Grand Challenge: Resilience of East Coast Infrastructure

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NHERI Lehigh Researcher Workshop

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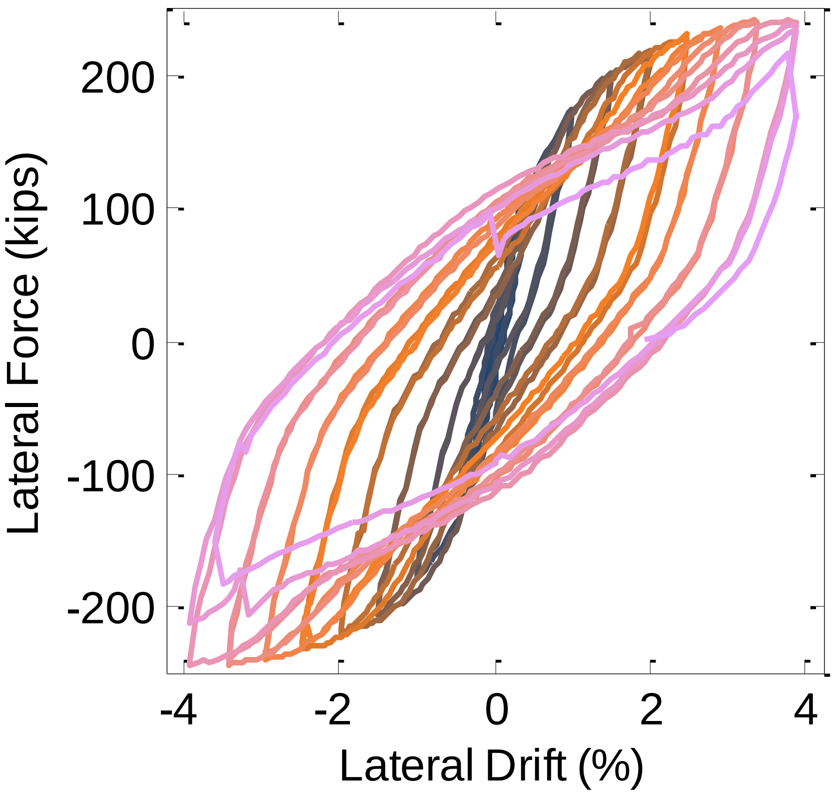
Resilience

- The ability to recover quickly from a difficulty or disturbance

West Coast Perspective

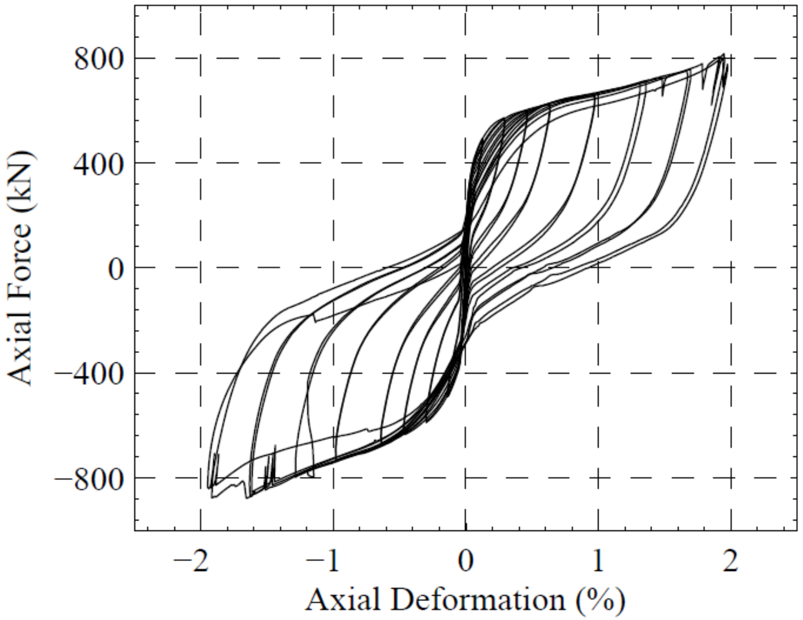
- Ductile structural systems that are rigorously designed for seismic effects
- Public awareness of earthquake hazard supports initial investment in life safety



Borello and Fahnestock (2017), *Journal of Structural Engineering*, 143 (10): 04017133.

West Coast Perspective

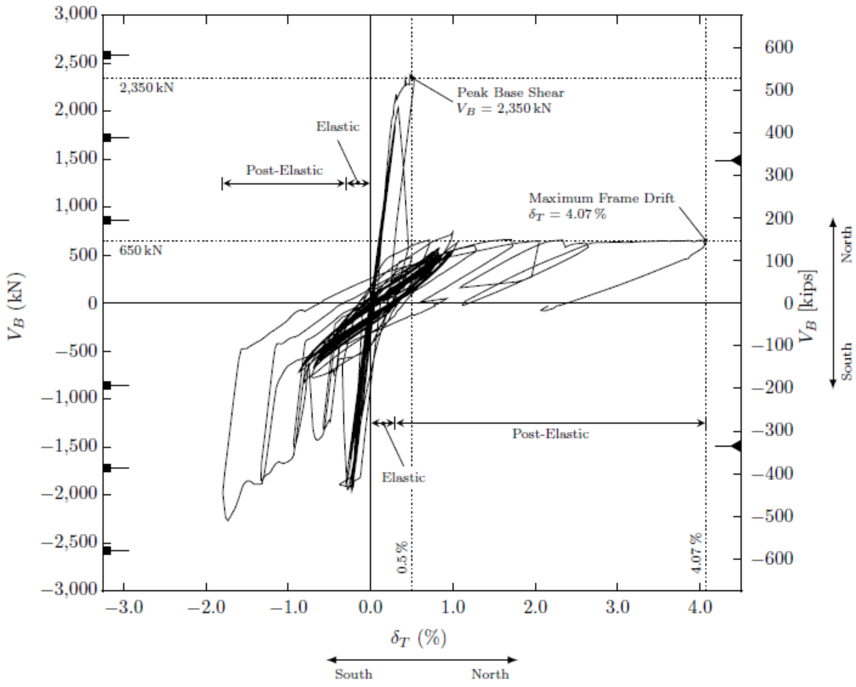
- Growing understanding of the need for even more investment toward resilience (high performance systems)



Miller, Fahnestock and Eatherton (2012), *Engineering Structures*, 40: 288-298.

East Coast / Central US Perspective

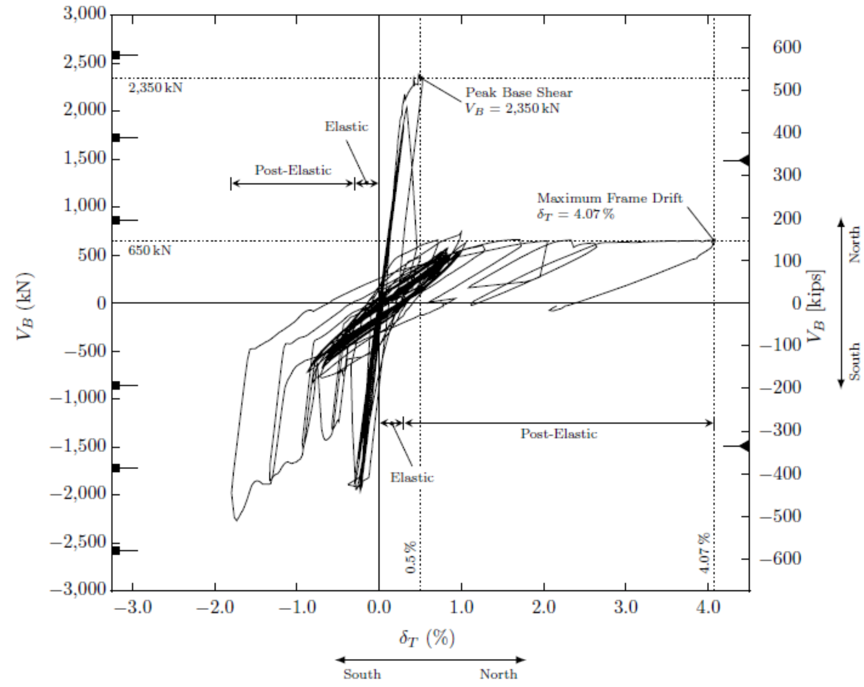
- Economical, efficient structural systems
- Gravity and wind are primary considerations
- Seismic is part of the design framework, but response is not well understood



Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

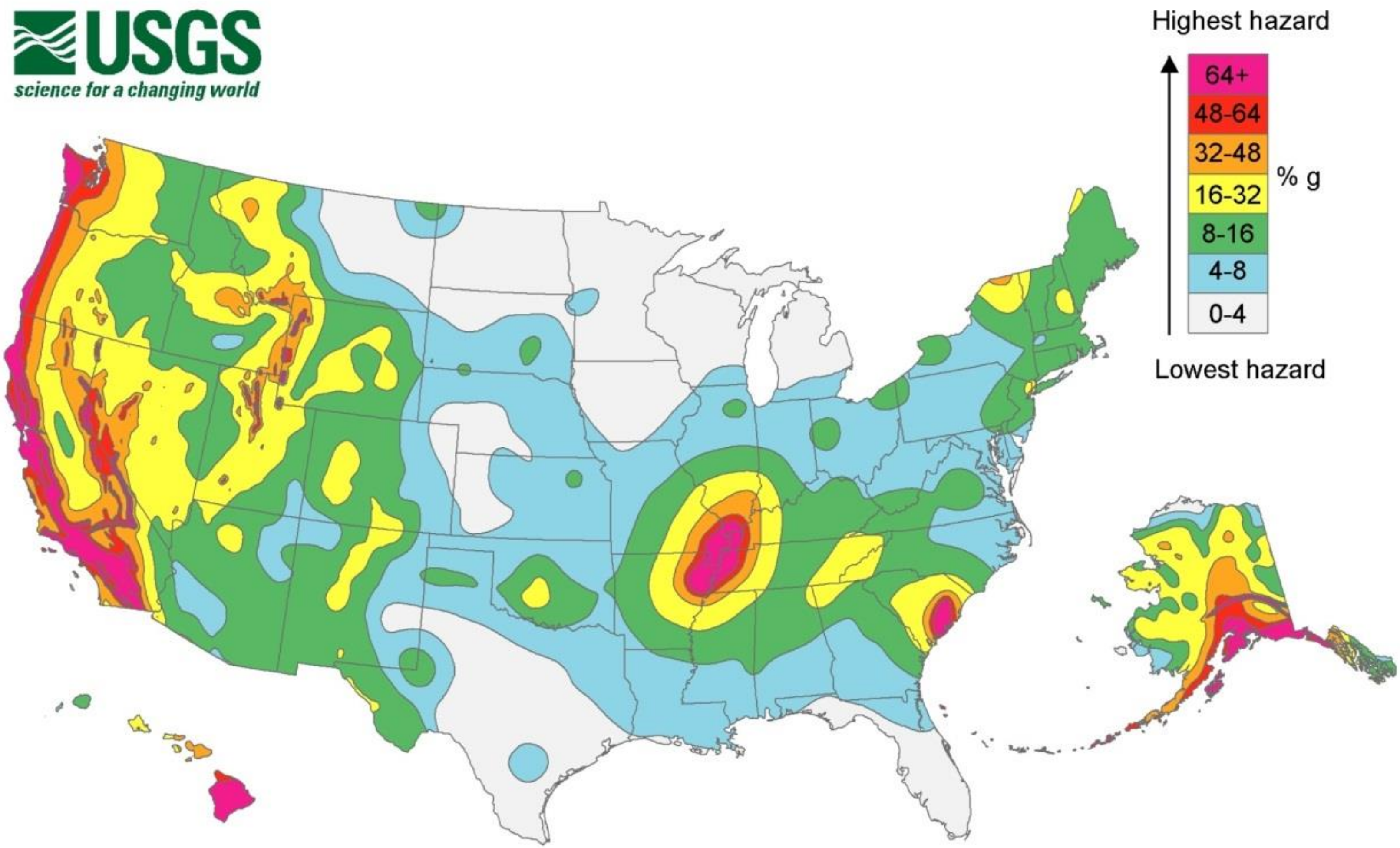
East Coast / Central US Perspective

- Structural systems are likely to exhibit brittle limit states
- Little public support for additional investment in seismic resilience



Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

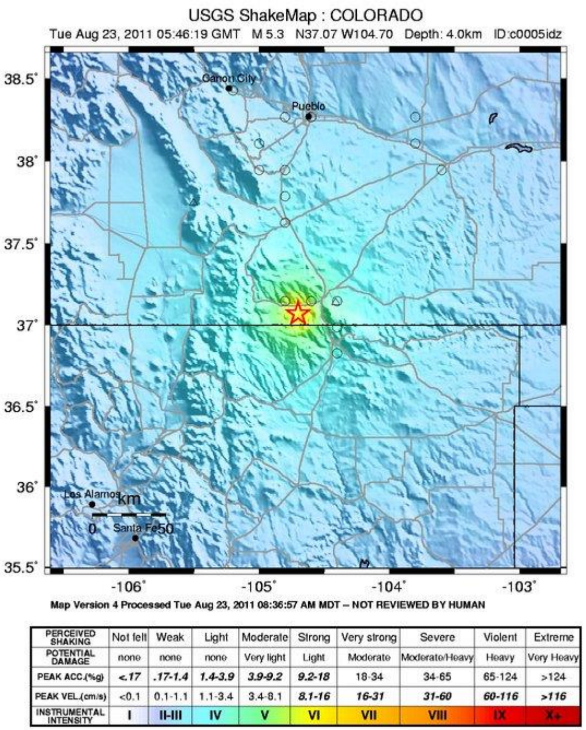
East Coast / Central US Seismic Hazard



(USGS)

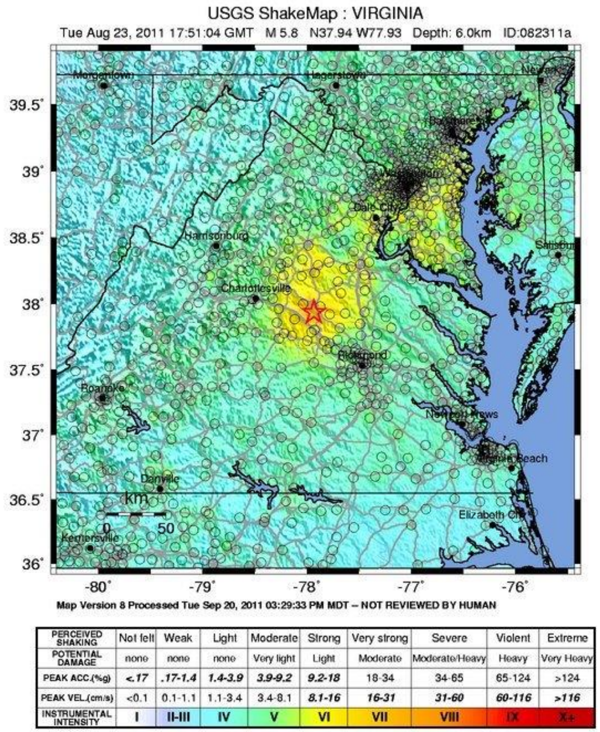
East Coast / Central US Earthquakes

Colorado



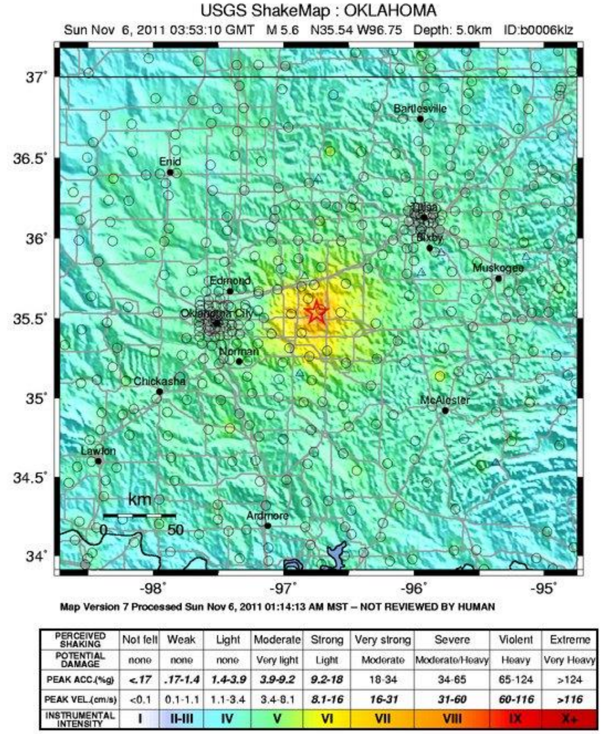
Magnitude: 5.3
Depth: 2.5 miles
Intensity: VI

Virginia



Magnitude: 5.8
Depth: 3.7 miles
Intensity: VI

Oklahoma



Magnitude: 5.6
Depth: 3.1 miles
Intensity: VI

(USGS)

Seismic Resilience

- How should resilience objectives vary for different seismic hazard characteristics?
  - High hazard, sort recurrence
    - Past to Current – life safety / collapse prevention
    - Current to Future – rapid return to occupancy
  - Moderate hazard, long recurrence
    - Current – uncertain
    - Future – life safety / collapse prevention / functionality for emergency response

East Coast Seismic Resilience Research

1. Buildings: Reserve Capacity
2. Bridges: Quasi-isolation

- Theme: employ existing systems and components, with modest modifications to enhance seismic performance
- Approach: full-scale testing and extensive numerical simulations

East Coast Seismic Resilience Research – Project 1

NEESR: Reserve Capacity in New and Existing Low-Ductility Braced Frames

Funding: NSF (CMMI-1207976), AISC

Full-Scale Testing: NEES@Lehigh

Numerical Simulations: XSEDE

NEES @ Lehigh
George E. Brown, Jr. Network for Earthquake Engineering Simulation

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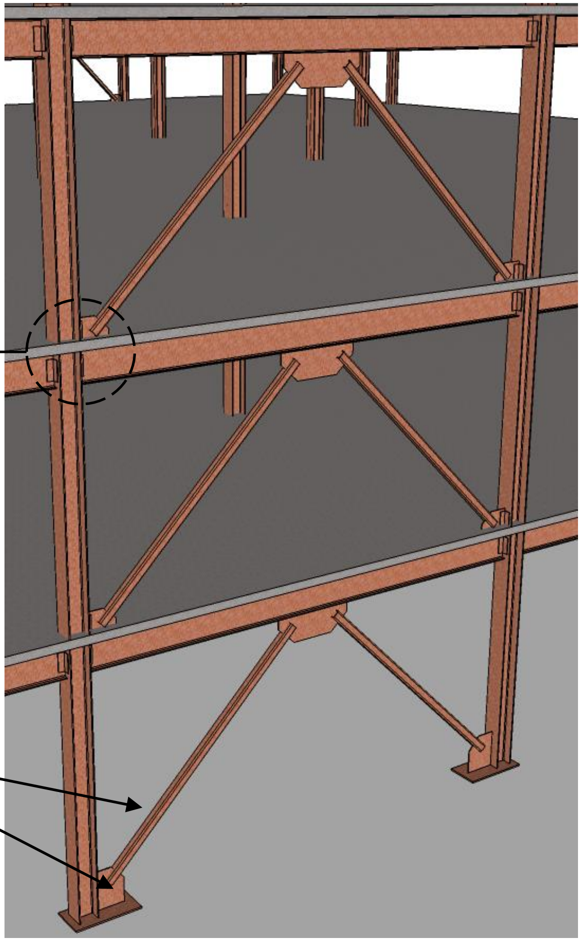
NEESR: Reserve Capacity in New and Existing Low-Ductility Braced Frames

- University of Illinois at Urbana-Champaign
  - Larry Fahnestock (PI)
  - Josh Sizemore (RA, former PhD student)
- Tufts University / LeMessurier Consultants
  - Eric Hines (Co-PI)
  - Cameron Bradley (RA, former PhD student)
  - Jessalyn Nelson (RA, former MS student)
- École Polytechnique Montréal
  - Robert Tremblay (Co-PI)
  - Thierry Beland (RA, PhD student)
  - Ali Davaran (former research scientist)

East Coast / Central US Braced Frames

- Assume pin connections
- Statically determinate
- Stiff and efficient
- No seismic detailing
- R = 3



- Seismic design using high-ductility structural systems is not feasible
- R = 3 concentrically-braced frames (CBF) systems are prevalent in moderate seismic regions

East Coast / Central US Braced Frames

- How does a typical braced frame (R = 3) respond when it is loaded beyond the elastic range of behavior?

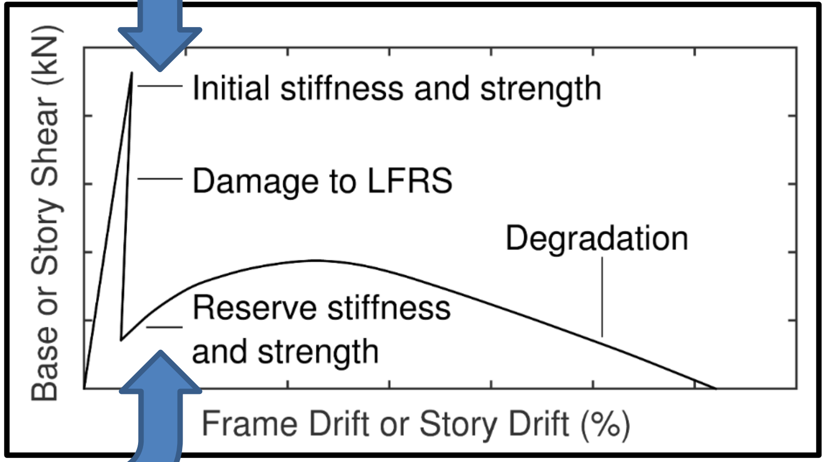
CBF Seismic Performance

Rai and Goel (2003)

- CBFs, which were viewed at the time as ductile designs, have exhibited nonductile behavior in historical earthquakes (like 1994 Northridge and 1995 Kobe)
- However, these CBFs did not collapse. Why?

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



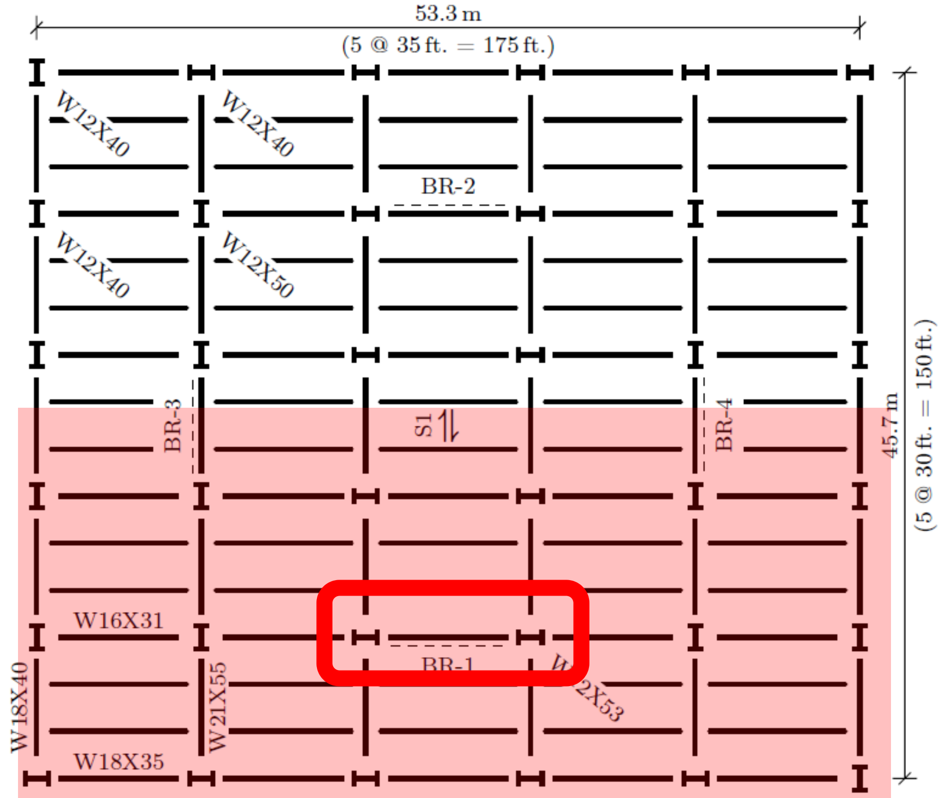
Static Pushover Curve

Research Overview

- Objective: Develop a simple yet rigorous design approach for CBF buildings in moderate seismic regions that economically and reliably provides seismic stability
- Approach:
  - Conduct full-scale CBF tests
  - Develop CBF numerical models and conduct comprehensive simulations
  - Develop recommendations for seismic design

Full-Scale CBF Tests

- Lower two stories of three-story prototypes
- *R* = 3
  - Chevron configuration
  - No seismic requirements
- Ordinary concentrically-braced frame (OCBF)
  - *R* = 3.25
  - Split-X configuration
  - Ductile detailing (*b/t*, *KL/r*)
  - Ad hoc capacity design (beams, columns and connections)



