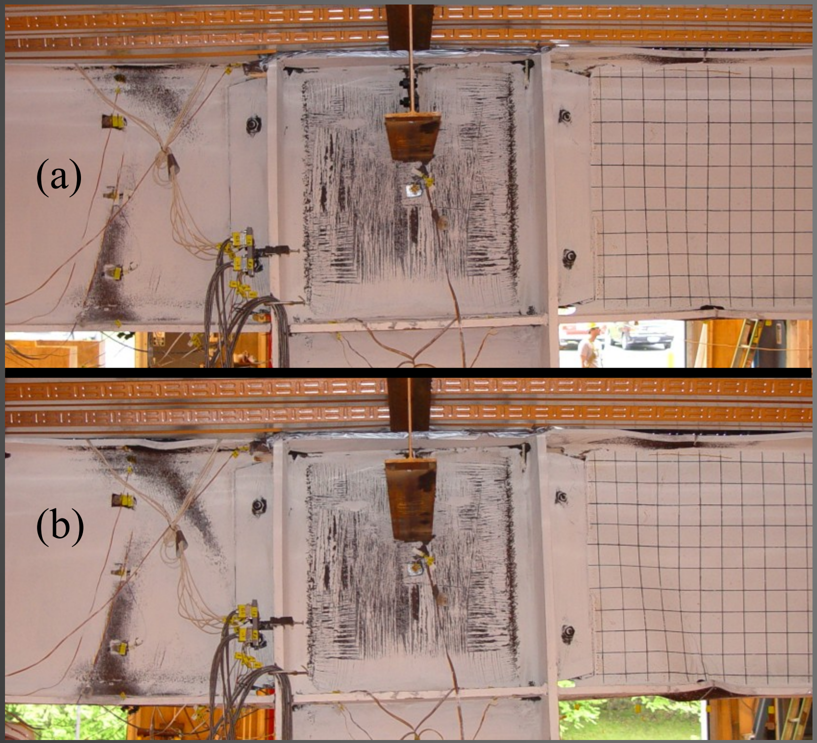
Motivation: Expected Damage for Conventional Steel Frames

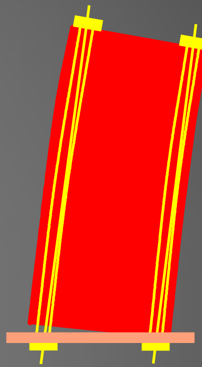


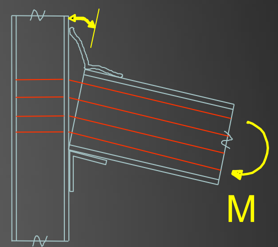
Conventional Moment Resisting Frame System

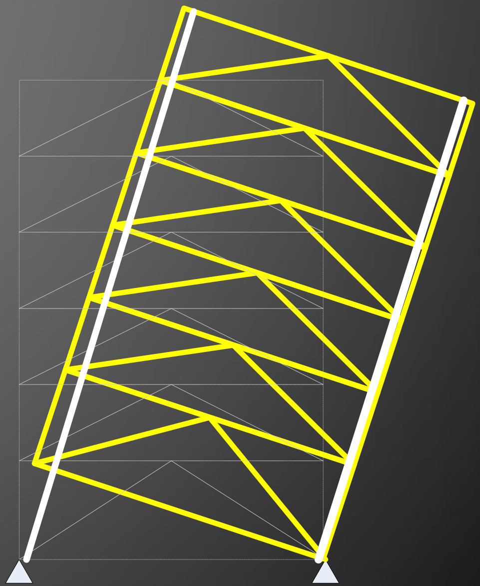
Reduced beam section (RBS) beam-column test specimen with slab: (a) at 3% drift, (b) at 4% drift.

Self Centering (SC) Seismic-Resistant System Concepts

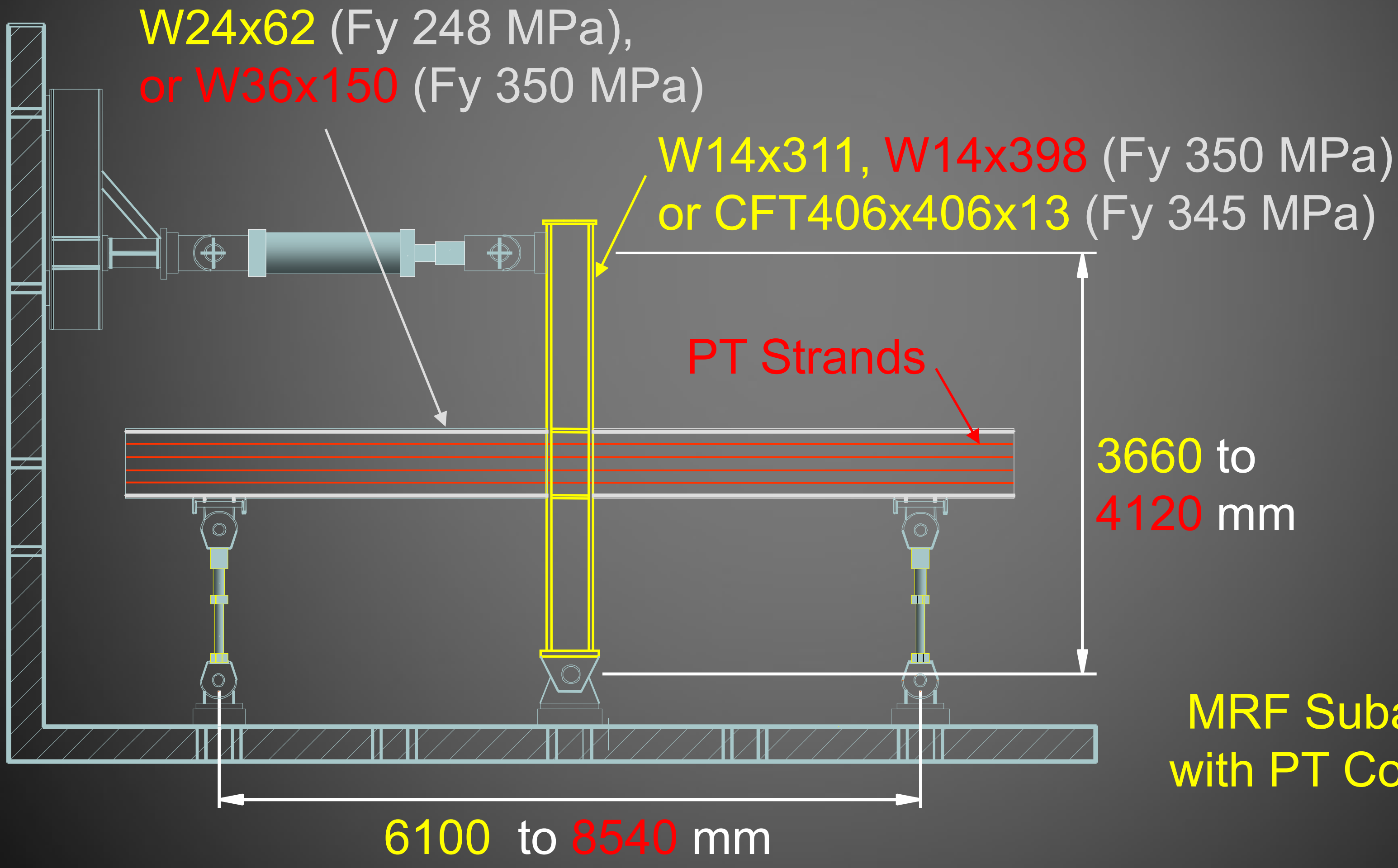
- Discrete structural members are post-tensioned to pre-compress joints.
- Gap opening at joints at selected earthquake load levels provides softening of lateral force-drift behavior without damage to members.
- PT forces close joints and permanent lateral drift is avoided.





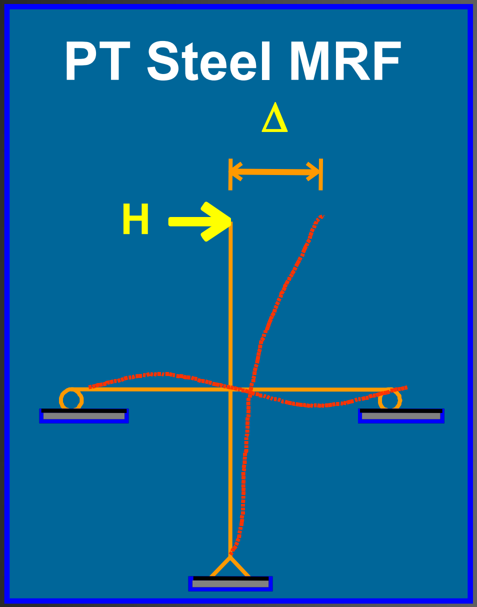


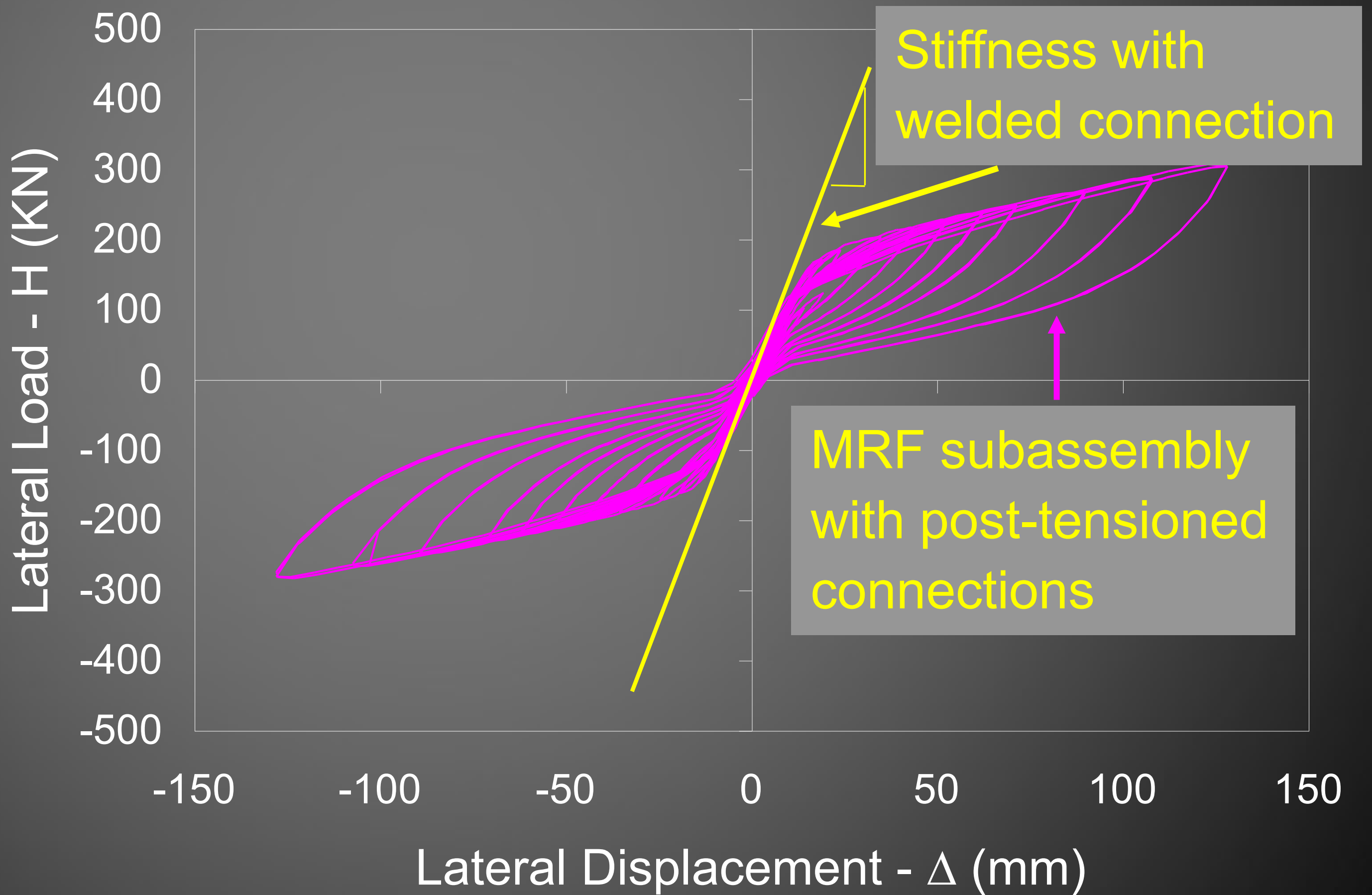
Previous Work on SC Steel Moment Resisting (MRF) Connections



