Seismic Performance of Tall Buildings with Core Walls Allowed to Uplift on Their Foundations

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Outline

- **Ground motion concerns for tall buildings**
- Characteristics of Fixed-base and Rocking-base tall buildings
- Rigid body rocking dynamics and model validation
- Benchmark building and ground motions
- Performance of Fixed-base and Rocking-base tall buildings
- Ongoing work

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Ground Motion Concerns for Tall Buildings

- Near-fault velocity pulses due to forward directivity and fling
- Long period ground motion content
- Long duration shaking for large magnitude events
- Poorly constrained ground motion prediction for near-fault large magnitude events
- Higher mode effects

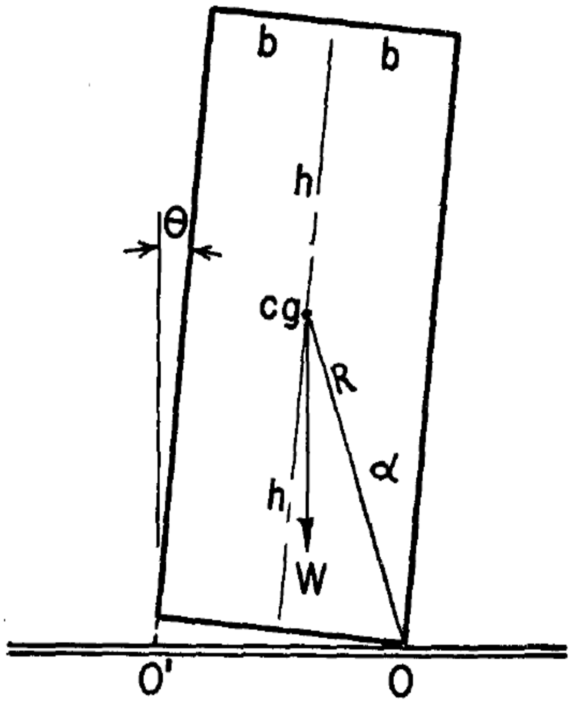
Deficiencies of Fixed-base Tall Buildings

- Base wall plastic hinge formation
  - Limited ductility for walls with significant axial loads
  - Global residual drift
  - Cyclic degradation under long duration motion
  - Large ductility demand for near-fault pulses
- Damage
  - Residual drifts and possible total loss of investment depending on severity
  - Large repair cost and downtime
  - Unsustainable practice

Can Rocking Systems Help?

- Uplifting core walls concentrate deformation without damage
  - Large deformation capacity (“ductility”) due to rocking
  - No residual drifts
  - No cyclic degradation if rocking system kept elastic
  - Sustainable
- Concerns:
  - Global stability and risk of overturning
  - Base restraint and sliding
  - Behavior under multi-directional motions
  - Behavior of coupled rocking walls

Rigid Body Rocking Dynamics



- Equation of motion (originally Housner 1963)

$$\ddot{\theta}(t) = -p^2 \left\{ \sin(\alpha \mathrm{sgn}\theta(t) - \theta(t)) + \frac{\ddot{u}_g(t)}{g} \cos(\alpha \mathrm{sgn}\theta(t) - \theta(t)) \right\}$$

$$\text{where } p = \sqrt{\frac{3g}{4R}} \text{ and } \mathrm{sgn}\theta = \begin{cases} 1 & \text{for } \theta \geq 0 \\ -1 & \text{for } \theta < 0 \end{cases}.$$

- Coefficient of Restitution ("damping")

$$I_o \dot{\theta}(t_o^-) - 2mRb\dot{\theta}(t_o^-) \sin\alpha = I_o \dot{\theta}(t_o^+)$$

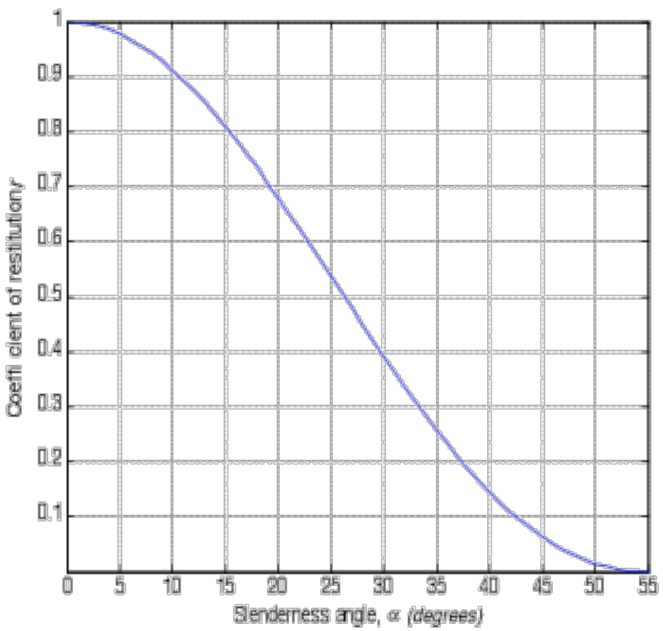
$$\dot{\theta}^2(t_o^+) = r\dot{\theta}^2(t_o^-)$$

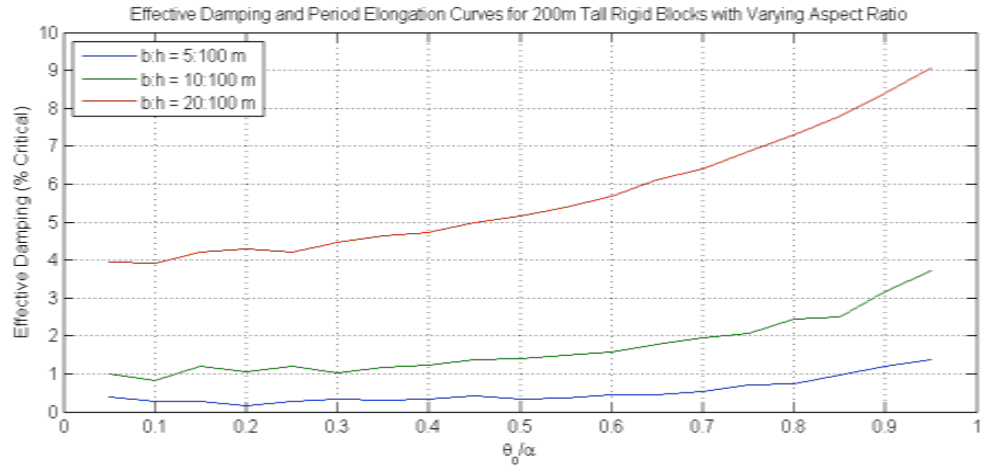
$$r = \left(1 - \frac{3}{2}\sin^2\alpha\right)^2$$