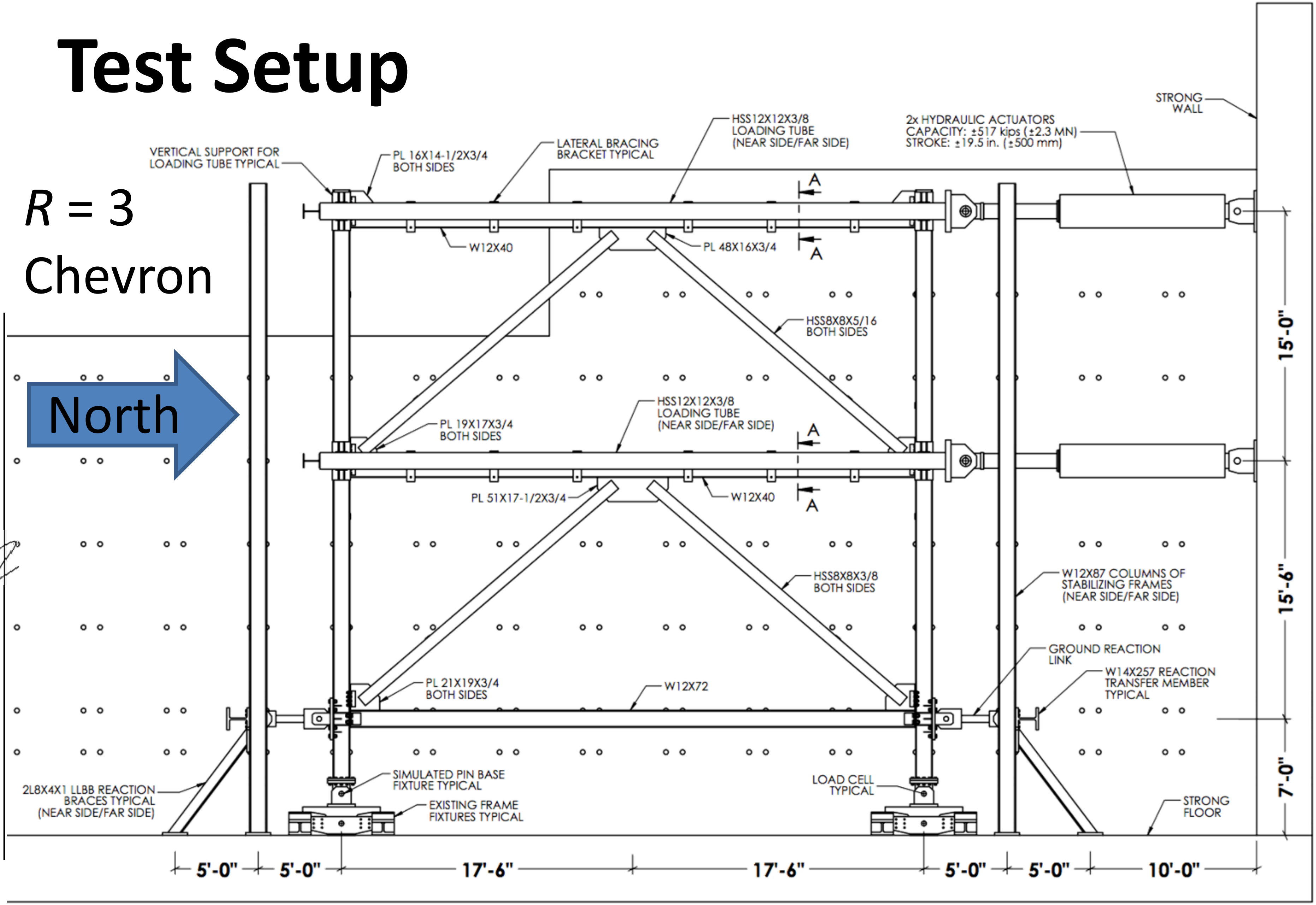
Three-Story Prototype Building Plan

Test Setup

R = 3

Chevron

North



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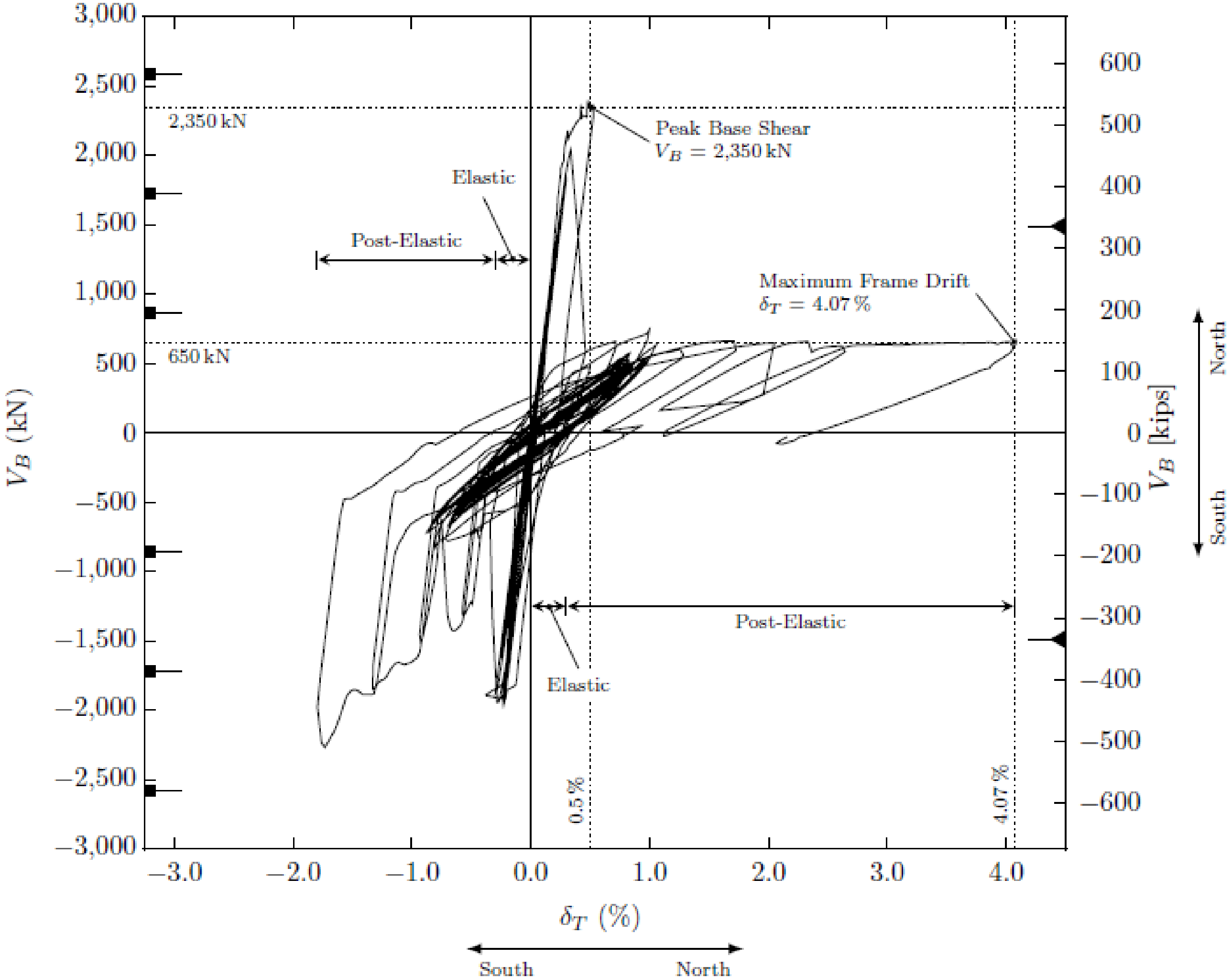
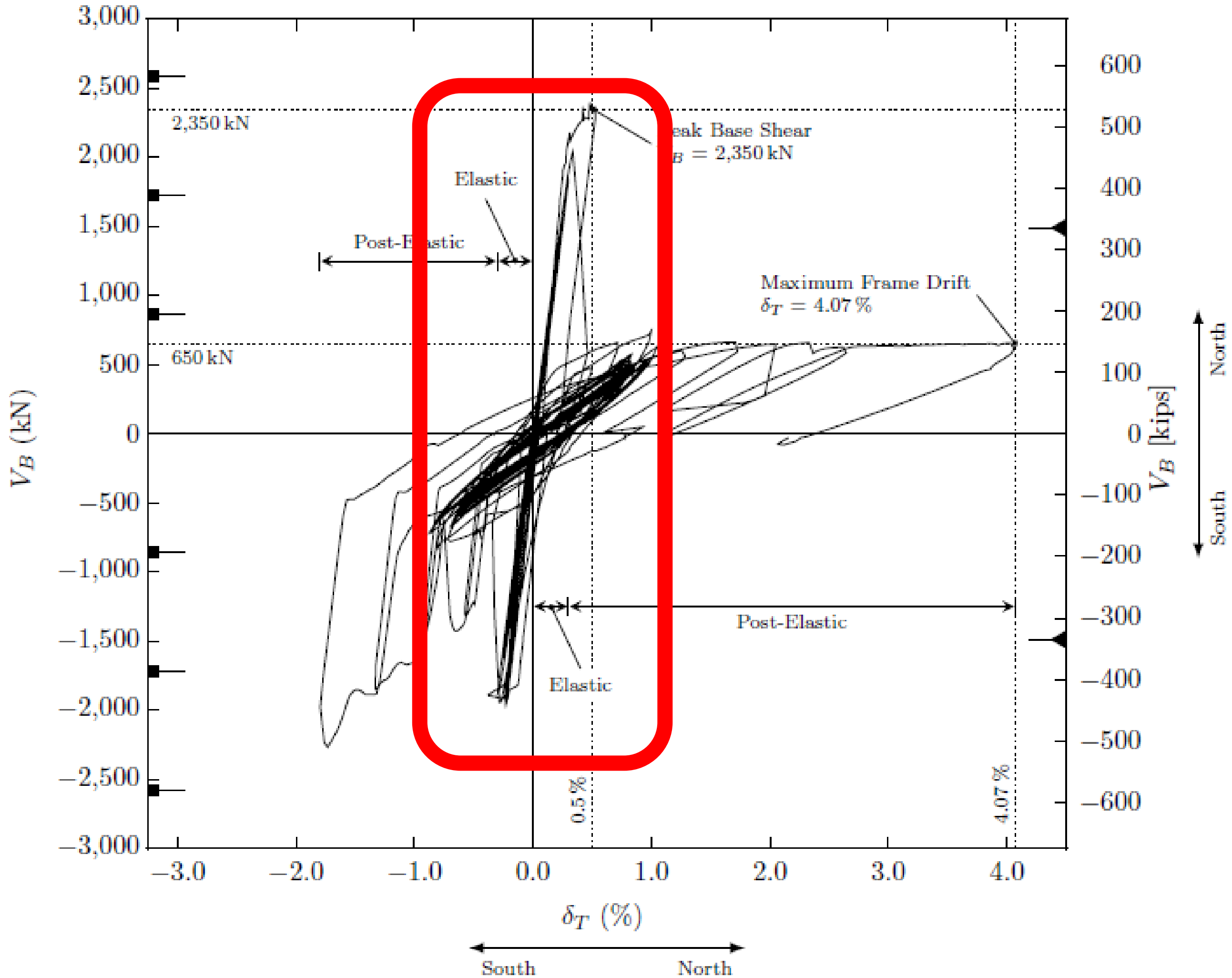
R = 3 CBF

R = 3 CBF – Overall Behavior



Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

R = 3 CBF – Initial Behavior



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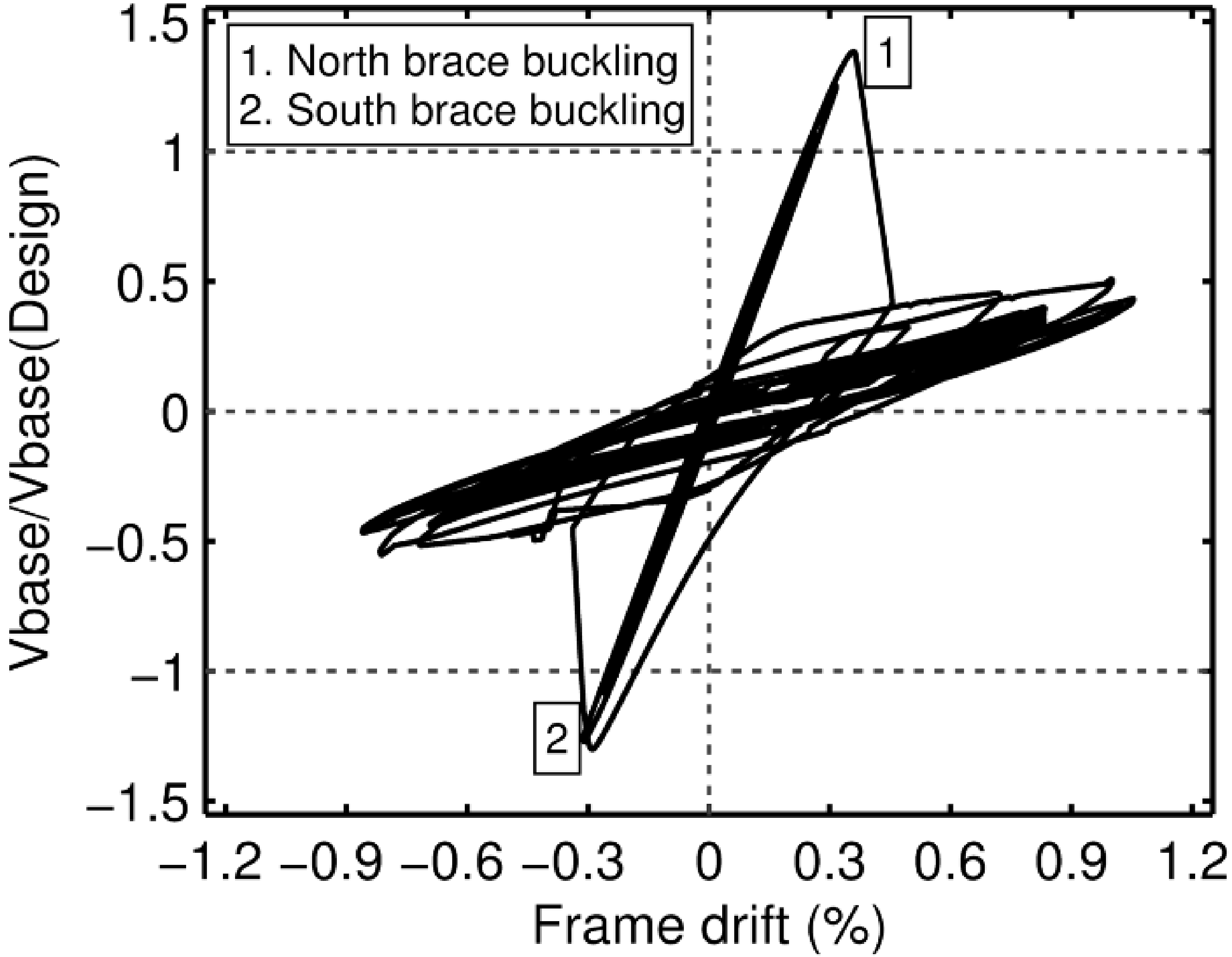
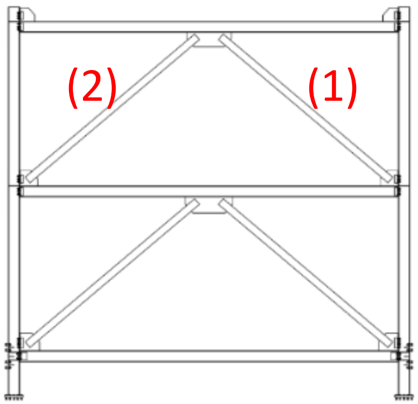
R = 3 CBF – Initial Behavior





Upper story brace buckling

Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

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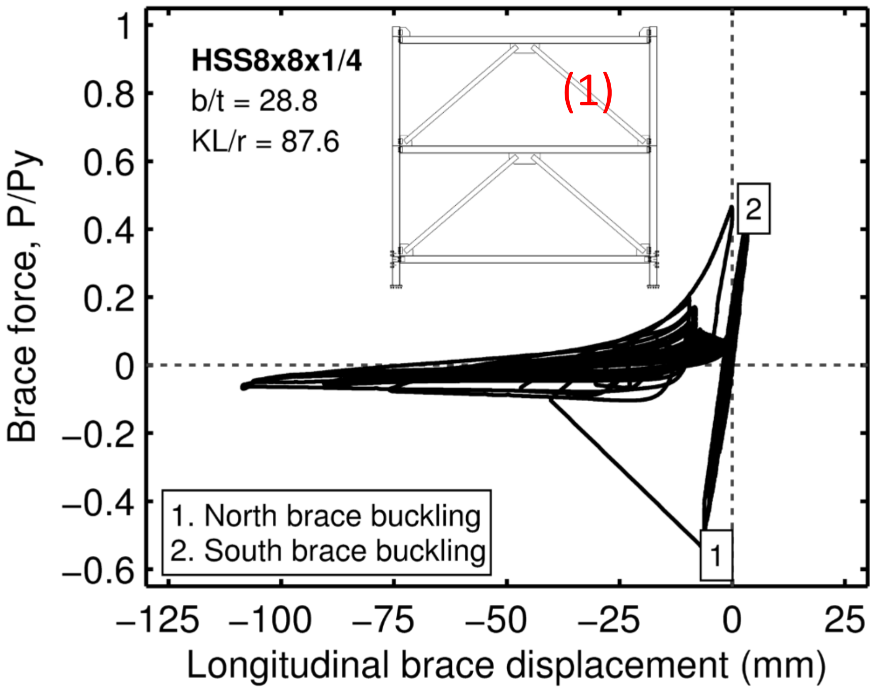
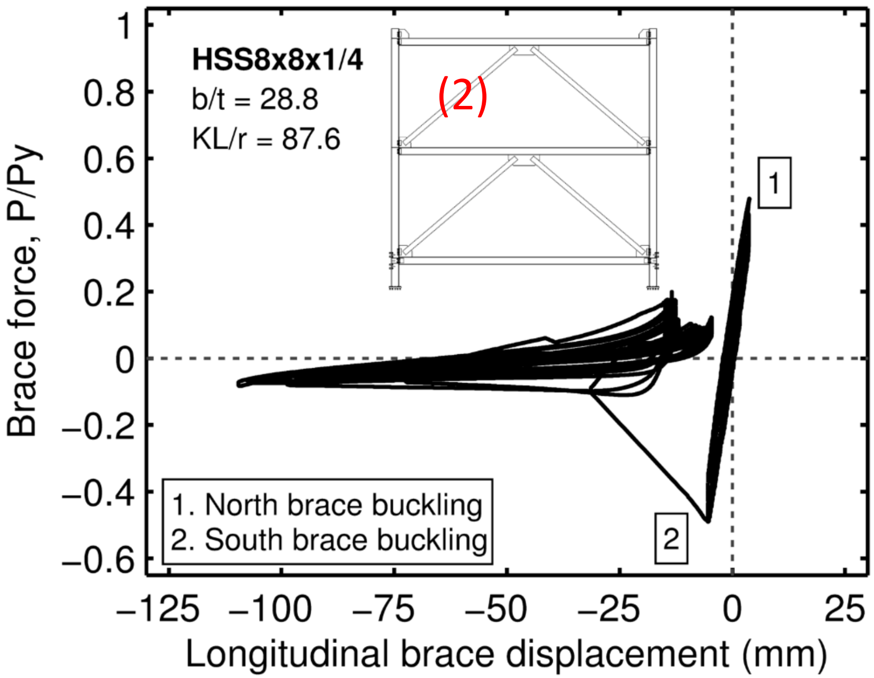
R = 3 CBF – Brace Behavior





North brace initial buckling

South brace final state

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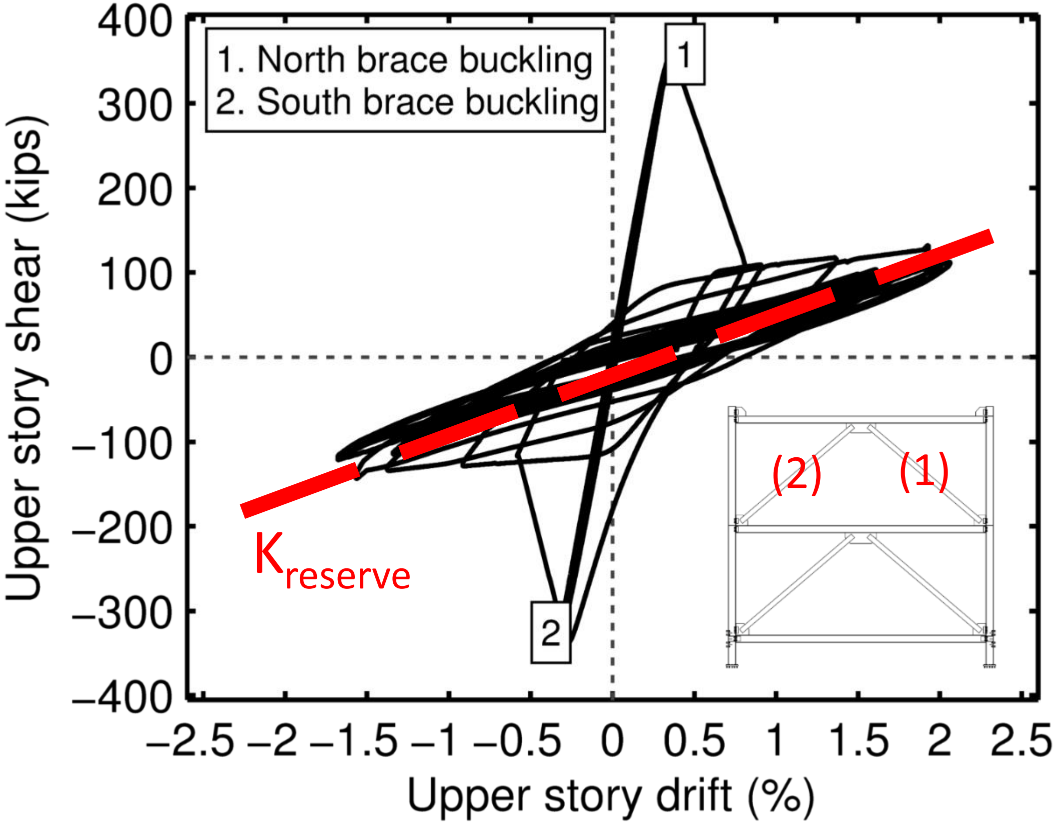
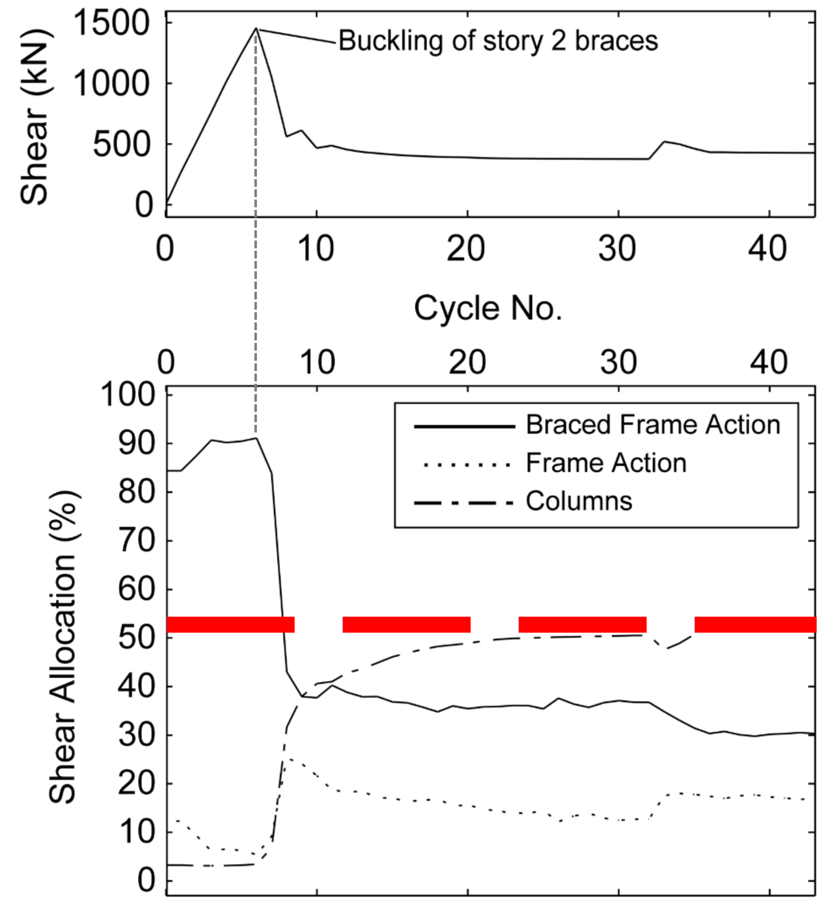
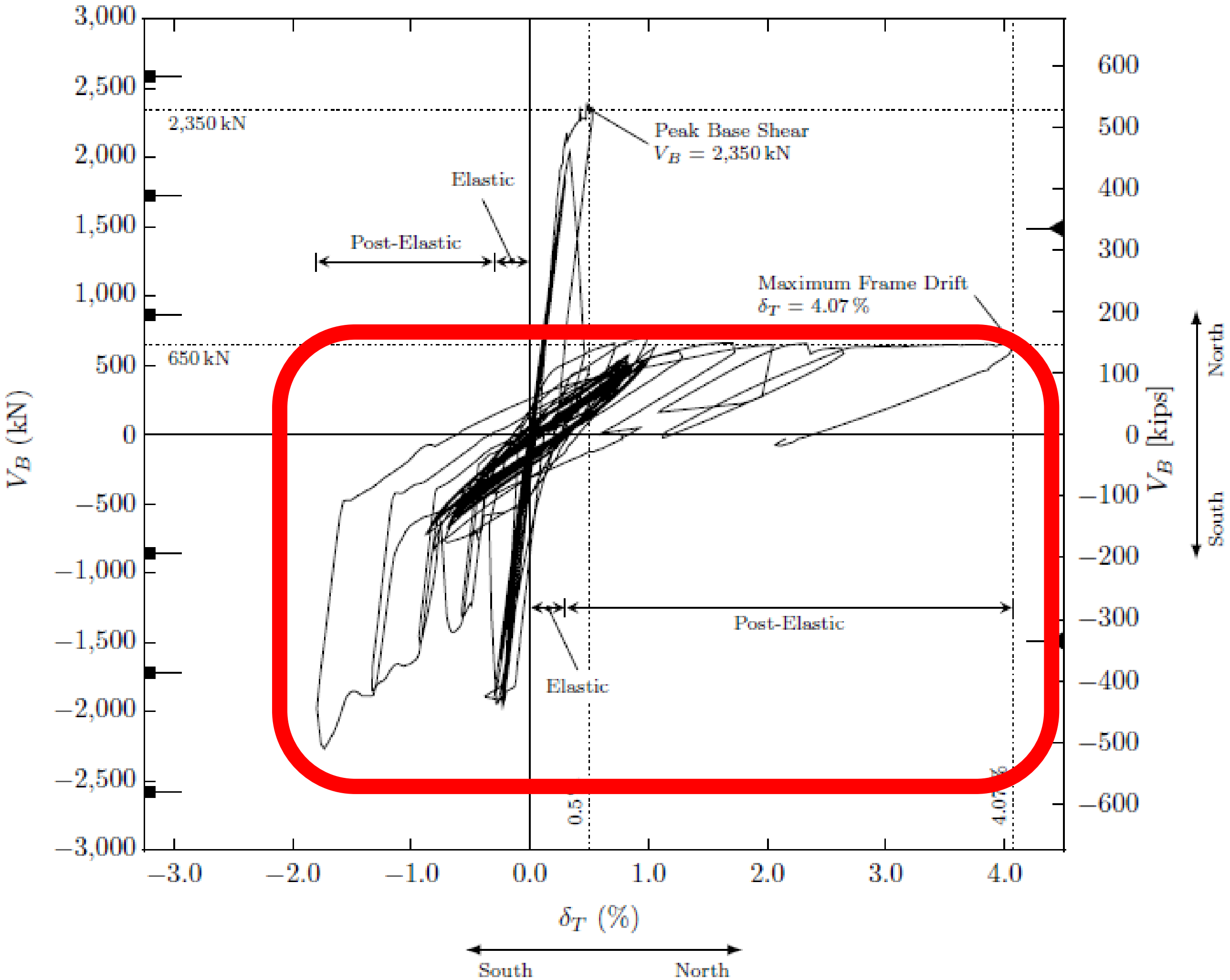
R = 3 CBF – Top Story Behavior





Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

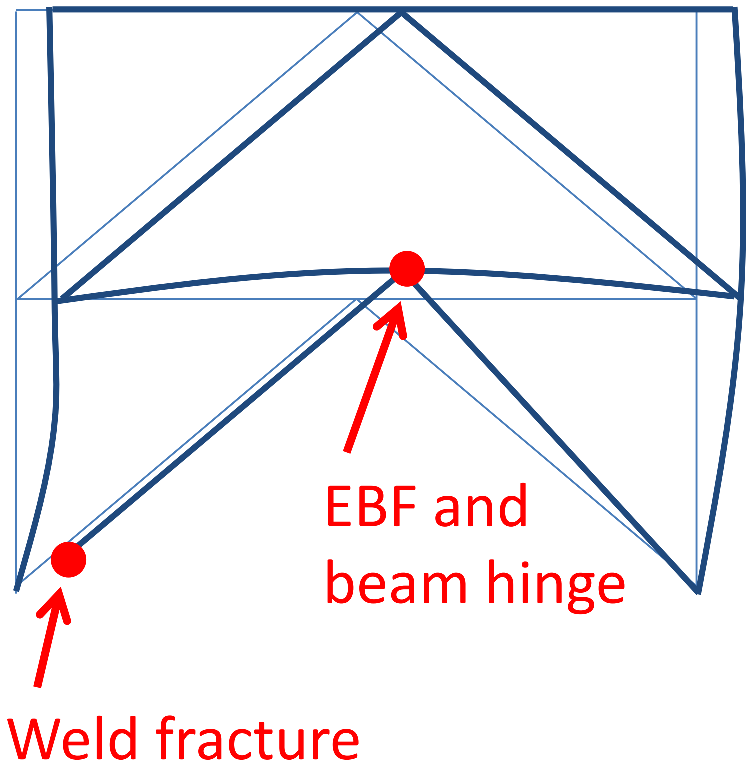
R = 3 CBF – Secondary Behavior



Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

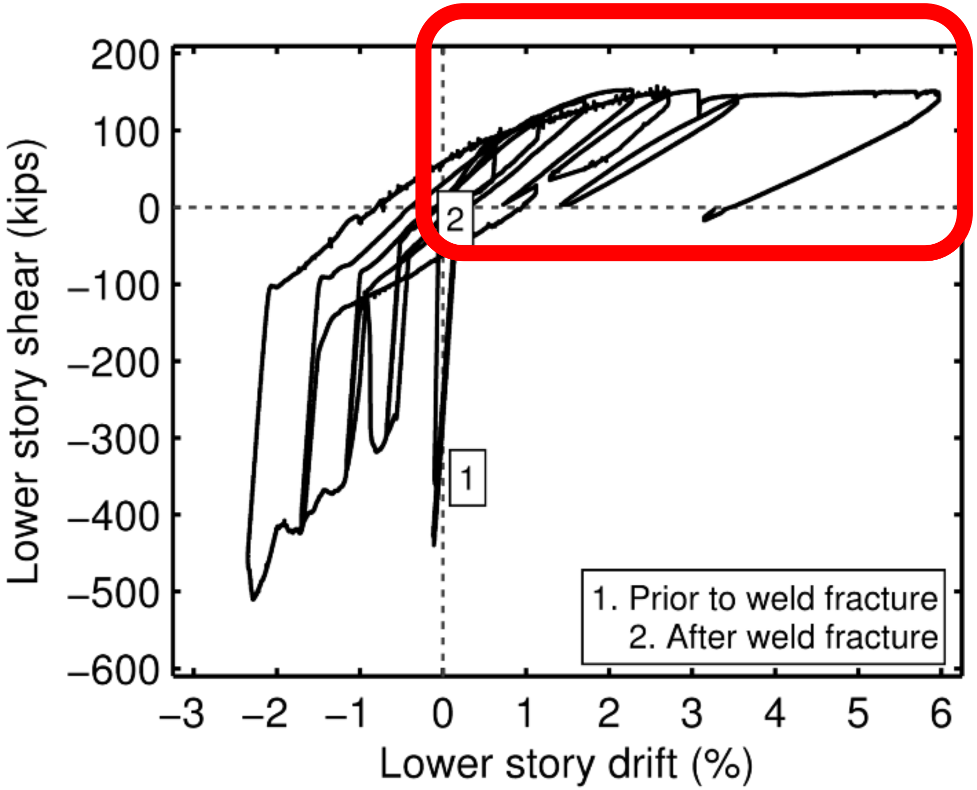
R = 3 CBF – Secondary Behavior

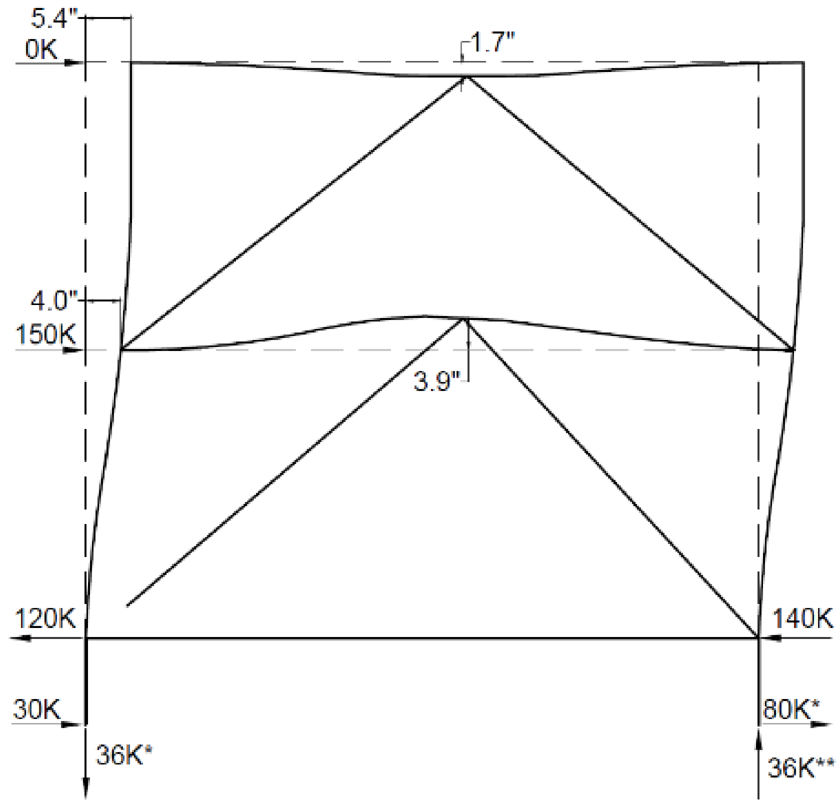
- Adjust loading
- Fracture lower story brace end connection (weld)
- Observe reserve capacity mechanisms
  - Brace reengagement
  - Long-link eccentrically-braced frame (EBF) behavior



