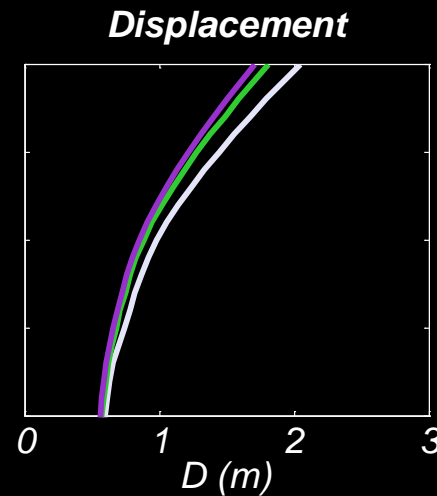
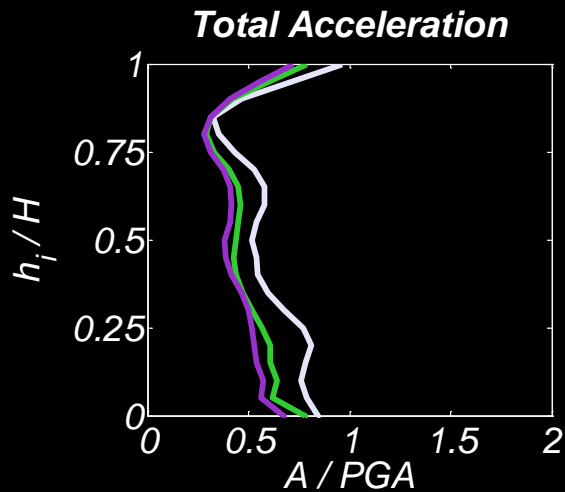
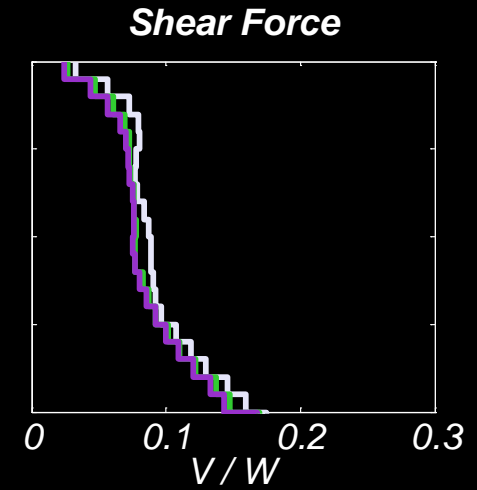
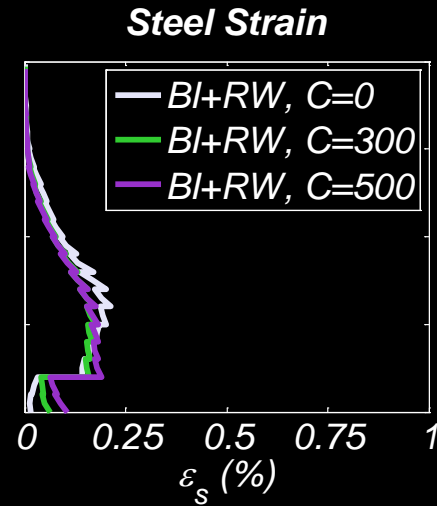
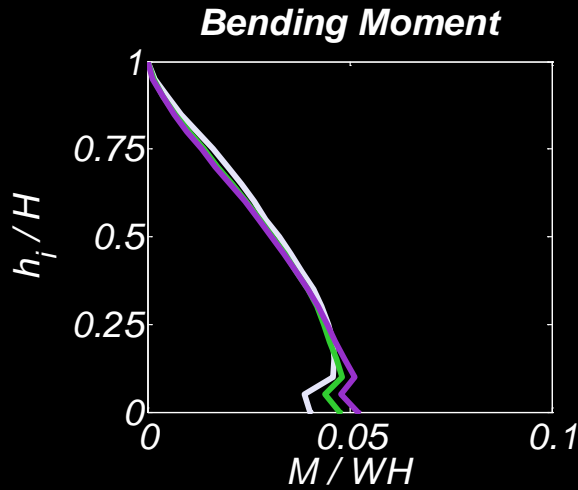
Mean rocking plane rotation uplift = 2.6% (max = 5%)

Mean isolator displacement = 57 cm (max = 102 cm)



Effect of Viscous Dampers

C	0	300	500
Uplift (cm)	24 (49)	20 (42)	18 (38)
Isolator Disp. (cm)	60 (117)	57 (102)	56 (94)



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*



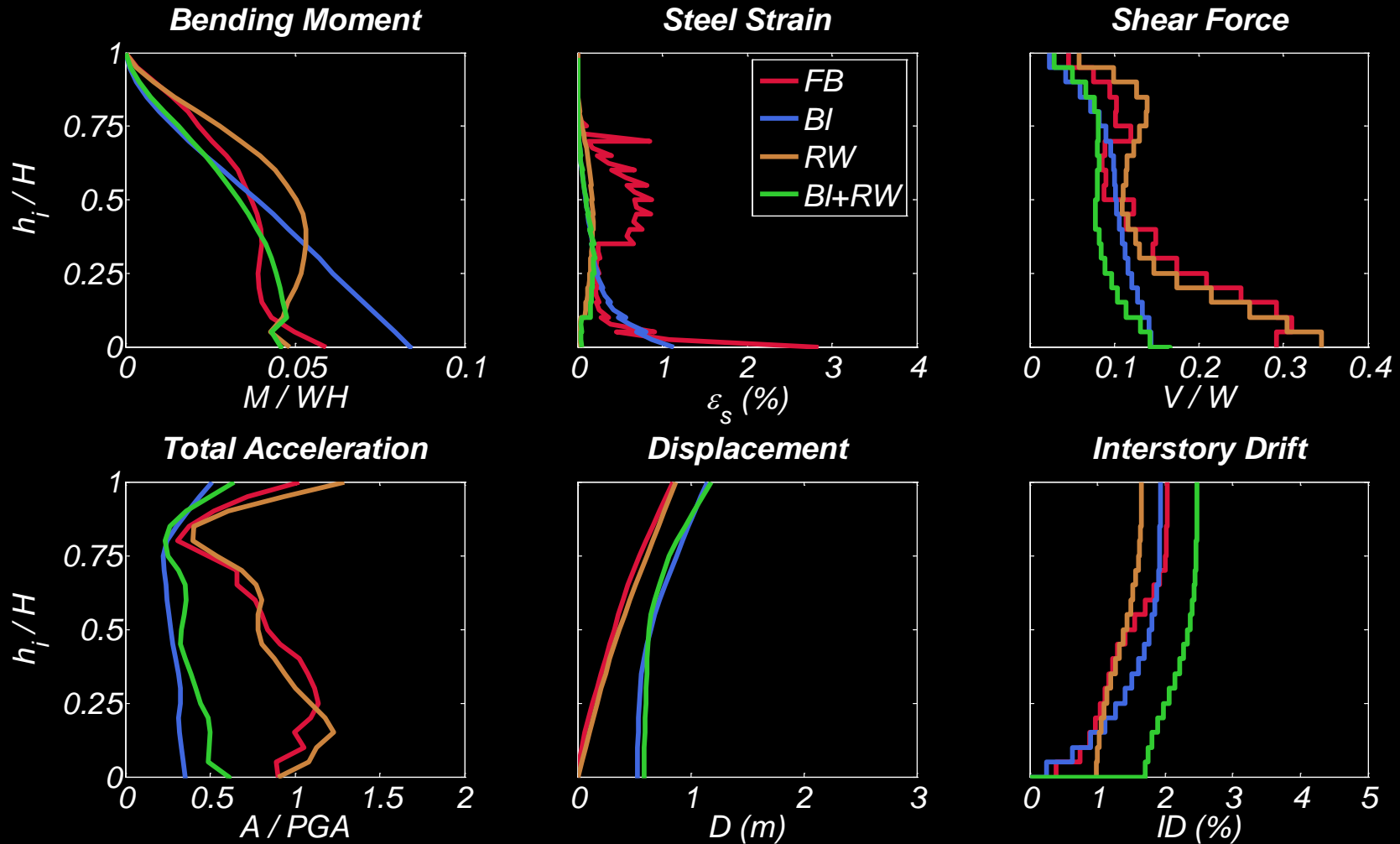
EQE (1995)