MRF Subassembly with PT Connections

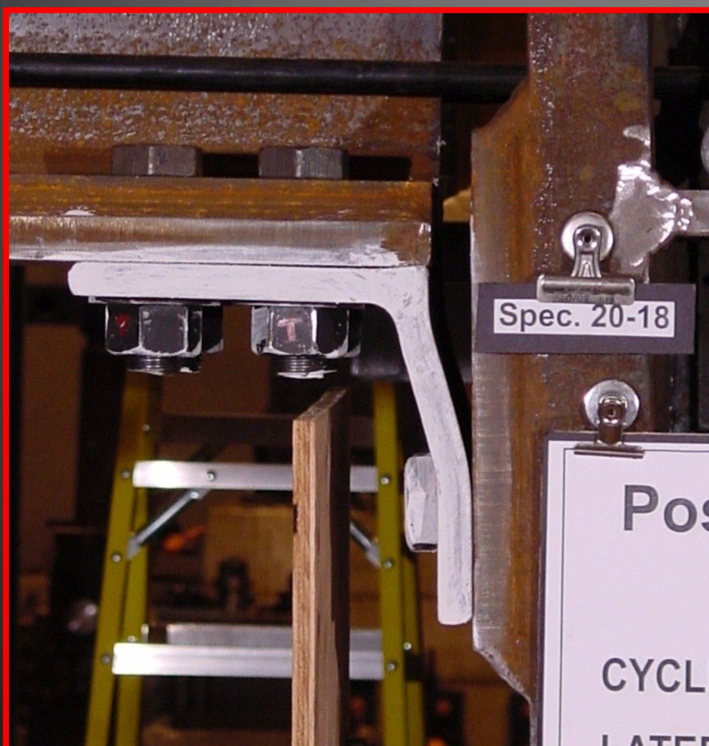
Initial Stiffness Is Similar to Stiffness of Conventional Systems

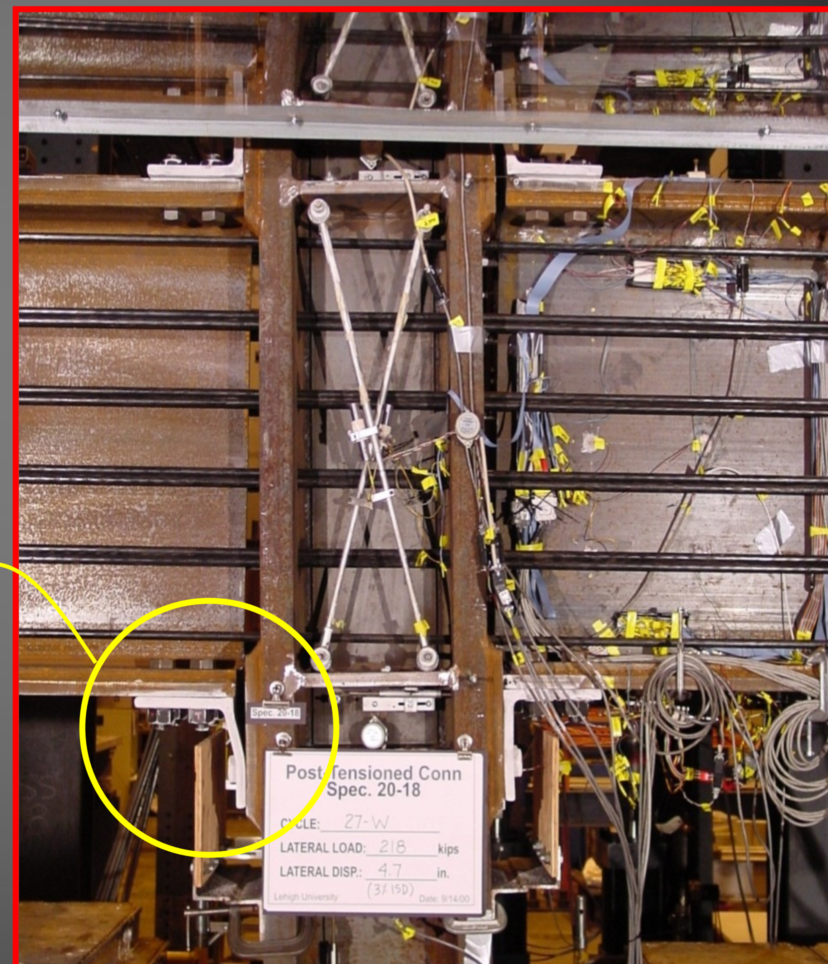




Lateral Force-Drift Behavior Softens Due to Gap Opening

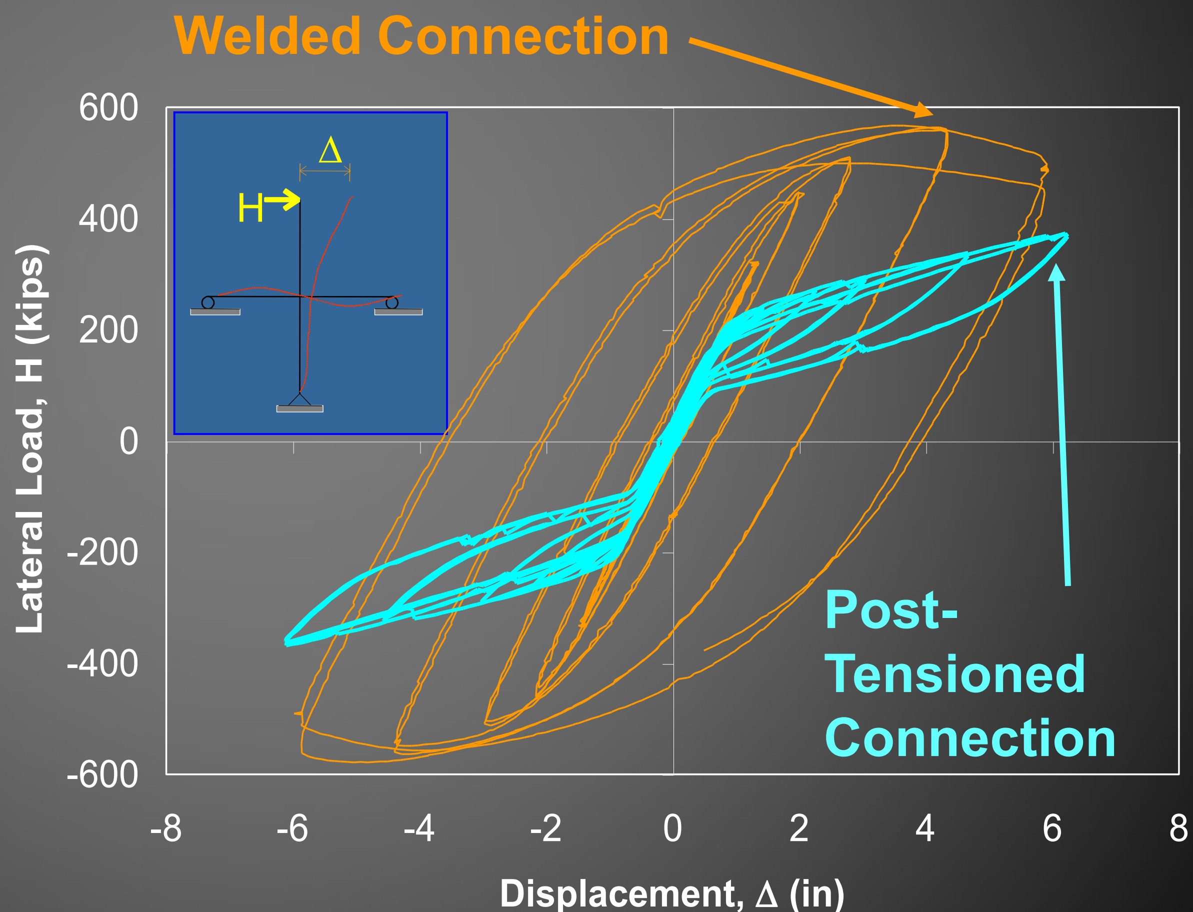
Steel MRF subassembly with post-tensioned connections and angles at 3% drift



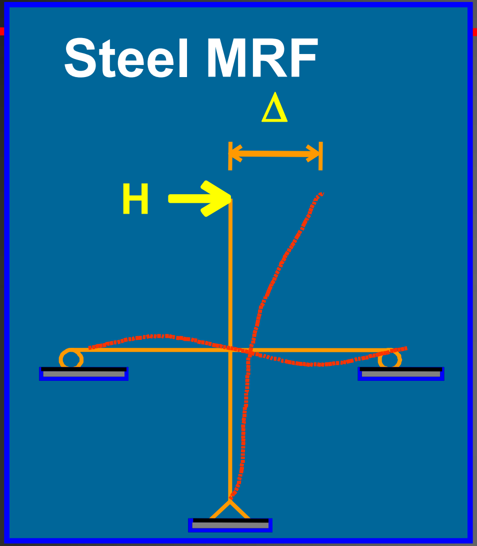


Lateral Force-Drift Behavior Softens Without Significant Damage

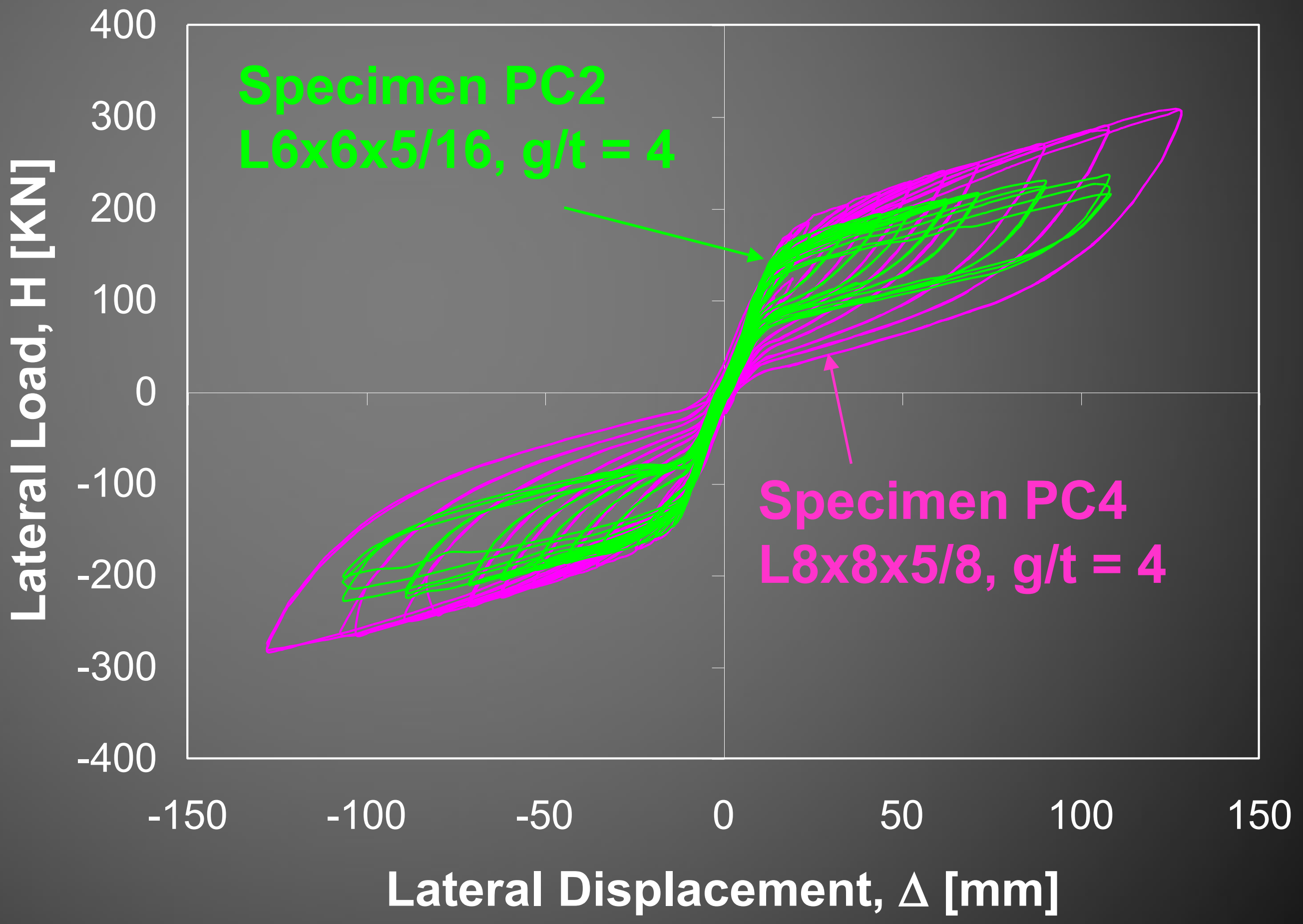
- Conventional steel MRFs soften by inelastic deformation, which damages main structural members and results in residual drift
- SC steel MRF softens by gap opening and reduced contact area at joints



