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Seismic evaluation of columns to improve design criteria for transverse reinforcement

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ABSTRACT: This paper describes a test program to develop design criteria for transverse reinforcement in reinforced concrete columns for seismic resistant buildings. Variables include level of axial load, amount and type of transverse reinforcement, and details of transverse reinforcement. Results indicate that flexural capacity of a column increases with axial load but deformability reduces substantially. Reduction in the amount of transverse reinforcement results in lower deformability. Details of transverse reinforcement including hook bends and hook extensions can be further simplified.

1 INTRODUCTION

Columns in building frames are normally designed not to hinge, crush, or otherwise lose their capacity to support the building during an earthquake. However, columns in buildings subjected to an earthquake may sometimes be subjected to forces that cause hinging. The possibility of hinging occurring at the column ends makes it important to ensure that columns are capable of behaving in a ductile manner under the required deformations.

Performance of concrete structures in recent earthquakes has clearly demonstrated the need for adequate information on behavior and design of columns (Ghosh and Corley 1986, Zeris and Altmann 1984: 823-830, Kreger and Sozen 1983, and Reconnaissance Report 1980). Inadequate transverse column reinforcement has resulted in severe damage to structures. Current code provisions (ACI Building Code 1983 and Uniform Building Code 1985) for confining steel are based on providing confinement to increase concrete strain capacity. However, confinement reinforcement may not always be the governing criteria for columns. Transverse reinforcement is also needed to prevent premature buckling of vertical reinforcement and to provide shear resistance at the potential plastic hinge regions. As part of the experimental program being carried out at Construction Technology Laboratories (CTL), test columns with differing amounts and details of transverse reinforcement and under different levels of axial load are subjected to moment reversals at increasing inelastic deformations. Observed behavior from the tests of ten columns is described and a summary of the test results is presented.

2 EXPERIMENTAL PROGRAM

Dimensions and reinforcement details of a representative test specimen are illustrated in Figs. 1 and 2. Design compressive strength of concrete was 6,000 psi (41.4 MPa). Specified yield stress of vertical and transverse reinforcement was 60 ksi (414 MPa). Vertical reinforcement consisted of eight No. 8 bars providing a reinforcement ratio of 0.0195.

2.1 Test specimens

Ten full-scale column specimens have been tested. The test portion of each specimen represents the column extending upward from the beam-column connection to approximately the point of inflection. Cross-sectional dimensions are 18x18 in. (457x457 mm) and height between horizontal supports is 10.5 ft (3.20 m). The beam portion was simulated