*Chile 2010 Earthquake
23-story O'Higgins 241 tower*

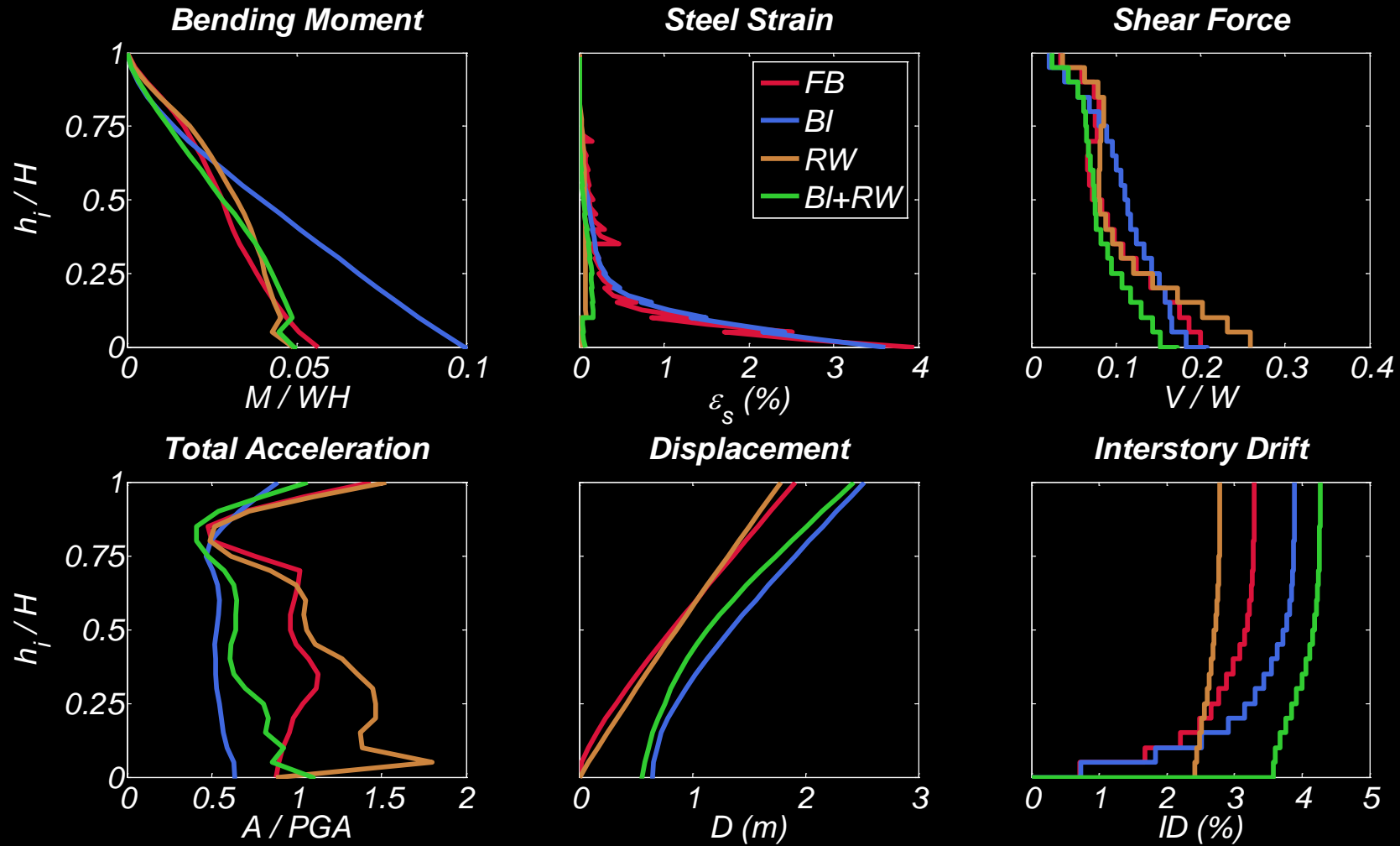


EERI (2010)

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



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



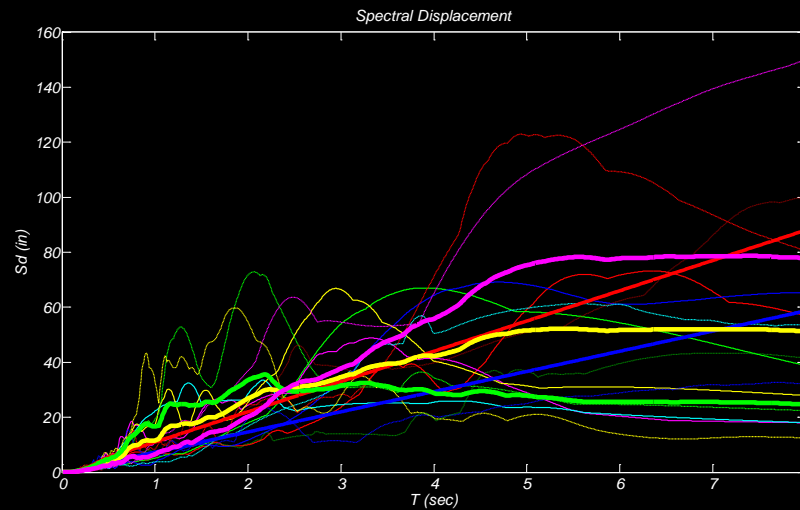
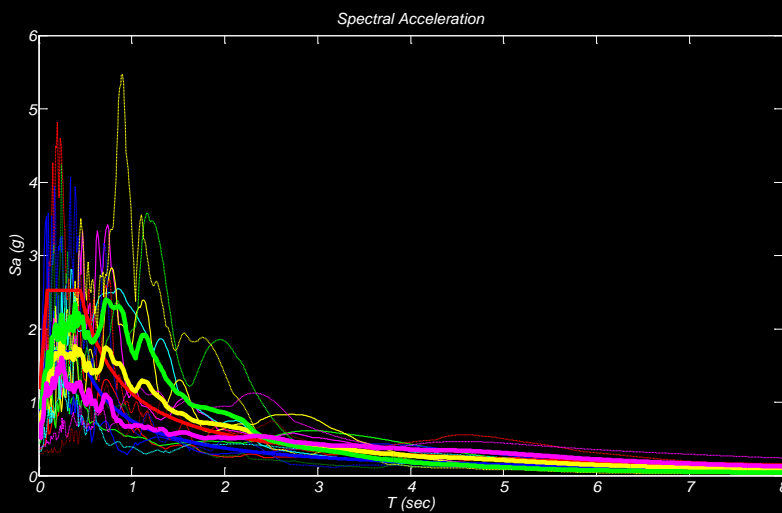
Mean Peak Responses

Peak Response. Mean of 14GM (Max of 14GM)	EP	SPH	BI	RW	BI+RW
Base shear (V/W)	0.25 (0.38)	0.24 (0.41)	0.22 (0.31)	0.30 (0.54)	0.15 (0.20)
Roof acceleration (A/PGA)	1.35 (2.67)	1.42 (2.12)	0.80 (1.48)	1.52 (2.95)	1.00 (2.05)
Steel strain at wall base (%)	3.40 (5.25)	3.80 (6.29)	2.37 (5.42)	0.04 (0.07)	0.06 (0.12)
Steel strain anywhere along building height (%)	3.40 (5.25)	3.80 (6.29)	2.37 (5.42)	0.15 (0.28)	0.20 (0.69)
Concrete compression Strain at wall base (%)	0.20 (0.26)	0.21 (0.28)	0.20 (0.28)	0.50 (0.98)	0.73 (1.42)
Wall uplift (cm)				13 (29)	20 (42)
Isolator displacement (cm)			59 (82)		57 (101)

Ground Motions

The study considers 14 **strong near-fault** ground motions from the Tabas (1978), Imperial Valley (1979), Loma Prieta (1989), Landers (1992), Northridge (1994), Kobe (1995), Chi-Chi (1999), and Duzce (1999) earthquakes.

