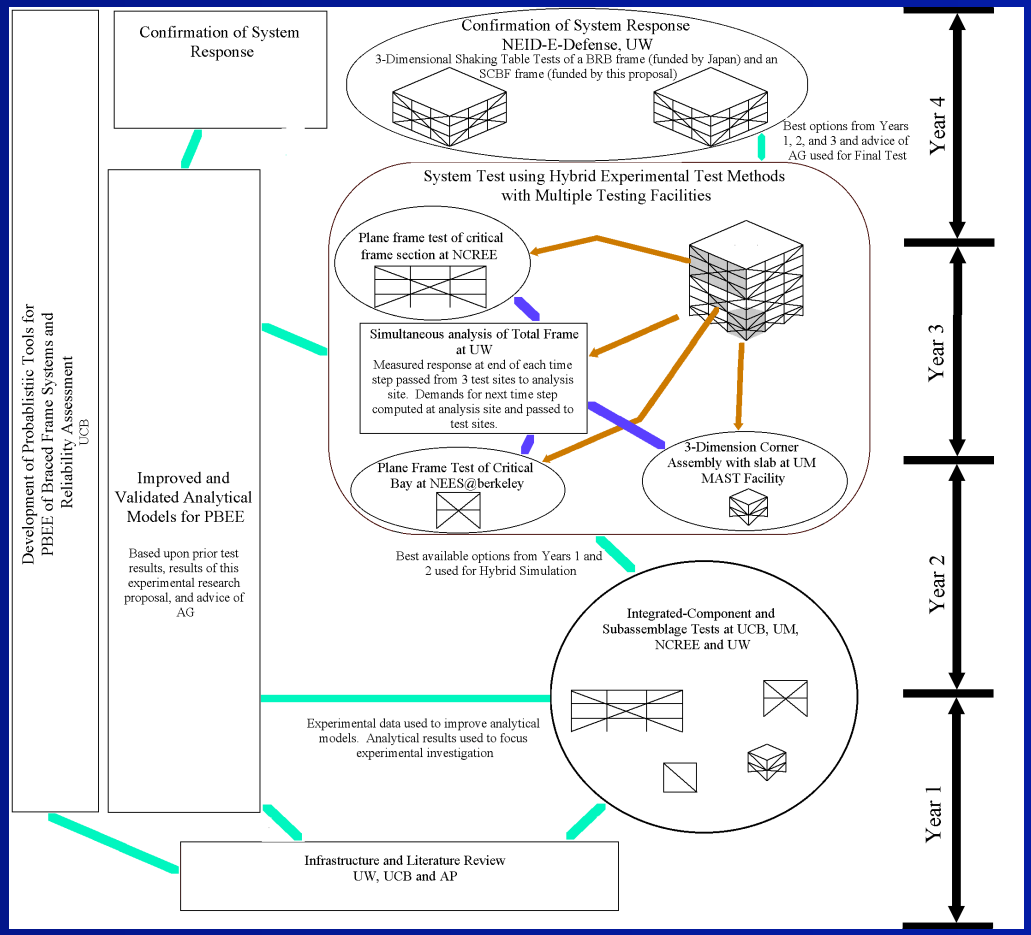
Simulating the Performance of Multi-Story Concentrically Braced Frame Systems

Dawn E. Lehman, Charles W. Roeder, Po-Chien Hsiao, and Eric Lumpkin
University of Washington
Department of Civil and Environmental Engineering

A NEES-SG 4 year multi-institutional research program is in progress to improve understanding and seismic design guidelines for concentrically braced frames.

Researchers from Univ. of California , Berkeley, Univ. of Minnesota, National Center for Research in Earthquake Engineering (NCREE) in Taiwan as well as Univ. Of Washington are engaged in the project.



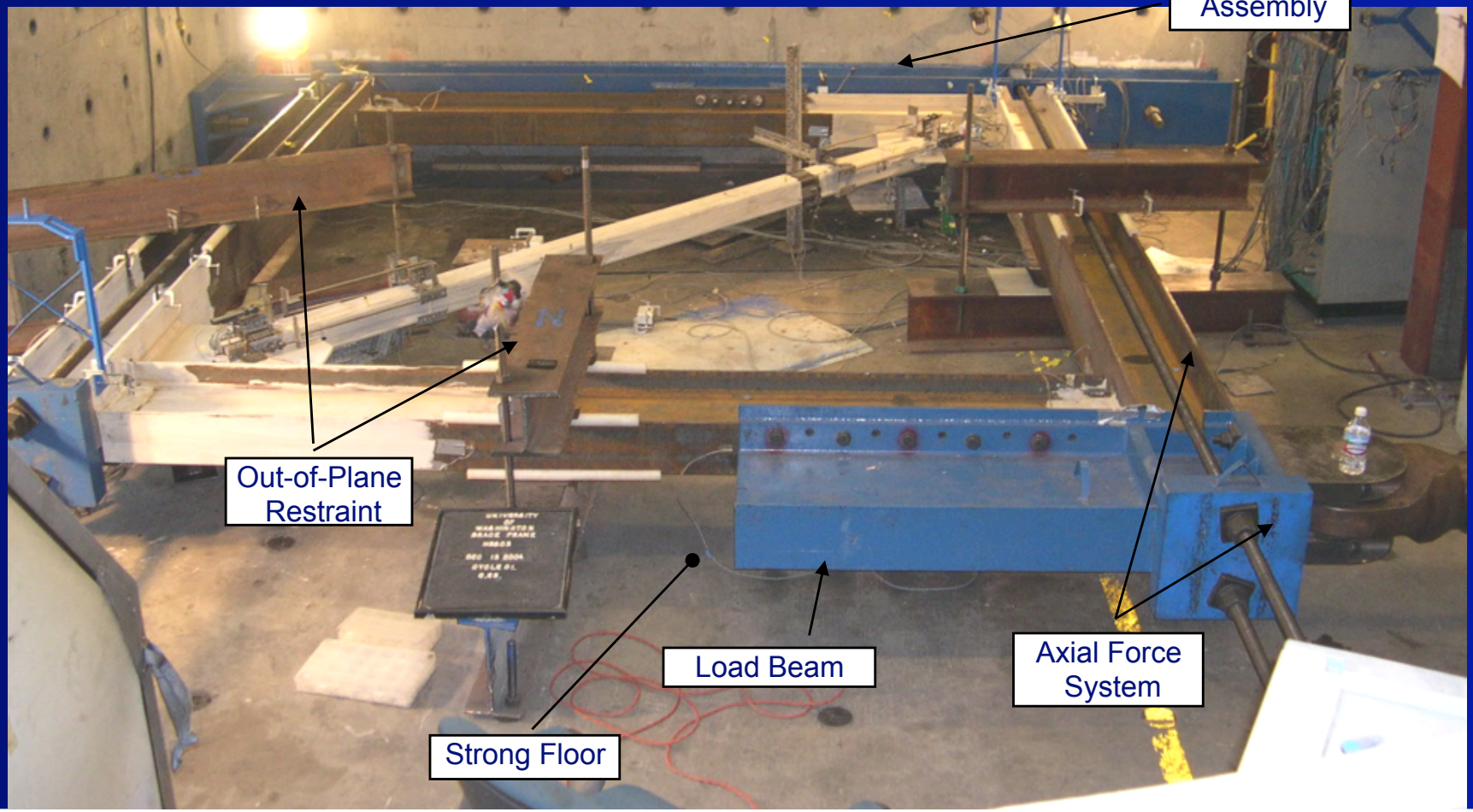
The U. of Washington is lead institution for the research and its focus is on the overall seismic performance of braced frames with a particular emphasis on the influence of gusset plate connections on system performance.