Schematic Frame Elevation

R = 3 CBF – Secondary Behavior





Eccentrically-Braced Frame Behavior

Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

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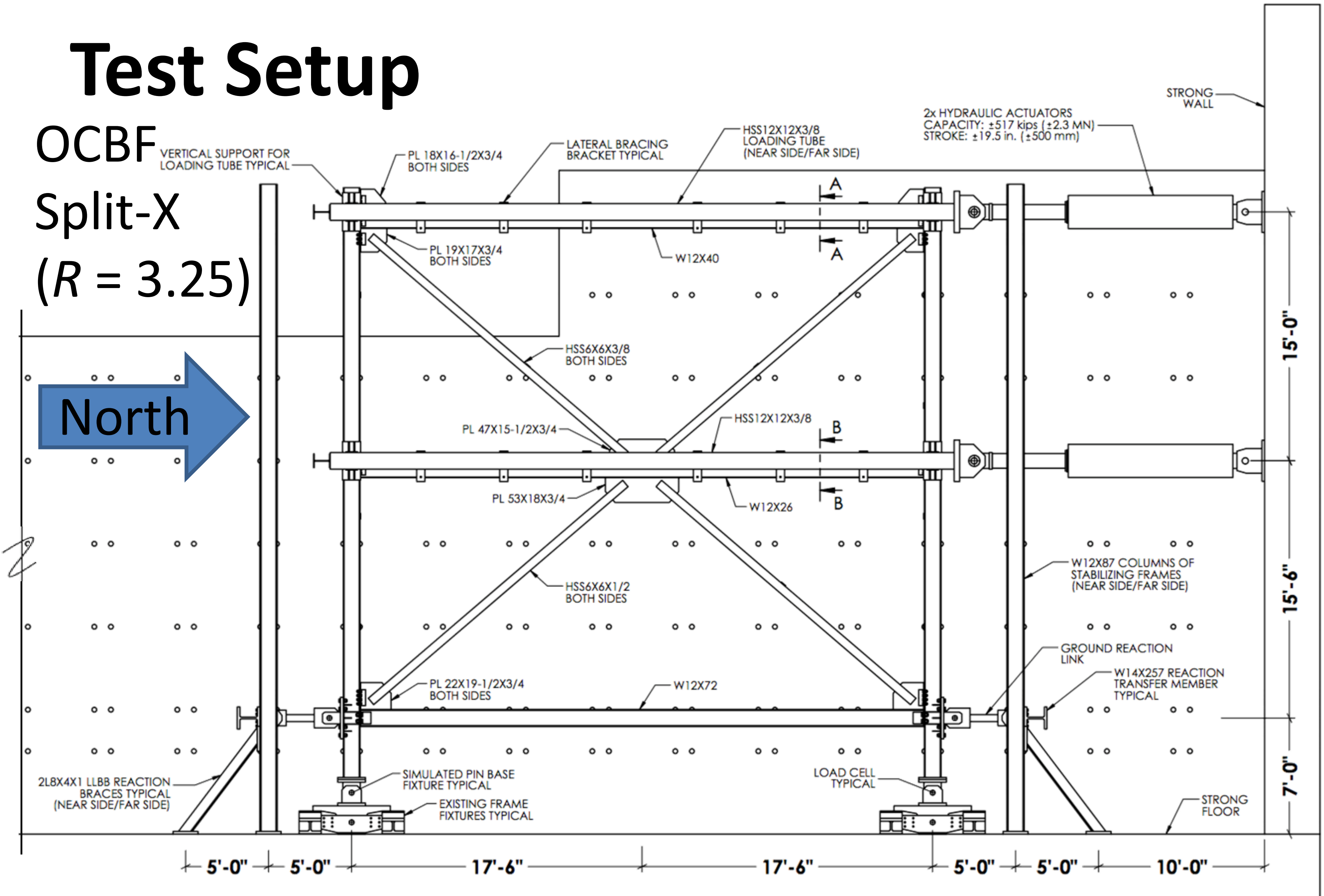
Test Setup

OCBF
Split-X
(R = 3.25)



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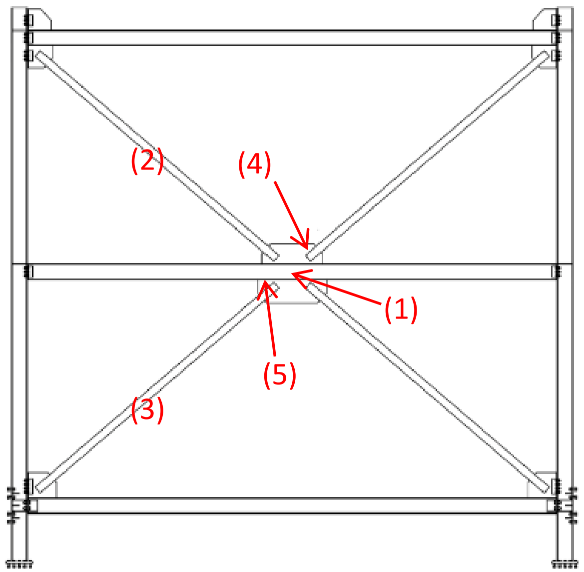
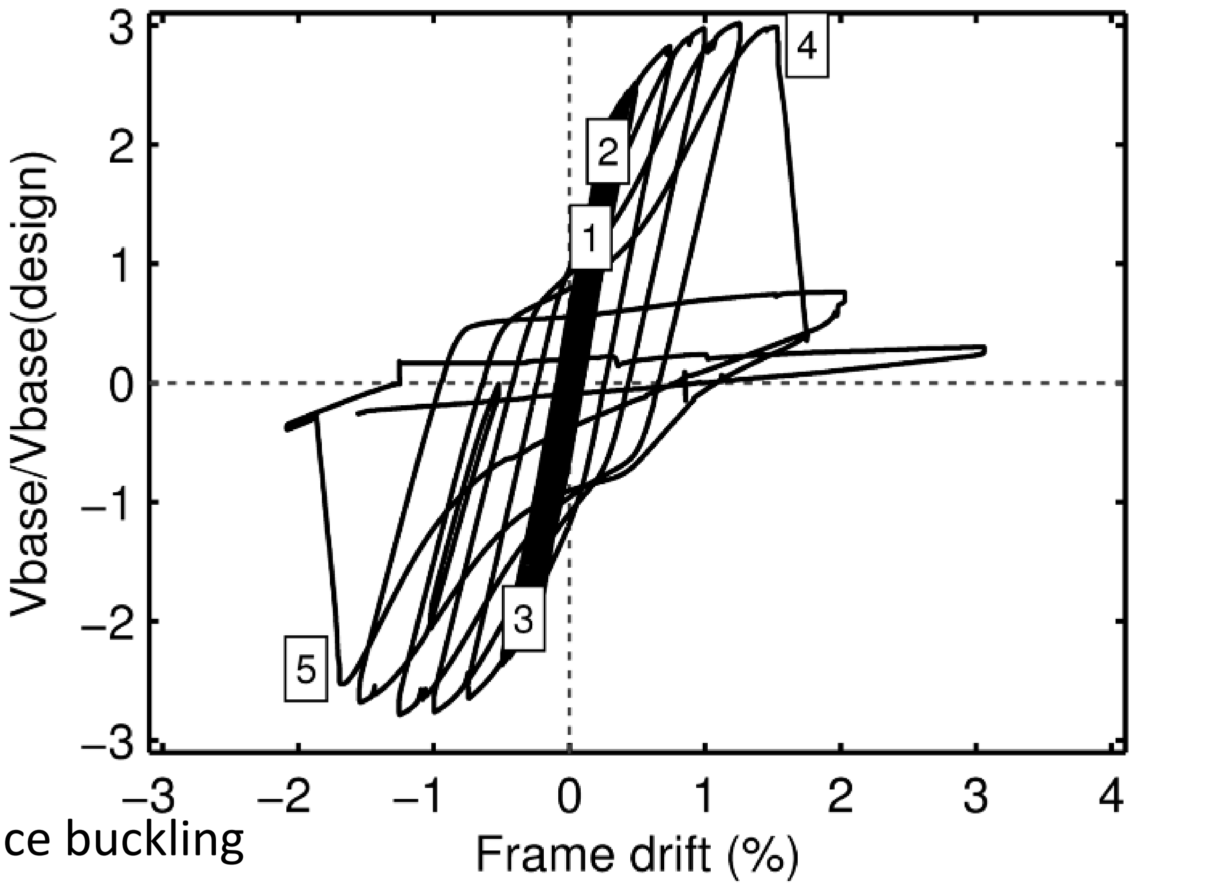
Ordinary Concentrically-Braced Frame

Bradley, Fahnestock, Hines and Sizemore (2017), *Journal of Structural Engineering*, 143 (6): 04017029.

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

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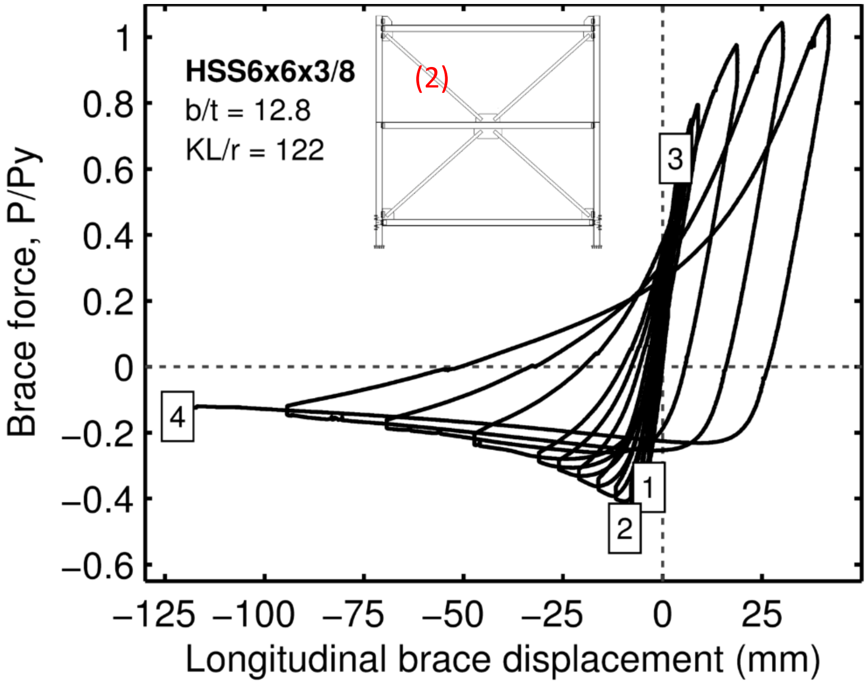
OCBF Brace Buckling (2)



Upper Story South

(1) Beam yielding

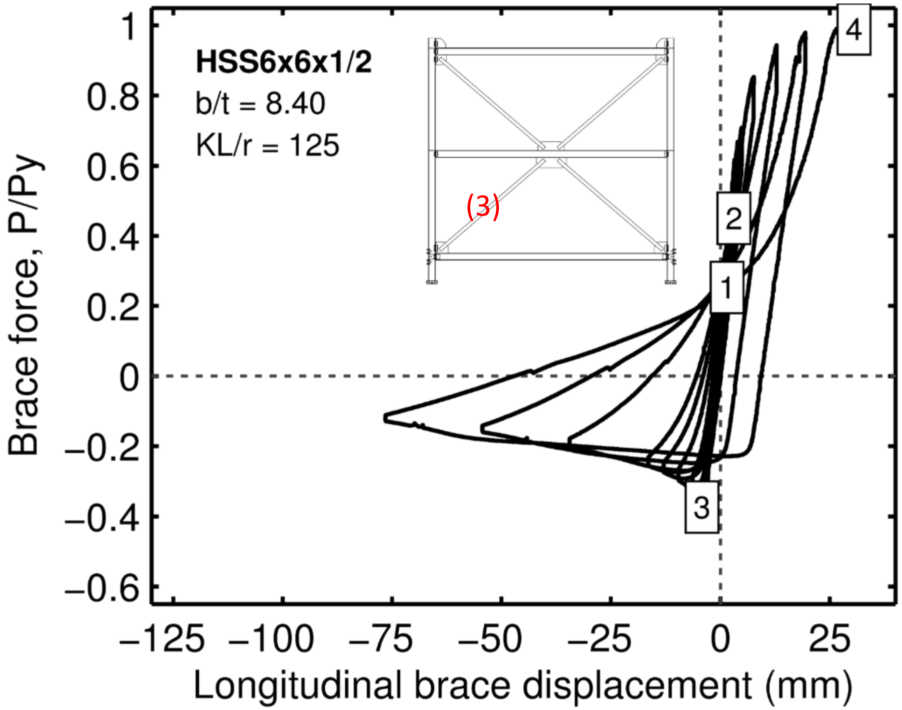
(2) Upper story south brace buckling

(3) Lower story south brace buckling

(4) Upper story north brace-gusset weld fracture

(5) Lower story beam-gusset weld fracture

OCBF Brace Buckling (3)



(1) Beam yielding

(2) Upper story south brace buckling

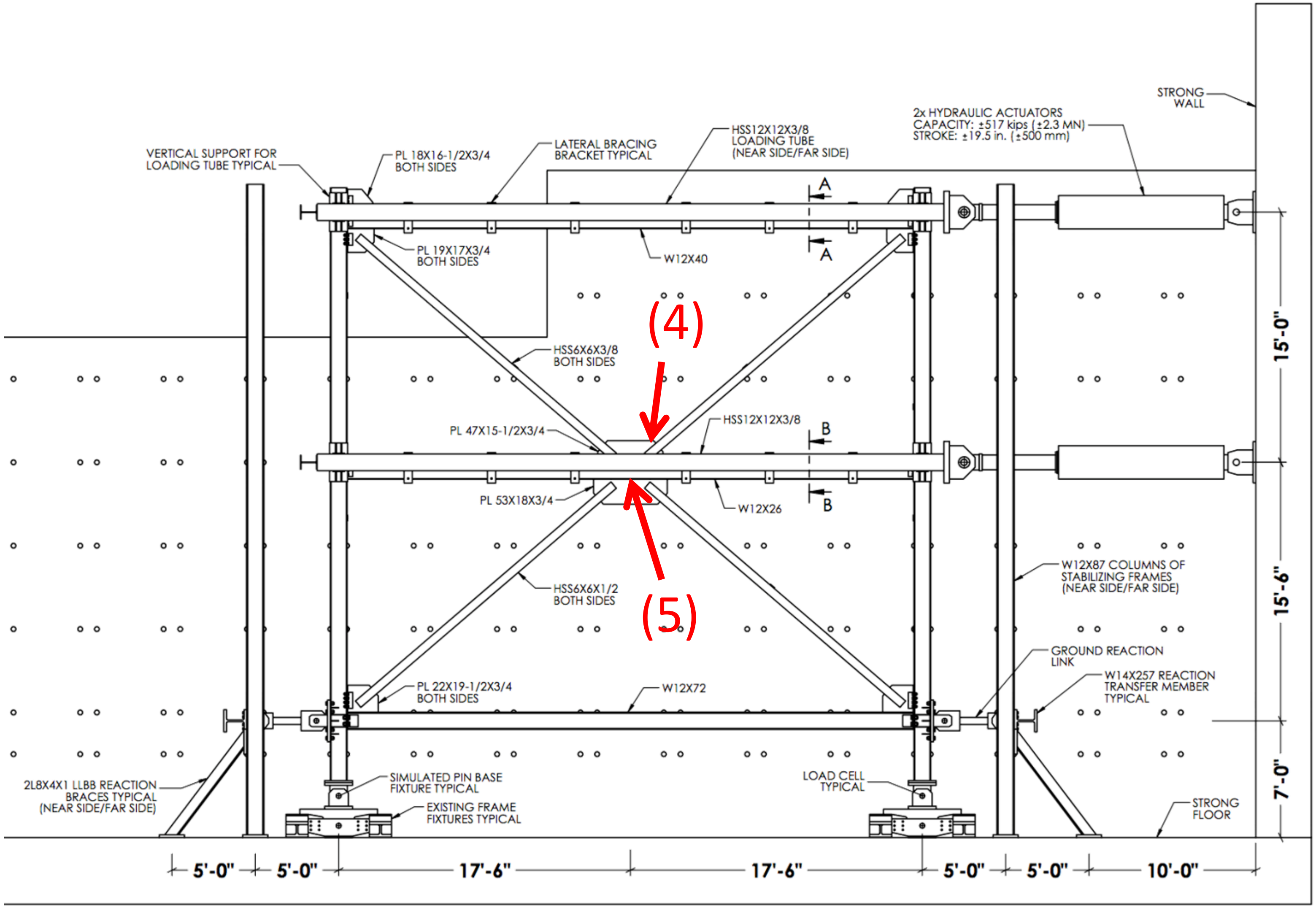
(3) Lower story south brace buckling

(4) Upper story north brace-gusset weld fracture

(5) Lower story beam-gusset weld fracture

Lower Story South

OCBF Weld Fractures



OCBF Weld Fracture (4)

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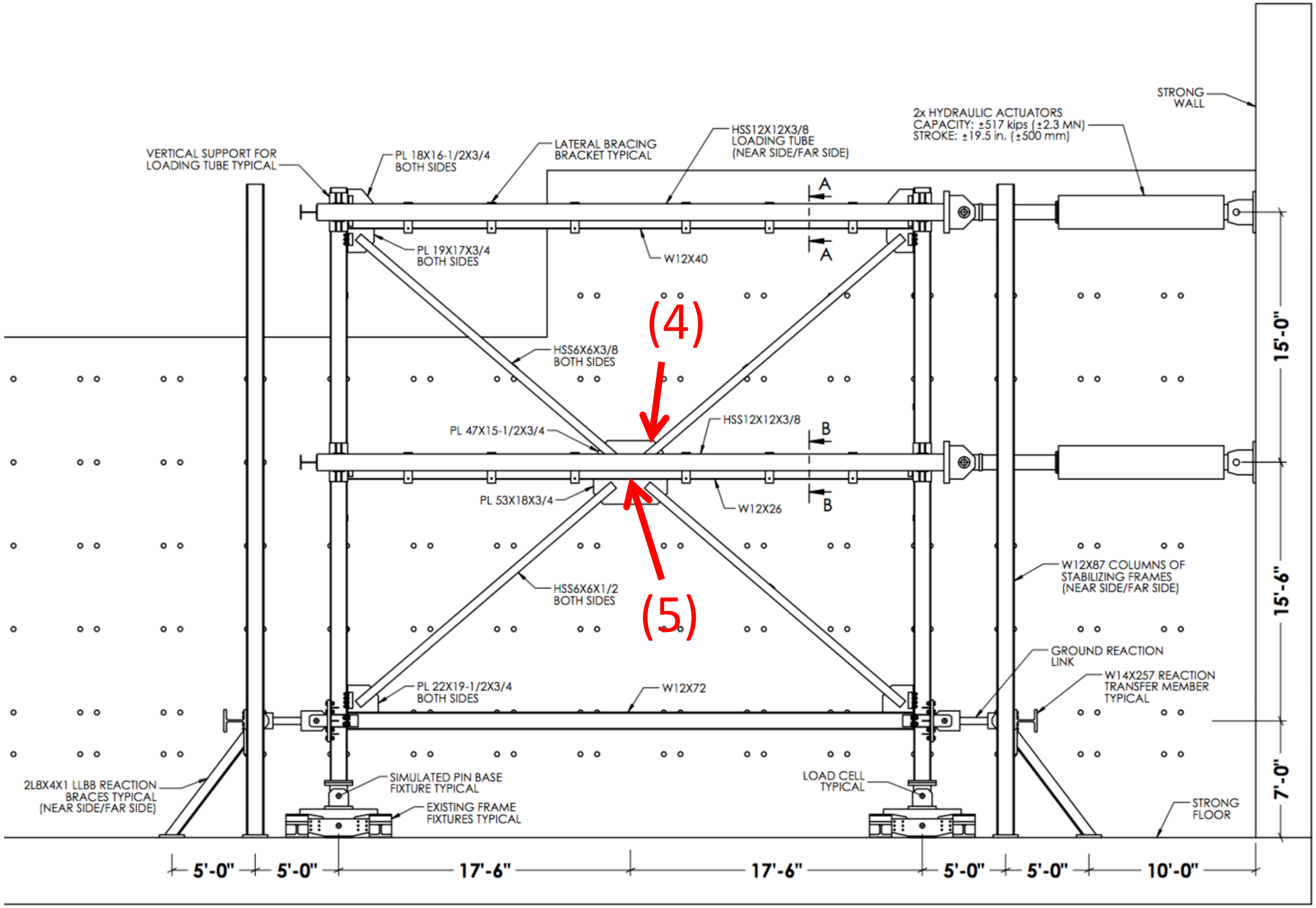
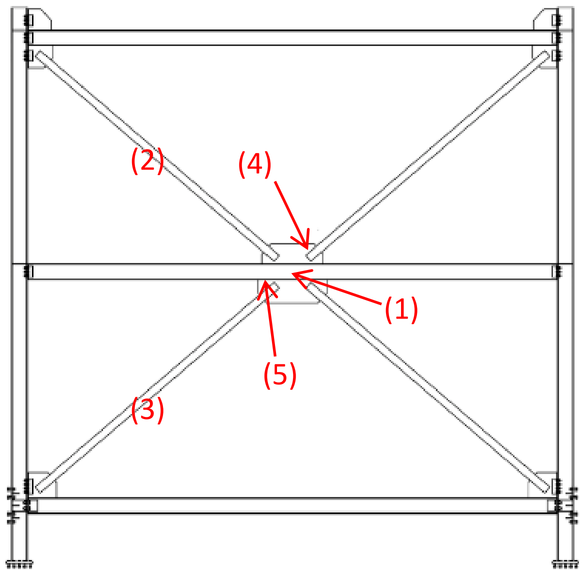
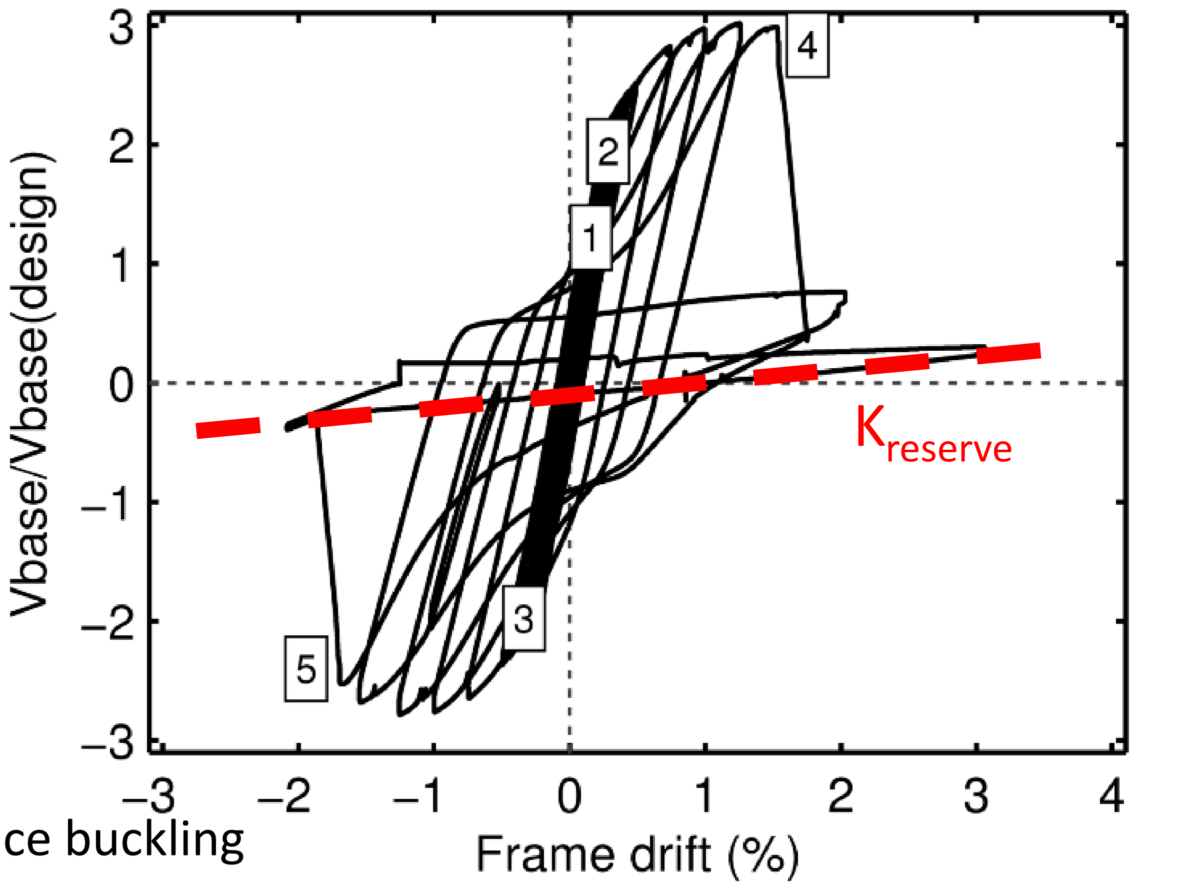
OCBF Weld Fractures



OCBF Weld Fracture (5)