EXPLAIN BINs HERE

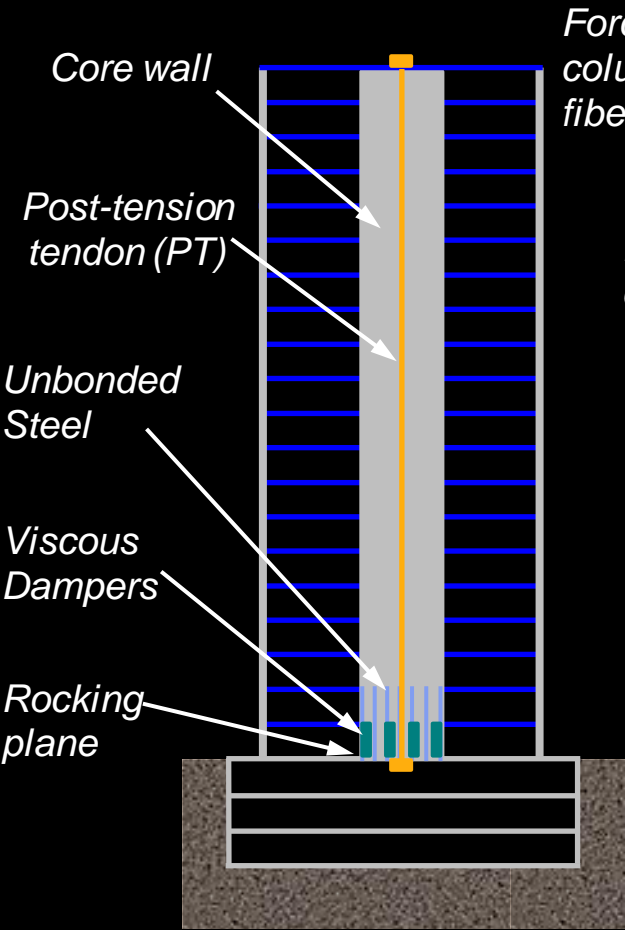


- DUZCE
- ELCEN6
- LCN
- LGP
- RRS
- SCS
- TABAS
- TAK
- TARZANA
- TCU052
- TCU075
- TCU084
- TCU102
- TCU129
- DBE
- MCE
- Mean 14EQ
- Mean Bin 1
- Mean Bin 2

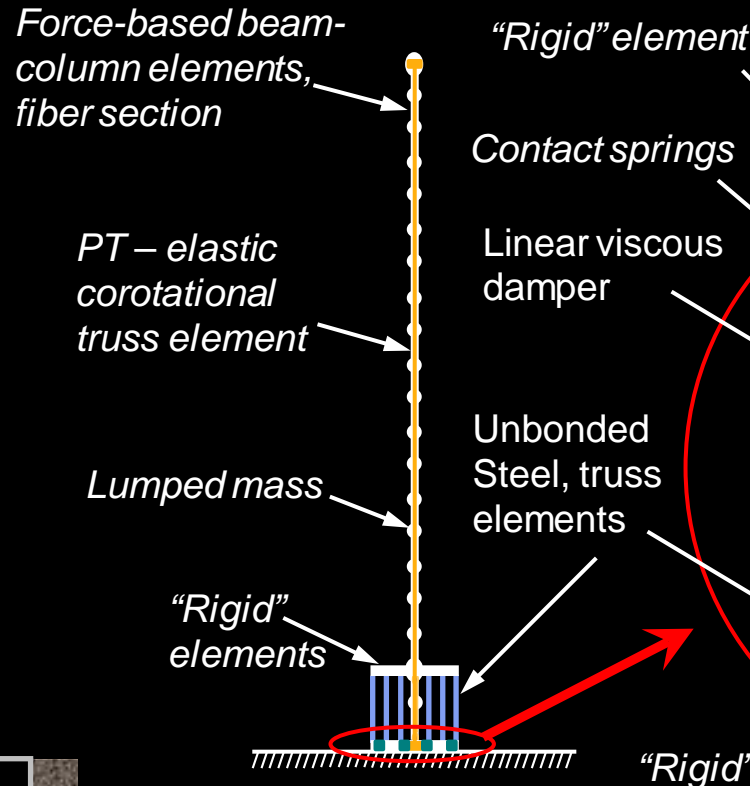
High Frequency (Bin 1) – LGP, RRS, SCS, TAK, TARZANA, TCU084, TCU129