Acknowledgements

- National Science Foundation
- American Institute of Steel Construction
- National Center for Research in Earthquake Engineering (NCREE) in Taiwan
- Nucor Yamato Steel
- Chaparral Steel Company
- Columbia Structural Tubing
- Magnusson Klemencic Associates
- CANRON Western Constructors Ltd
- Rutherford and Chekene
- Dasse Design Inc - Walter P. Moore
- Many graduate students including Shawn Johnson, Adam Christopulos, David Herman, and Brandon Kutolka

UW Experimental Program on gusset plate connections

- Tested 27 SCBFs with wide range of gusset connection configurations subjected to cyclic inelastic deformation



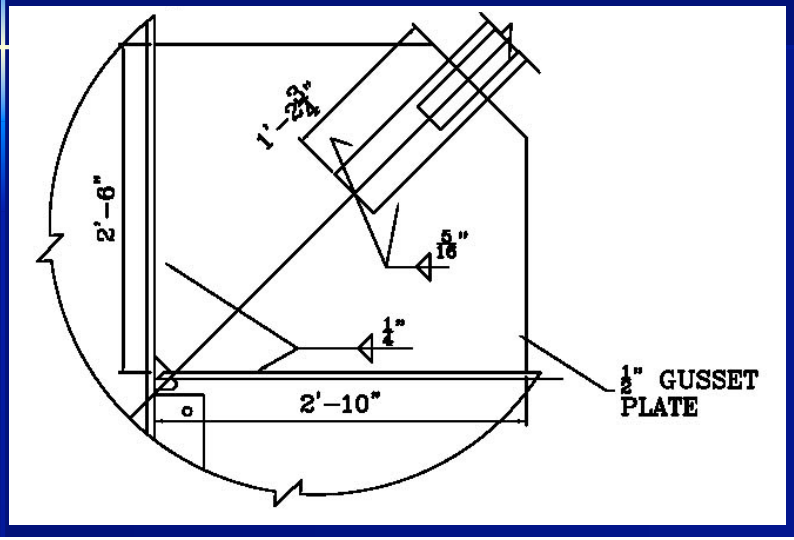
Brace Buckling Important to CBF Behavior

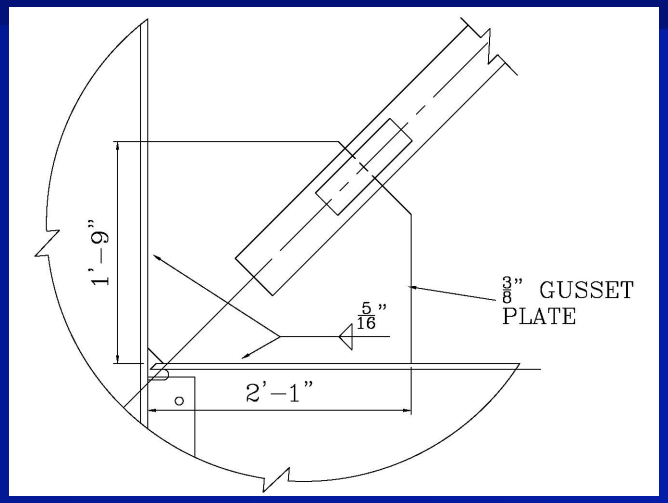
B1

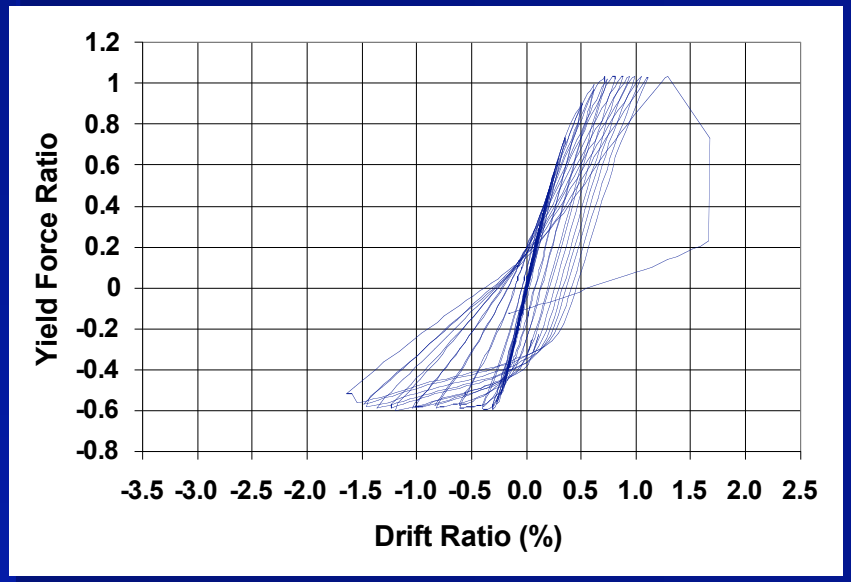
B2

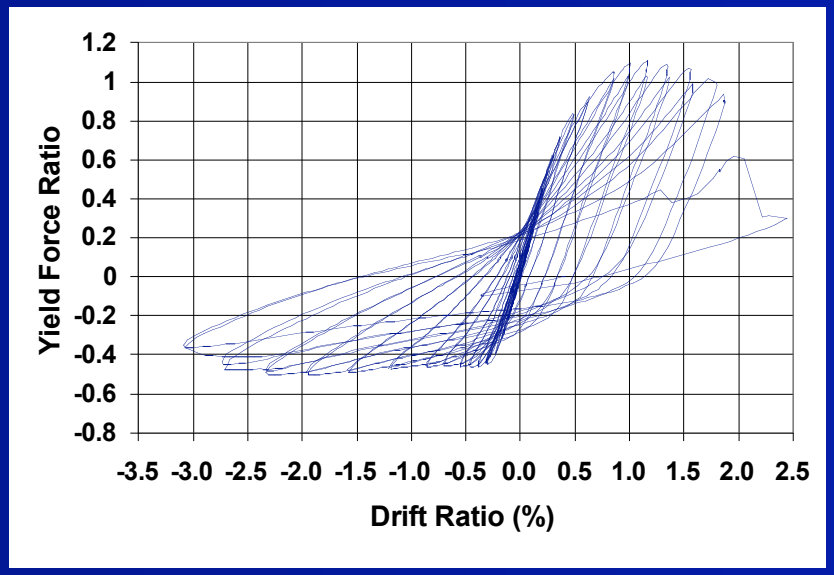
B3

Elliptical clearance model developed to produce more compact gussets and improved seismic performance.









Current design methods imply that are better - but

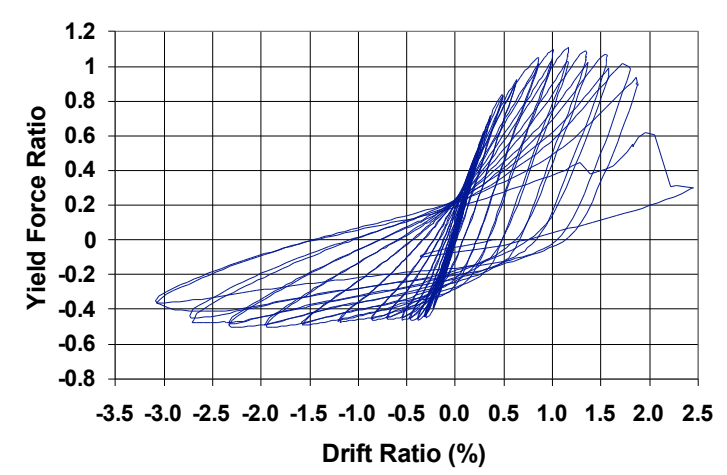
- One connections with very conservative design and other with a balance design
- Failure Mode: Brace Fracture
- Drift Capacities:

3/8" = 3.1% to 1.7% (4.8%)

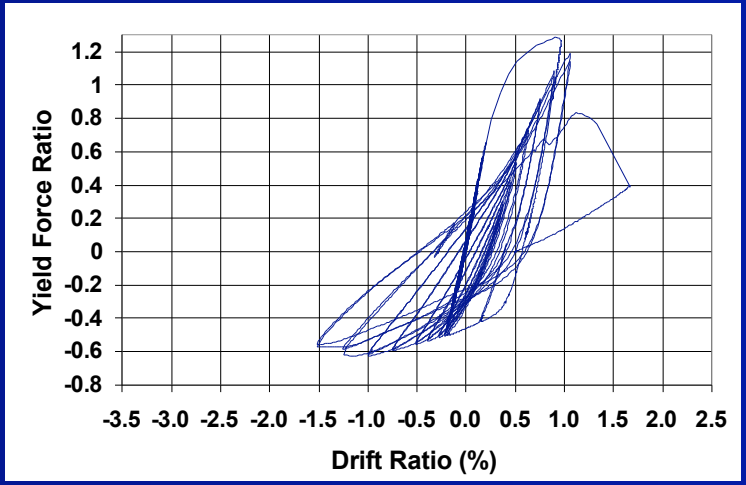
7/8" = -1.5% to 1.0% (2.5%)

- Significant Reduction in drift capacity for brace in compression

3/8 " Plate



7/8 " Plate w/ Large Beam



Recommendations from experimental program

- Design of the gusset plate has a significant impact on the seismic performance of the braced frame
- Don't want gusset to remain totally elastic - limited yielding is beneficial
- Current AISC Seismic Design Provisions do not permit frame to achieve full ductility. Need to consider actual deformation demands on plate and weld
- 6t to 8t elliptical clearance model with thin plate provide good inelastic deformation capacity for corner gusset plate connections
- Brace should be designed with a effective length coefficient of 1.0 and the true length of the brace