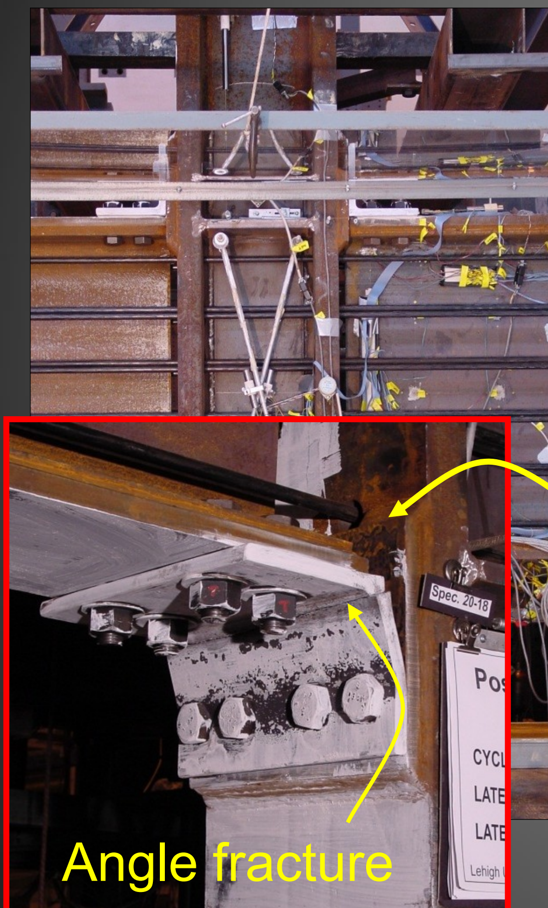
Energy Dissipation from Energy Dissipation (ED) Elements



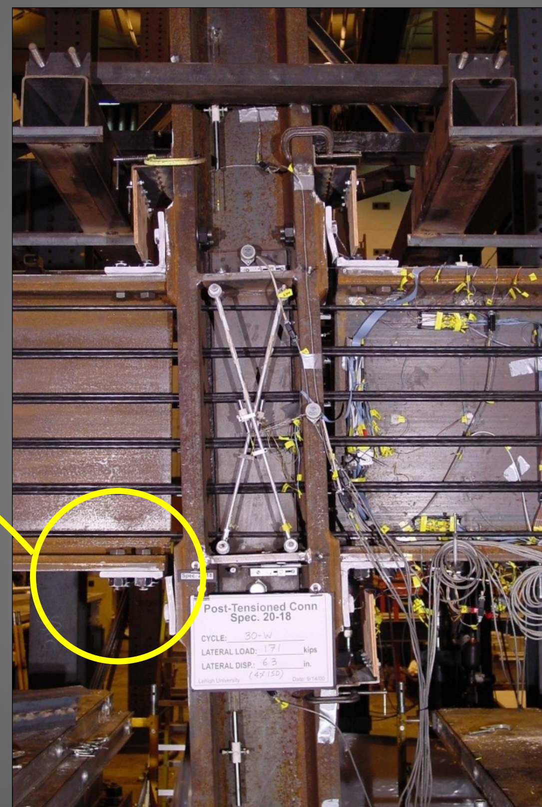
Steel MRF subassemblies with post-tensioned connections with different size ED elements.



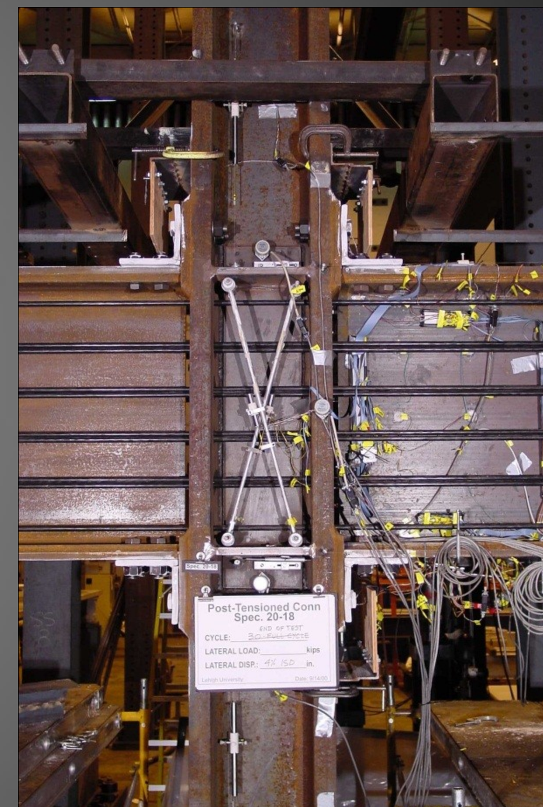
Limited, Repairable Damage



Before testing



@ 4% Drift



After testing

Summary of SC Seismic-Resistant Structural System Behavior

- Initial lateral stiffness is similar to that of conventional seismic-resistant systems.
- Lateral force-drift behavior softens due to gap opening at selected joints and without significant damage to main structural members.
- Lateral force-drift behavior softening due to gap opening controls force demands.
- Energy dissipation provided by energy dissipation (ED) elements, not from damage to main structural members.

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

- Project Scope.
- Project Goals.
- Status of Selected Research Tasks.
- Summary.

NEESR-SG: SC Steel Frame Systems Project Scope

- Develop two SC steel frame systems:
  - Moment-resisting frames (SC-MRFs).
  - Concentrically-braced frames (SC-CBFs).
- Conduct large-scale experiments utilizing:
  - NEES ES (RTMD facility) at Lehigh.
  - non-NEES laboratory (Purdue).
  - international collaborating laboratory (NCREE)
- Conduct analytical and design studies of prototype buildings.
- Develop design criteria and design procedures.

NEESR-SG: SC Steel Frame Systems Project Goals

- Overall: self-centering steel systems that are constructible, economical, and structurally damage-free under design earthquake.
- Specific:
  - Fundamental knowledge of seismic behavior of SC-MRF systems and SC-CBF systems.
  - Integrated design, analysis, and experimental research using NEES facilities.
  - Performance-based, reliability-based seismic design procedures.

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

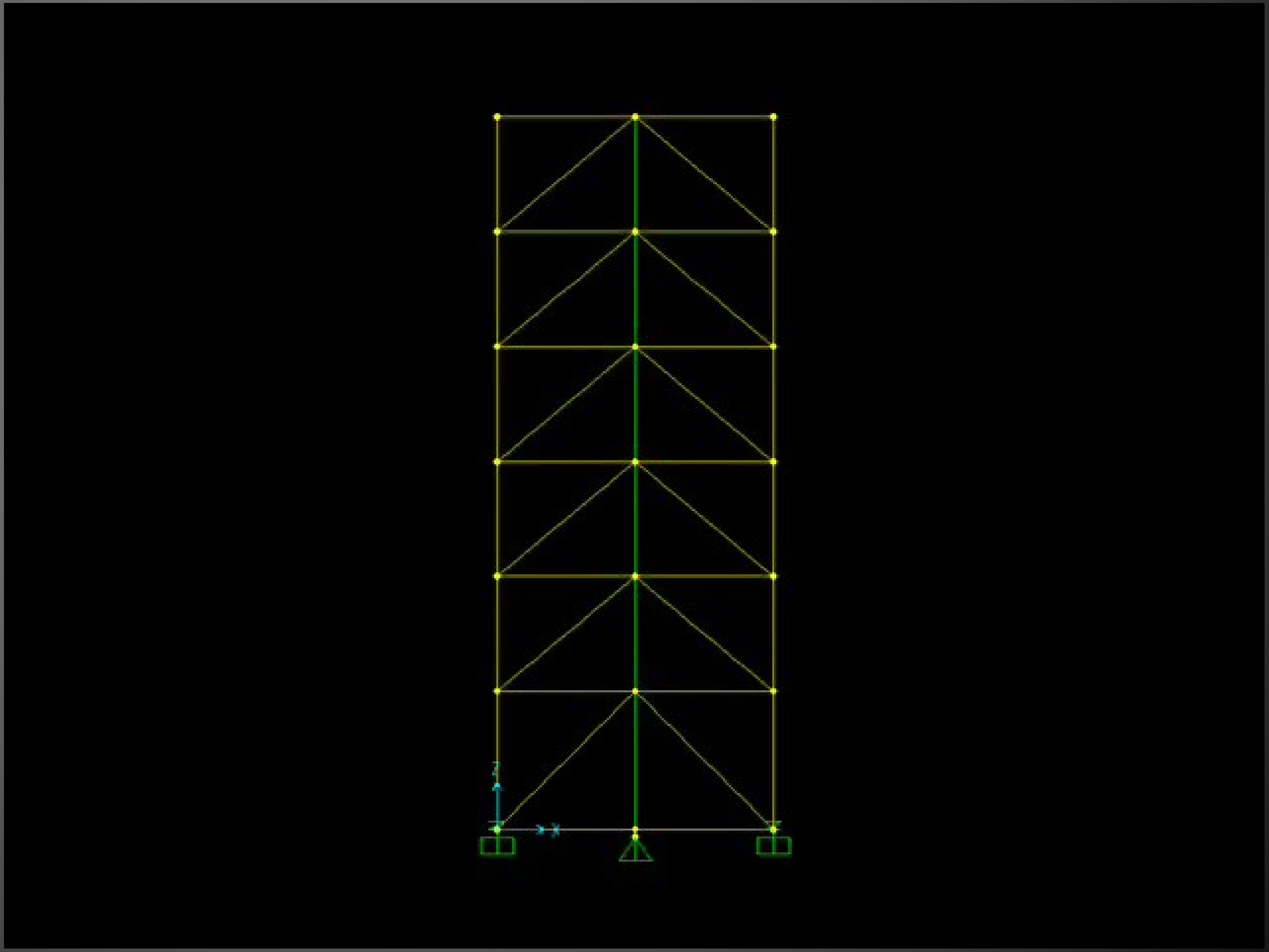
- Project Scope.
- Project Goals.
- Status of Selected Research Tasks.
- Summary.

