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

3 Questions

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

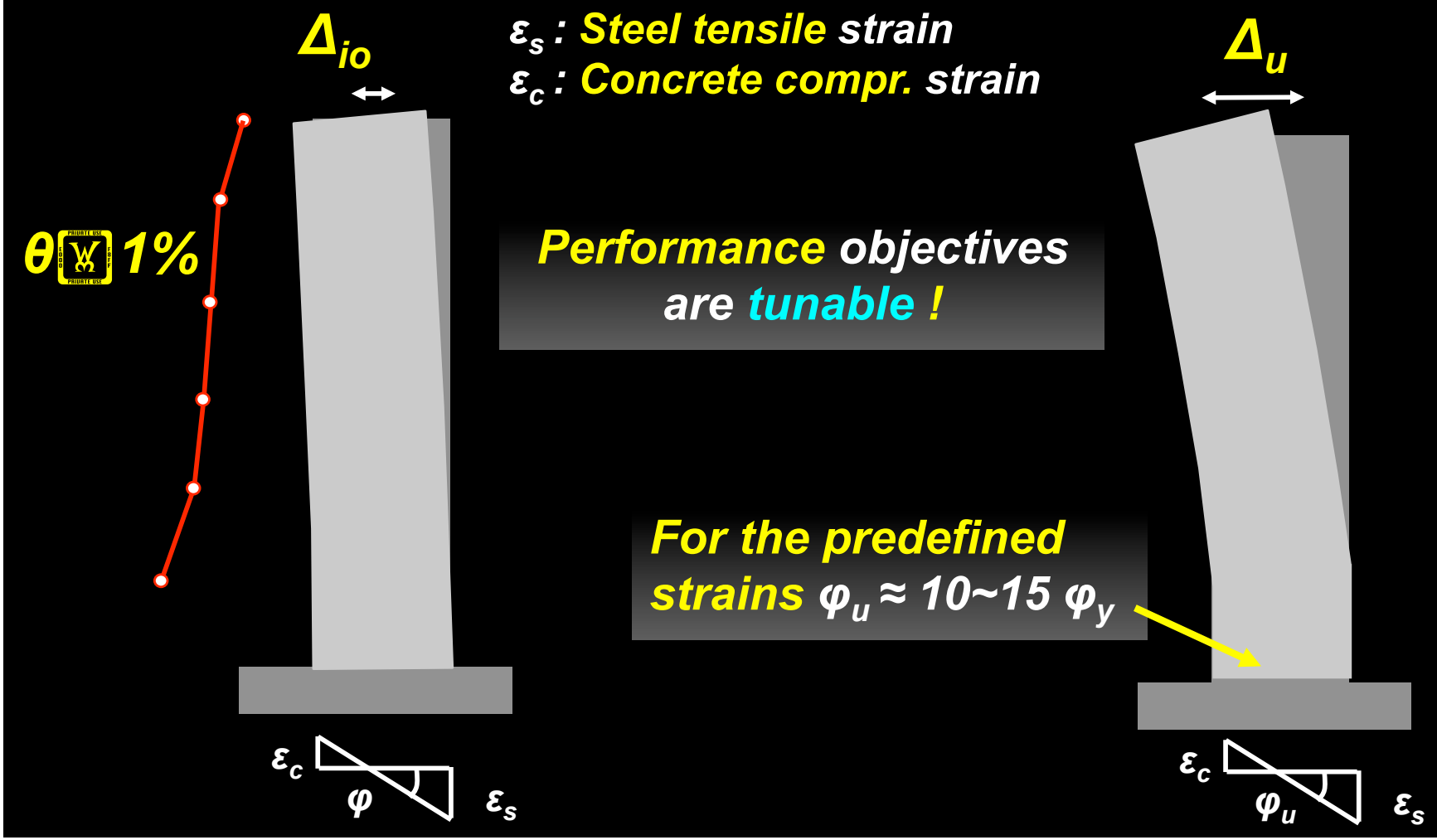
Displacement-based Design for 2 Performance Levels

Immediate Occupancy in frequent EQs

- Minimize non structural damage
  Interstory drift $\theta \leq 1\%$

Collapse Prevention in rare EQs

- Prevent bar buckling, fracture
  $\varepsilon_s \leq 5\%$, $\varepsilon_c \leq 2\ \%$



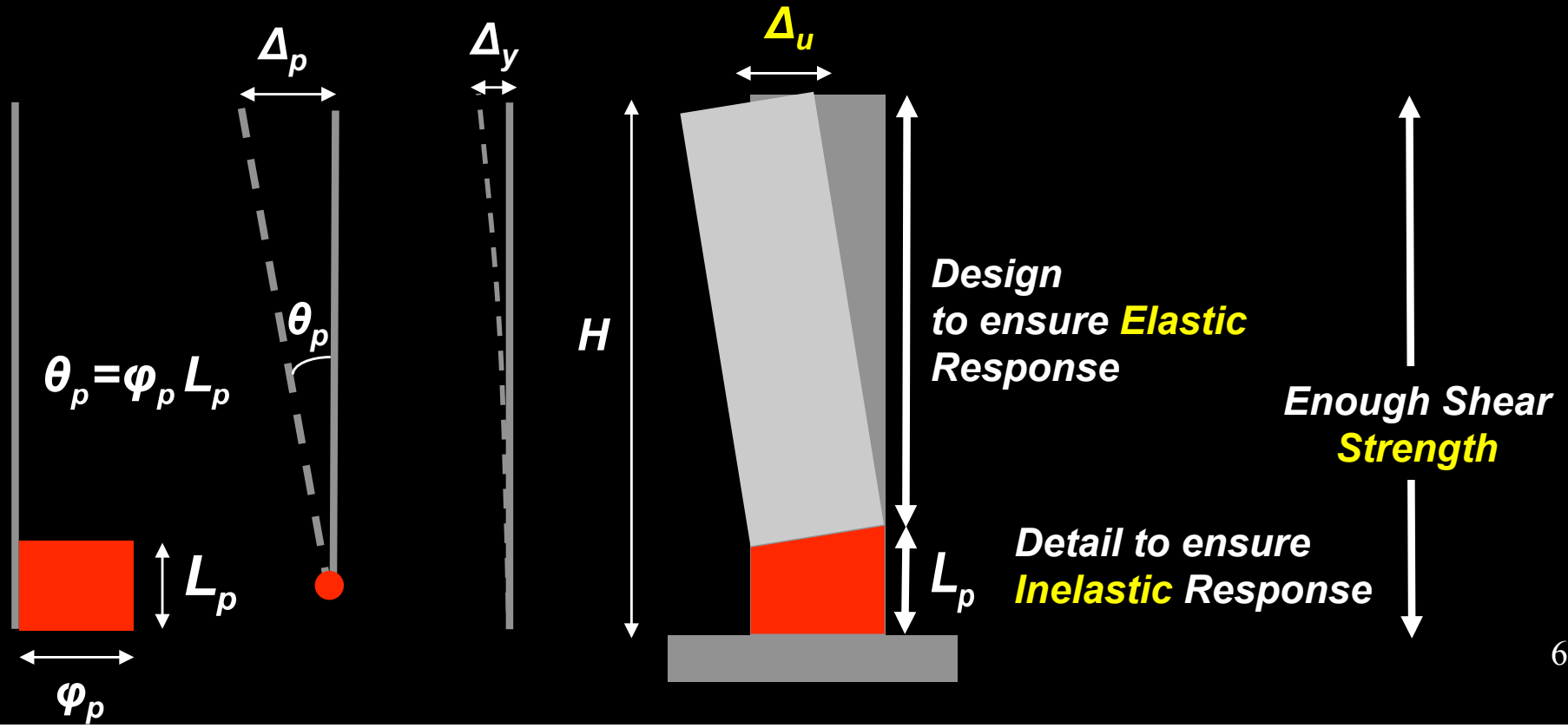
Explicit Selection of Mechanism of Inelastic Response – Basic Mechanics

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

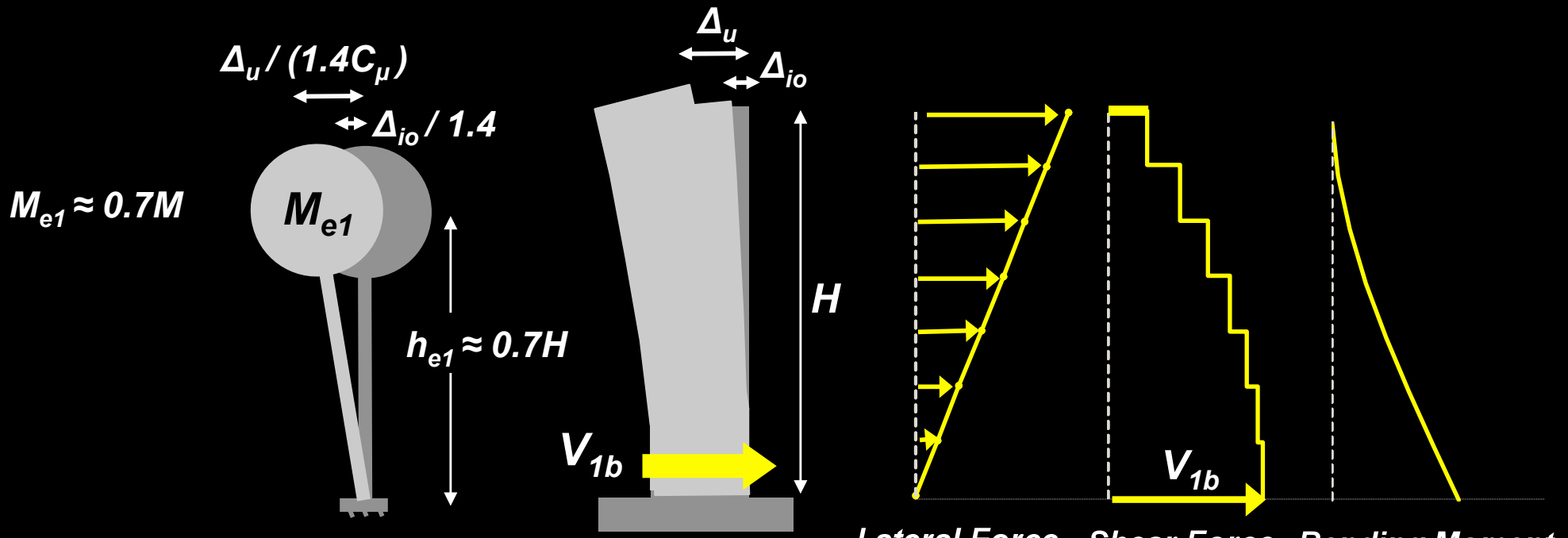
$\Delta_u = \Delta_y + \Delta_p$

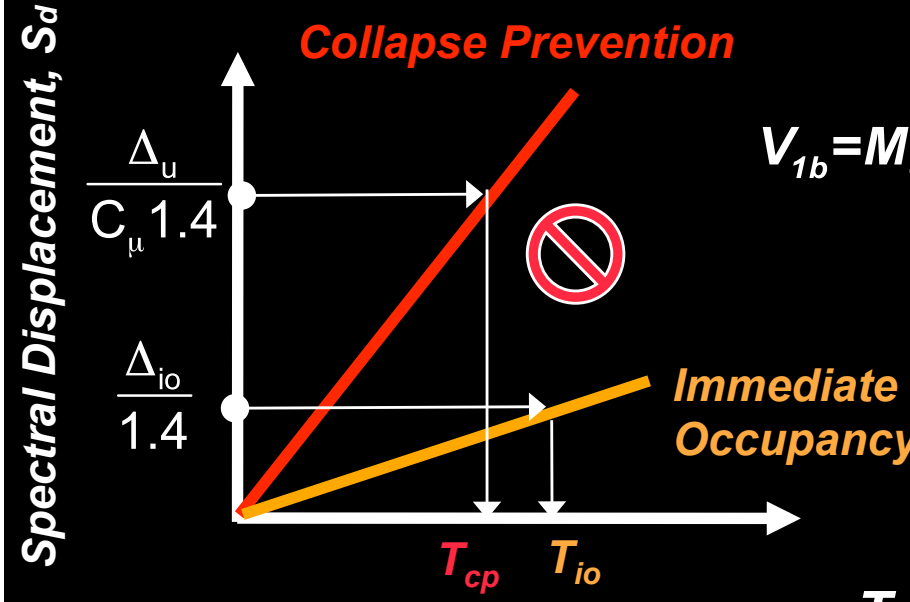
Inelastic Range : $\varphi_p = 10 \sim 15\varphi_y$ $\Delta_p = \varphi_p L_p (H - L_p / 2)$

Which is the Δ_u corresponding to the predefined objectives ?



Displacement-based Design – First Mode

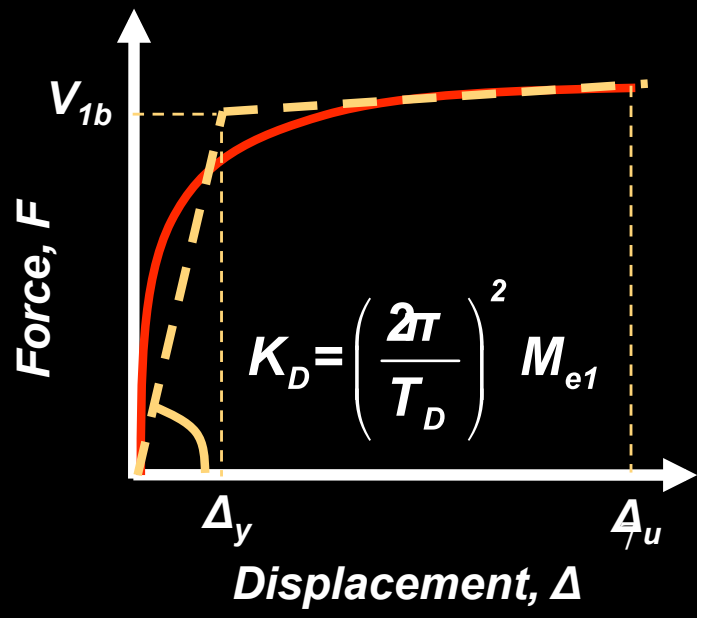




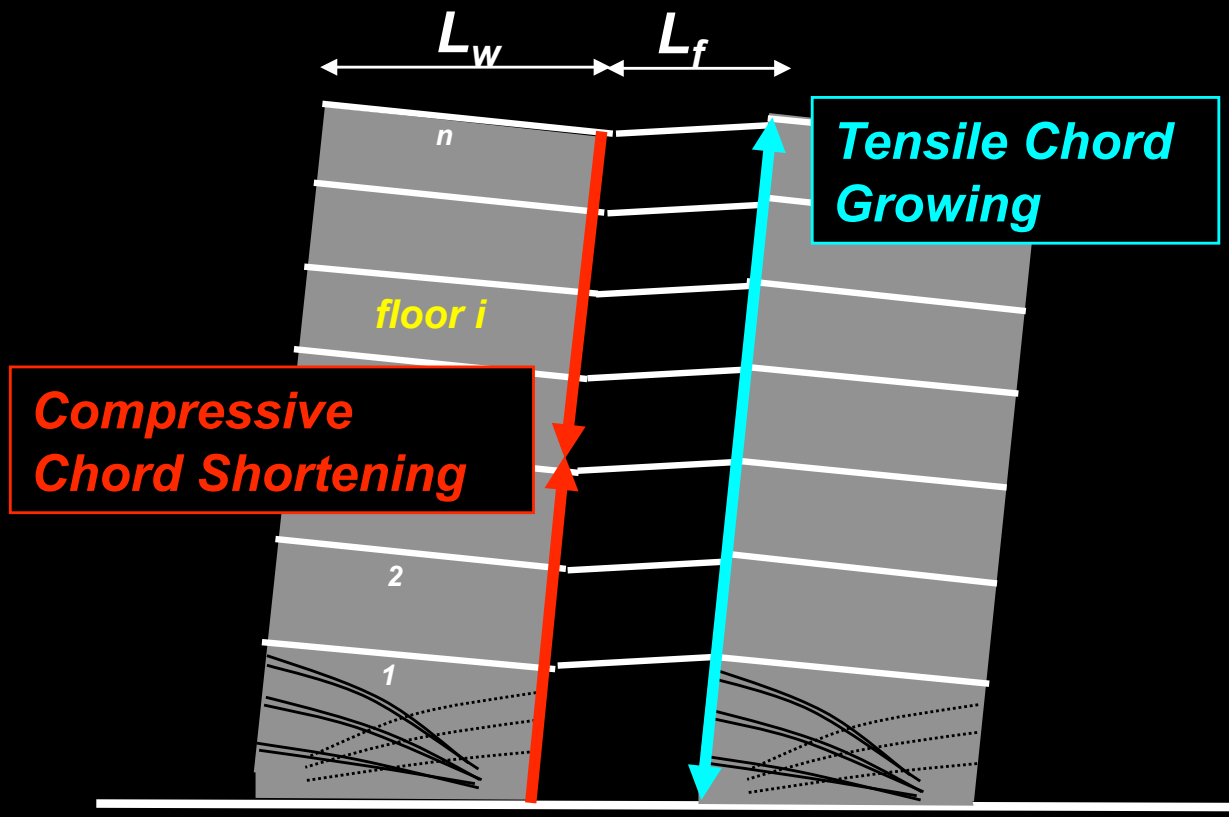
$$V_{1b} = M_{e1} \left(\frac{2\pi}{T_D} \right)^2 \frac{\Delta_y}{1.4}$$