Recommendations from experimental program

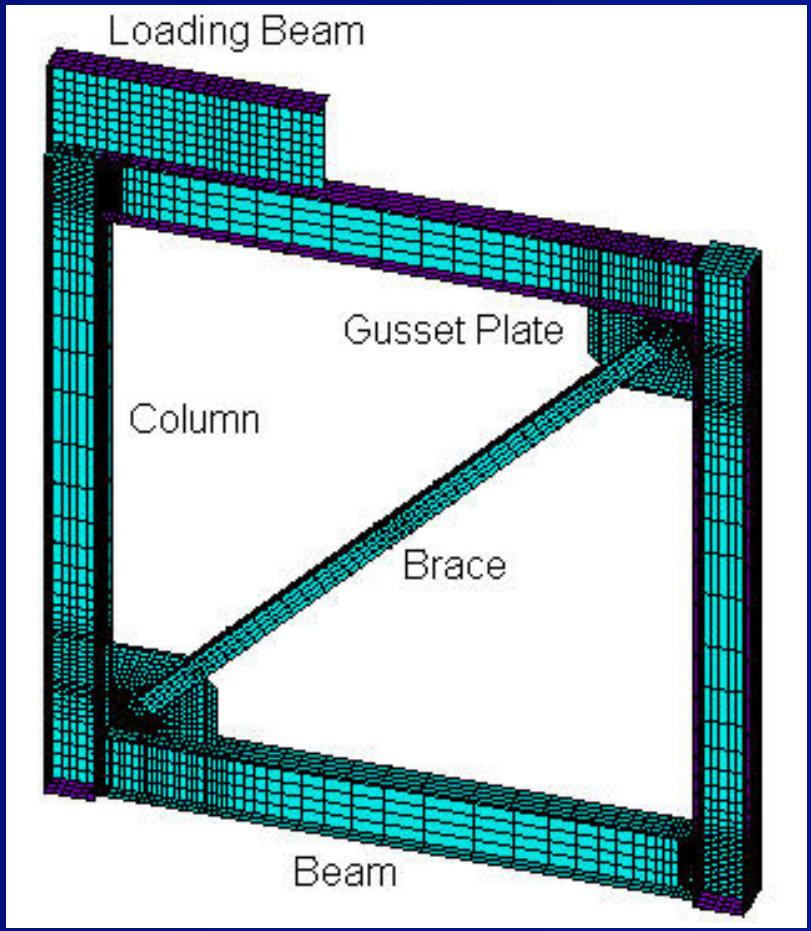
- Tapered plates achieve similar performance but often improve constructability and may have greater demands on welds
- Strength and stiffness of gussets must develop the brace, but additional stiffness and resistance are counter productive
  - Beam strength and stiffness should be considered as part of this evaluation
- Welds should be designed to resist the plastic capacity of the plate (not the brace)
- Whitmore width yielding should be only slightly larger than the yield capacity of the brace

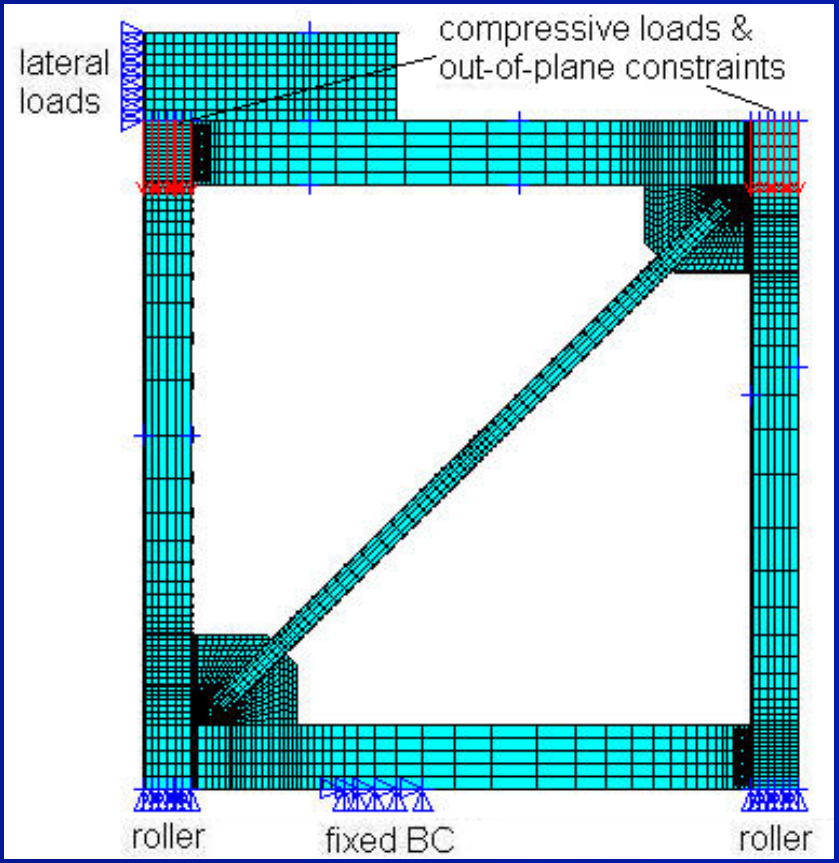
Inelastic Nonlinear Analysis of Cyclic Behavior with ANSYS and OpenSees was performed to extend and support the experimental research program

Nonlinear FEM Analysis with ANSYS -- Model Description

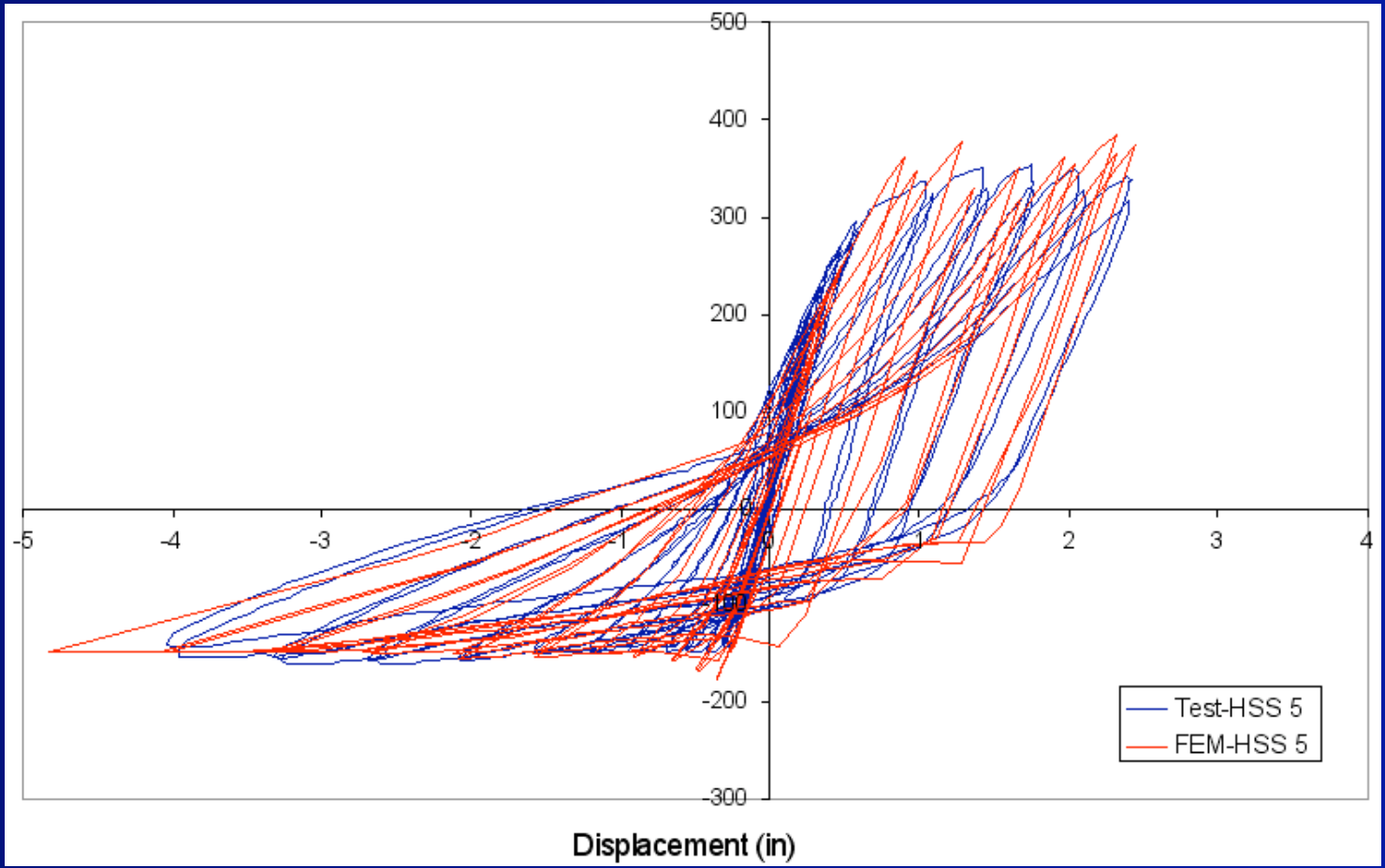
- Each component was modeled using shell elements.
- Steel response was modeled using a cyclic, bi-linear kinematic-hardening constitutive model.
- Shear tab was modeled explicitly. Shear stiffness of individual bolts modeled using concentrated springs.
  - Very important to achieving good comparison with experiments
- Model did not include capabilities to model weld tearing and fracture.
- Fine mesh in critical areas, but coarser mesh in less critical areas to achieve more rapid convergence