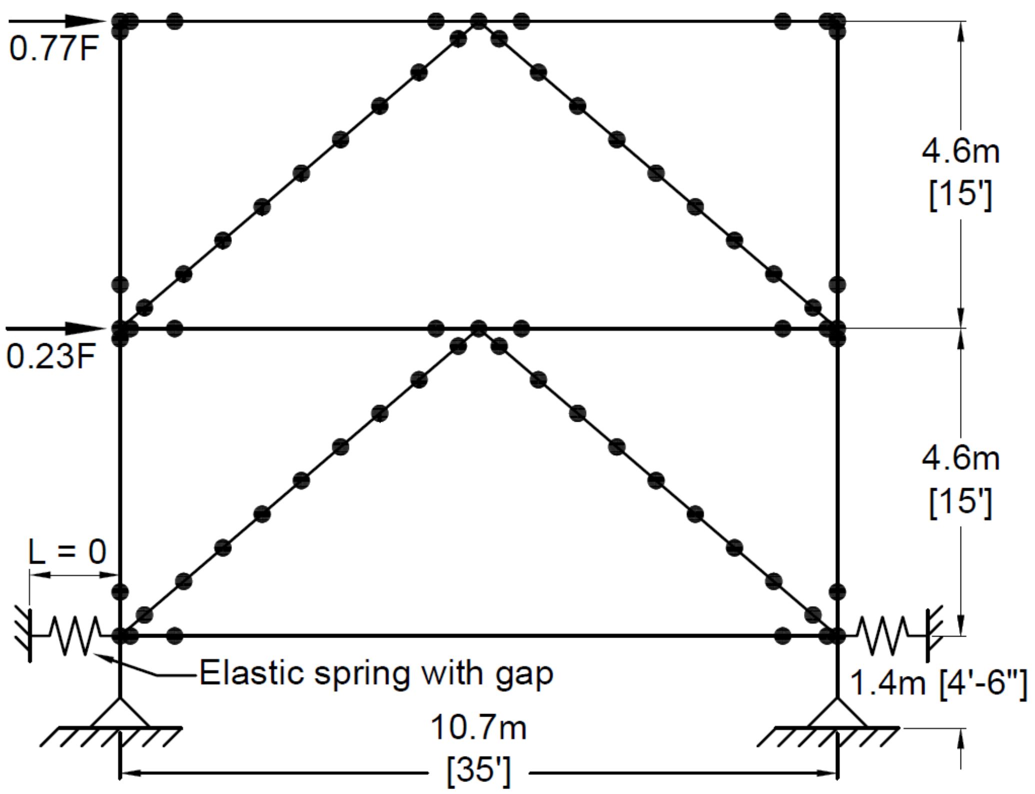
OCBF Overall Behavior



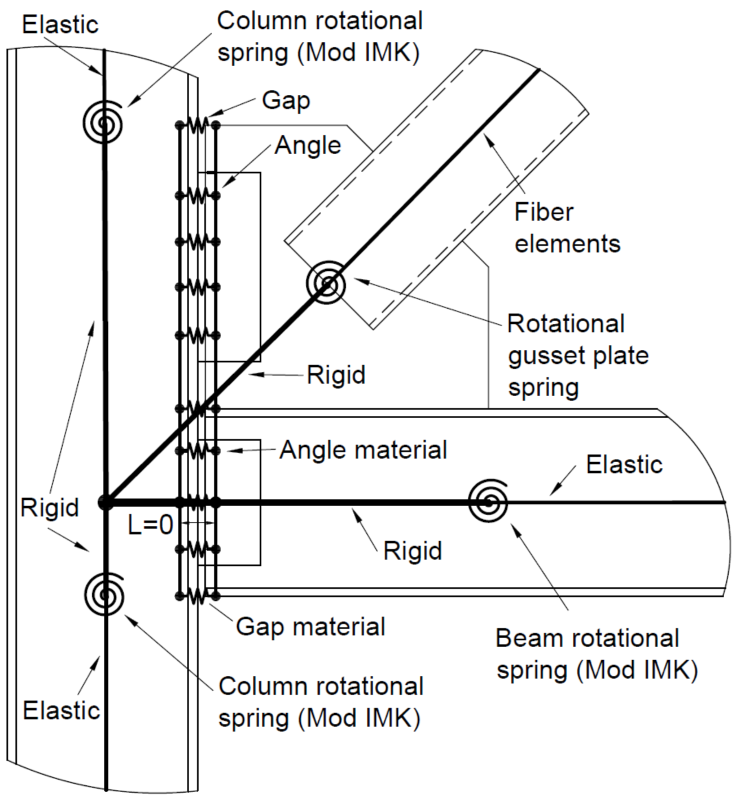


(1) Beam yielding
(2) Upper story south brace buckling
(3) Lower story south brace buckling
(4) Upper story north brace-gusset weld fracture
(5) Lower story beam-gusset weld fracture

Test Frame Numerical Simulations



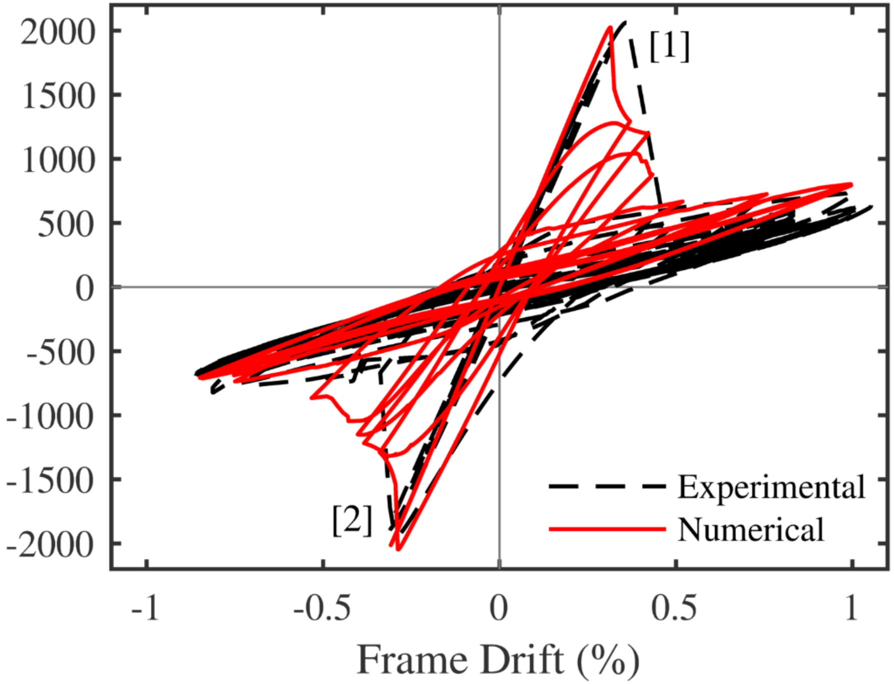
Model Elevation



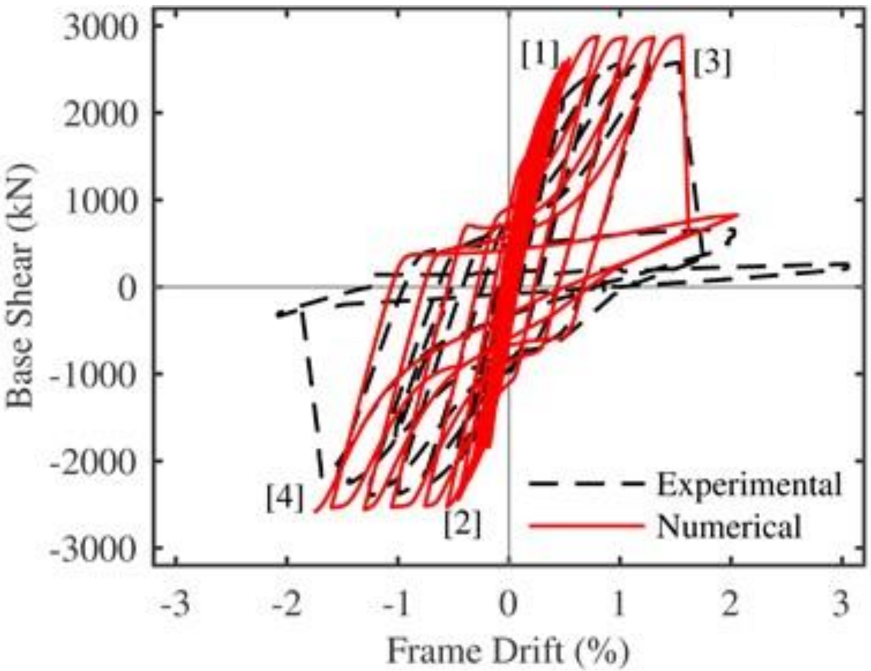
Connection Detail

Sizemore, Fahnestock, Hines and Bradley (2017), *Journal of Structural Engineering*, 143 (6) 04017032

Experimental-Numerical Comparison



***R* = 3 Chevron**



OCBF Split-X

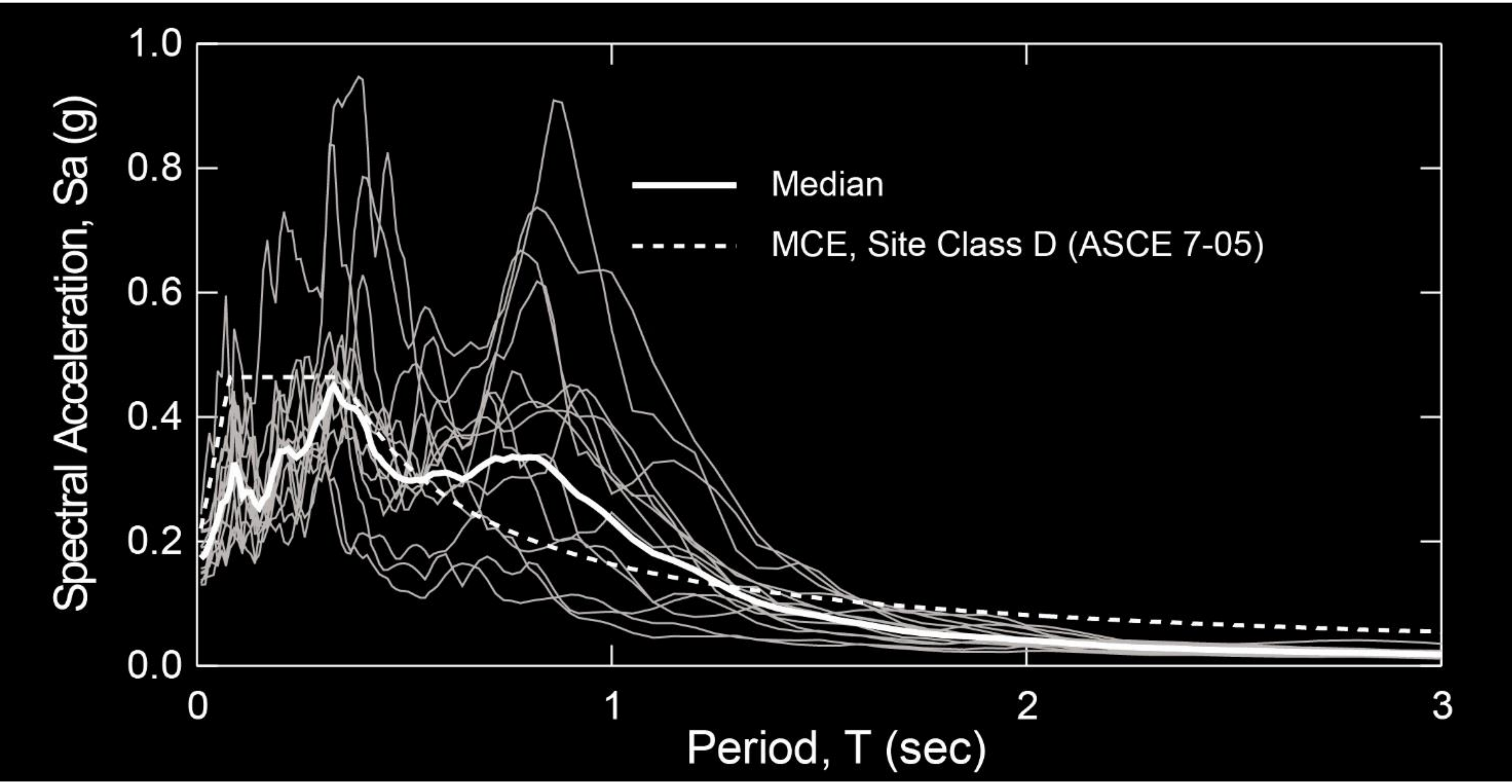
Sizemore, Fahnestock, Hines and Bradley (2017), *Journal of Structural Engineering*, 143 (6) 04017032

Numerical Simulation Cases

- R = 3 CBFs
- OCBFs
- R = 4 CBFs (new concept)
  - Design CBF for lower force level
  - Take simple measures to add reserve capacity
- Various heights and configurations
  - Chevron and Split-X
  - 3, 6 and 9 stories tall

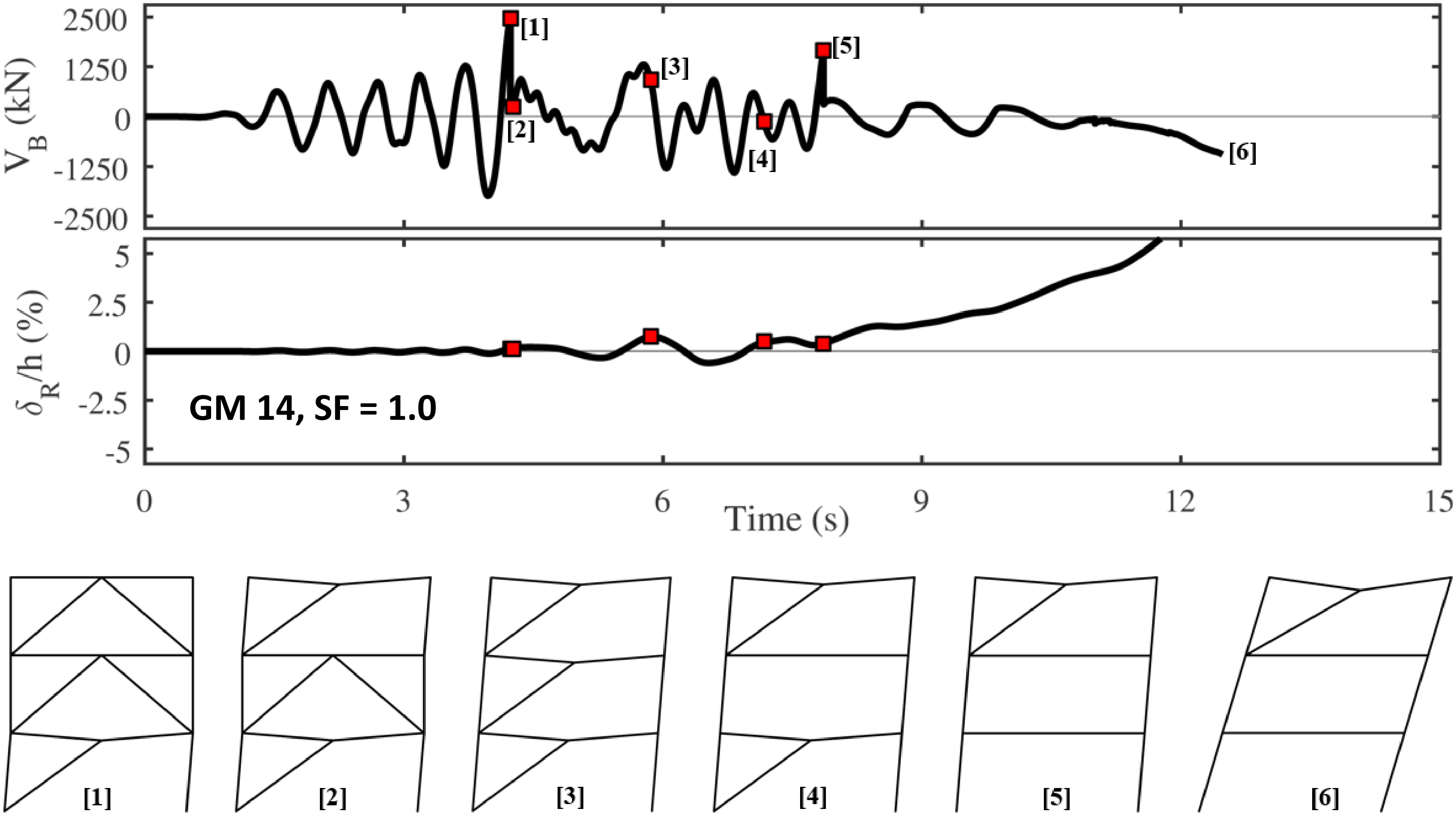
Sizemore, Fahnestock and Hines (201), *Journal of Structural Engineering*, 145 (4), 04019016

Earthquake Simulations

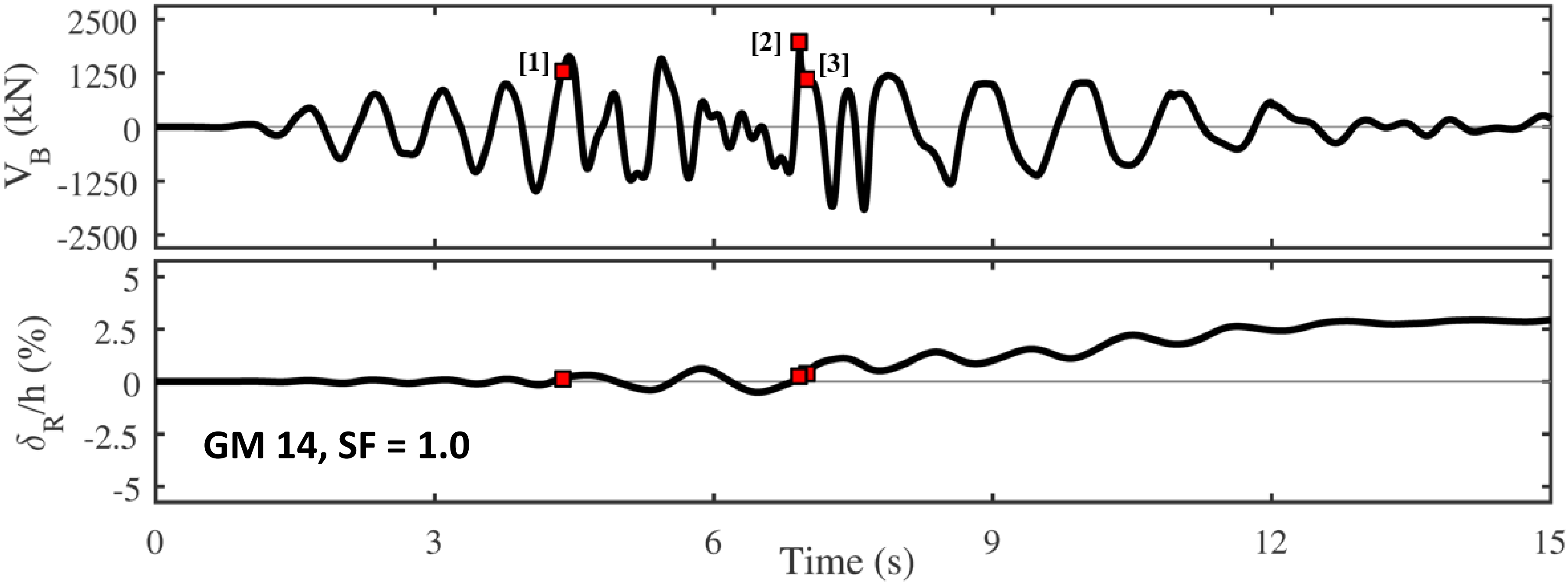


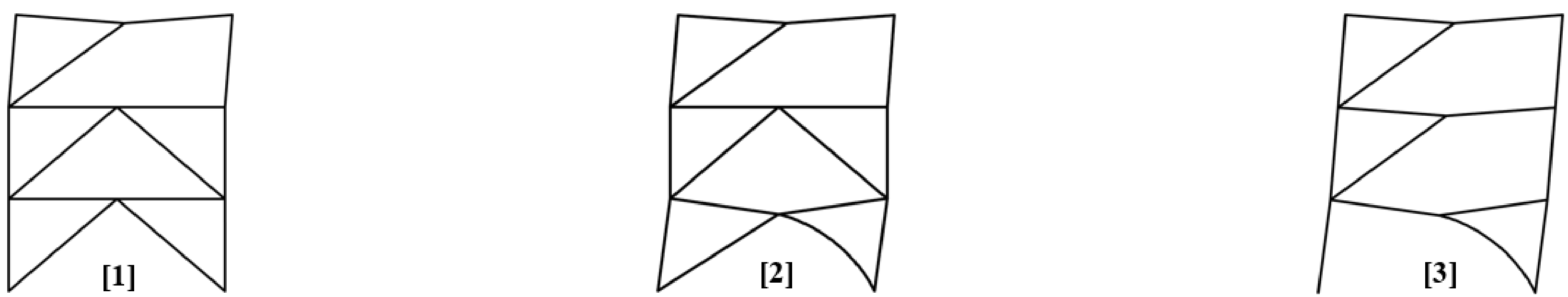
Hines, Baise and Swift (2011), *Journal of Structural Engineering*, 137 (3): 358-366.

Current *R* = 3.25 OCBF Chevron (Single-Record Response)

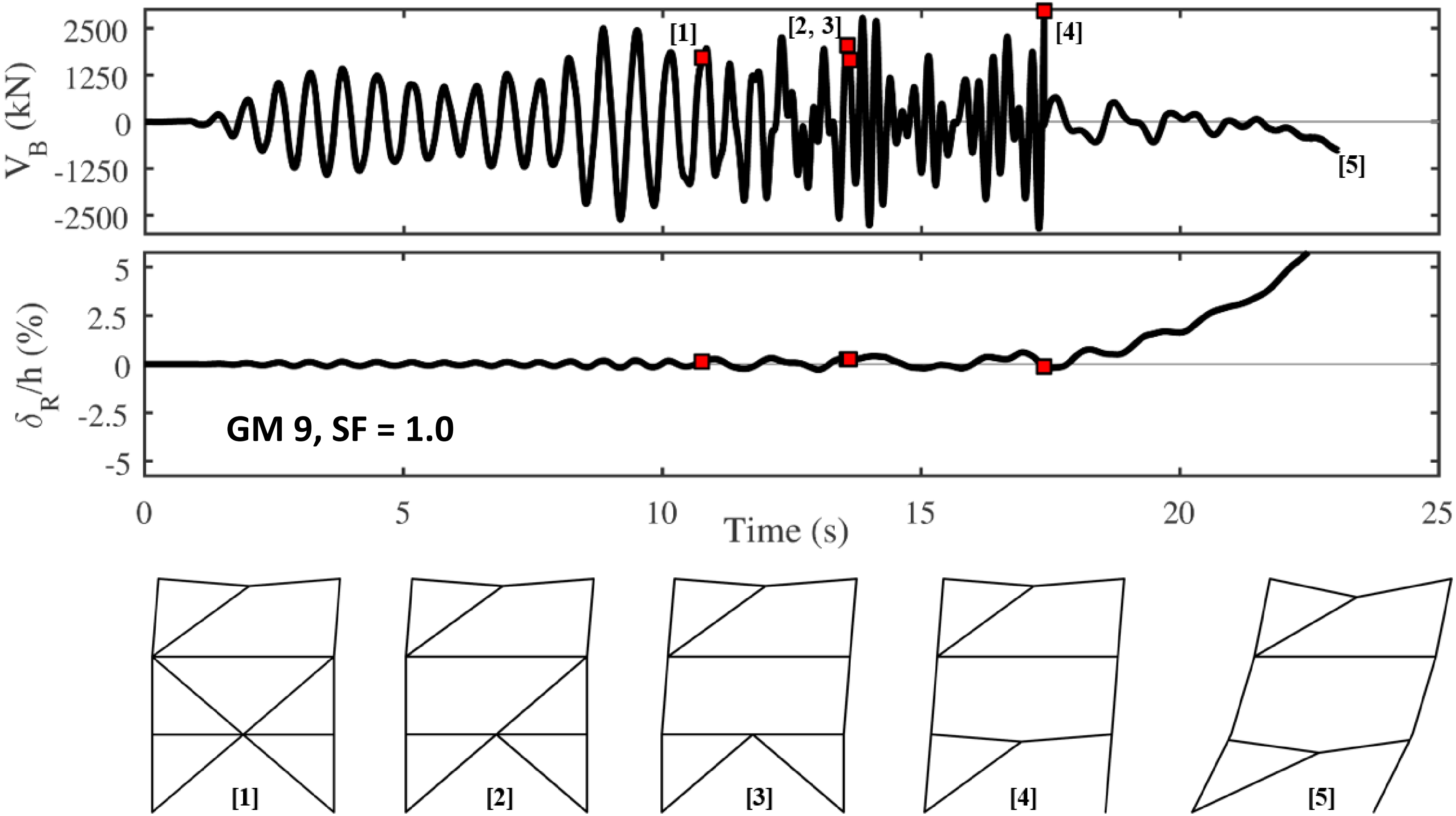


New *R* = 4 CBF Chevron (Single-Record Response)

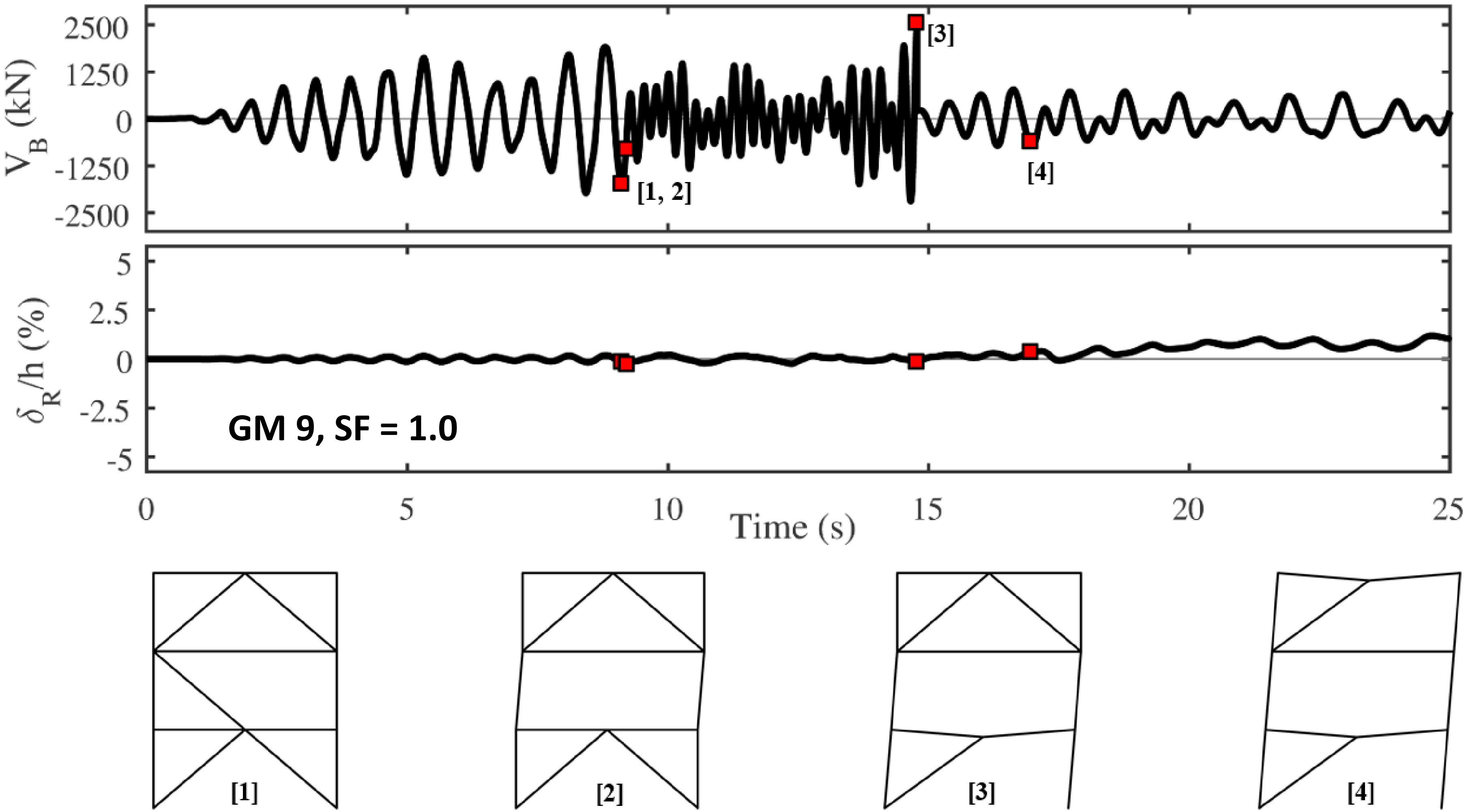




Current *R* = 3.25 OCBF Split-X (Single-Record Response)



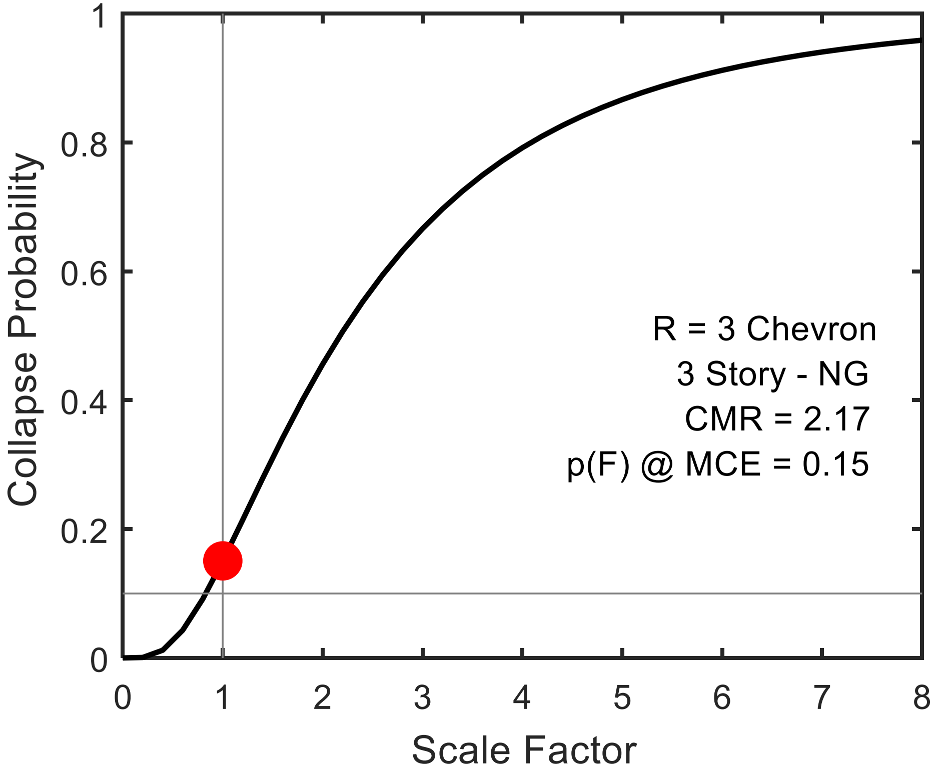
New *R* = 4 CBF Split-X
(Single-Record Response)