Low Frequency (Bin 2) – DUZCE, ELCEN6, LCN, TABAS, TCU052, TCU075, TCU102

Rocking Plane Detail

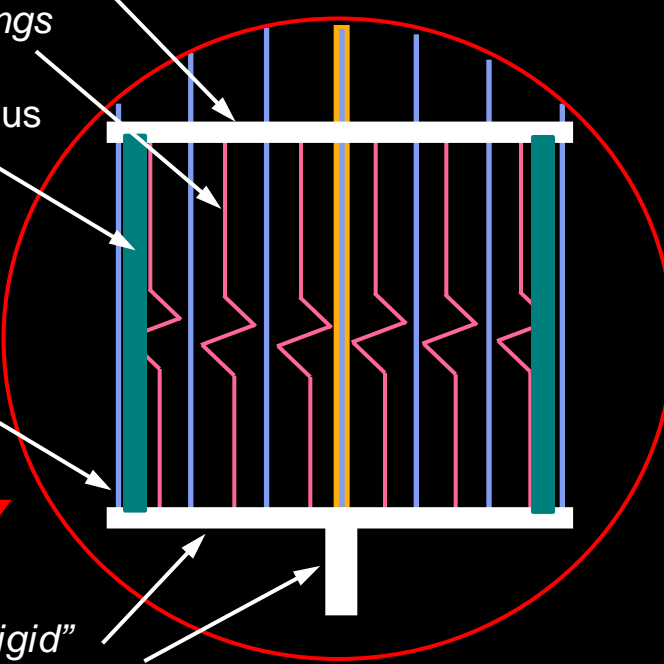


Building Elevation



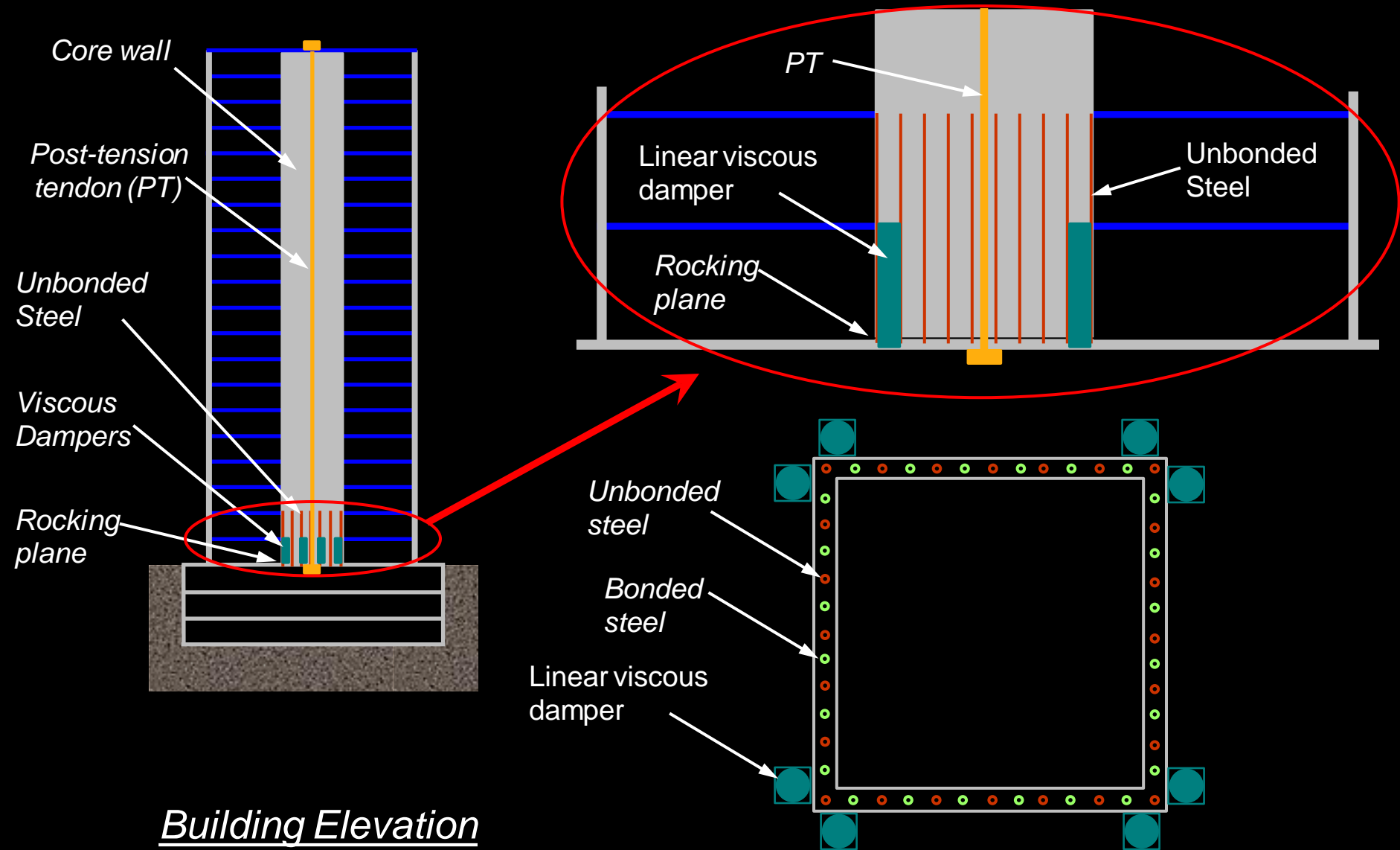
OpenSees Model

Rocking Plane Close-up View

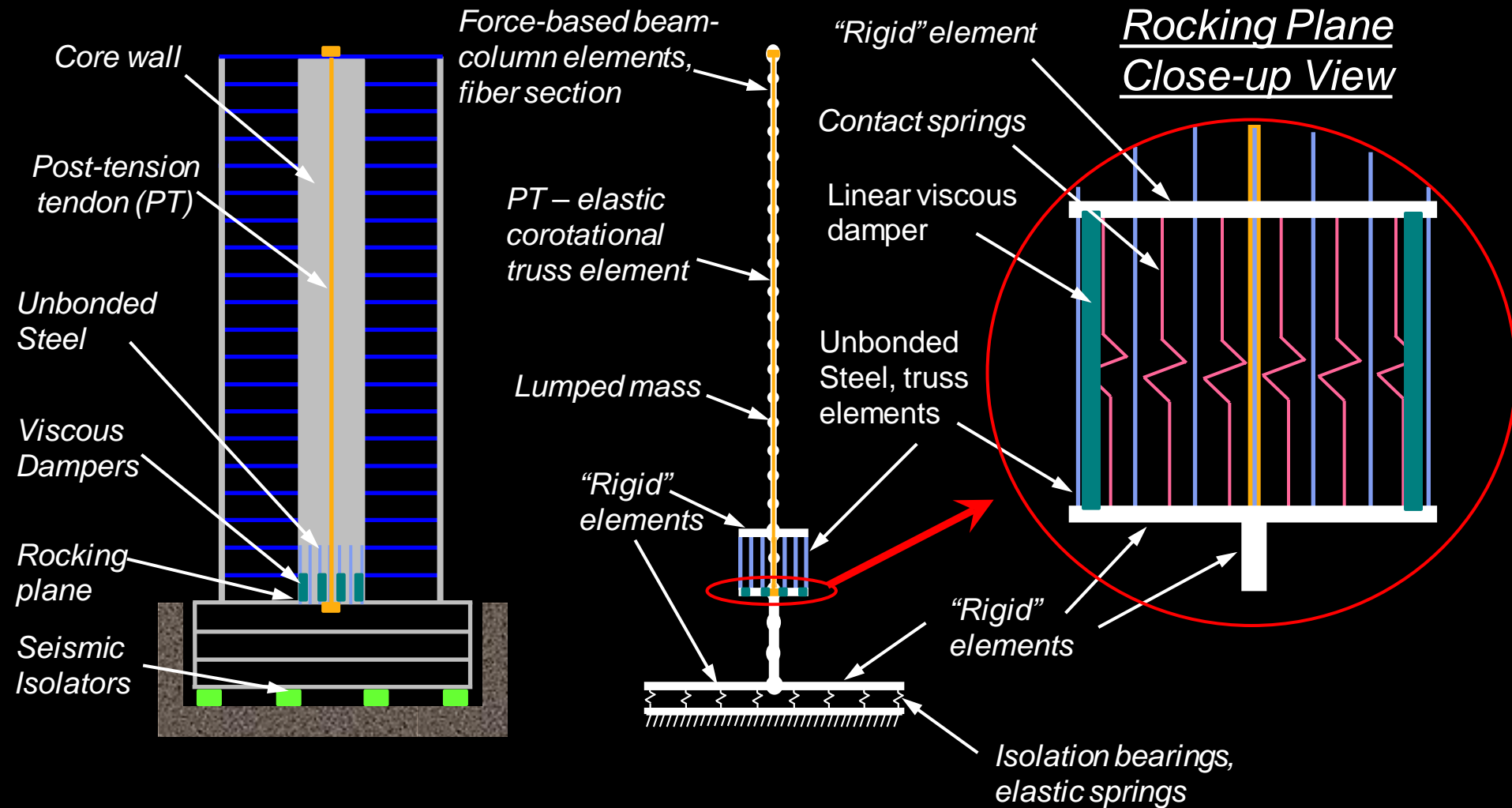


Seismic fluid viscous dampers for large highway bridge, 1.5 million pounds output force.

Base of Rocking Wall Detail



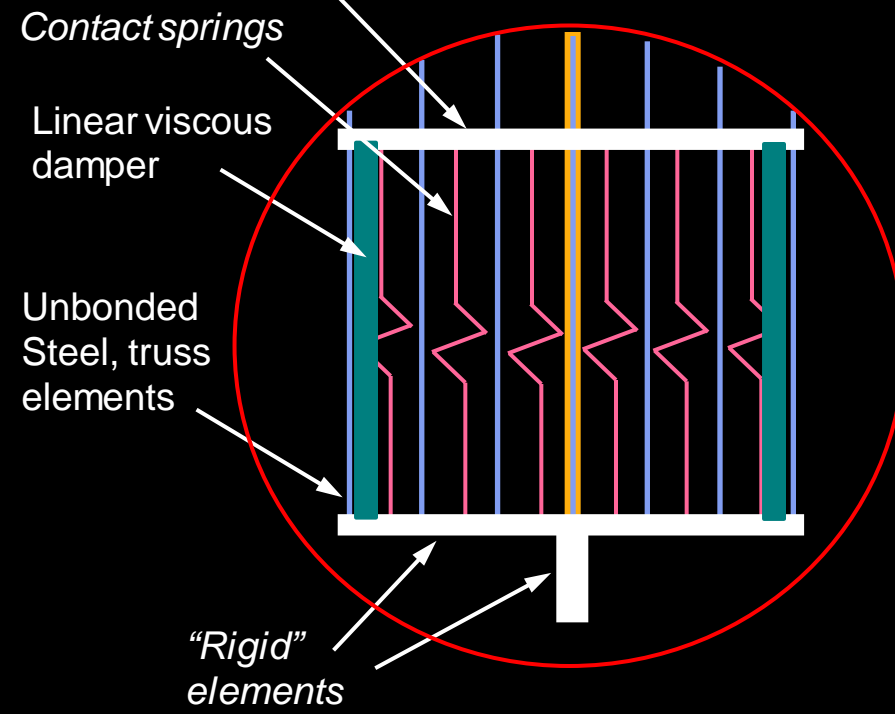
Base Isolation and Rocking Core Wall (BI+RW) Building