$$a_1$$

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



Kinematic System Overstrength
Framing Effects



Kinematic System Overstrength

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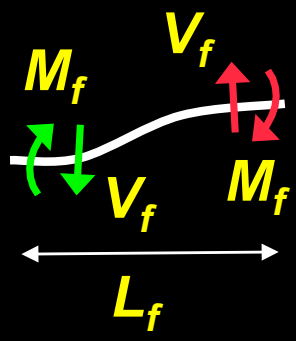
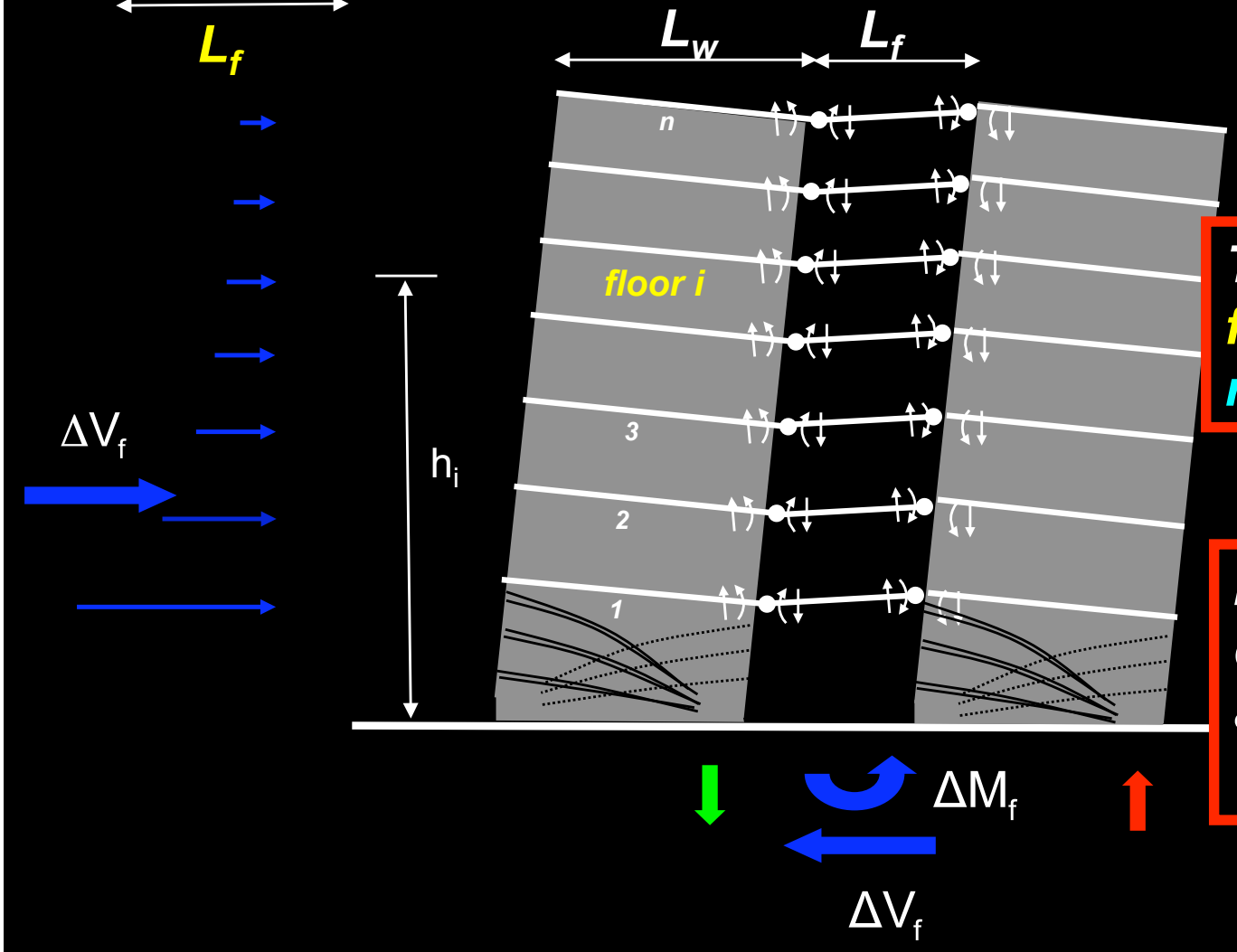


$V_f = 2M_f / L_f$

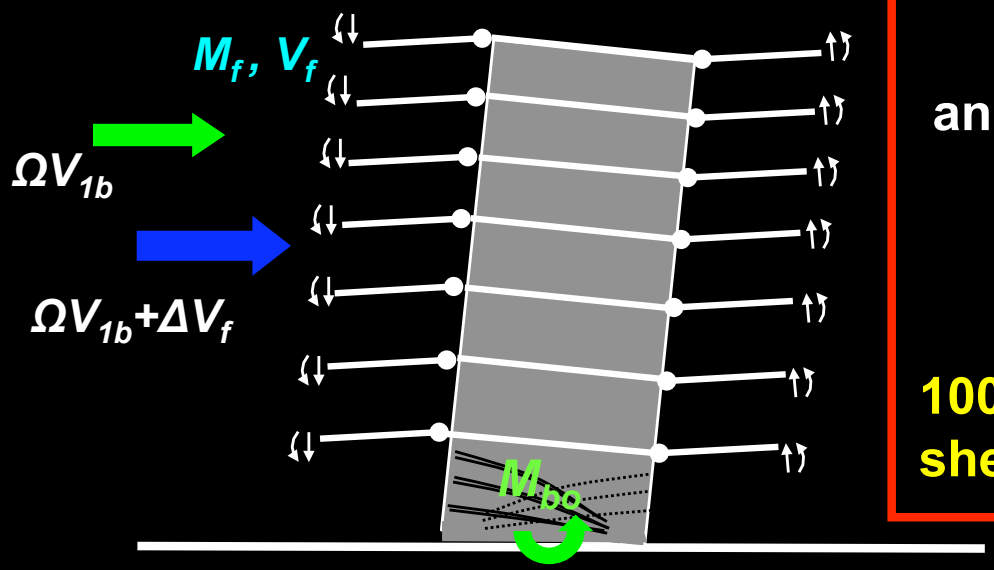
$$\Delta V_f \approx \sum_{i=1}^{n} \frac{2M_f}{h_i}\left(1+\frac{L_w}{L_f}\right)$$



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

In a more "aggressive" design we can take advantage of increased OTM capacity

Displacement-based Design - Static Part

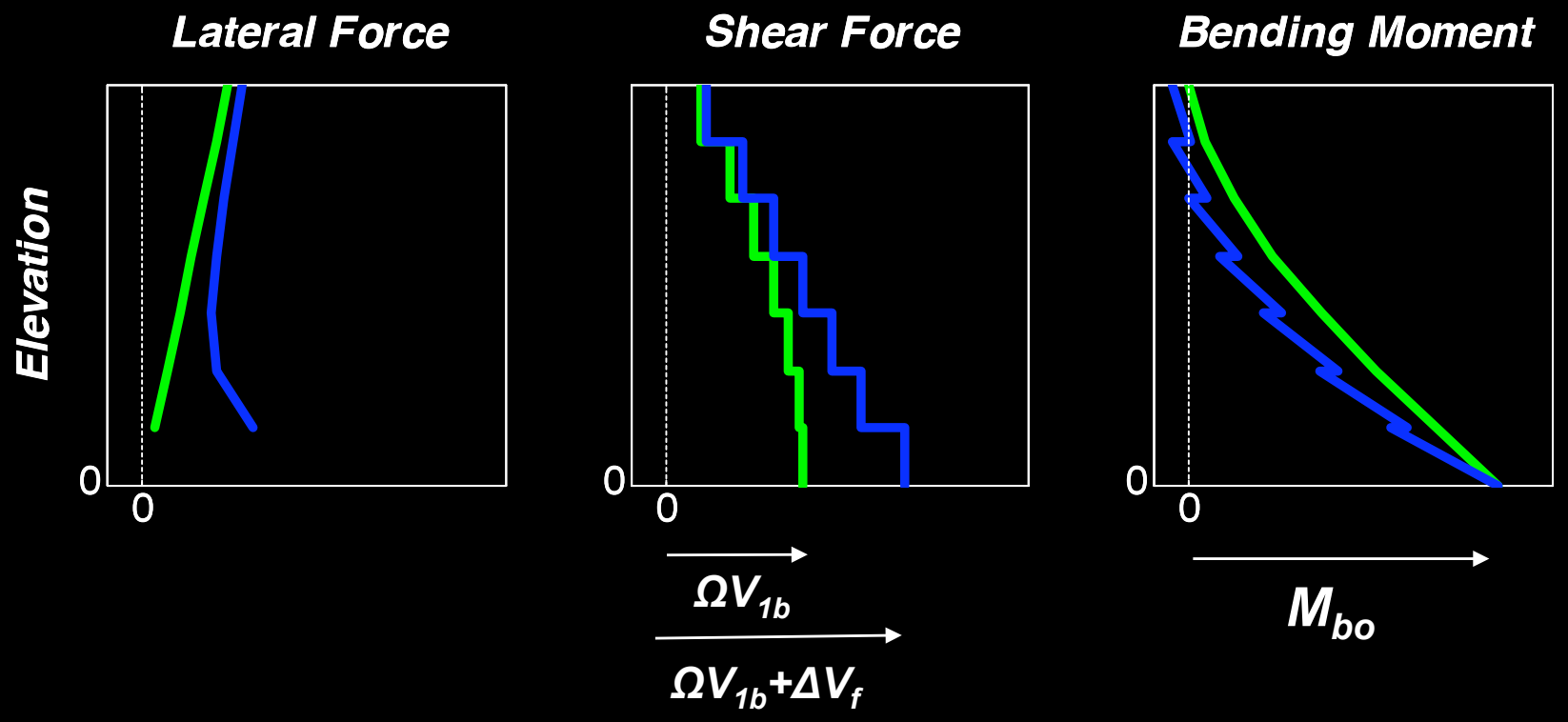


For a 7-Story Wall

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

$\Delta V_f = V_{1b}$

100% Increase of base shear due to frame action !



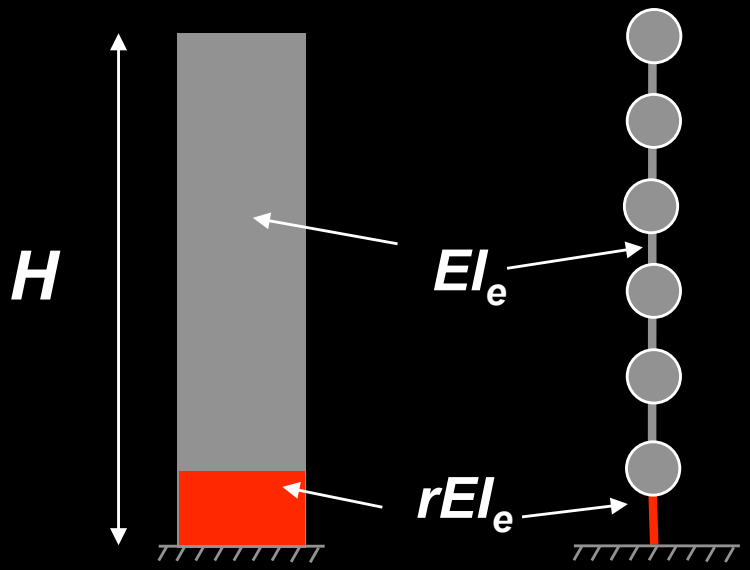
Dynamic Response – 2nd Mode Effects

Lateral Forces due to :

System static flexural Overstrength + 2nd Mode (elastic)

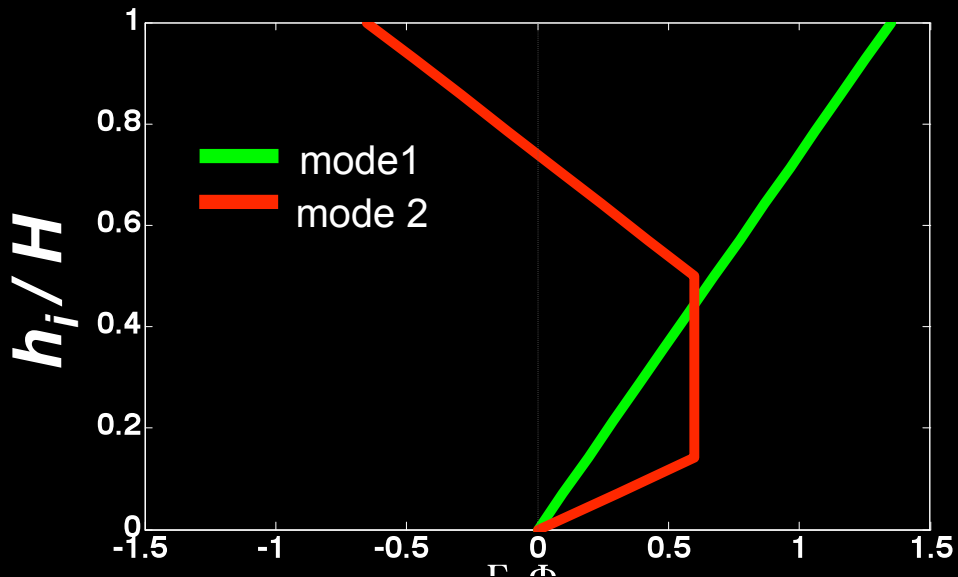
(Wall Overstrength + Framing)

$$F_{1o}^{\ i} = F_{wo}^{\ i} + \Delta V_f^{\ i} \qquad F^i = \sqrt{\left(F_{1o}^{\ i}\right)^2 + \left(F_2^{\ i}\right)^2}$$

