Laboratory Evaluation of Perimeter Beam Integrity Detailing Requirements of ACI 318-19

Sergio F. Breña
University of Massachusetts Amherst

Jorge Rivera Cruz
US Army Corps of Engineers

Outline of Presentation

- Background and motivation for the research
- Specimen details
- Laboratory testing results
- Discussion of testing results
- Conclusions

Background and Motivation for the Research

Research Objectives

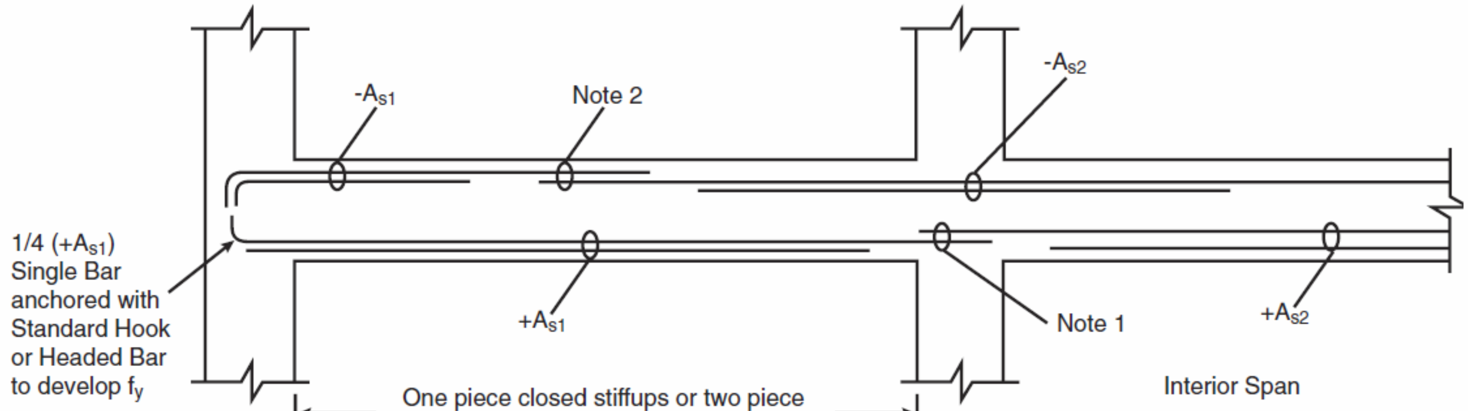
- The primary objective of this research was to evaluate structural integrity detailing provisions of ACI 318-19 for cast in place perimeter beams
  - Effect of bottom bar splice location along beam
  - Transverse reinforcement spacing of perimeter beams in buildings designed for Seismic Design Category A or B (prompted by observations during tests)

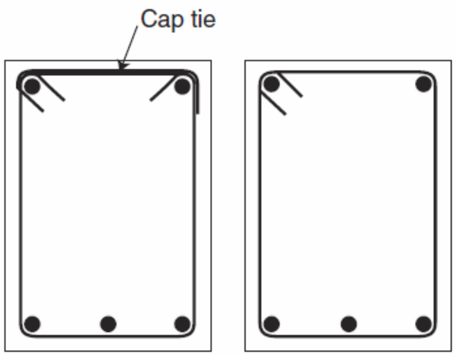
ACI 318 Section 9.7.7 Intent for Providing Structural Integrity Reinforcement

- To prevent disproportionate collapse of large portions of a structure after localized failure of a small portion of the structure
- ACI 318 R9.7.7 states: "It is the intent of this section of the Code to improve the redundancy and ductility in structures so…that resulting damage may be localized" [in the event of abnormal loading event].
  - Ability to redistribute internal forces after local failure
  - Implies capacity to maintain load-carrying capacity at large (plastic) deformation demands (displacements and rotations)

ACI 318-19 Structural Integrity Requirements

ACI 318-19 Section 9.7.7.1 – continuity of longitudinal reinforcement





Longitudinal reinforcement enclosed by closed stirrups or hoops ACI 318-19 Section 25.7.1.6

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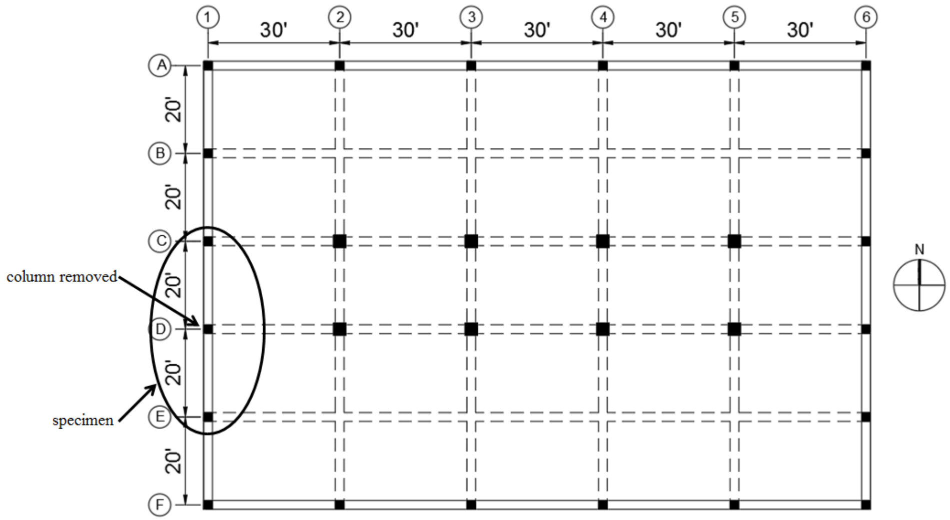
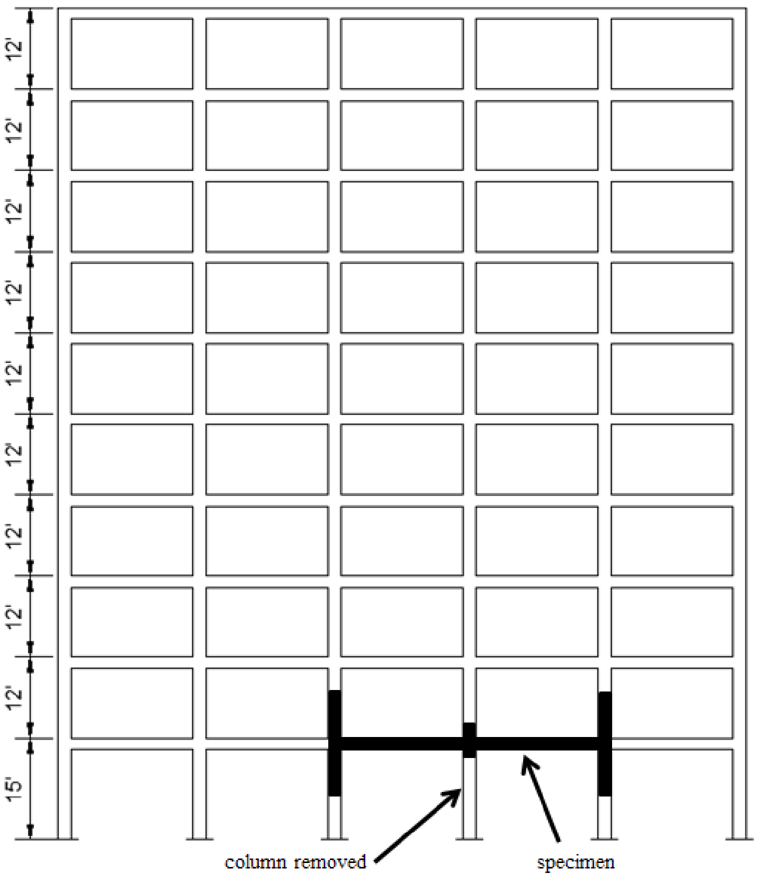
Specimen Details