Building Elevation

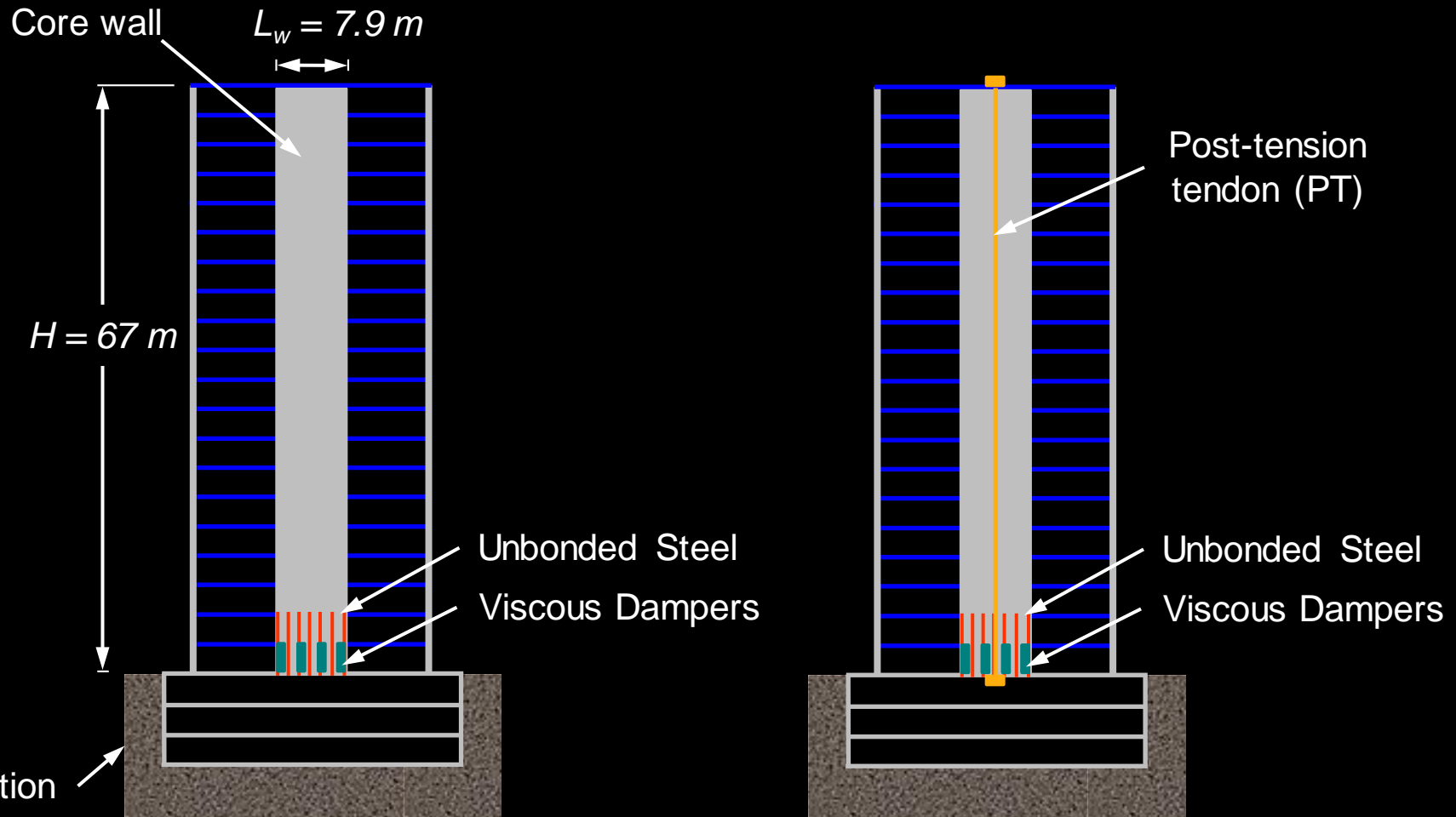
OpenSees Model

"Rigid" element Rocking Plane
Close-up View



*Isolation bearings,
elastic springs*

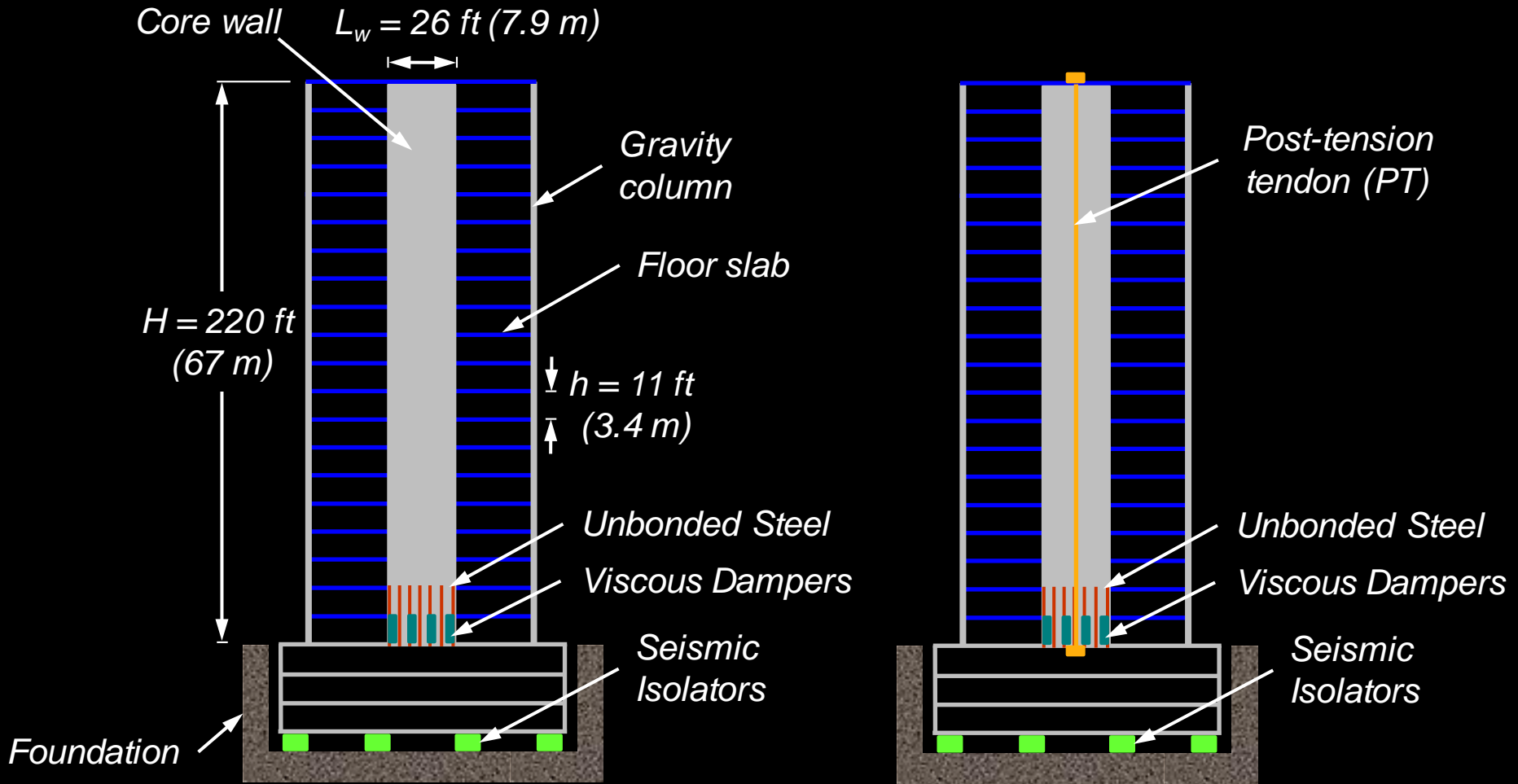
Rocking Core Wall (RW) Building



Elevation (no PT)

Elevation (with PT)