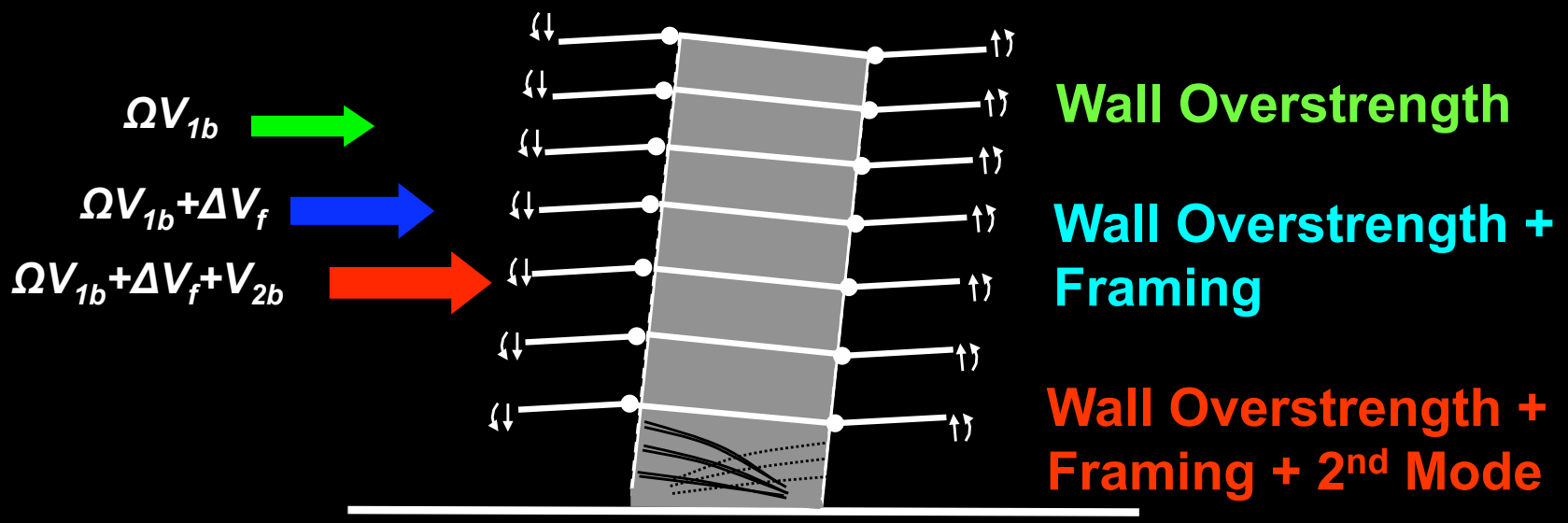


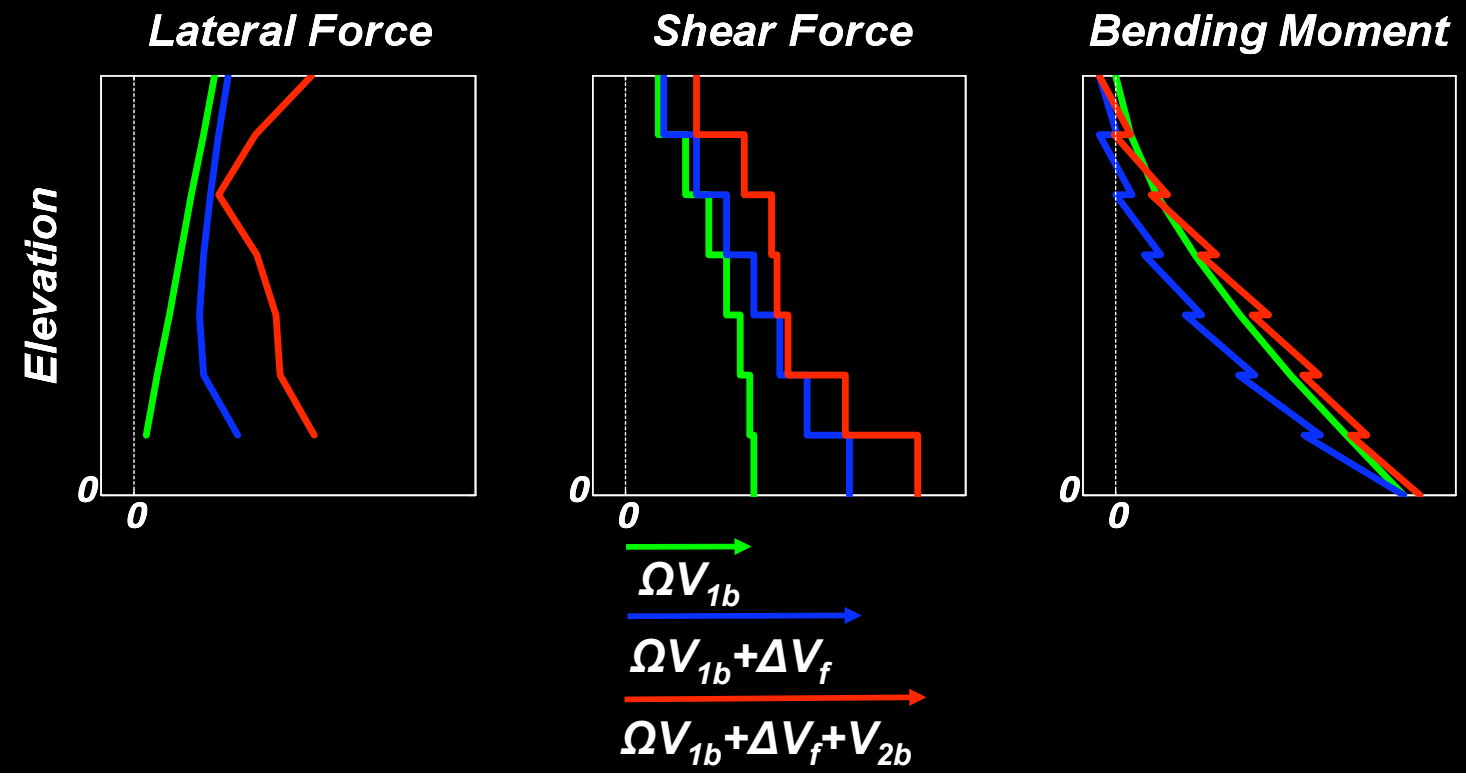
Lumped Mass Model

Modal Force Shape

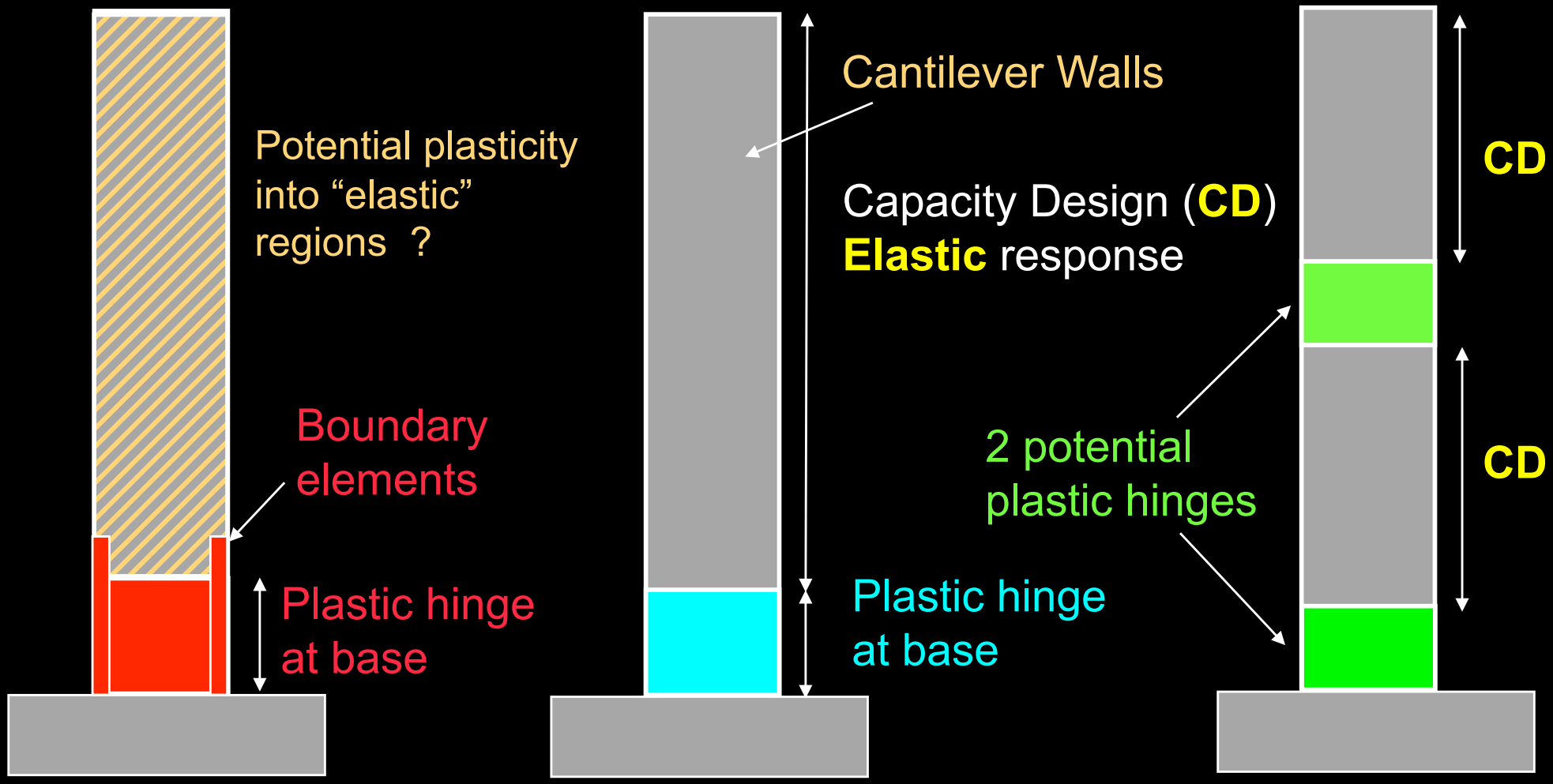


Summary


ΩV_{1b}
$\Omega V_{1b}+\Delta V_f$
$\Omega V_{1b}+\Delta V_f+V_{2b}$
Wall Overstrength
Wall Overstrength + Framing
Wall Overstrength + Framing + 2nd Mode


Lateral Force
Shear Force
Bending Moment
Elevation
0
0
0
0
0
0
ΩV_{1b}
$\Omega V_{1b}+\Delta V_f$
$\Omega V_{1b}+\Delta V_f+V_{2b}$

2nd Mode Effects -3 Design Cases of Cantilever Walls

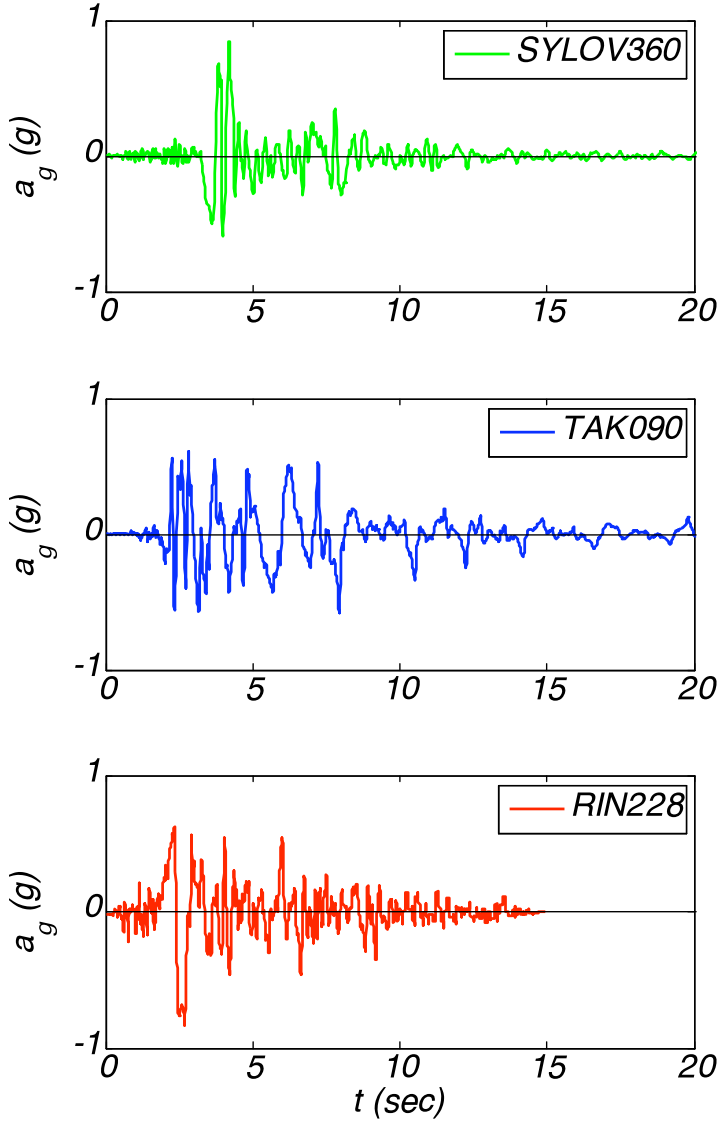


ACI-318 Design

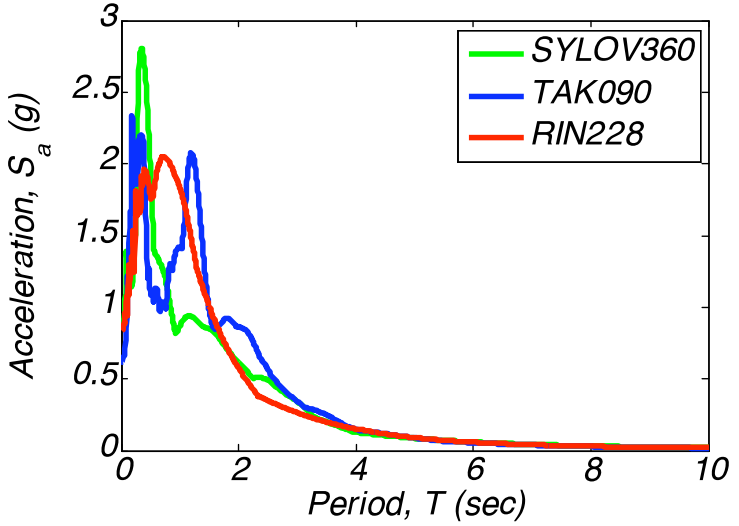
EC-8 Design
Single Plastic Hinge (SPH)

Dual Plastic Hinge (DPH)

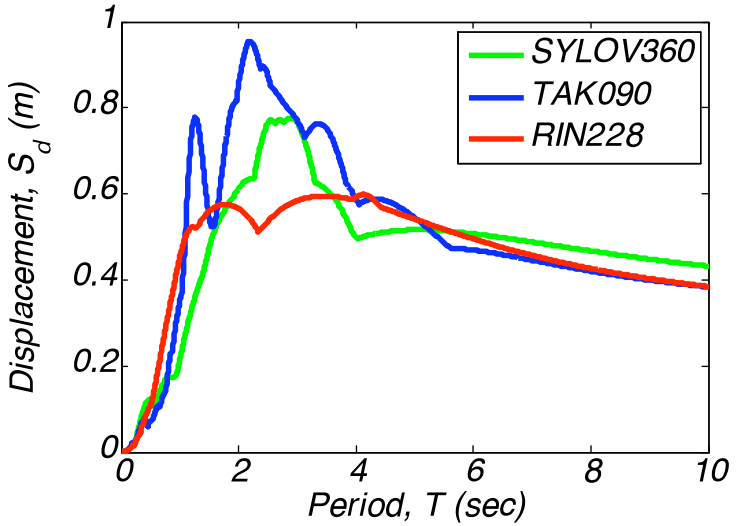
Design and analysis of 10-, 20- and 40-story cantilever walls for 3 near-fault records



(a) Time histories

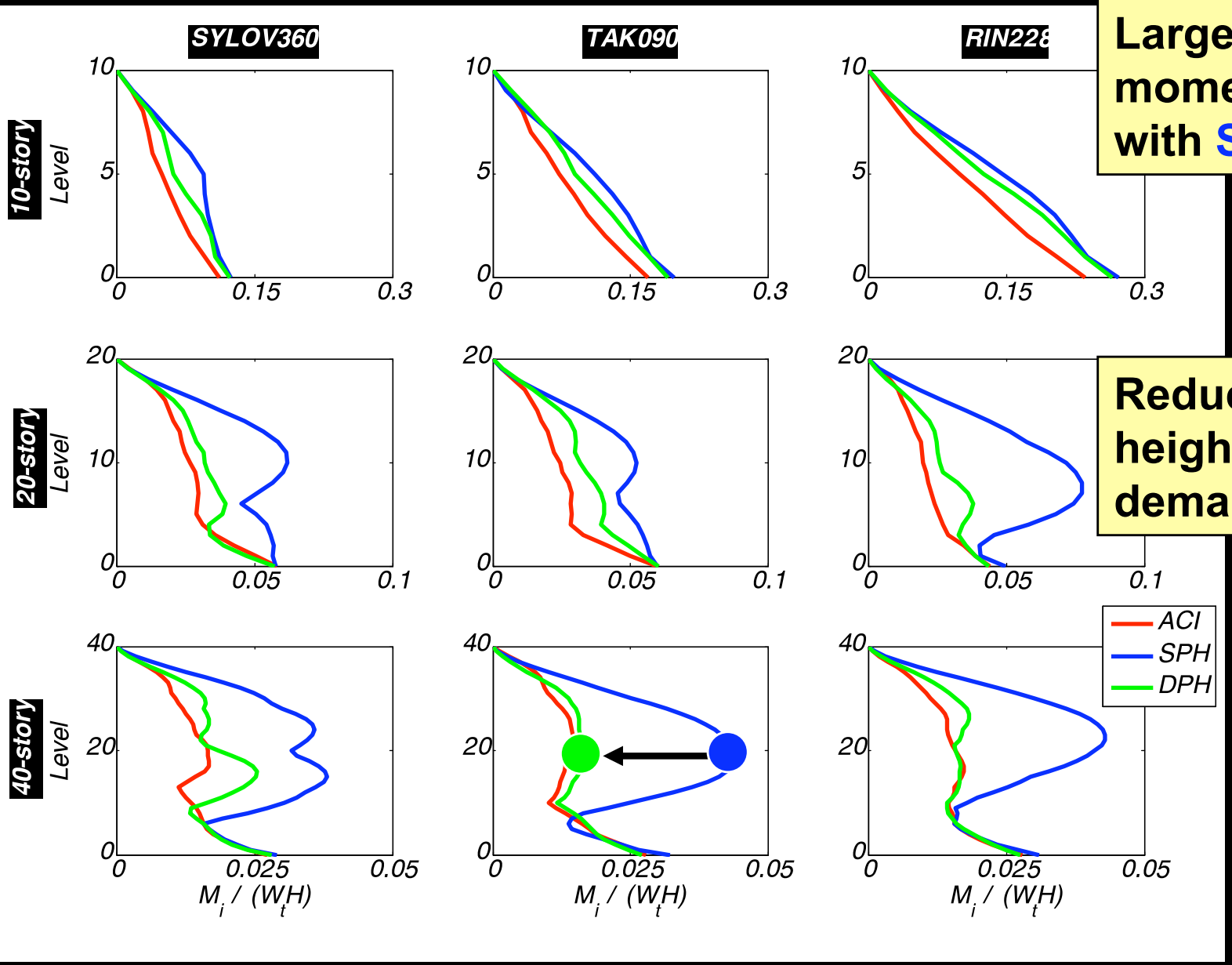


(b) Acceleration response spectra



(c) Displacement response spectra

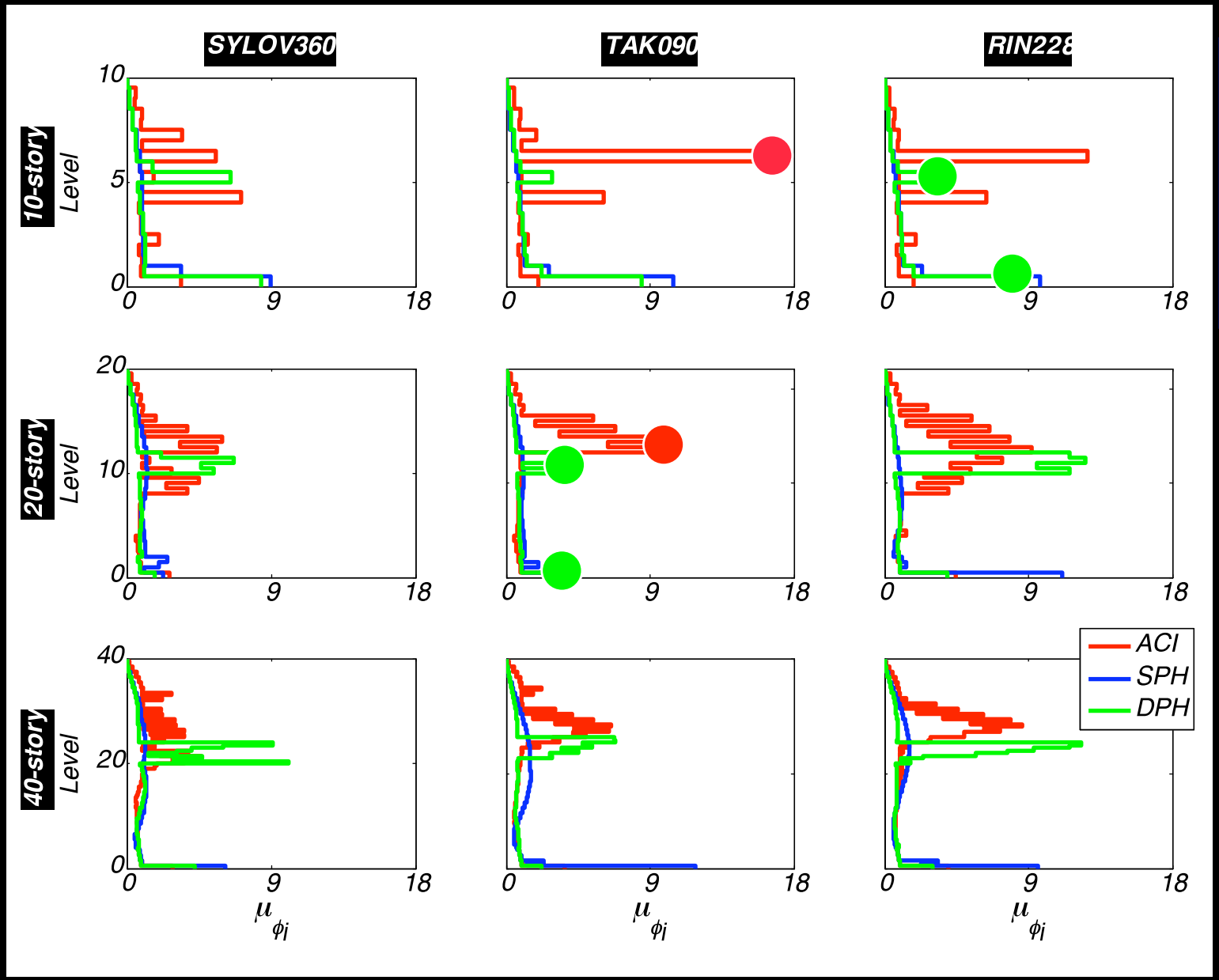
Bending Moment Envelopes – Comparison of designs