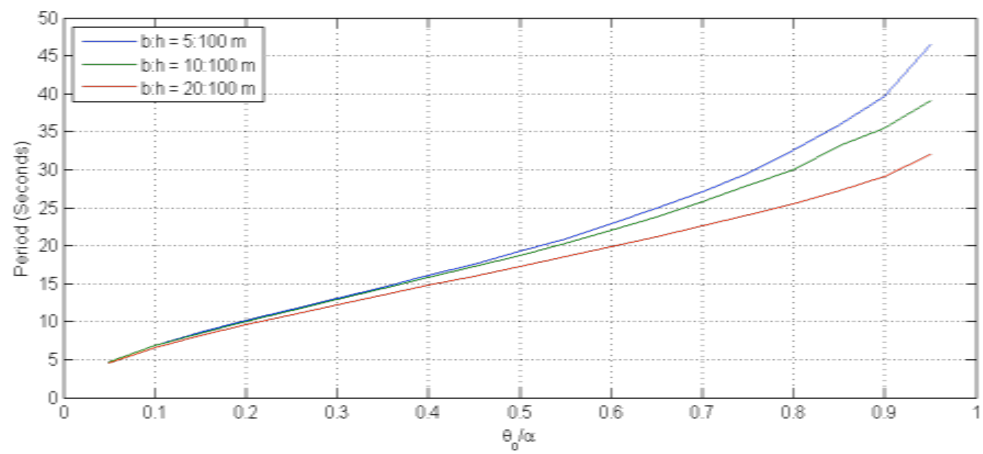
- Solved piecewise

Rigid Body Rocking Dynamics

- Amplitude-dependent period and damping







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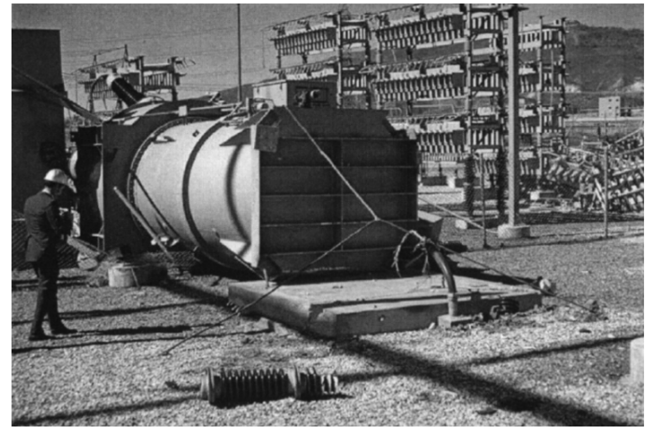
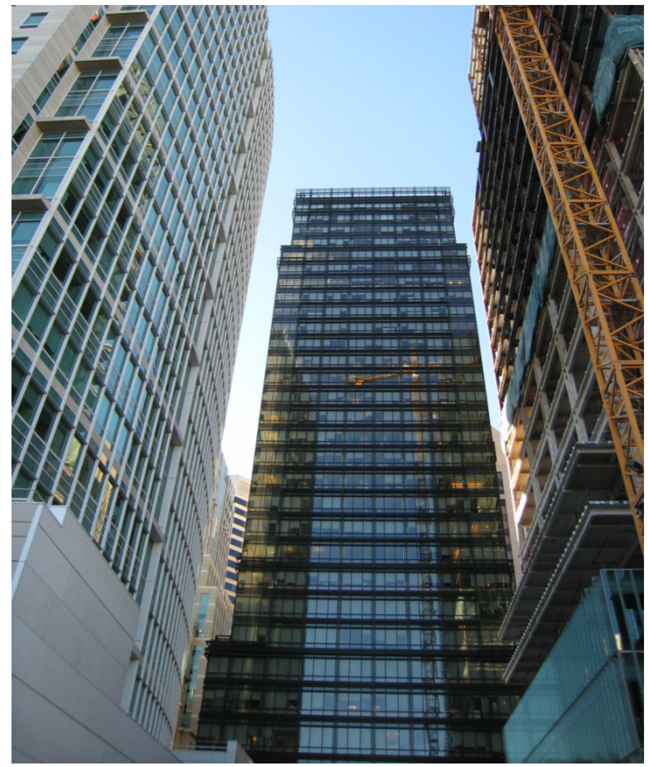
Global Stability

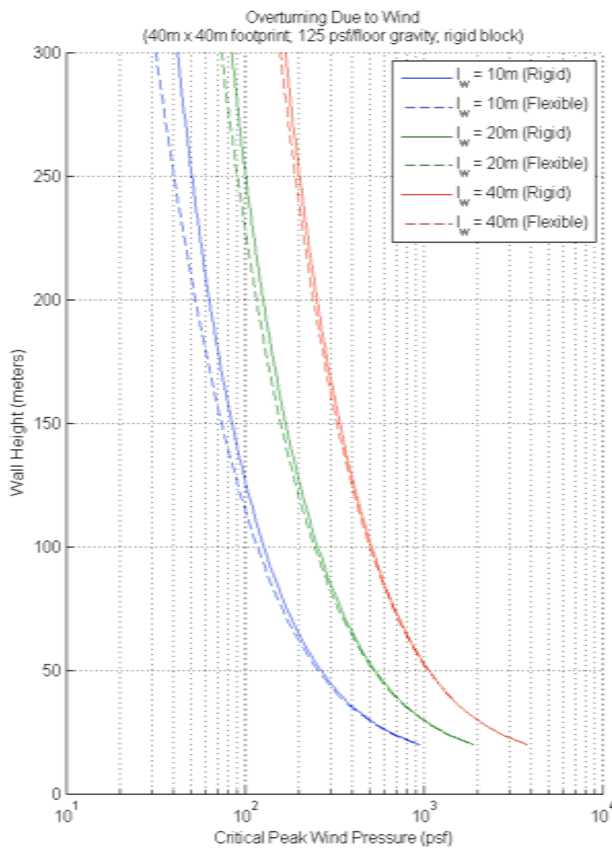
- Scale of rocking structure affects global stability and risk of overturning
- Housner found that the probability of a rocking structure overturning is inversely proportional to its height
- Long period structures are less susceptible to overturning due to shorter period transient ground motion
- For typical tall buildings, there is little risk of overturning due to earthquakes

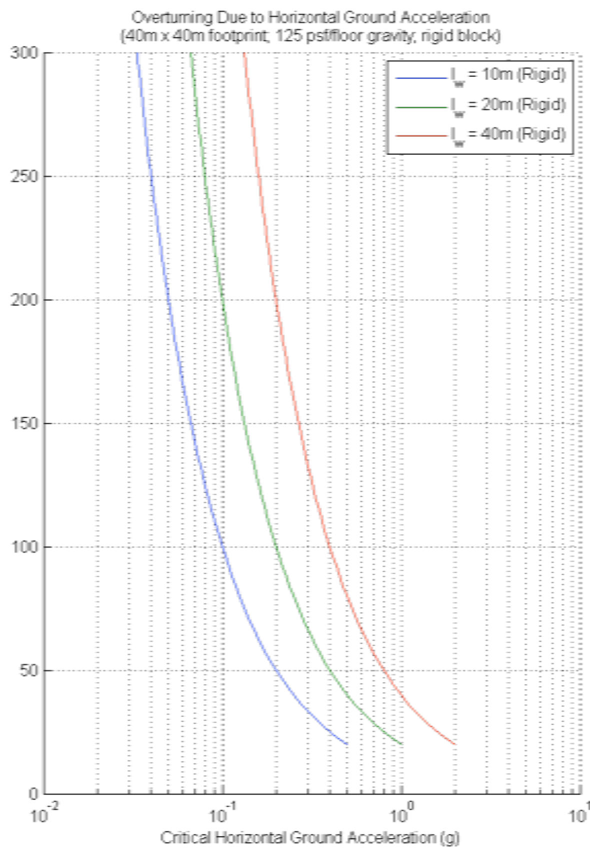




Wind Overturning and Seismic Initiation of Rocking

- For benchmark building, critical uniform wind pressure is 100 psf while initiation of rocking can occur at 0.1g PGA
- Can use wind-lock dampers if wind demand is too high