Current *R* = 3 CBF (IDA, FEMA P-695)

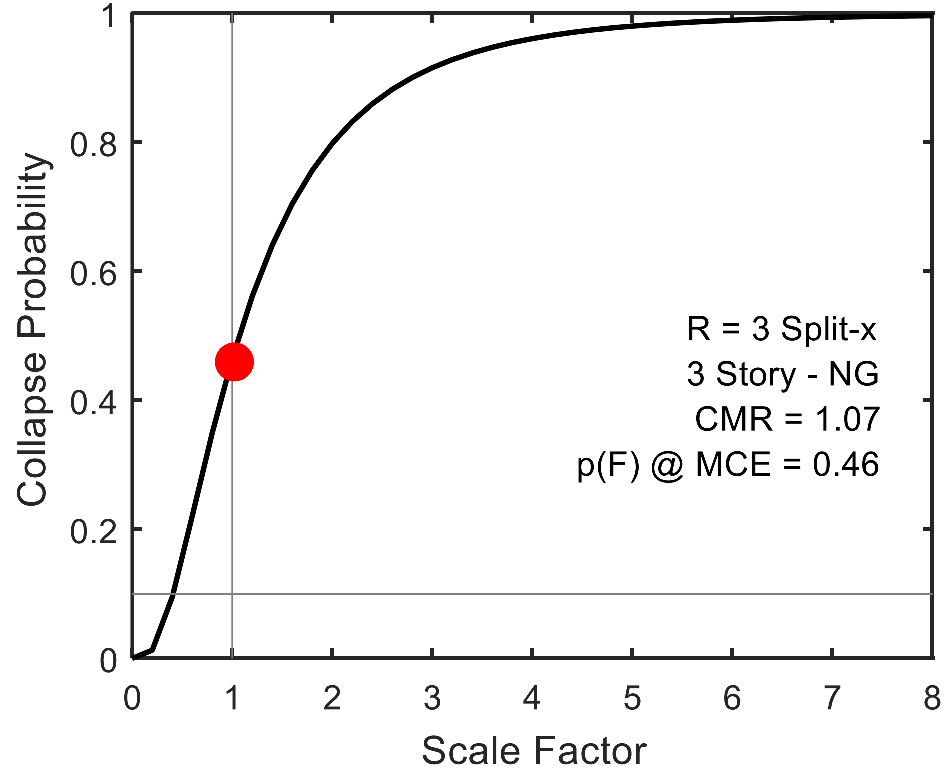
Chevron

Collapses at MCE = 1



Split-X

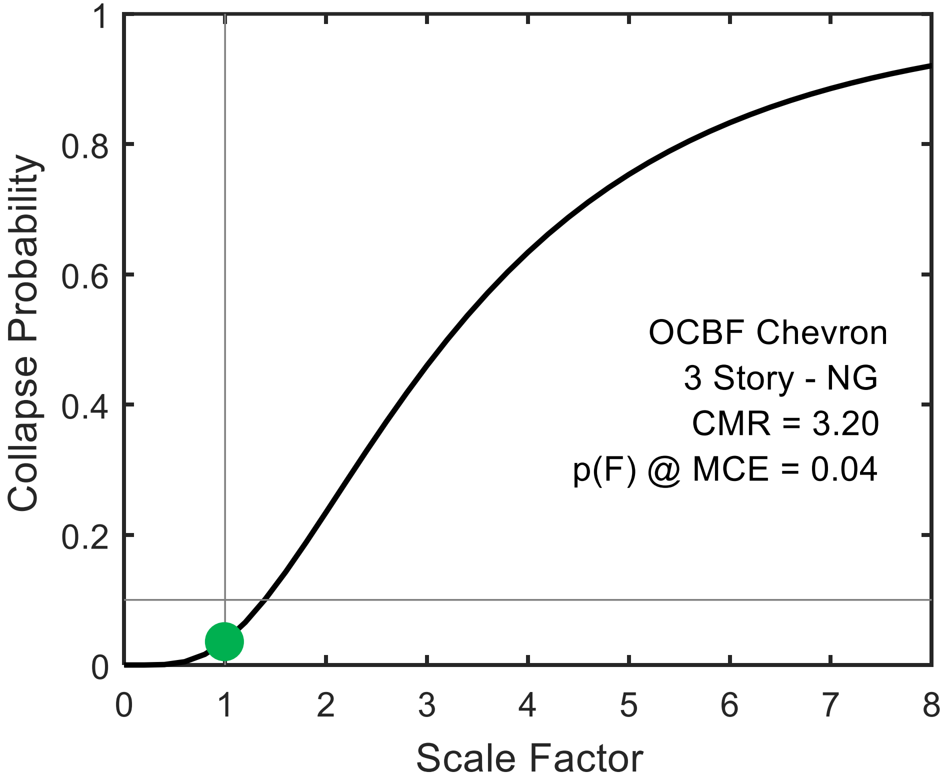
Collapses at MCE = 7



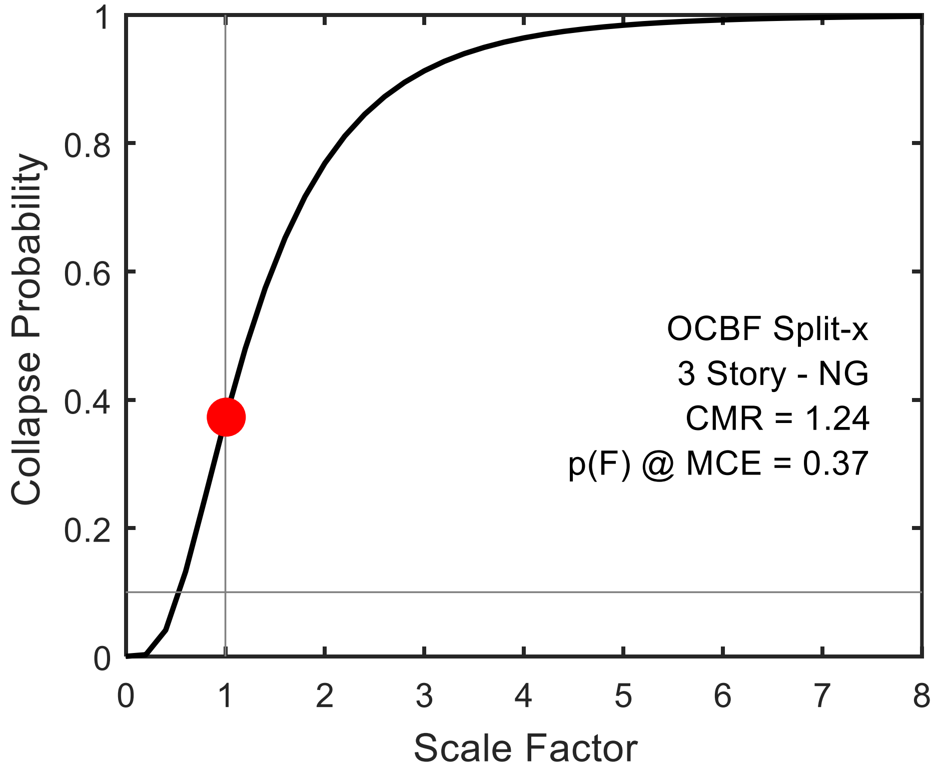
Sizemore, Fahnestock and Hines (201), *Journal of Structural Engineering*, 145 (4), 04019016

Current *R* = 3.25 OCBF (IDA, FEMA P-695)

Chevron
Collapses at MCE = 1



Split-X
Collapses at MCE = 5



Sizemore, Fahnestock and Hines (201), *Journal of Structural Engineering*, 145 (4), 04019016

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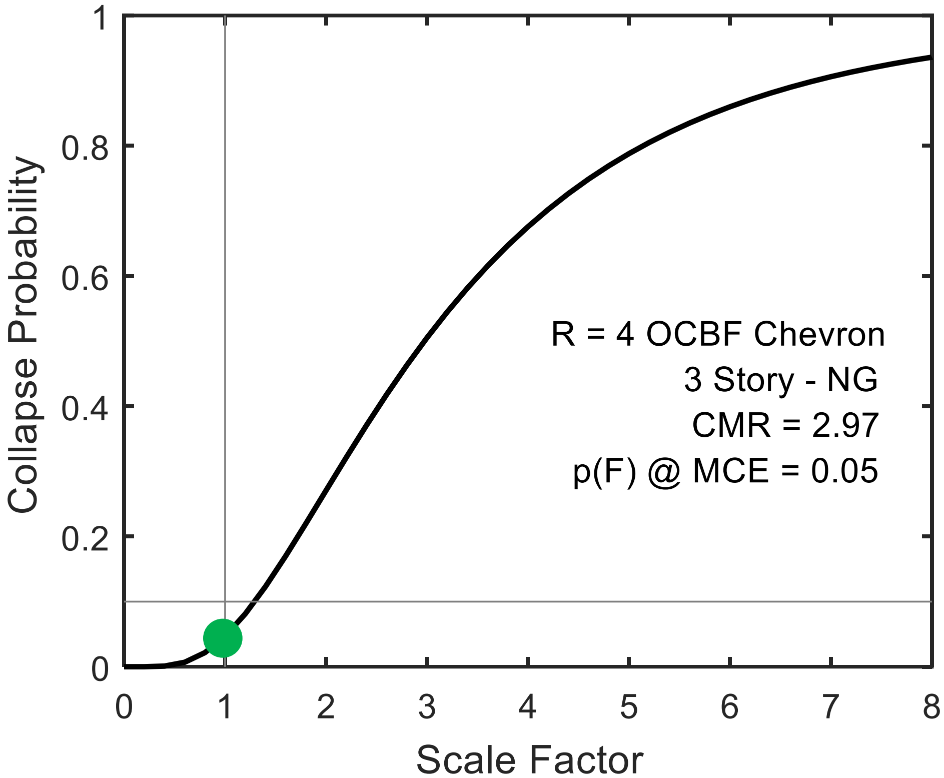
Current *R* = 4 CBF (IDA, FEMA P-695)

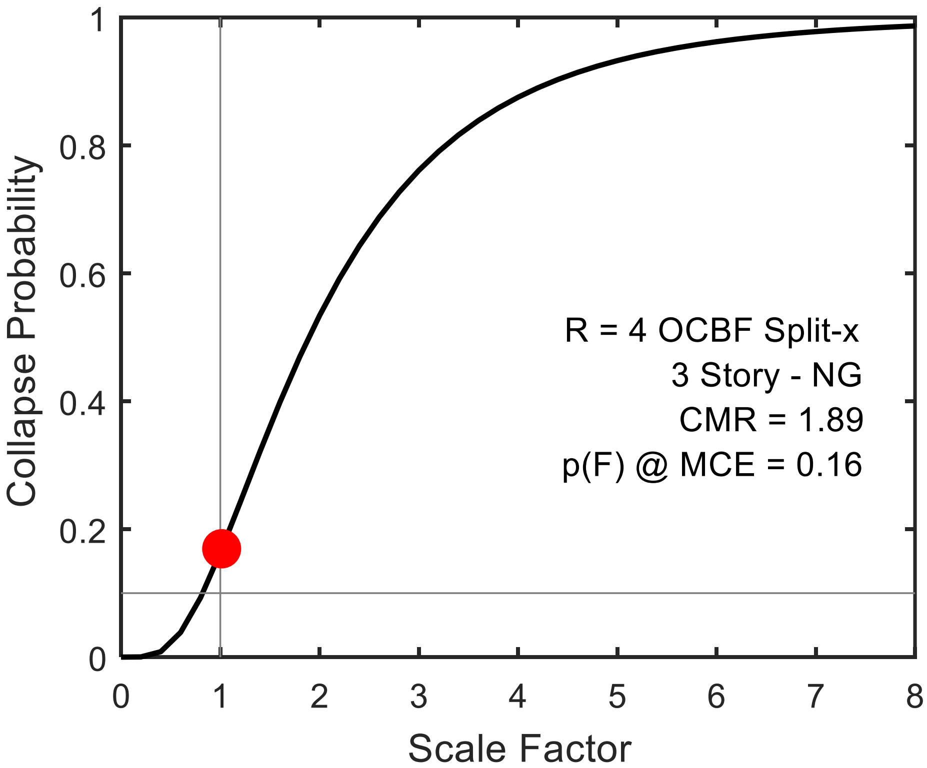
Chevron

Collapses at MCE = 0



Split-X

Collapses at MCE = 0



Sizemore, Fahnestock and Hines (201), *Journal of Structural Engineering*, 145 (4), 04019016

Building Reserve Capacity Summary

- Split-X configuration without ductility can be harmful
- Connection strength can be helpful
- Strong chevron-configuration beams can be harmful
- In design, must anticipate post-elastic system behavior
- Steel frames naturally possess reserve capacity mechanisms
- Fundamental design philosophy: primary + reserve system

East Coast Seismic Resilience Research – Project 2

ICT/IDOT: Seismic Quasi-Isolation Bridge Design using Common Bearing Components

Funding: ICT/IDOT (R27-70, R27-133)

Full-Scale Testing: Newmark Laboratory

Numerical Simulations: XSEDE

Illinois Center for Transportation

Illinois Department of Transportation

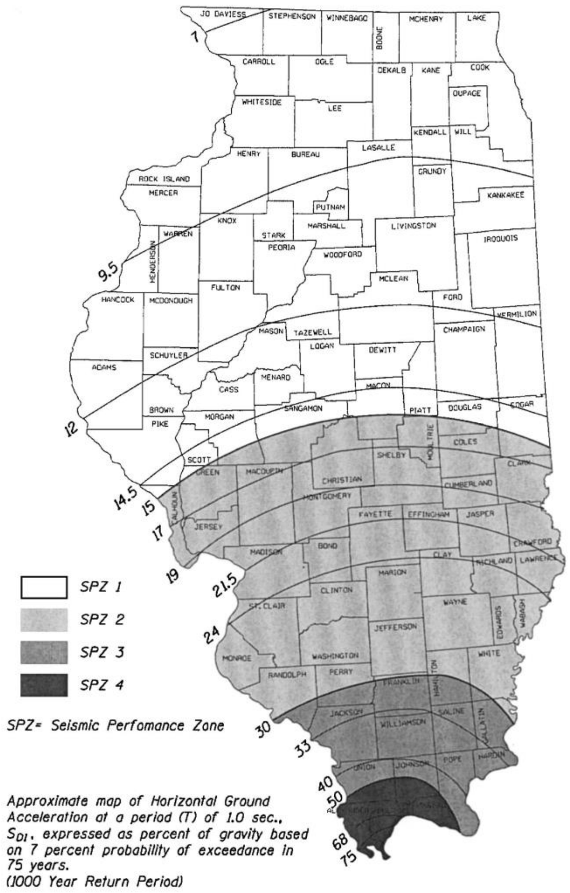
ICT/IDOT: Seismic Quasi-Isolation Bridge Design using Common Bearing Components

- James LaFave (PI)
- Larry Fahnestock (Co-PI)
- Doug Foutch (Co-PI)
- Jerry Hajjar (Co-PI)
- Josh Steelman (RA, former PhD student)
- Jie Luo (RA, former PhD student)
- Derek Kozak (RA, former PhD student)
- Evgueni Filipov (RA, former MS student)
- Jessica Revell (RA, former MS student)

Quasi-isolation

- An approach that uses typical bridge bearings as fuses to limit the forces transmitted from the superstructure to the substructure during a seismic event, while accommodating the displacement demands
- Differs from classical seismic isolation in that it:
  - Does not require a complex design process
  - Does not require special components

Illinois Seismicity



(Tobias et al. 2008)

- Wide range of seismic hazard in the state of Illinois (lower probability events may be quite severe, even though higher probability events are not)
- IDOT Earthquake Resisting System (ERS):
  - Recently developed and adopted design approach tailored to typical Illinois bridge types

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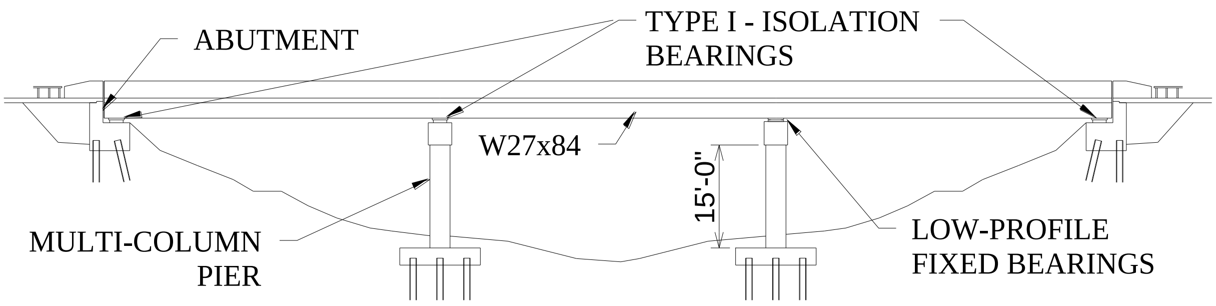
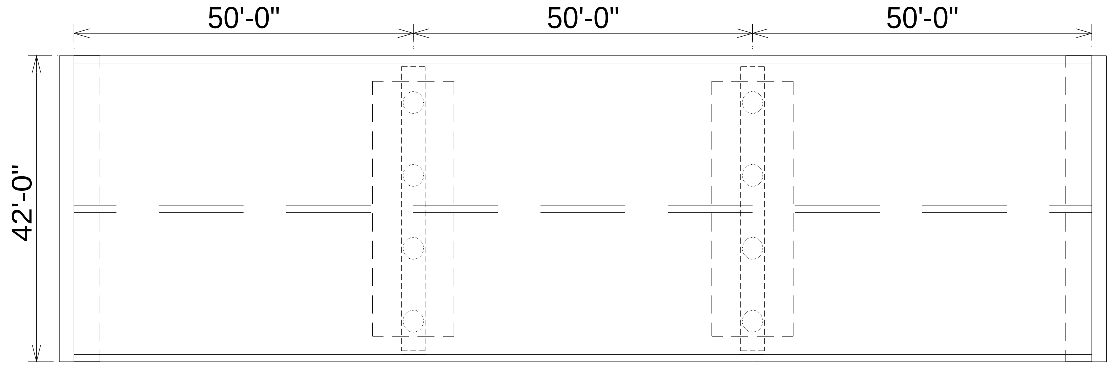
Typical Illinois Highway Overpass Bridge



Sample Prototype Bridge Elevation



Sample Prototype Bridge Plan
(w/ Expansion Joints @ Each End)

IDOT Earthquake Resisting System

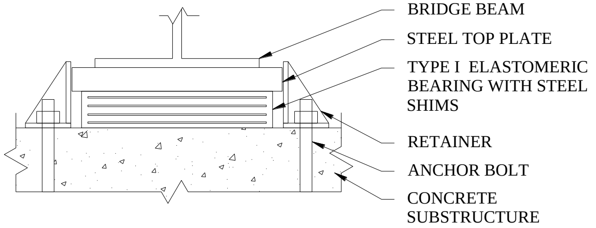
- Primary objective: Prevent span loss (allow access for emergency vehicles)
- Three design / performance targets:
  - Level 1 – Connections between the superstructure and substructures are designed to provide a nominal fuse capacity
  - Level 2 – Sufficient seat widths at substructures are provided to allow for “unrestrained” superstructure motion
  - Level 3 – Some plastic deformation in substructure and foundation elements may be allowed

Research Overview

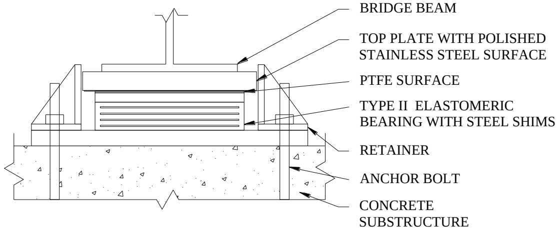
- Objective: To calibrate and refine the IDOT ERS
- Tasks:
  - Conduct full-scale tests of typical bridge bearings
  - Develop bridge numerical models and conduct extensive parametric studies
  - Develop recommendations for seismic design of bridges using the quasi-isolation philosophy

Experimental Program

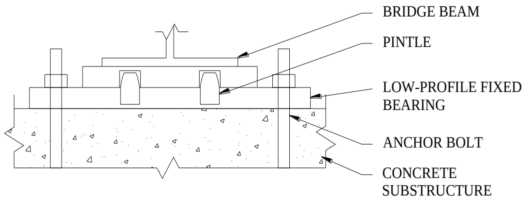
- Quantify fuse behavior of typical IDOT bridge bearing systems:
  - Type I bearings: bearings with an elastomer to concrete sliding surface
  - Type II bearings: elastomeric bearings with PTFE sliding surface
  - L-shaped retainers: designed to limit transverse service load deflections
  - Low-profile “fixed” bearings with steel pintles and anchor bolts



Elastomeric bearing (w/ steel shims) on concrete (Type I)

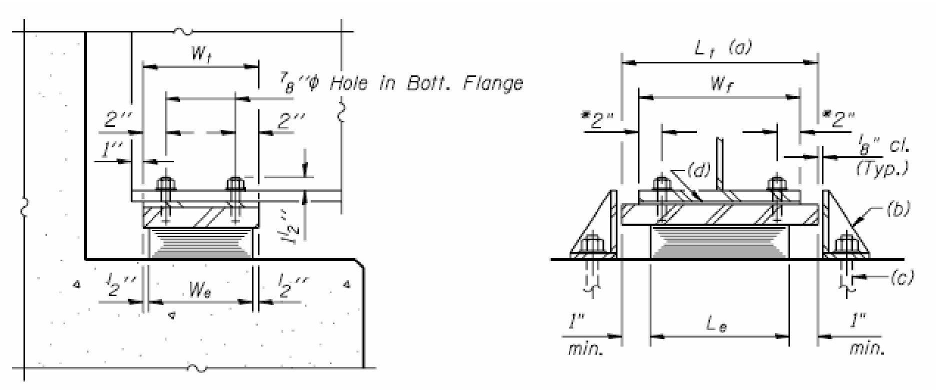


Elastomeric bearing with PTFE sliding surface (Type II)

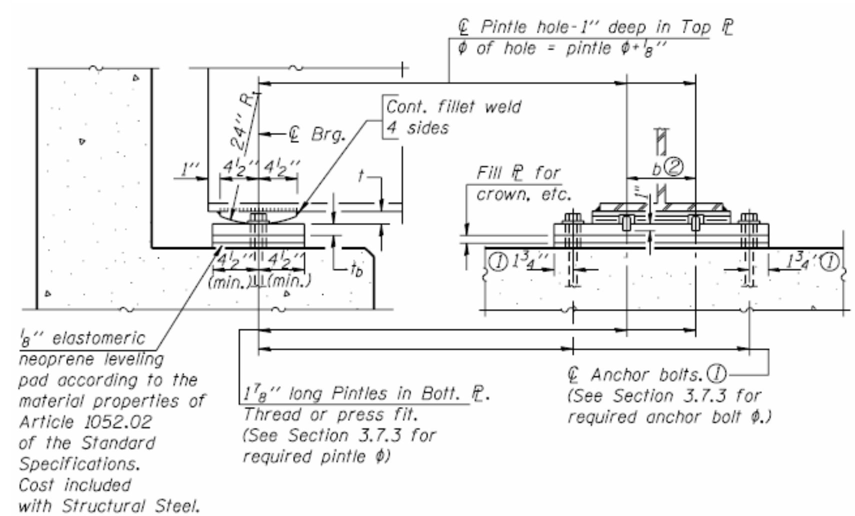


Low-profile fixed bearing

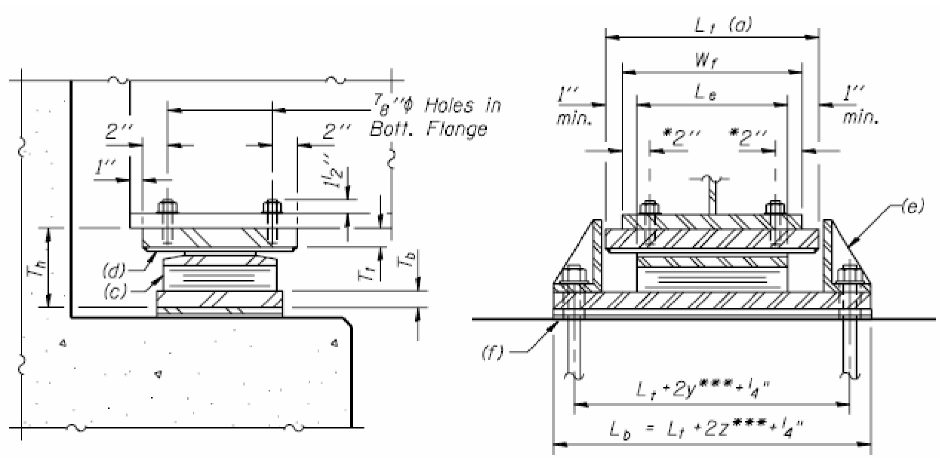
Full-Scale Testing of Bridge Bearings



TYPE I
ELASTOMERIC
EXPANSION BEARING

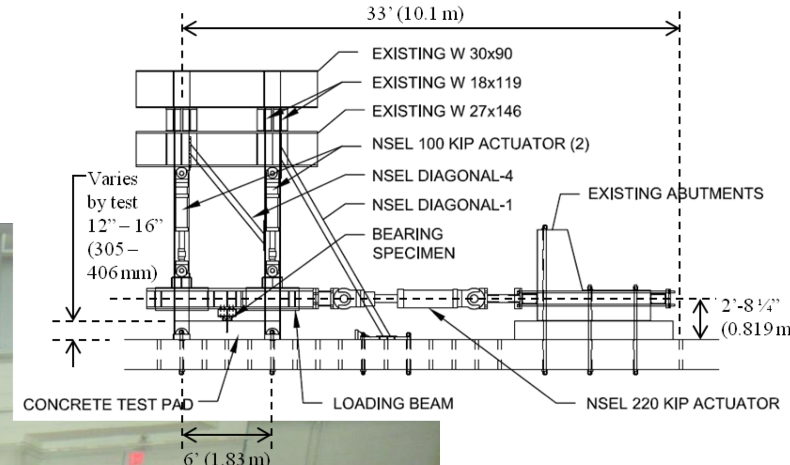


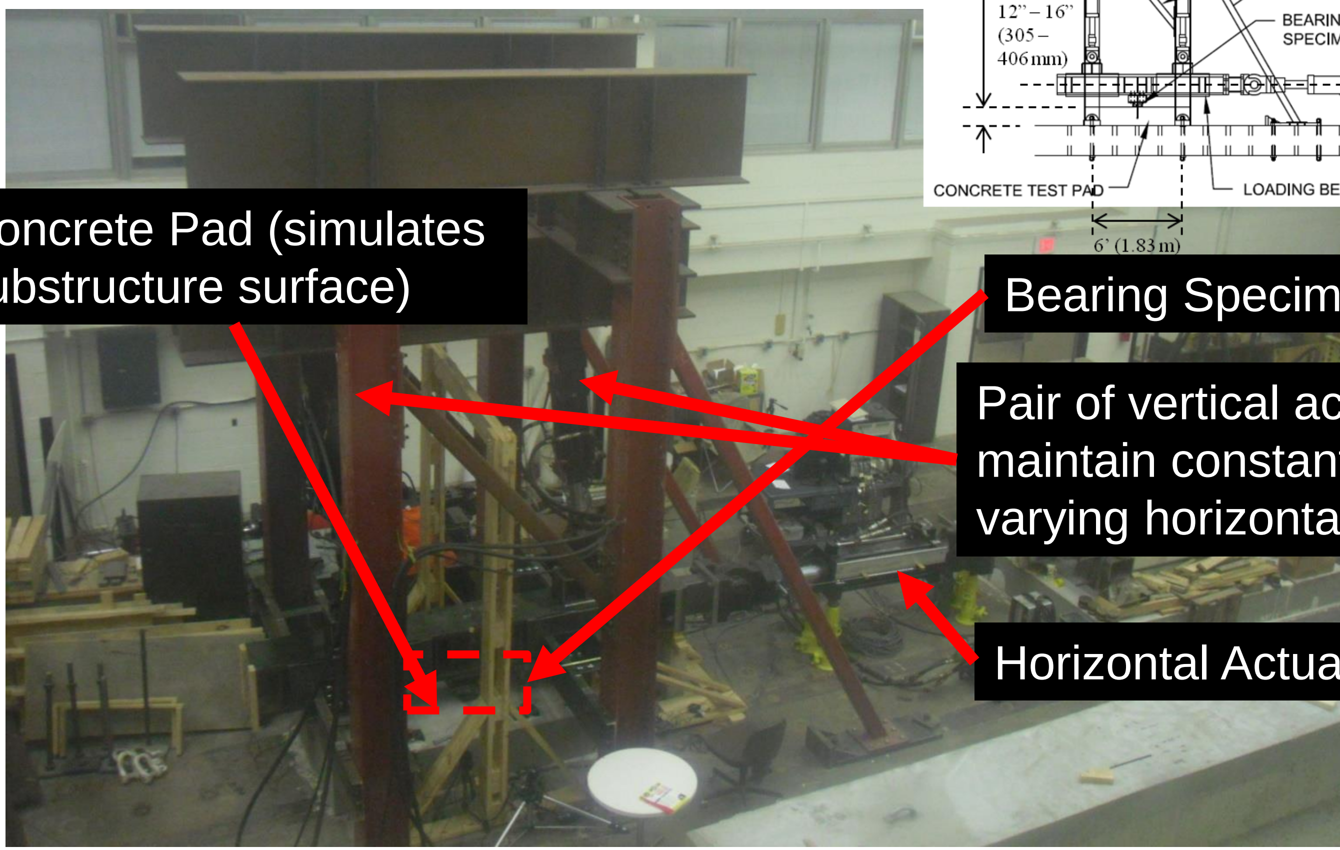
LOW PROFILE
FIXED BEARING



TYPE II
ELASTOMERIC
EXPANSION BEARING

Experimental Set-Up





Concrete Pad (simulates substructure surface)