Large mid-height moment demand with SPH

Reduction of mid-height moment demand with DPH

Curvature Ductility Envelopes - Comparison of designs



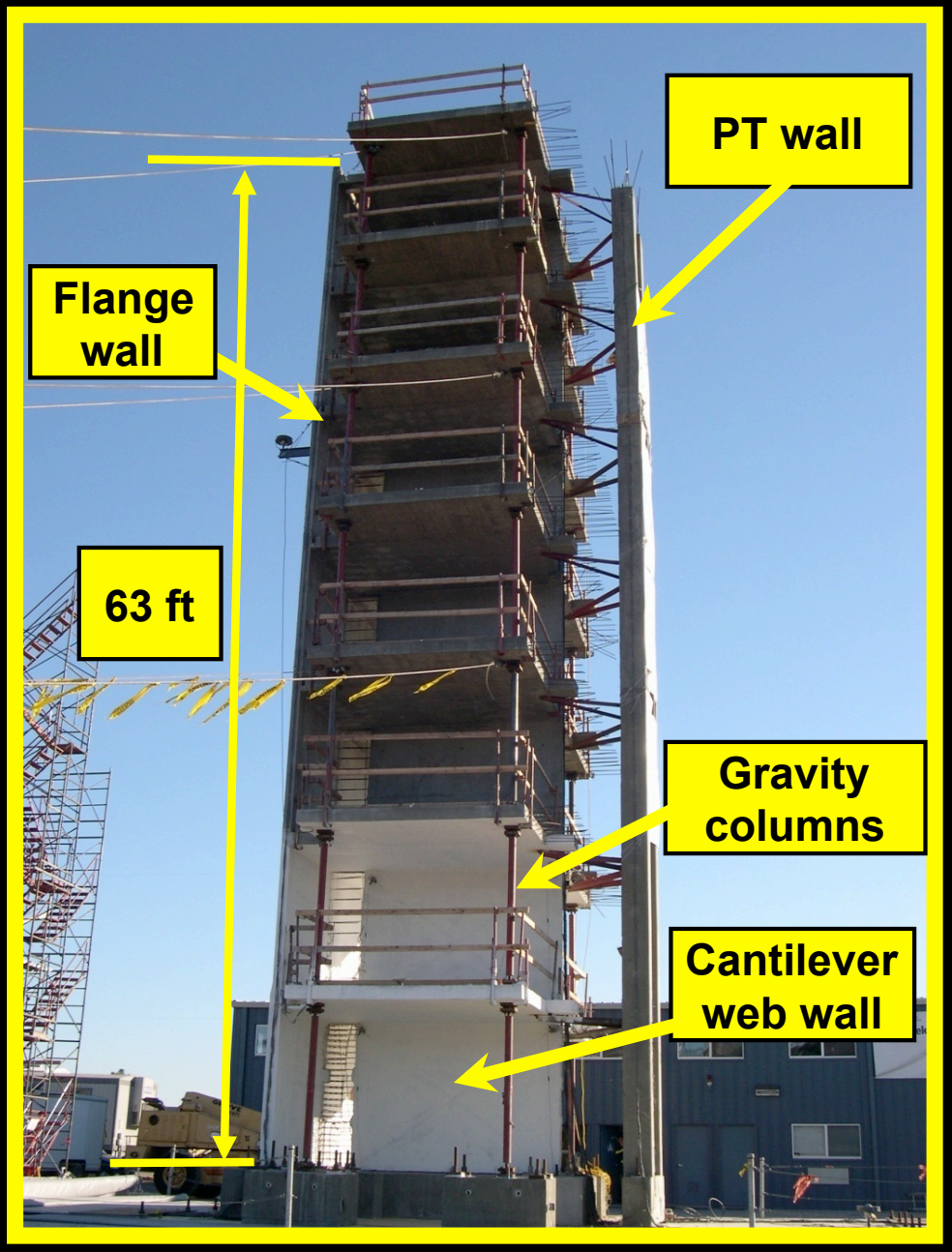
Large μ_Φ demand in unexpected regions with ACI design

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

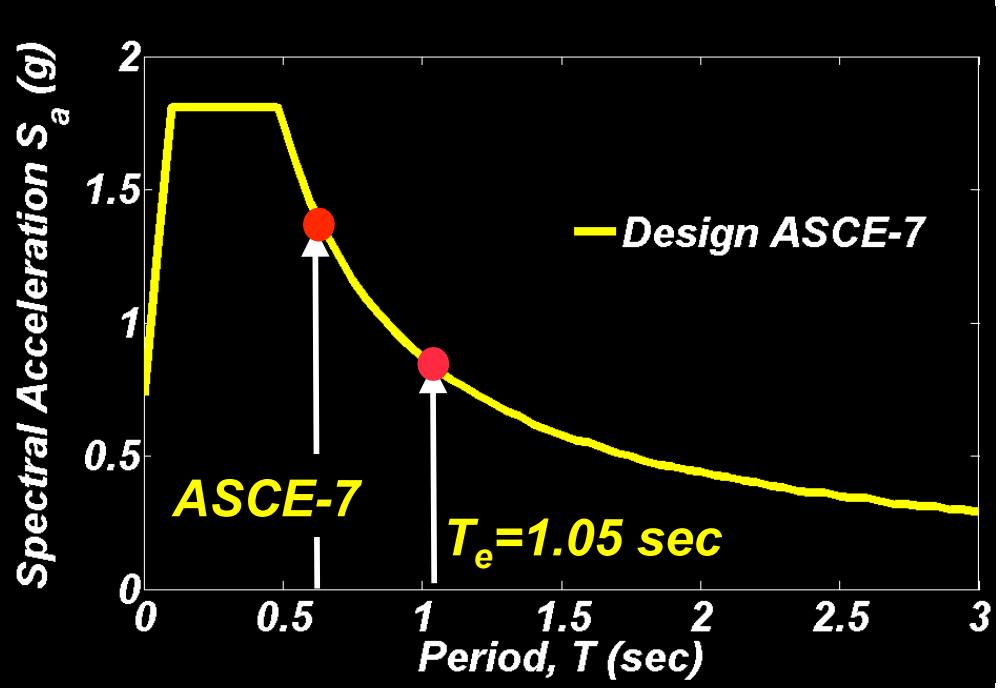
- Verify the seismic performance of medium rise RC wall buildings designed with displacement-based method (DbD)

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

V = 0.28 W (T=0.63 sec)

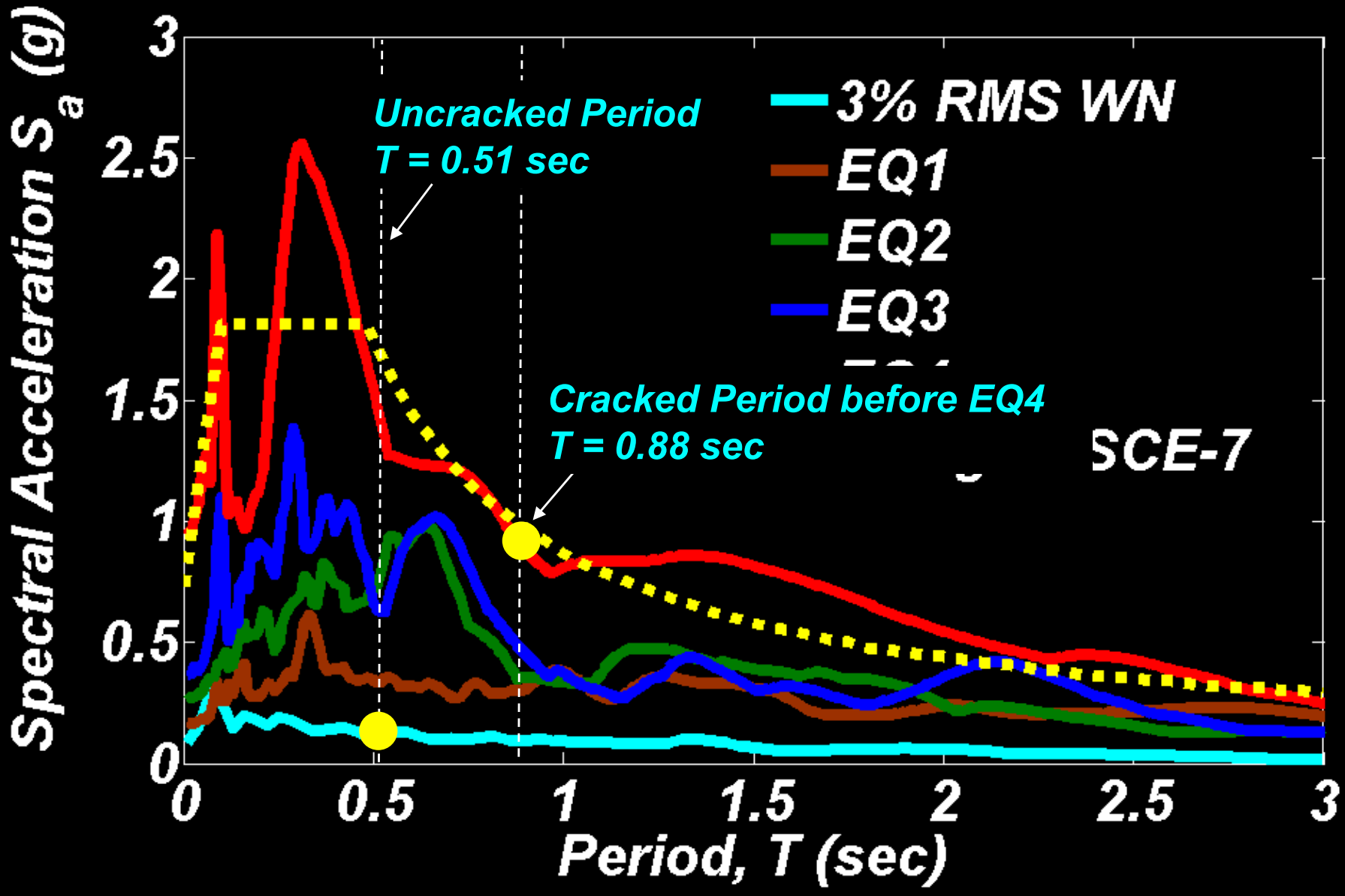
- Displacement-based Design

V = 0.15 W (T_e=1.05 sec)



Period T and R unknown until the end of the design

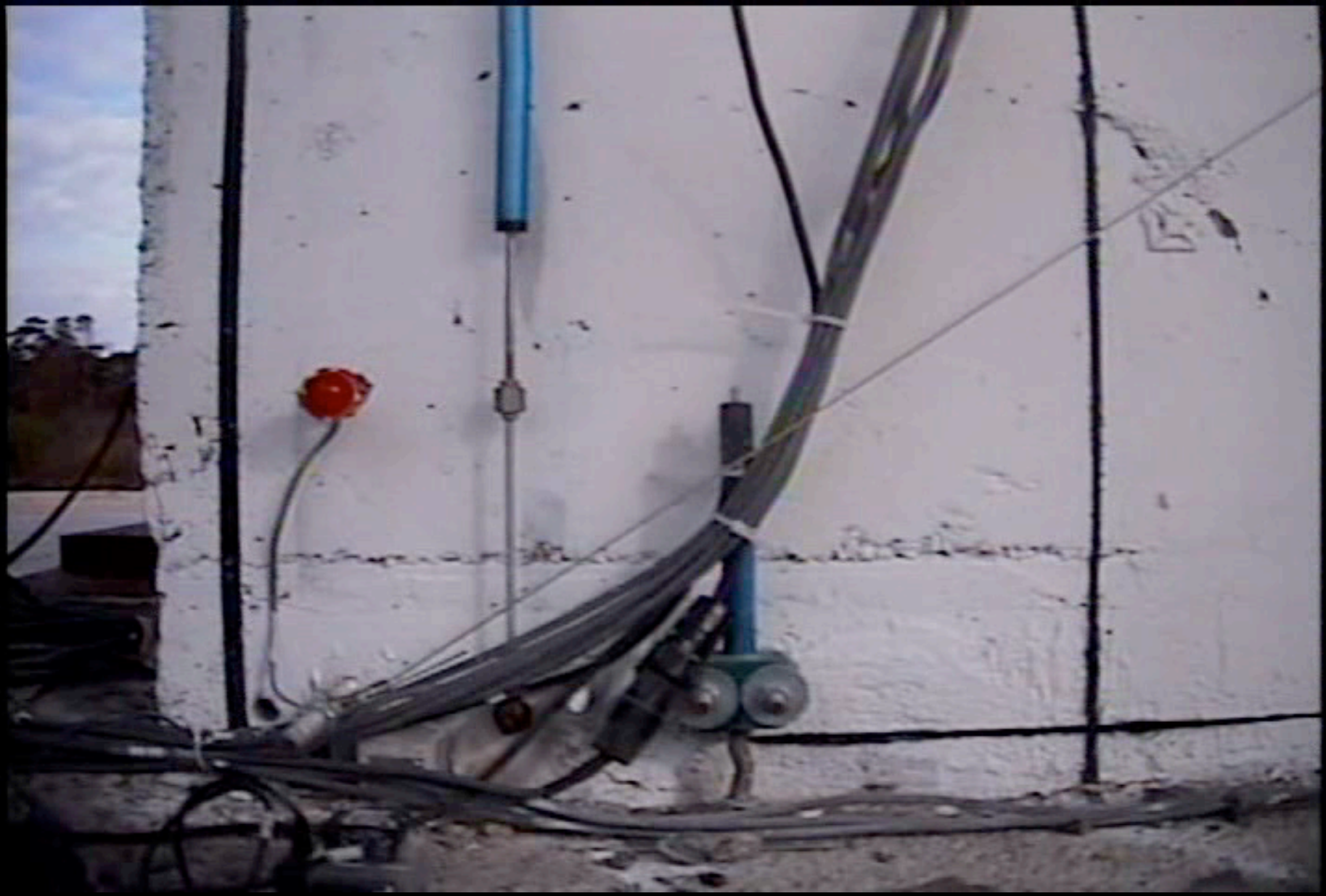
Acceleration Response Spectra
damping=5%



EQ4: Roof Drift Ratio 2.1%, PGA = 0.93g

EQ4: Level 1 – Plastic Hinge Region

EQ4: max Steel Tensile Strain ε_s=2.7%



Experimental Response – *Observations*

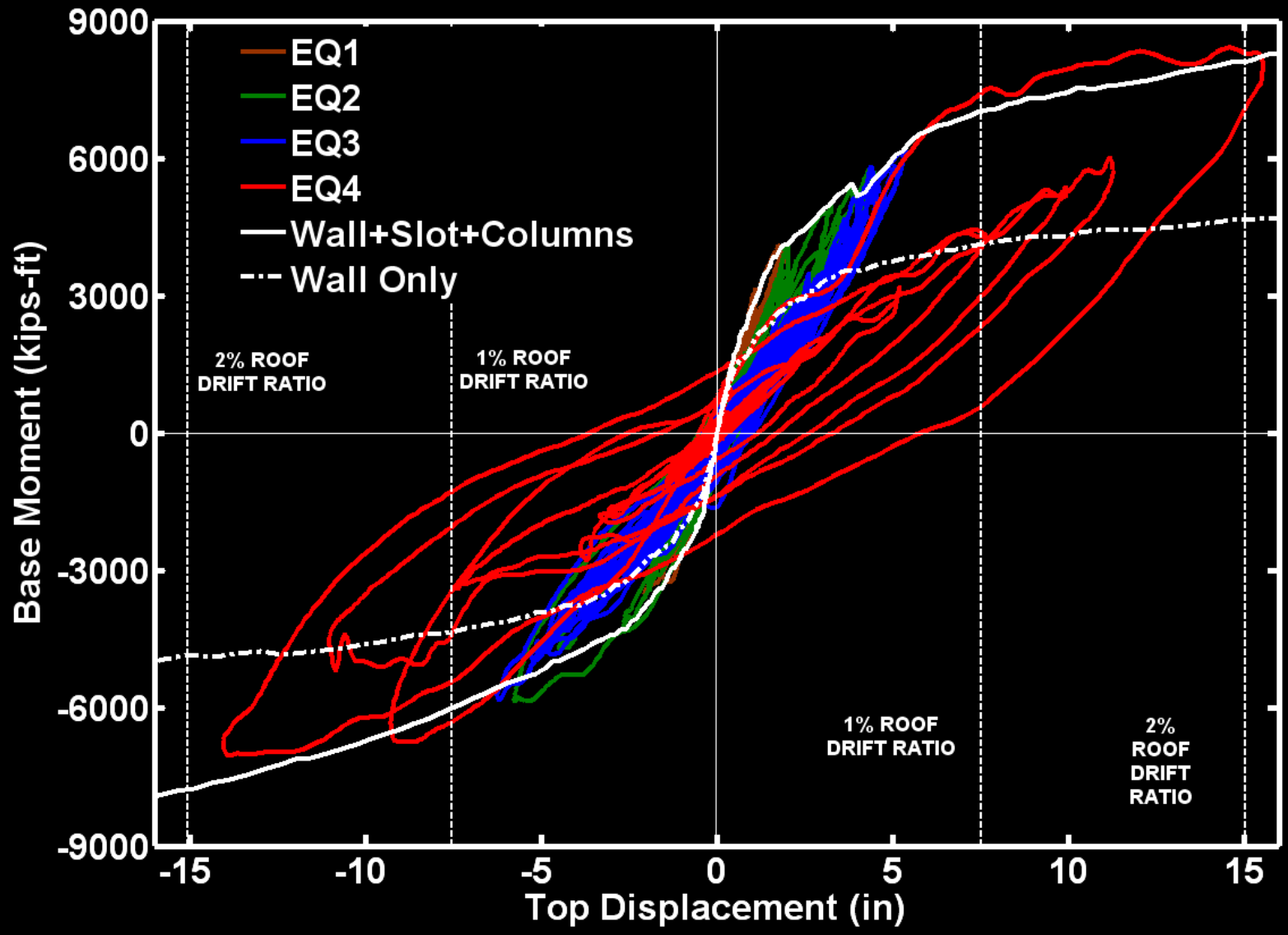
1. *The performance objectives were met for significantly reduced (50%) design seismic forces*