Building Prototype

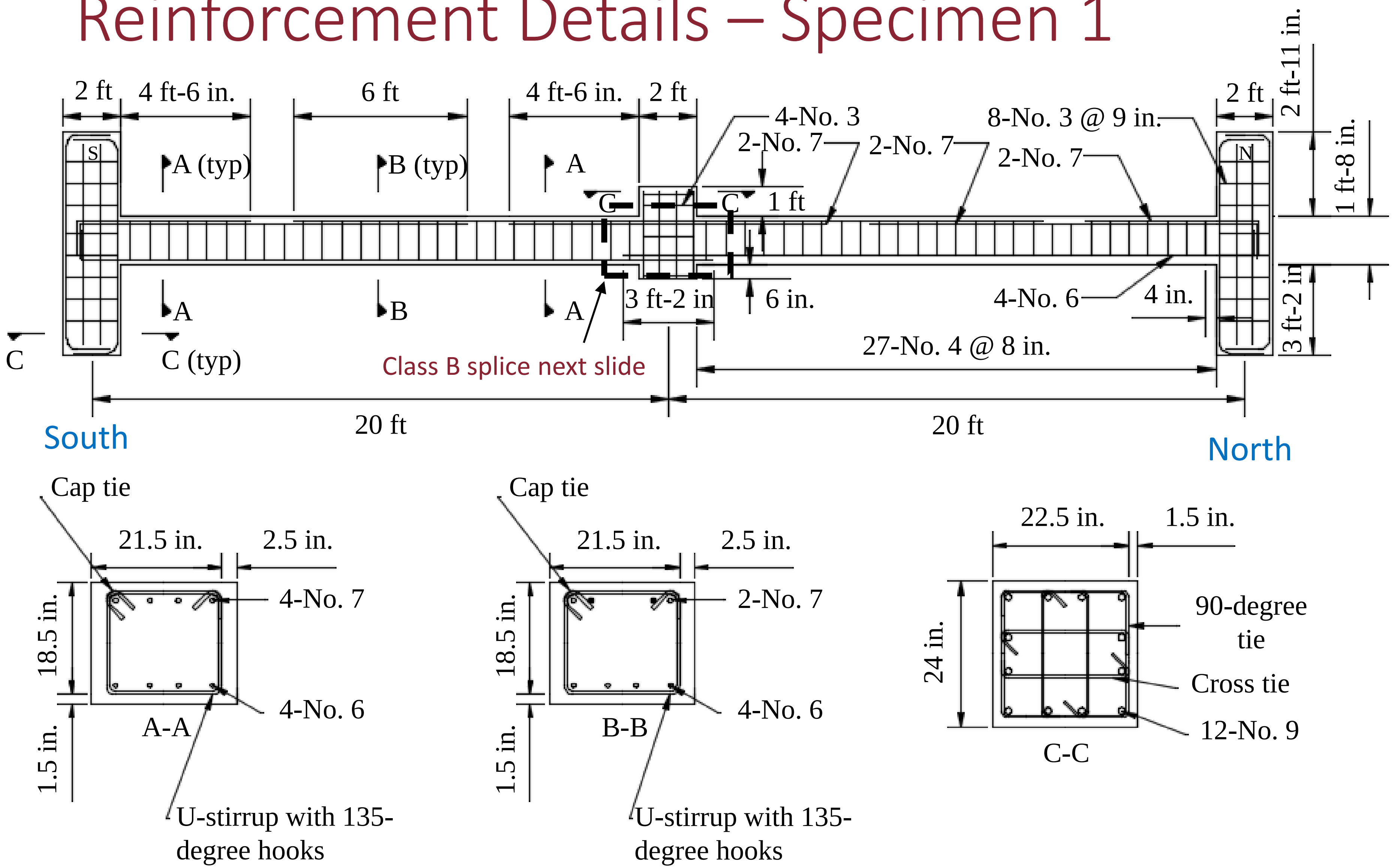


Building Plan



Elevation (Column Line 1)

Reinforcement Details – Specimen 1

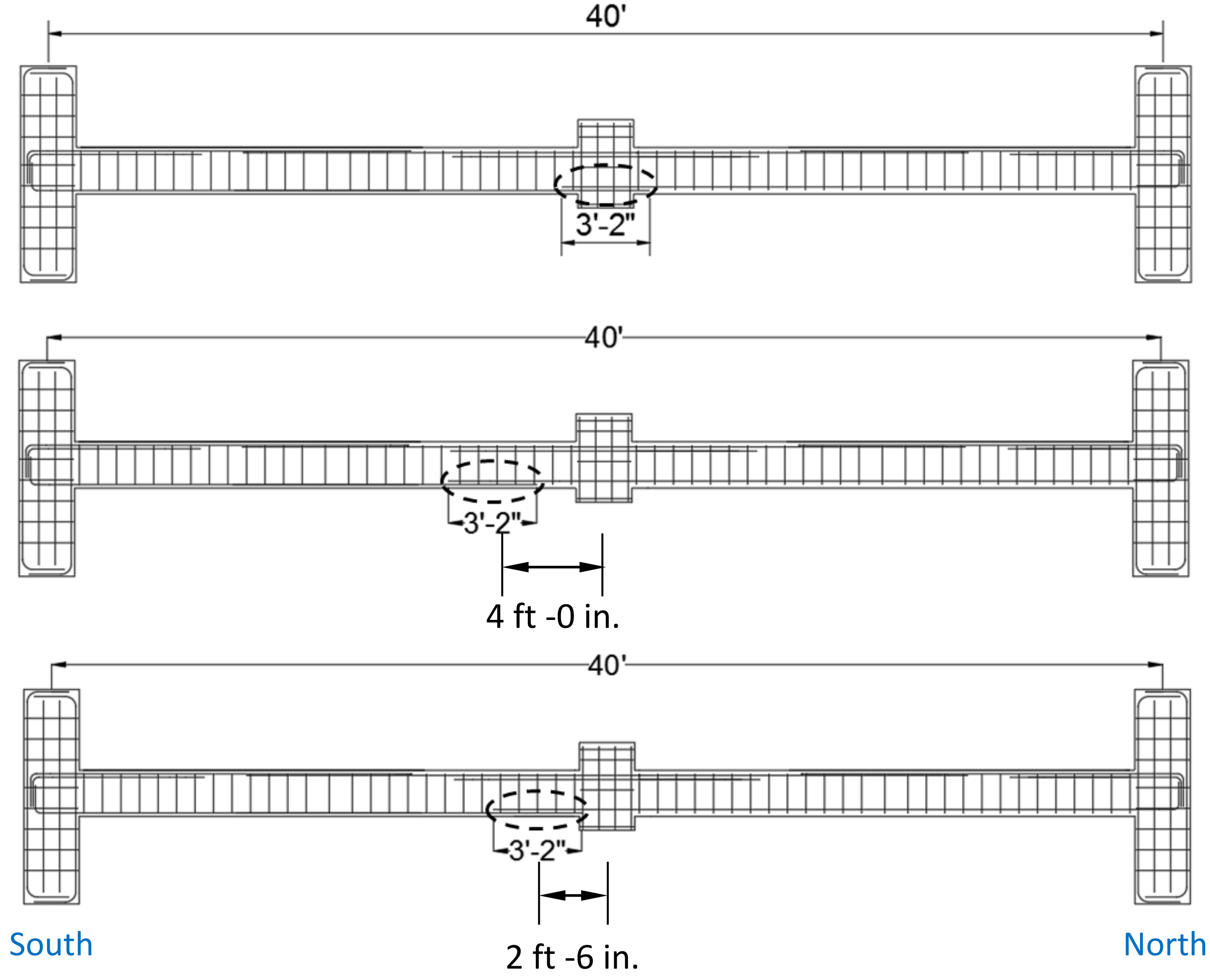


Bottom Longitudinal Bar Splice Locations

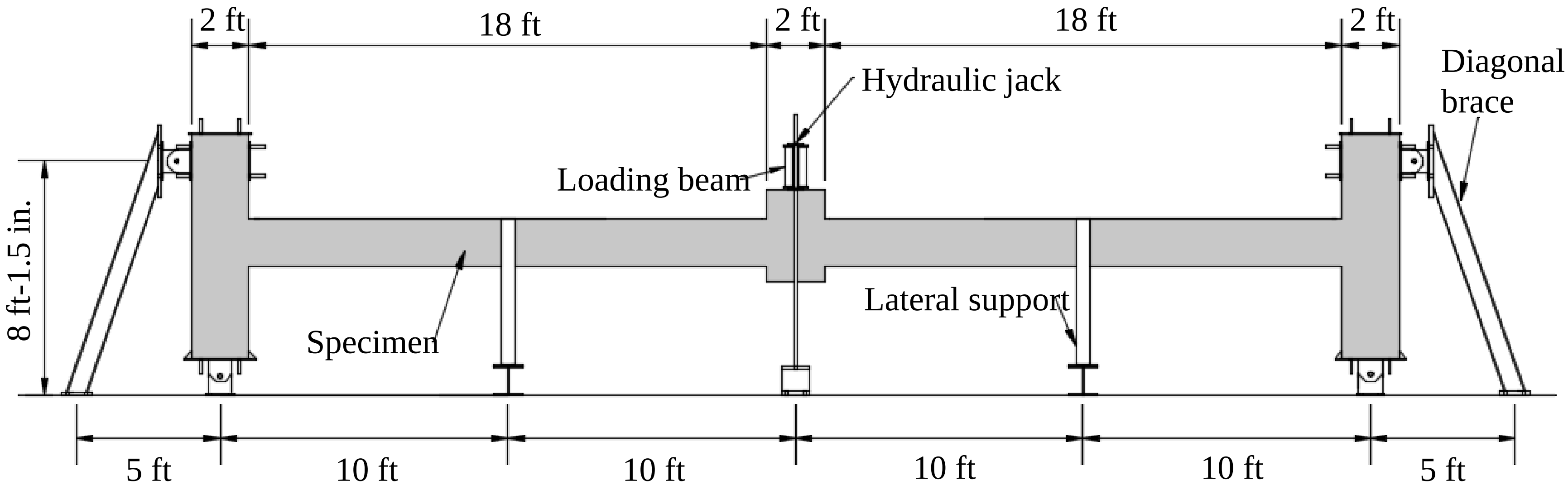
Specimen 1

Specimen 2

Specimen 3

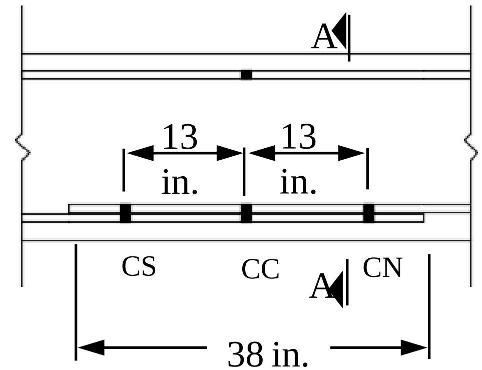


Overall View of Test Setup



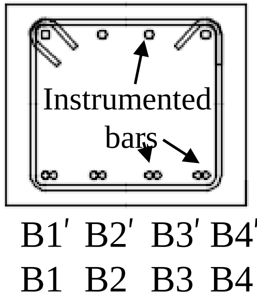
Specimen Instrumentation

SG Instrumentation of spliced bars



Splice detail (elevation)

