Validating Performance of Self-Centering Steel Frame Systems Using Hybrid Simulation

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Introduction – Current Seismic Design Practice

- Design for “Life Safety” for the “Design Basis Earthquake”.
- No specific focus on damage or collapse; expect (hope?) current practice will also provide:
  - “Immediate Occupancy” for “Frequently Occurring Earthquake”.
  - “Collapse Prevention” for the “Maximum Considered Earthquake”.
- These earthquake intensities are defined (U.S.) as follows:
  - Frequently Occurring Earthquake (FOE) – 50% in 50 years.
  - Design Basis Earthquake (DBE) – approx. 10% in 50 years.
  - Maximum Considered Earthquake (MCE) – 2% in 50 years.

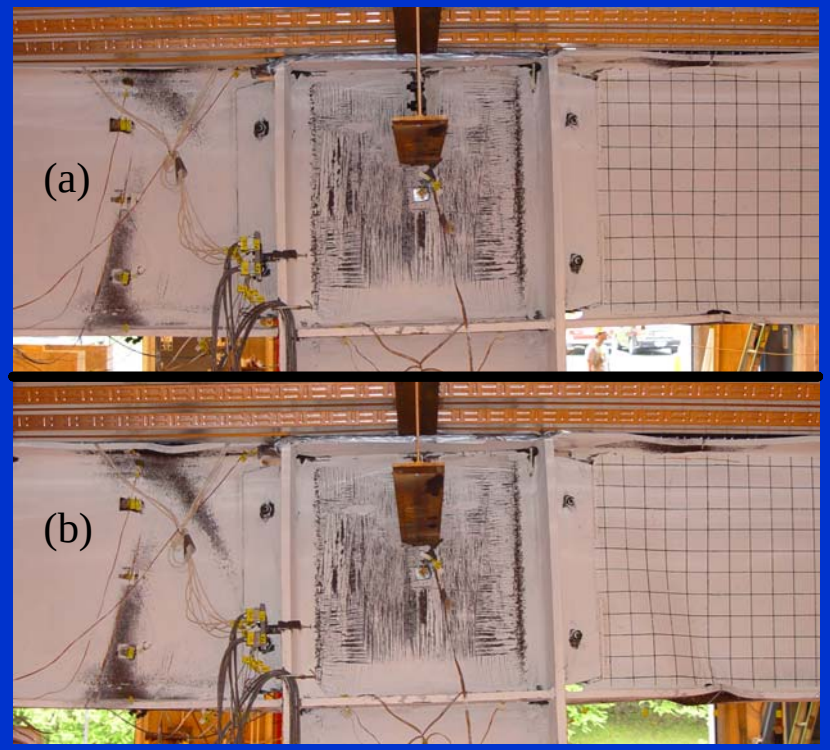
Introduction – Current Design Practice
What does it provide?

- "Life Safety" for "DBE".
  - Expect serious structural damage for ground motion with a return period of 400 to 500 years.
- "Immediate Occupancy" for "FOE".
  - Expect that buildings may be damaged and unusable after ground motion with a return period more than 75 years.

At the same time…

- Recent research (Miranda) shows that significant economic loss is due to damaged buildings that must be demolished during post-earthquake recovery because of structural damage (e.g., residual drift).

Introduction: Expected Damage for Conventional Steel Frames



Conventional Moment Resisting Frame System

Reduced beam section (RBS) beam-column specimen with slab: (a) at 3% drift, (b) at 4% drift.

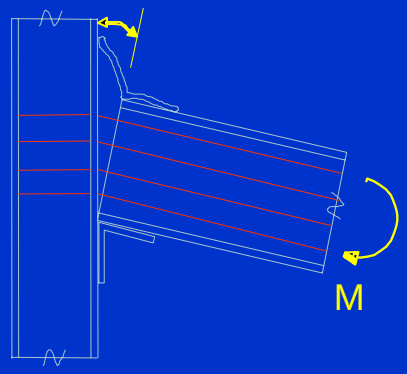
Introduction – Two Current Research Themes for Earthquake-Resistant Structures

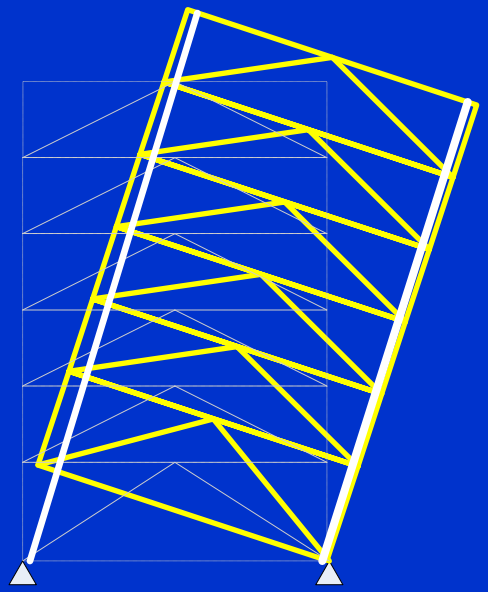
- **Innovations to reduce damage and residual drift:**
  - Goal: reduce economic losses and social disruption from future earthquakes.
  - Protective systems (base isolation, passive dampers, semi-active control, etc.).
  - Self-centering structural systems.

- **Rational approaches to prevent collapse:**
  - Goal: prevent loss of life.
  - Estimates of the probability of collapse and develop consensus on acceptable probability.

Self Centering (SC) Seismic-Resistant Structural System Concepts

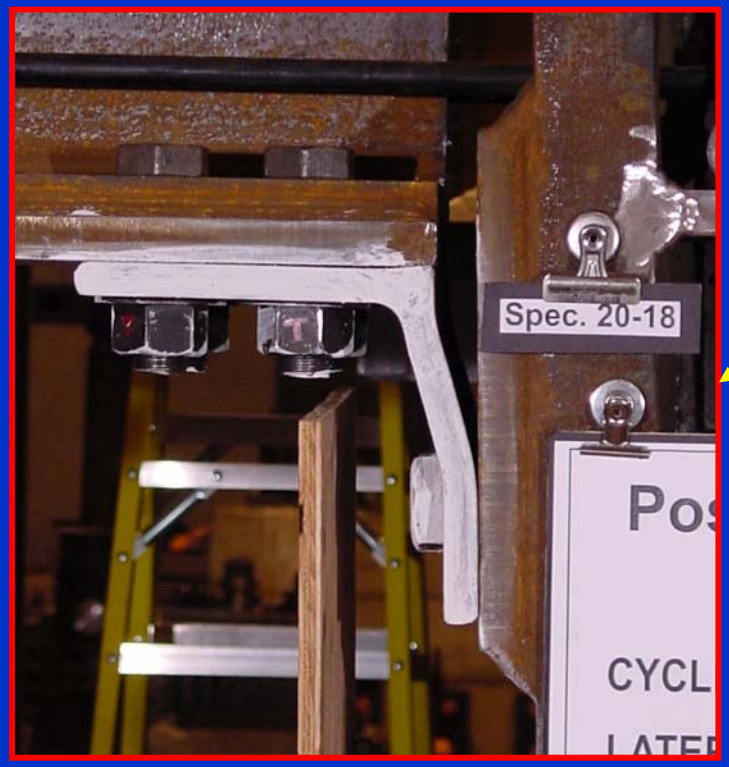
- Discrete structural members are post-tensioned to pre-compress joints.
- Gap opening at joints at selected earthquake load levels provides softening of lateral force-drift behavior without damage to members.
- PT forces close joints and permanent lateral drift is avoided.