NEESR-SG: SC Steel Frame Systems Project Research Tasks

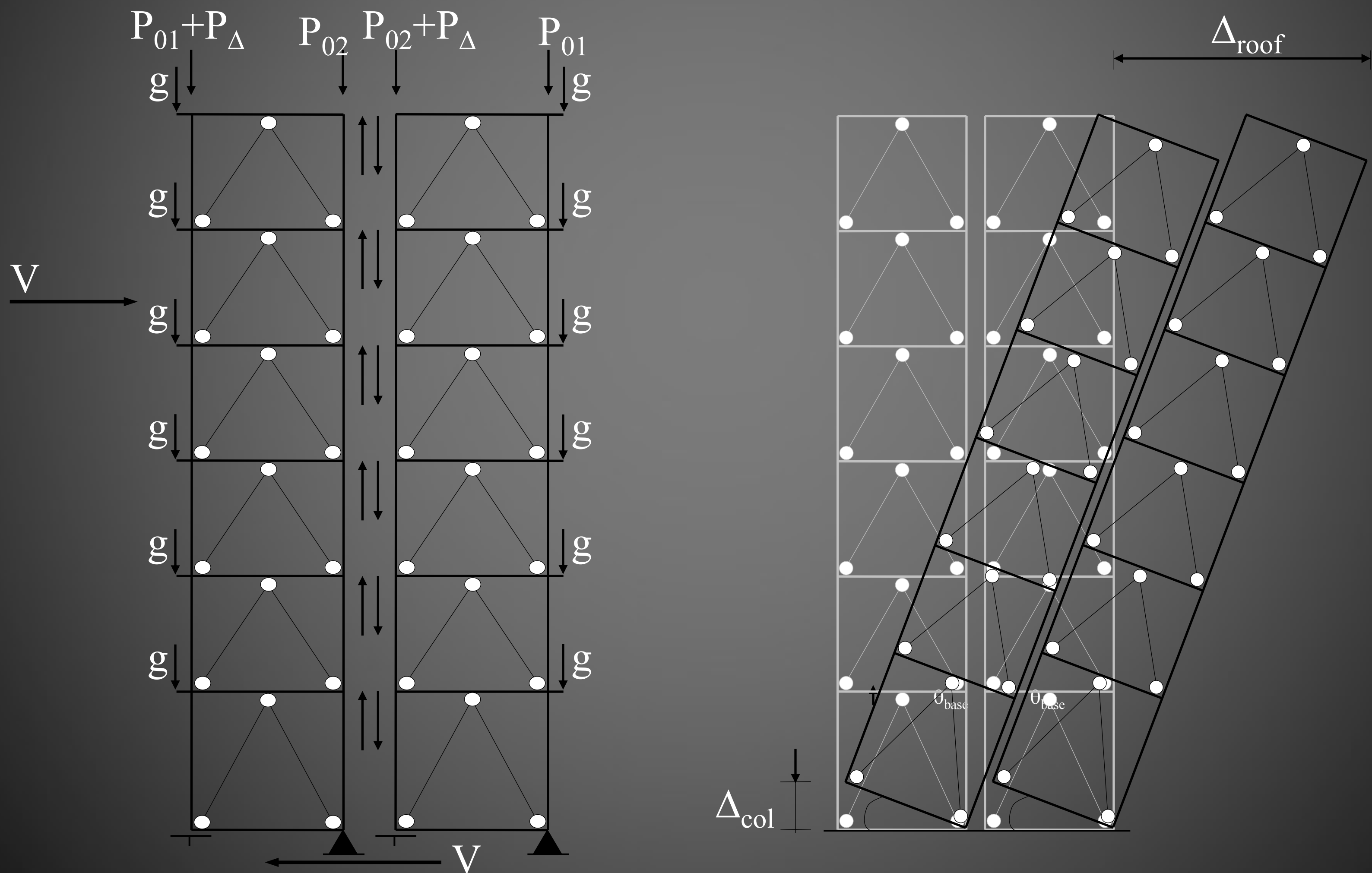
1. Develop reliability-based seismic design and assessment procedures.
2. Develop SC-CBF systems.
3. Further develop SC-MRF systems.
4. Develop energy dissipation elements for SC-MRFs and SC-CBFs.
5. Develop sensor networks for damage monitoring and integrity assessment.
6. Design prototype buildings.
7. Perform nonlinear analyses of prototype buildings.
8. Conduct large-scale laboratory tests of SC-MRFs and SC-CBFs.
9. Collaborate on 3-D large-scale laboratory tests on SC-MRF and SC-CBF systems.

Task 2. Develop SC-CBF Systems: SC-CBF System Concept

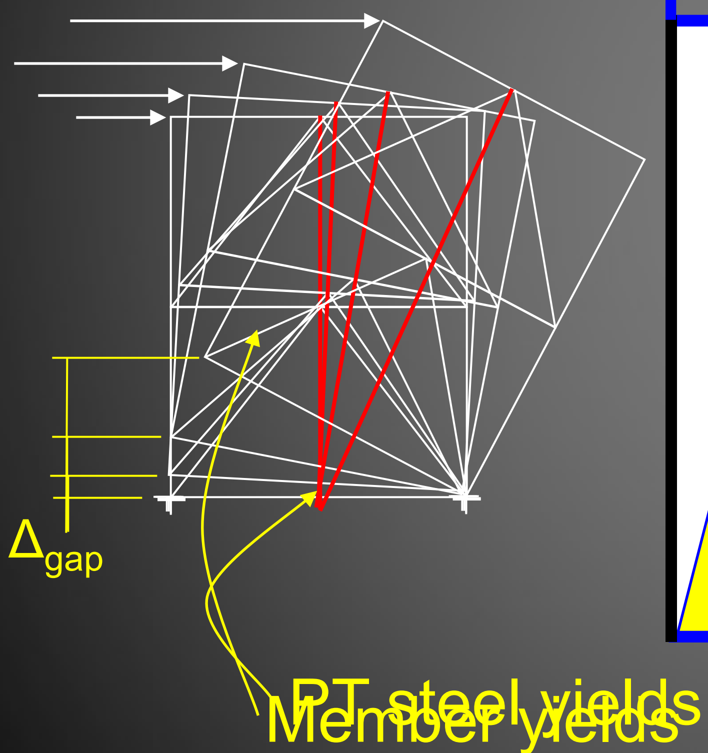
Rocking behavior of simple SC-CBF system.

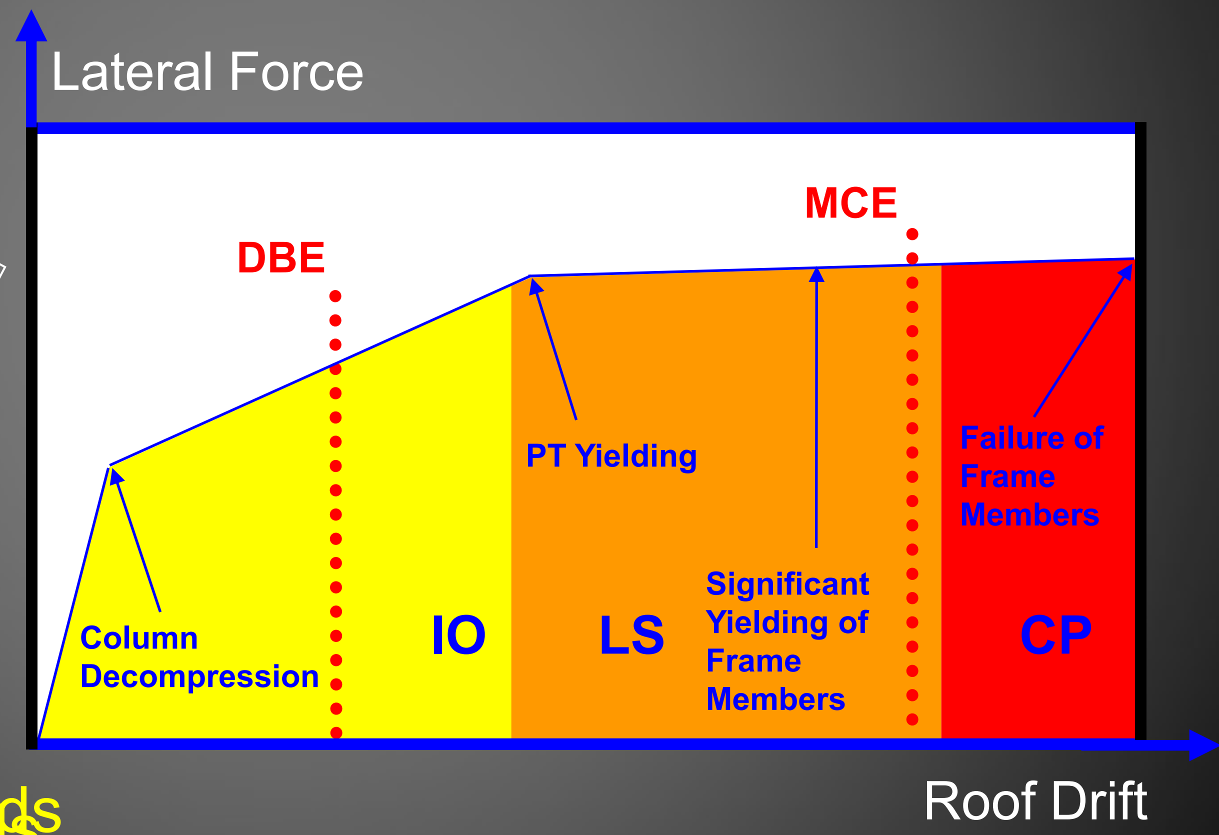


More Complex SC-CBF Configurations Being Considered



SC-CBF Design Criteria

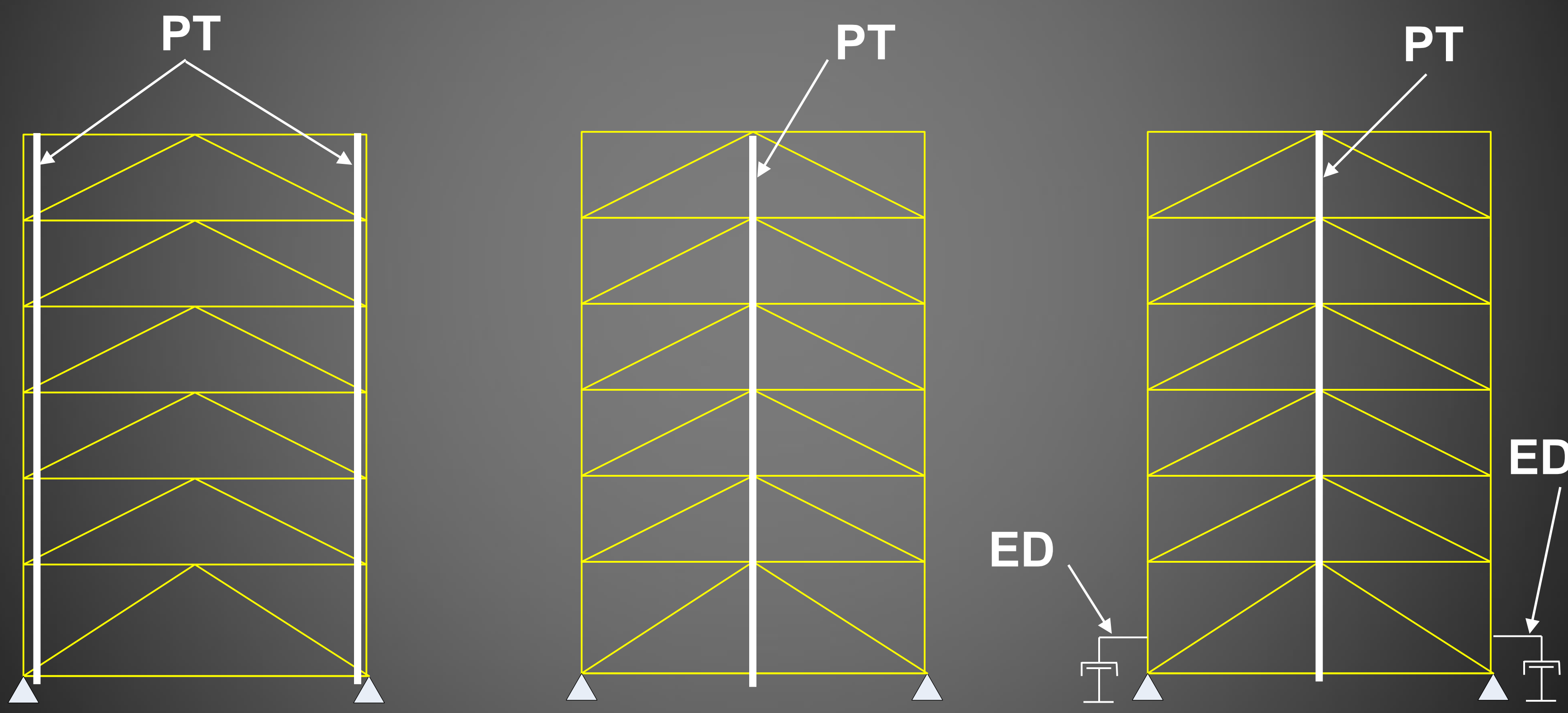




Current Work on SC-CBF Systems

- Evaluate frame configurations.
- Evaluate effect of energy dissipation (ED) elements.
- Develop and evaluate performance-based design approach.