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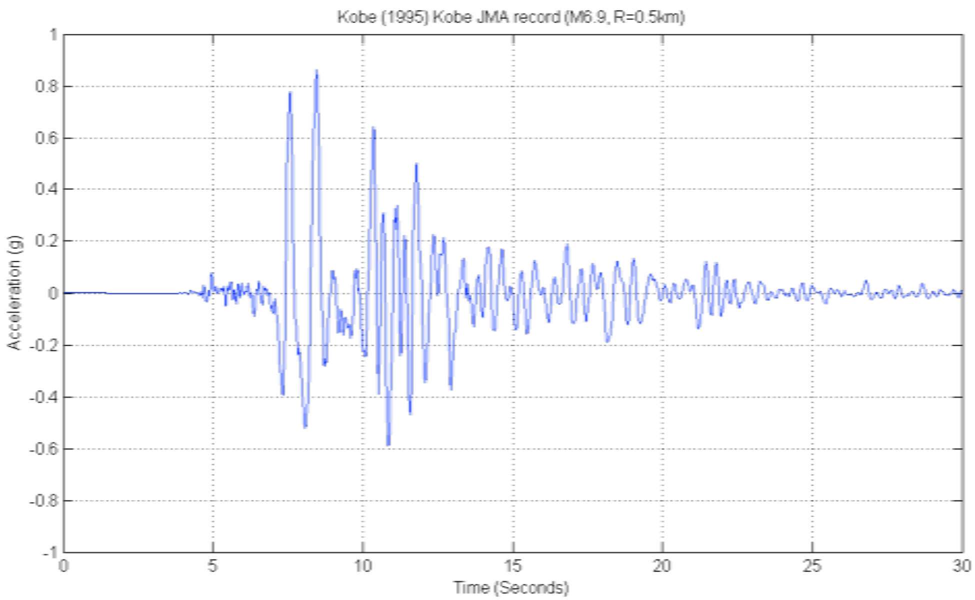
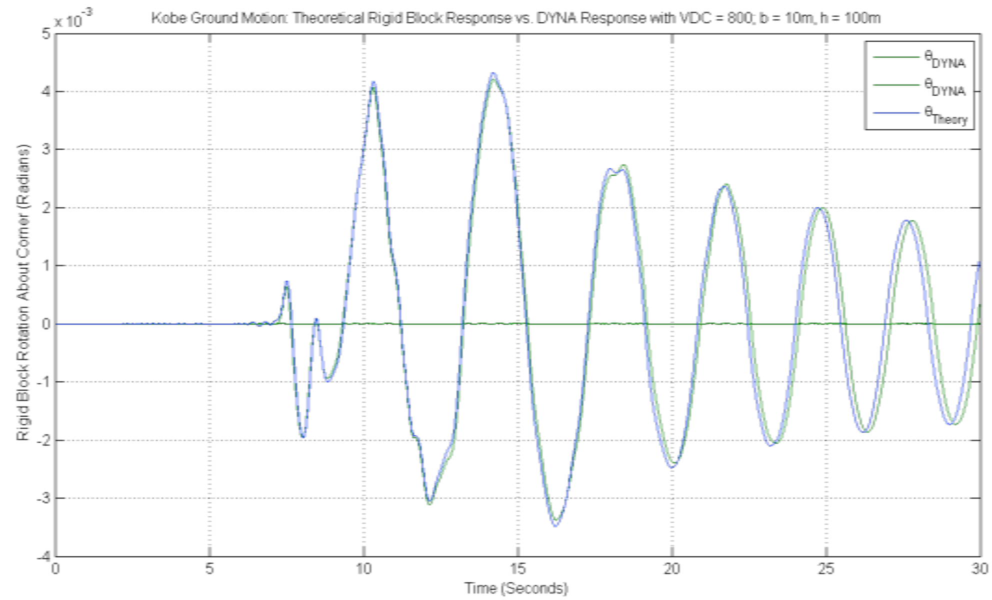
LS-DYNA Model Validation

- Compare analytical to LS-DYNA rigid body with contact surface
  - Excellent agreement during forced response
  - Minor period lengthening during free response





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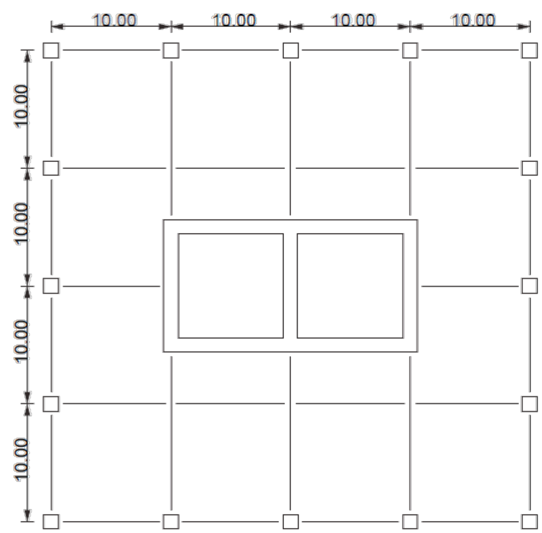
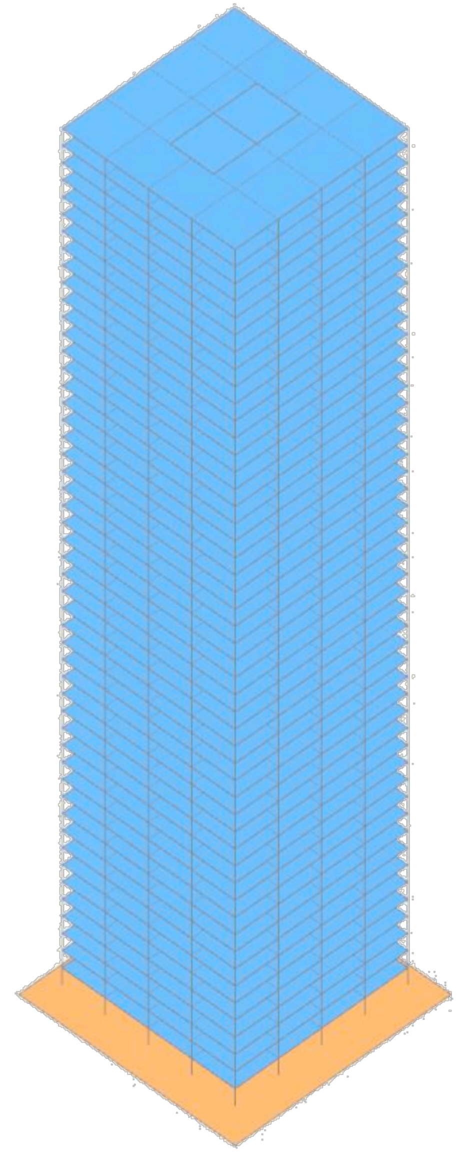
Idealized Building with Solid Wall

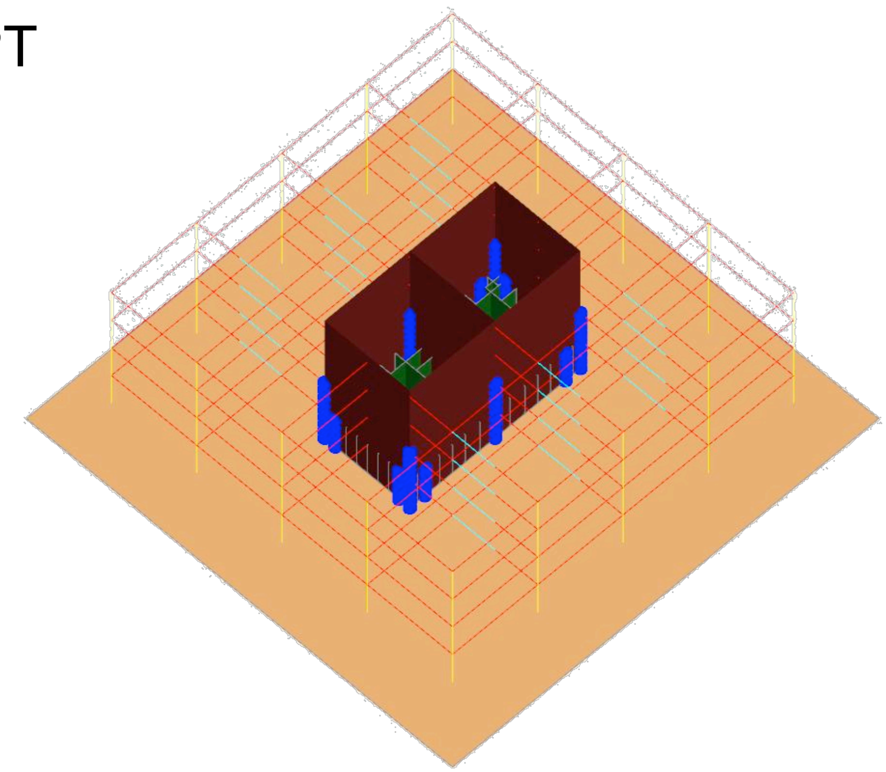
- Core-only building
- 200m tall, 50 storeys
- 40m x 40m footprint
- 20m x 10m x 1m core
- 8000 psi concrete
- 125 psf per floor
- Nonlinear slabs and gravity frame
- Separate layers for unconfined and confined concrete, longitudinal and transverse reinforcement in wall
- $T_{1,2,3}$ = (6.6, 5.0, 2.4 sec)





