Full-Scale Testing of Low-Ductility Braced Frames in the Lehigh Experimental Facility

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Researchers Workshop: Advanced Simulation for Natural Hazards Mitigation

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NEESR: Reserve Capacity in New and Existing Low-Ductility Braced Frames (Grant No. CMMI-1207976)

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- Tufts University / LeMessurier Consultants
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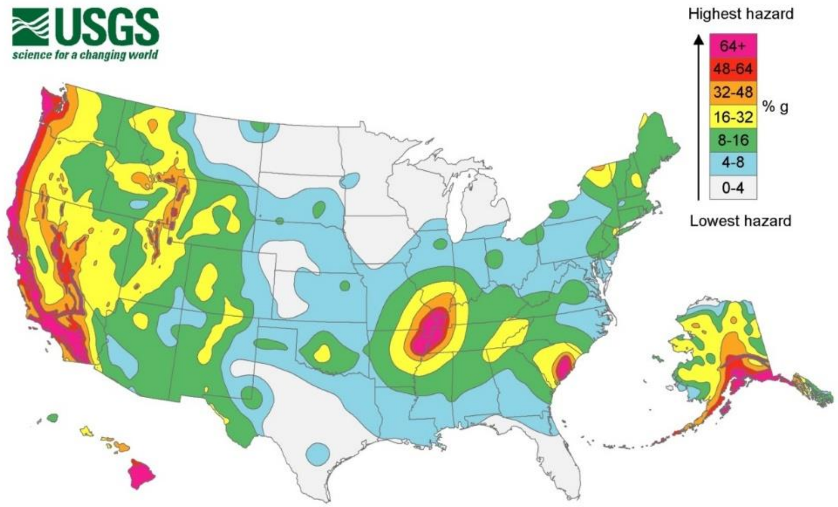
  - Ali Davaran (post-doctoral researcher)

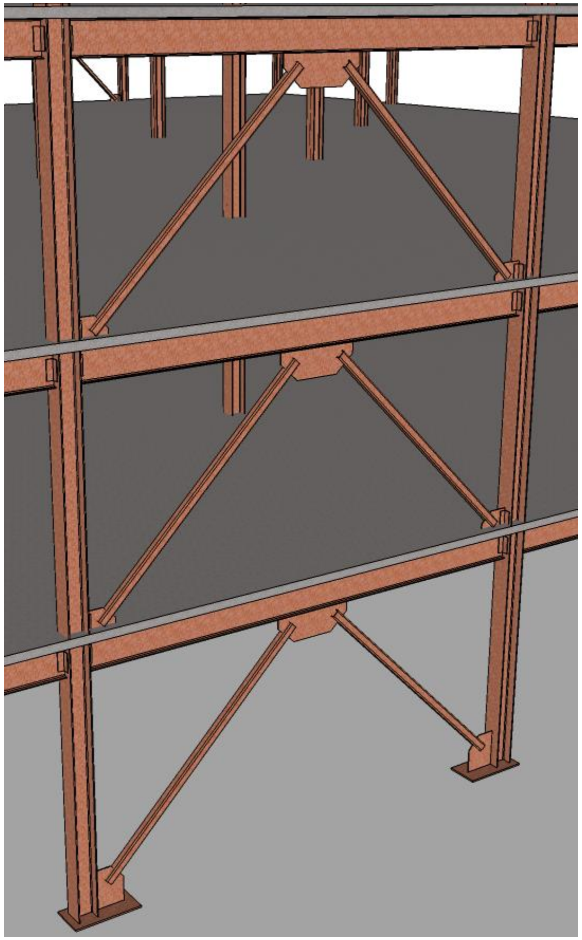
Research Objective

- Develop a simple yet rigorous design approach for concentrically-braced frame (CBF) buildings in moderate seismic regions that economically provides reliable seismic stability



Research Motivation

- CBFs are the predominant steel system used in moderate seismic regions
- Minimal to no seismic detailing and proportioning are required
- Inelastic response is expected to be nonductile, but little experimental data



Historical Perspective

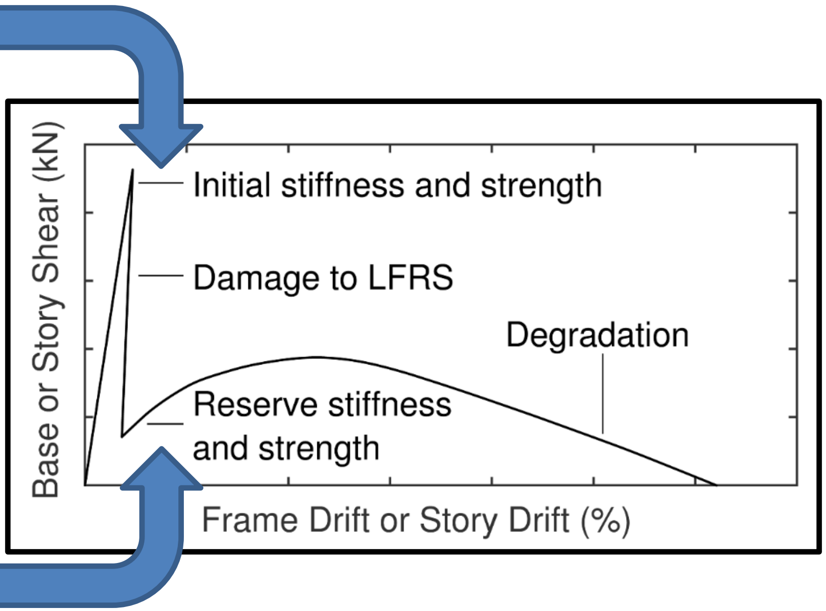
- CBFs have exhibited nonductile behavior in large earthquakes (1994 Northridge and 1995 Kobe), yet not collapsed
- Commonly attributed to lateral resistance from outside the primary CBF – reserve capacity


(EERI)


Rai and Goel (2003)

Fundamental Paradigm

- Primary system (CBF) behavior is relatively unimportant for seismic stability of low-ductility frames
- Secondary system behavior (reserve capacity) – development of a predictable mechanism or sequence of mechanisms – is critical



Experimental Needs

- Full-scale system testing
- Data on behavior of low-ductility CBFs
- Characterization of reserve capacity in CBFs

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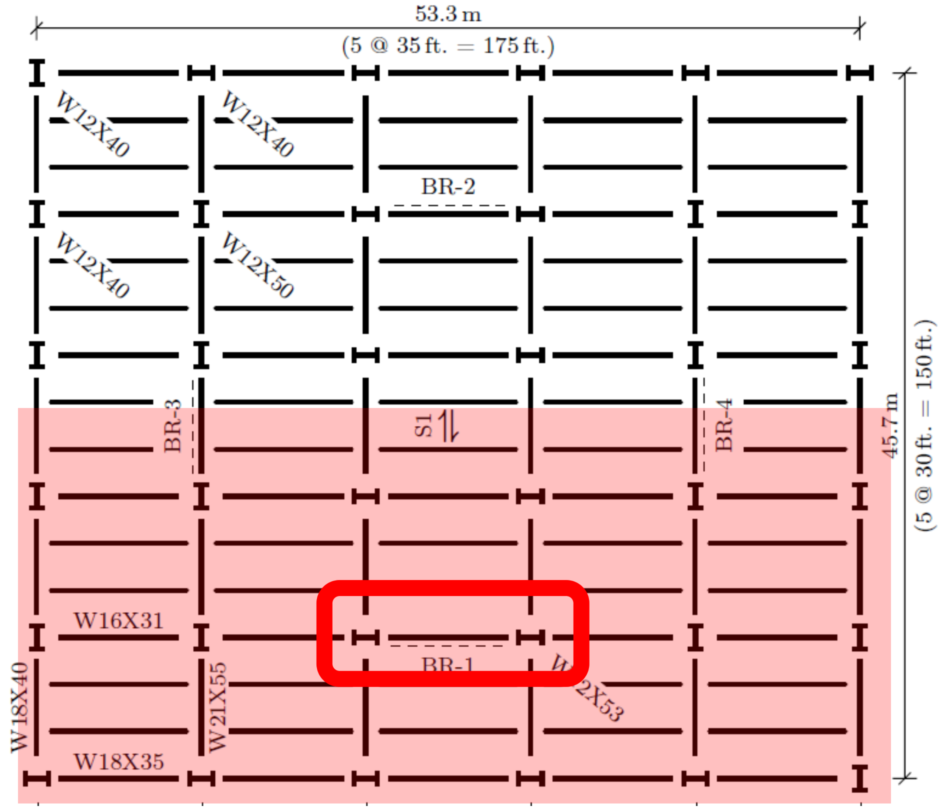
Braced Frame Tests