Note: bars are on same horizontal plane

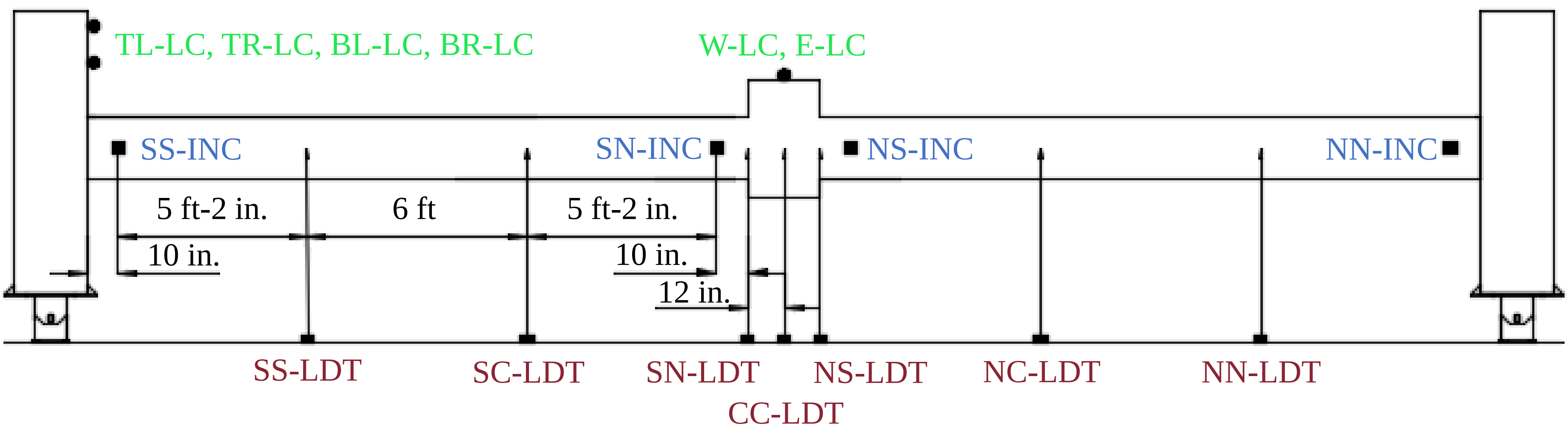


Section A–A
(Cross section)

Displacement transducers

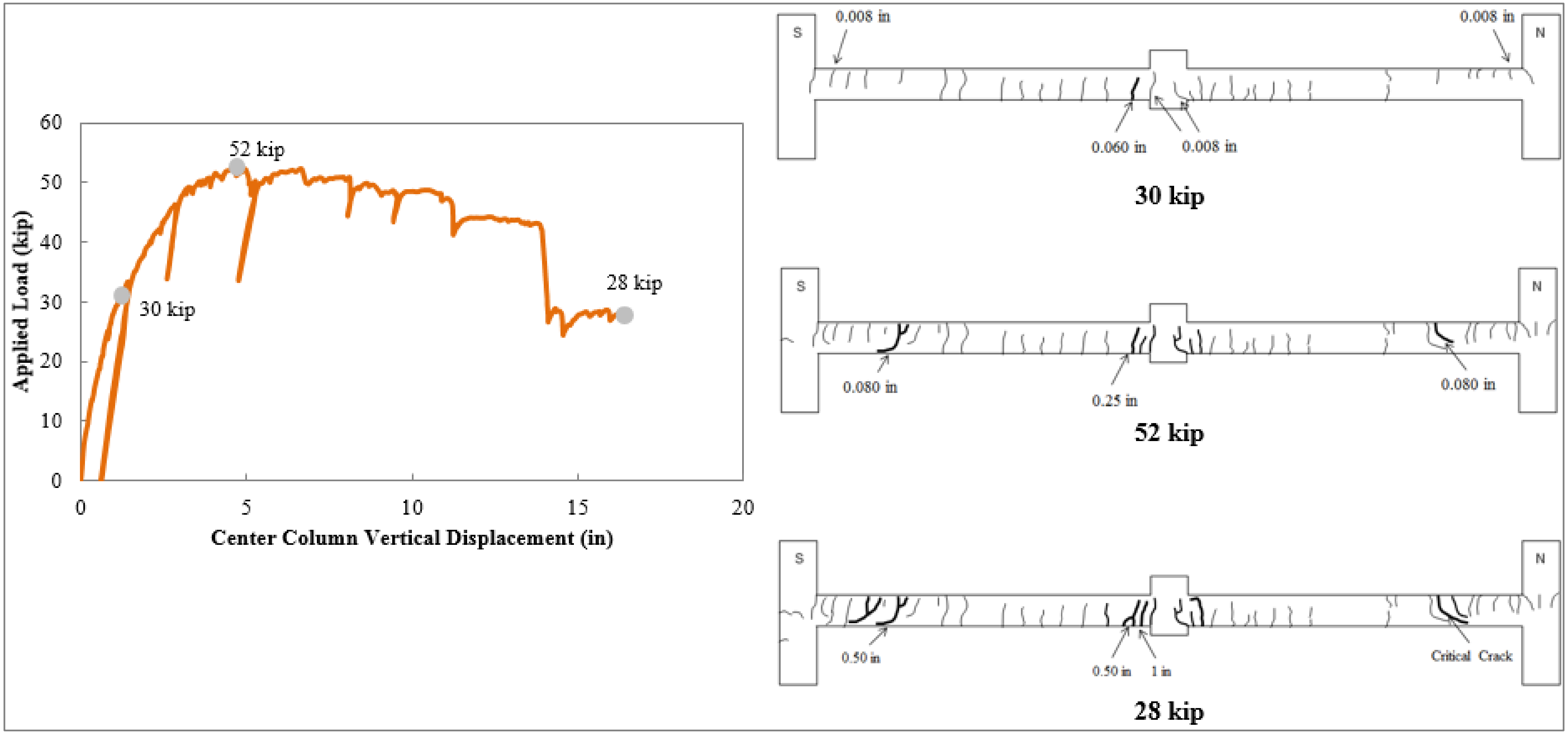
Inclinometers

Load cells



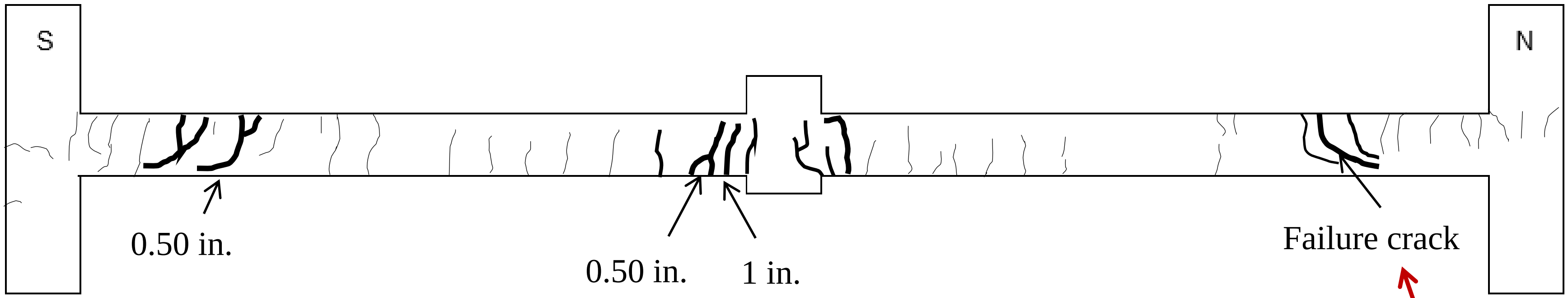
Laboratory Testing Results

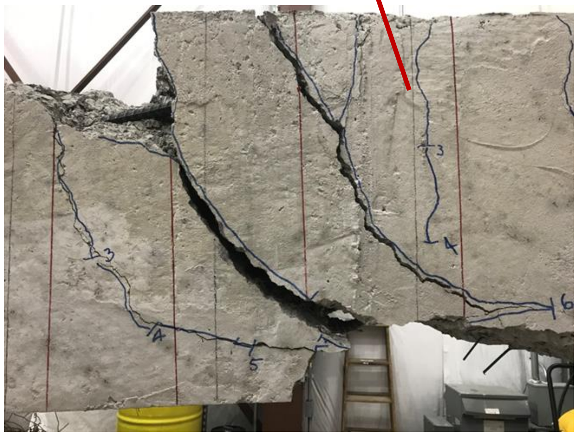
Specimen 1

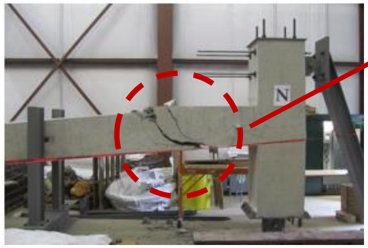


60
50
40
30
20
10
0
Applied Load (kip)
52 kip
30 kip
28 kip
0
5
10
15
20
Center Column Vertical Displacement (in)
S
N
0.008 in
0.008 in
0.060 in
0.008 in
30 kip
S
N
0.080 in
0.25 in
0.080 in
52 kip
S
N
0.50 in
0.50 in
1 in
Critical Crack
28 kip