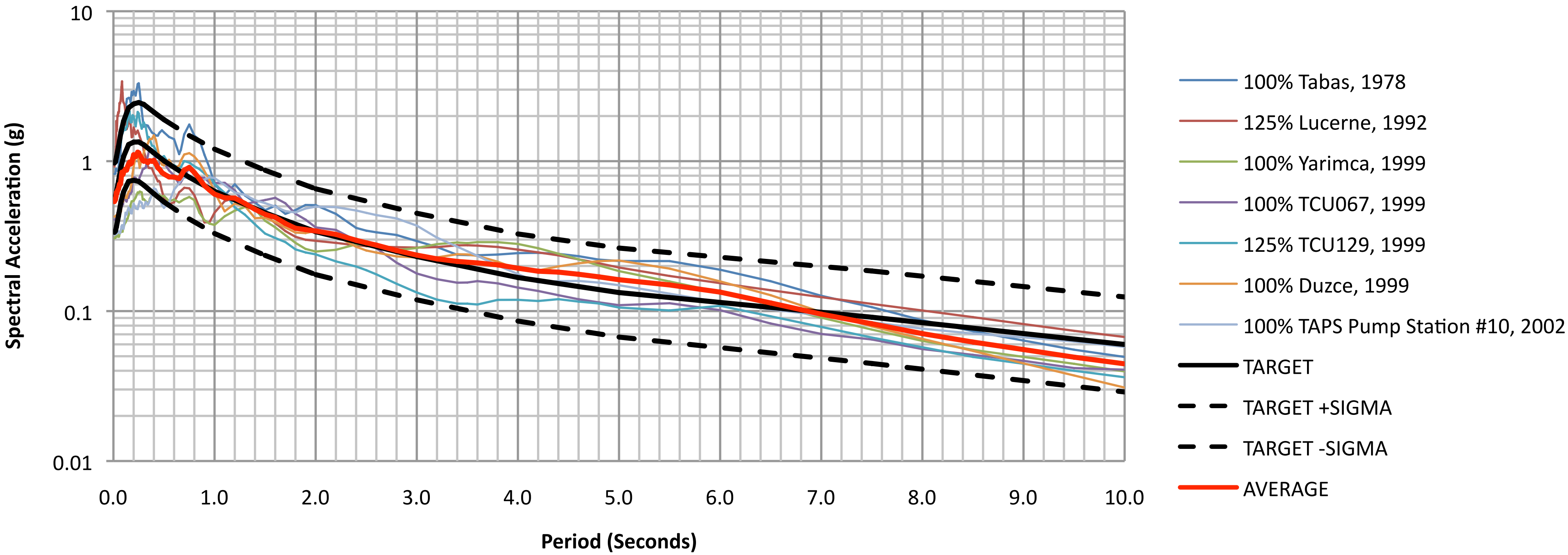
Proposed Rocking System

- Gravity the sole restoring force (no PT tendons)
- Base shear taken through friction between core and foundation mat
- Strengthened corner elements at the base of the wall for bidirectional response
- Stiffened base zone to restrain wall buckling upon uplift



Hypothetical Seismic Hazard and Ground Motion Suite

- Deterministic event: M_w 8.0, R=10 km, +1ε
- 7 ground motions from NGA database bins for M > 7.0, R < 10



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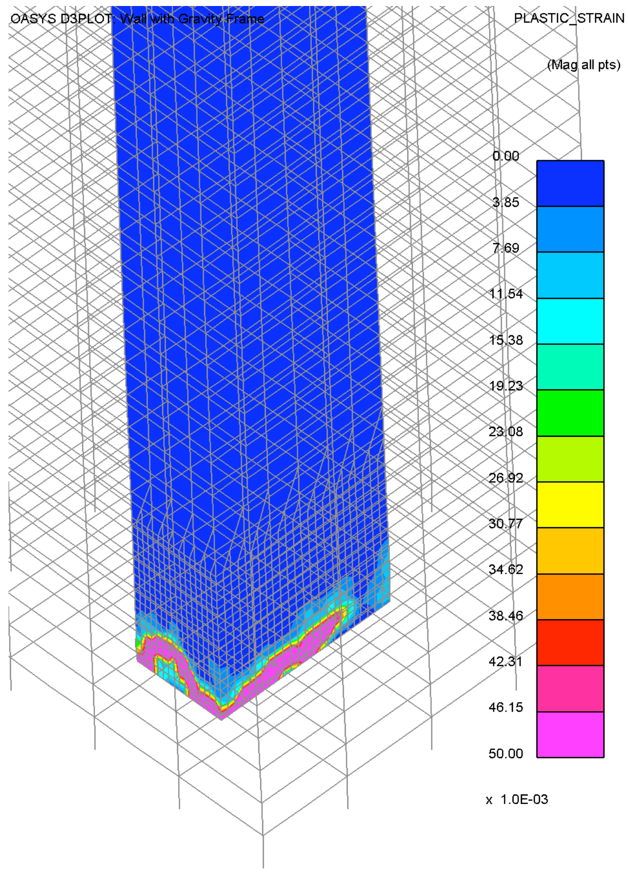
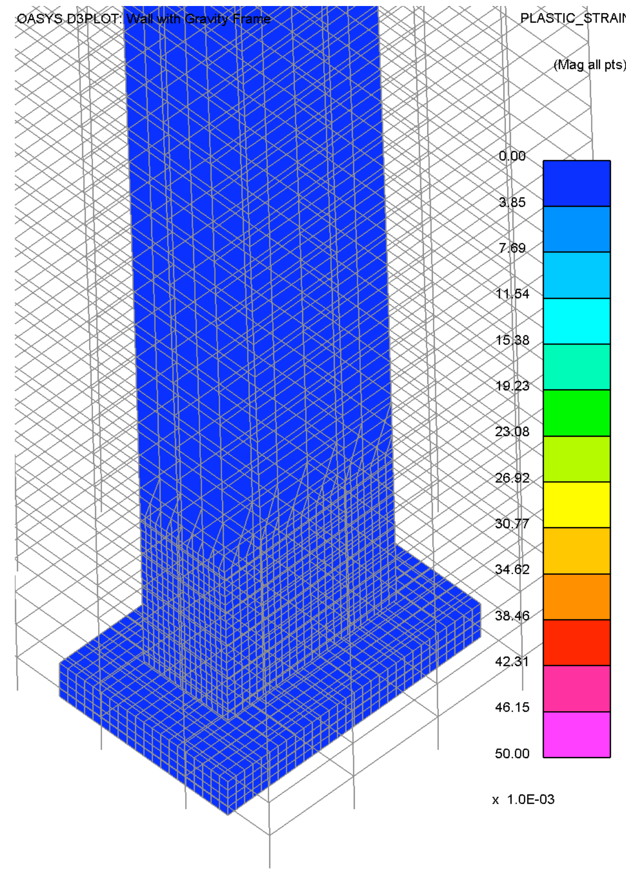
Response to 125% Landers/Lucerne FD Motion