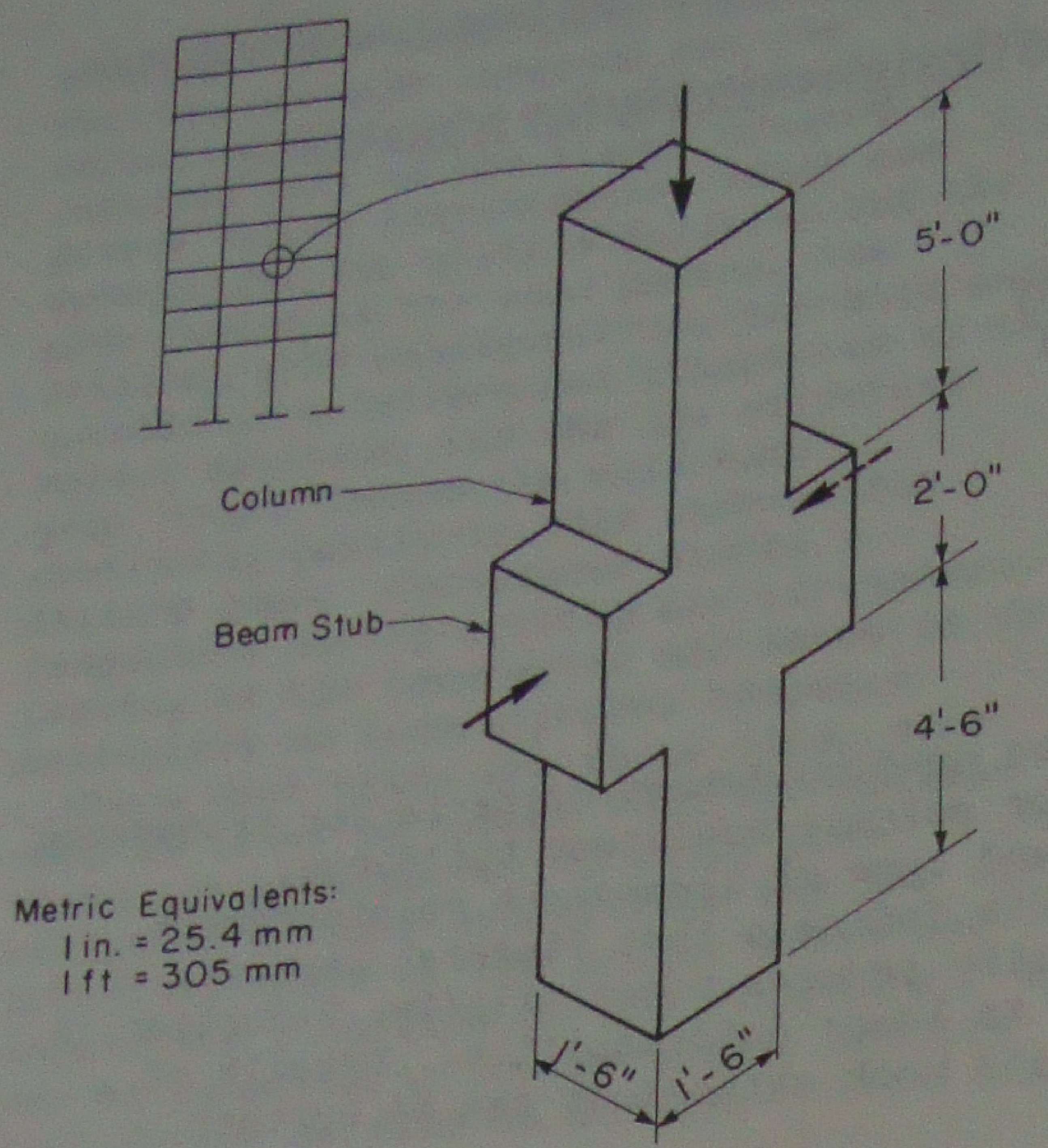


Figure 1. Test specimen.