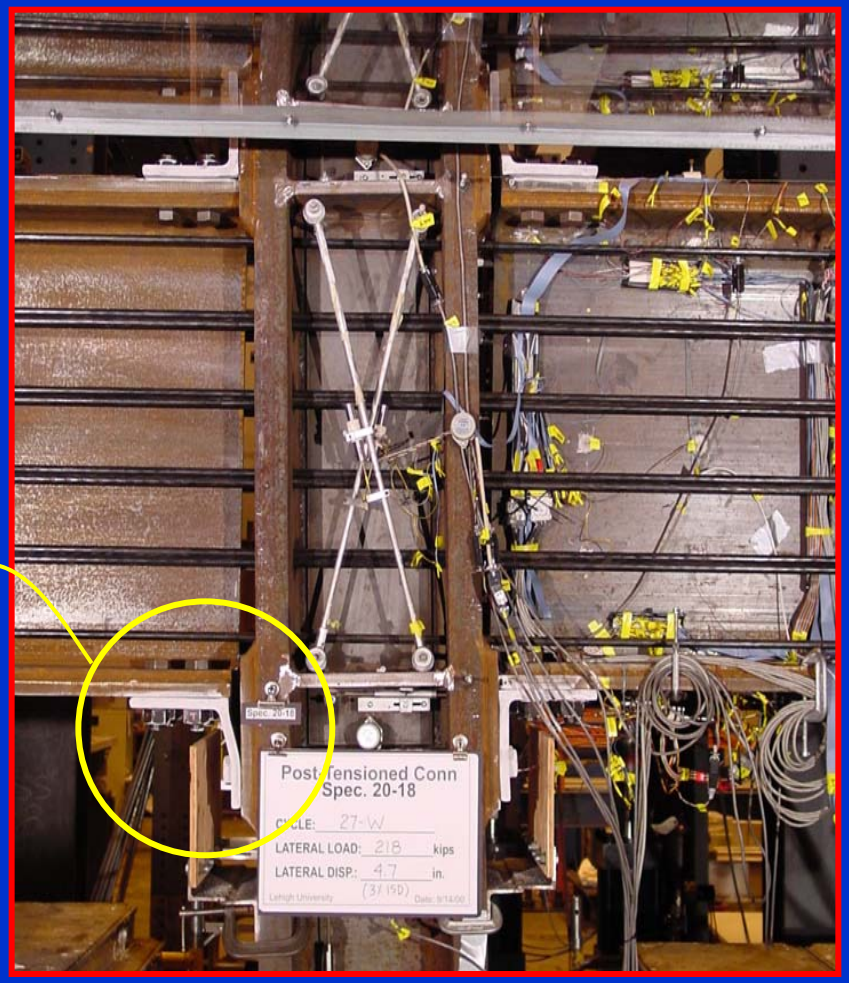




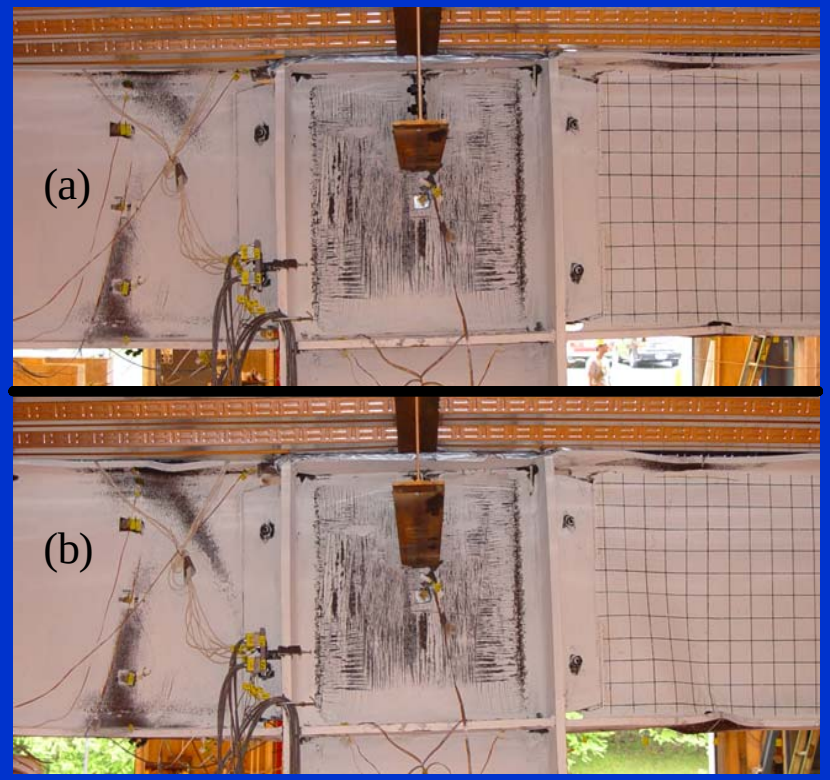
Lateral Force-Drift Behavior Controlled by Gap Opening, not by Member Damage

Steel MRF subassembly with SC connections at 3% drift





Expected Damage for Conventional Steel Frames

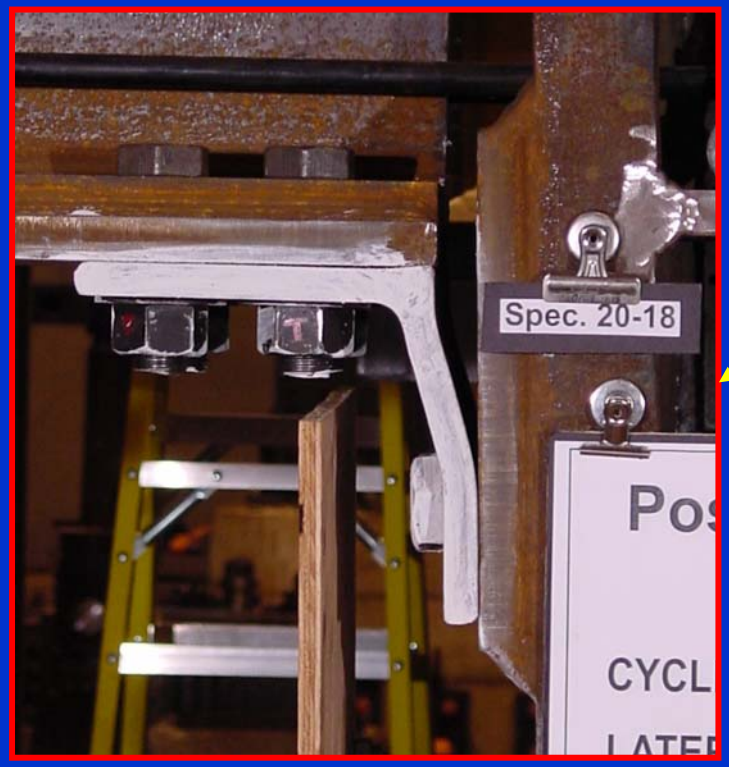


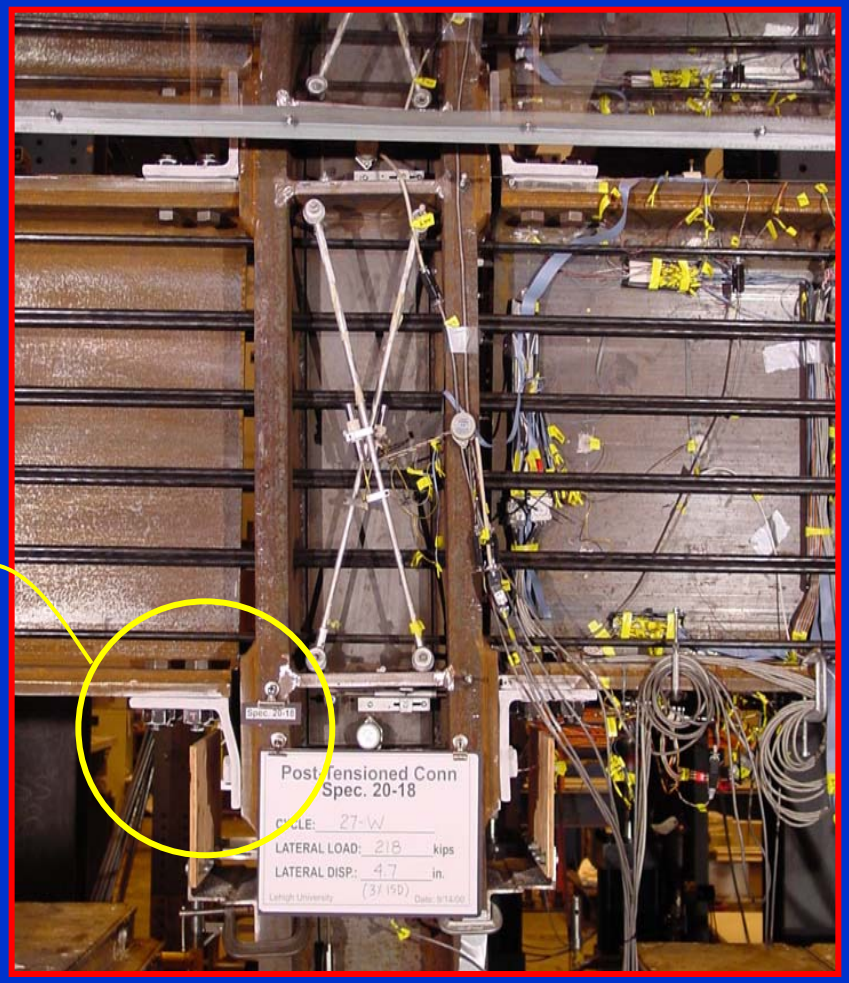
Conventional Moment Resisting Frame System

Reduced beam section (RBS) beam-column specimen with slab: (a) at 3% drift, (b) at 4% drift.

Lateral Force-Drift Behavior Controlled by Gap Opening, not by Member Damage

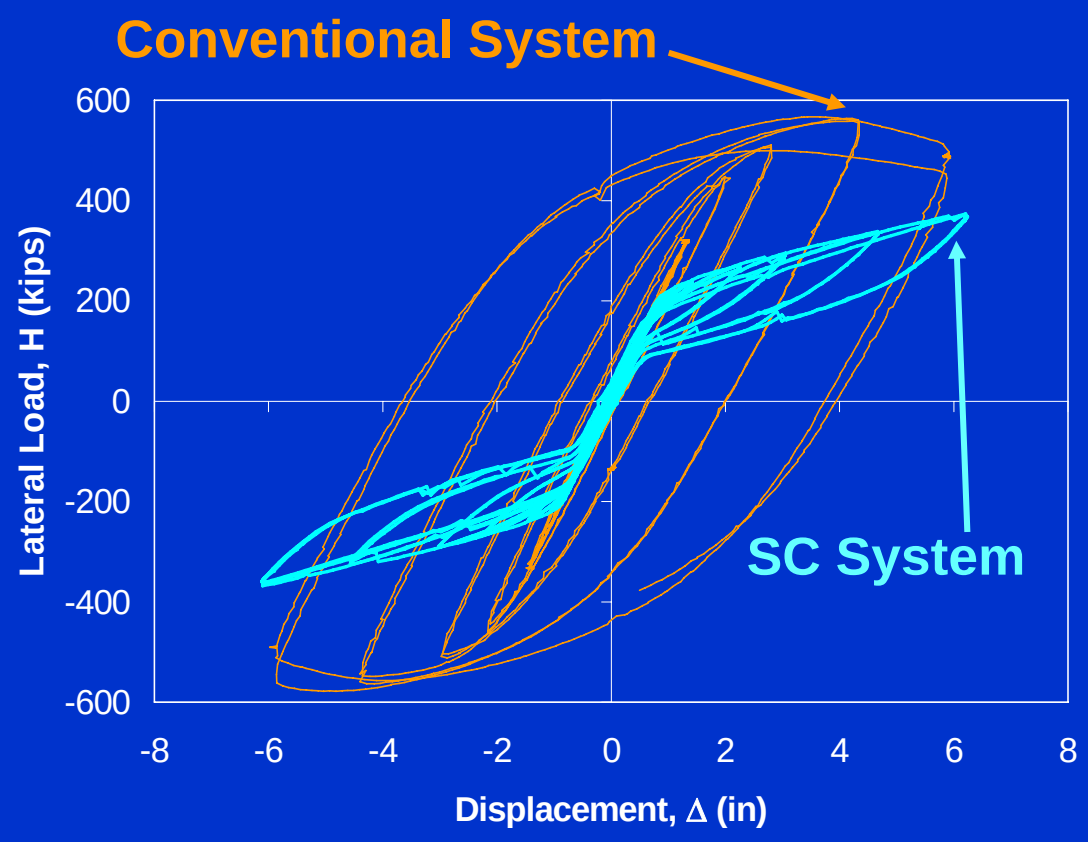
Steel MRF subassembly with SC connections at 3% drift