- Full scale
- Lower two stories of three-story prototypes
- Frame 1:
  - R = 3 chevron
  - No seismic requirements
- Frame 2:
  - R = 3.25 OCBF split-X
  - Ductile detailing (*b/t, KL/r*)
  - Ad hoc capacity design (beams, columns and connections)



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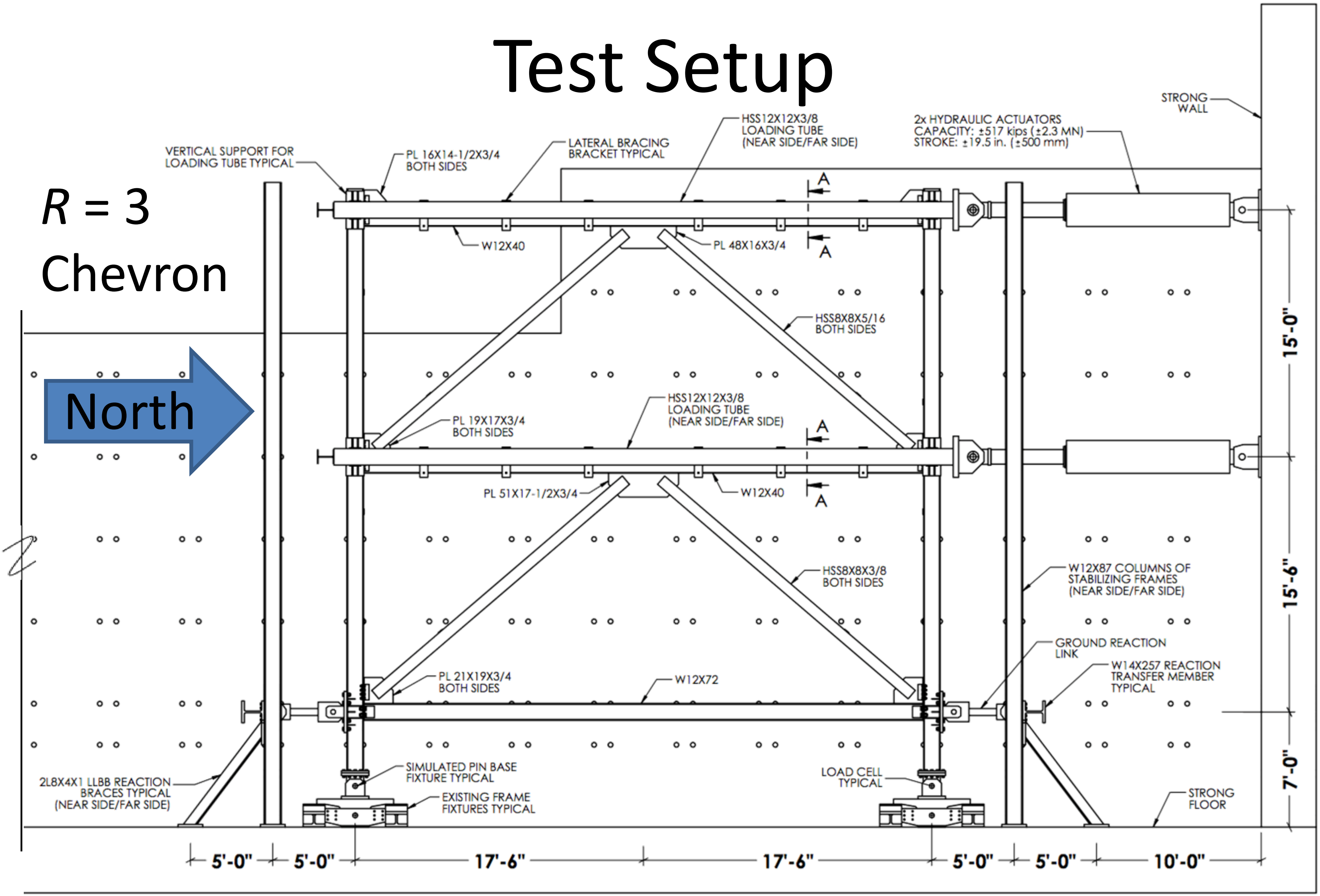
Test Setup

R = 3
Chevron



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Loading Scheme

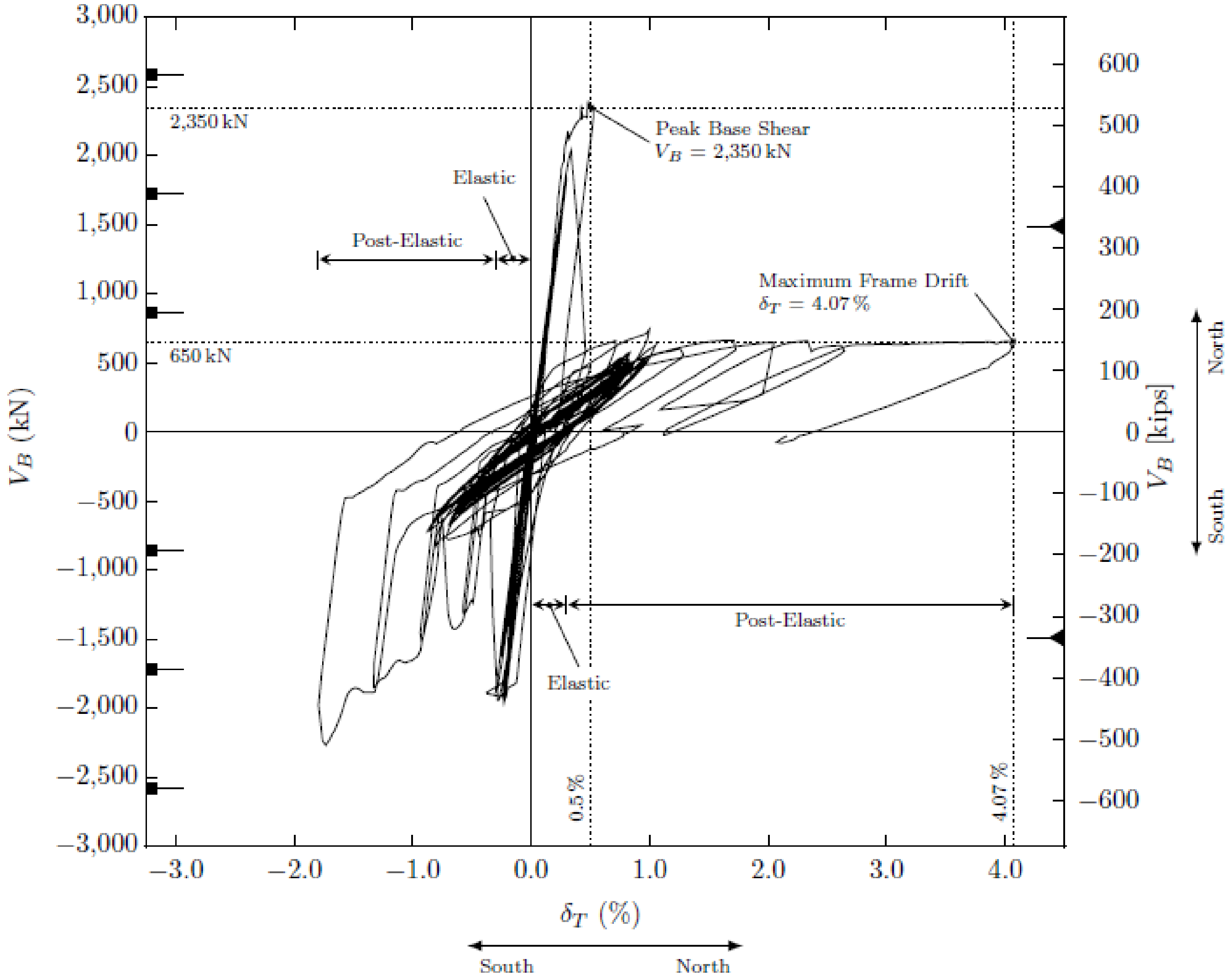
- Quasi-static loading
- Increasing amplitude cyclic protocol
- Mixed-mode control based on top drift
- Loading beam system wrapped around test frame
- Load always applied by pushing on the test frame
- Loading beams not attached to test frame
- Test frame beams braced laterally by loading beams
- Test frame beams free to move vertically