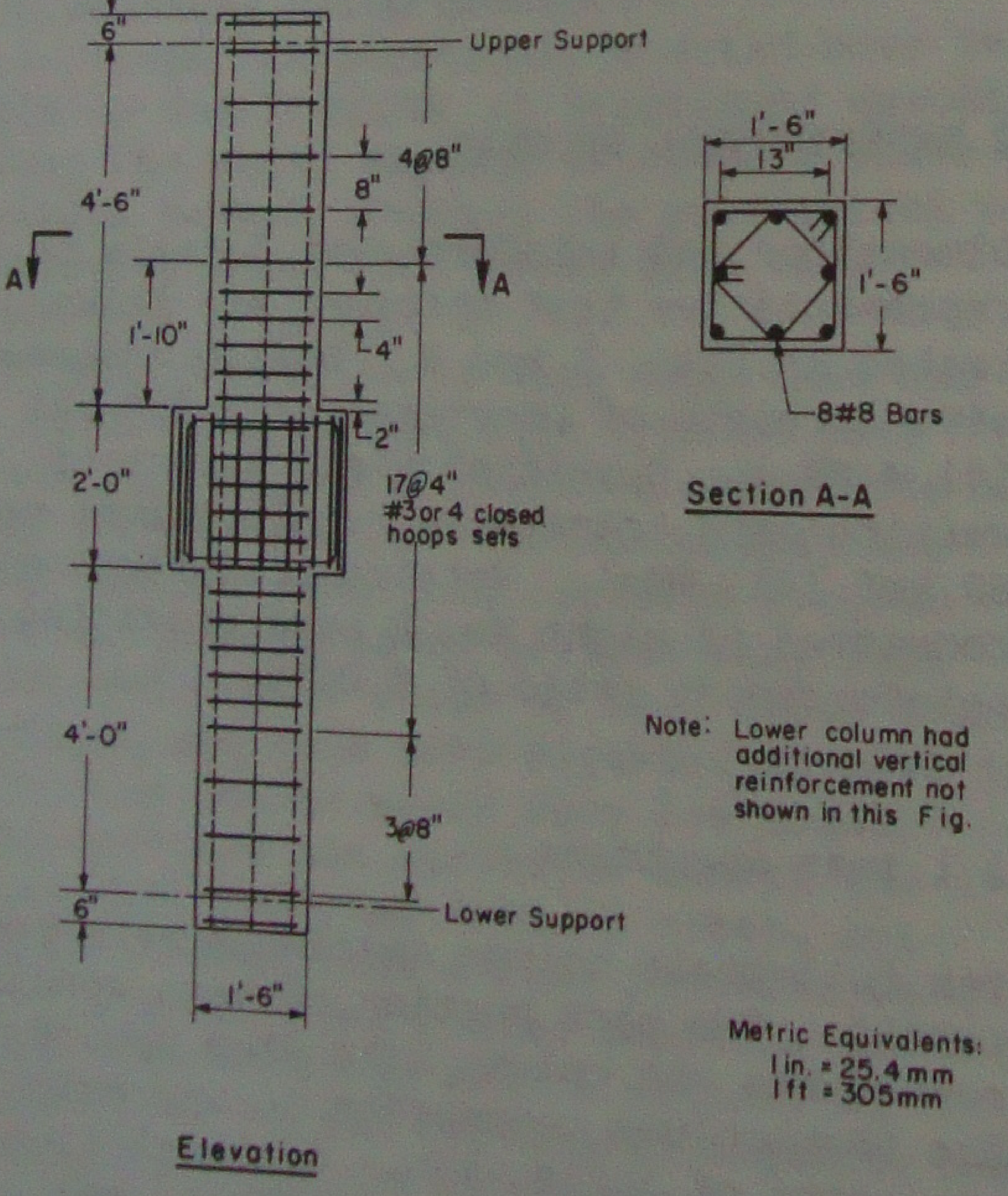


Figure 2. Representative reinforcement details.

by a short stub that also provided a loading point for the lateral load. Test specimens were designed and detailed in a manner to force hinging into the upper column.

Applied vertical load, P_V, for each specimen is listed in Table 1. Level of vertical load ranged from 20 to 40% of the column axial load capacity, P_O. Column axial load capacity, P_O, was determined in accordance with ACI Building Code requirements.