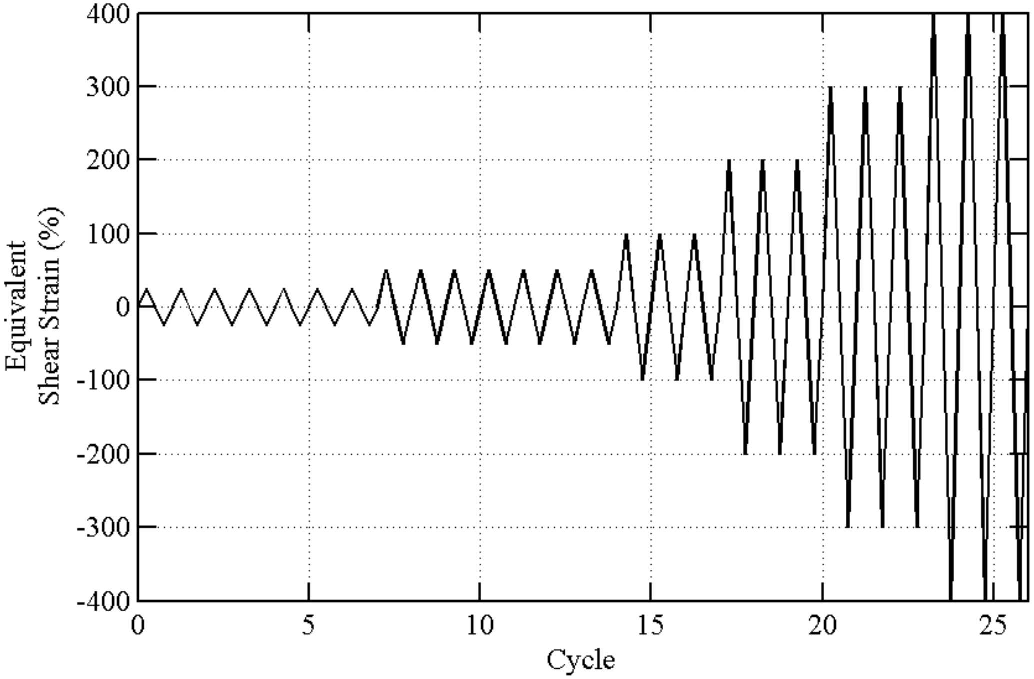
Bearing Specimen

Pair of vertical actuators, to maintain constant vertical load with varying horizontal bearing position

Horizontal Actuator (stroke = +/- 15")

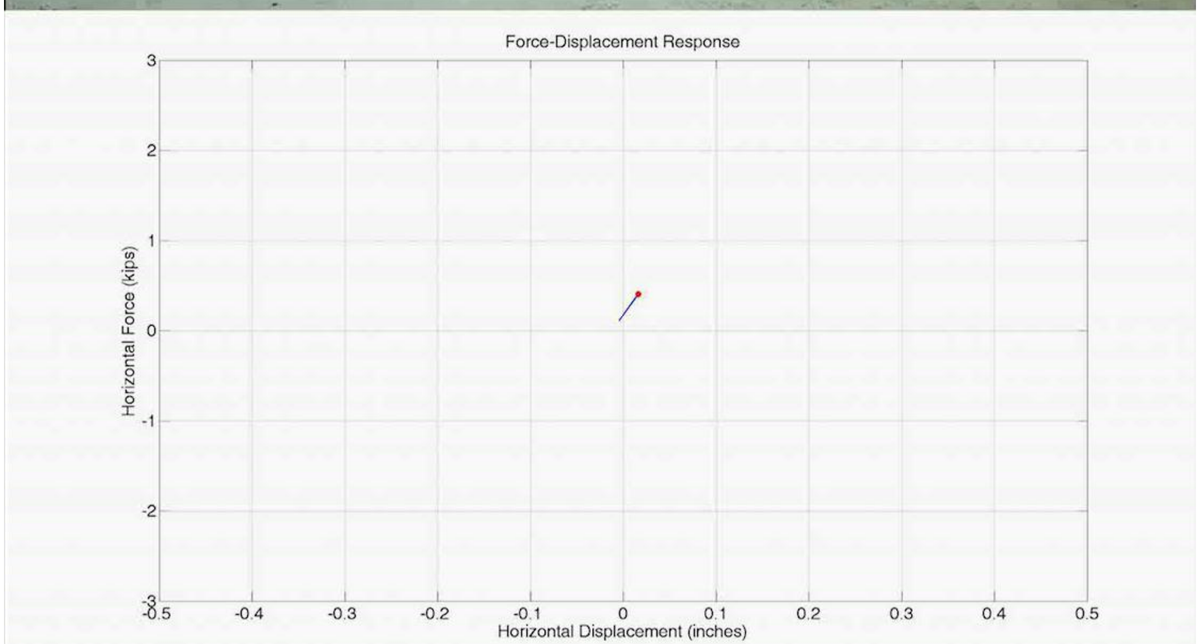
Type I – Longitudinal Cyclic Tests

- Type I displacement-based protocol for quasi-static (QS) cyclic tests, which were run in addition to monotonic and increased strain rate (ISR) tests

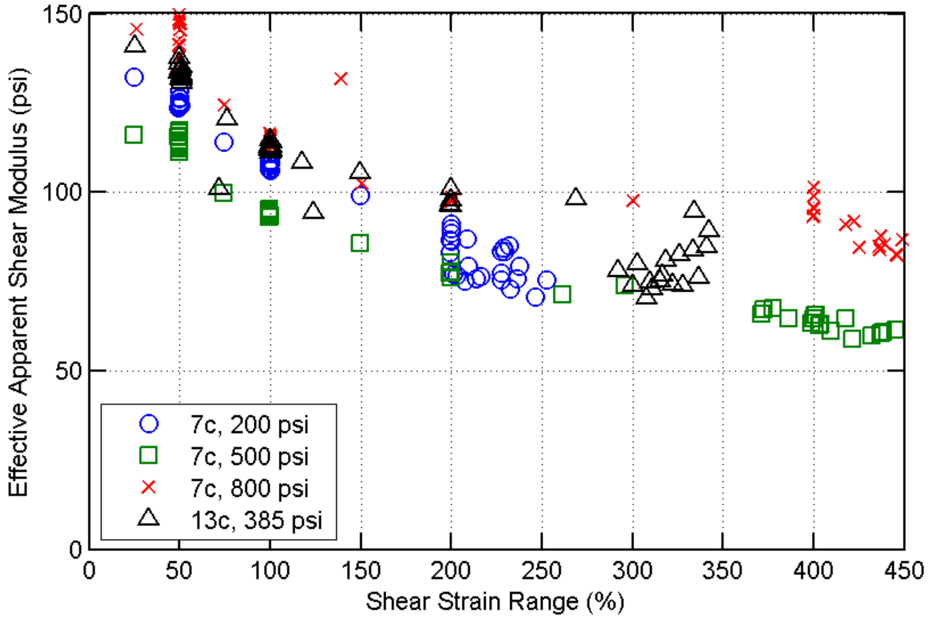


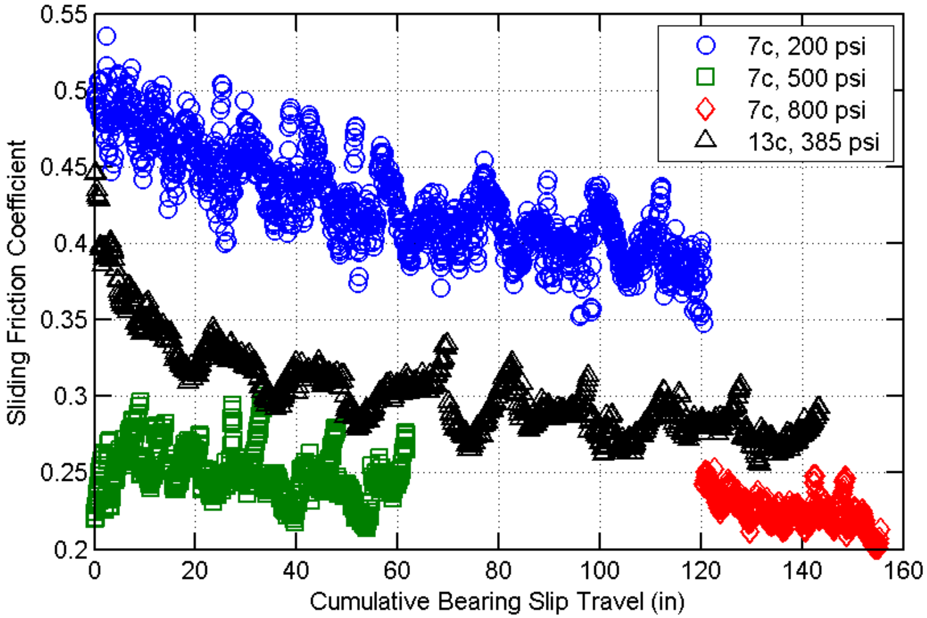
Type I Longitudinal Cyclic Tests

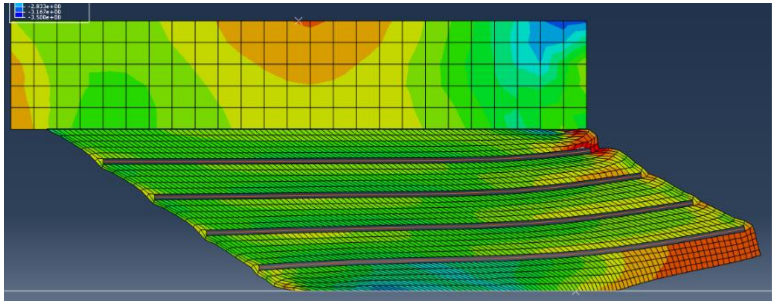
7 in. x 12 in. elastomer; h_{rt} = 1.875 in.; σ = 200 psi psi



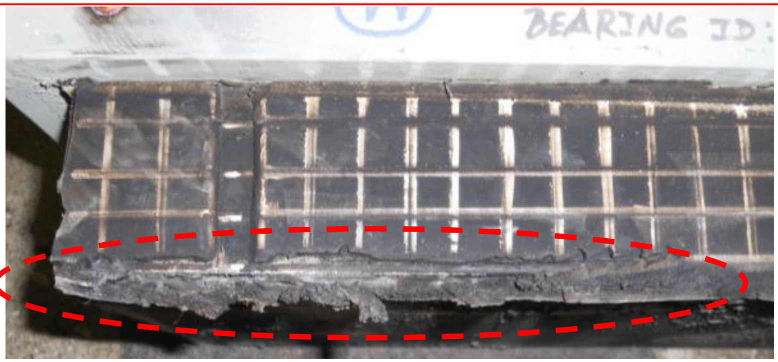
Type I Sliding Response Characteristics



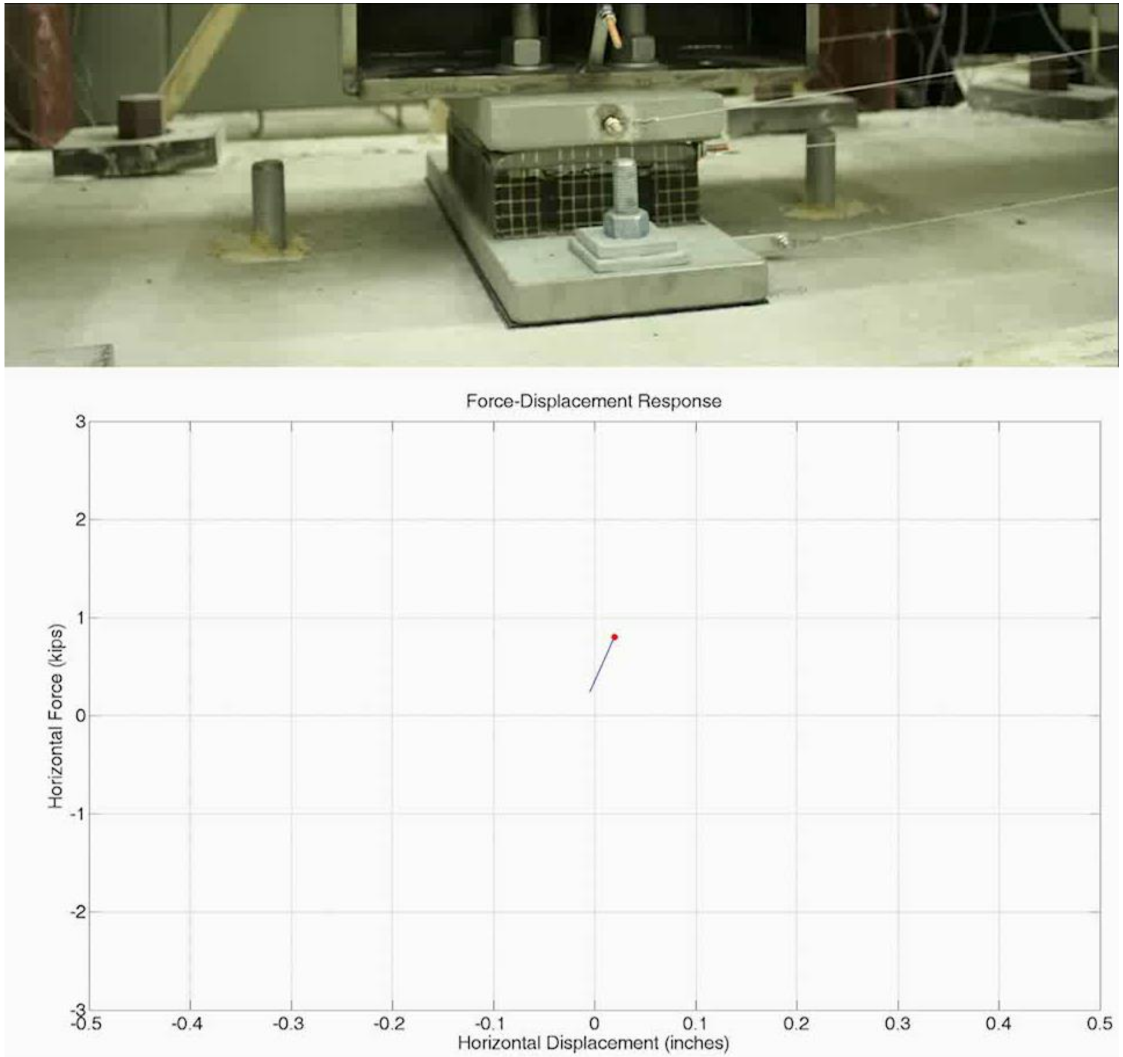




$$G_{eff} = \frac{K_{h,eff}\, h_{rt}}{A}$$

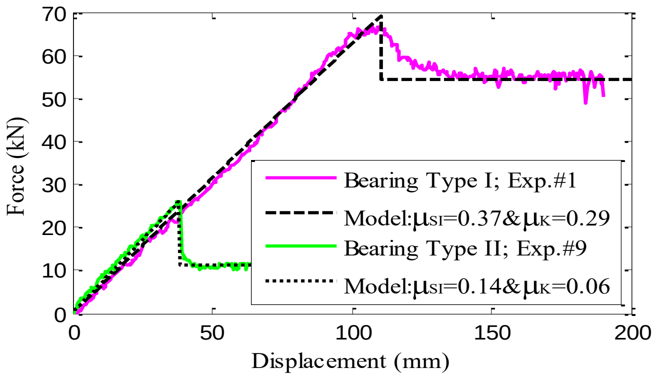


Type II – (QS) Longitudinal Sliding

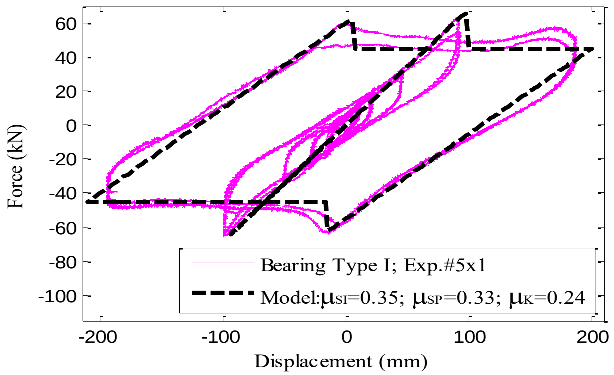


Type I Bearing Sliding Model

- Difference in static vs. kinetic coefficient of friction
- Force-displacement behavior coupled in orthogonal shear directions



Monotonic



Cyclic

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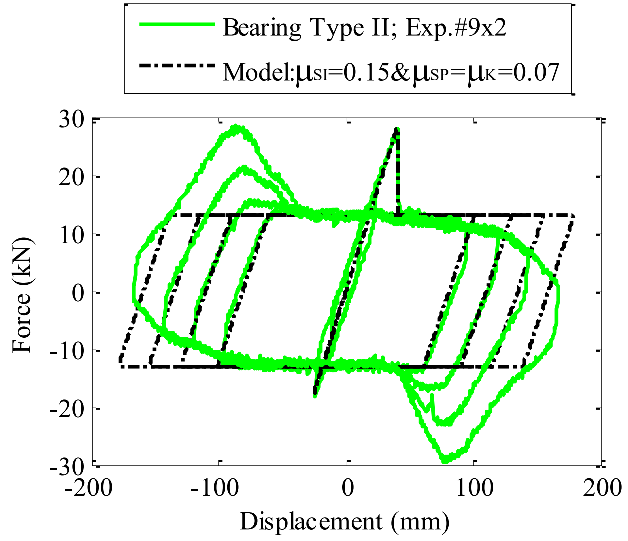
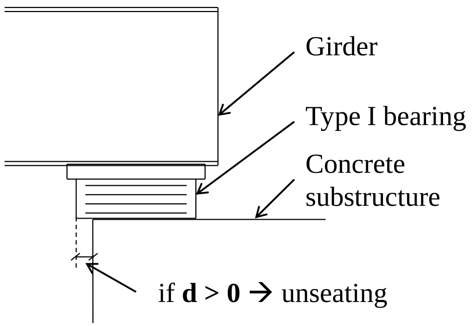
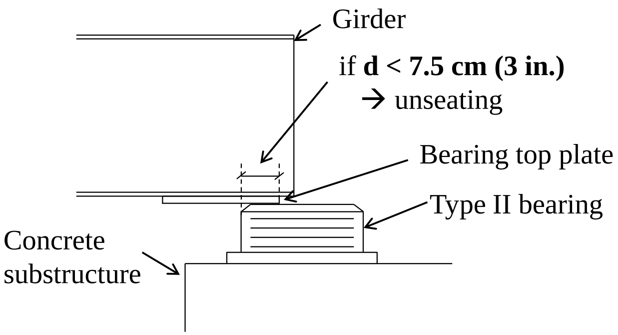
Type II Bearing Sliding Model

- Friction characterized based on experimental data
- Unstable hysteresis at large displacements
- Unseating is a critical limit state; it would likely lead to damage and possibly collapse

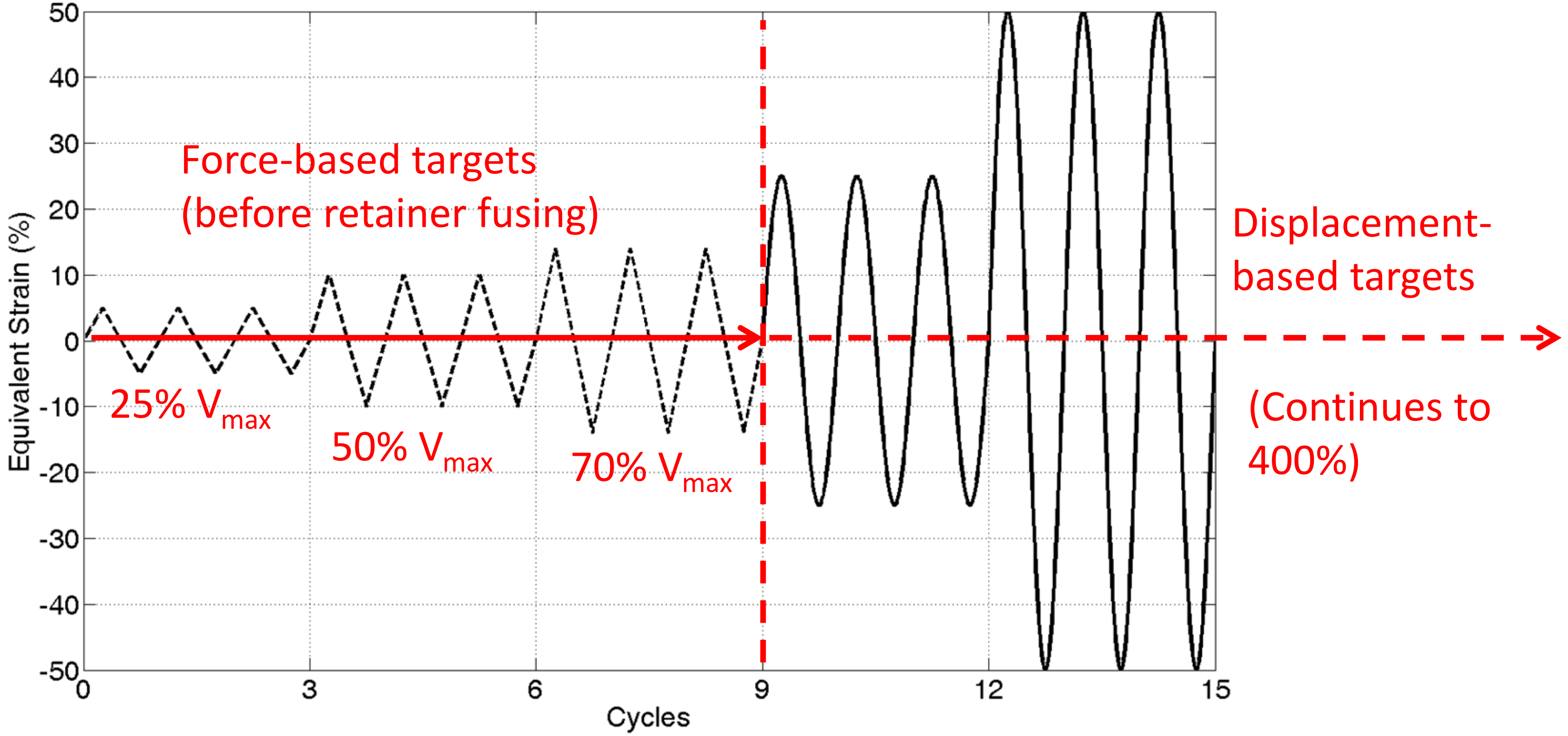






Transverse Cyclic Tests with Retainers

- Augmented Type I protocol with force-based targets



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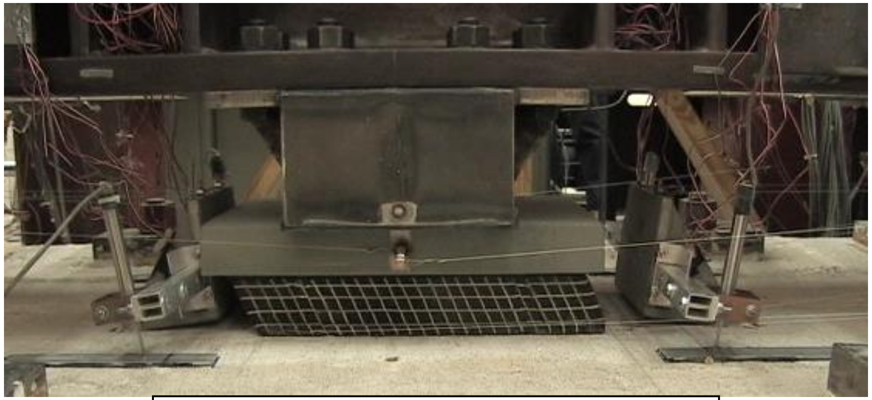
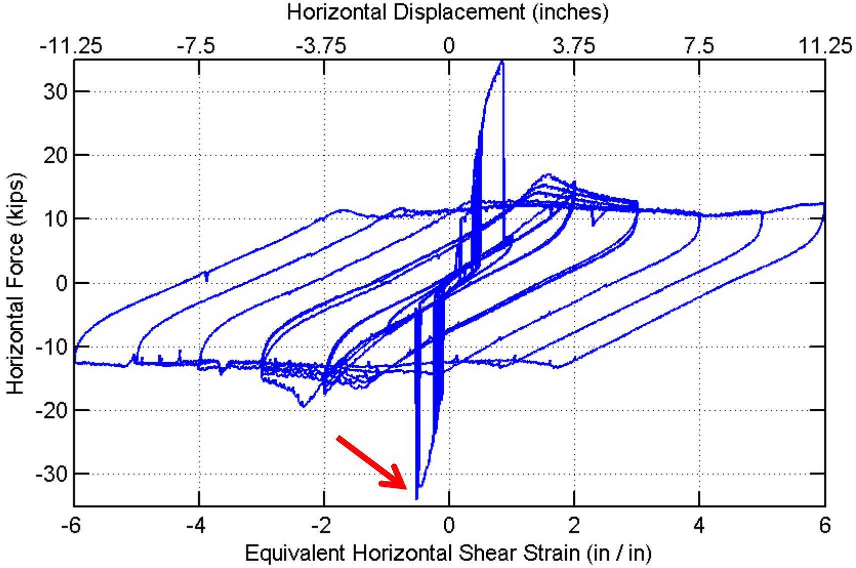
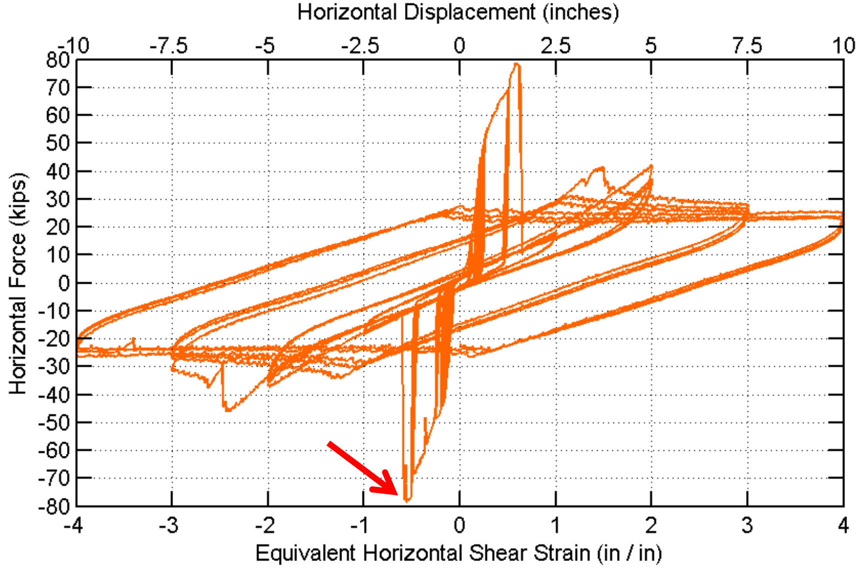
Type I Transverse Response w/o Lift-Off



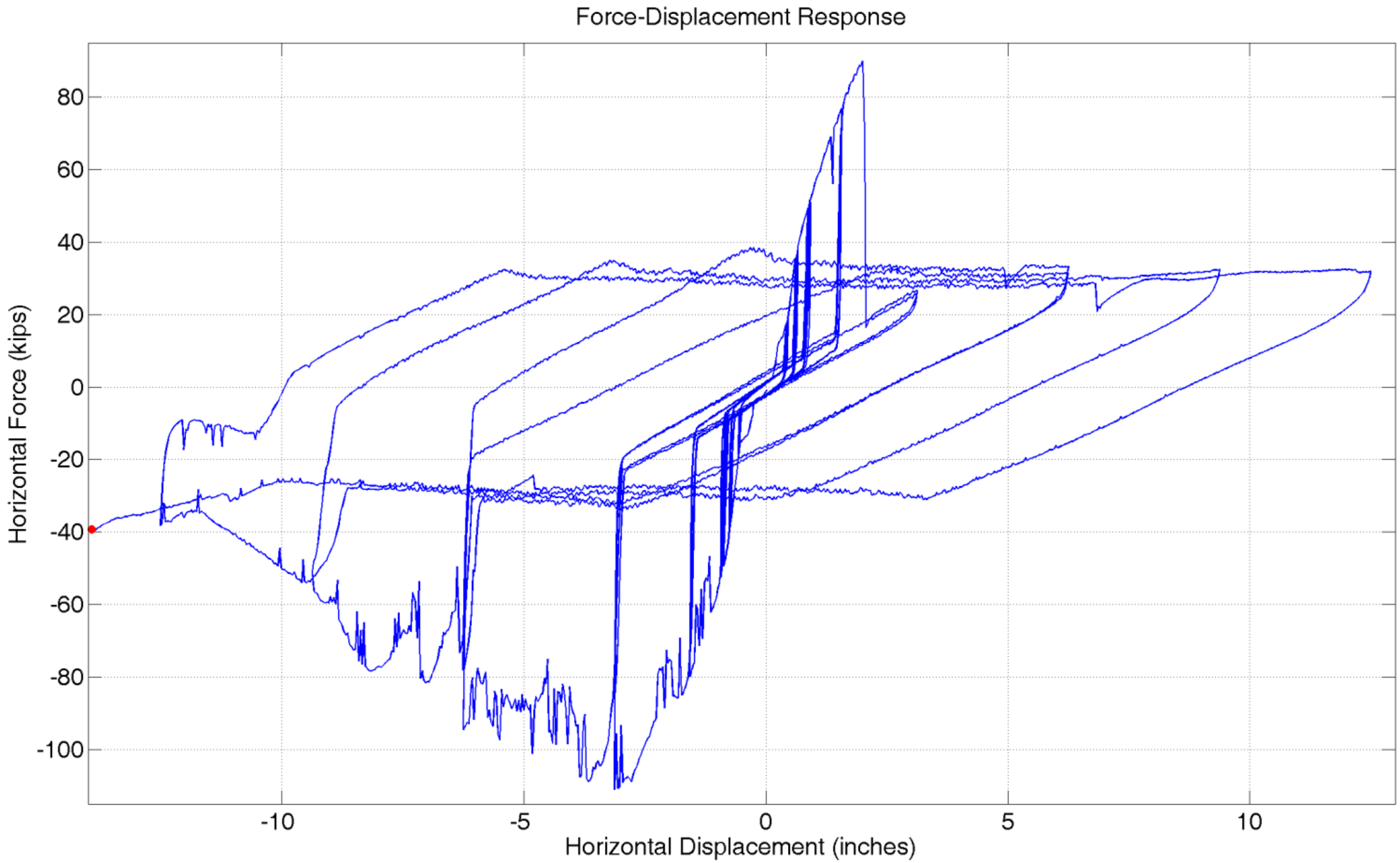
A = 7 in. x 12 in.; h_{rt} = 1-7/8 in.