Laboratory Instrumentation

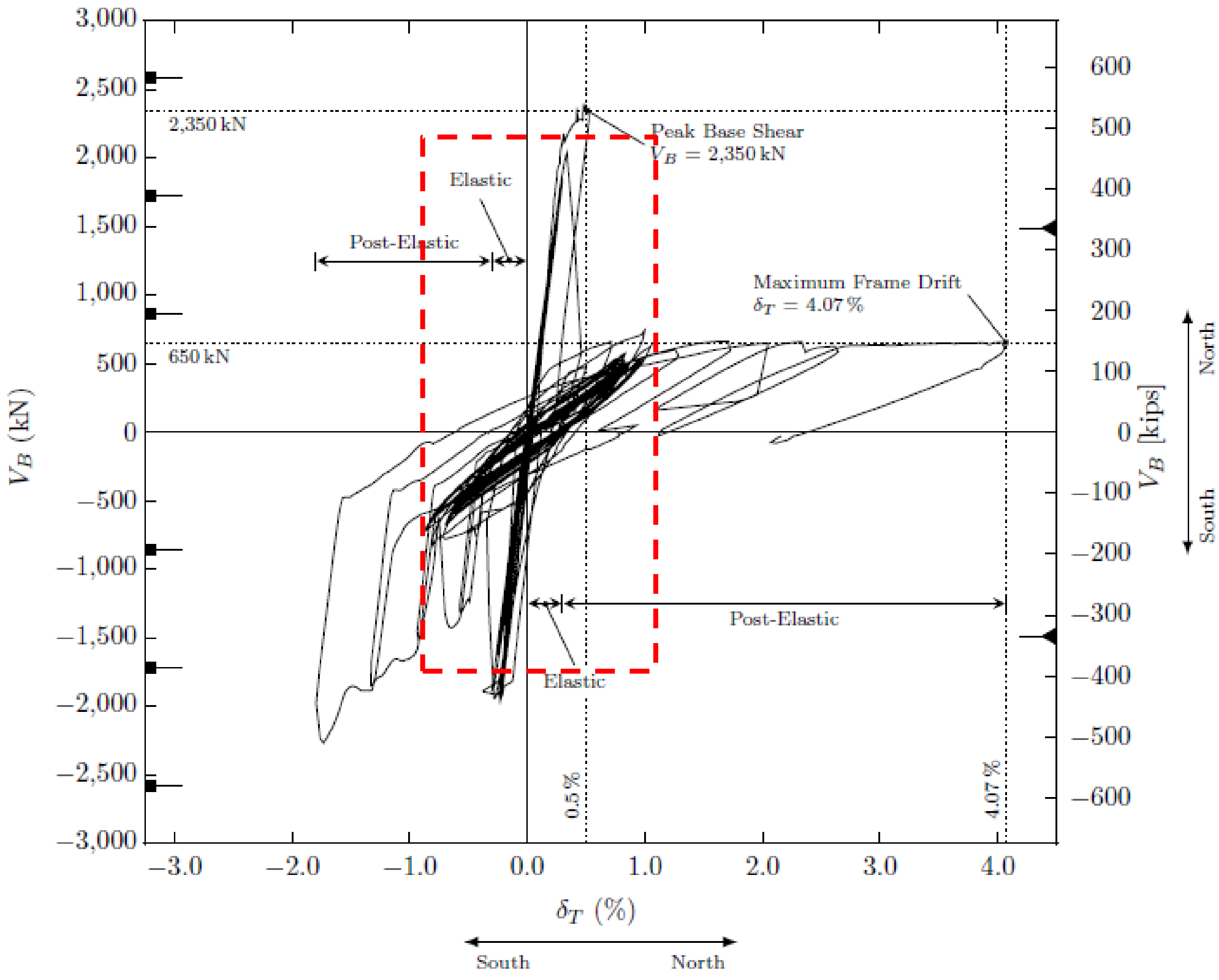
- 2 load cells (actuators)
- 2 load cells (reactions)
- 4 load cell pins (reactions)
- 8 string potentiometers (brace axial displacements)
- 18 inclinometers (connection rotations)
- 22 LVDTs (displacements, connection rotations)
- 80 strain gages (internal forces)

Frame 1 (R = 3)