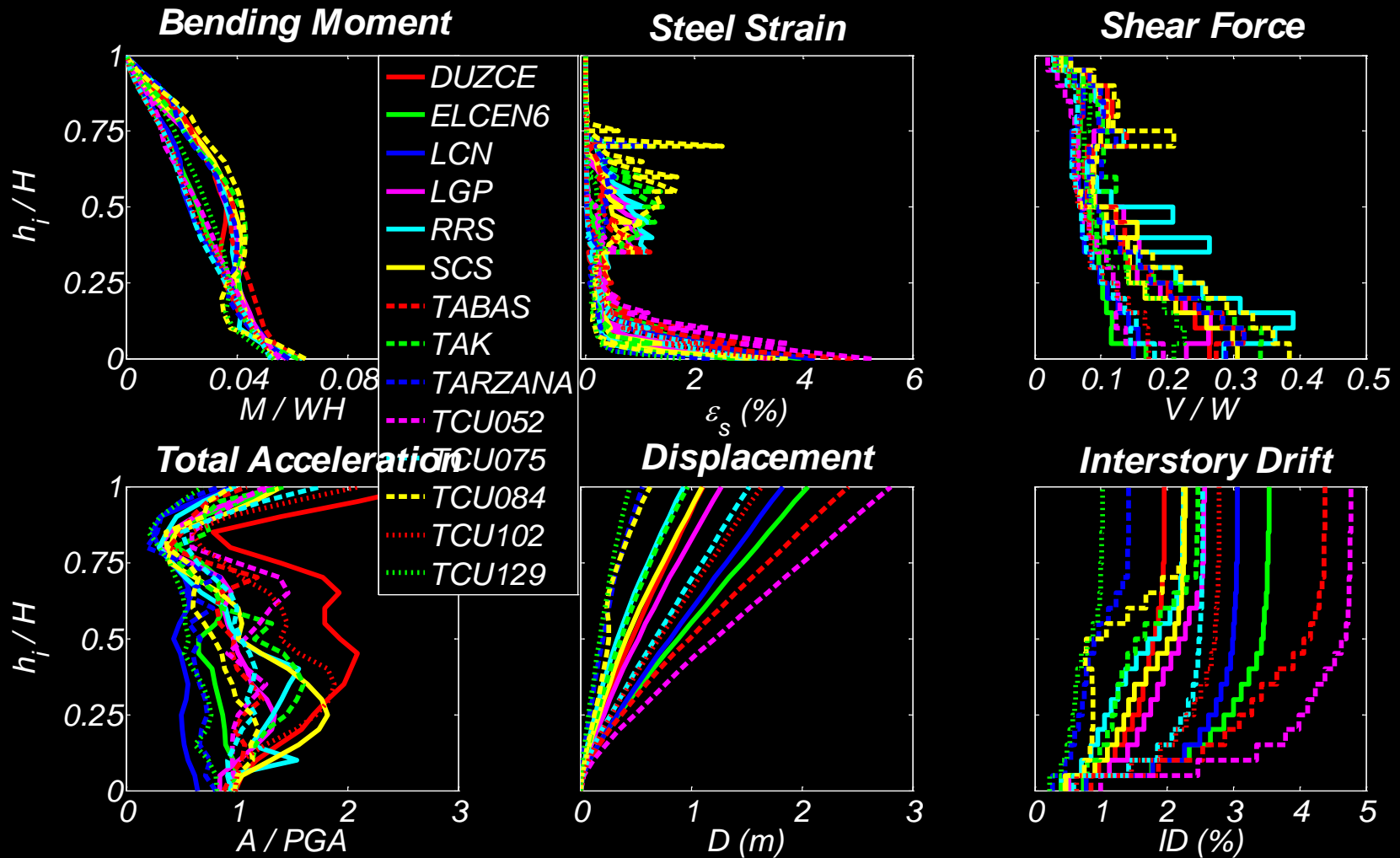
Base Isolation and Rocking Core Wall (BI+RW) Building



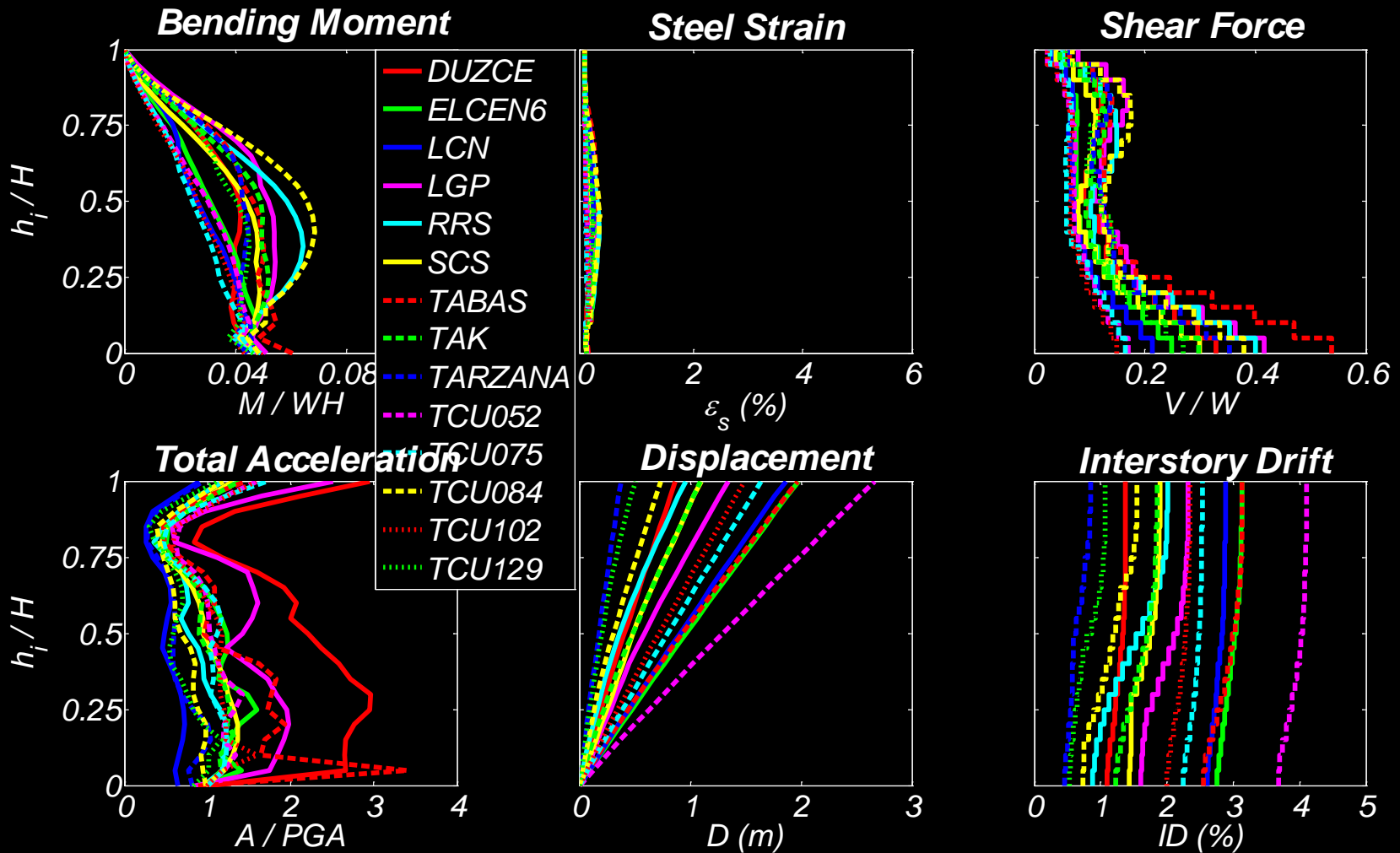
Elevation (no PT)

Elevation (with PT)