Model Configuration, Elements and Boundary Conditions

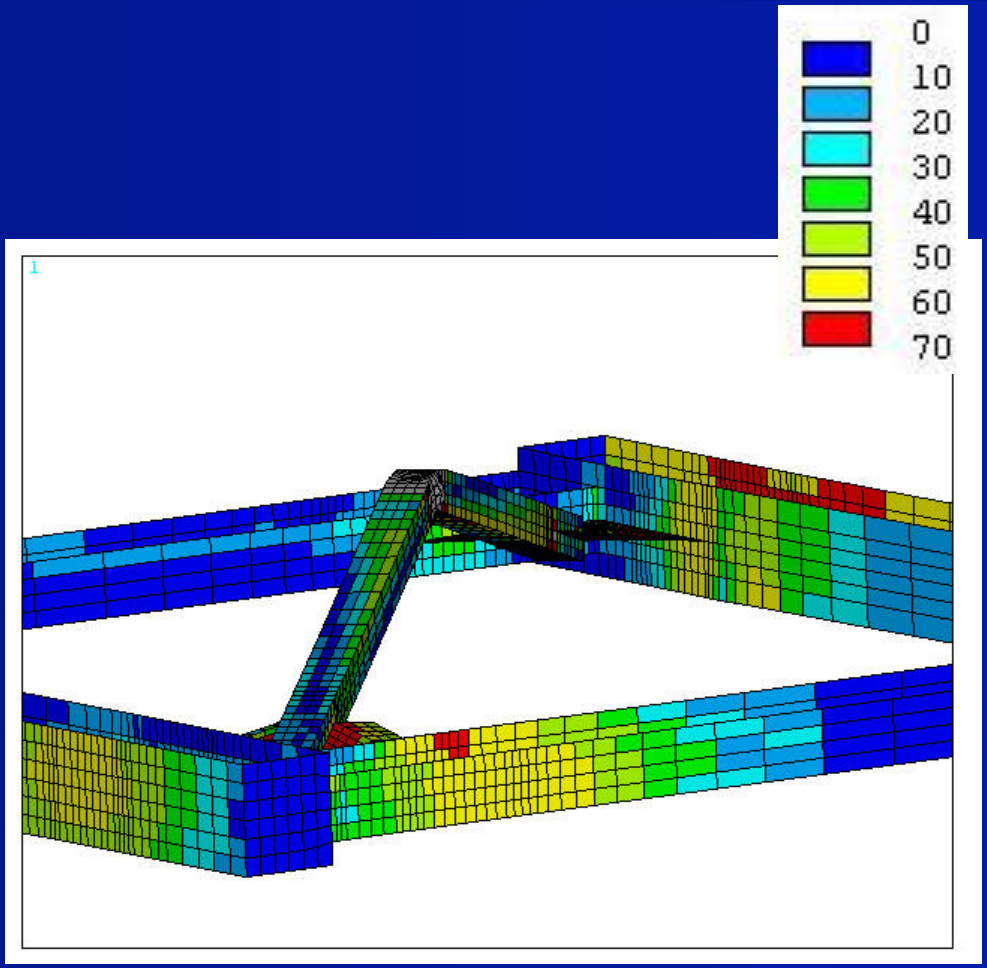




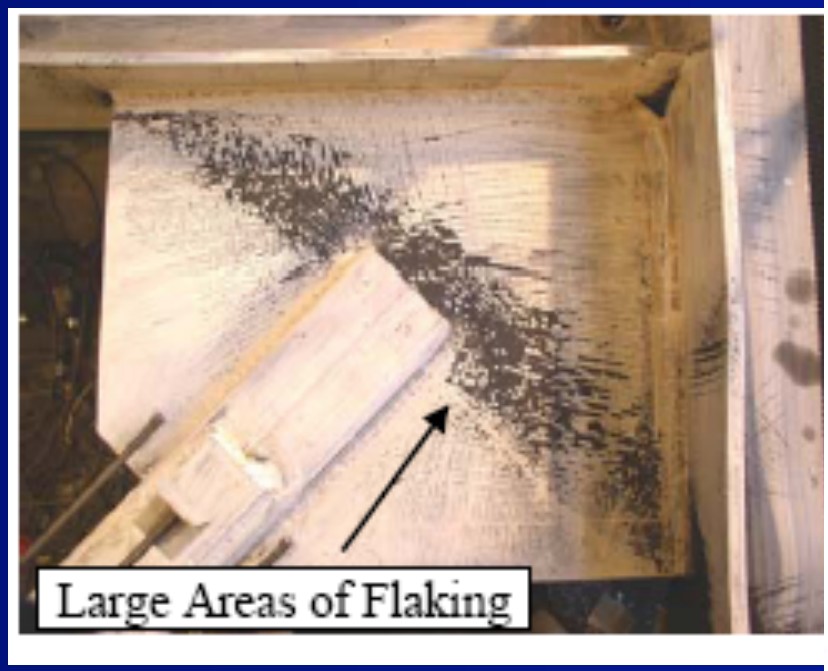
Predicted and Measured Force-Displacement Response (HSS-5)