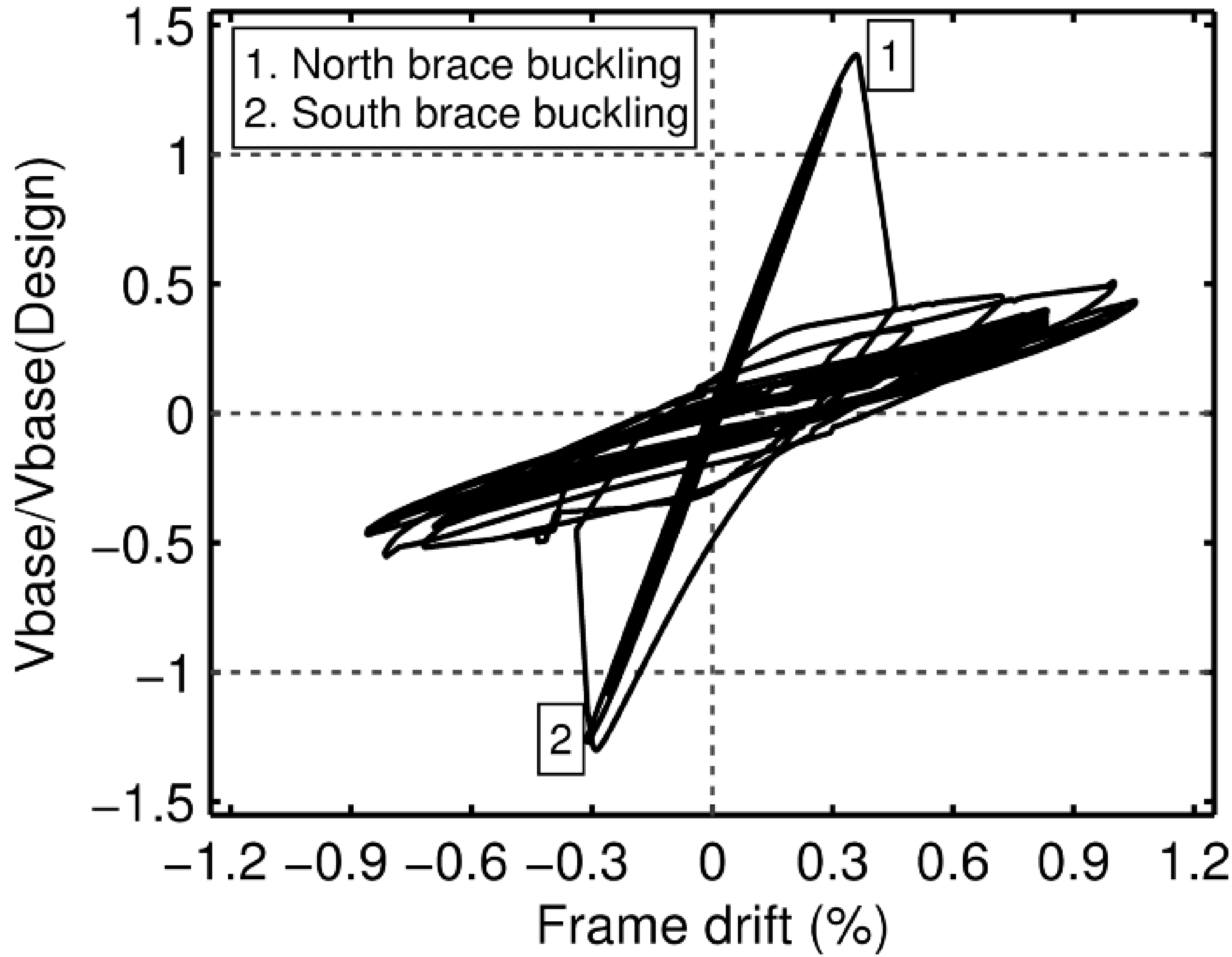
Frame 1 (R = 3) Overall Behavior

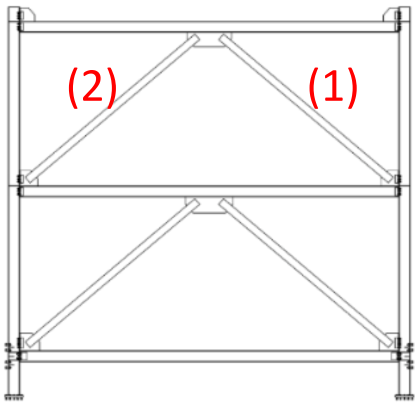


Frame 1 (R = 3) Initial Behavior



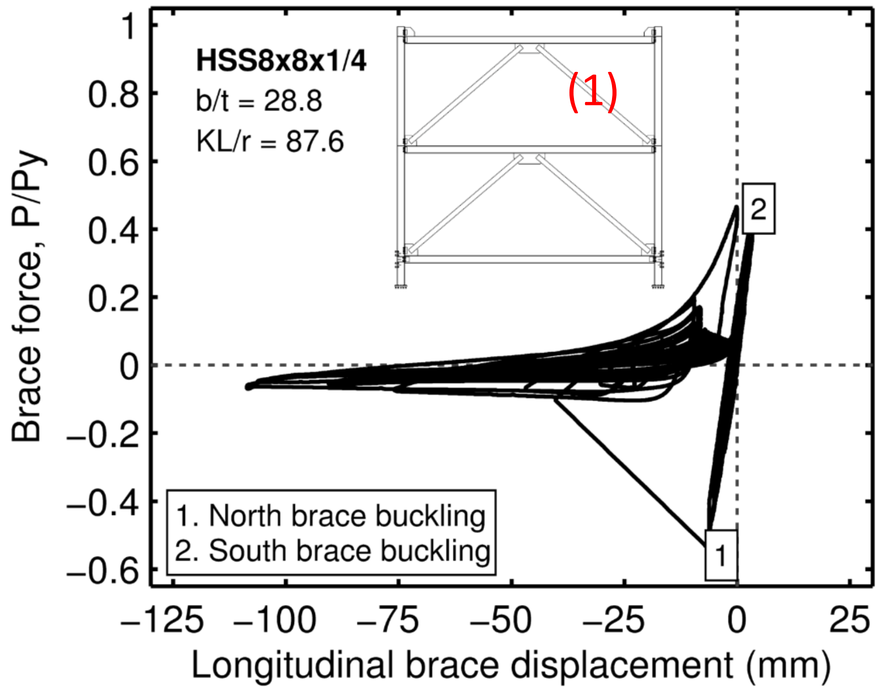
Frame 1 (R = 3) Initial Behavior

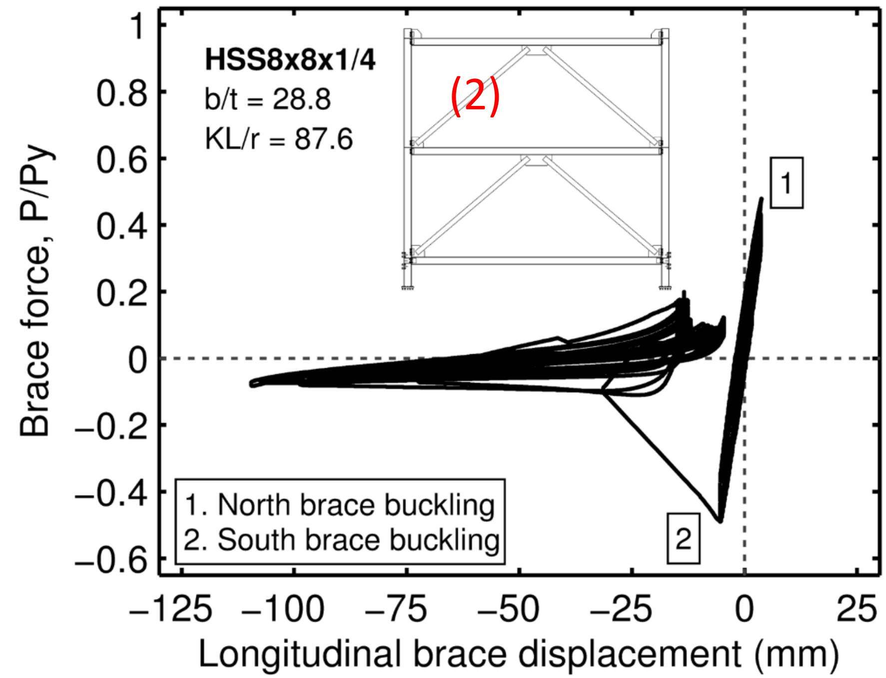




Upper story brace buckling