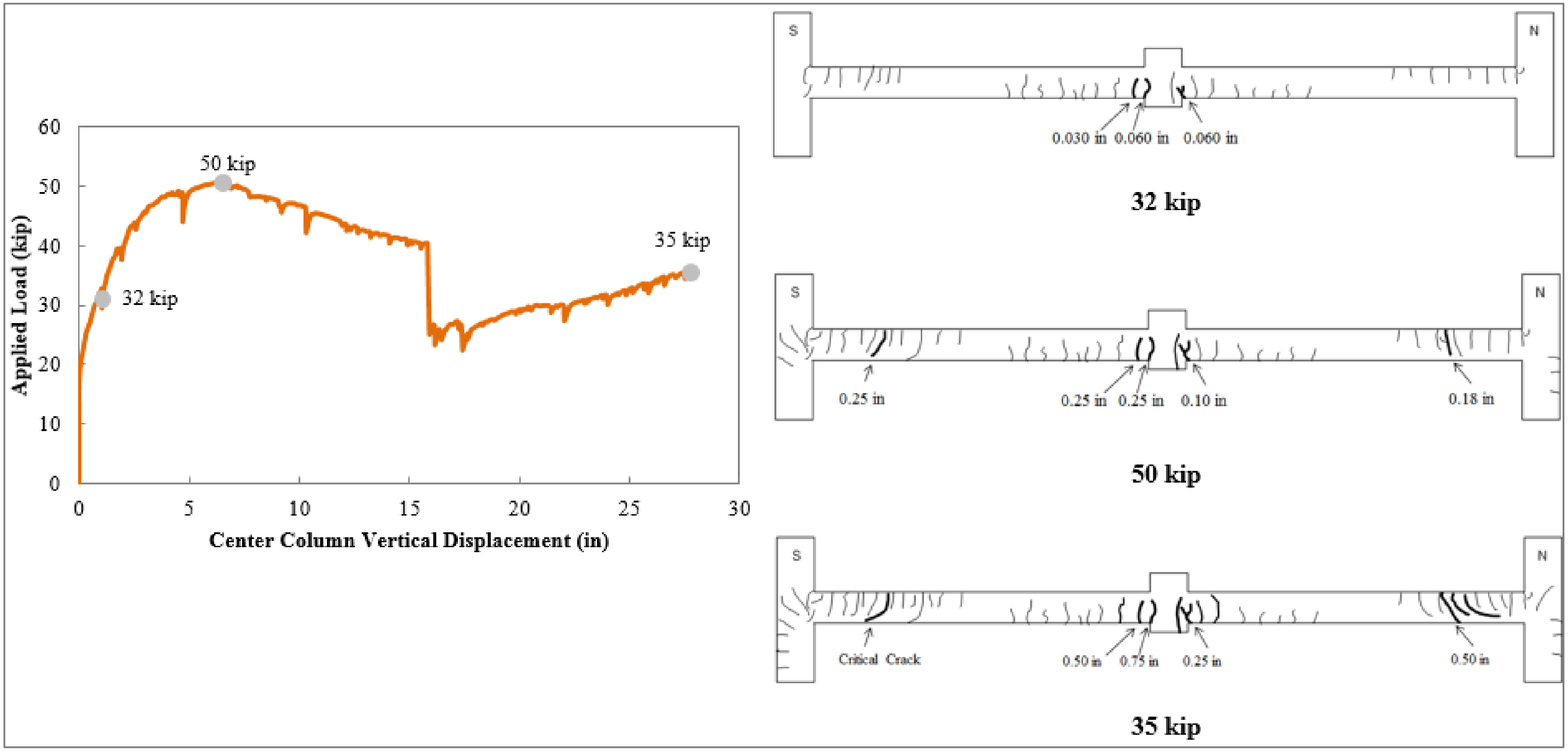
Specimen 1





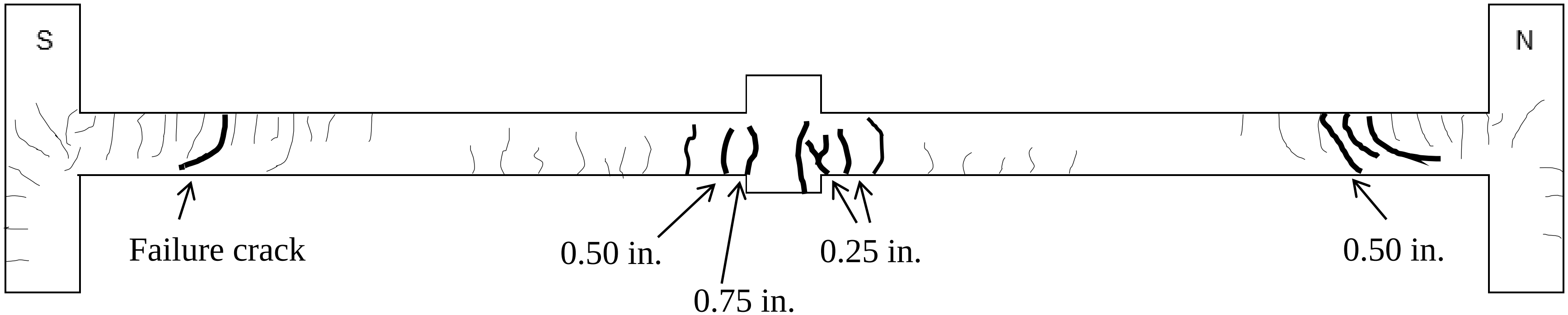


Specimen 2

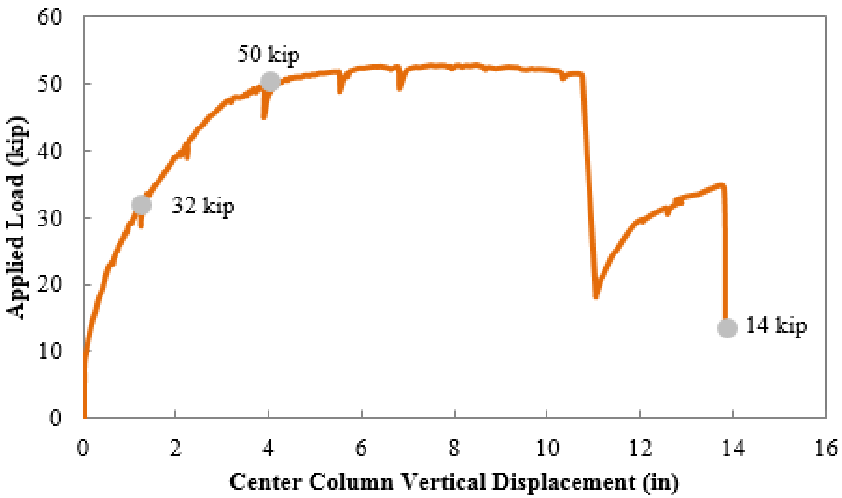


Applied Load (kip)
Center Column Vertical Displacement (in)
60
50
40
30
20
10
0
0
5
10
15
20
25
30
50 kip
32 kip
35 kip
S
N
0.030 in
0.060 in
0.060 in
32 kip
0.25 in
0.25 in
0.25 in
0.10 in
0.18 in
50 kip
Critical Crack
0.50 in
0.75 in
0.25 in
0.50 in
35 kip