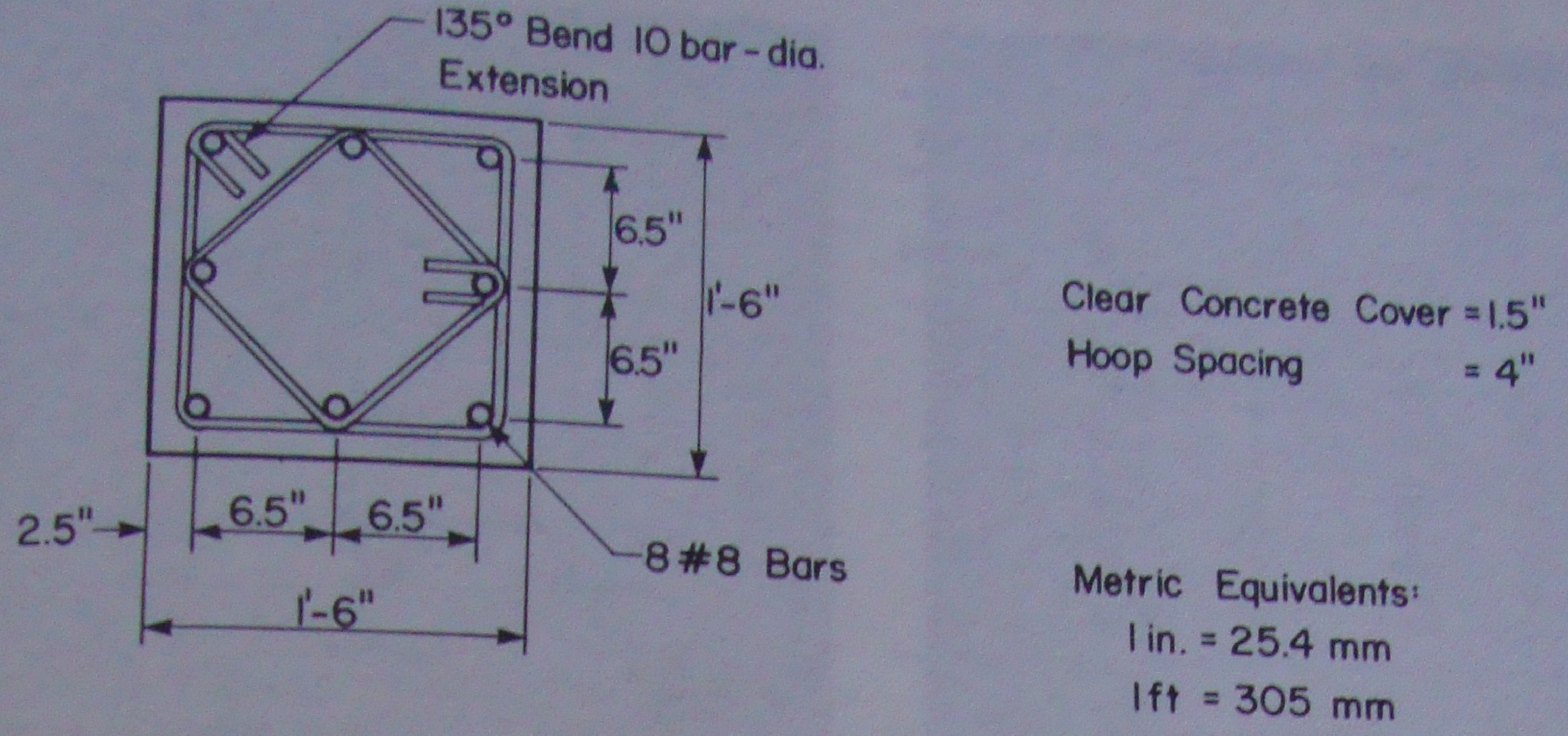
2.2 Reinforcement details and materials

Transverse reinforcement details designated A, B, C, D, and E are shown in Fig. 3, and listed in Table 1. Transverse reinforcement for test specimen NC-1, as shown in Fig. 3(a), was designed in accordance with the provisions of Section A.4.4 of the ACI Building Code. This required 135 degree hook bends with 10 bar-diameter extensions for both inner and peripheral confining hoops. For all other specimens, hook extensions were reduced to six bar-diameter lengths. In addition, in Specimens NC-2, NC-3, NC-4, NC-5, and NC-8, hook bends for the inner hoops were reduced to 90 degrees as shown in Fig. 3(b). Specimen NC-5 also used overlapping peripheral hoops as shown in Fig. 3(c). Specimen NC-6 used single peripheral hoops with 135 degree hook bends and six bar-diameter extensions as shown in Fig. 3(d).

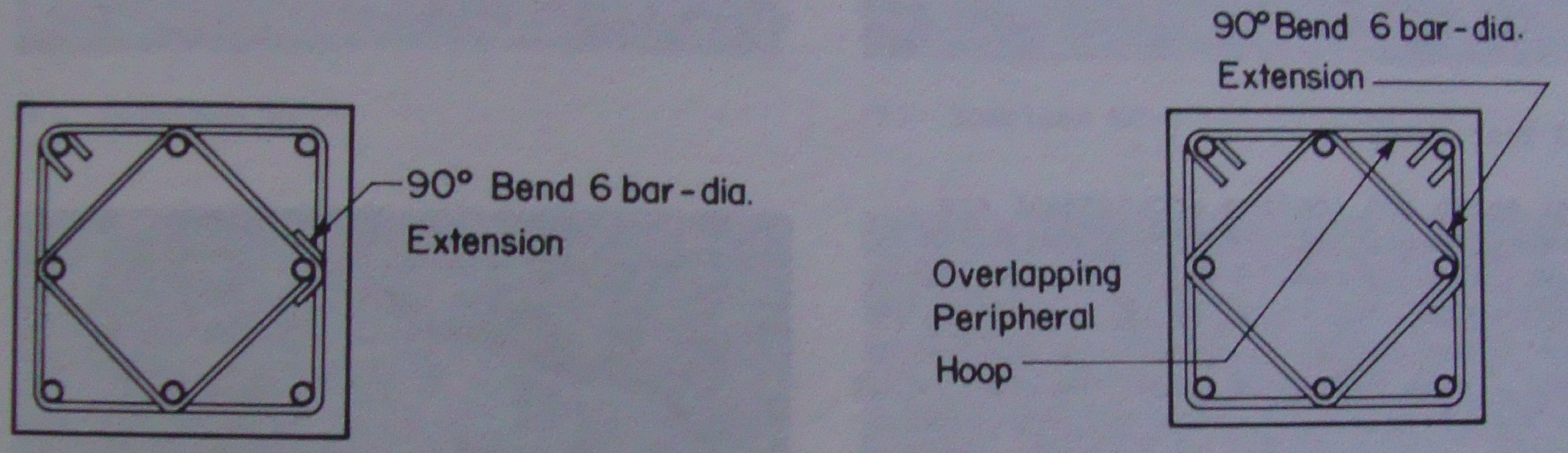
Transverse reinforcement for Specimen NC-7 also consisted of single peripheral hoops. Each of these hoops was formed with four identical ties as shown in Fig. 3(e). Specimen NC-8 used an arrangement as shown in Fig. 3(b) except that the inner and peripheral hoops were staggered vertically to provide a 2-in. (50 mm) center-to-center spacing between them.