Frame 1 (*R* = 3) Upper Story Behavior

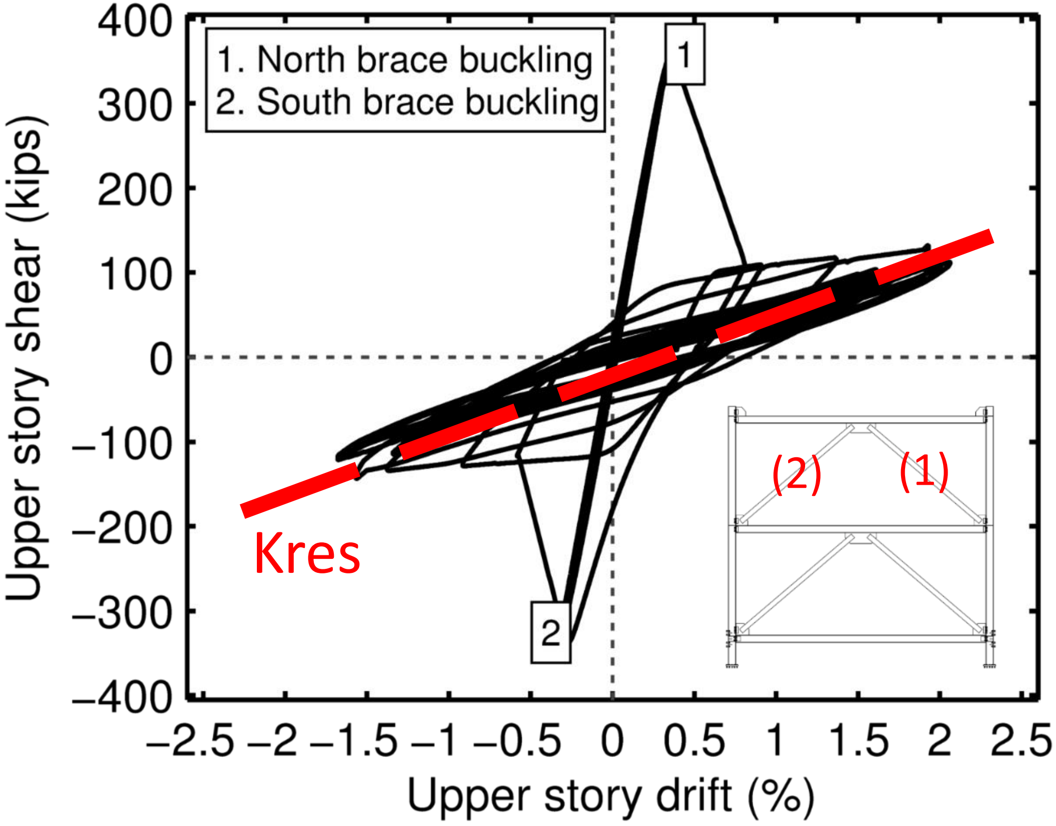


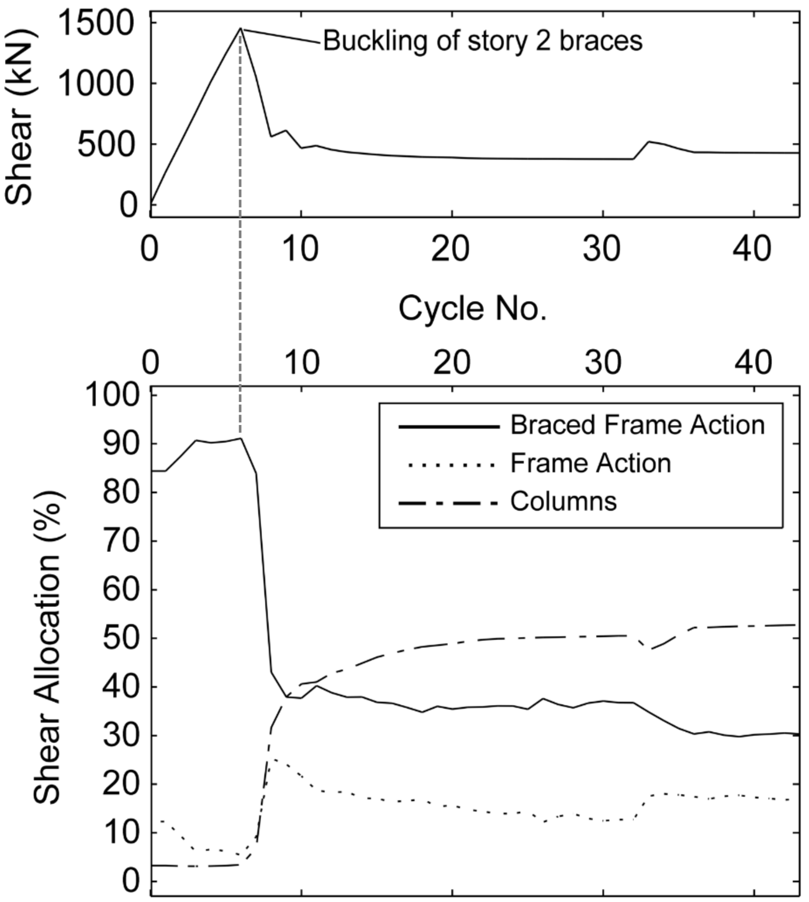


North brace initial buckling

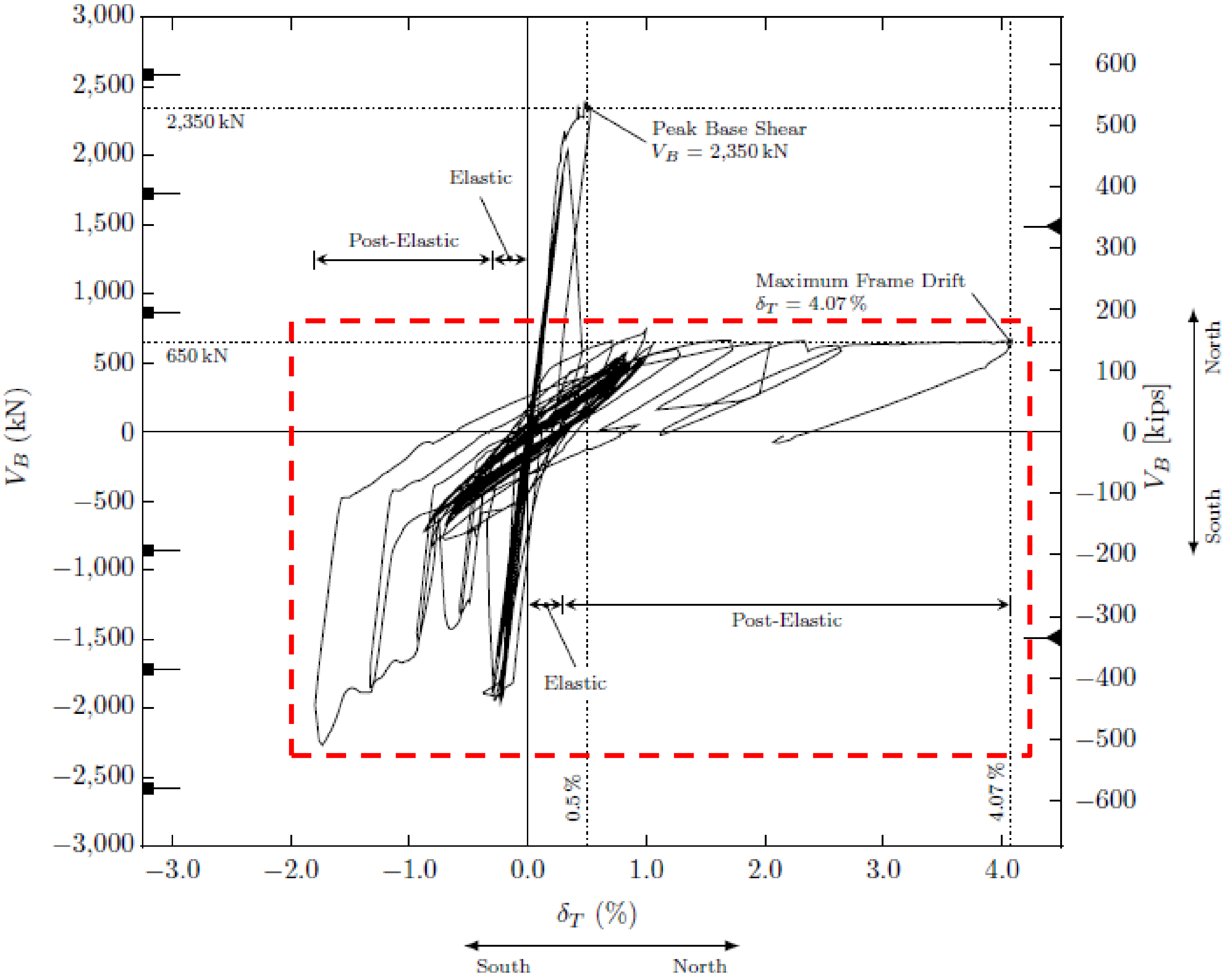
South brace final state

Frame 1 (R = 3) Upper Story Behavior



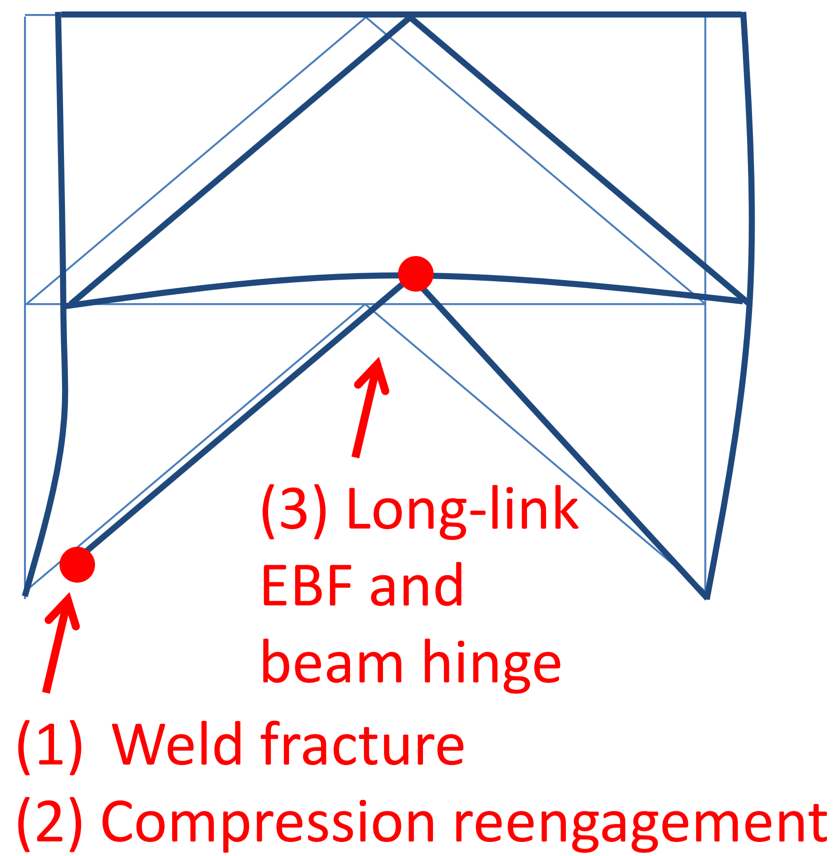


Frame 1 (R = 3) Secondary Behavior