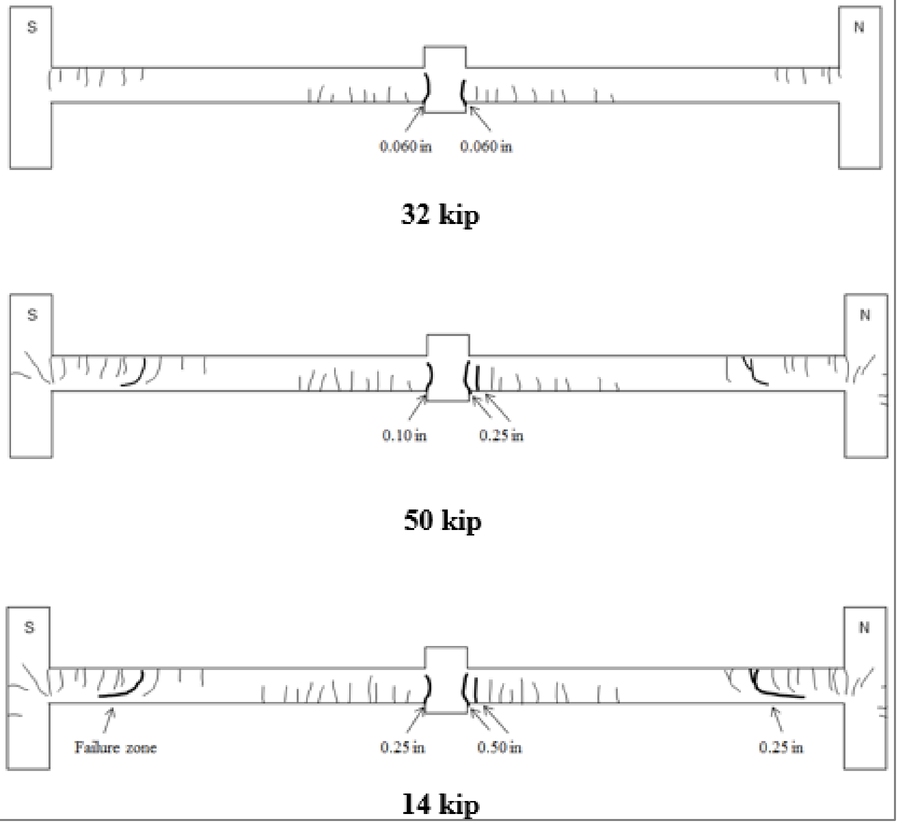
Specimen 2



Specimen 3

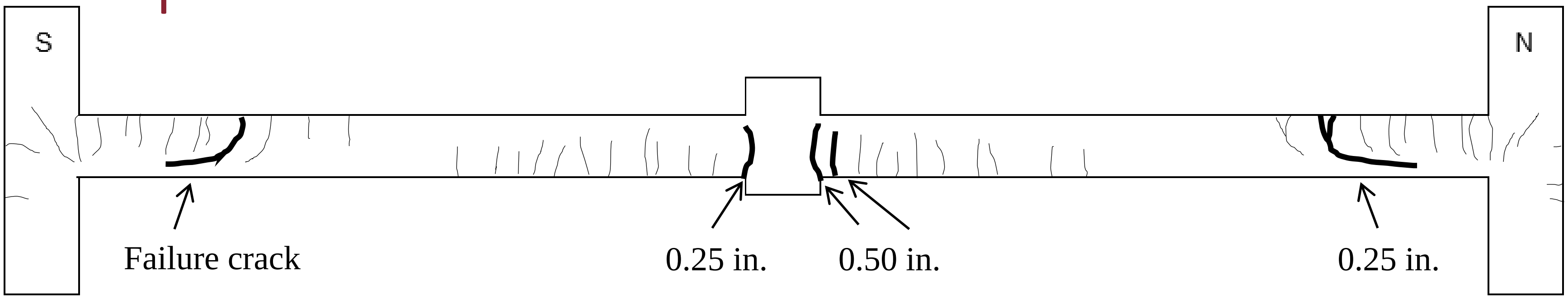


Applied Load (kip)
Center Column Vertical Displacement (in)
50 kip
32 kip
14 kip
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16

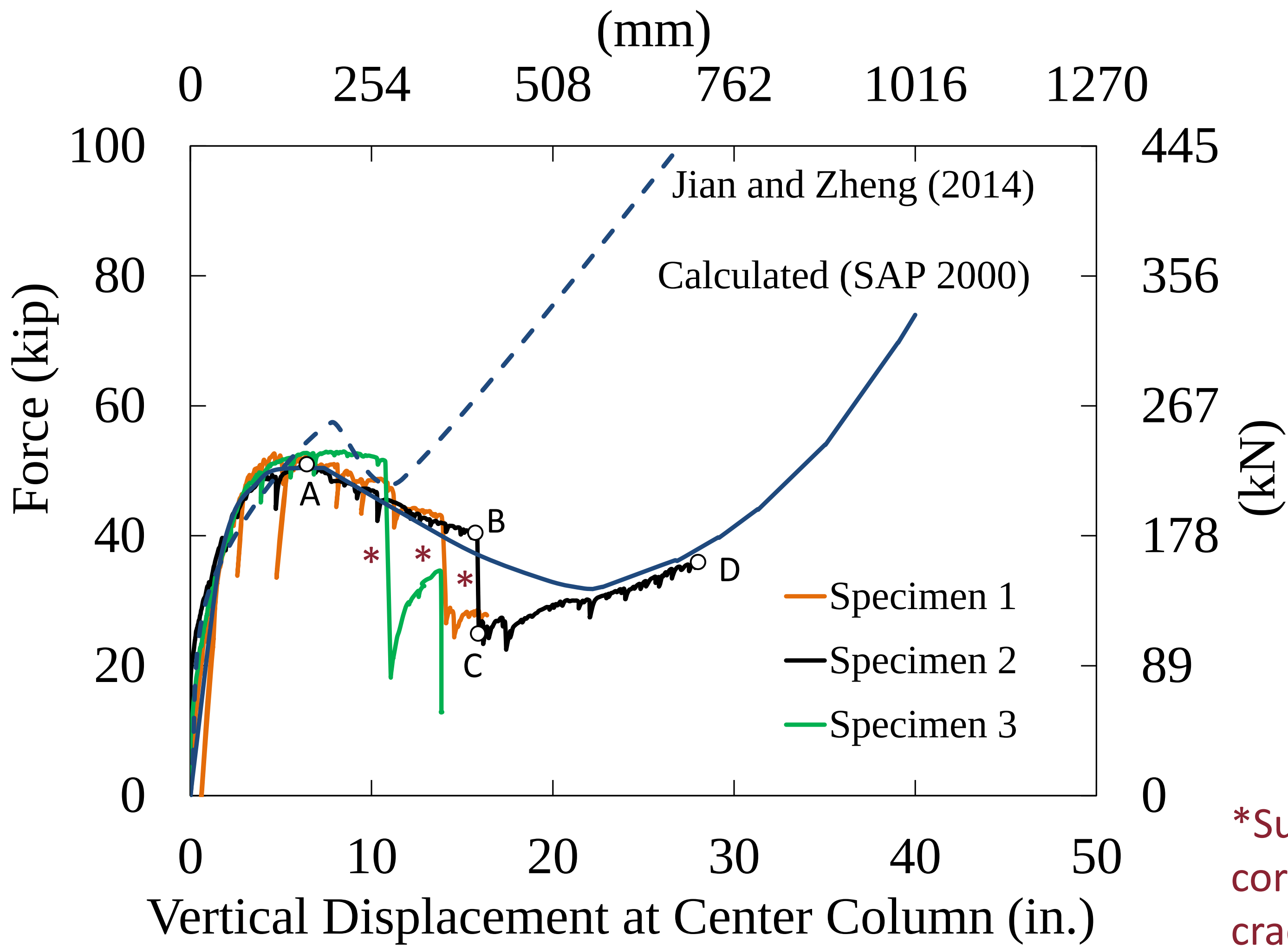


S
N
0.060 in
0.060 in
32 kip
S
N
0.10 in
0.25 in
50 kip
S
N
Failure zone
0.25 in
0.50 in
0.25 in
14 kip

Specimen 3



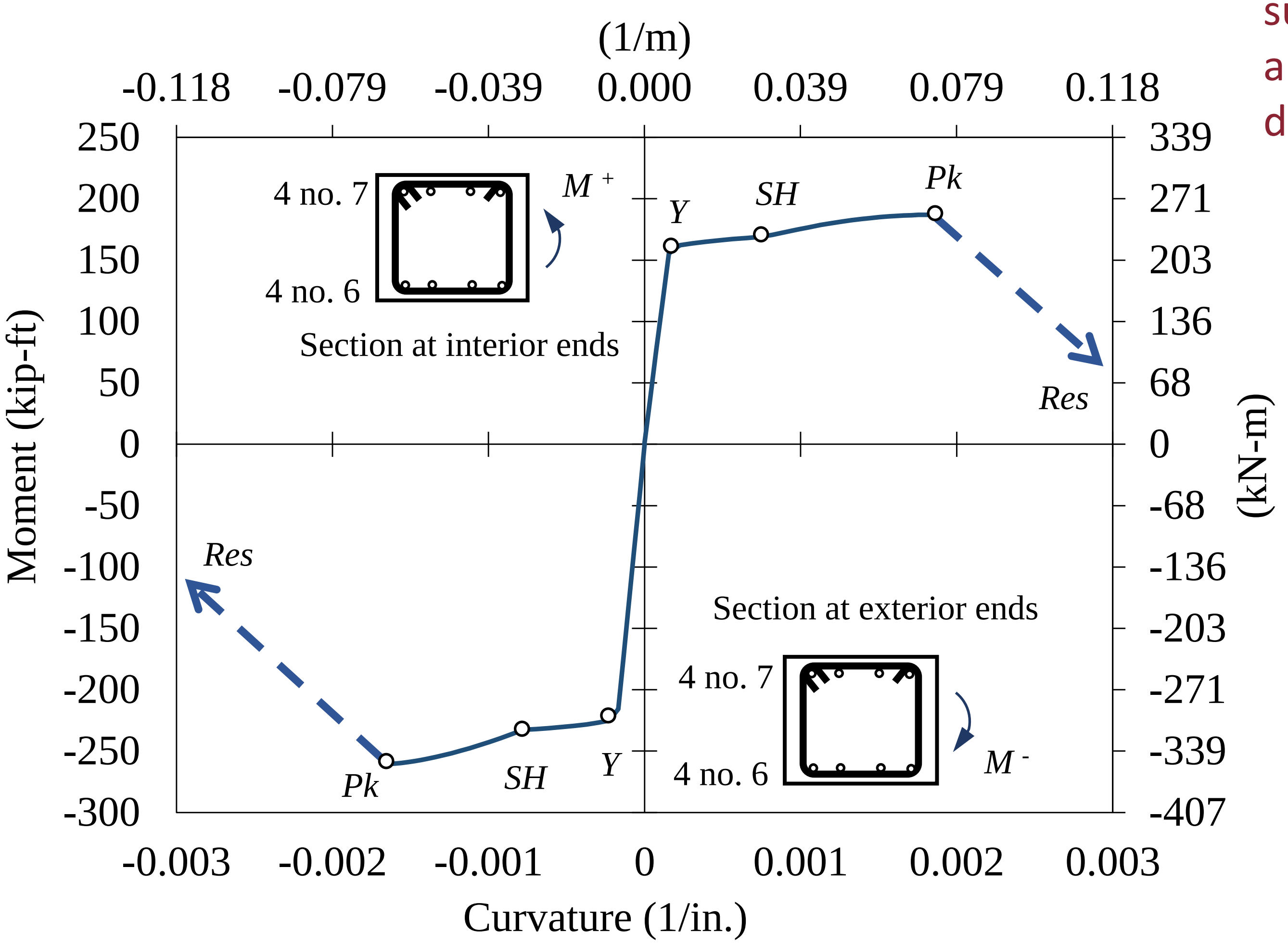
Measured and Calculated Load-Deflection Response