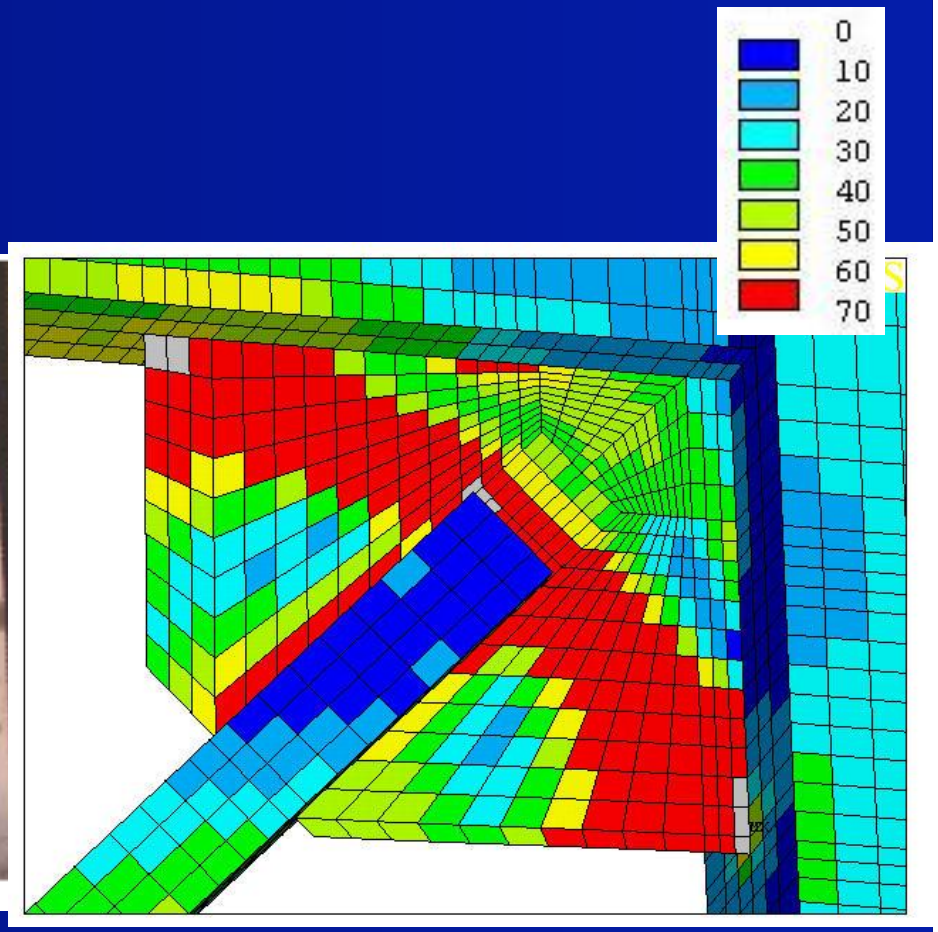


Predicted Response: Brace

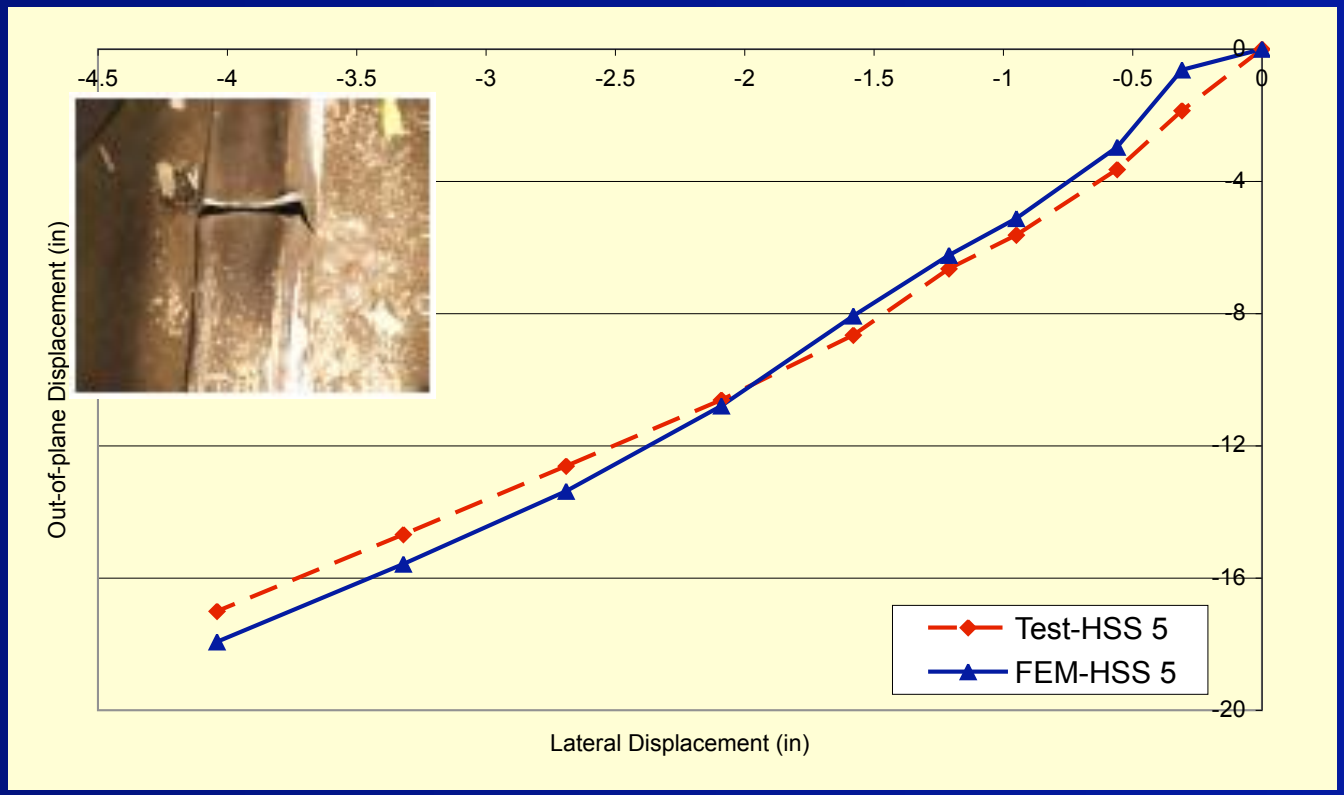


Predicted Response: Gusset Plate





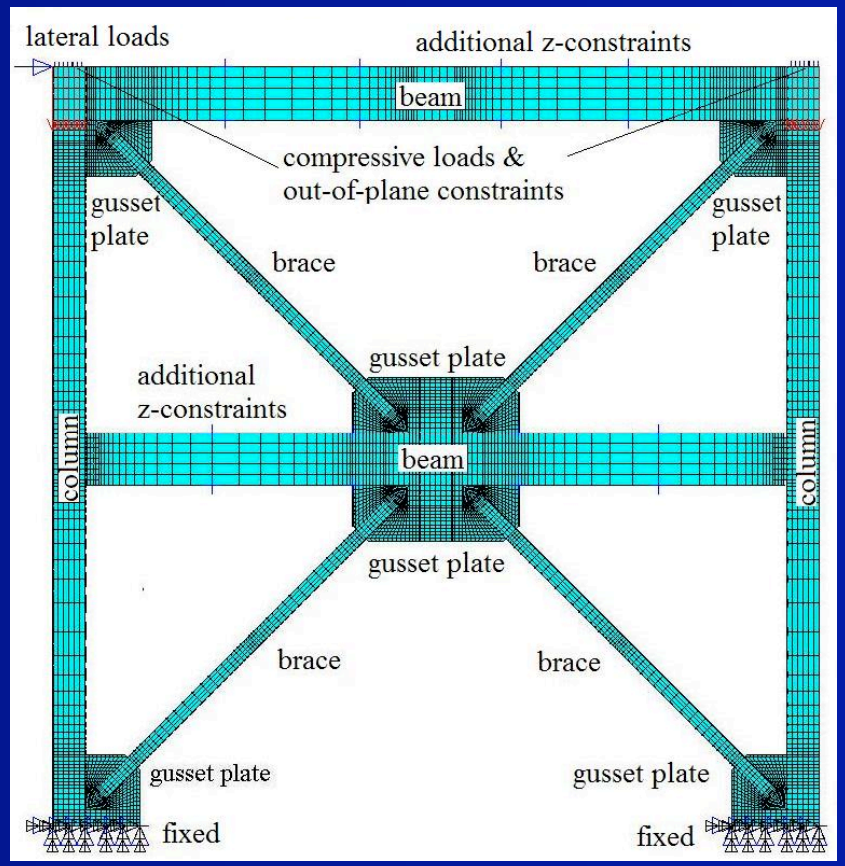
Brace Out-of-Plane Displacement



Result of comparisons to 27 test results leads us to have considerable confidence in the analytical predictions.

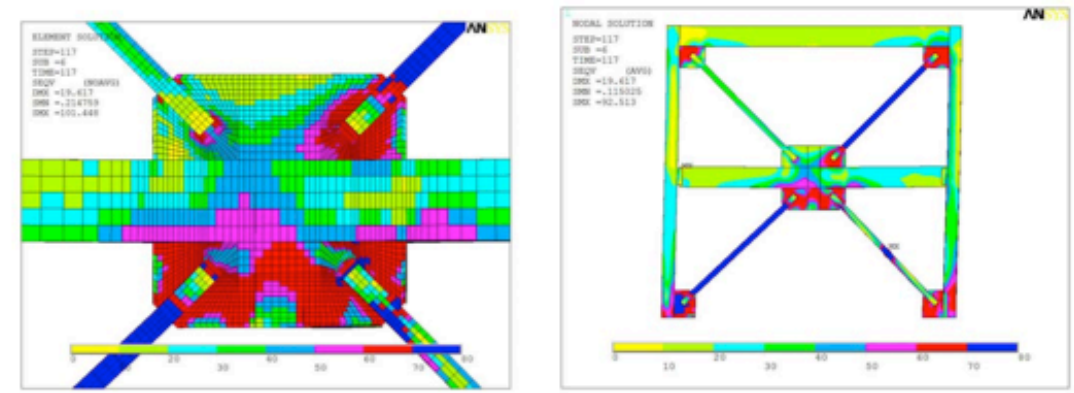
Analtical Results Extended to Multi-Story Frames

- Developed models for initiation of cracking at gusset welds and fracture of the brace based upon Equivalent Plastic Strain