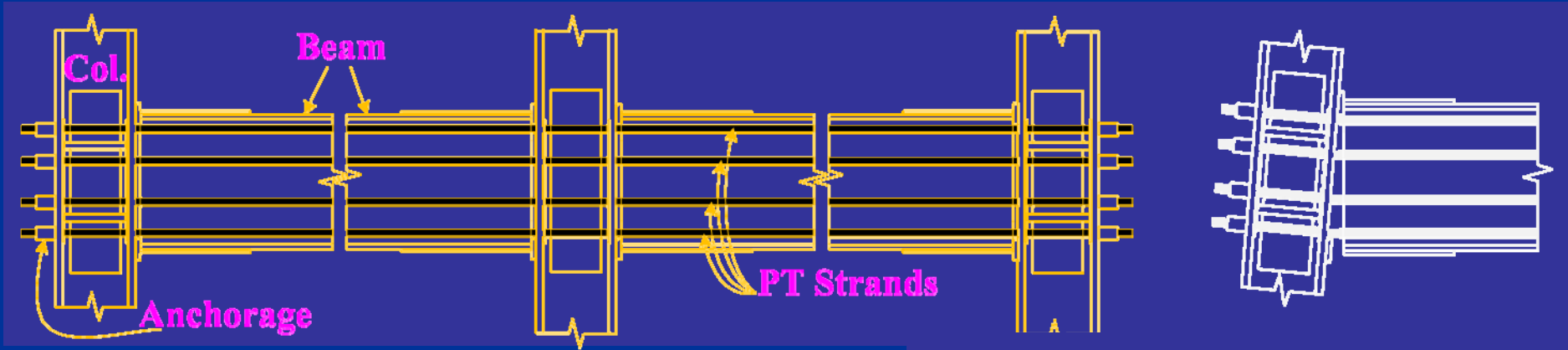
Comparison of Lateral Force-Drift Behavior

- Conventional system softens by inelastic damage to main structural members producing residual drift
- SC system softens by gap opening and reduced contact area at joints
- SC system energy dissipation is designed feature of system
- Two systems have similar initial stiffness

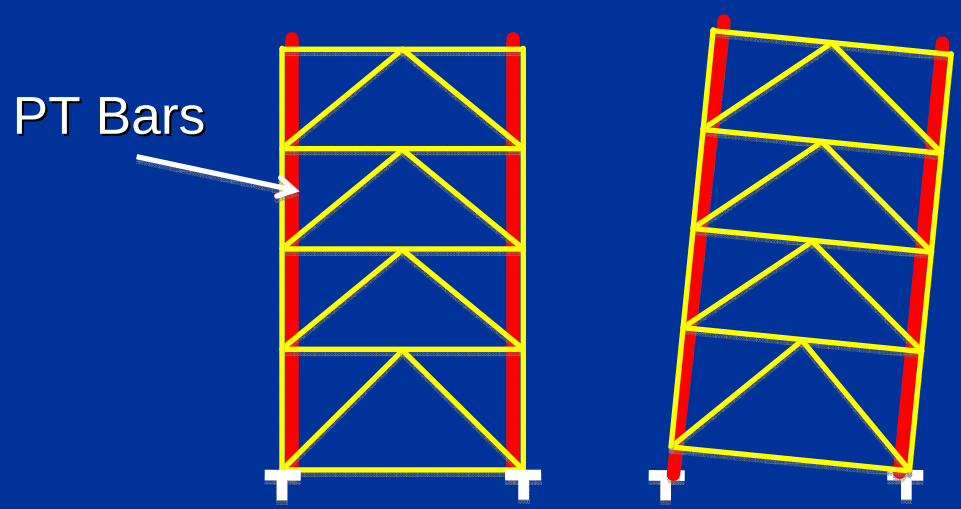


Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project

- Develop two SC steel frame systems



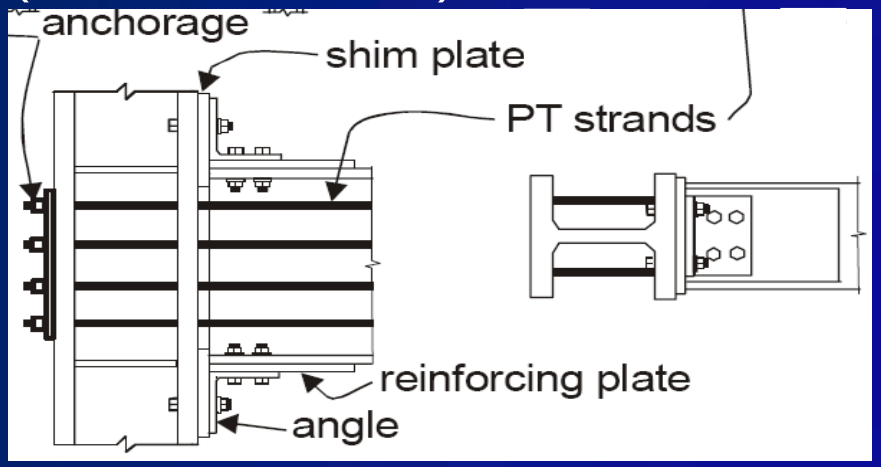
Moment-resisting frames (SC-MRFs)

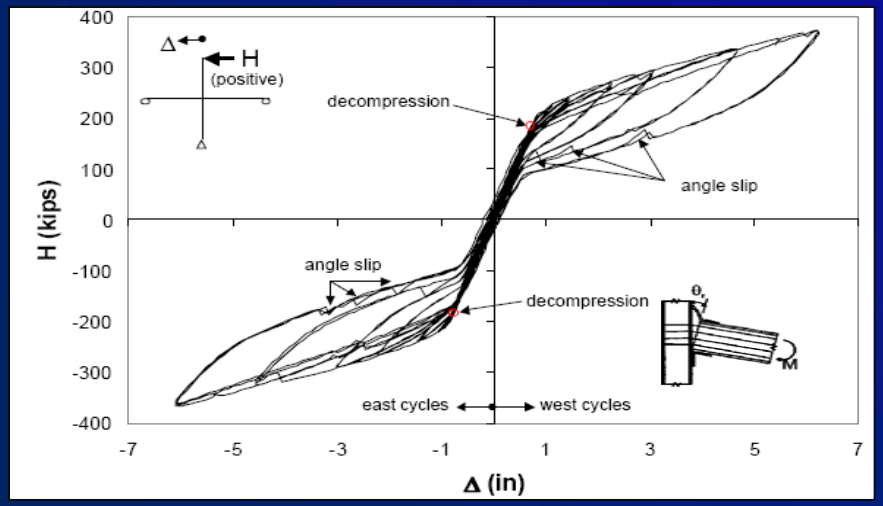


Concentrically-braced frames (SC-CBFs).

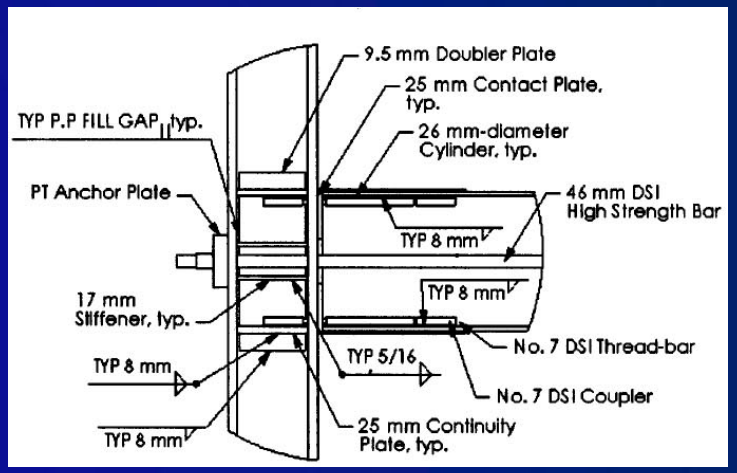
Research on SC-MRF Systems– Prior Work

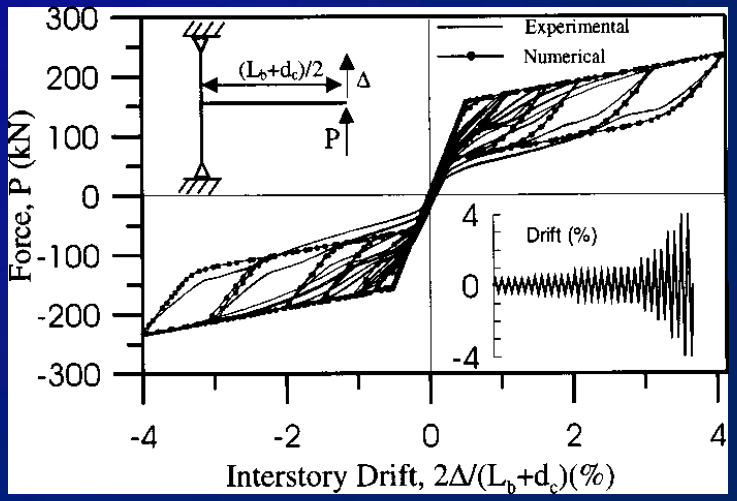
PT Strands and Angles
(Ricles et al. 2000)