- Collapse of fixed-base wall due to pulse motion
- Rocking-base structure survives motion without damage



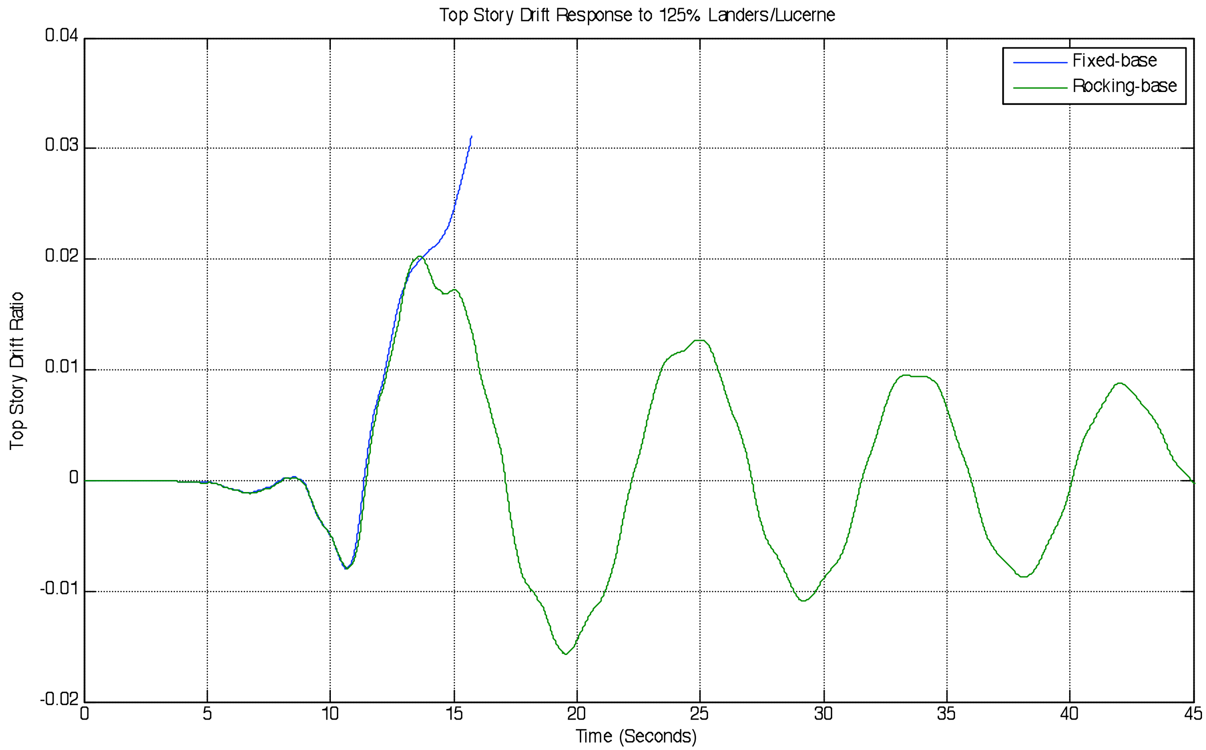
Fixed-base



Rocking-base

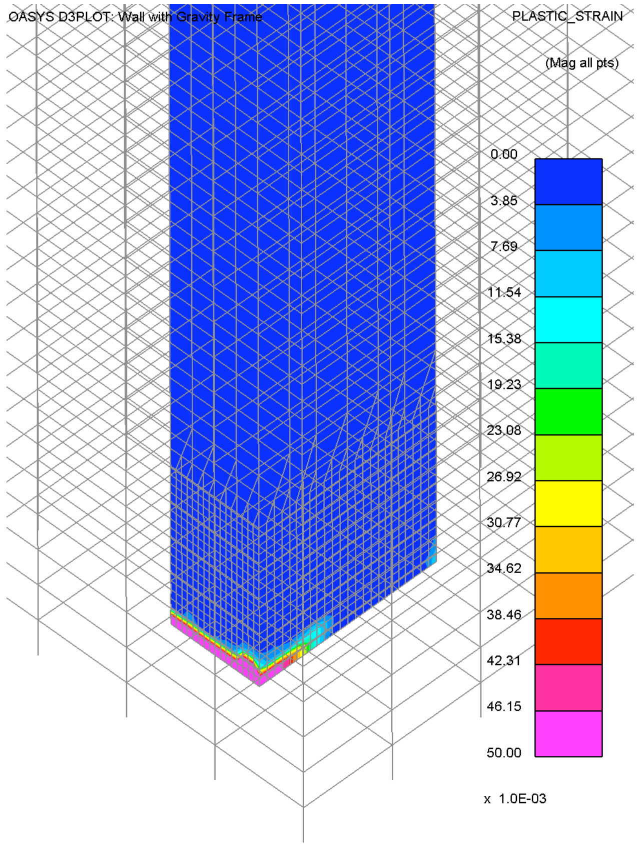
Response to 125% Landers/Lucerne FD Motion

- Fixed-base structure collapses at 16 seconds

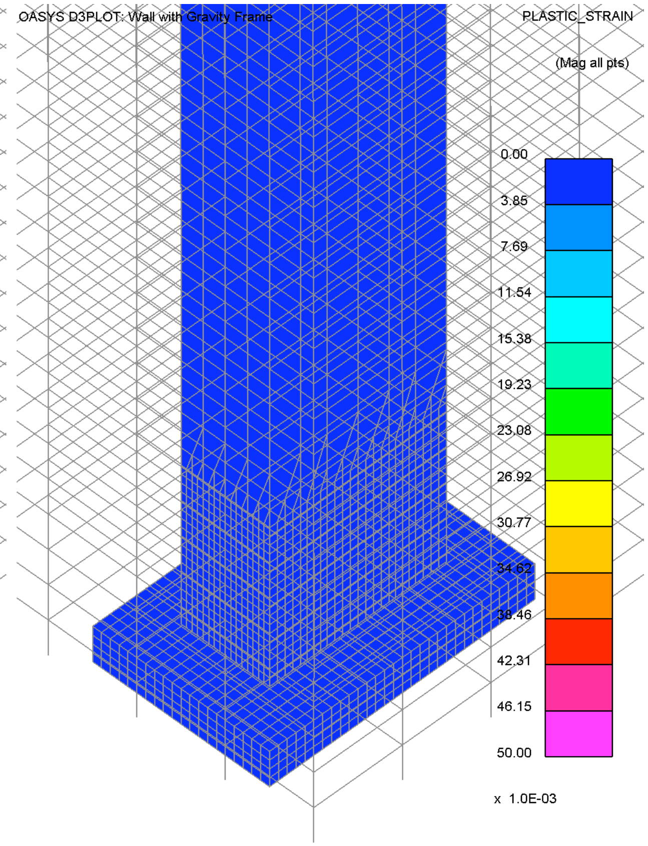


Response to 100% Denali PS10 Ground Motion

- Yielding of fixed-base flexural hinge leading to residual drift
- Rocking-base structure survives motion without damage