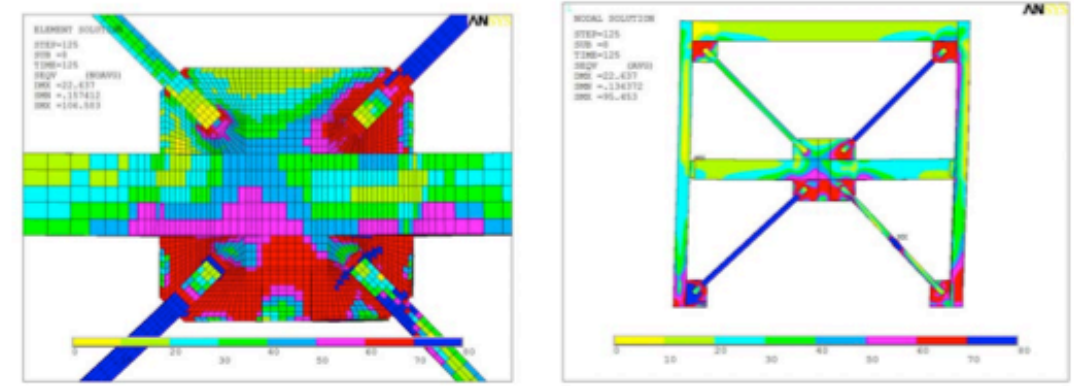


Analtical Results Extended to Multi-Story Frames

Analysis of multi-story systems clearly shows different behavior of midspan gusset plates. First they are more susceptible to lateral stability issues due to lateral support and twist of the brace. End rotation models don't work the same as for corner gusset plates.



c) 2.0%



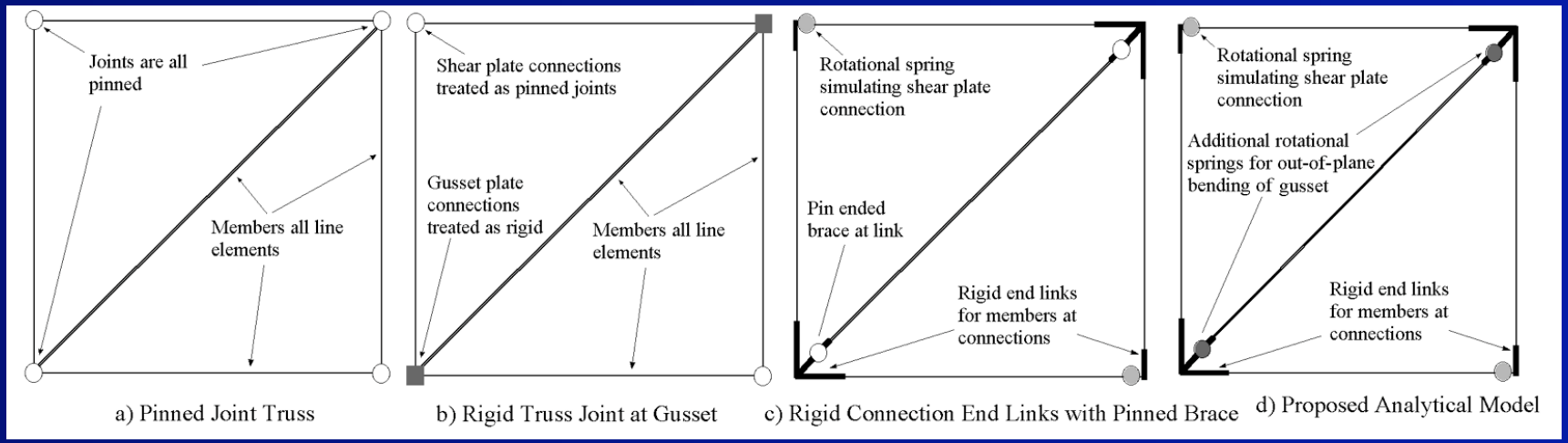
d) 2.5%

For Good Accuracy Detailed FEM Models Require:

- Careful modeling of both gusset plate and beam-column connections
  - Including modeling of bolt deformation and bolt hole elongation
- Composite slabs and lateral restraint must also be accurately estimate cyclic response

OpenSees models also developed

- Accuracy of these models also strongly dependent upon connection modeling
- Four models shown



Accuracy of OpenSees strongly dependent upon models

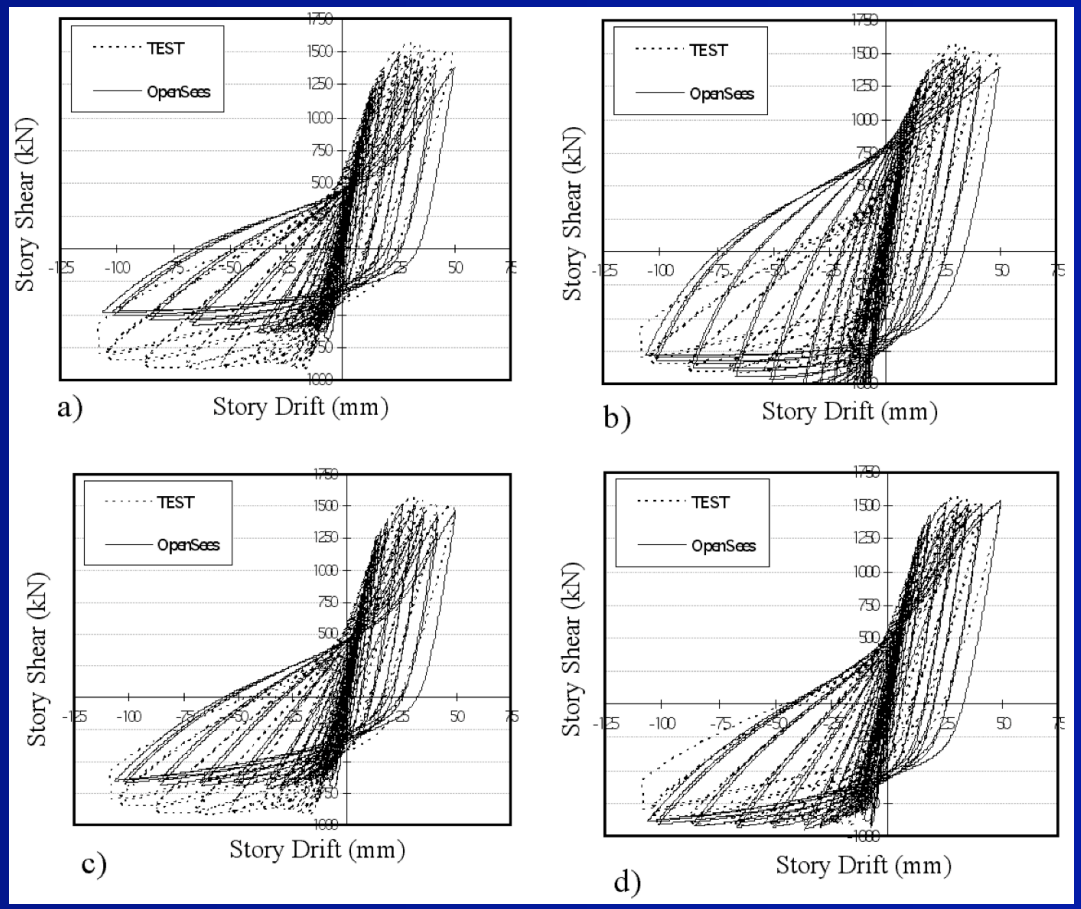
- Four analysis from 4 models shown

a) Pinned braces severely underestimate resistance.

b) Rigid brace connections overestimate resistance and stiffness

c) Rigid links for gusset with pinned braces stiff significantly underestimate resistance

d) Rigid links with spring stiffness provide best estimate

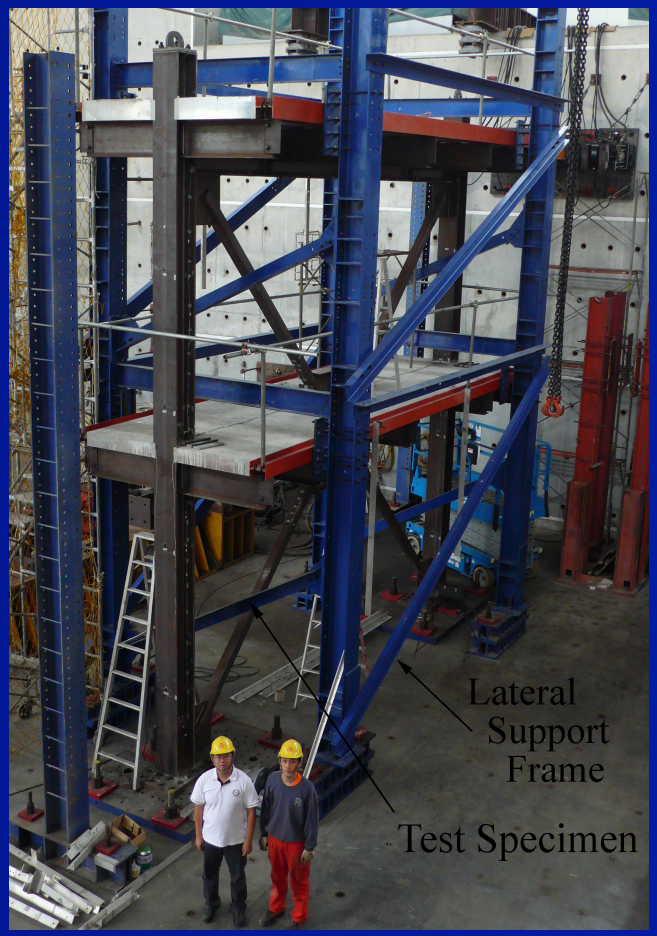


These models have been used to aid in the design of Six 2- and 3-story frames to:

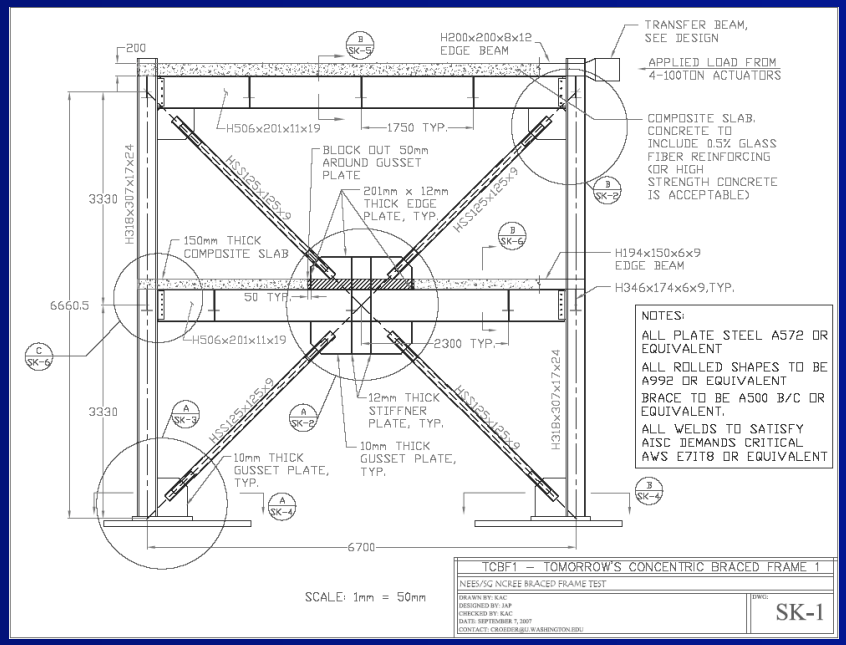
- Estimate strains and deformations prior to testing to finalize design issues,
- Predict the response of the braced frames prior to testing, and
- Aid in the interpretation and evaluation of test results

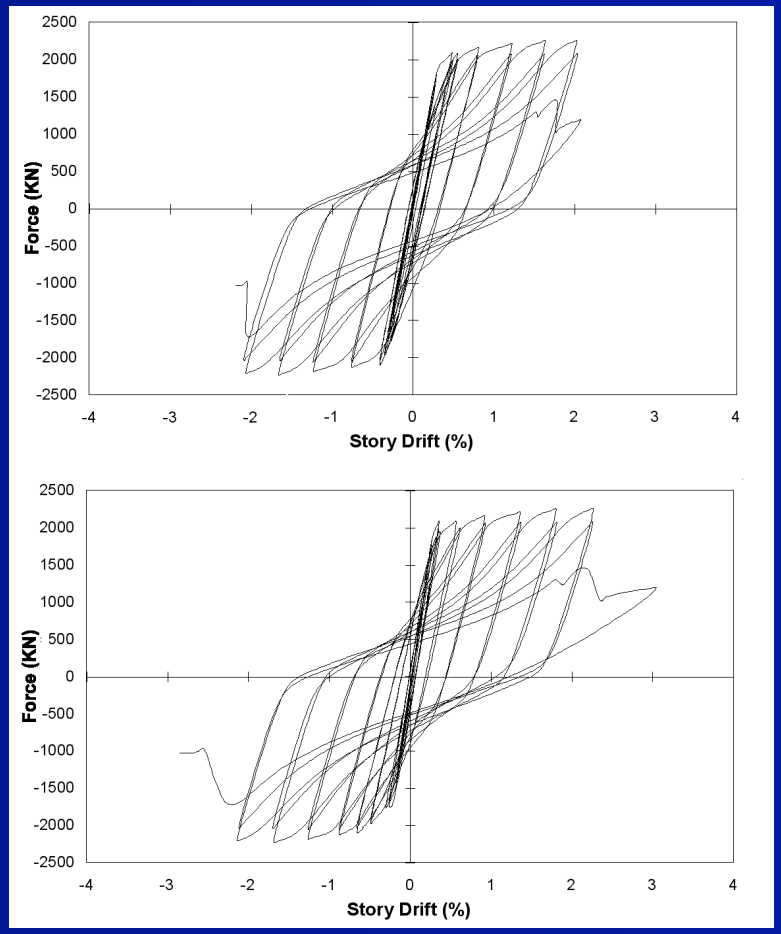
Experimental Studies at NCREE

- Three full-scale 2-story steel frames tested at NCREE under cyclic inelastic deformation
  - Rectangular gussets with HSS tubular braces
  - Rectangular gussets with wide flange braces
  - Tapered gussets with HSS tubular braces
- Multi-story X-brace configuration

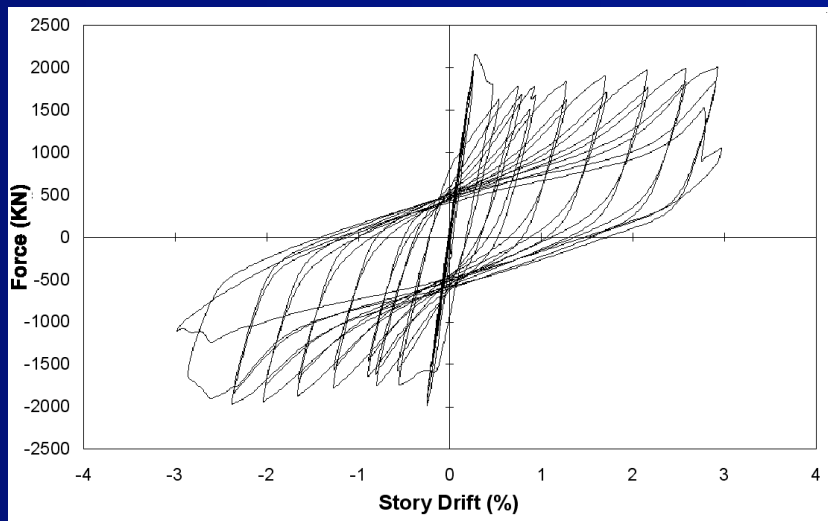


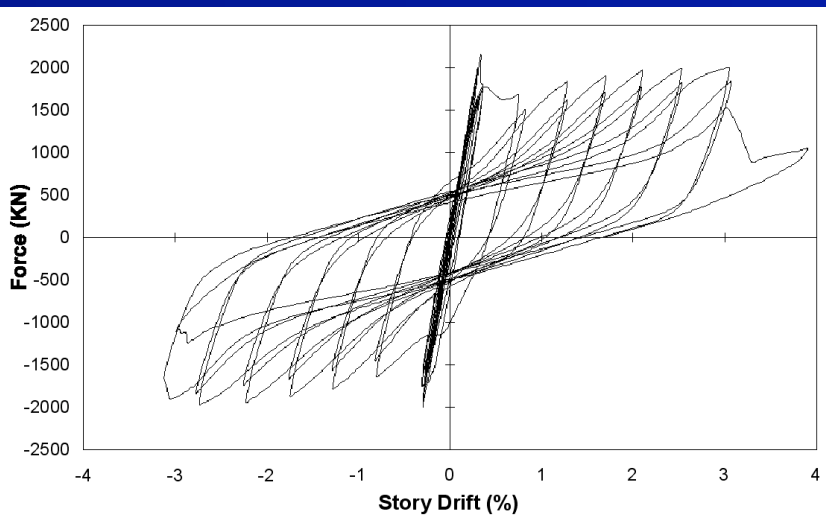
Relatively good inelastic deformation capacity





Wide Flange Braces Provide Greater Ductility and Deformation Capacity but Place Greater Demand on Connections