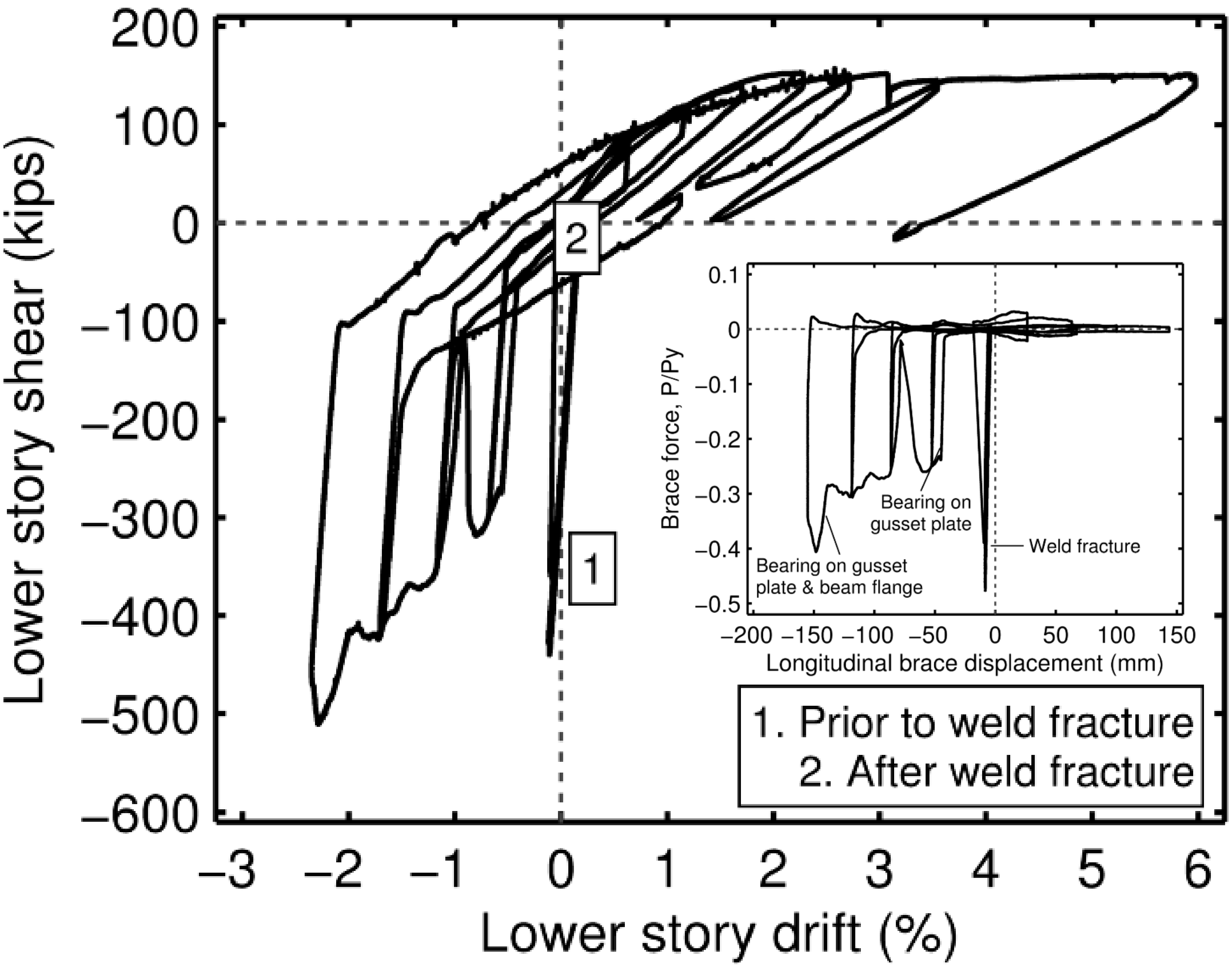


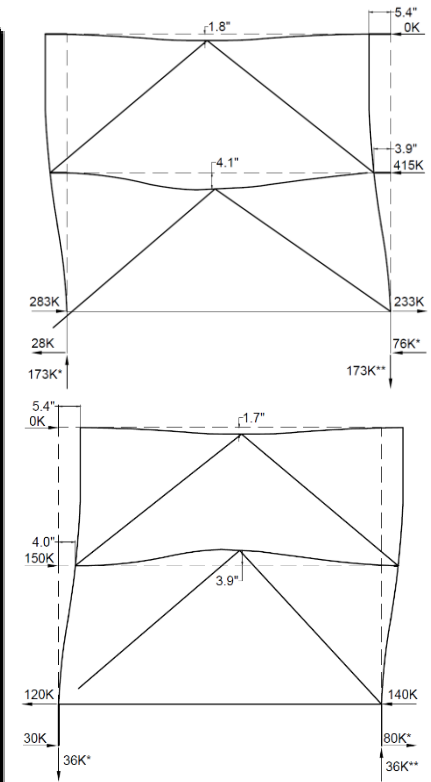
Frame 1 (R = 3) Secondary Behavior

- Adjust loading
- Fracture lower story brace end connection (weld)
- Observe reserve capacity mechanisms
  - Brace reengagement
  - Long-link eccentrically-braced frame (EBF) behavior