SC-CBF Configurations Studied



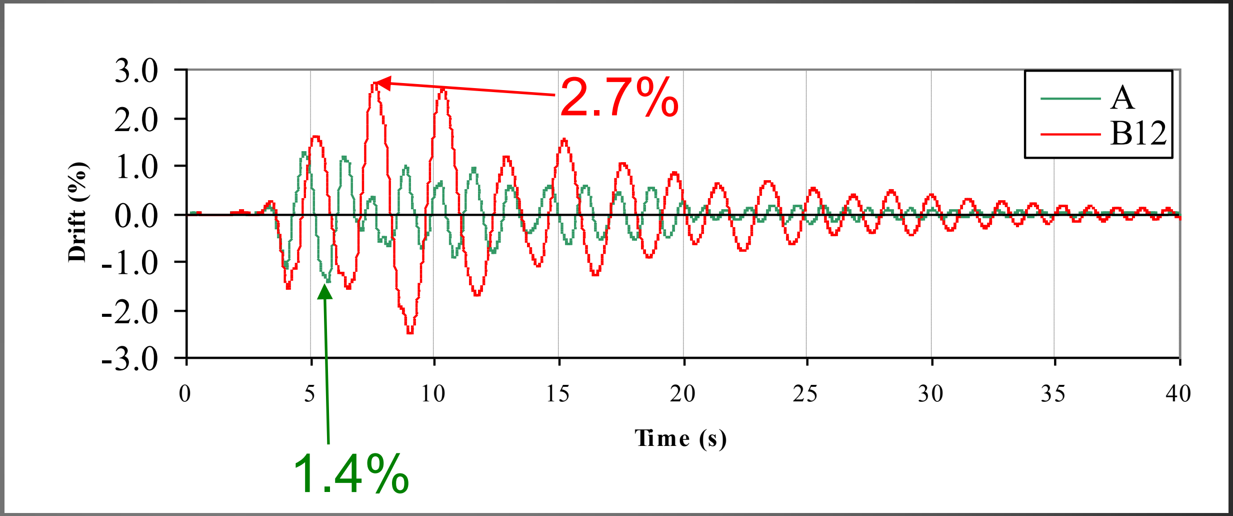
Frame A

Frame B12

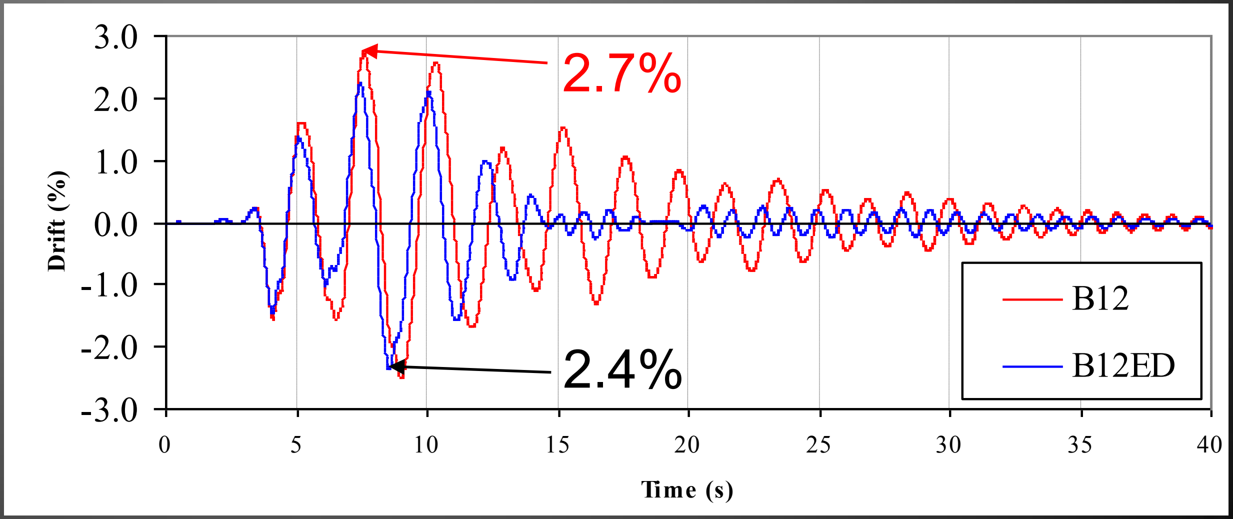
Frame B12ED

Dynamic Analysis Results (DBE)

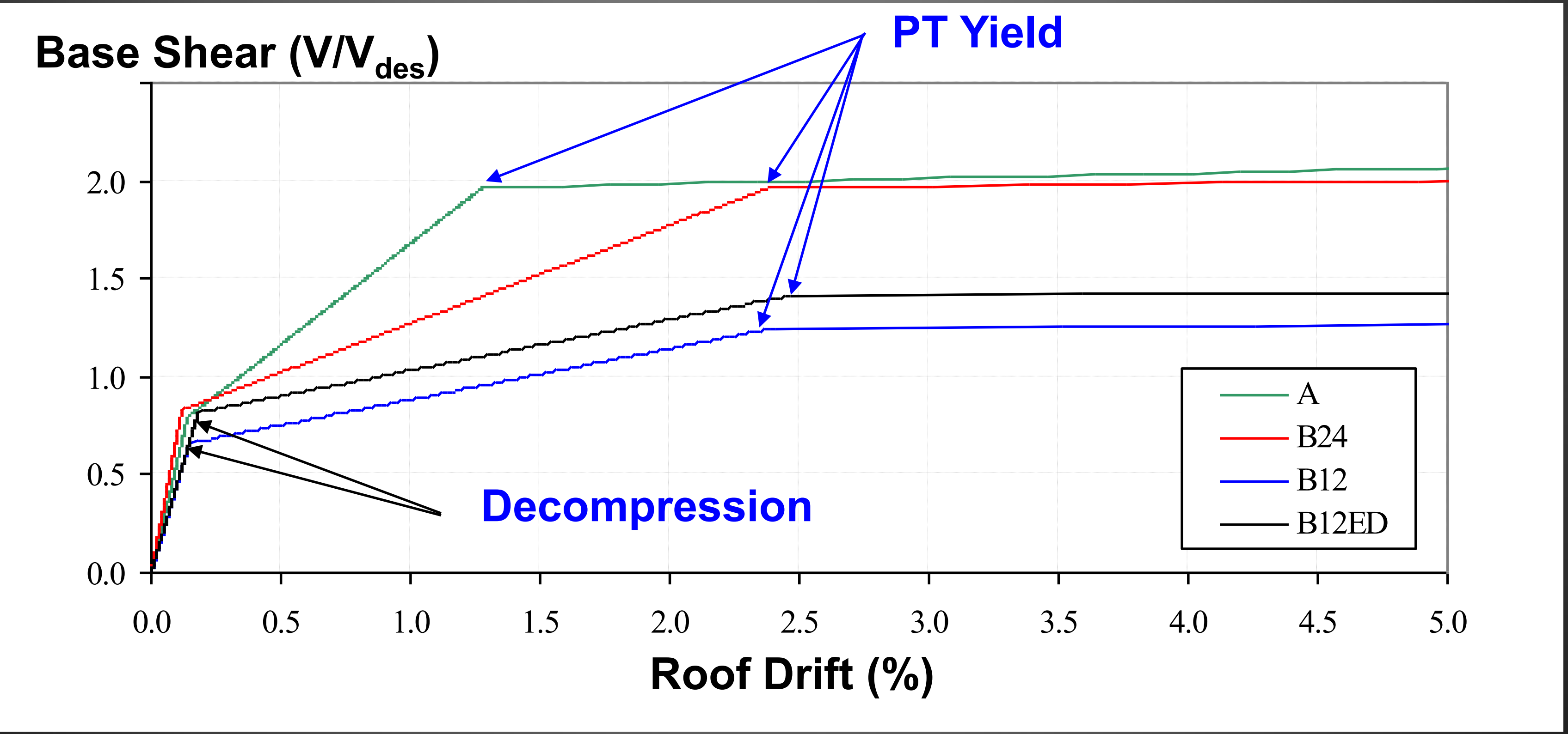
- Roof drift:
  - Effect of frame configuration.



  - Effect of ED elements.



Pushover Analysis Results



Preliminary Results for SC-CBF

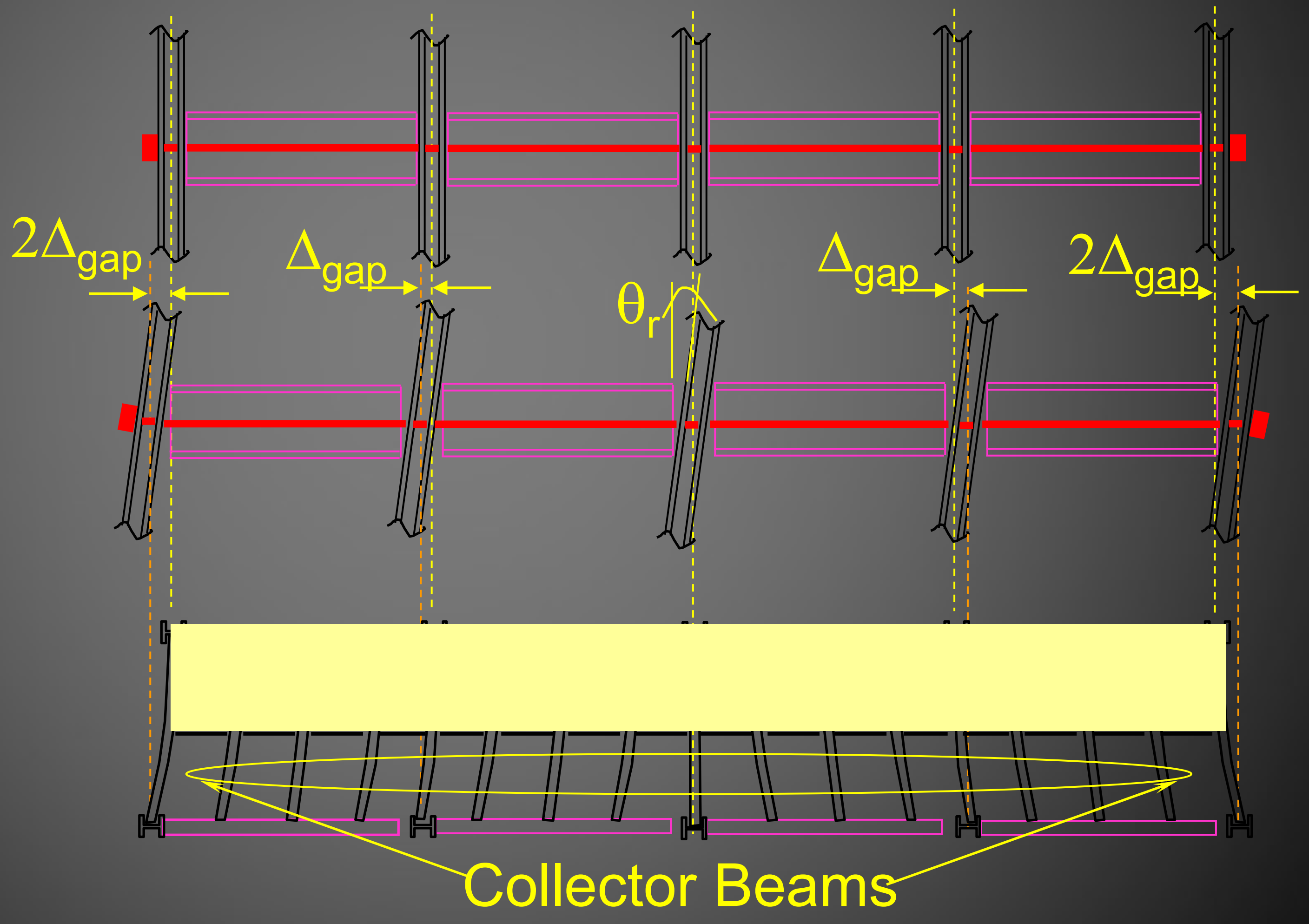
- Dynamic analysis results indicate self-centering behavior is achieved under DBE.
- Frame A has lower drift capacity before PT yielding than Frame B:
  - PT steel is at column lines rather than mid-bay.
- Frame A also has lower drift demand.
- Energy dissipation helps to reduce drift demand and improve response.