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

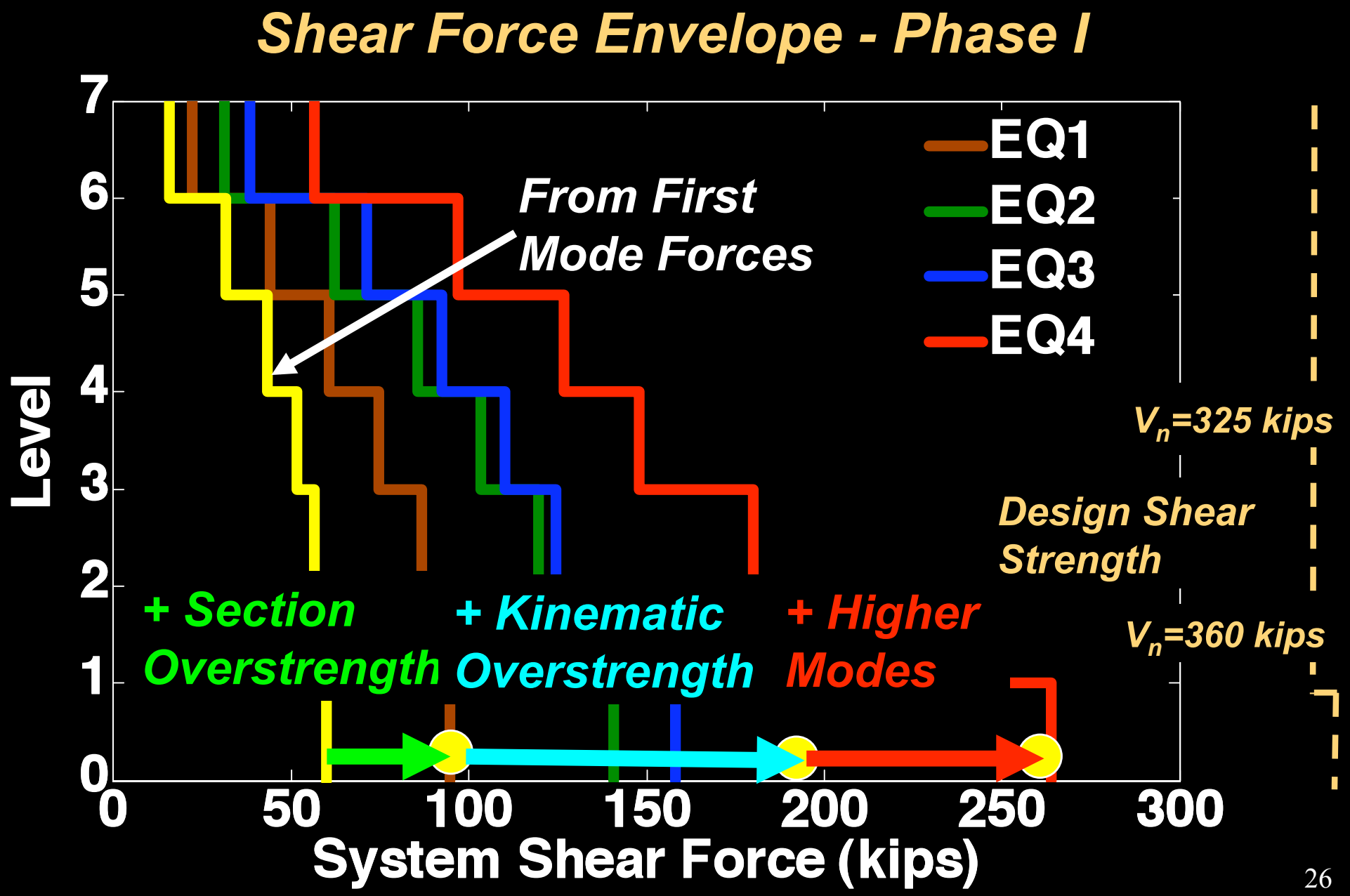
3. *Higher mode effects, additionally increased shear forces and floor accelerations*

Observation 2. Kinematic System Overstrength

Hysteretic Response - Phase I



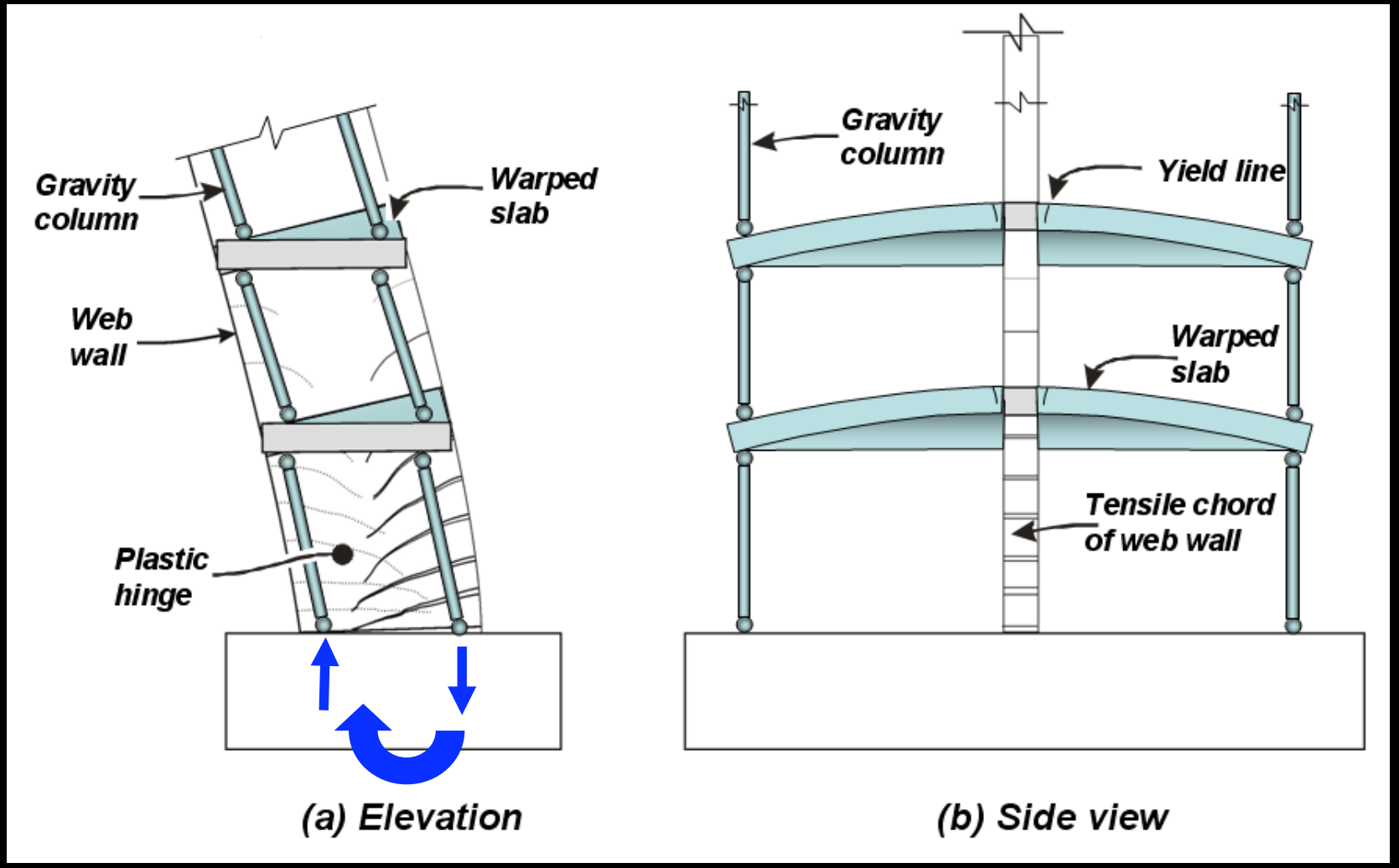
Observ. 2&3. System Overstrength & Higher Modes




End

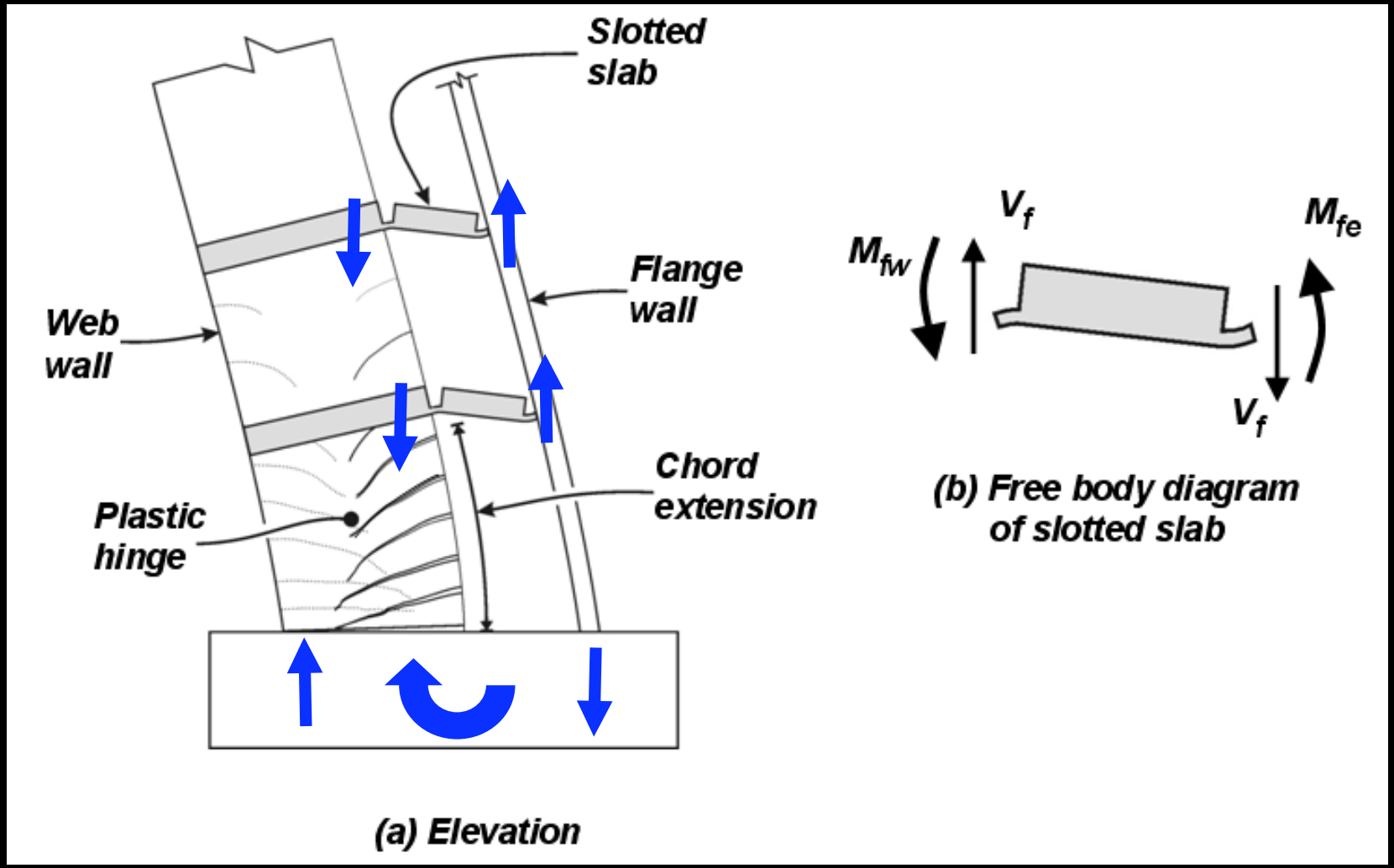
Observation 3. Kinematic System Overstrength

Framing between web wall - slab – gravity columns

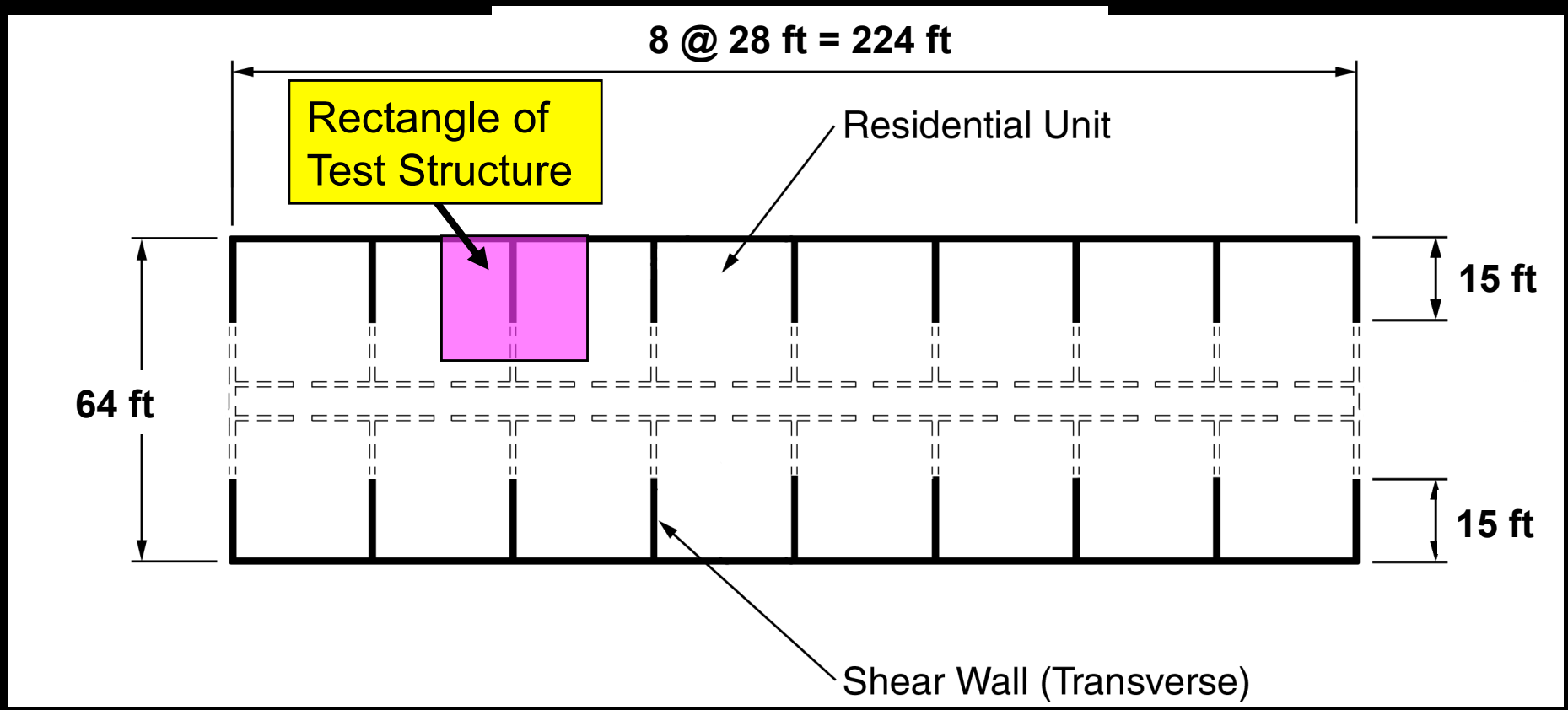


Observation 3. Kinematic System Overstrength

Framing between web wall – slotted slab – flange wall



Plan of 7-Story Prototype Building

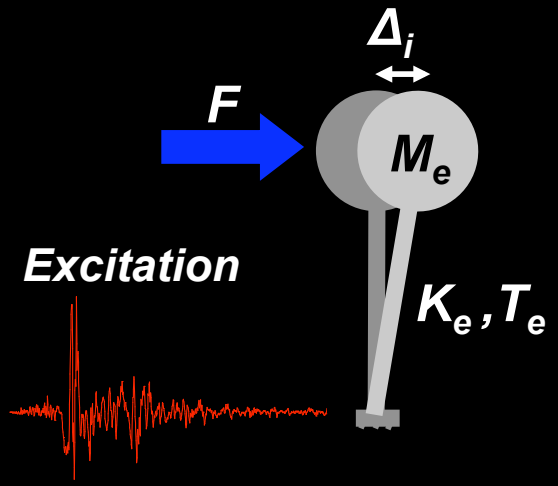


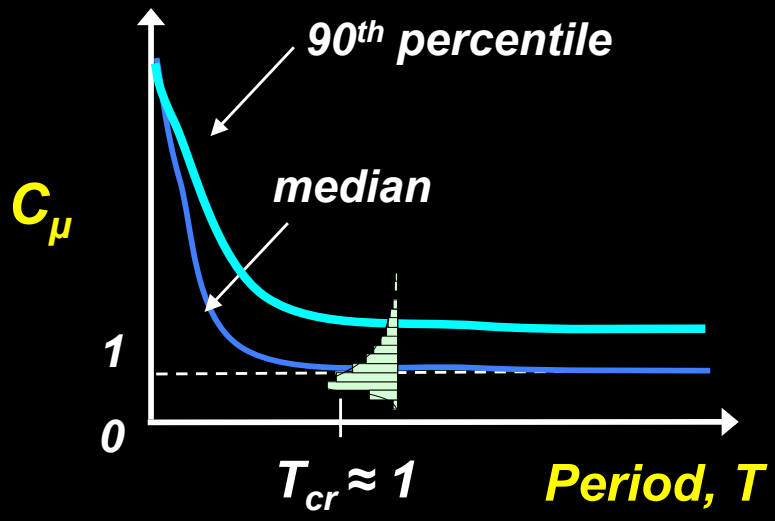
Conclusions

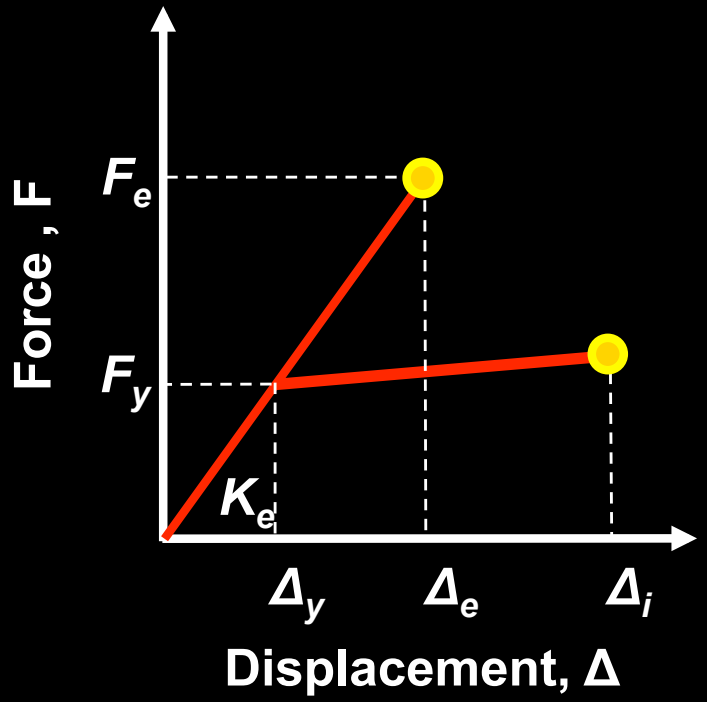
1. The 7-story building test verified the Db seismic design approach indicating the important effects of system overstrength and higher modes of response