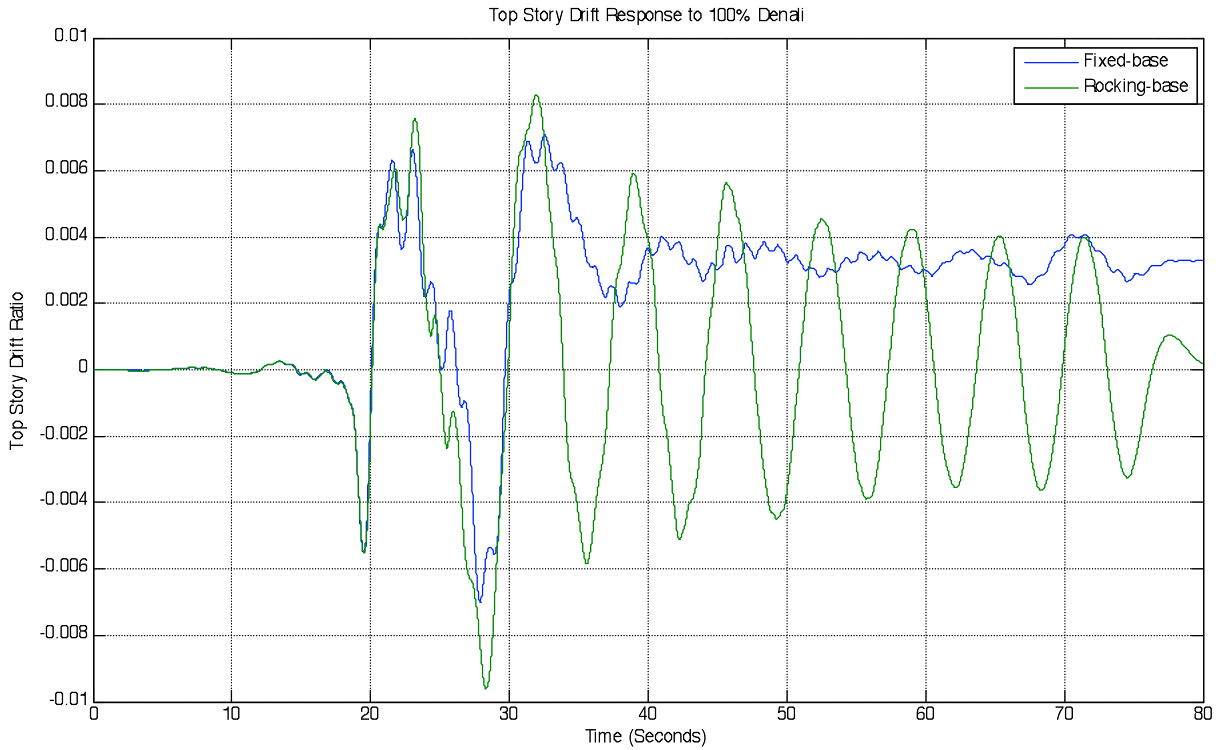
Fixed-base



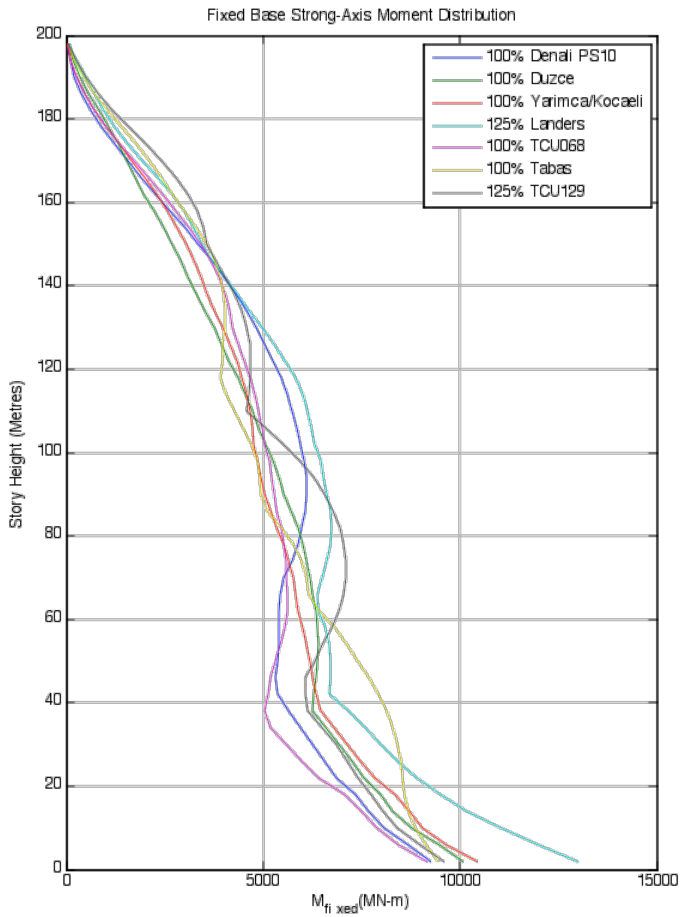
Rocking-base

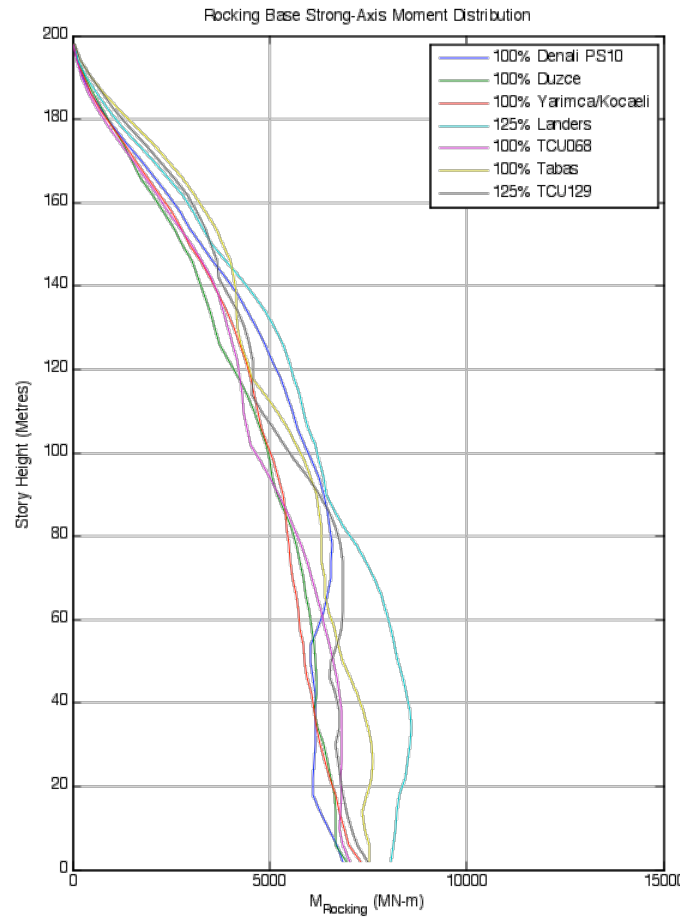
Response to 100% Denali PS10 Ground Motion