Task 3. Further Develop SC-MRF Systems: Current Work

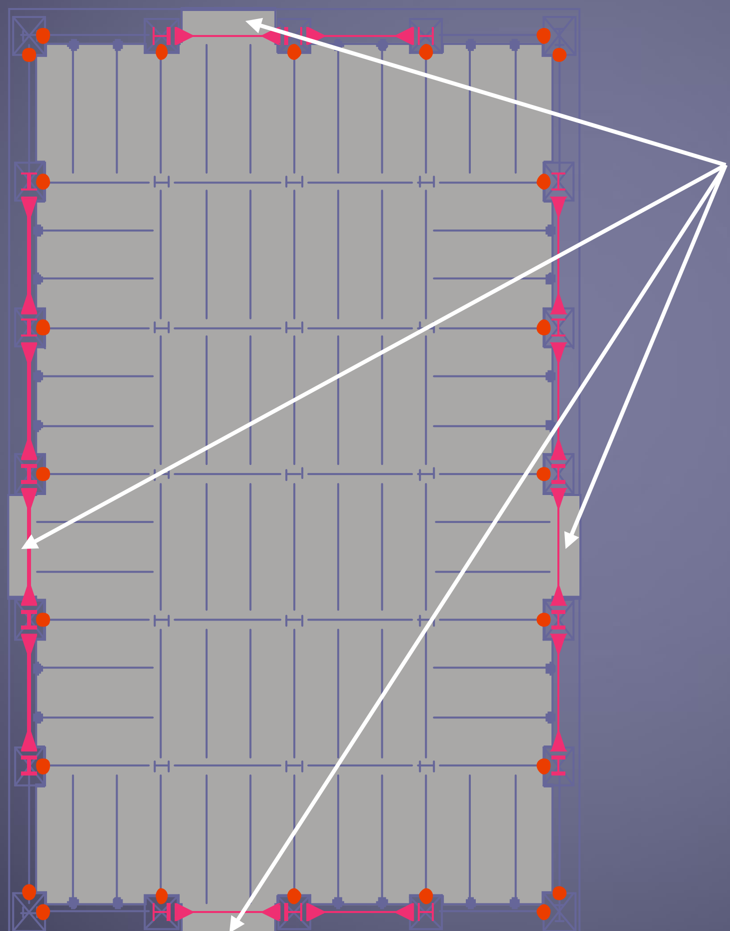
- Study of interaction between SC-MRFs and floor diaphragms by Princeton and Purdue.
- SC column base connections for SC-MRFs being studied by Purdue.

Interaction of SC-MRFs and Floor Diaphragms (Princeton)

Approach 1. Transmit inertial forces from floor diaphragm without excessive restraint of connection regions using flexible collectors.



Interaction of SC-MRFs and Floor Diaphragms (Purdue)



Approach 2. Transmit inertial forces from floor diaphragm within one (composite) bay for each frame.

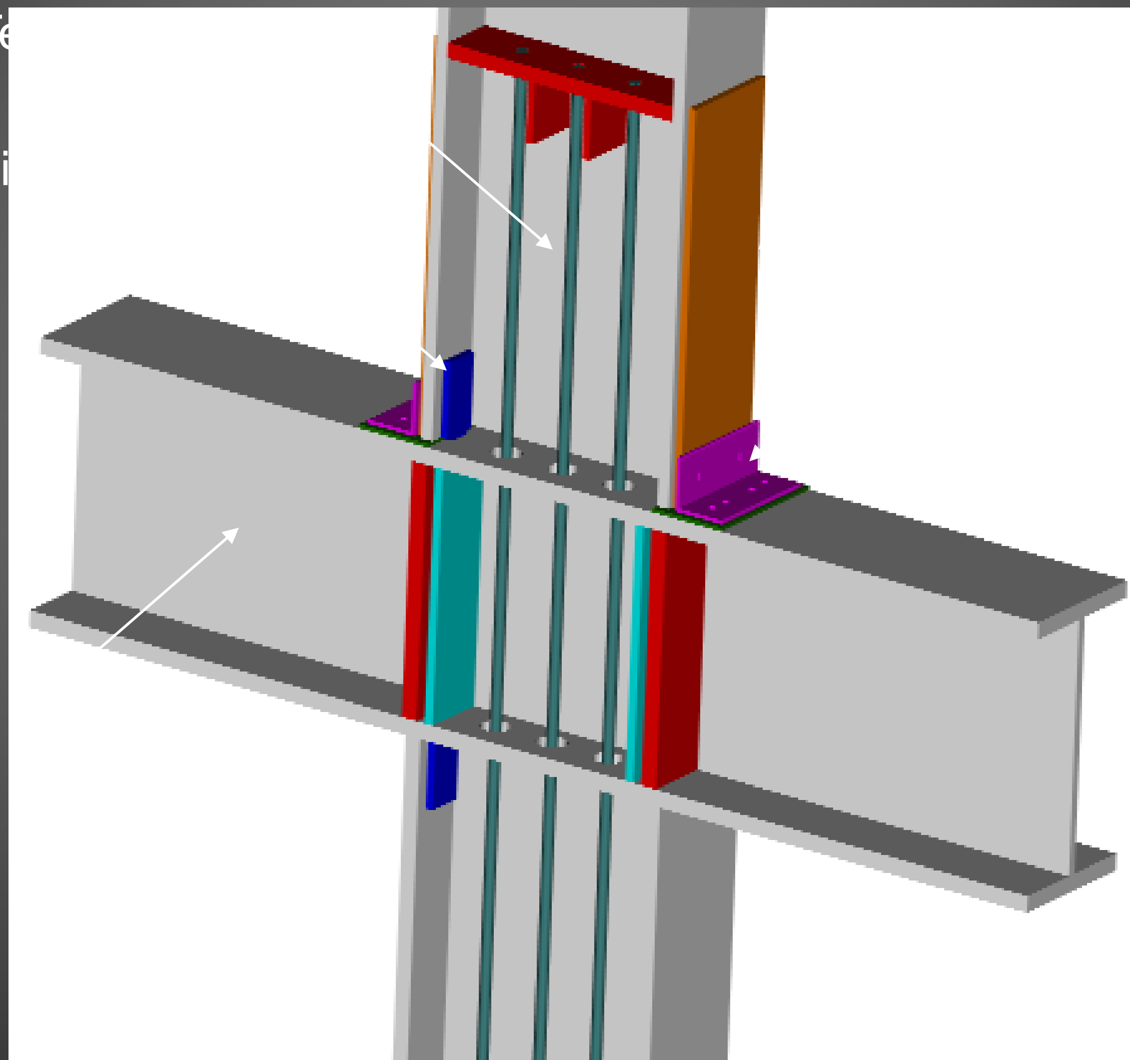
SC Column Base Connections for SC-MRFs (Purdue)

Post-Te

Plate

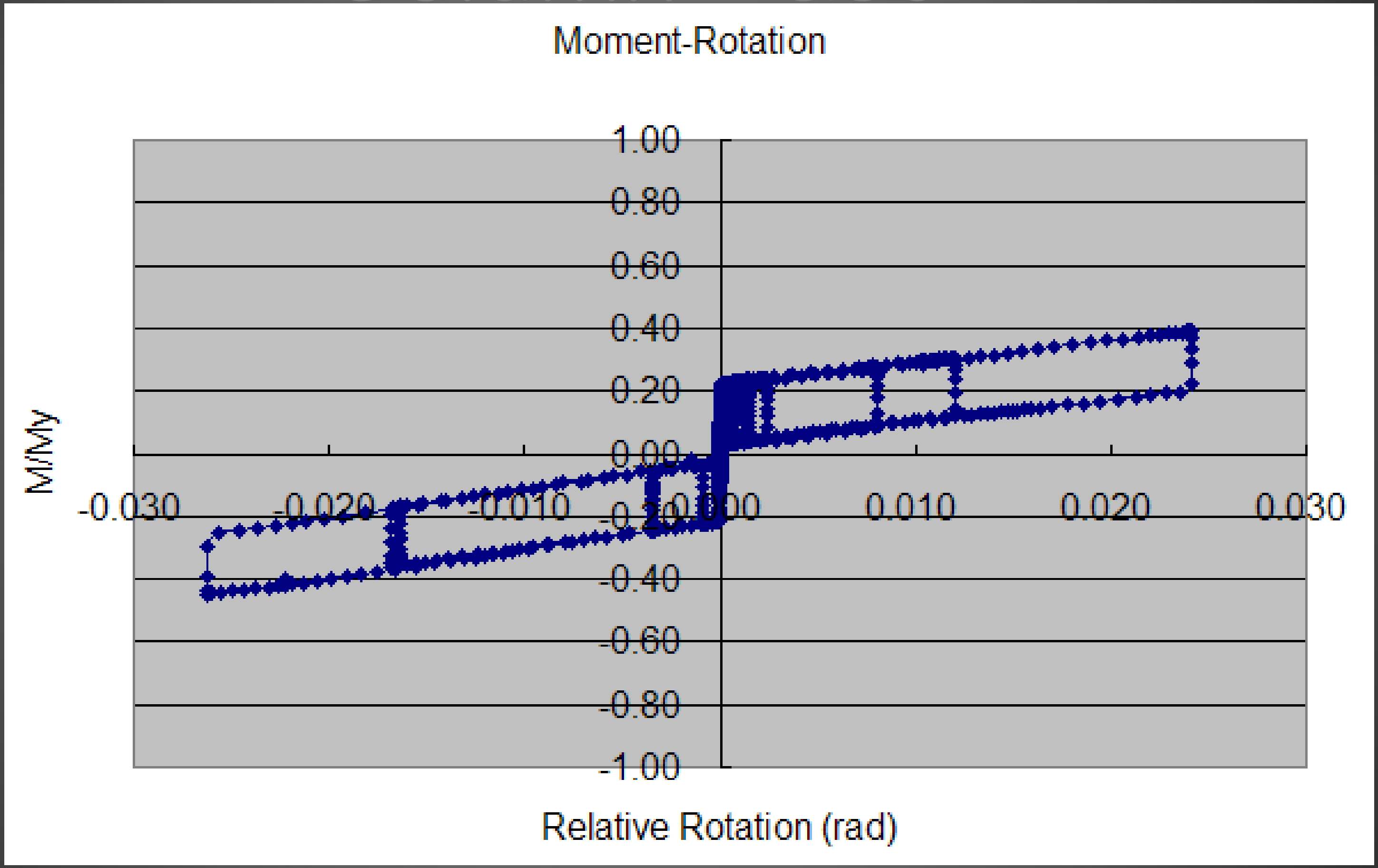
Energy Dissipati

per Angle



Beam at Grade

Moment-Rotation Response at Column Base



Identifying appropriate level of column base moment capacity and connection details, leading to laboratory experiments.

Task 4. Develop Energy Dissipation Elements for SC-MRFs

- SC systems have no significant energy dissipation from main structural elements:
  - Behavior of energy dissipation elements determined SC system energy dissipation.
- Energy dissipation elements may be damaged during earthquake and replaced.
- For SC-MRFs, energy dissipation elements are located at beam-column connections.