Frame 1 (R = 3) Secondary Behavior



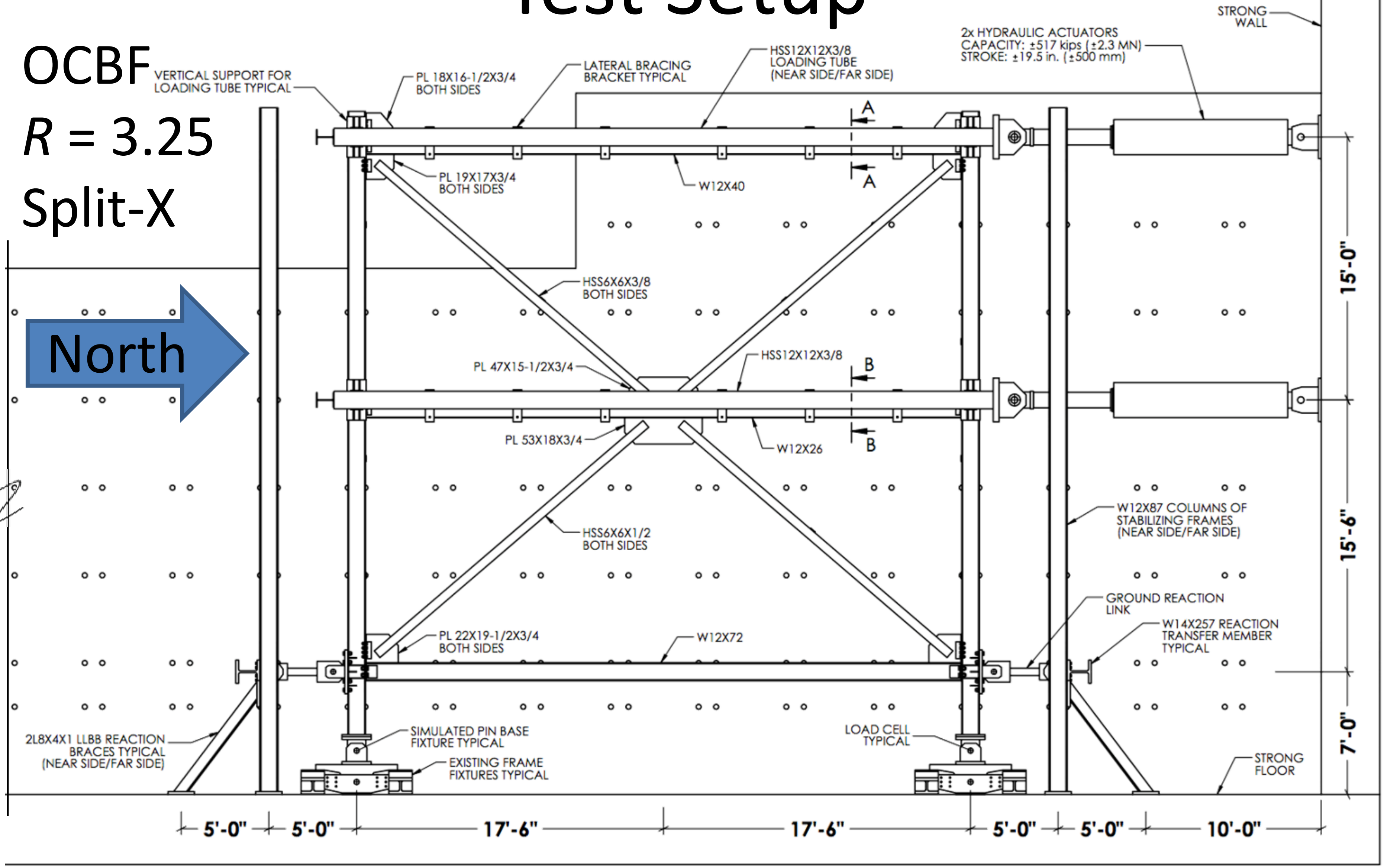


Test Setup

OCBF

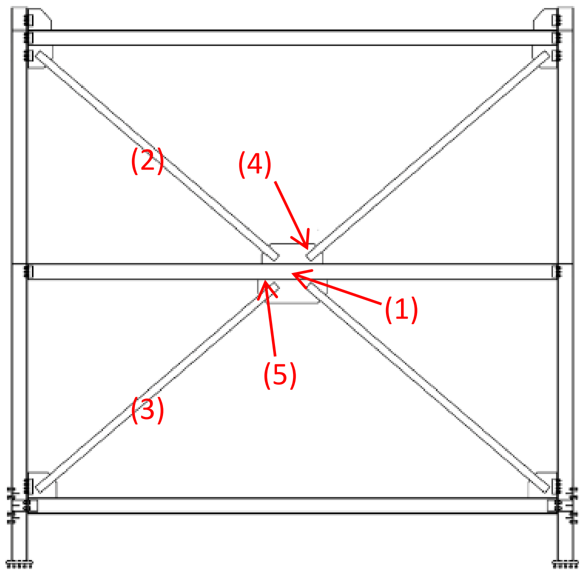
R = 3.25

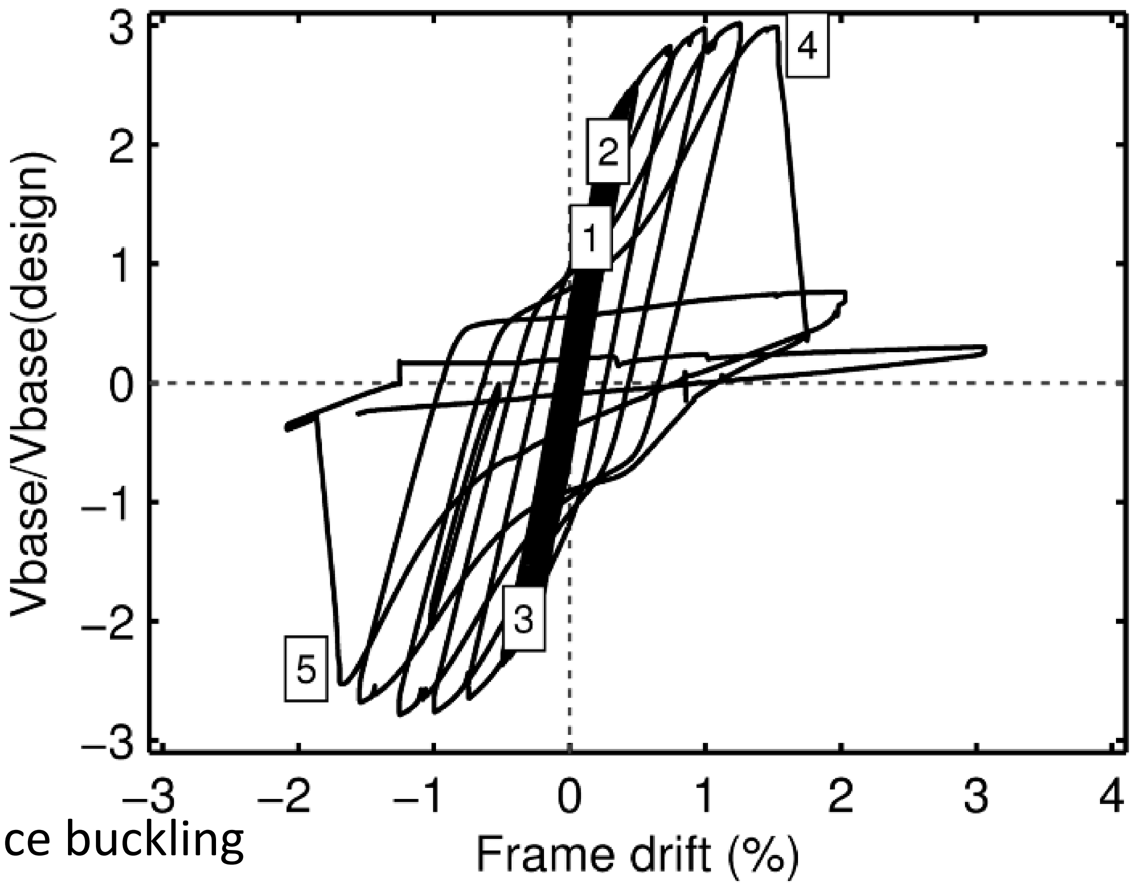
Split-X



Frame 2 (OCBF)

Frame 2 (OCBF) Overall Behavior





(1) Beam yielding

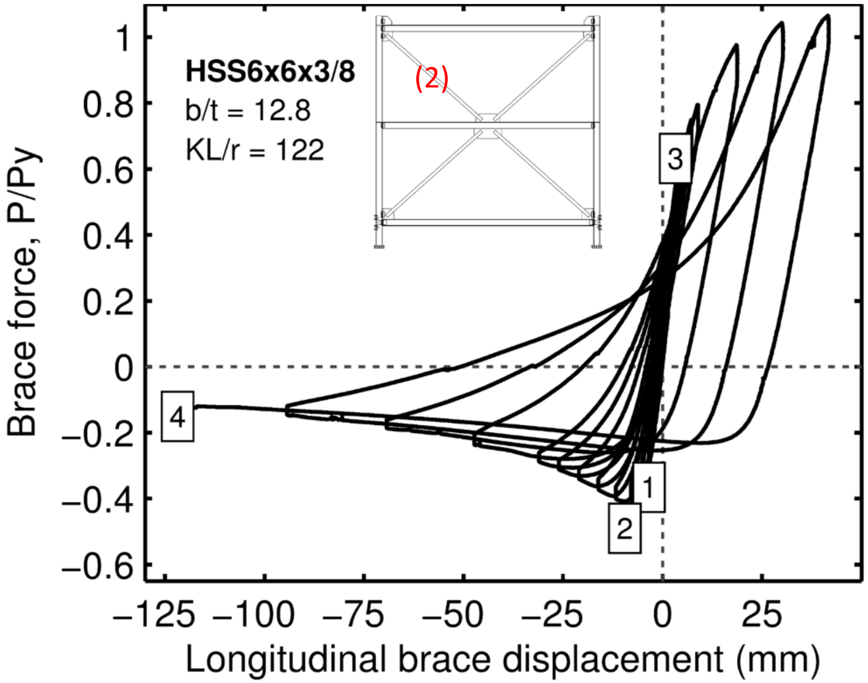
(2) Upper story south brace buckling

(3) Lower story south brace buckling

(4) Upper story north brace-gusset weld fracture

(5) Lower story beam-gusset weld fracture

Frame 2 (OCBF) Brace Buckling (2)



(1) Beam yielding

(2) Upper story south brace buckling

(3) Lower story south brace buckling

(4) Upper story north brace-gusset weld fracture

(5) Lower story beam-gusset weld fracture

Upper Story South

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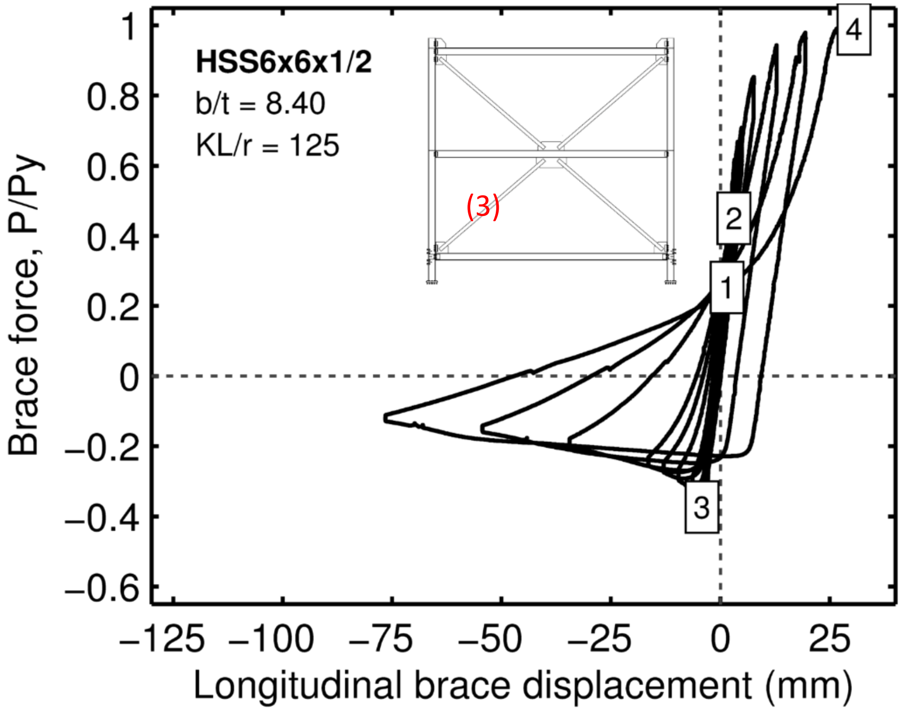
Frame 2 (OCBF) Brace Buckling (3)