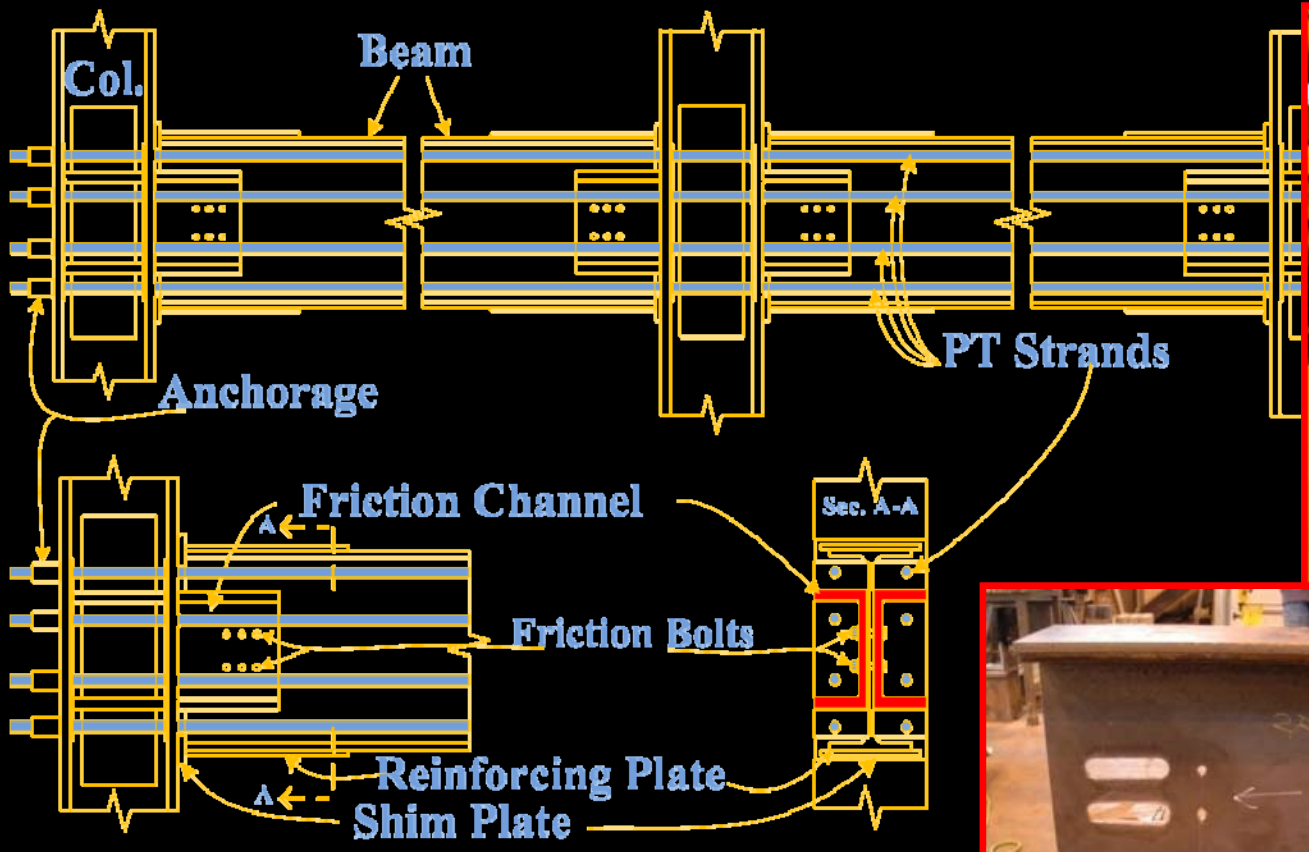
PT Bars and ED Bars
(Christopoulos et al. 2002)





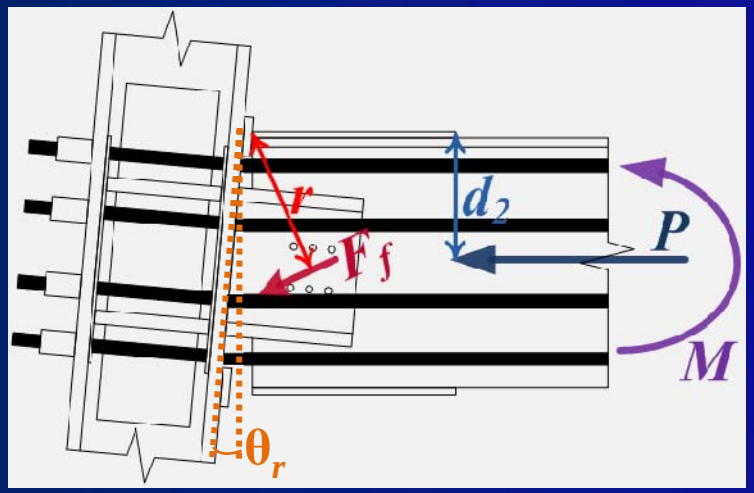
Beam-Column Connection and Energy Dissipation Details

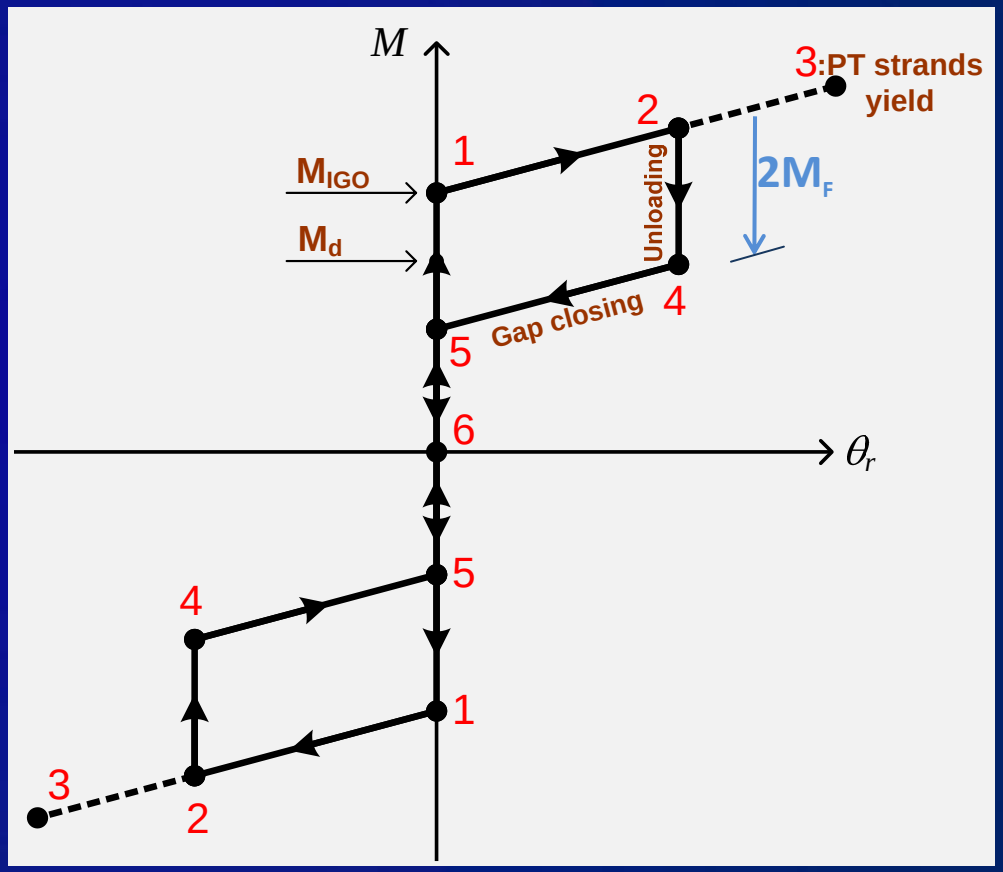
PT Strands and Web Friction Device (WFD) (Lin et al. 2008)



Used in large-scale SC-MRF tests.

Behavior of SC WFD Connection



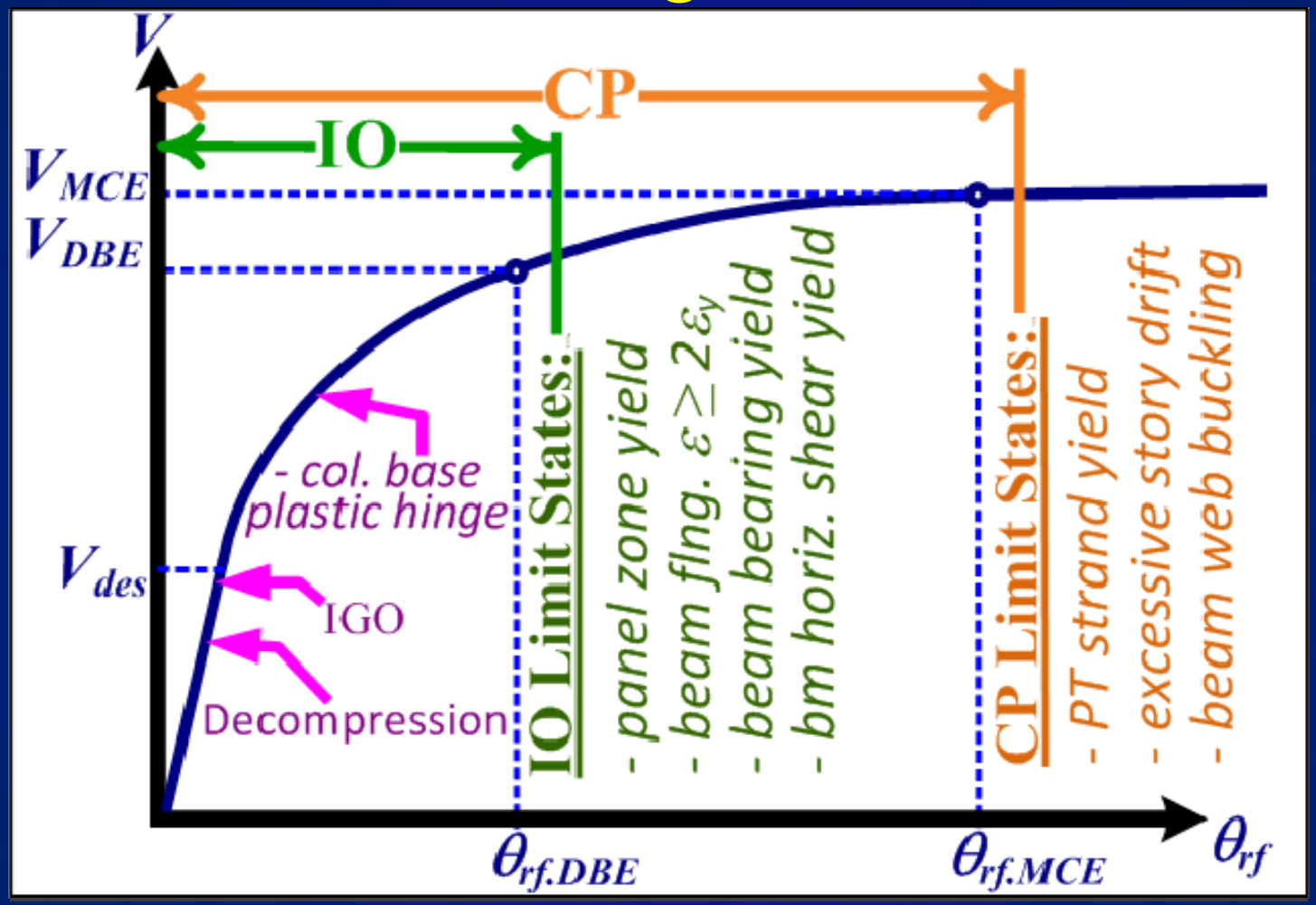


Performance-Based, Probabilistic Seismic Design Procedure

Target Performance

- Damage free for Immediate Occupancy (IO) under Design Basis Earthquake (DBE).
- Collapse Prevention (CP) under the Maximum Considered Earthquake (MCE).
- MCE – 2% probability of exceedance in 50 years.
- DBE – 10% probability of exceedance in 50 years (or 2/3 of MCE).