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







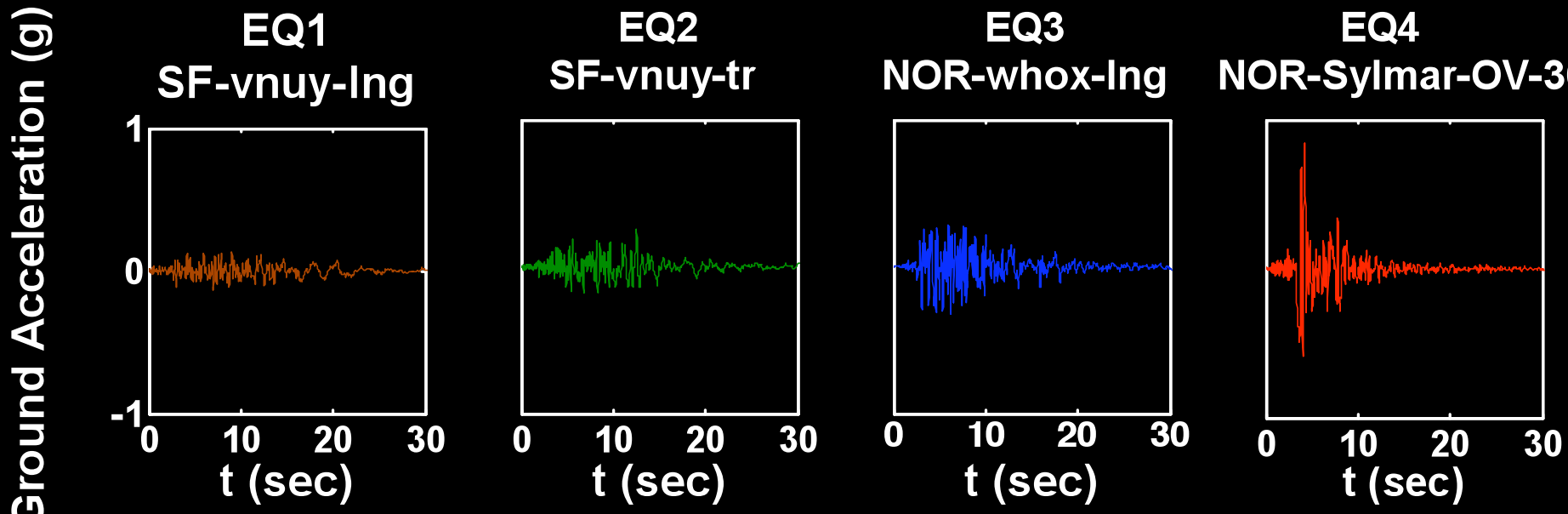
$$R = \frac{F_e}{F_y} \qquad \mu = \frac{\Delta_i}{\Delta_y}$$