A = 11 in. x 16 in.; h_{rt} = 2-1/2 in.





Retainer Designs to Minimize Lift-Off



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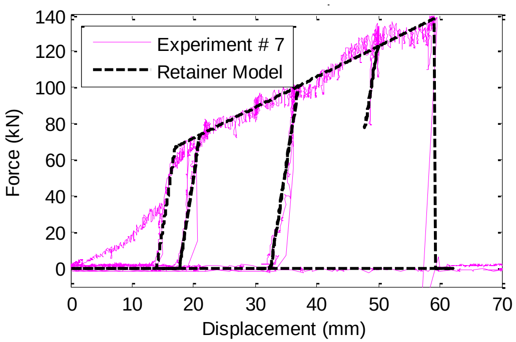
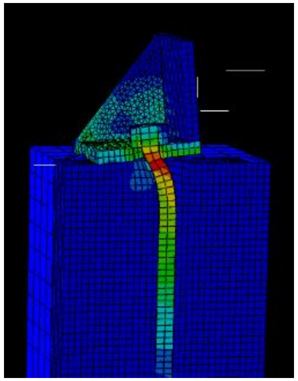
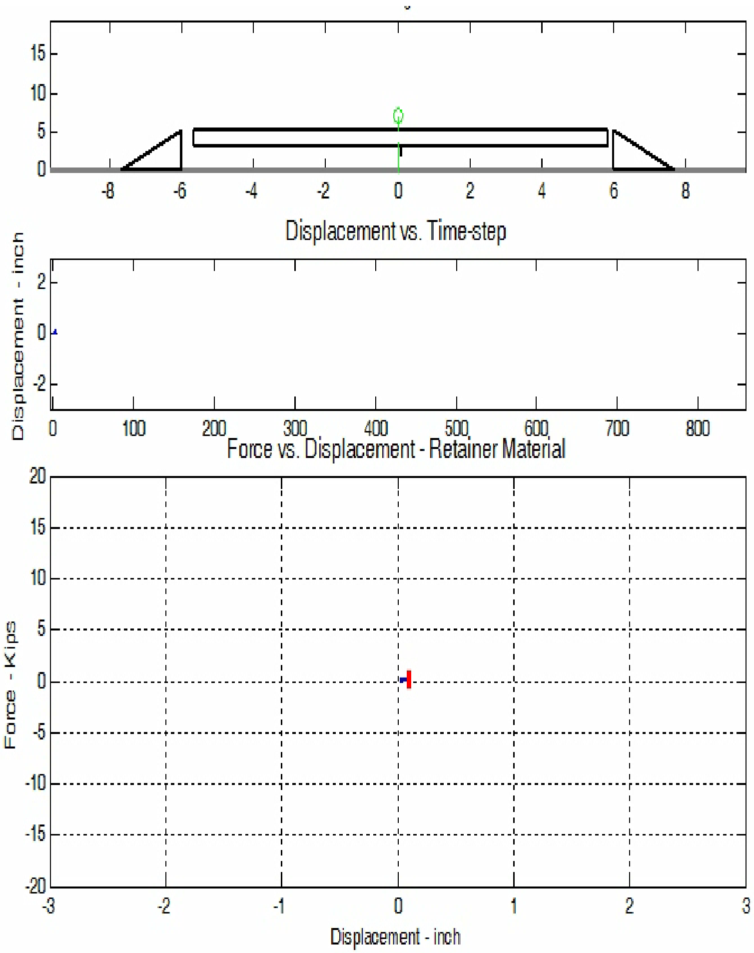
Retainer Model

- Gap with elasto-plastic response until retainer fracture
- Independent behavior of the 2 retainers
- Calibrated based on experiments and finite element modeling



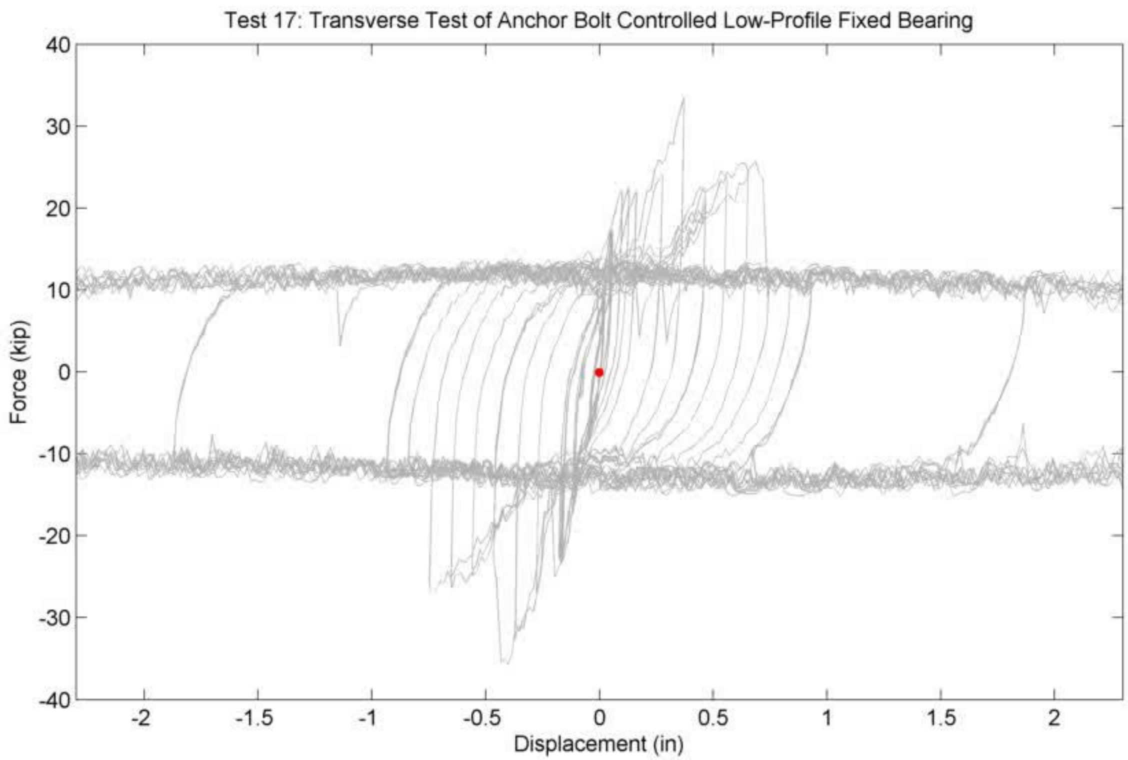
Uni-directional pushover of retainer





Low-Profile Fixed Bearing Model

Bi-directional fixed bearing model with yielding, anchor-bolt fracture, friction, and variable pinching



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Parametric Study of Quasi-Isolated Bridges with Seat-Type Abutments

2 span arrangements:
- 80'-120'-80' (3 spans) (24.4 m - 36.6 m – 24.4 m)
- 145'-160'-160'-145' (4 spans) (42.2 m - 48.8 m - 48.8 m – 42.2 m)

×

2 girder types:
- Steel-plate girders
- Prestressed-precast-concrete girders

×

5 skew angles:
0°, 15°, 30°, 45°, 60°

×

2 pier column heights:
15' (4.57 m) and 40' (12.19 m)

×

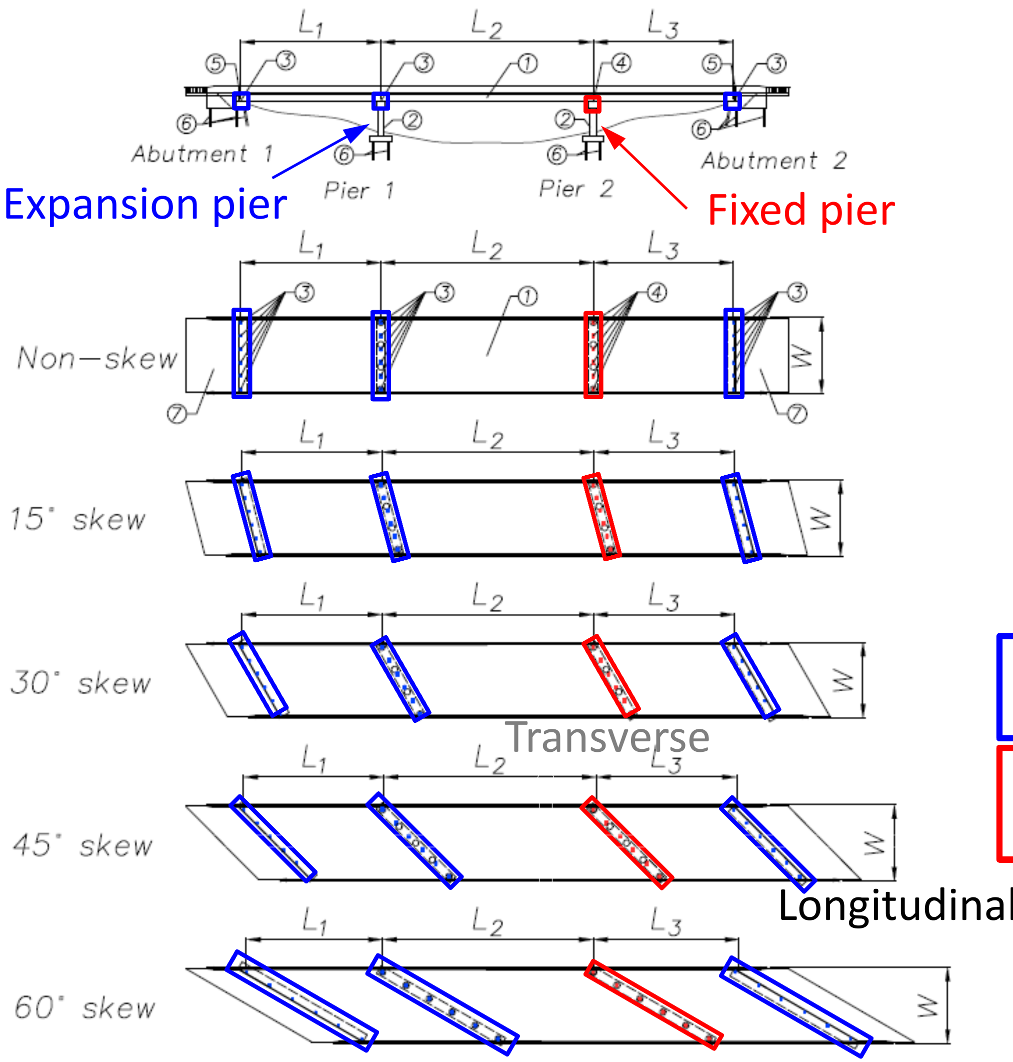
2 foundation soil conditions:
Hard and Soft

=

80 prototype bridge variants in total

4 major types:
- **3**-span **S**teel-plate-girder (3S) bridges
- **4**-span **S**teel-plate-girder (4S) bridges
- **3**-span prestressed-precast-**C**oncrete-girder (3C) bridges
- **4**-span Prestressed-precast-**C**oncrete-girder (4C) bridges

Plans of 3-Span Prototype Bridges



W = 13.16 m (43'−2")
L_1 = 24.38 m (80')
L_2 = 36.58 m (120')
L_3 = 24.38 m (80')

Note: Superstructure consists of six girders. Each girder is supported by one bearing at substructures.

① Steel plate girders / PPC girders with composite concrete deck
② Multi-column reinforced concrete pier
③ Elastomeric expansion bearing (Type I) with side retainers
④ Low-profile steel fixed bearing / #8 (U.S.) steel dowel connection
⑤ Expansion joint
⑥ Steel H pile
⑦ Approach slab

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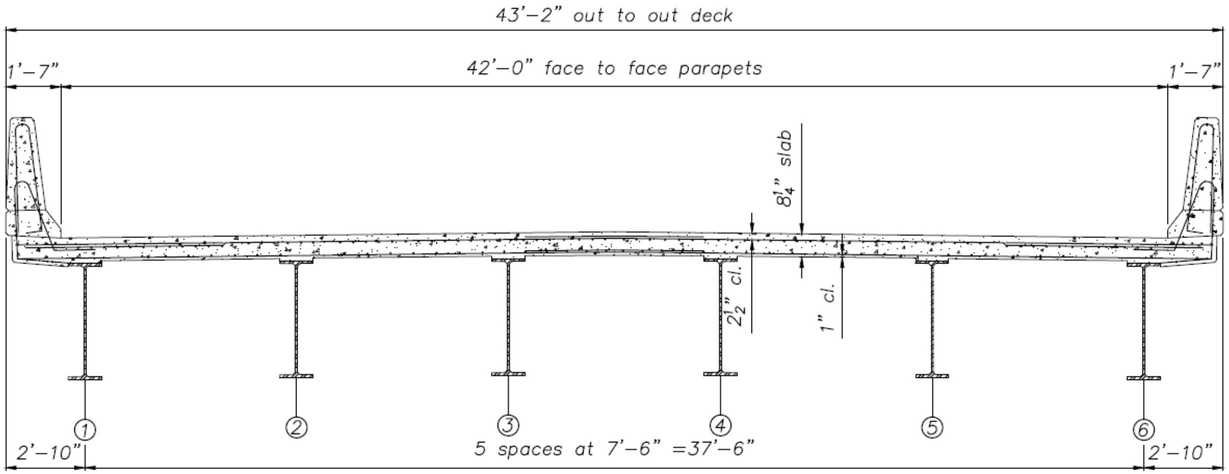
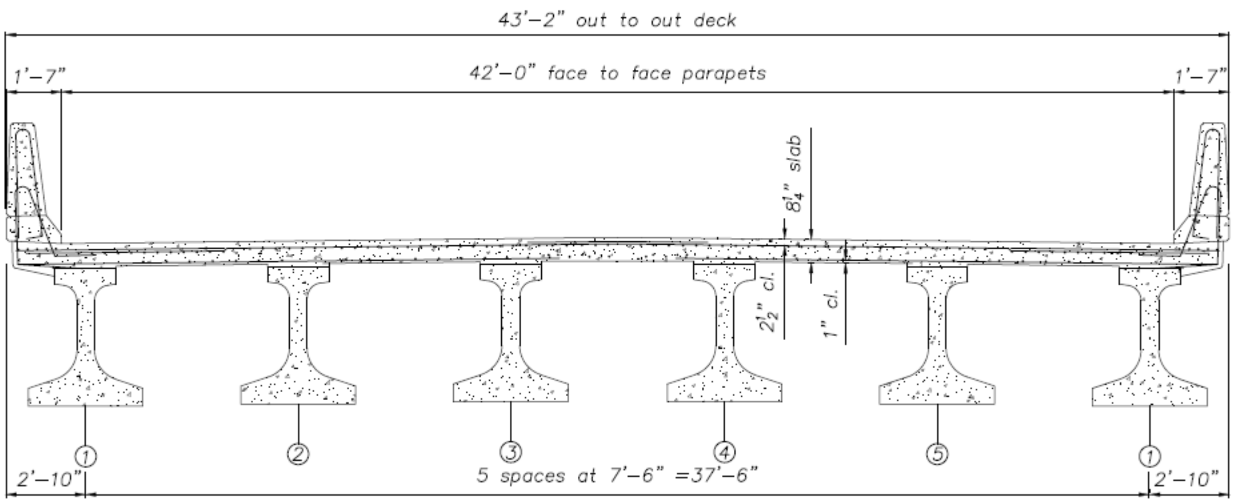
Sections of 3-Span Prototype Bridges





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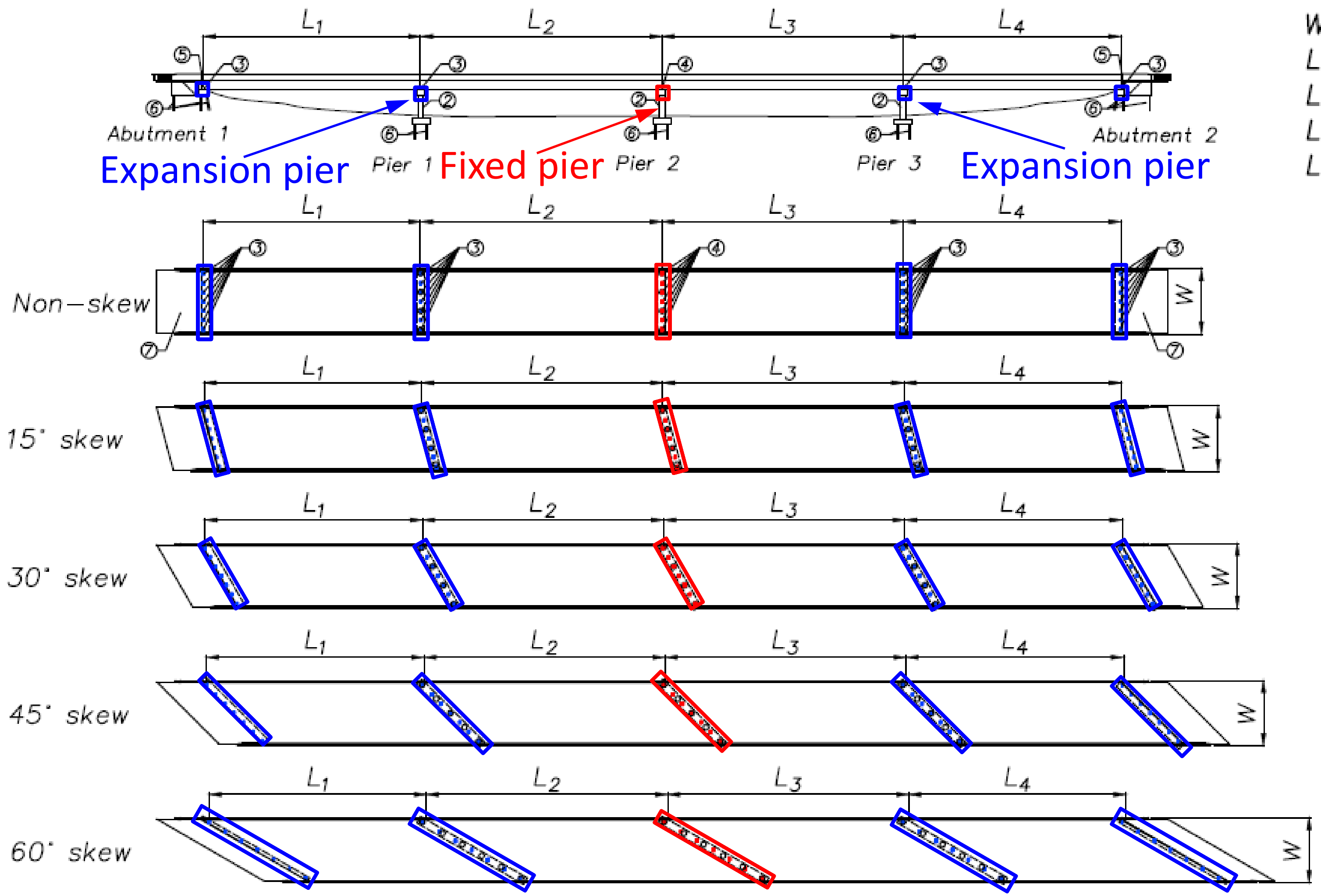
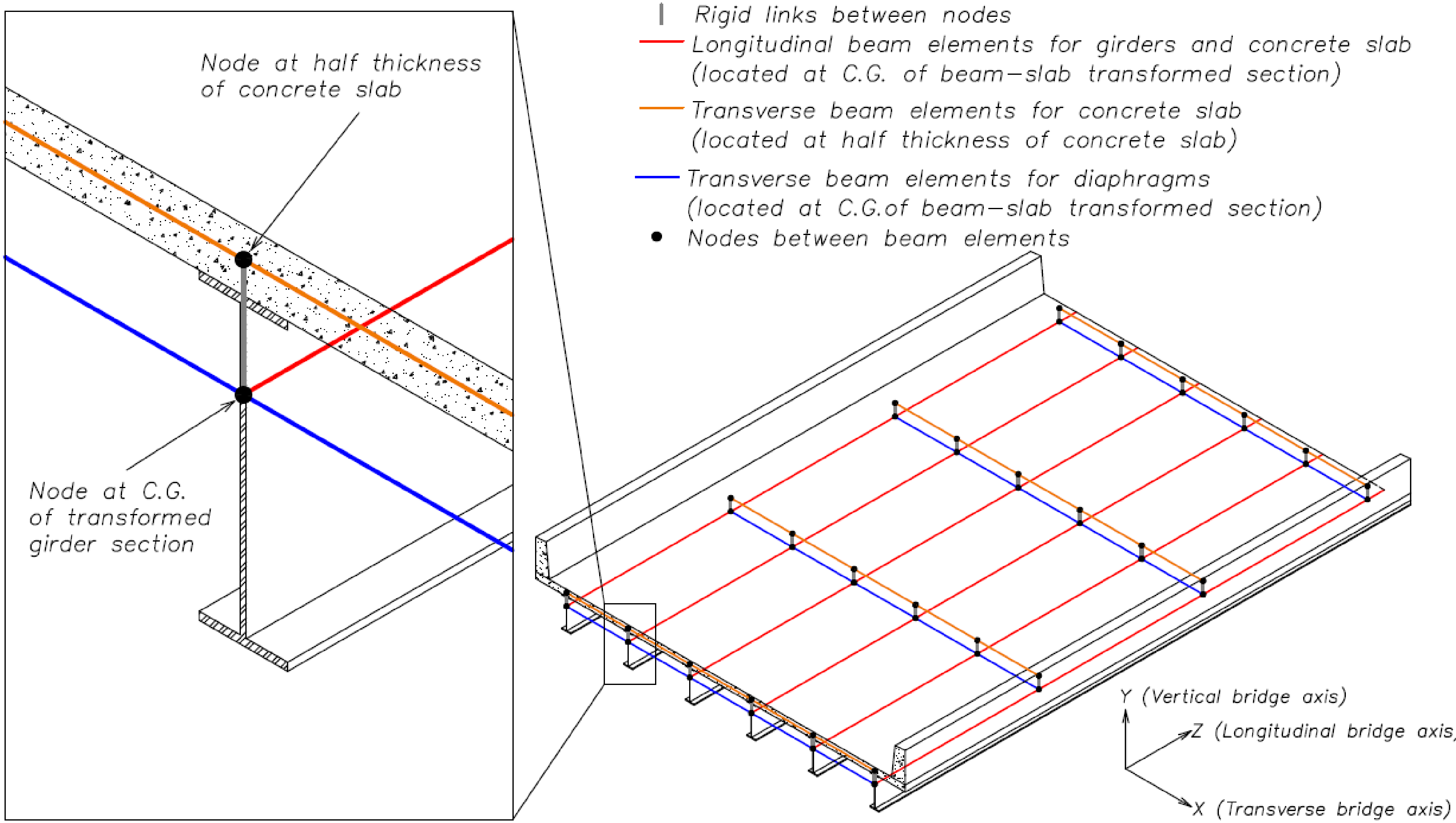
Plans of 4-Span Prototype Bridges

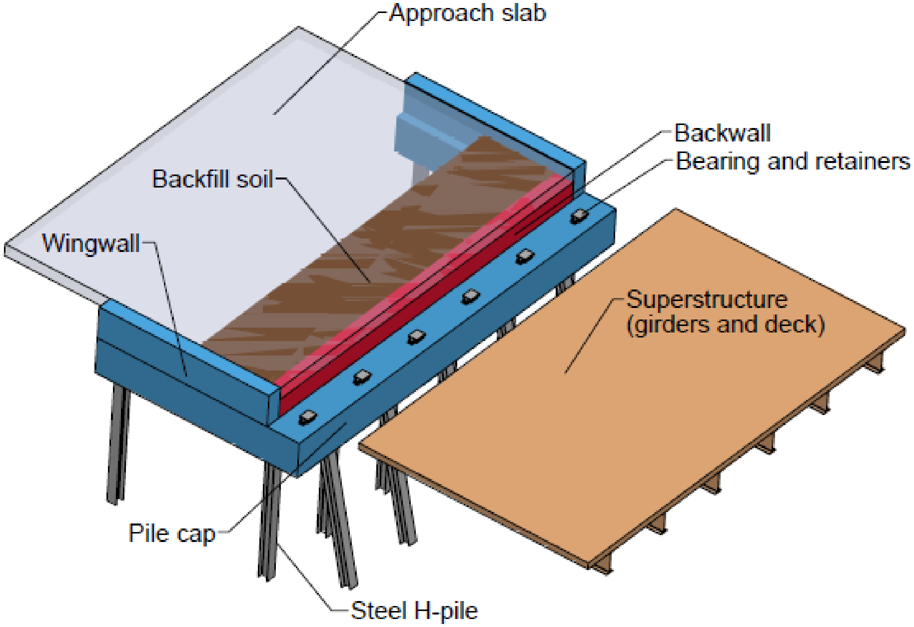


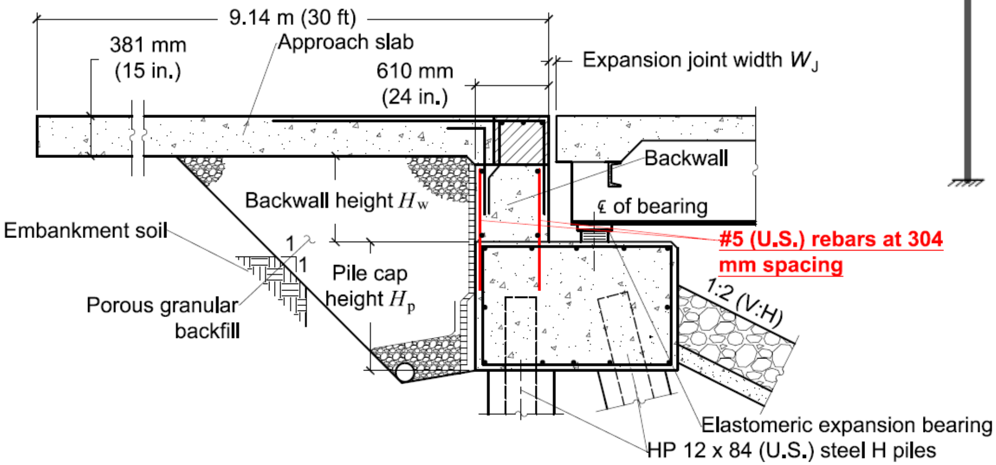
$W = 13.16\ m\ (43'-2")$
$L_1 = 44.20\ m\ (145')$
$L_2 = 48.77\ m\ (160')$
$L_3 = 48.77\ m\ (160')$
$L_4 = 44.20\ m\ (145')$