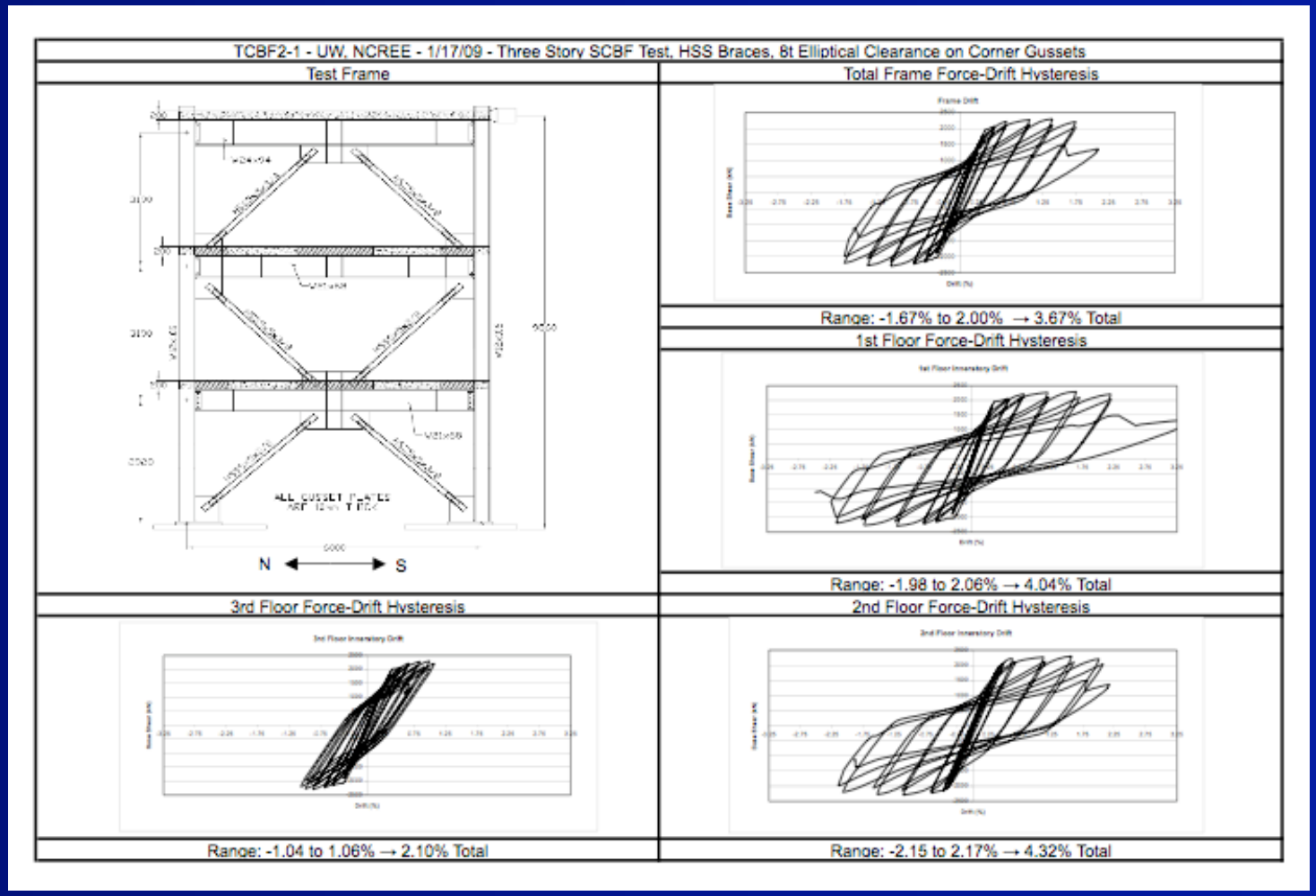




Full-Scale 3-Story Frames also tests at NCREE

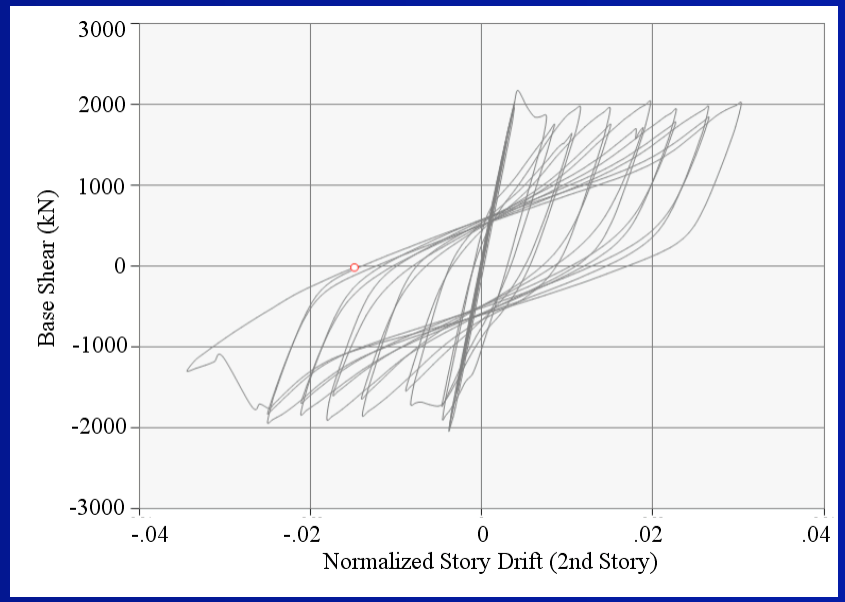
- Two full-scale 3-story steel frames tested at NCREE under cyclic inelastic deformation
  - Rectangular gussets with HSS tubular braces
  - Rectangular gussets with wide flange braces
- Multi-story X-brace configuration
- Modified midspan gusset plate clearance criteria using a 6tp horizontal clearance zone

Inelastic Performance Very Good for Frame and Connections -HSS 3-Story test



Wide Flange Braces Again Achieved Somewhat Greater Ductility than HSS Tubes

- Reasonable distribution of inelastic deformation between 3 stories
- Greater inelastic deformation capacity prior to brace fracture with wide flange braces
- Good performance from both mid-span and corner gusset plate connections



Proposed Design Procedure Based on Work to Date

Proposed Design Method

1) Design beams, columns and braces for required seismic design forces as with current approach
2) Establish expected plastic capacity of brace under tension ($R_yA_gF_y$) and compression ($1.1\ R_yA_gF_{cr}$) as currently done.
   - Effective length of brace can be taken as true length
3) For connection design, propose a balance procedure to assure good seismic performance rather than current forced based method.

Expected Brace Capacity $< \beta_{yield,1}R_yR_{yield,1}$ .....

..... $< \beta_{yield,i}R_yR_{yield,i}$ (1)

and

Expected Brace Capacity $< \beta_{fail,1}R_{fail,1} < \beta_{fail,2}R_{fail,2} \ldots$

and $\beta_{yield} < \beta_{fail}$ (2)

Proposed Design Method (2)

4) Size weld joining the tube for the expected tensile force with β equal to normal weld resistance factor

5) Check the net section of the brace at tip of the slot. Use the expected tensile yield force of the brace and the expected tensile capacity of the net section with β of 0.9.

- Note that analysis and experiments suggest that net section fracture is controlled by the limit if flexible connections are employed. However, net section fractures have been noted primarily with overly stiff, strong connections.

6) Based upon the weld length and tube diameter check block shear of the gusset plate with β of 0.85

Proposed Design Method (3)

8) Establish the Whitmore width by the 30° projected angle method as currently used.
9) Establish the dimensions of corner gusset plates with the elliptical clearance model with an 8t clearance
   - This can be done graphically or by an approximate equation developed in research
10) Establish the dimensions of midspan gusset plates with 6tp linear (horizontal) clearance

Proposed Design Method (4)

11) Use these dimensions and Whitmore width to check gusset for buckling, tensile yield and tensile net section fracture.

- Use average gusset length and K of 0.65 for corner gussets
- Use average gusset length and K of 1.2 for midspan gussets
- More conservative K (> 1) needed for midspan gussets
- For tensile yield compare the expected tensile yield of the plate to the expected tensile capacity of the brace with a β of 0.9
- For tensile fracture compare the nominal ultimate tensile capacity of the plate to the expected yield capacity of the brace with a β of 0.85.

Proposed Design Method (5)

12) Size the welds joining gusset plate to the beam and column to develop the full plastic capacity of the gusset plate -- not the expected tensile capacity of the brace
    - CJP welds of matching weld metal achieve this
    - Fillet welds of matching metal on both sides of the gusset must be slightly larger than t_p
13) The beam-to-column connection must use full CJP welds to join the beam flanges to the column
14) The resulting gusset plate should be stiff and strong enough to support full loads but should not have any extra stiffness or resistance

Limitations of the Method

- Intended to achieve the maximum possible ductility from SCBFs with HSS tube braces
- Must design the connection to have adequate stiffness and resistance but not excess stiffness and resistance - Overly conservative connection design reduces the expected performance of the system
- Additional work is needed and is in progress