$$C_\mu = \frac{\mu}{R} = \frac{\Delta_i}{\Delta_e}$$

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*

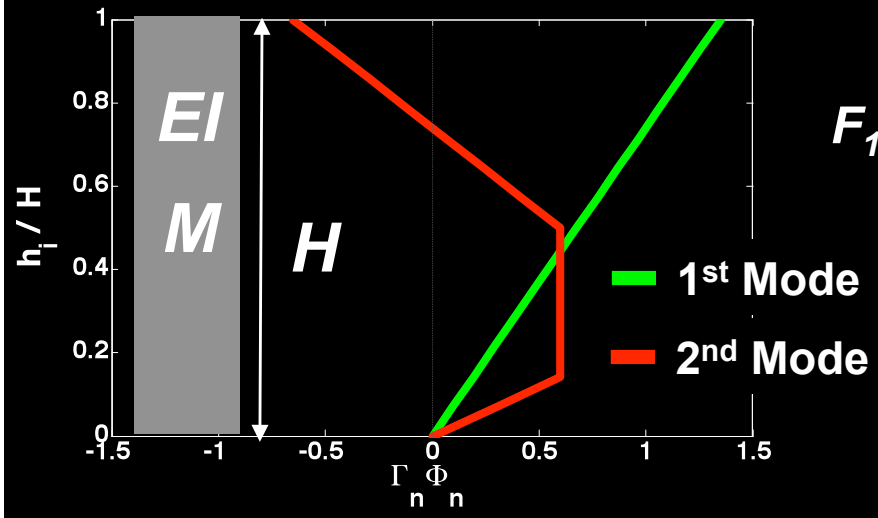
Test Regime



- *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

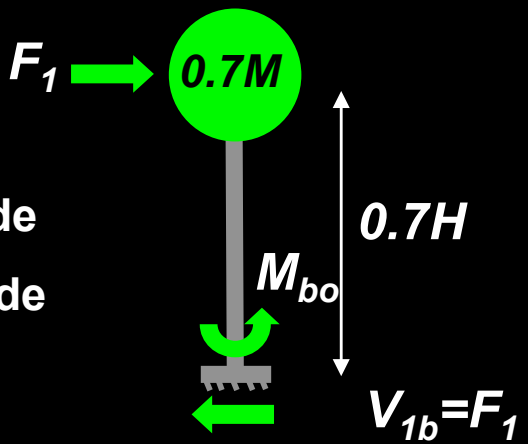
Dynamic Response – 2nd Mode Effect

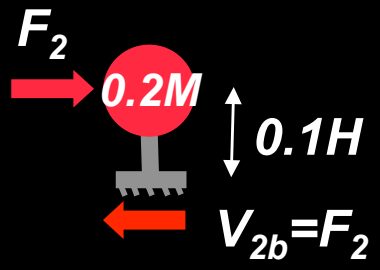


$$F_1 = (0.7M)Sa_1 \qquad \frac{M_{bo}}{0.7H}$$

$T_2 \approx T_1 / 5$

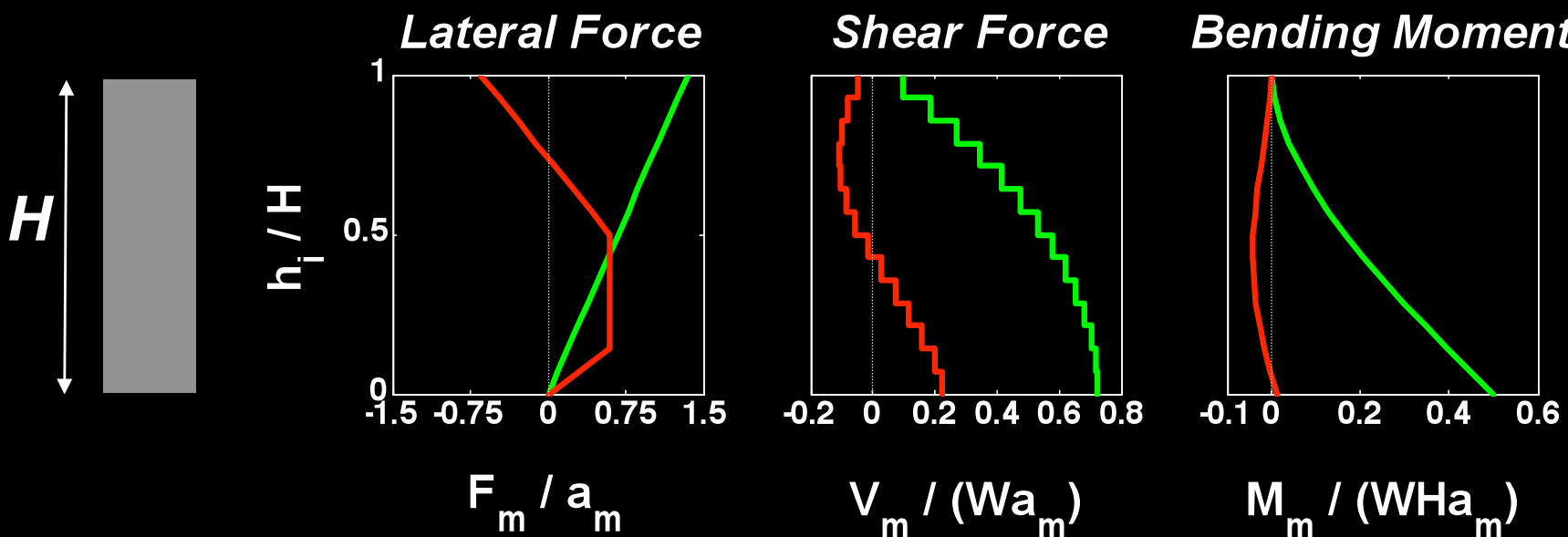
$F_2 = (0.2M) * Sa_2$





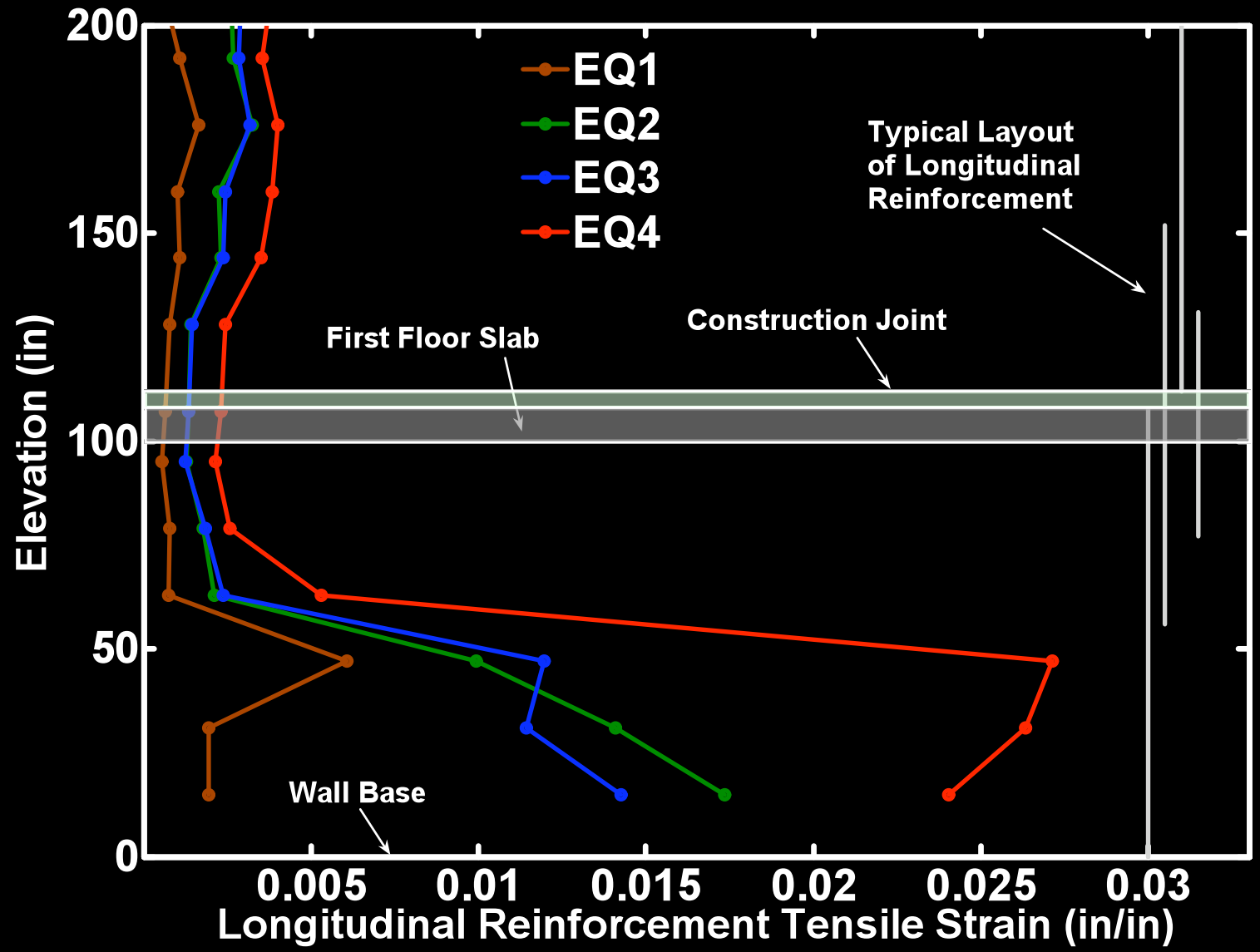
a_m: modal acceleration

Dimensionless Response

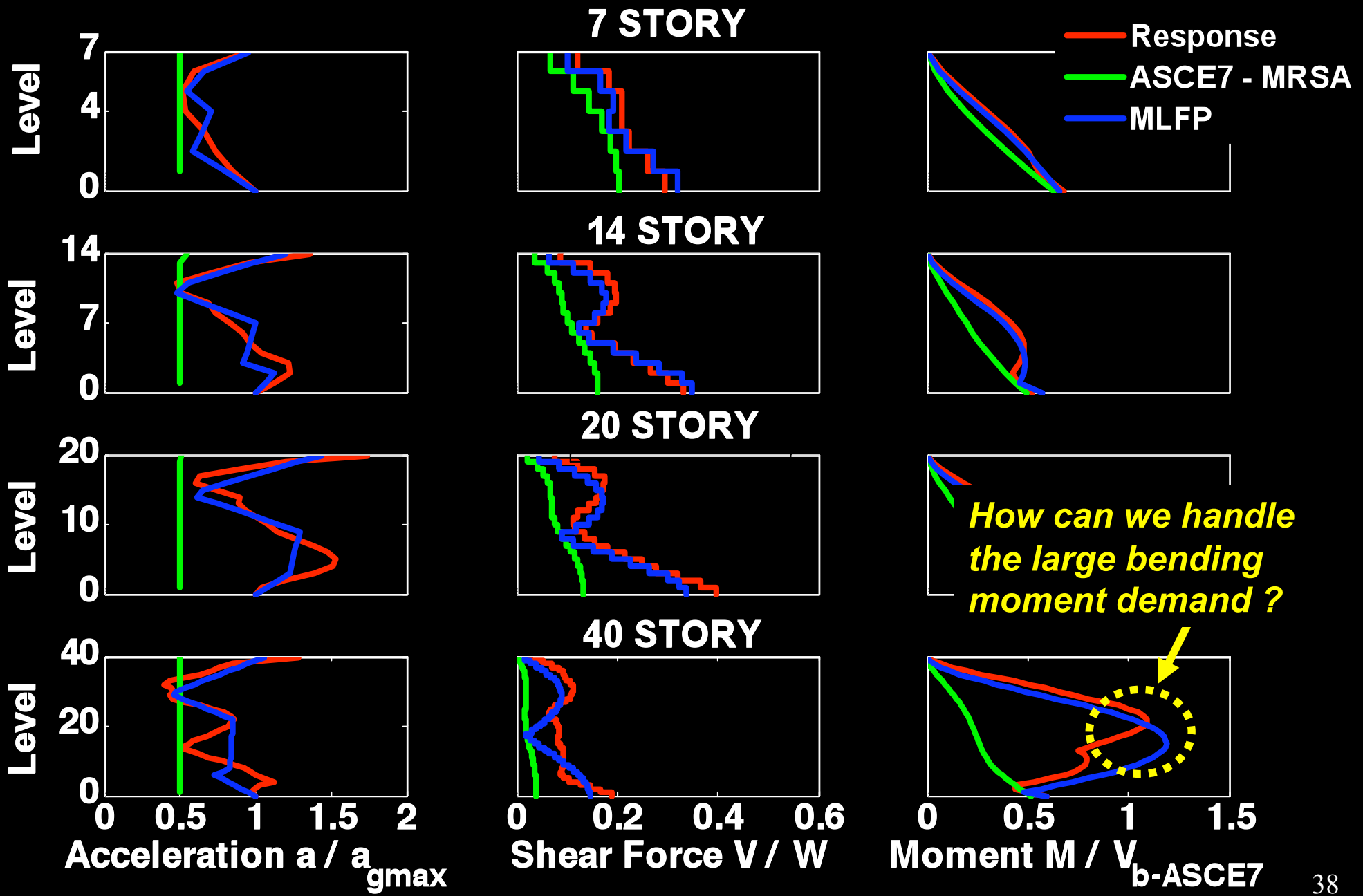


Observation 1. Strain Performance Objectives Met

Levels 1 and 2 - Tensile Strain Envelope

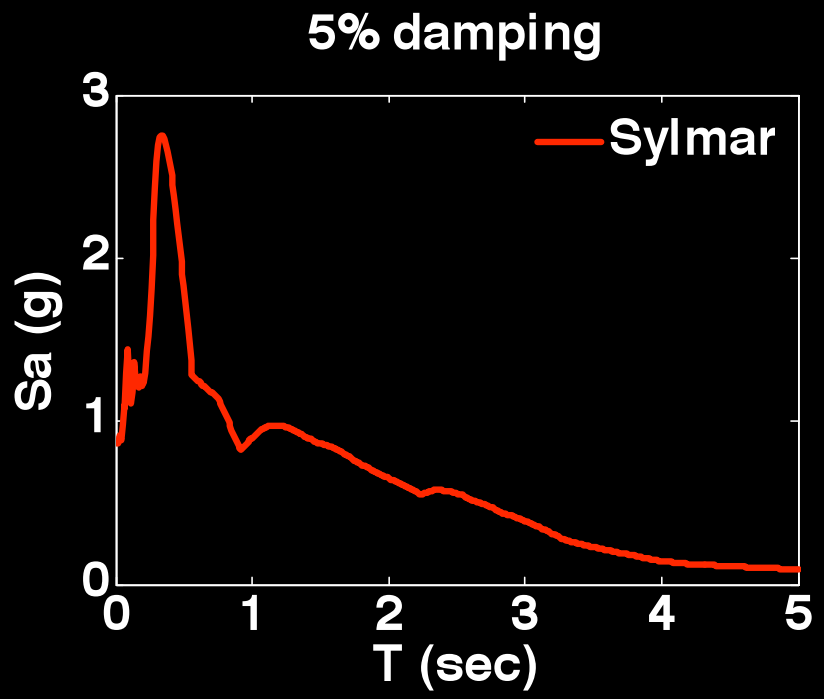


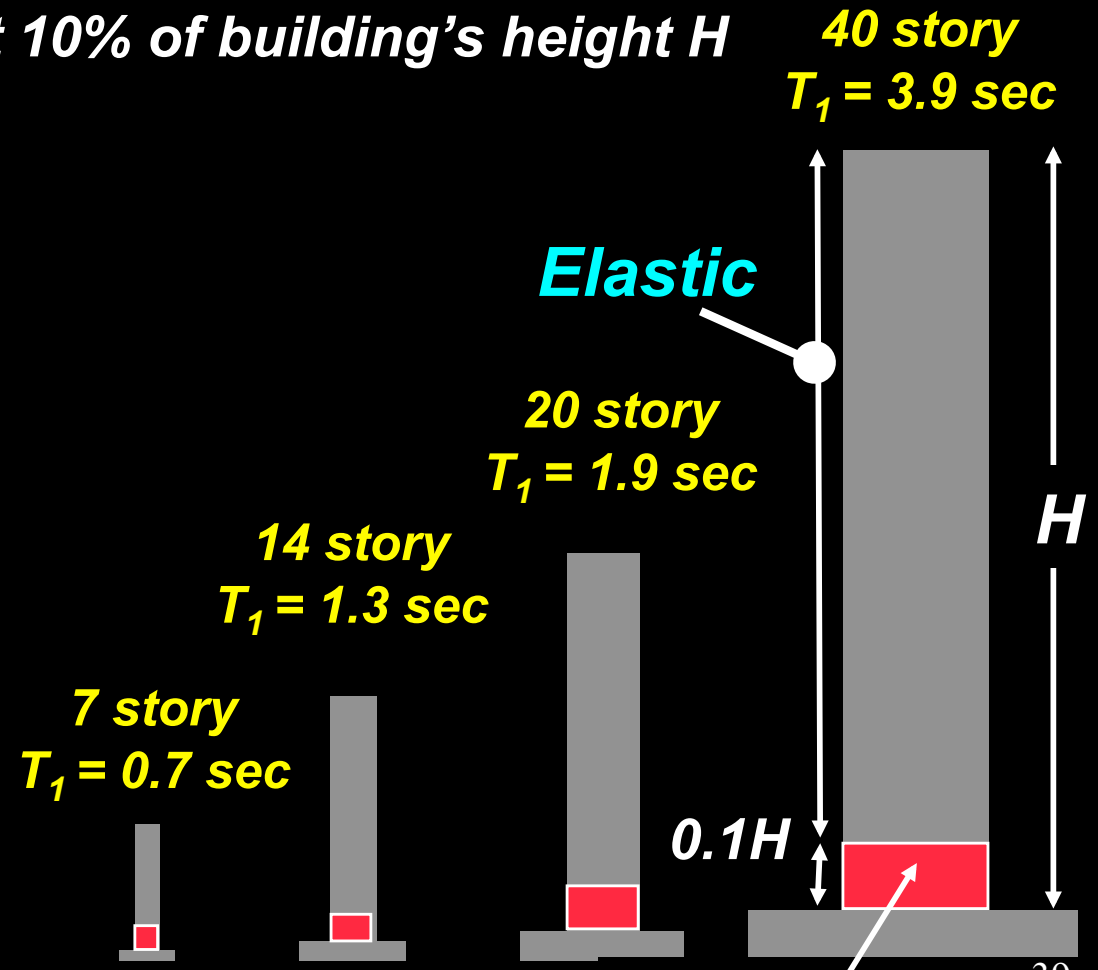
Effect of Higher Modes – Numerical Example



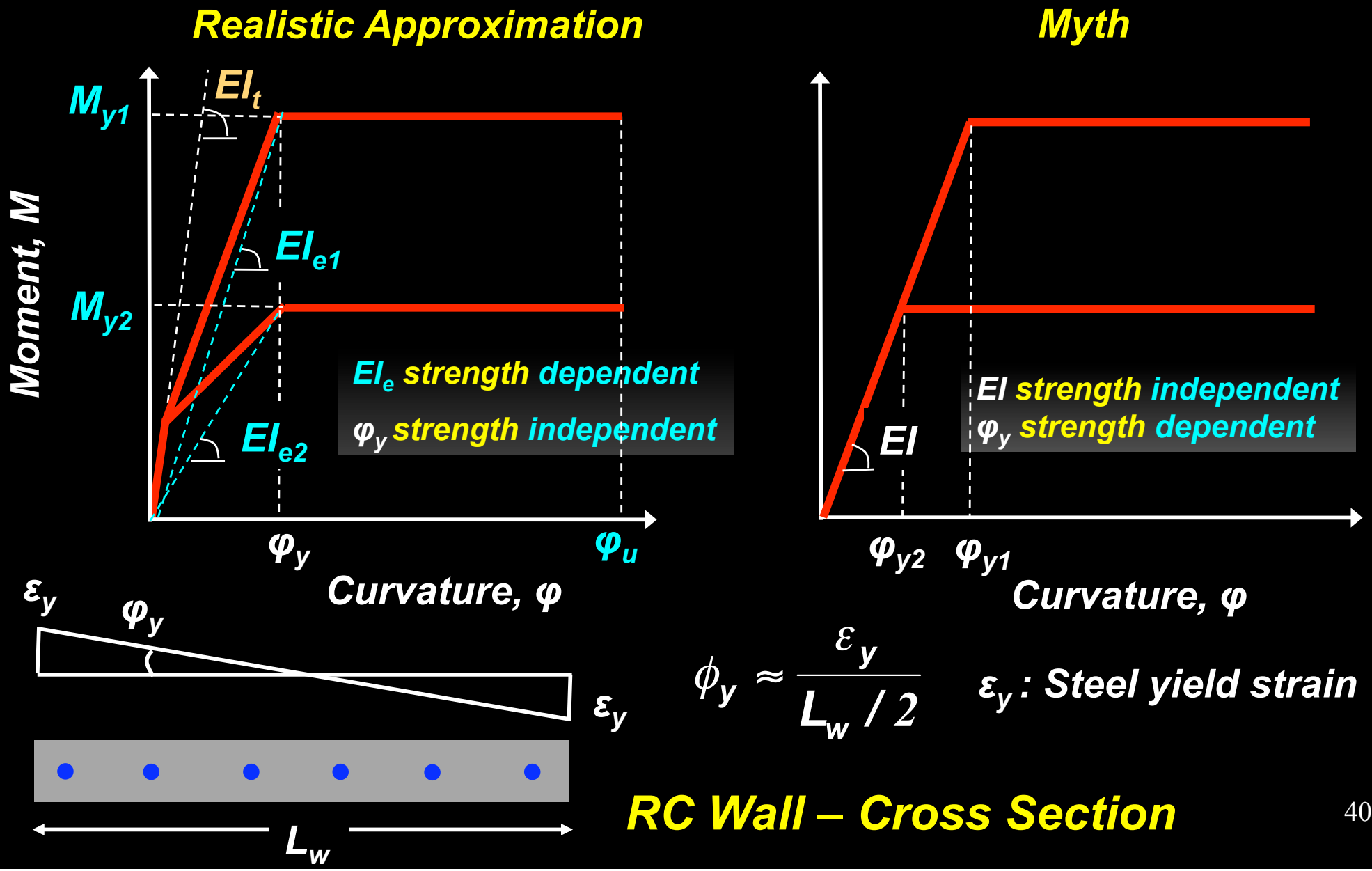
Effect of Higher Modes – Numerical Example

- 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

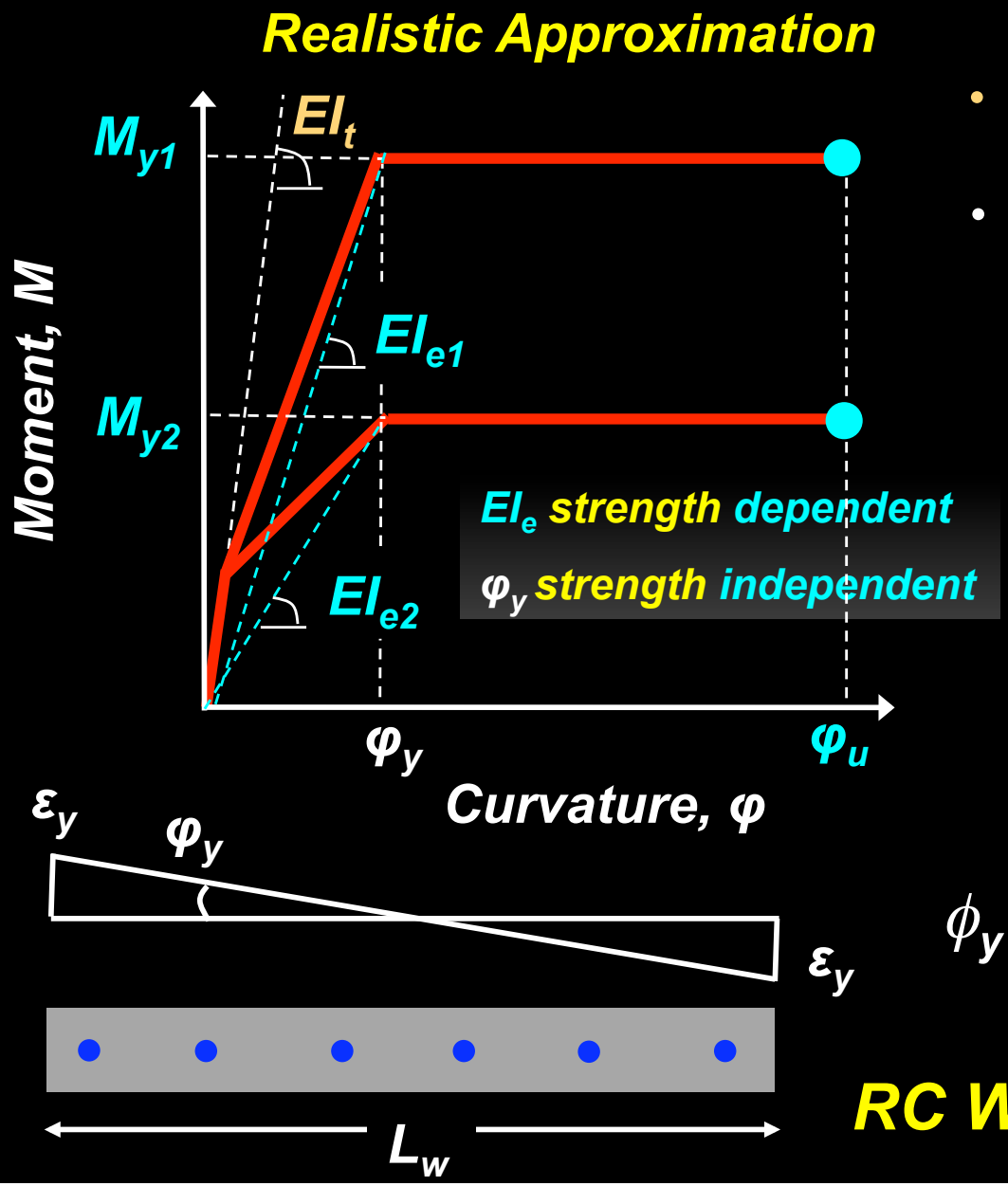




Stiffness in RC structures is Strength dependent



Stiffness in RC structures is Strength dependent



For large curvature ductility $\mu_\varphi = \varphi_u / \varphi_y$:

- Uncracked stiffness EI_t is immaterial
- Demand (φ_u) depends on effective stiffness EI_e

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

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

ε_y : Steel yield strain

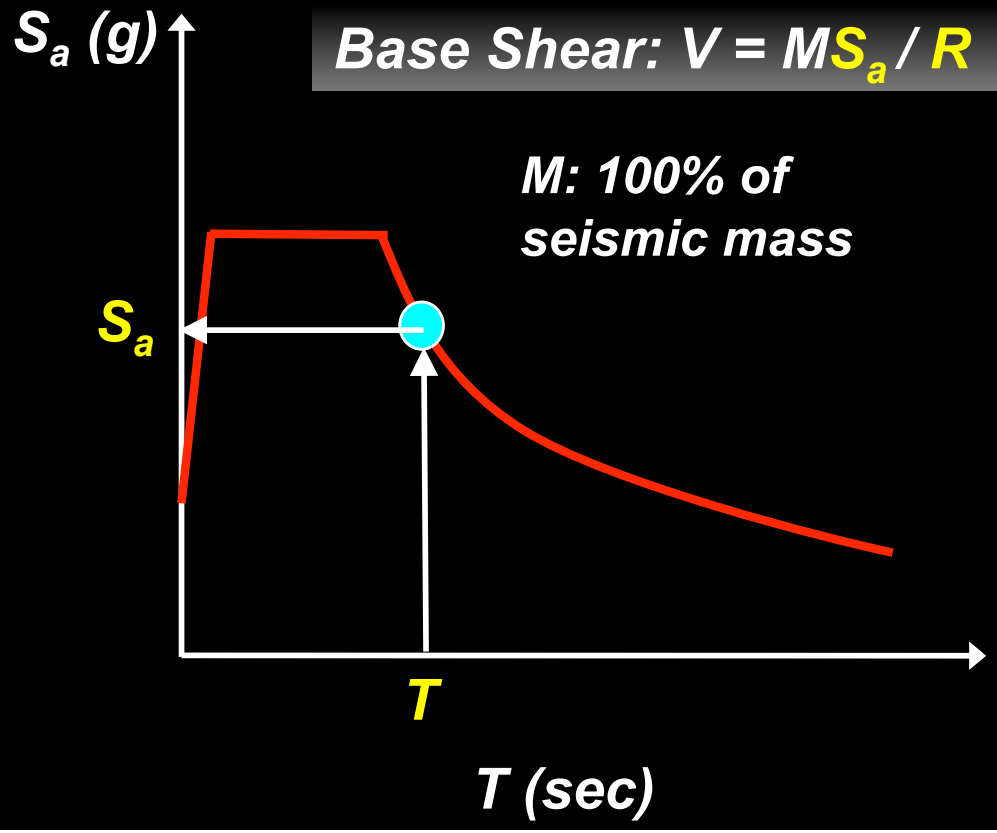
RC Wall – Cross Section

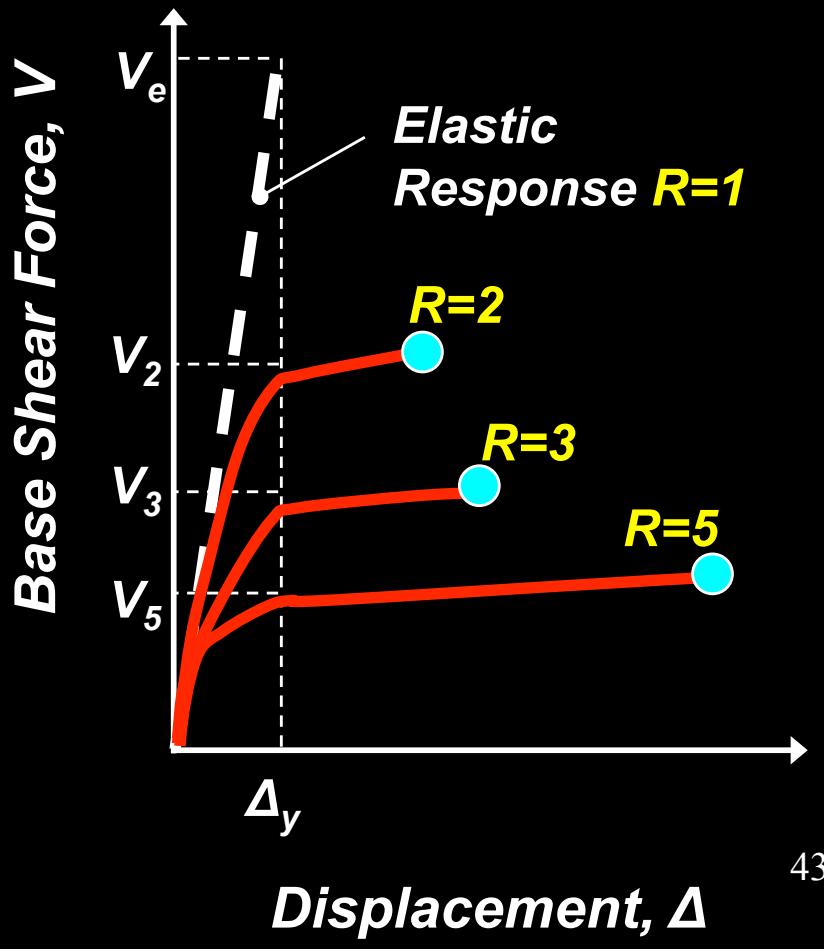
UCSD 7-Story Building Slice - 3%g RMS WN Test

Force-based Design

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

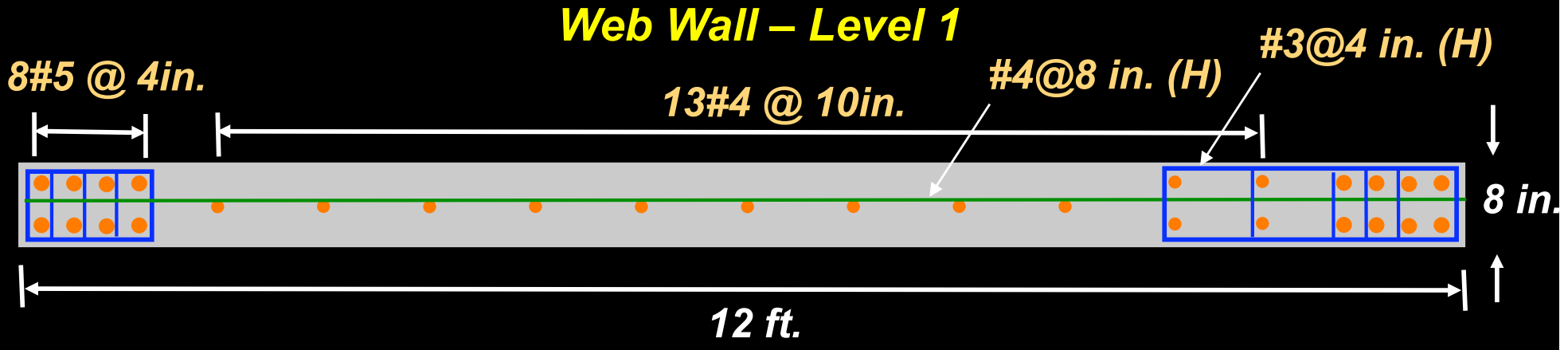
Design only for Collapse Prevention Performance Objective
How about Immediate Occupancy?