Performance-Based, Probabilistic Seismic Design Procedure

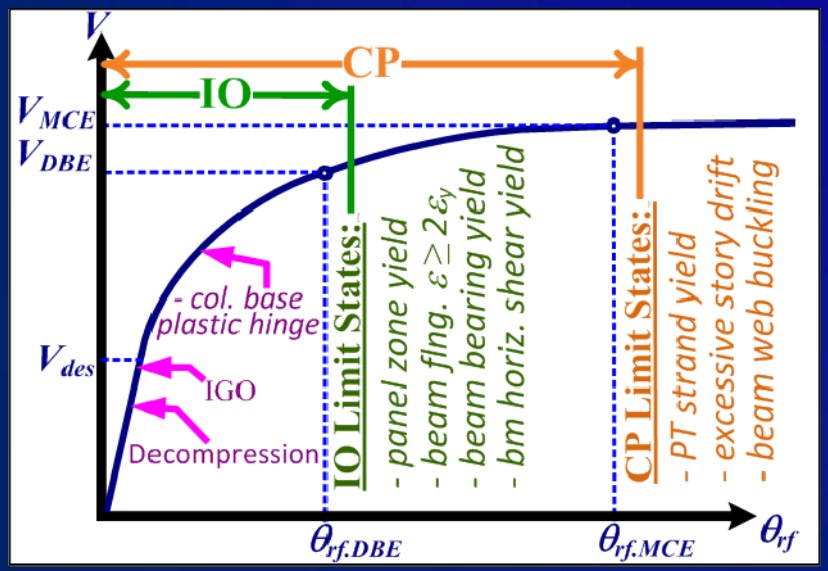


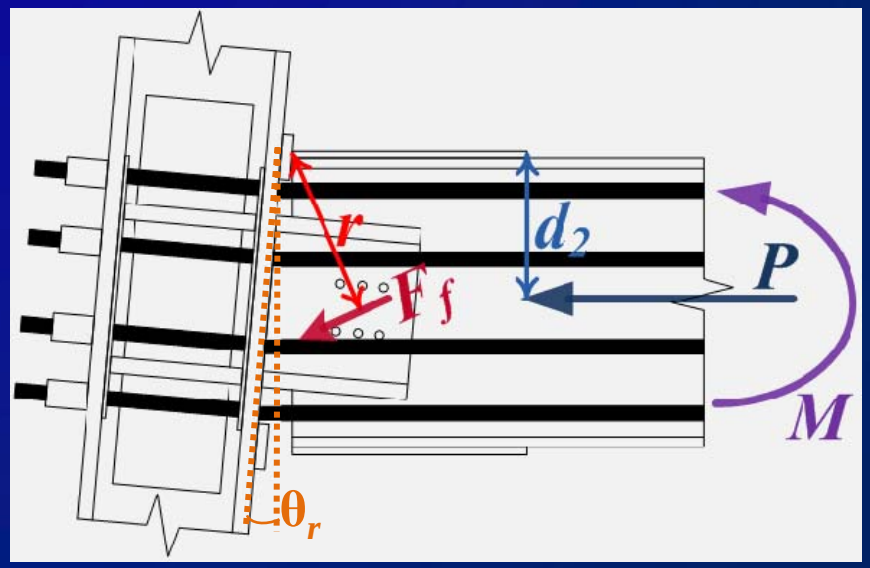
$\theta_{rf,DBE}$ = roof drift under DBE

$\theta_{rf,MCE}$ = roof drift under MCE

Performance-Based, Probabilistic Seismic Design Procedure

- Reliable estimates of global response $\theta_{rf,DBE}$ and $\theta_{rf,MCE}$ are critical for design procedure.
- Reliable estimates of corresponding local response variables $\theta_{r,DBE}$ $\theta_{r,MCE}$ are similarly critical.

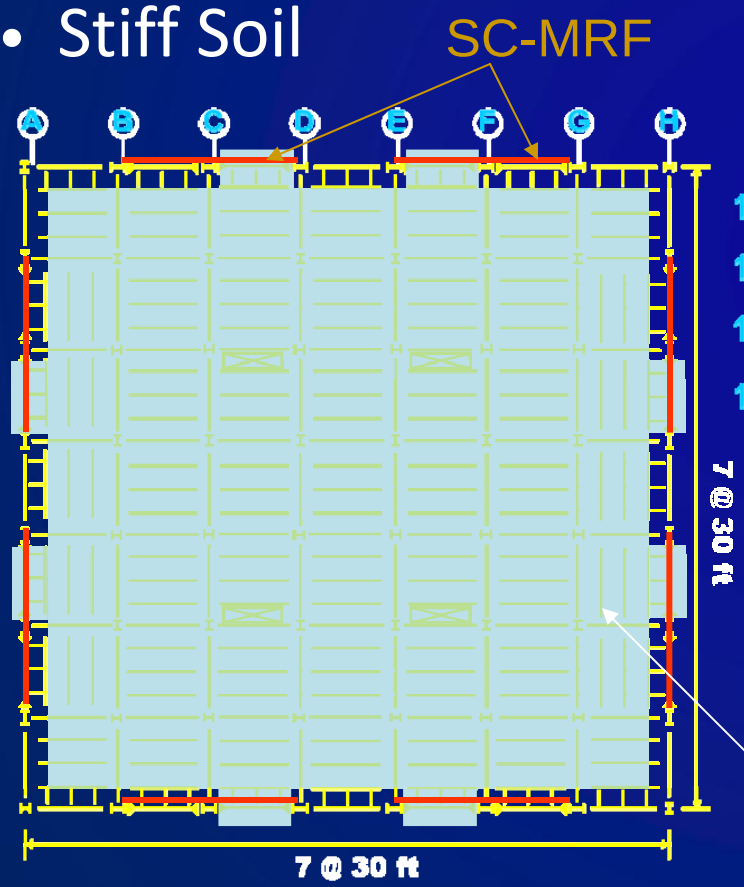




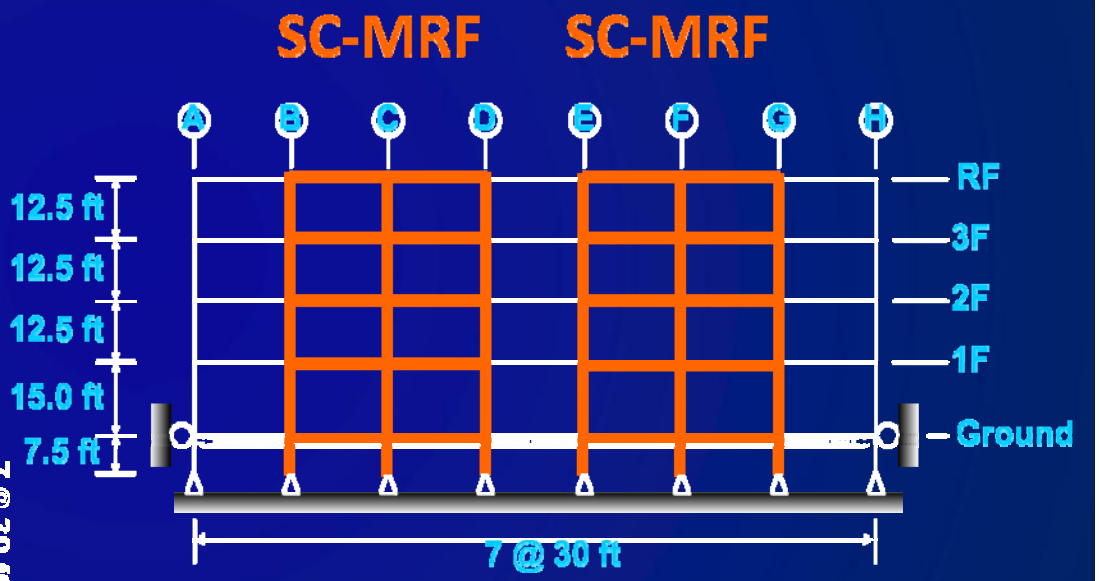
Large-Scale Hybrid Simulations on SC-MRF