EP Response Envelopes for 14 ground motions

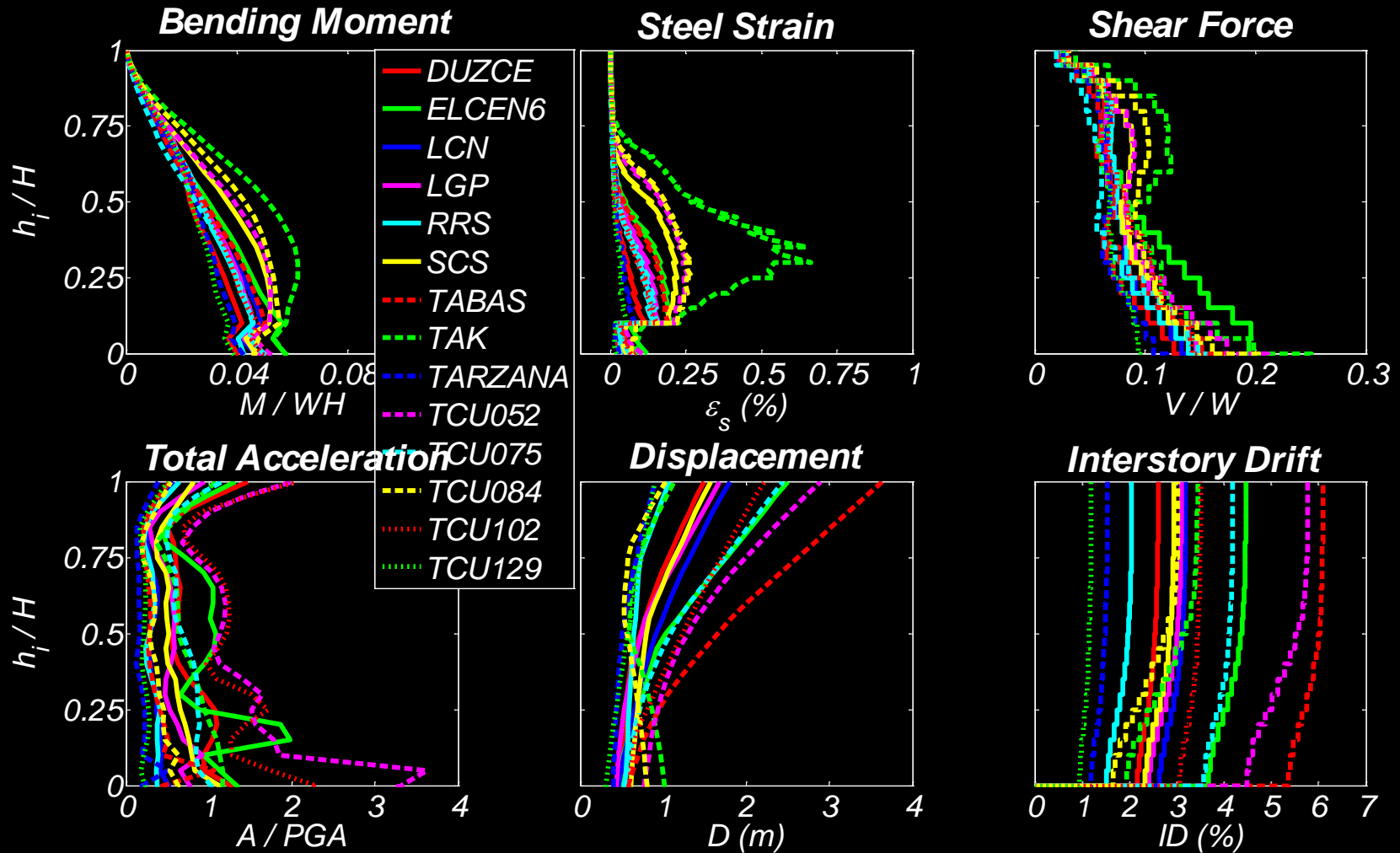


RW Response Envelopes for 14 ground motions



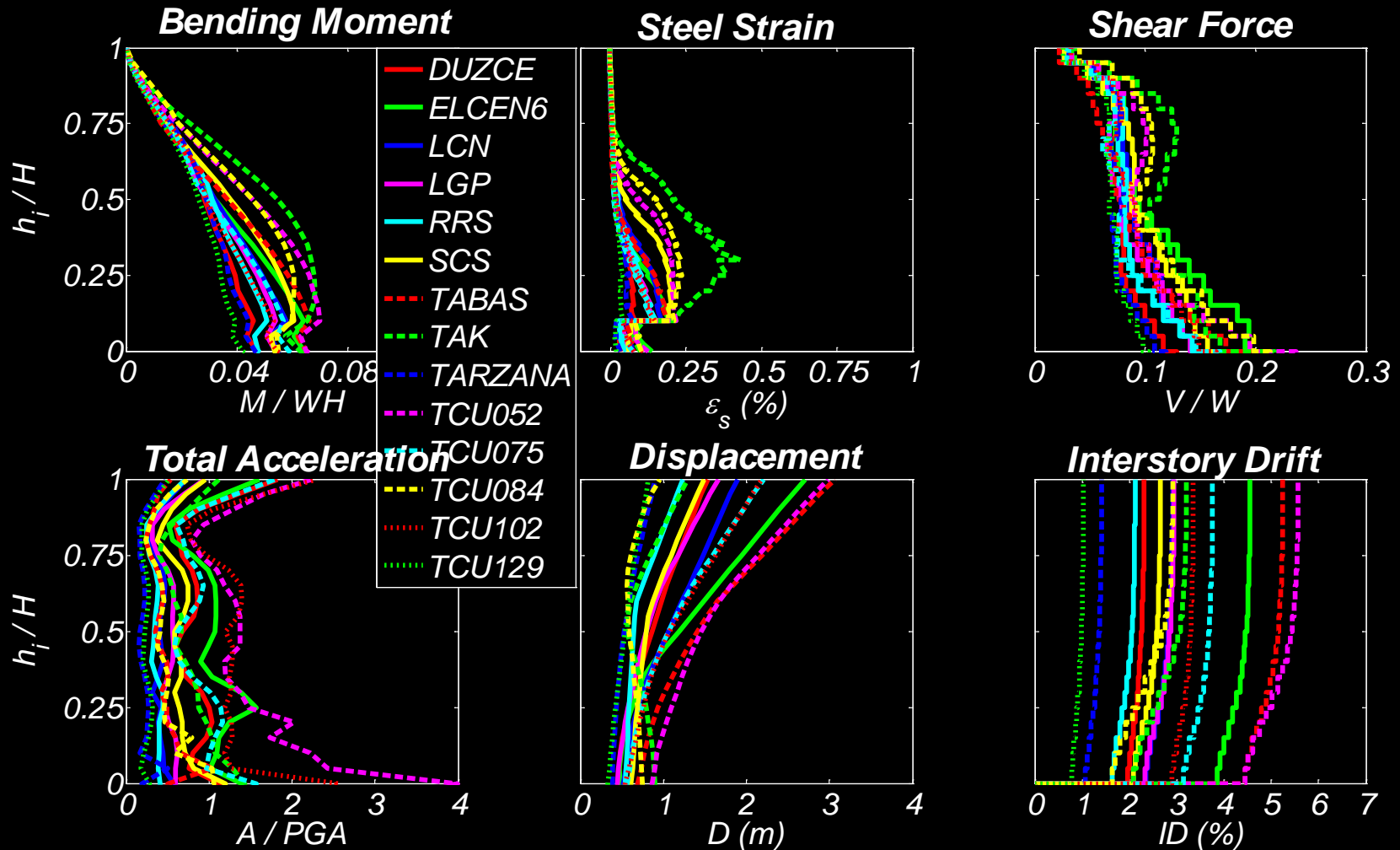
BI+RW Response Envelopes for 14 ground motions

No PT



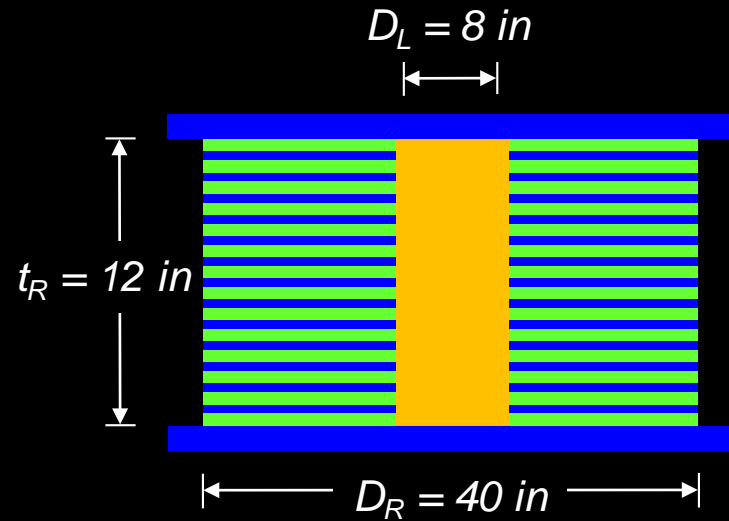
BI+RW Response Envelopes for 14 ground motions