*Sudden drop in force corresponds to diagonal crack widening

Discussion of Testing Results

Moment-curvature Response used in SAP 2000 Analysis



Assumes gradual (not sudden) drop in strength to allow catenary behavior to develop

Y = Yield
SH = Strain hardening
Pk = Peak
Res = Residual

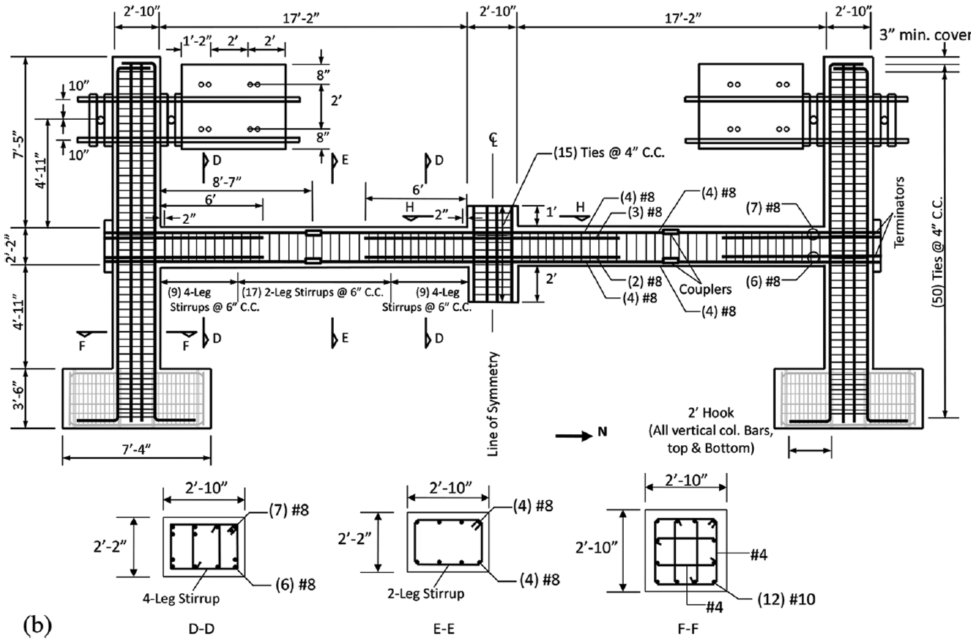
Tests by Lew et al. (2014)

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title No. 111-S74

Experimental Study of Reinforced Concrete Assemblies under Column Removal Scenario

by H. S. Lew, Yihai Bao, Santiago Pujol, and Mete A. Sozen



(b)

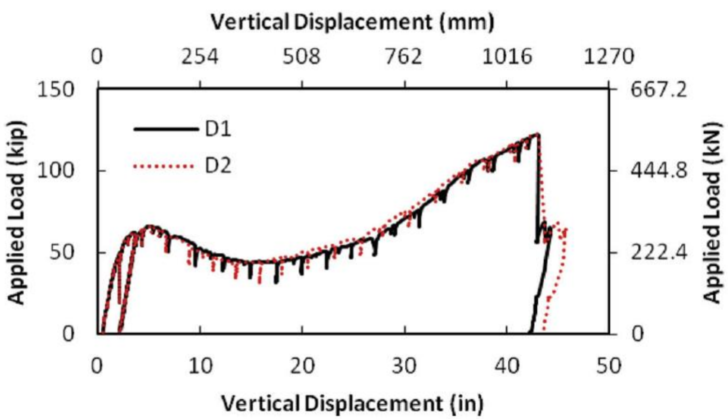


Fig. 8—Vertical load versus center column displacement for IMF specimen.

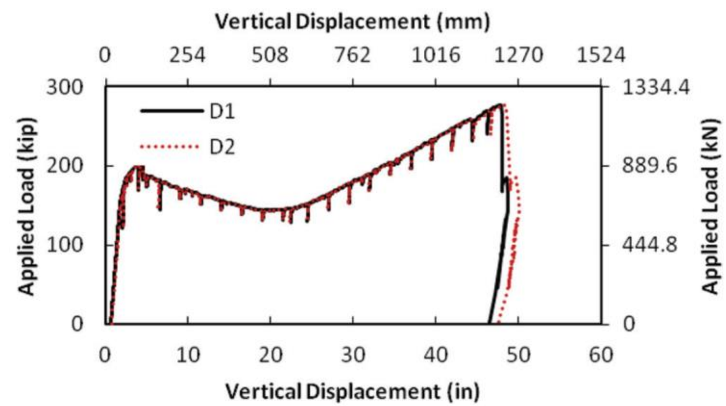


Fig. 15—Vertical load versus center-column displacement for SMF specimen.

Tests by Lew et al. (2014)

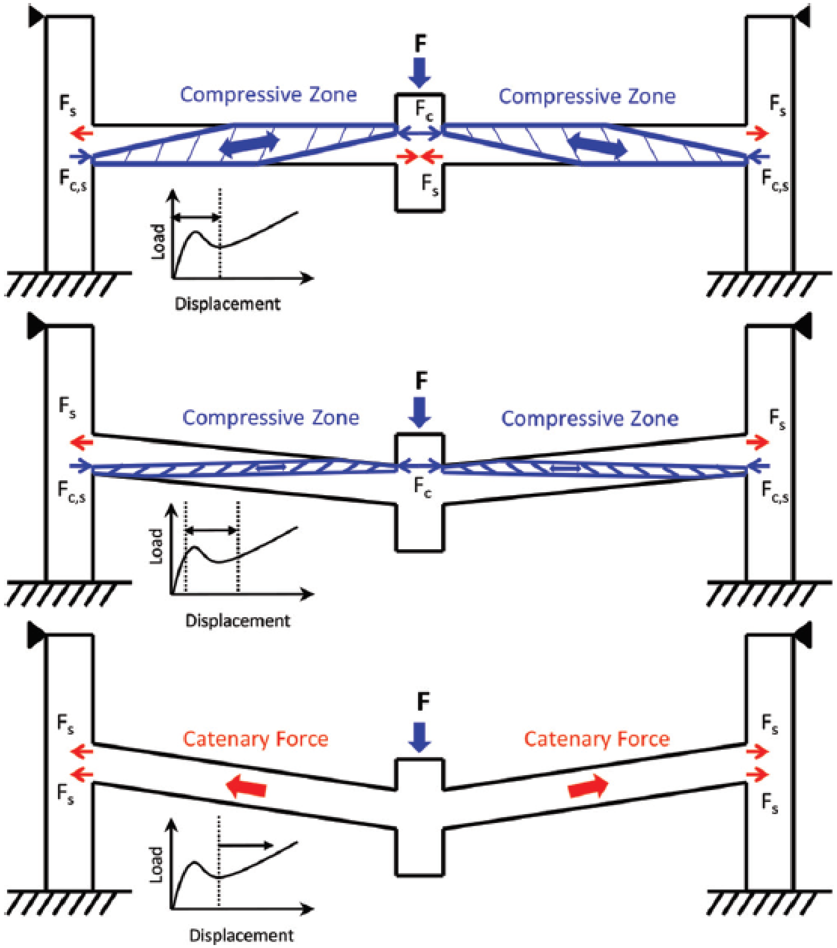
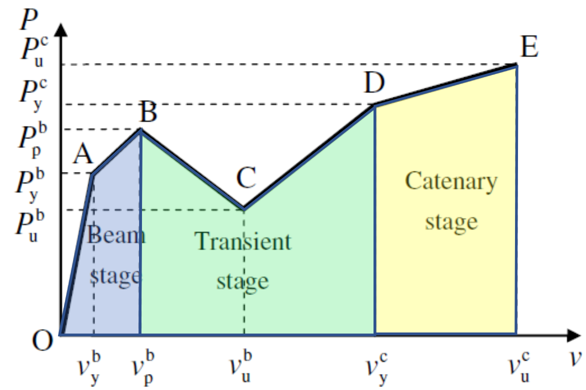


Fig. 19—Three stages of load transfer: (a) arching action; (b) plastic hinge formation; and (c) catenary action. (Note: F_s is force in steel; F_c is force in concrete; and $F_{c,s}$ is force in concrete and steel.)