Prototype SC-MRF

- 7x7-bay 4-story
- Office Building in Los Angeles, California
- Stiff Soil



Plan of Building



Elevation of perimeter frame

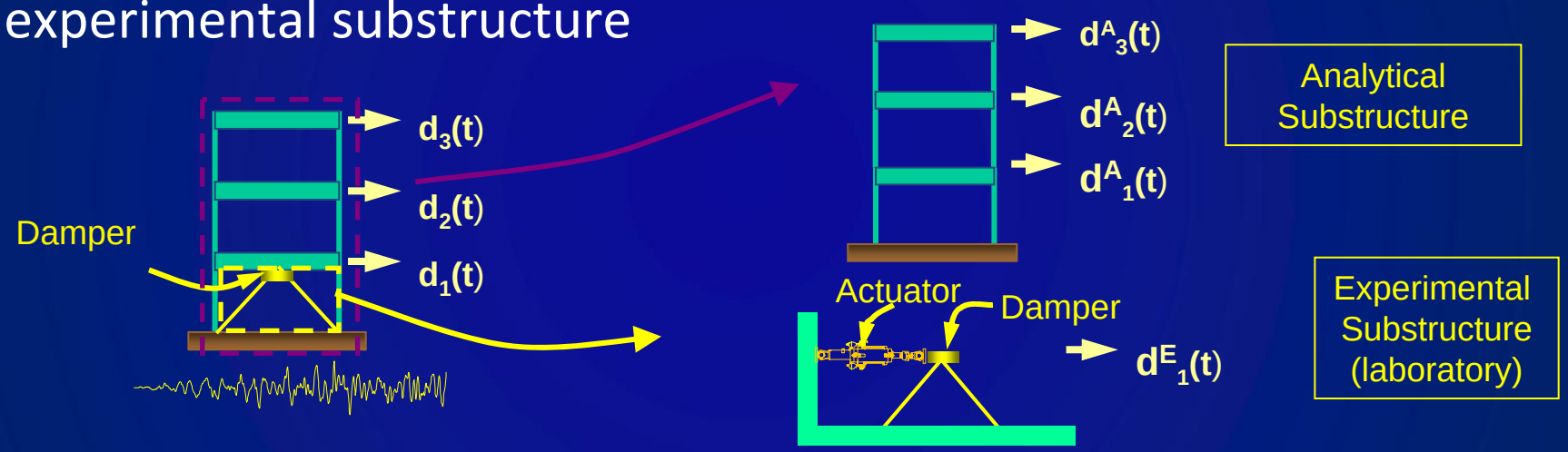
Composite/non-composite floor system to permit unrestrained gap opening of SC-WFD

Hybrid Simulations

- Direct integration of equations of motion with restoring forces ***r***(t)

$$\boldsymbol{M} \cdot \ddot{\boldsymbol{x}}_{i+1} + \boldsymbol{C} \cdot \dot{\boldsymbol{x}}_{i+1} + \boldsymbol{r}_{i+1} = \boldsymbol{F}_{i+1}$$

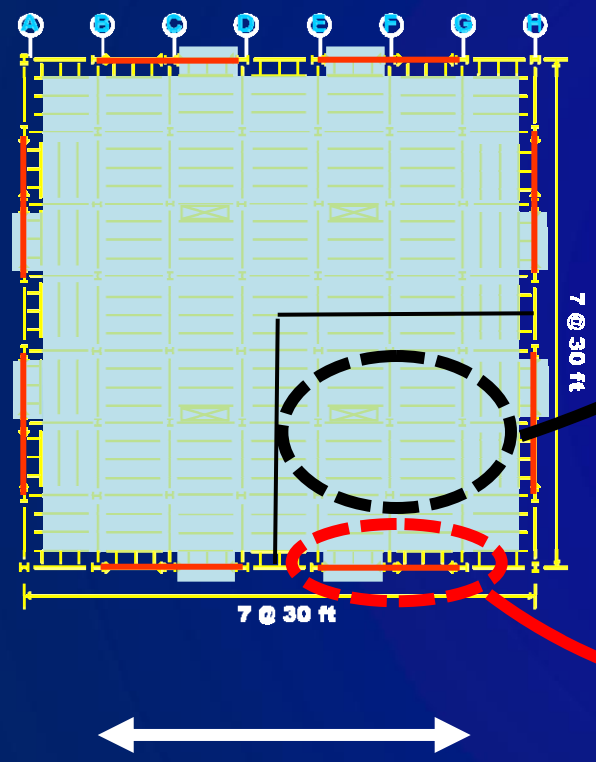
- Structural system divided into analytical substructure and experimental substructure



- Restoring forces from analytical substructure and experimental structure are combined

$$\boldsymbol{M} \cdot \ddot{\boldsymbol{x}}_{i+1} + \boldsymbol{C} \cdot \dot{\boldsymbol{x}}_{i+1} + \underbrace{\boldsymbol{r}^{a}_{i+1}}_{\text{analytical structure}} + \underbrace{\boldsymbol{r}^{e}_{i+1}}_{\text{experimental structure}} = \boldsymbol{F}_{i+1}$$

Large-Scale Hybrid Simulations on SC-MRF

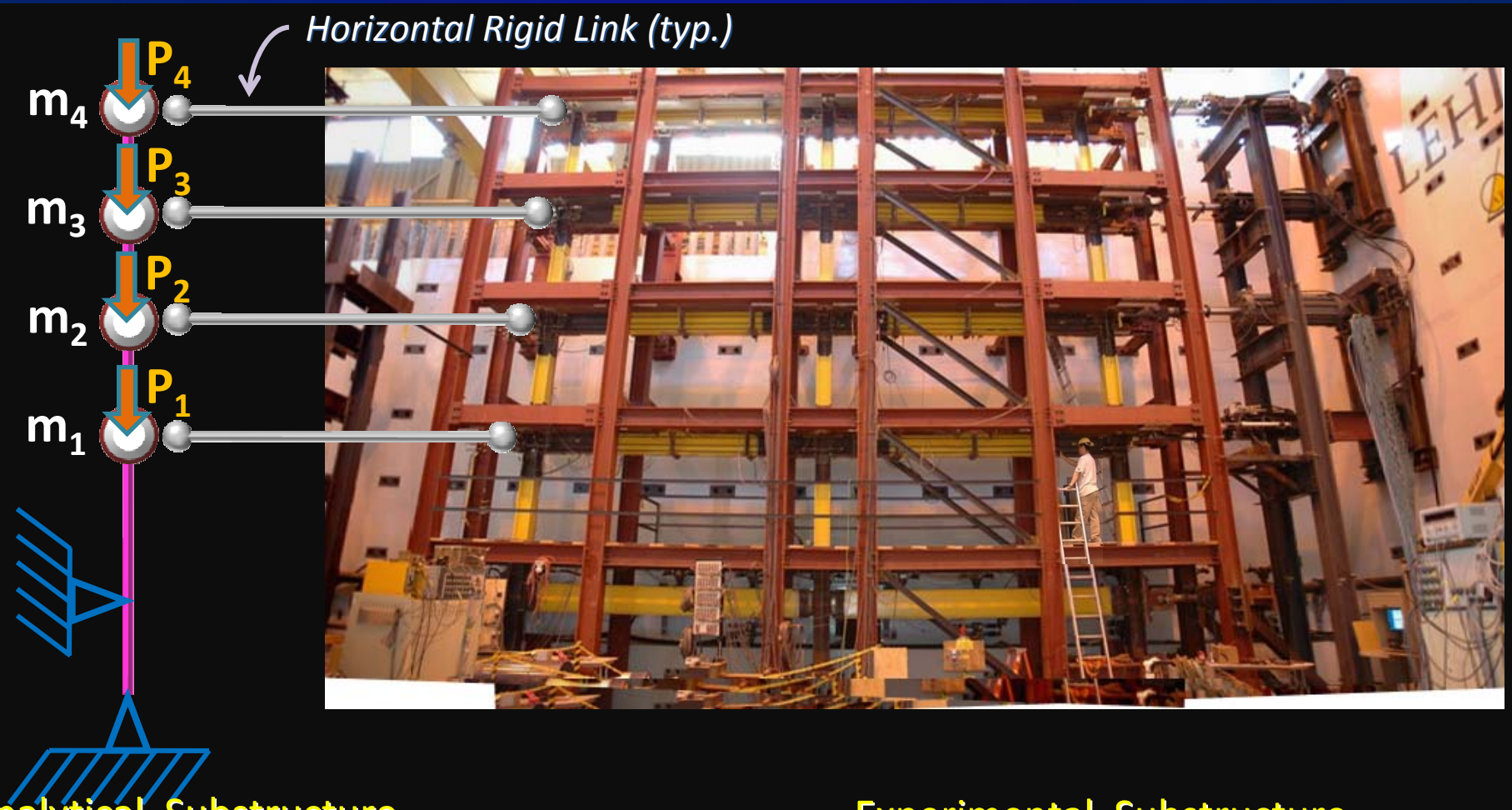


Tributary Gravity Frames, Seismic Mass, and Inherent Damping as Analytical Substructure