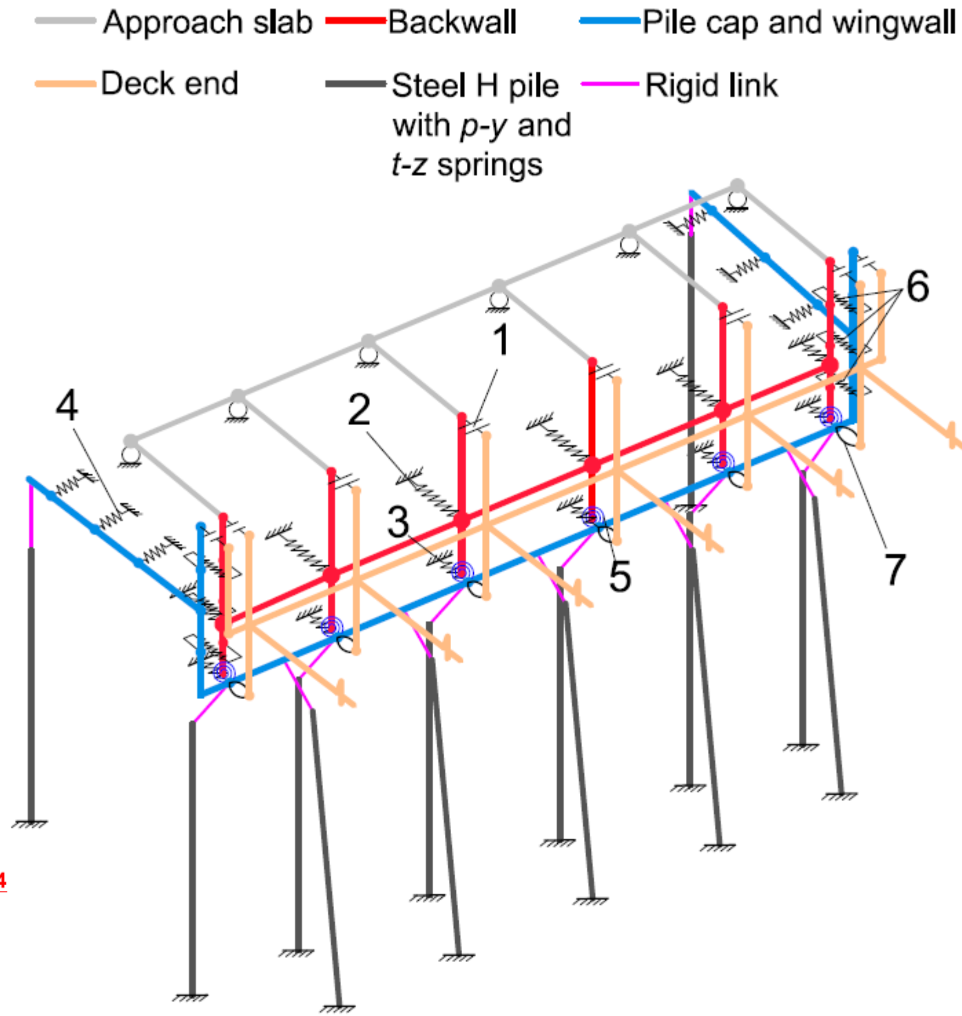
OpenSees Bridge Model



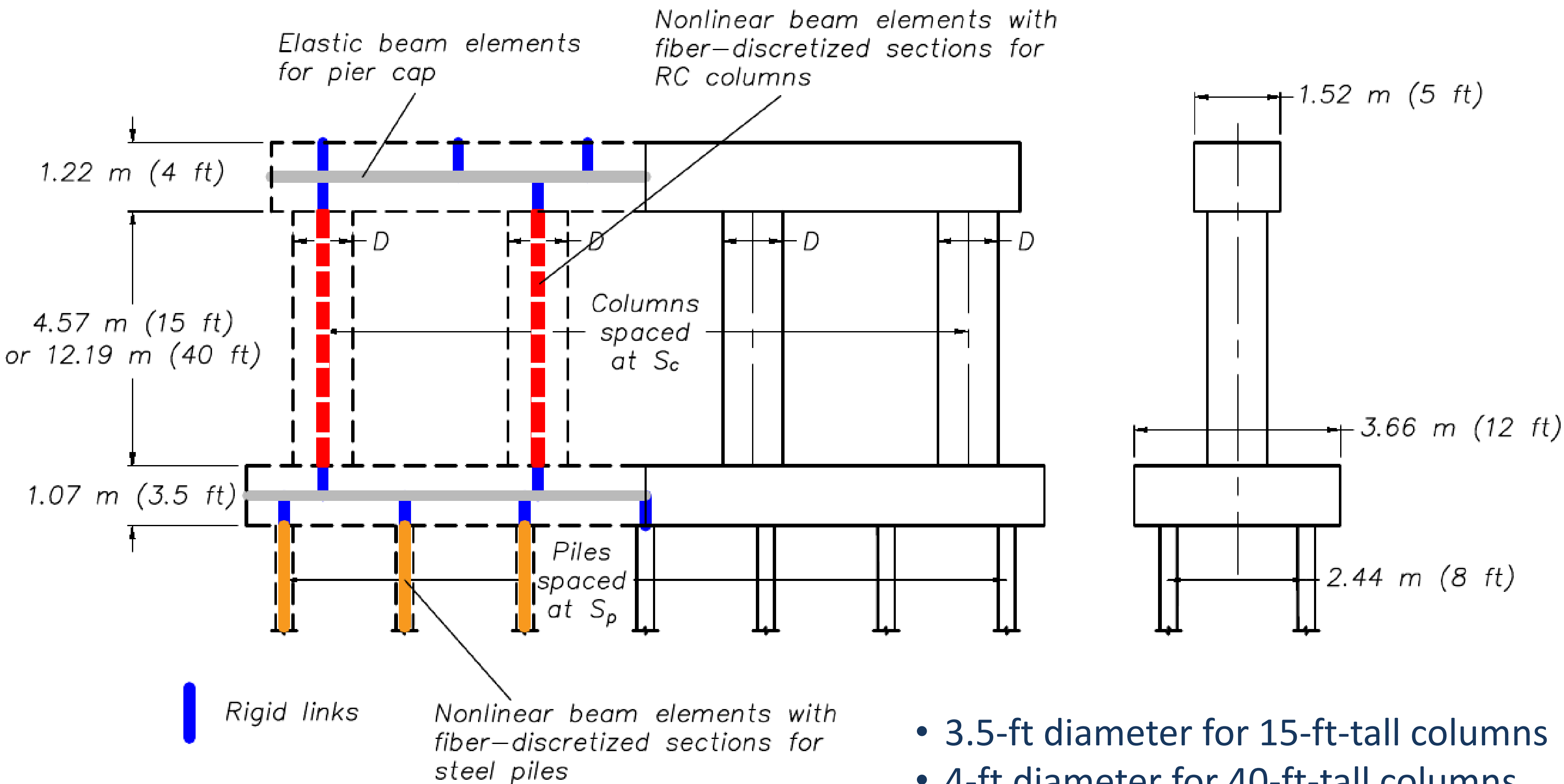
OpenSees Bridge Model







OpenSees Bridge Model



- 3.5-ft diameter for 15-ft-tall columns
- 4-ft diameter for 40-ft-tall columns
- 2% vertical reinforcement ratio

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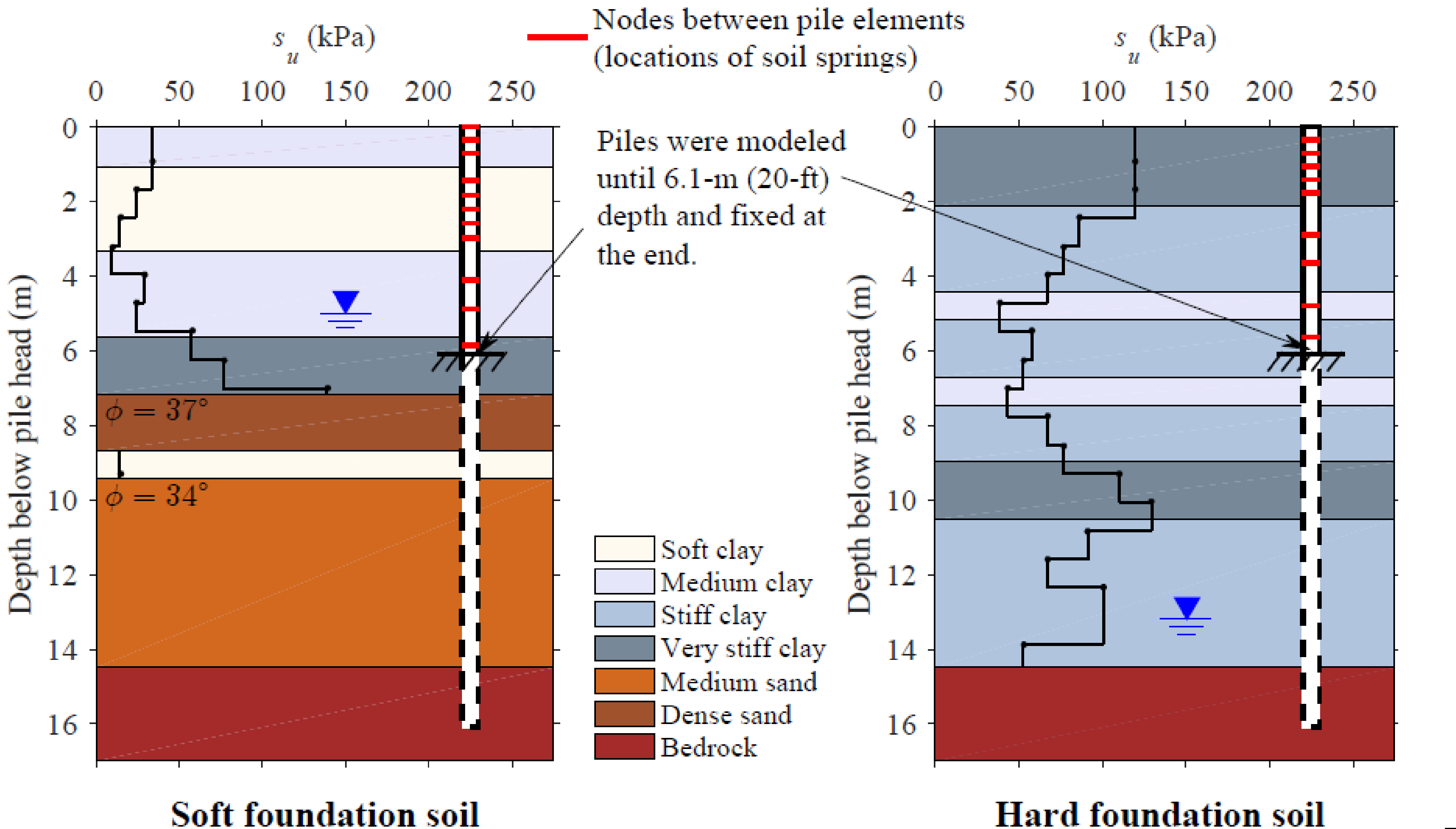
OpenSees Bridge Model



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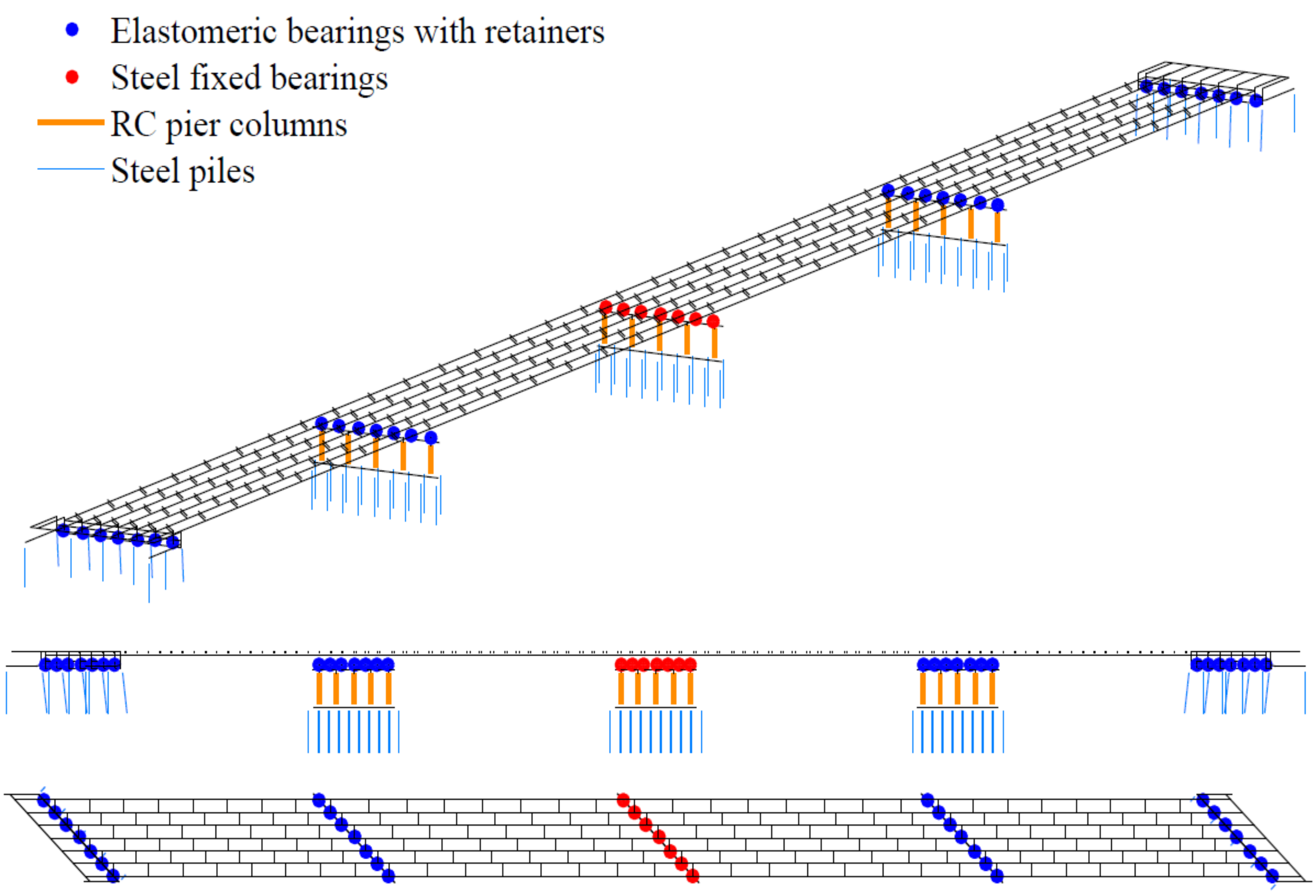
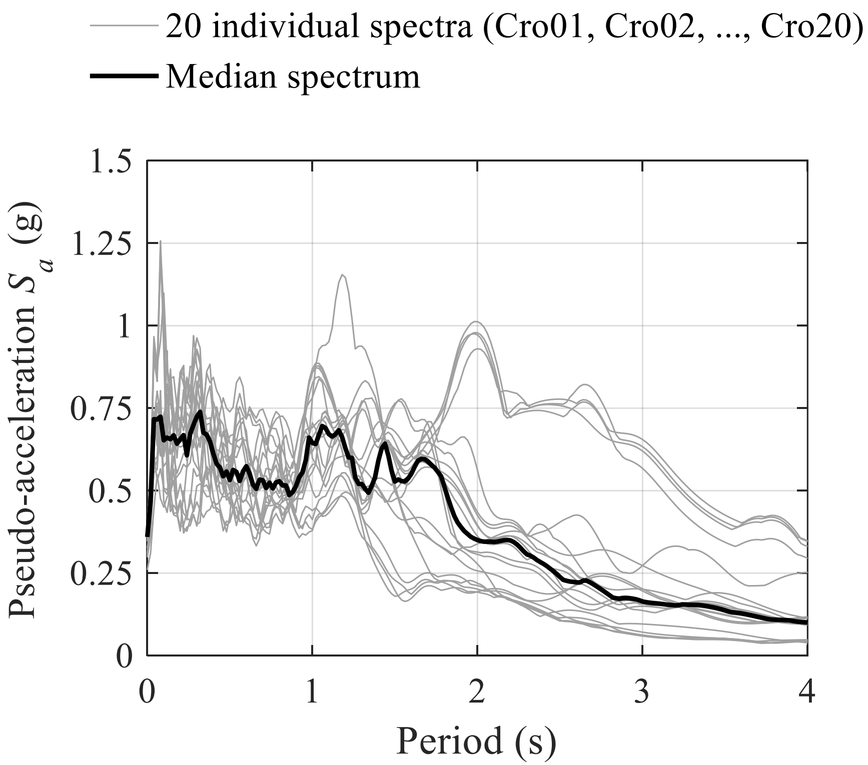
OpenSees Bridge Model

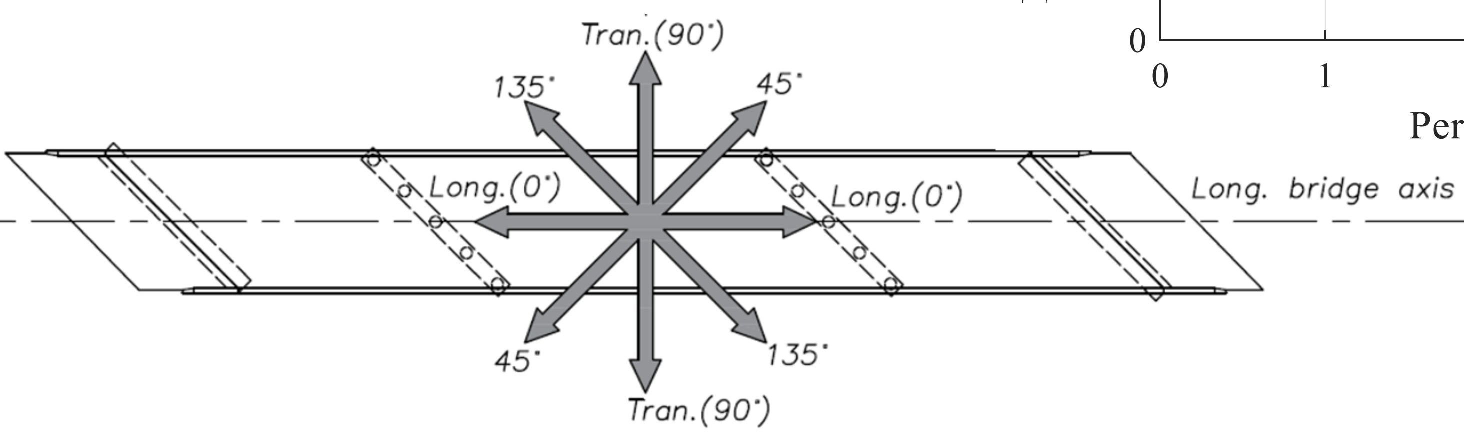


Nonlinear Dynamic Analysis

A suite of 20 site-specific earthquake ground motions for Cairo, IL with a 1,000-year return period (Kozak et al. 2016) were employed for nonlinear dynamic bridge analyses

- PGA: 0.26 ~ 0.40 g
- PGV: 0.31 ~ 1.10 m/s
- PGD: 0.11 ~ 0.72 m
- Arias Intensity: 2.18 ~ 6.45 m/s





- Longitudinal (0°)
- 45°
- Transverse (90°)
- 135°

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Observations from Analysis

Most bridges only sustained limited local damage and were unlikely to collapse when subjected to horizontal earthquake ground motions with a 1,000-year return period in the Midwestern U.S.

Two major seismic performance deficiencies

- Large skew (45°, 60°)
- Tall pier columns
- Transverse or 45° ground motions

Bridge variants: 4S60P40S, 3C60P40S, 4C45P40H, 4C60P40H, 4C60P40S

→ **Bearing unseating at deck corners supported by abutments**

- Non-skew or small skew (0°, 15°, 30°)
- Short pier columns
- Longitudinal or 45° ground motions

Bridge variants: 4C00P15S, 4C15P15S, 4C30P15S, 4S00P15S, 4S15P15S, …

→ **Moderate to severe pier column damage**

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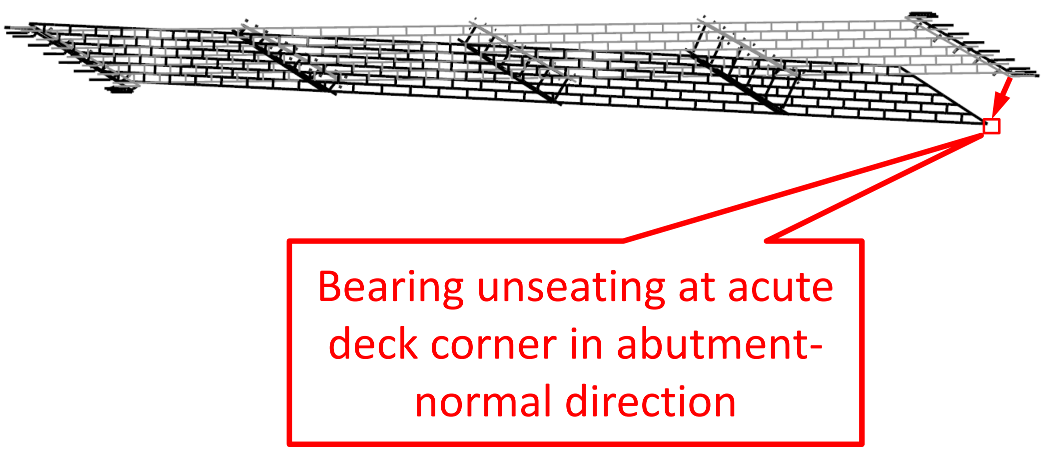
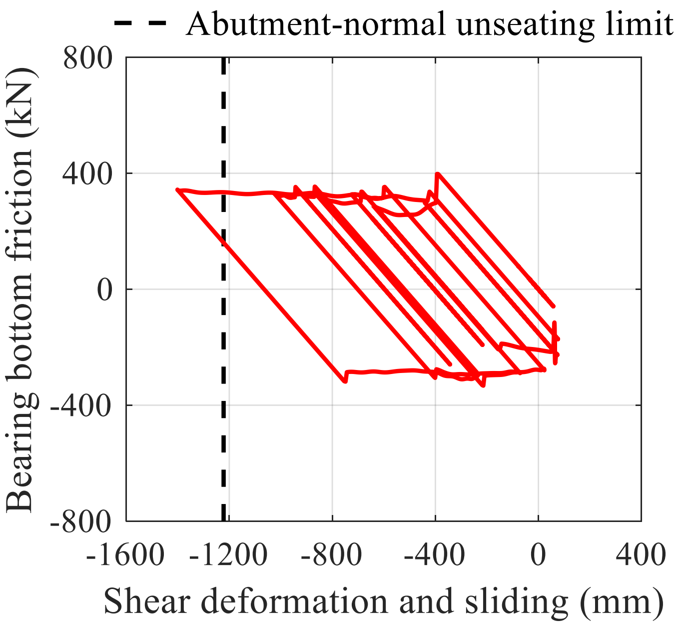
Limited Bearing Unseating

- Bearing unseating at abutments was observed in 13 out of 6,400 analyses (< 1%)

Example: 4C60P40S bridge subjected to a transverse ground motion (deformation magnified by 10 times)



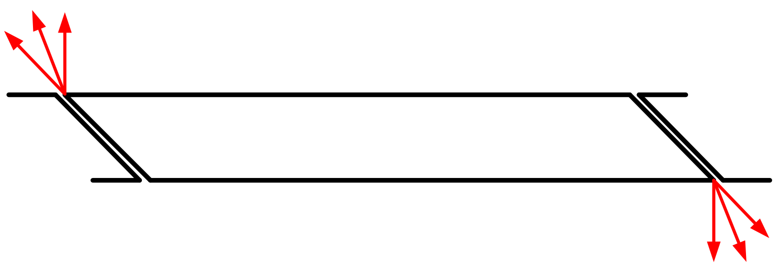


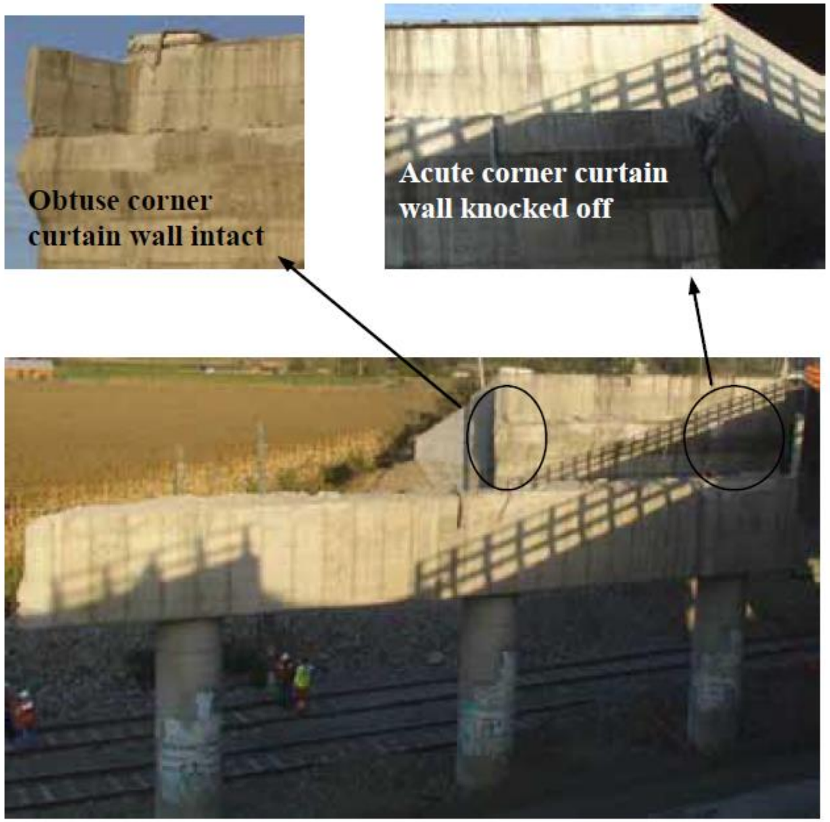
Confirmation from Field Observations

Skew highway bridges collapsed during 2010 Chile earthquake

- Miraflores bridge (20° skew)
- Northeast-bound bridge at Lo Echevers (33° skew)
- Romero overpass (31° skew)
- Route 5 railway overpass at Hospital (40° skew)
- Quilicura railway overpassing at the Avenida Manuel Antonio Matta (45° skew)

All of these skew bridges collapsed with acute deck corners moving away from seat-type abutments.





Damage at south abutment of Route 5 overcrossing at Hospital
Source: Yen et al. (2011)

Yen, W. et al. (2011). *Rep. No.* FHWA-HRT-11-030.

Bridge Quasi-isolation Summary

- Flexibility and sliding response of common elastomeric bearings can allow for quasi-isolated behavior
- Retainer elements and fixed bearings need to be carefully detailed to limit forces on substructures
- Vulnerability to large displacement demands is increased by: skew, tall substructures, flexible foundations / softer soils, and Type II bearings
- The current IDOT ERS prevents unseating and potential span loss under design-level events for most bridges in Illinois

Overall Summary for East Coast / Central US Infrastructure

- Current practice does not rigorously consider seismic design
- A large portion of current infrastructure will perform adequately in a design-level seismic event, owing to inherent redundancy and robustness
- However, vulnerabilities do exist, and there is an opportunity to enhance seismic performance and increase resilience through modest and relatively inexpensive modifications

Scope of Problem / Open Issues / Potential Use of NHERI Facilities

- **Data:** Develop inventory of critical and potentially vulnerable infrastructure, including projected societal impact
- **Experimental:** Characterize fundamental seismic behavior of existing infrastructure (older up through current practice)
- **Simulation:** Develop tools for modeling components and systems with limited ductility, up through collapse
- **Experimental / Simulation:** Develop innovative engineering strategies for enhancing performance and increasing resilience
  - New construction
  - Retrofit existing
- **Outreach:** Communicate to government agencies and the public what resilience means for the East Coast / Central US

Grand Challenge: Resilience of East Coast Infrastructure

Larry Fahnestock, PhD, PE

Professor, CEE

University of Illinois at Urbana-Champaign

September 24, 2019

NHERI Lehigh Researcher Workshop

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