Quantifying Energy Dissipation

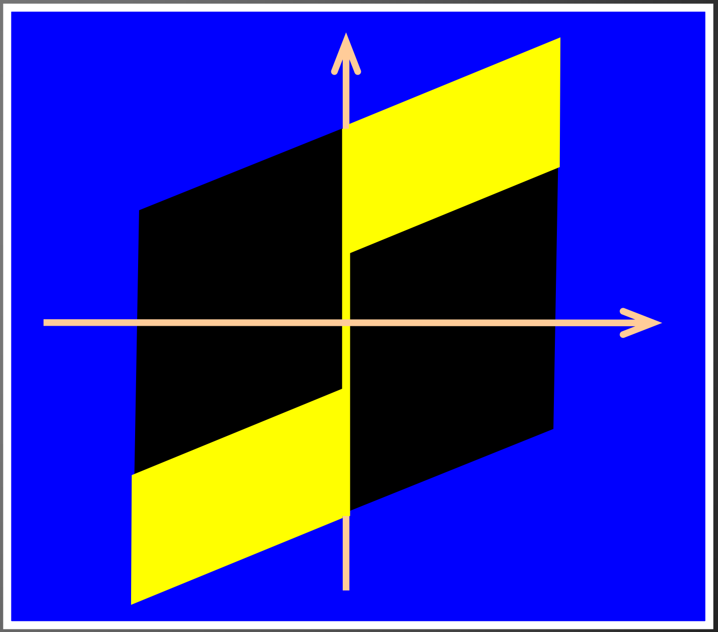
- Define relative hysteretic ED ratio β_E

β_E : Relative ED capacity

$$\beta_E = \frac{\text{Area of yellow}}{\text{Area of blue}} \times 100(\%)$$

For SC systems: $0 \leq \beta_E \leq 50\%$

Target value: $\beta_E = 25\%$

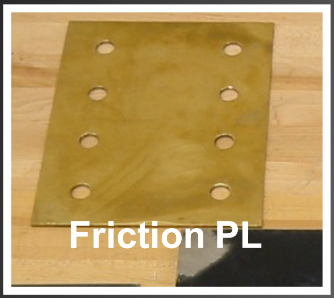


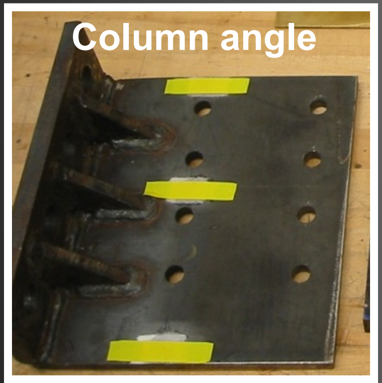
Hysteresis Loop

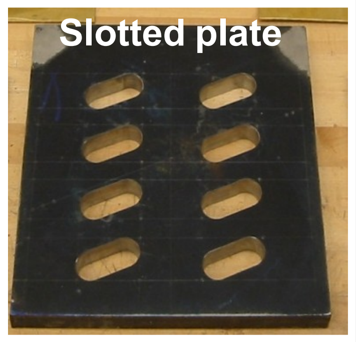
ED Element Assessment

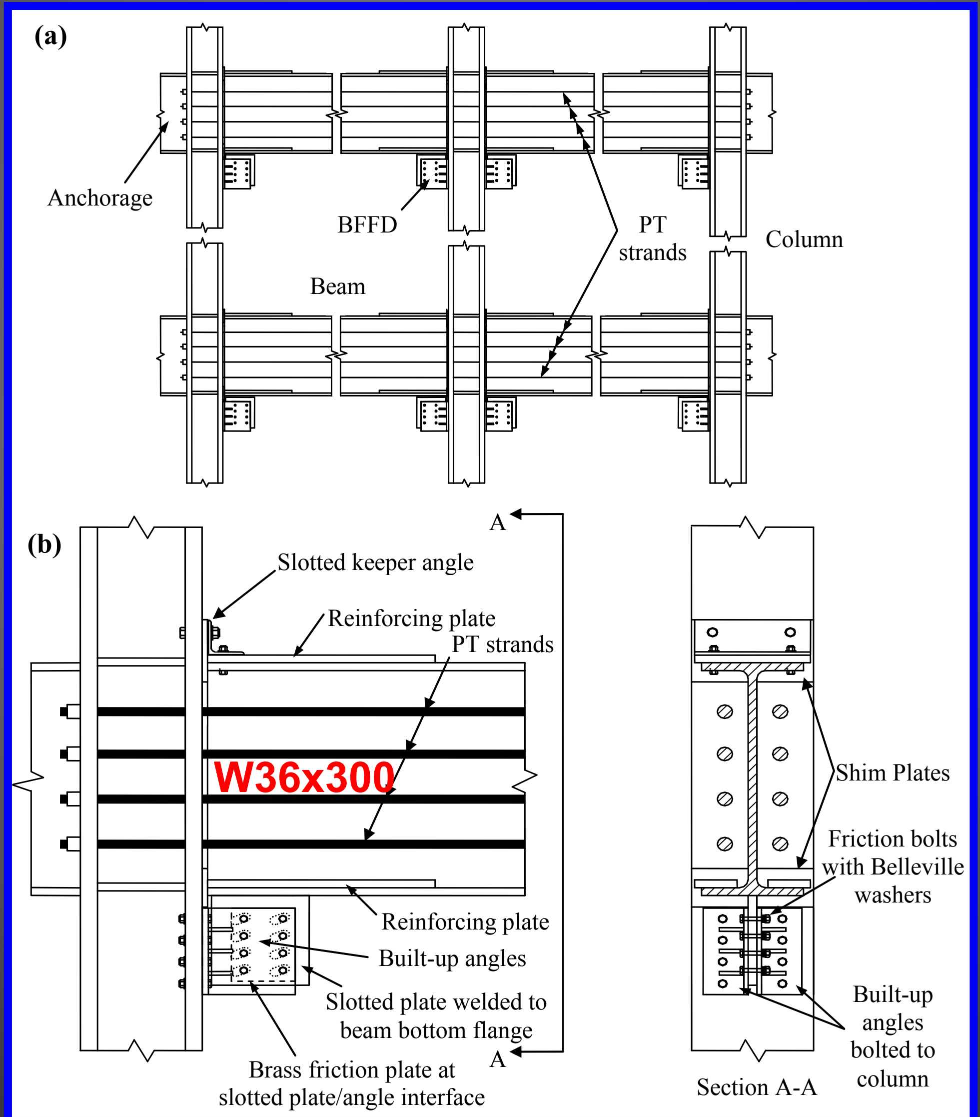
- Consider several ED elements:
  - Metallic yielding, friction, viscoelastic, elastomeric, and viscous fluid.
- Evaluation criteria:
  - Behavior, force capacity versus size, constructability, and life-cycle maintenance.
- Friction ED elements selected for further study.