Perimeter SC-MRF as Experimental Substructure

Earthquake Loading Direction

Large-Scale Hybrid Simulations on SC-MRF



Analytical Substructure

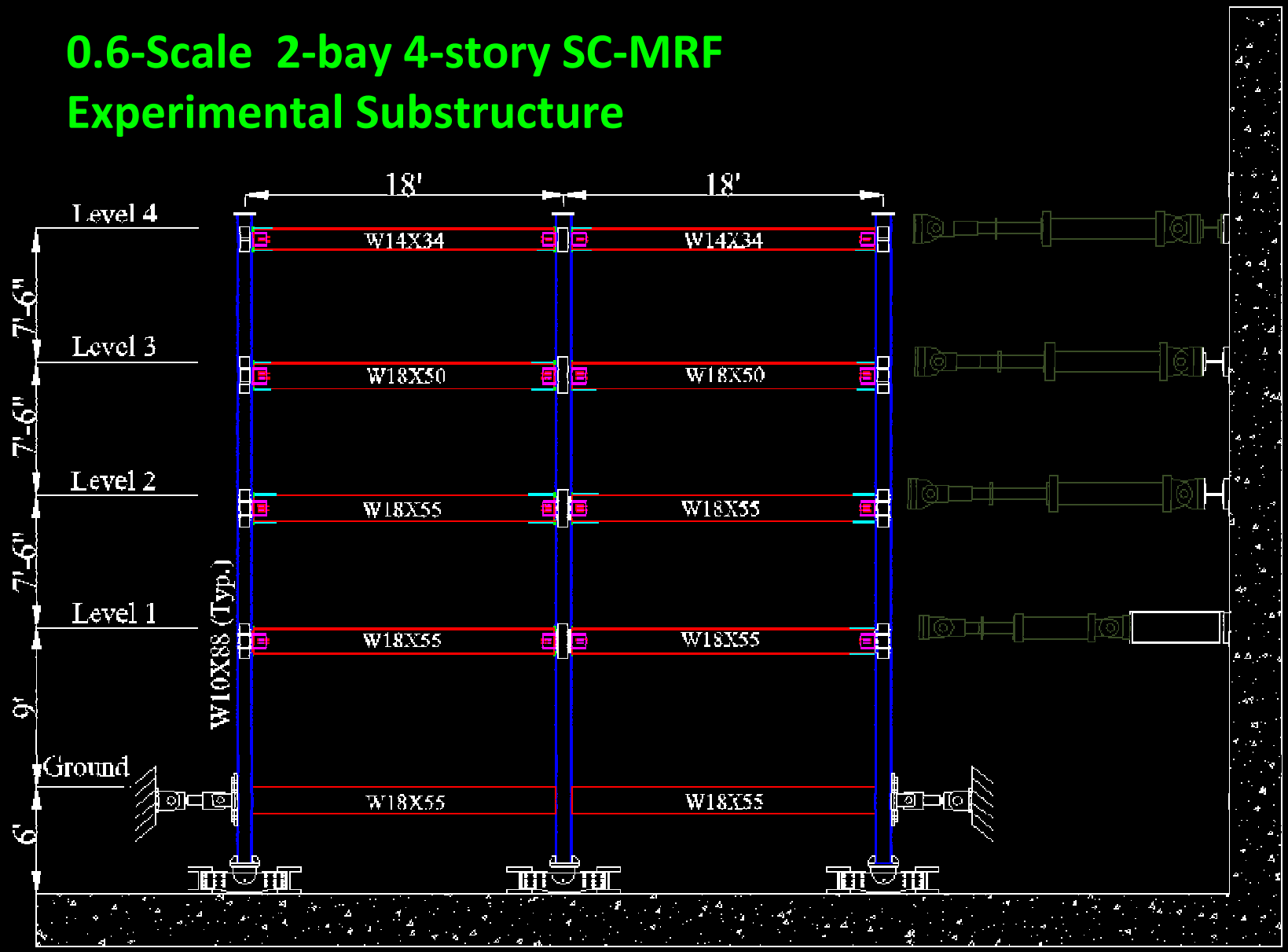
- Gravity Columns – column stiffness and axial loads P, building mass m and damping.

Experimental Substructure

- Displacements imposed through floor diaphragm system

Large-Scale Hybrid Simulations on SC-MRF

0.6-Scale 2-bay 4-story SC-MRF Experimental Substructure



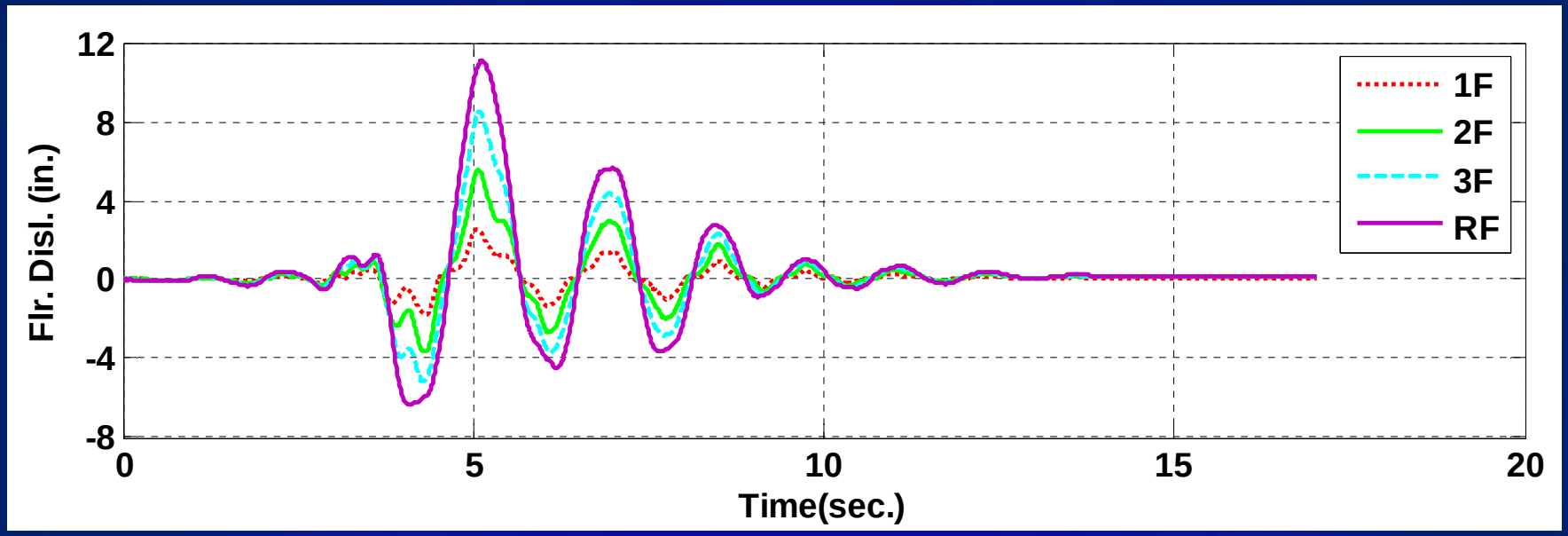
Large-Scale Hybrid Simulations on SC-MRF

Matrix of Simulations

Tests	Descriptions	Ground Motion Record	Scale Factor	Test Method
FOE-1	1979 Imperial Valley	H-CXO225	0.700	Hybrid
FOE-2	1979 Imperial Valley	H-CXO225	1.400	
DBE-1	1979 Imperial Valley	H-ECC002	0.943	
DBE-2	1989 Loma Prieta	SJTE315	-2.234	
DBE-3	1994 Northridge	LOS000	1.182	
MCEs	1994 Northridge	Varied w/ tests	Varied w/ tests	
Aftershocks	1989 Loma Prieta	SJTE315	-2.234	

Large-Scale Hybrid Simulations on SC-MRF

DBE-3 Floor Displacements and Story Drifts

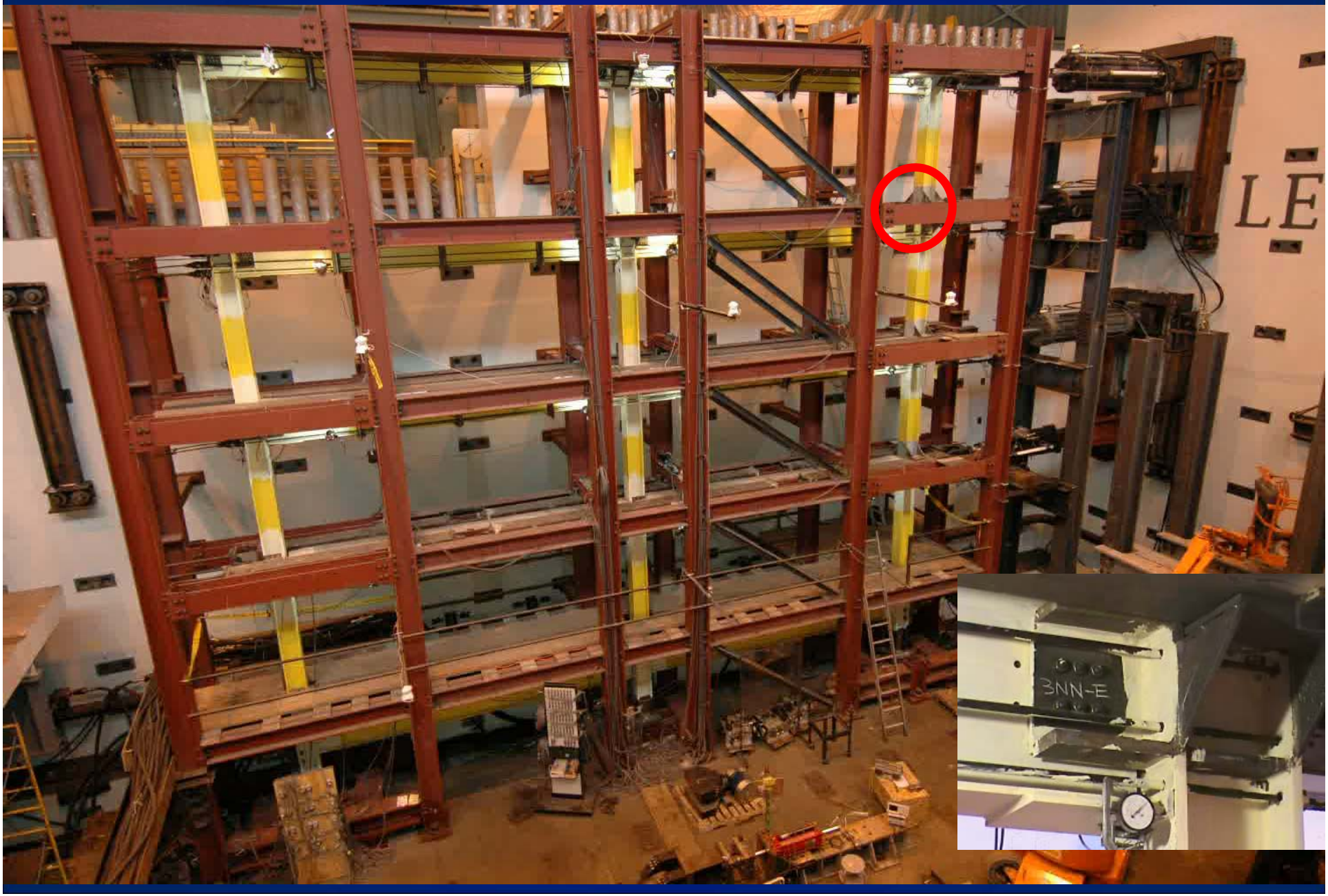


Level	$\theta_{s\,max}$ (% rad.)	Residual Drift (% rad.)
RF	3.9	0.008
3F	3.5	0.023
2F	3.5	0.063
1F	2.1	0.074