- Fixed-base structure has residual drift from wall plastic hinge

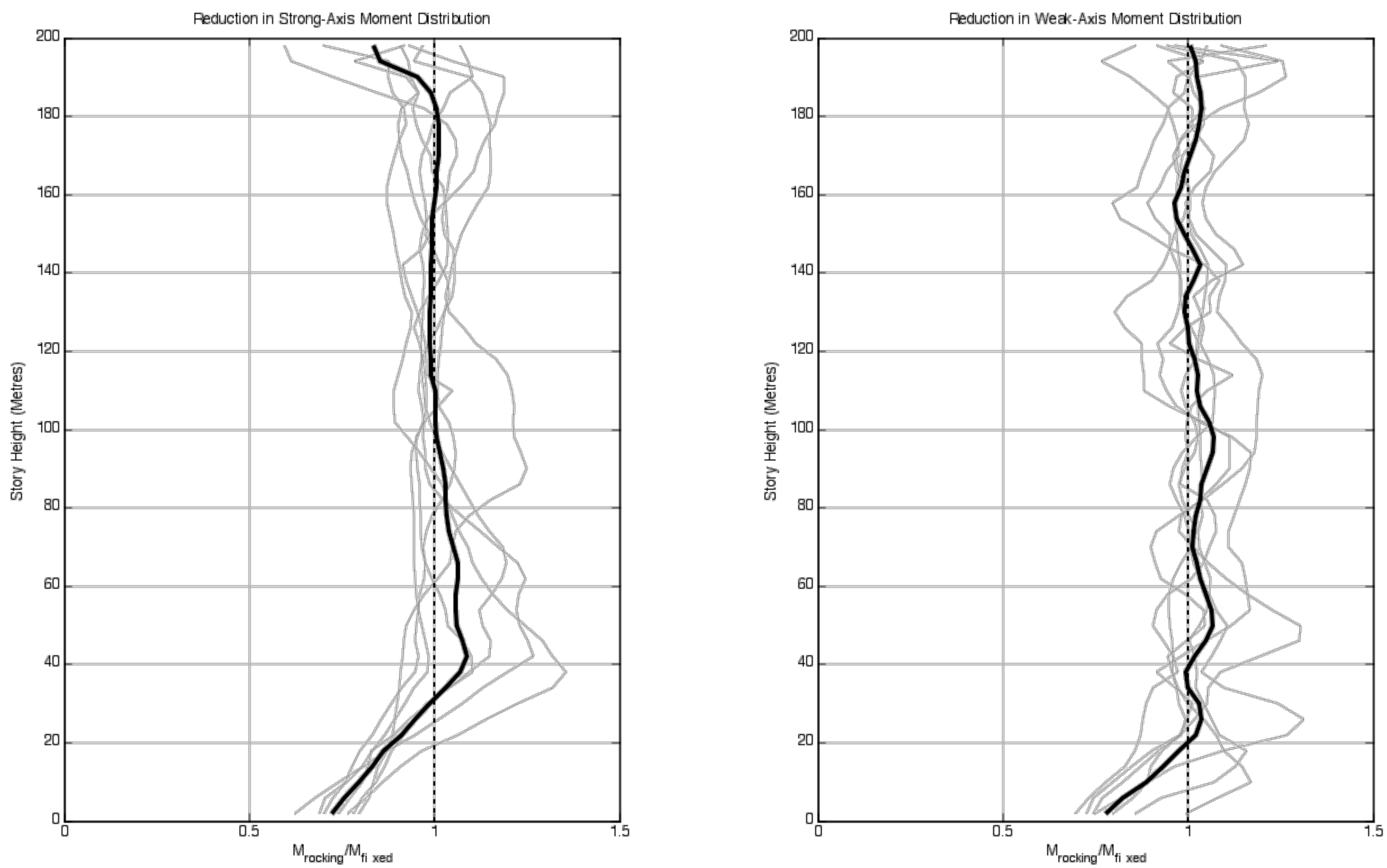


Strong-Axis Moment Distribution





30% Base Moment Reduction with Rocking Base



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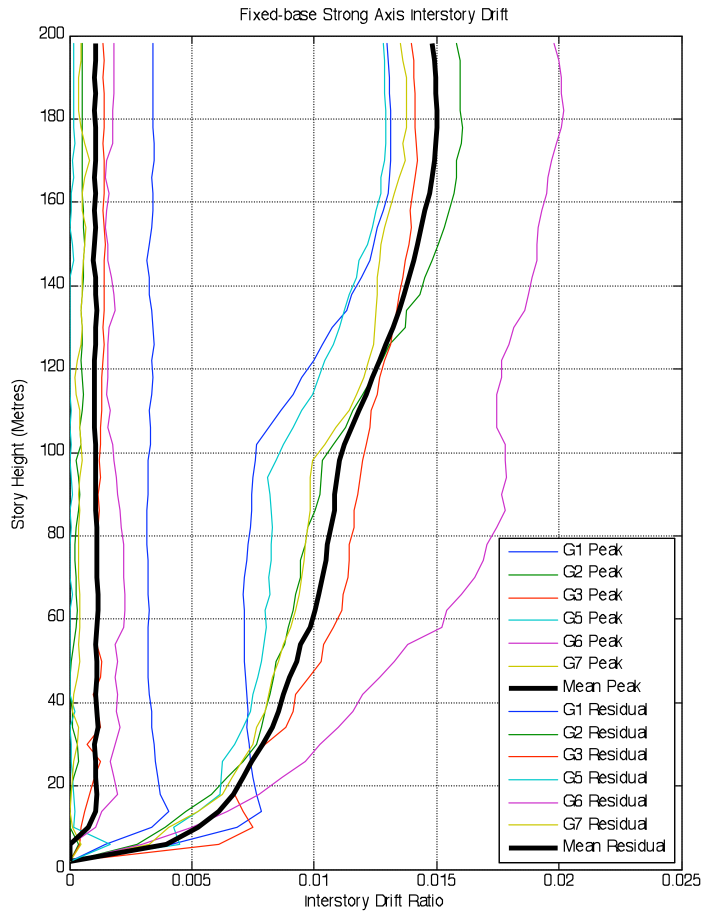
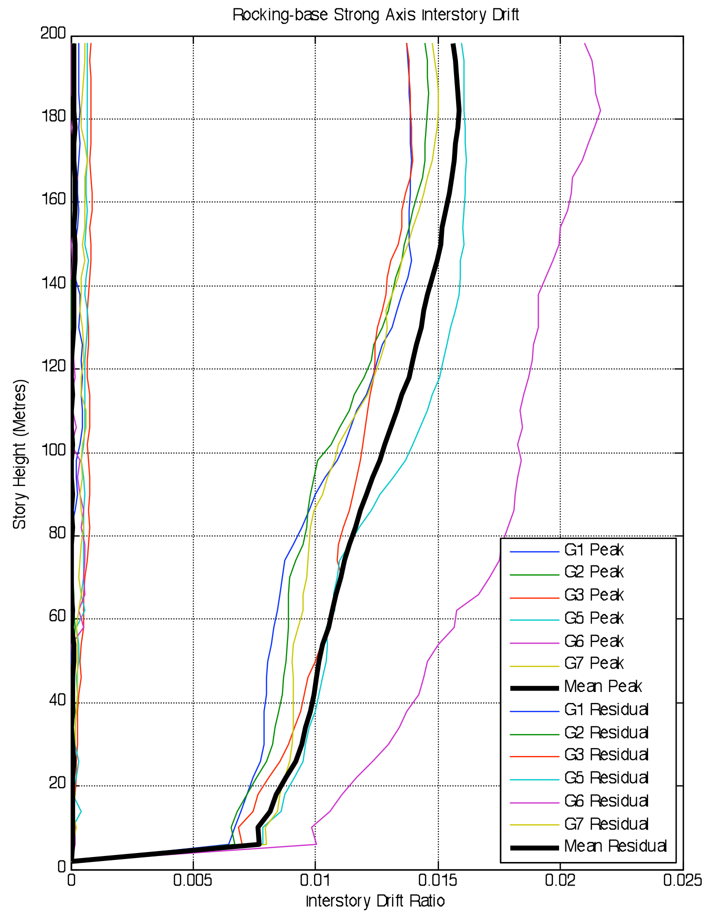
Interstory Drift Ratio