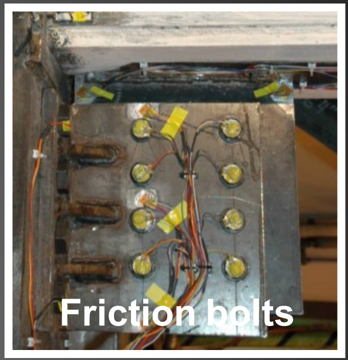
Bottom Flange Friction Device

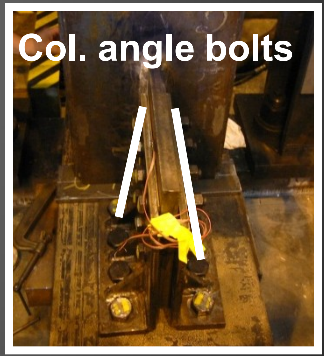






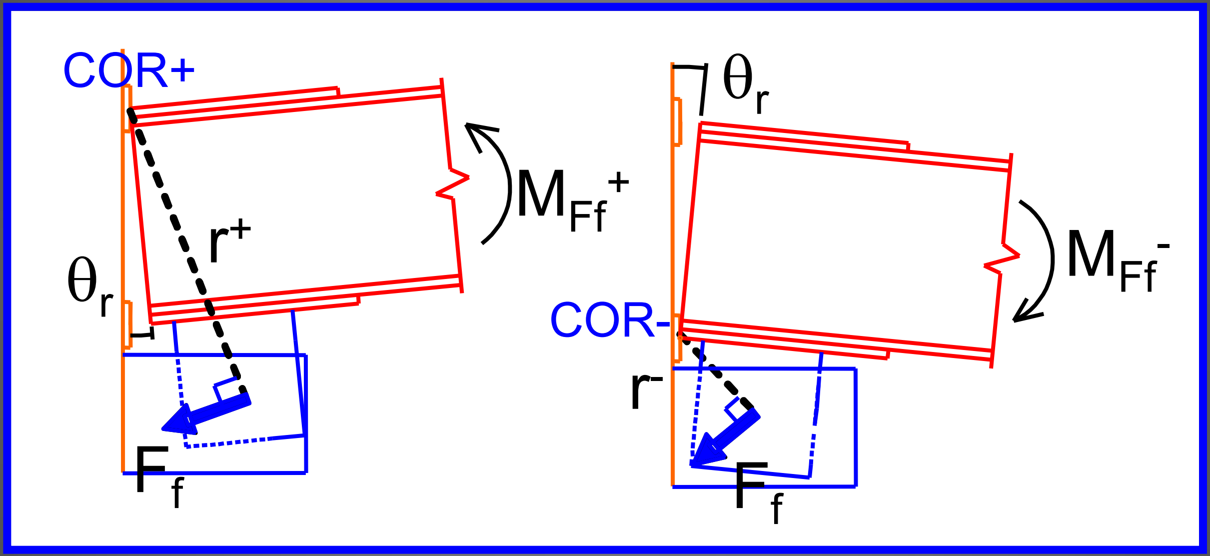






BFFD Moment Contribution

- BFFD contribution to connection moment capacity



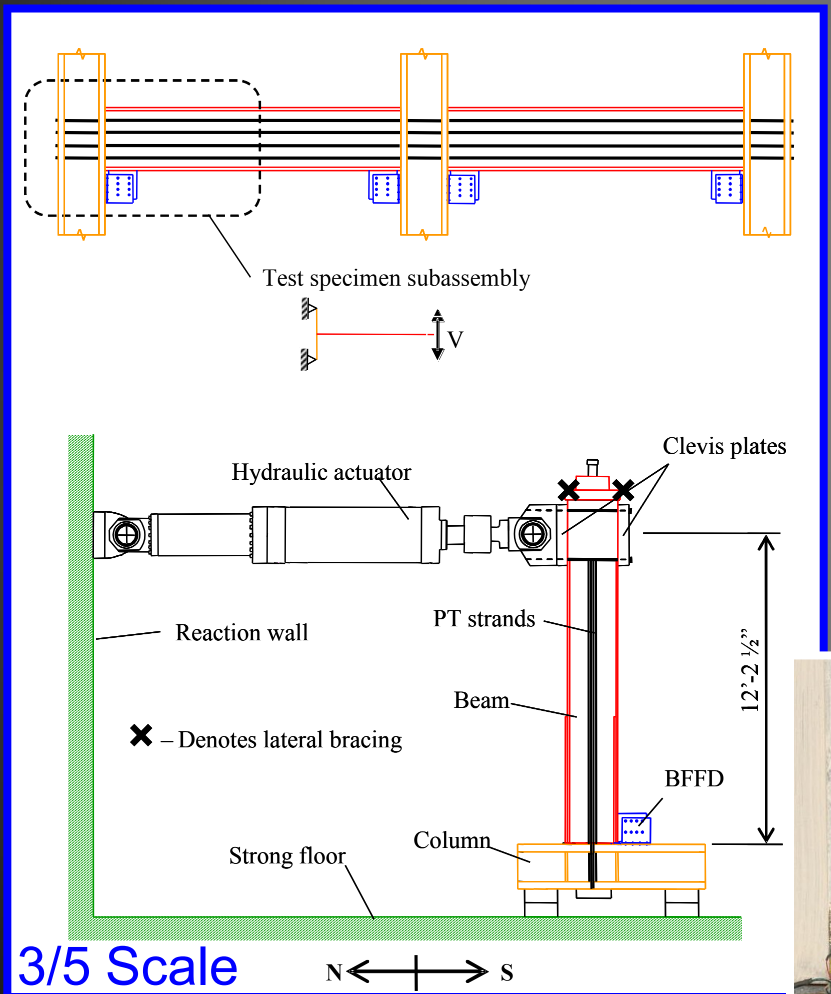
$M_{Ff} = F_f \cdot r$

$M_{Ff}^{+} = F_f \cdot r^{+}$

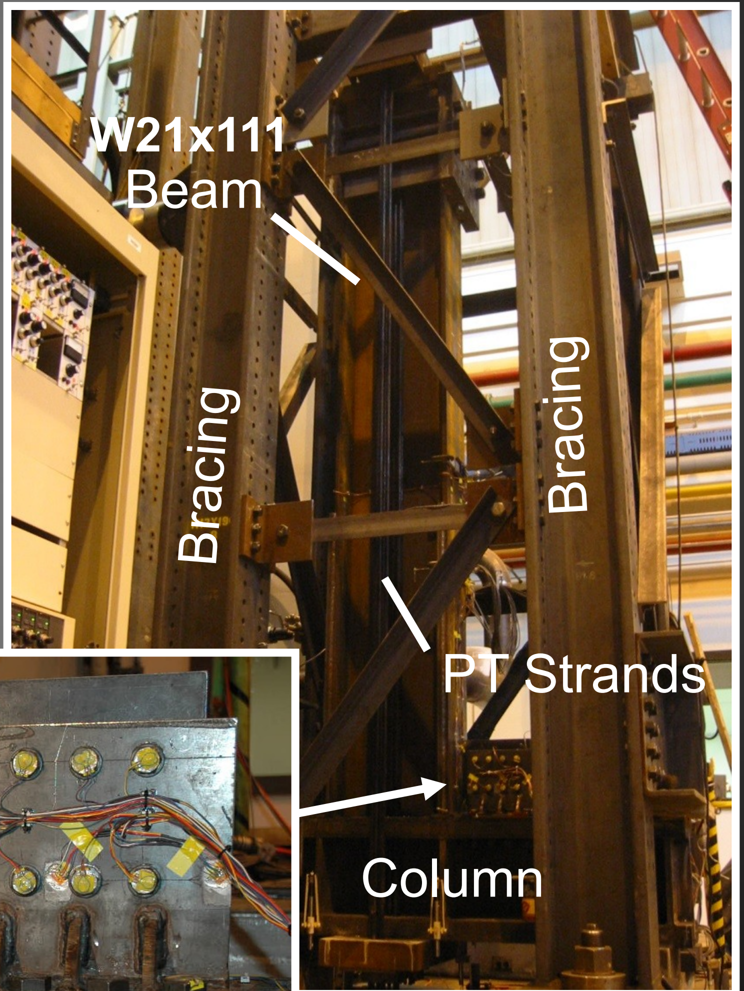
$M_{Ff}^{-} = F_f \cdot r^{-}$

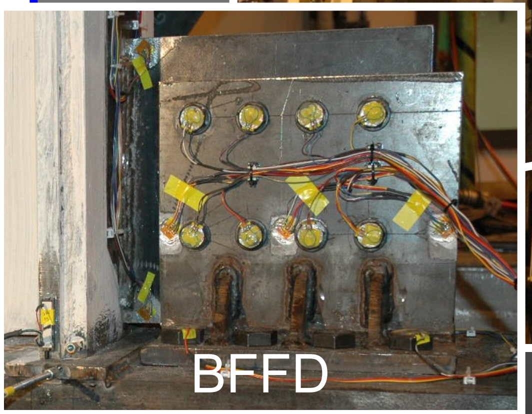
$|M_{Ff}^{+}| > |M_{Ff}^{-}|$

Test Setup



Test setup elevation





Test setup

Test Matrix

Test No.	Loading Protocol	$\theta_{r,max}$ (rads)	Experimental Parameter
1	CS	0.035	Reduced Friction Force
2	CS	0.030	Design Friction Force
3	CS	0.030	Fillet Weld Repair
4	EQ	0.025	Response to EQ Loading
5	CS	0.065	Effect of Bolt Bearing
6	CS	0.035	Assess Column L Flex., CJP
7	CS	0.065	Effect of Bolt Bearing, CJP

CS: Cyclic Symmetric

EQ: Chi-Chi MCE Level Earthquake Response

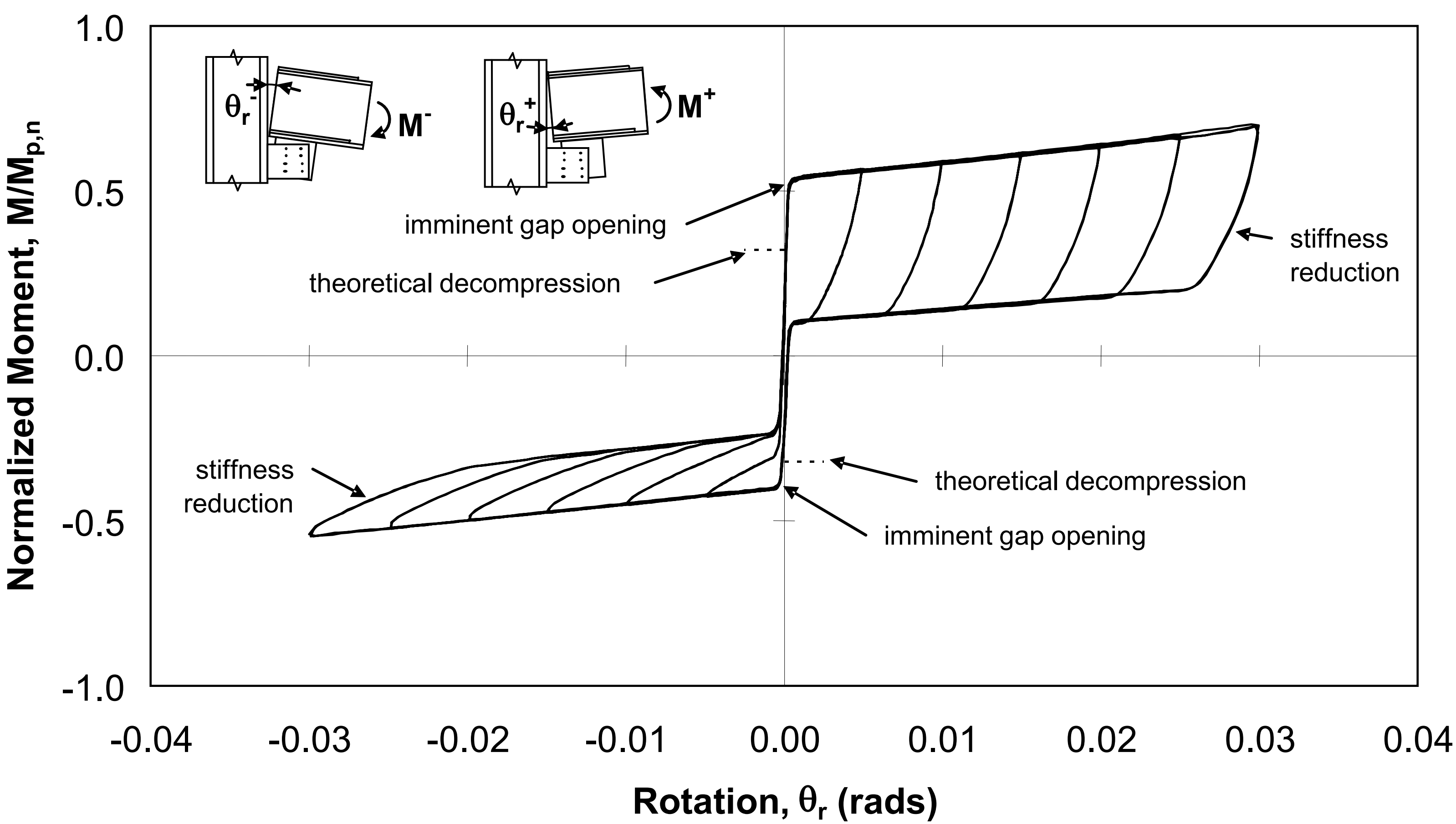
Test 2: Design Friction Force

Beginning of Test 2

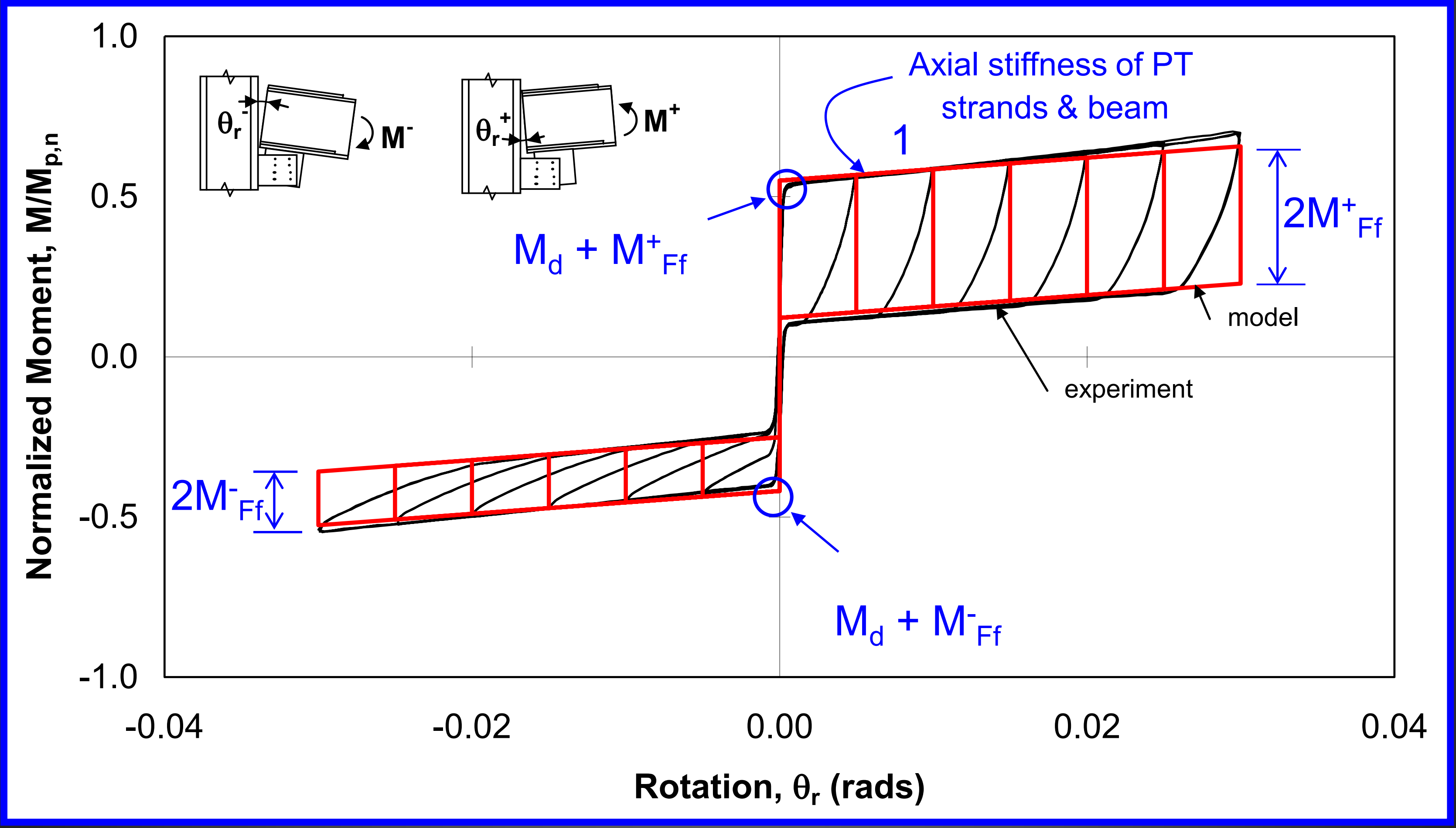
θ_r = +0.03 rads

θ_r = -0.03 rads

Test 2: Response



Test 2: Comparison with Simplified Model



Results for ED Elements for SC-MRFs

- Friction ED element:
  - Reliable with repeatable and predictable behavior.
  - Large force capacity in modest size.
- BFFD:
  - Provides needed energy dissipation for SC-MRF connections.
  - When anticipated connection rotation demand is exceeded, friction bolts can be designed to fail in shear without damage to other components.

Task 8. Conduct Large-Scale Laboratory Tests

- Two specimens, one SC-MRF and one SC-CBF, tested at Lehigh NEES ES (RTMD facility).
- 2/3-scale 4 story frame.
- Utilize hybrid test method (pseudo dynamic with analytical and laboratory substructures).
- Utilize real-time hybrid test method, if energy dissipation elements are rate-sensitive.

9. Collaborate on 3-D Large-Scale Laboratory Tests

- Large-scale 3-D SC steel frame system tests at NCREE in Taiwan under direction of Dr. K.C. Tsai.
- Interaction of SC frame systems with floor diaphragms and gravity frames will be studied.
- 3-D tests are part of Taiwan program on SC systems.
- Project team is collaborating with Taiwan researchers:
  - US-Taiwan Workshop on Self-Centering Structural Systems, June 6-7, 2005, at NCREE.
  - 2nd workshop planned for October 2006 at NCREE.

Summary

- Two types of SC steel frame systems are being developed:
  - Moment-resisting frames (SC-MRFs).
  - Concentrically-braced frames (SC-CBFs).
- Research plan includes 9 major tasks:
  - Significant work completed on 7 tasks.
  - Numerous conference publications available from current project.
- Large-scale experiments utilizing NEES ES at Lehigh are being conducted.
- Ongoing collaboration with NCREE in Taiwan.