Observed Experimental Response

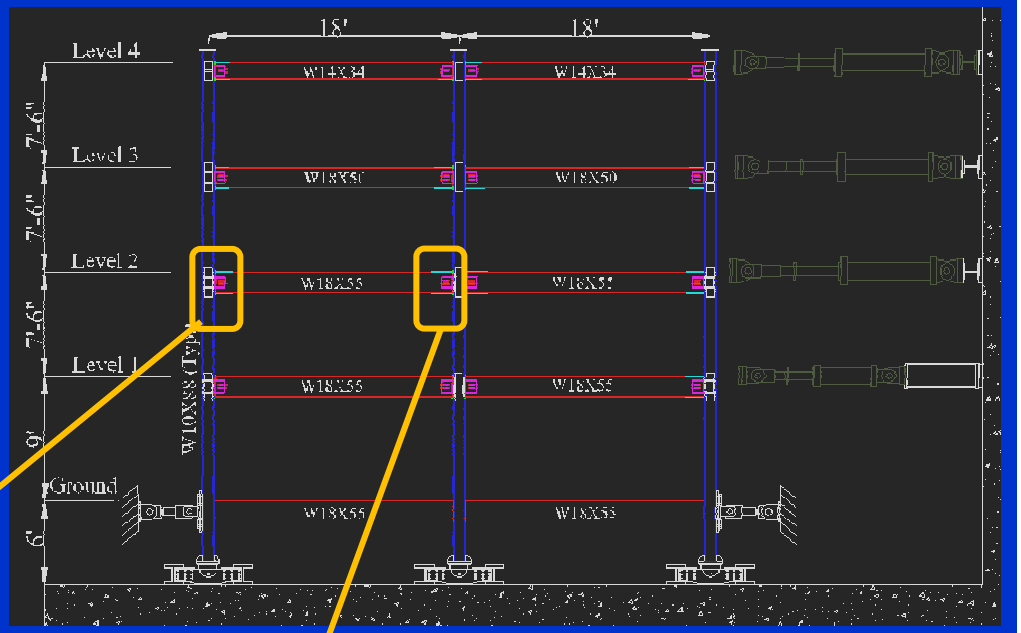
- ✓ No damage in beams and columns, except for yielding at column base.
- ✓ No residual drift: self-centering

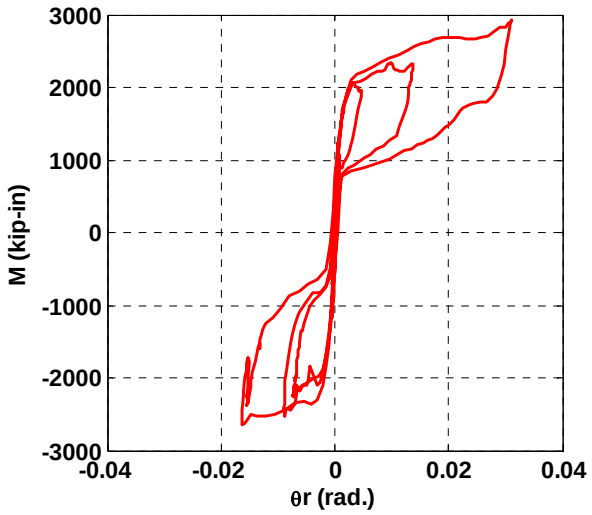
DBE-3 Simulation Results

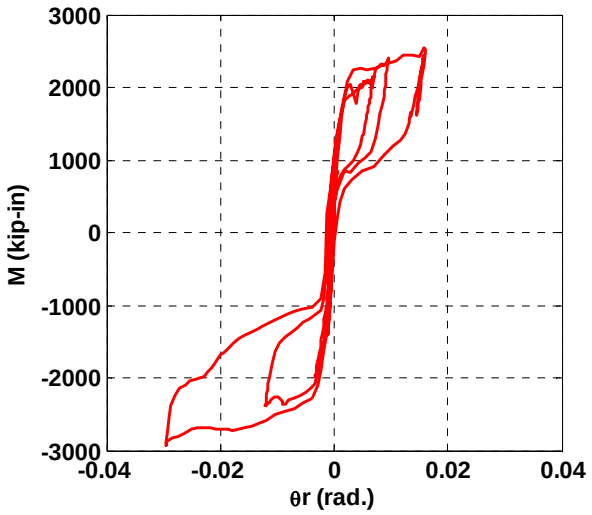


DBE-3 Simulation Results

Moment – θ_r response





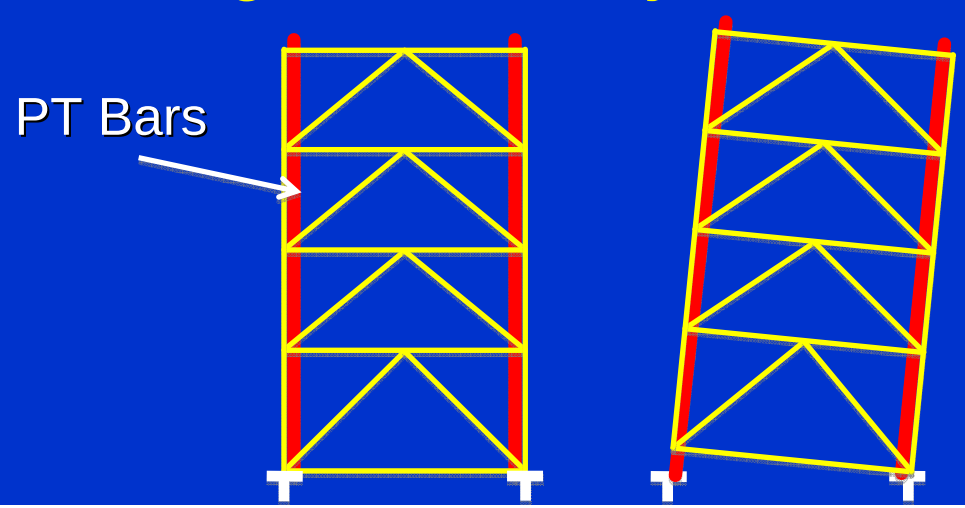


Summary and Conclusions from Large-Scale Hybrid Simulations on SC-MRF

- First large-scale simulations on steel SC-MRF system.
- Simulations validated the performance-based design procedure and criteria.
- SC-WFD beam-to-column connections performed well, dissipating energy while maintaining self-centering.
- Demonstrated that SC-MRF system can be designed to be damage free and achieve *Immediate Occupancy* (IO) performance under DBE.
- Also demonstrated that residual drift and damage of SC-MRF system is minimal under the MCE, achieving *Collapse Prevention (CP)* performance.

Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project: SC-CBF Systems

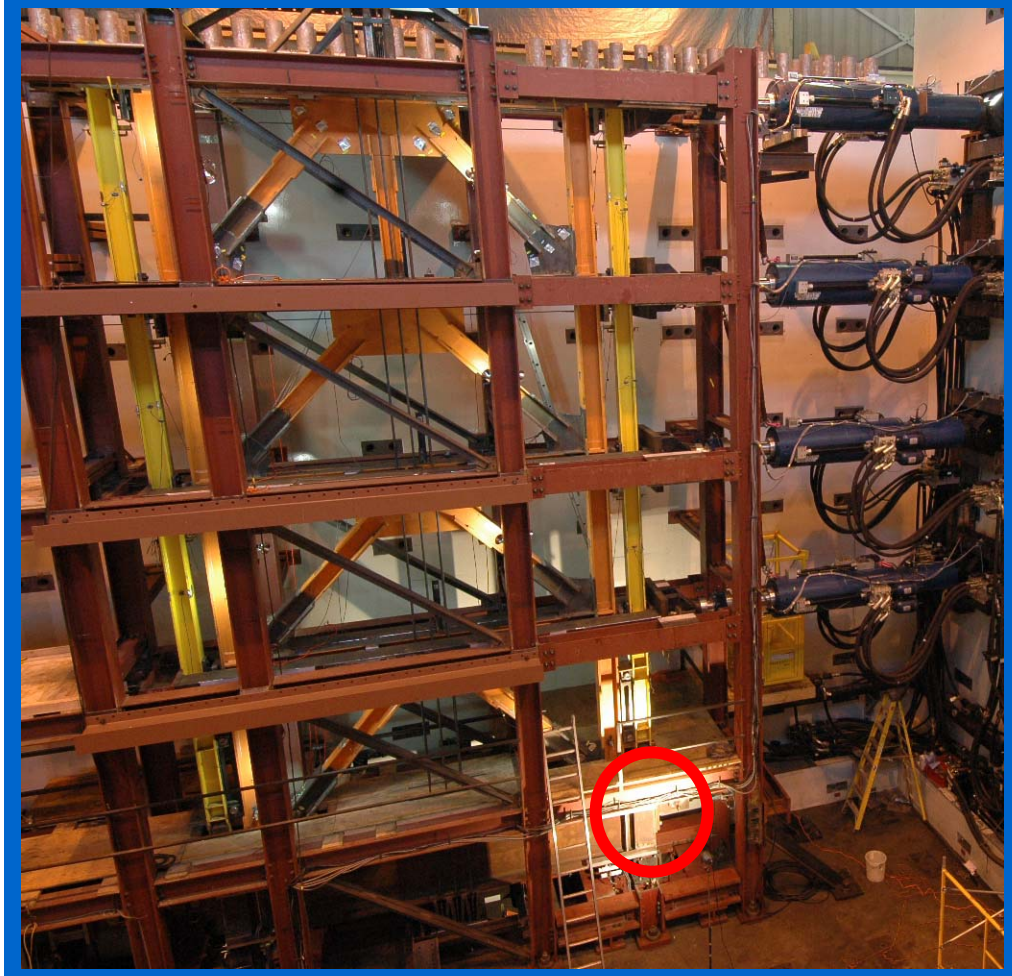
- **Develop SC-CBF concept and configurations.**
- **Develop performance-based, probabilistic seismic design procedure for SC-CBFs.**
- **Develop connection and energy dissipation details for SC-CBFs.**
- **Conduct large-scale laboratory tests of SC-MRFs using NEES facility.**



Concentrically-braced frames (SC-CBFs).

Large-Scale Hybrid Simulations on SC-CBF

- Large-scale hybrid simulations of 4-story SC-CBF at Lehigh NEES equipment site are in progress.



Acknowledgement

Project: NEESR-SG: Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems

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NEES

Thank you.