(1) Beam yielding

(2) Upper story south brace buckling

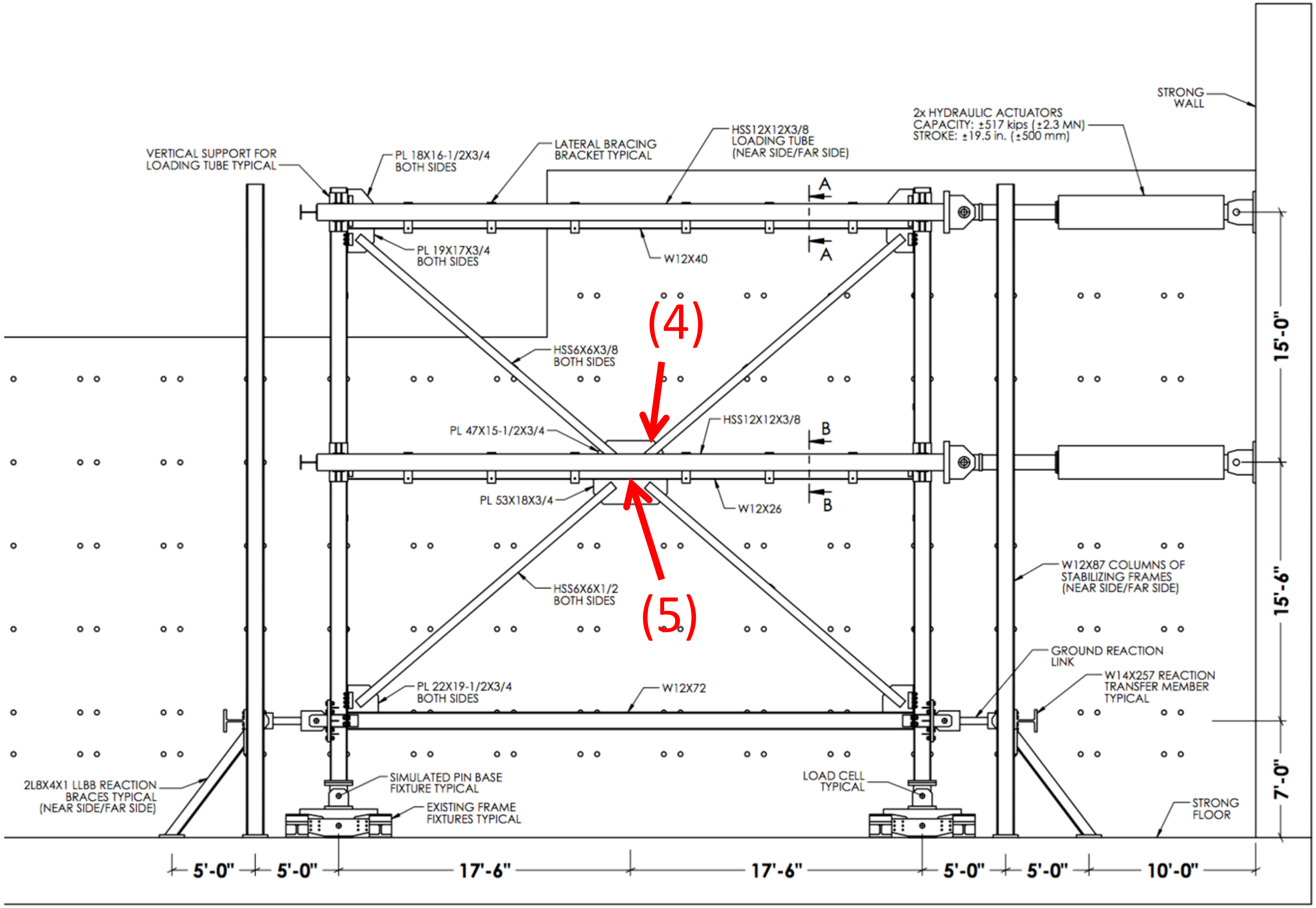
(3) Lower story south brace buckling

(4) Upper story north brace-gusset weld fracture

(5) Lower story beam-gusset weld fracture

Lower Story South

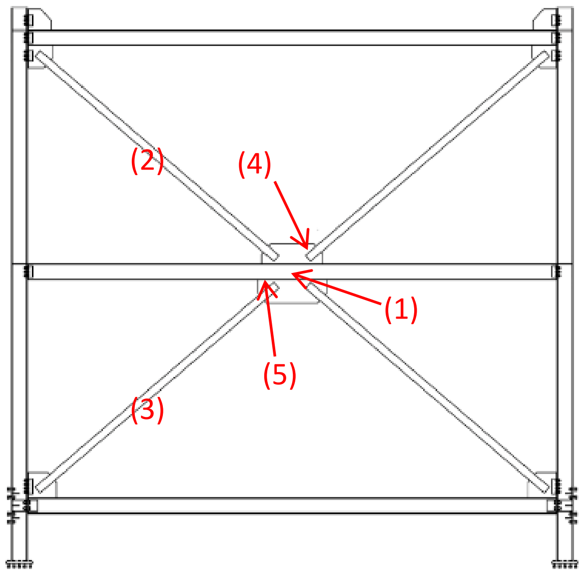
Frame 2 (OCBF) Weld Fractures

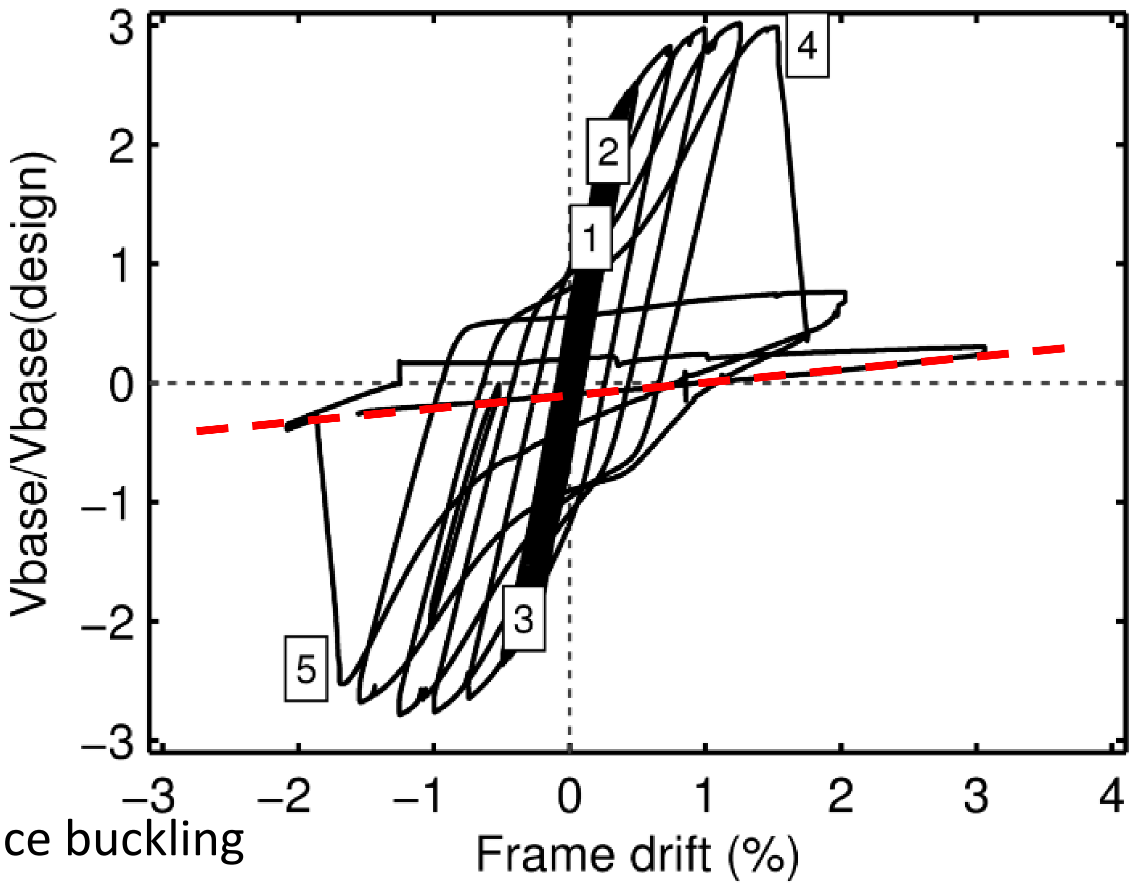


Frame 2 (OCBF) Weld Fracture (4)

Frame 2 (OCBF) Weld Fracture (5)

Frame 2 (OCBF) Overall Behavior





(1) Beam yielding
(2) Upper story south brace buckling
(3) Lower story south brace buckling
(4) Upper story north brace-gusset weld fracture
(5) Lower story beam-gusset weld fracture

Experimental Summary

- OCBF *b/t* requirements provided ductile brace buckling
- *R* = 3 exhibited brittle brace buckling (high *b/t*)
- Chevron can mobilize some level of EBF action
- Split-X redundancy can lead to multi-story brace failure
- Brace compression reengagement capacity can be significant

Project Summary

- Full-scale testing in Lehigh EF provided valuable new experimental data
- Tests were used to verify numerical modeling framework, which was then employed for extensive static and dynamic simulations
- Fundamental understanding of seismic stability for low-ductility braced frames is now established
- A new braced frame design approach is being proposed for incorporation in AISC *Seismic Provisions*

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