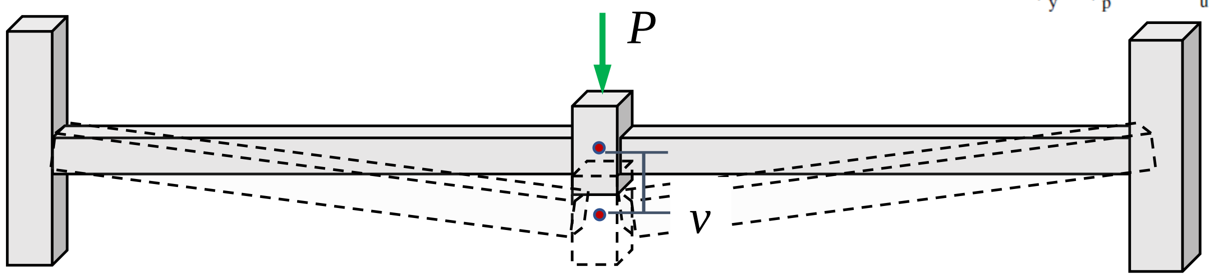
Simplified Progressive Collapse Model by Jian and Zheng (2014)



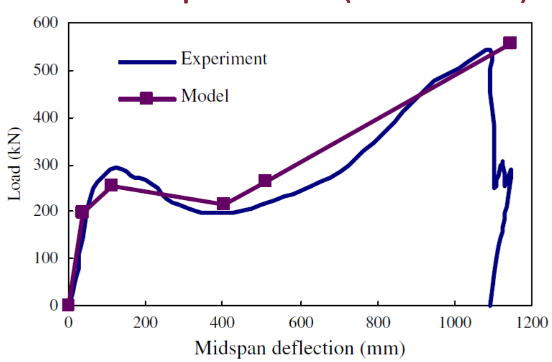
Simplified Models of Progressive Collapse Response and Progressive Collapse-Resisting Capacity Curve of RC Beam-Column Substructures

Hou Jian, Ph.D.[1]; and Yang Zheng, Ph.D.[2]

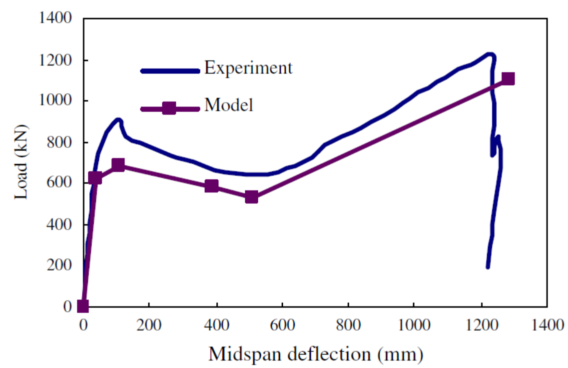
J. Perform. Constr. Facil., DOI: 10.1061/(ASCE)CF.1943-5509.0000492.



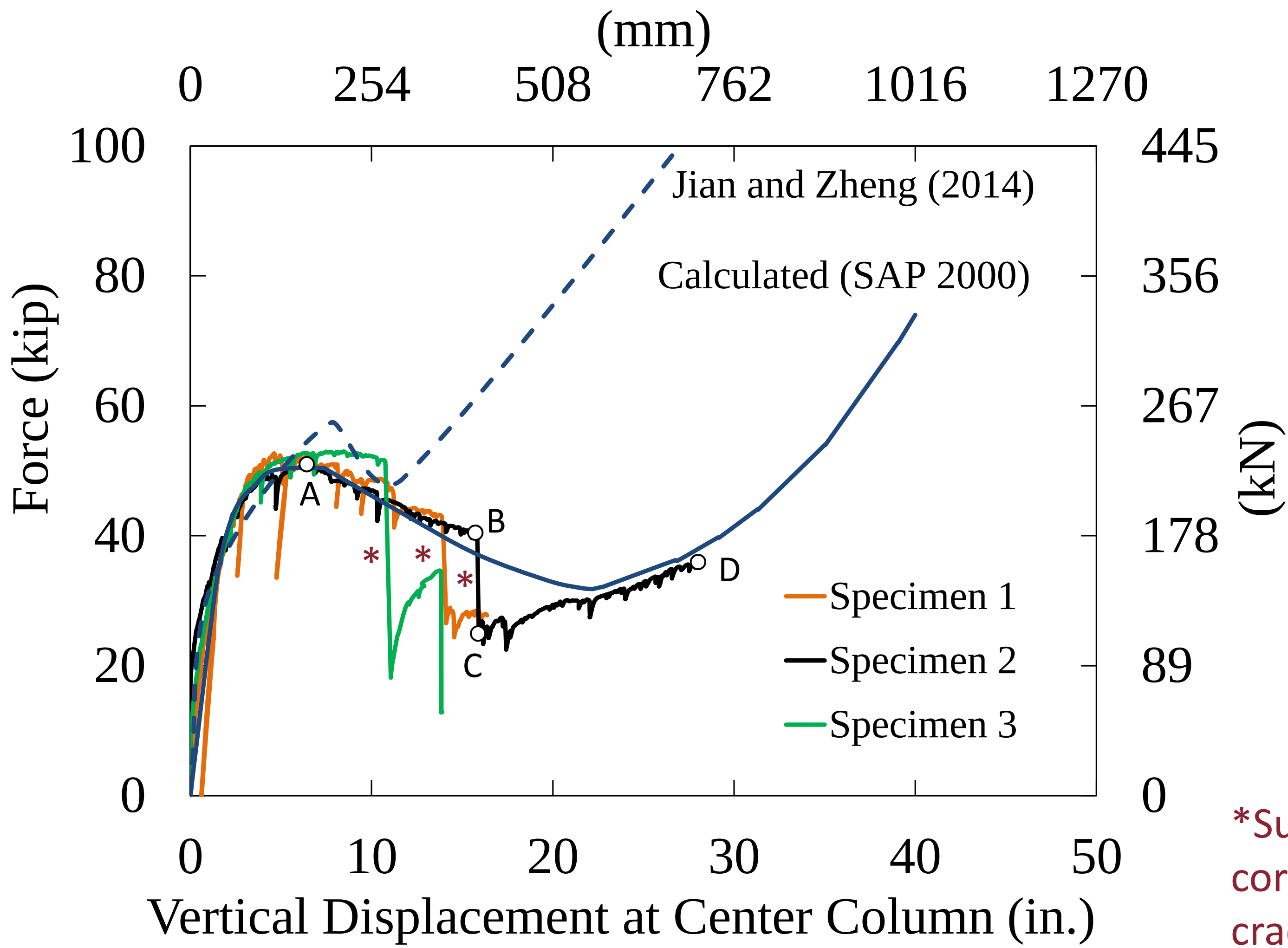
IMF Specimen (Lew et al.)



SMF Specimen (Lew et al.)

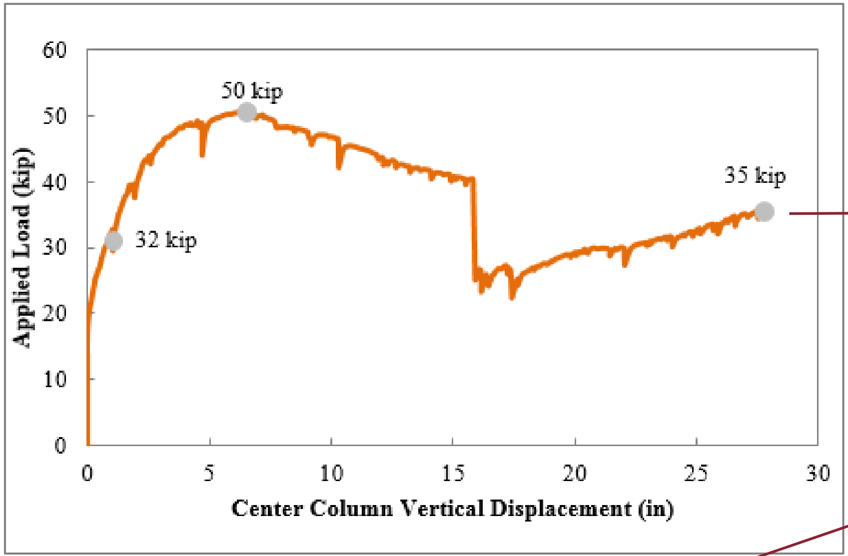


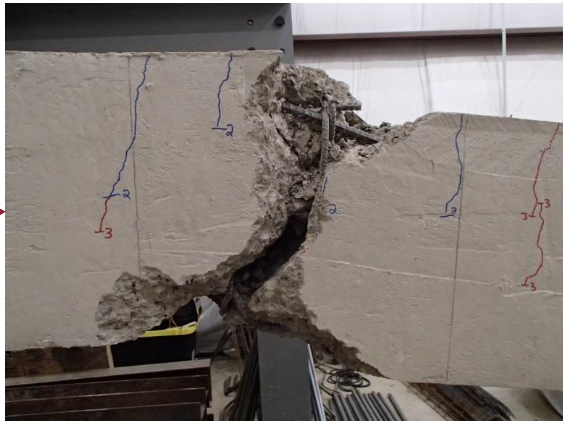
Measured and Calculated Load-Deflection Response

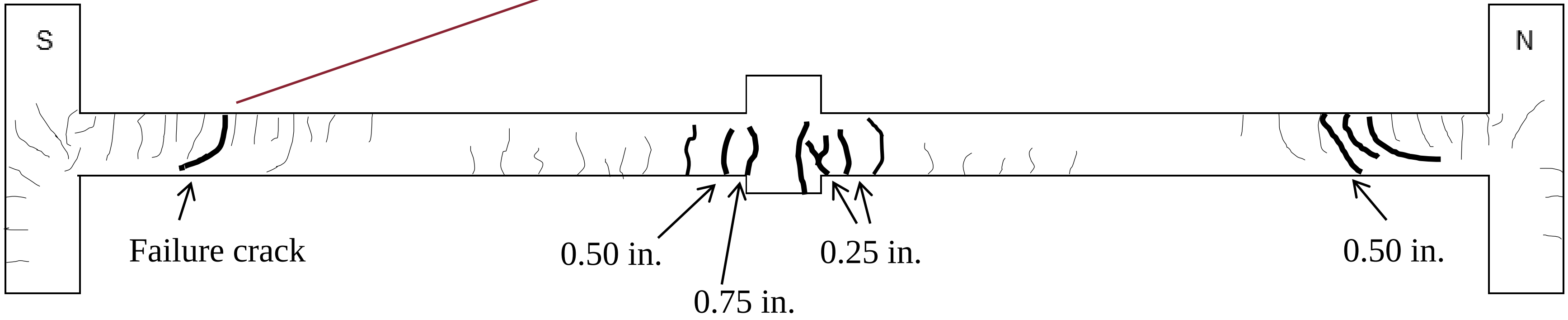


*Sudden drop in force corresponds to diagonal crack widening

Critical Diagonal Crack and Stirrup Fracture – Specimen 2







Concrete Contribution to Shear Strength

$$V_c = \left[2\lambda\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d$$

ACI 318-19 (22.5.5.1a)

$$V_c = \left[8\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d$$

ACI 318-19 (22.5.5.1b)