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

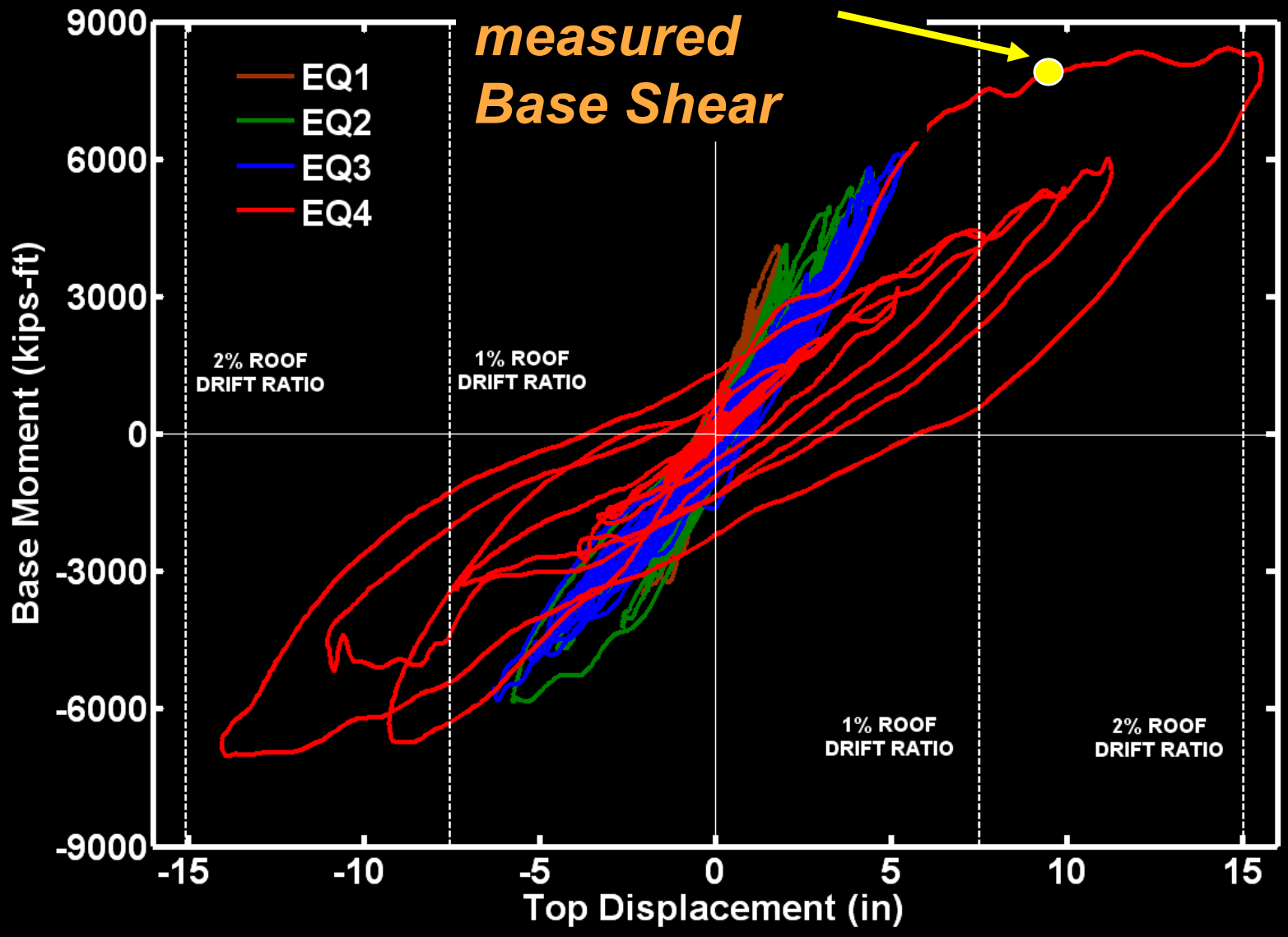


$\rho_l = 0.65\%$ $\rho_t = 0.31\%$ $\rho_v = 1.36\%$

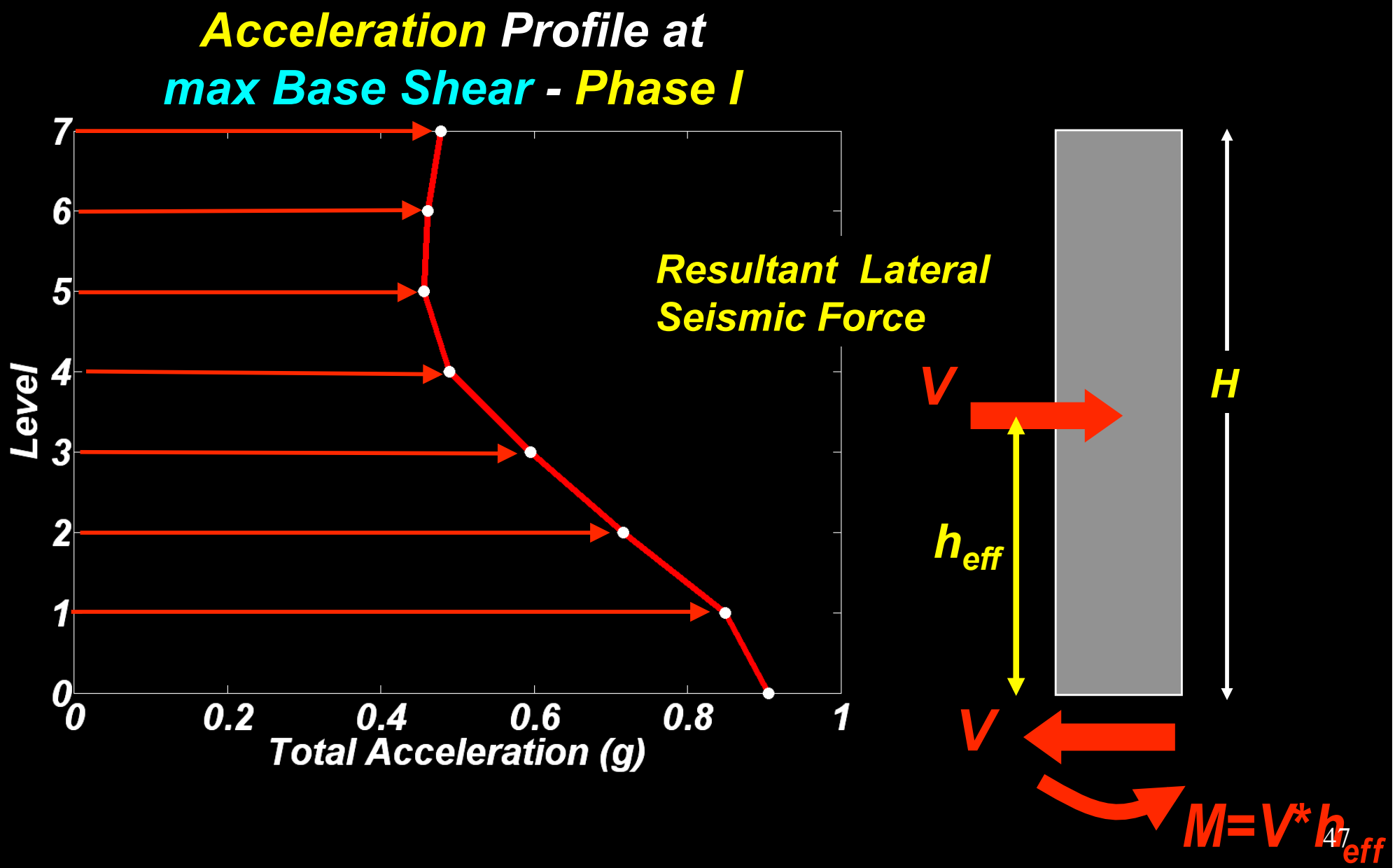
$\rho_l = 0.87\%$ $\rho_t = 0.4\%$ $\rho_v = 0$

Wall Reinforcement Level 1

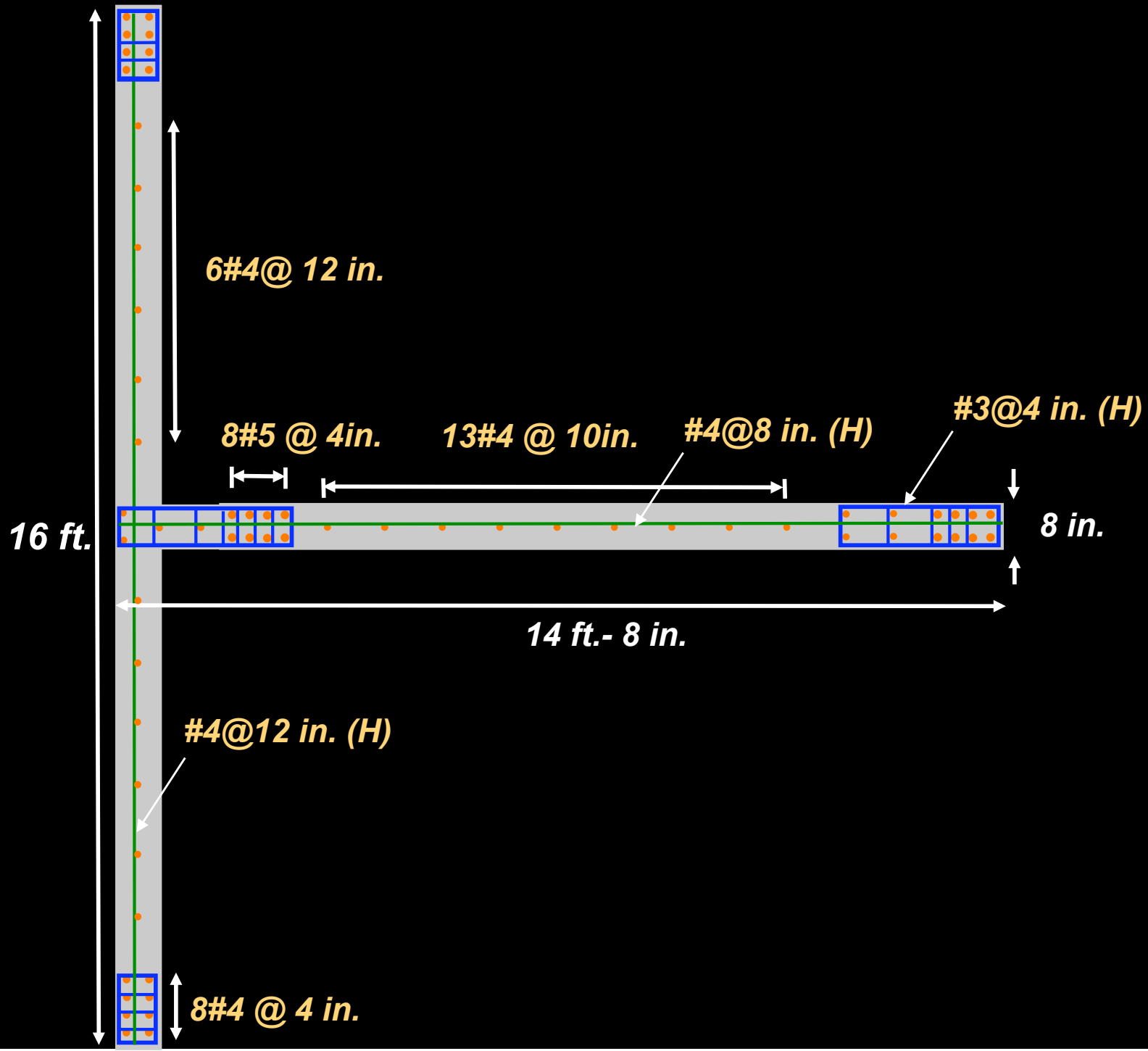
Observ. 3&4. System Overstrength & Higher Modes



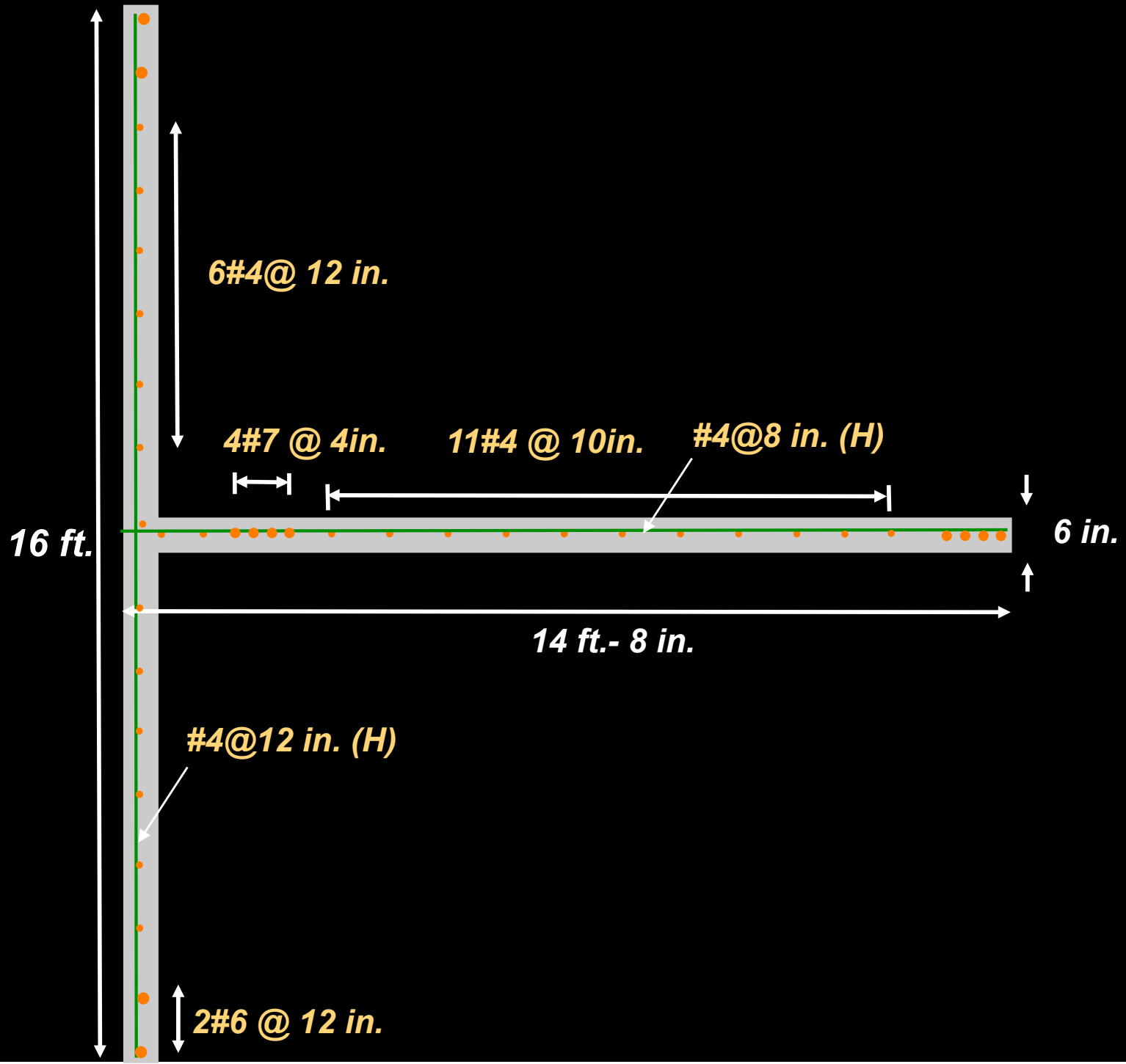
Observ. 3&4. System Overstrength & Higher Modes



Summary Detailing – T Wall – Level 1



Summary Detailing – T -Wall – Level 2-7



Interstory Drift Envelopes – Comparison of designs

- *Reduced interstory drifts with DPH in comparison with ACI*