0.4% PT 30ksi prestress



Seismic Isolator Design

20-story

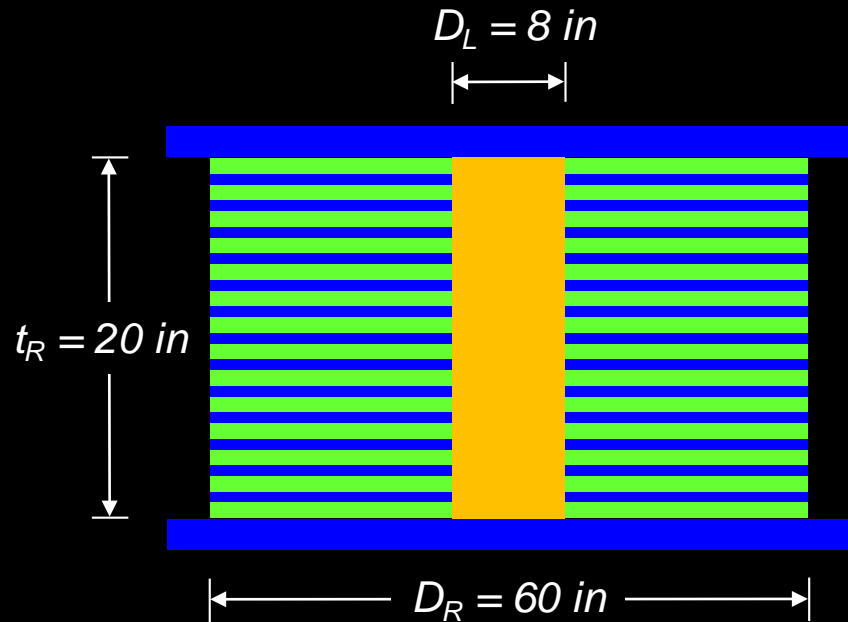


$$K_{hor} = 28\text{ kip / in}$$

$$K_{ver} = 12100\text{ kip / in}$$

$$F_y = 106\text{ kip}$$

40-story

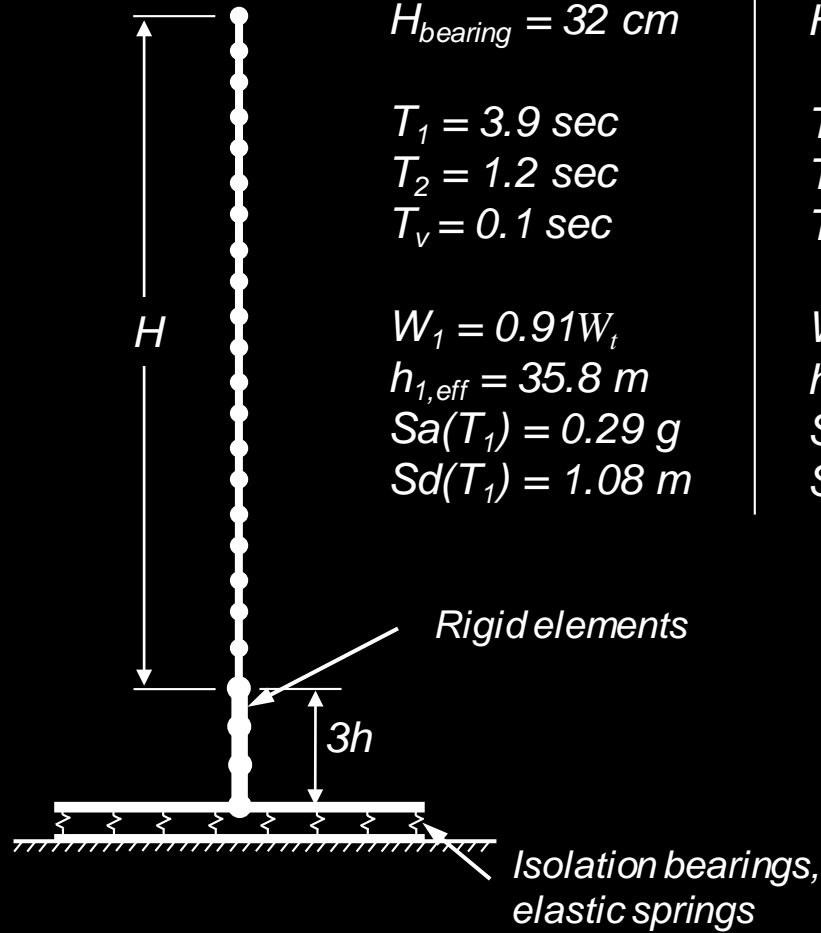
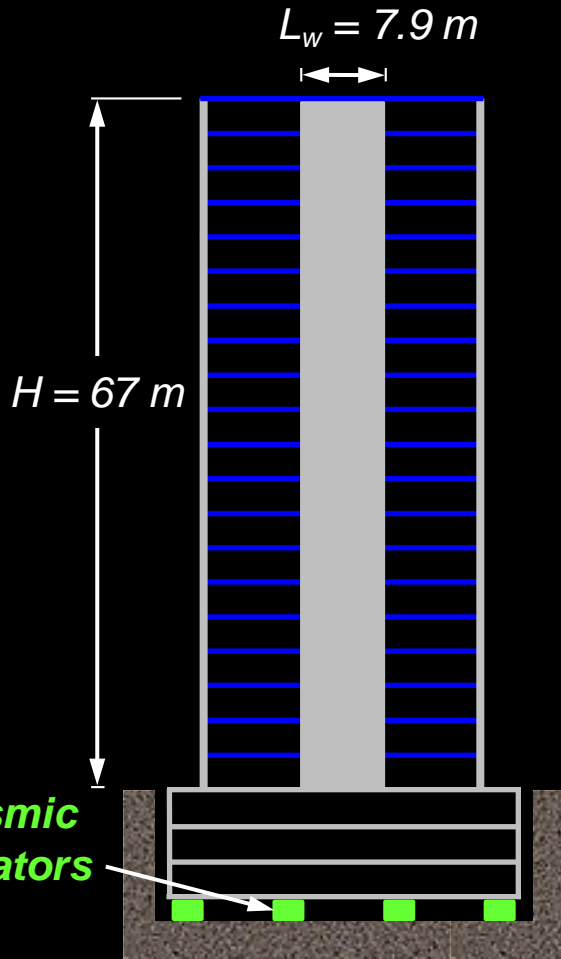


$$K_{hor} = 23\text{ kip / in}$$

$$K_{ver} = 17400\text{ kip / in}$$

$$F_y = 146\text{ kip}$$

Isolated Building Designs



$$H_{\text{bearing}} = 32 \text{ cm}$$

$$T_1 = 3.9 \text{ sec}$$

$$T_2 = 1.2 \text{ sec}$$

$$T_v = 0.1 \text{ sec}$$

$$W_1 = 0.91 W_t$$

$$h_{1,\text{eff}} = 35.8 \text{ m}$$

$$S_a(T_1) = 0.29 \text{ g}$$

$$S_d(T_1) = 1.08 \text{ m}$$

$$H_{\text{bearing}} = 47 \text{ cm}$$

$$T_1 = 4.6 \text{ sec}$$

$$T_2 = 1.3 \text{ sec}$$

$$T_v = 0.1 \text{ sec}$$

$$W_1 = 0.92 W_t$$

$$h_{1,\text{eff}} = 36.7 \text{ m}$$

$$S_a(T_1) = 0.24 \text{ g}$$

$$S_d(T_1) = 1.26 \text{ m}$$