Note ACI 318 equations do not consider reduction of Vc with plastic rotational demand

$$V_c = \alpha\beta\gamma\sqrt{f_c'}\left(0.8A_g\right)$$

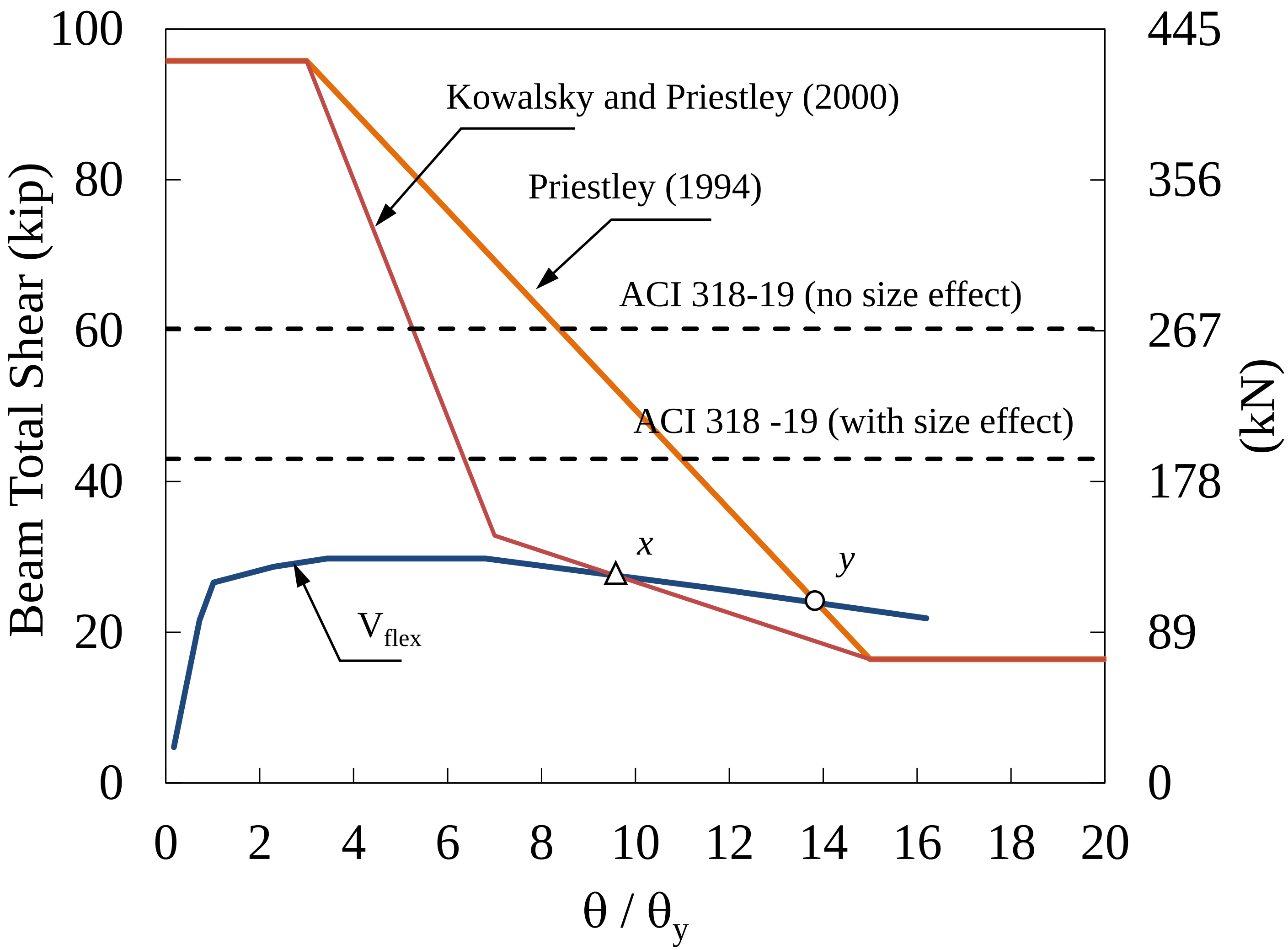
Kowalsky and Priestley (2000)

$$\gamma = \begin{cases} 3.5 & \text{for } \theta/\theta_y \le 3 \\ 3.5 - \frac{2.9}{12}\left(\theta/\theta_y - 3\right) & \text{for } 3 < \theta/\theta_y < 15 \\ 0.6 & \text{for } \theta/\theta_y \ge 15 \end{cases}$$

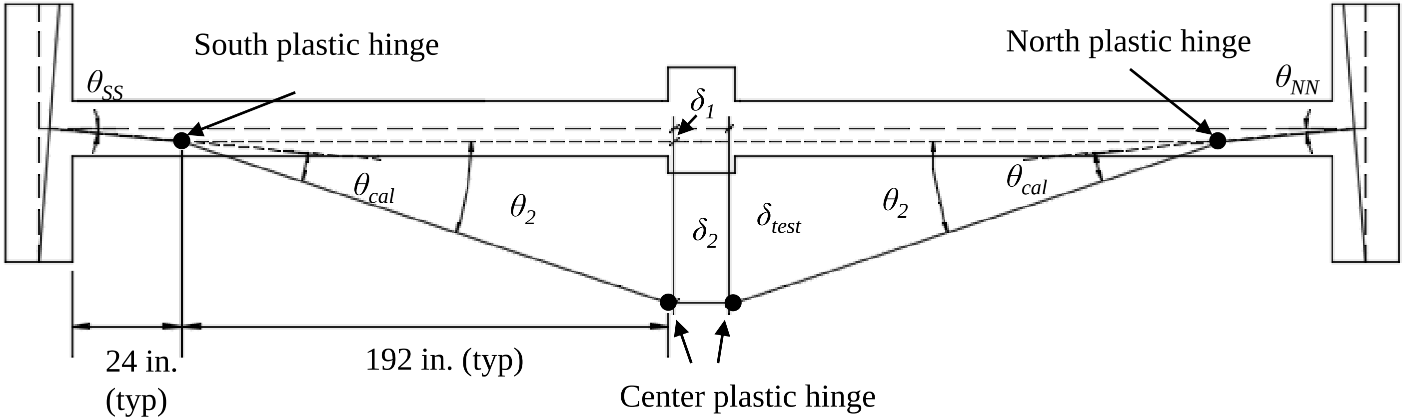
Priestley et al. (1994)

$$\gamma = \begin{cases} 3.5 & \text{for } \theta/\theta_y \le 3 \\ 3.5 - \frac{2.3}{4}\left(\theta/\theta_y - 3\right) & \text{for } 3 < \theta/\theta_y \le 7 \\ 1.2 - \frac{0.6}{8}\left(\theta/\theta_y - 7\right) & for\ 7 < \theta/\theta_y < 15 \\ 0.6 & for\ \theta/\theta_y \ge 15 \end{cases}$$

Reduction in V_c with Rotation Demand



Simplified Model to Estimate Rotation of Inelastic Hinges



Specimen	δ_{test}, in.	Beam end	θ_{SS} or θ_{NN}, rad	δ_1, in.	δ_2, in.	θ_2, rad	θ_{cal}, rad	$\frac{\theta_{cal} + \theta_D}{\theta_y}$*
Peak Load (Point A)								
1	6.7	South	0.015	0.36	6.3	0.033	0.018	4.3
		North	0.015	0.36	6.3	0.033	0.018	4.3
2	7.6	South	0.011	0.26	7.3	0.038	0.027	6.4
		North	0.005	0.12	7.5	0.039	0.034	7.9
3	7.4	South	0.014	0.34	7.1	0.037	0.023	5.4
		North	0.015	0.36	7.0	0.037	0.022	5.1
Diagonal Crack Widening (Point B)								
1	13.9	South	–§	–§	–§	–§	–§	–§
		North	0.029	0.70	13.2	0.069	0.040	9.2
2	15.8	South	0.018	0.43	15.4	0.080	0.062	14.3
		North	0.008	0.19	15.6	0.081	0.073	16.8
3	10.5	South	0.019	0.46	10.0	0.052	0.033	7.8
		North	0.019	0.46	10.0	0.052	0.033	7.8

§Instrument malfunction; *$\theta_D = 0.0008$ rad , $\theta_y = 0.0044$ rad

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Conclusions

- Bottom longitudinal bar splice location did not influence the behavior of the specimens tested in this research.

- Catenary behavior of the specimens was not developed because of loss of load-carrying capacity due to premature failure in shear at moderate rotation demands.

- Models that include reduction in V_c with increased rotational demand provided reasonable estimates of the rotations at loss of V_c contribution to shear strength for the beams tested in this research.

- Steep diagonal cracking after loss of V_c resulted in low residual shear strength and subsequent fracture of closed stirrups. A 45-degree truss model did not correctly estimate residual shear strength.

Acknowledgements

- CRSI for providing a graduate student fellowship
- Northeast Alliance for Graduate Education and the Professoriate
- Gerdau Steel for donating reinforcing steel used in the specimens
- The late Robert B. Brack for his longstanding support of the CEE program at UMass

Questions?