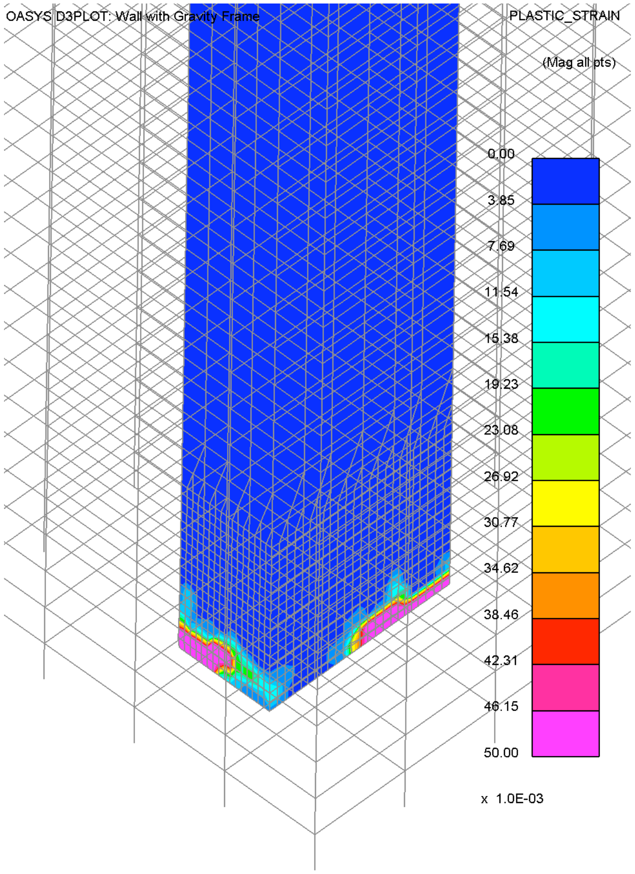


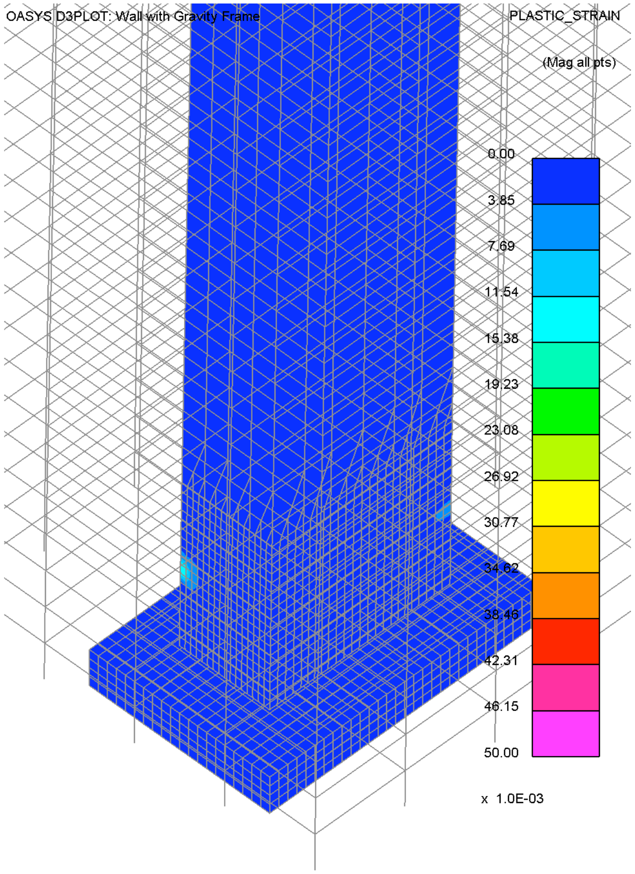
Uplift and Slip of Rocking Structure

	Denali	Duzce	Kocaeli	Landers	TCU067	Tabas	TCU129
Peak Uplift	11.9 cm	12.3 cm	12.7 cm	29.0 cm	14.6 cm	17.2 cm	13.8 cm
Peak X Slip	0.64 cm	1.86 cm	1.35 cm	1.25 cm	0.88 cm	1.13 cm	0.71 cm
Peak Y Slip	1.23 cm	1.41 cm	1.45 cm	1.02 cm	1.32 cm	1.52 cm	1.13 cm
Residual X Slip	0.01 cm	0.67 cm	0.04 cm	0.03 cm	0.10 cm	0.59 cm	0.16 cm
Residual Y Slip	0.06 cm	0.32 cm	0.85 cm	0.19 cm	0.04 cm	0.35 cm	0.12 cm

Limits of Rocking System?

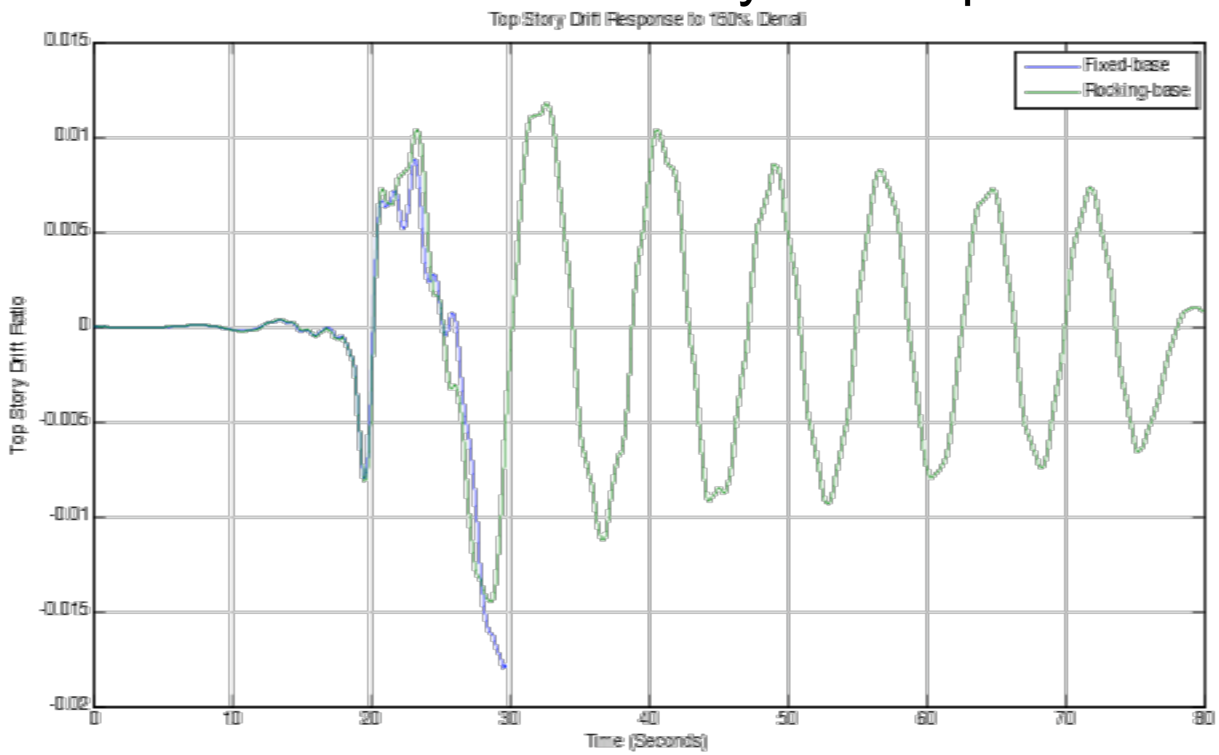
- **150%** Denali PS10?
- Fixed-base structure collapses at 24 sec
- **1%** local plastic strain in rocking-base structure
- Structure is limited by inter-story drift capacity of gravity columns rather than wall stability





150% Denali PS10

- Fixed-base structure collapses at 24 seconds, rocking-base structure has no residual drift and only limited plastic strain



Benefits of Rocking Wall System

- Elastic Response
  - Re-centering behavior under gravity
  - No residual drift
  - No cyclic degradation of wall
  - Limited repair costs following severe event
  - Extended life-cycle, more sustainable
- Design less sensitive to severity of ground motion (or ground motion variability)
  - Design for gravity + $PGA_{vertical}$
  - Displacement capacity a function of wall length

Conclusions

- Results indicate that a rocking wall system with sufficiently designed base can have superior performance over a comparable fixed base system for large seismic demands
- Rocking wall systems are more likely to withstand extremely large pulse displacements than comparable fixed base systems with limited ductility

Conclusions

- Design of rocking wall system is primarily driven by the gravity load of the building which is less variable than estimates on ground motions from a large earthquake

- If implemented correctly, a rocking system can significantly reduce the potential loss of investment due to large ground motions

Ongoing Work

- Behavior and performance of coupled rocking core walls
- Detailing and modeling of core wall and foundation mat interface
- Response surface reliability analysis of fixed-base and rocking-base tall buildings
- Possible applications to new construction and existing buildings