Transverse reinforcement for Specimen NC-9 consisted of a No. 4 continuous square helix at 4-in. (100 mm) pitch. Specimen NC-10 used a No. 3 continuous square helix at 2-1/4 in. (57 mm) pitch.

The length of column confined by transverse reinforcement was kept constant at 22 in. (0.56 m). Except for Specimens NC-8, NC-9, and NC-10, hoops were spaced 4 in. (100 mm) on centers in the confined region. These three specimens used staggered spacing and square helixes as described previously. Transverse reinforcement in the unconfined region of column was designed to carry maximum shear stress. Clear cover was maintained at 1.5 in. (38 mm) in upper and lower columns.

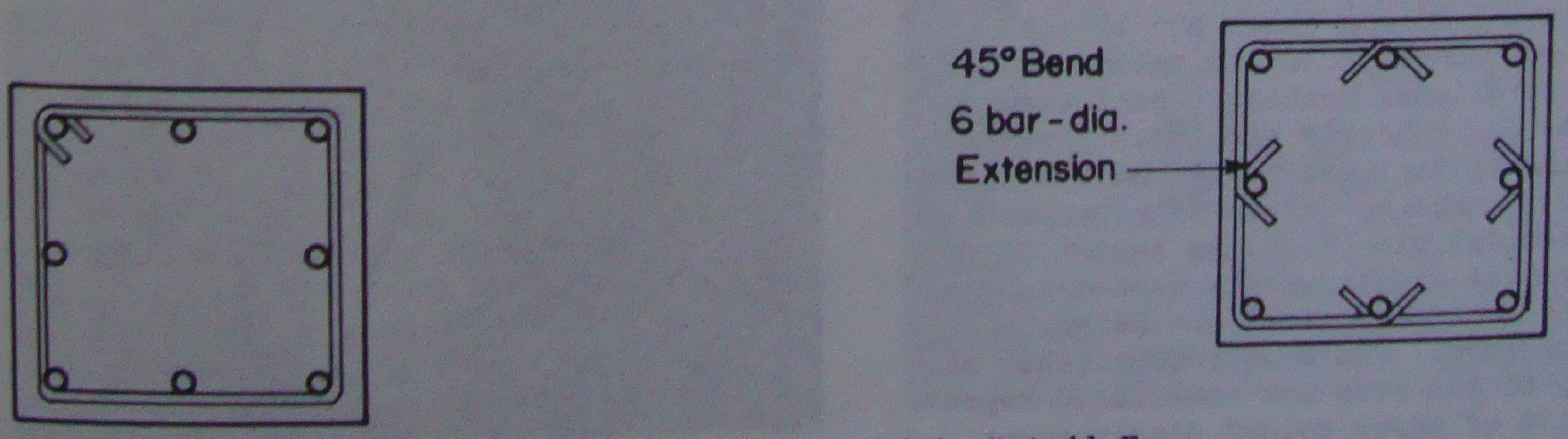


(a) Detail A



(b) Detail B

(c) Detail C



(d) Detail D

(e) Detail E

Figure 3. Details of transverse reinforcement.

Table 1. Details of test variables.

Specimen Designation	Vertical Load		Transverse Reinforcement		
	P_v/P_o	kips	Detail	A_{sh} (in.^{2})	Percent
NC-1	0.30	570	A	0.68	2.19
NC-2	0.20	380	B	0.68	2.19
NC-3	0.40	780	B	0.68	2.19
NC-4	0.30	580	B	0.38	1.26
NC-5	0.30	575	C	0.68	2.19
NC-6	0.30	520	D	0.40	1.29
NC-7	0.30	540	E	0.40	1.29
NC-8	0.30	560	B*	0.68	2.19
NC-9	0.30	530	D**	0.40	1.29
NC10	0.30	550	D†	0.22	1.29

*Detail B modified by staggering inner and peripheral hoops.
**No. 4 continuous square helix at 4-in. (100-mm) pitch.
†No. 3 continuous square helix at 2-1/4-in. (57-mm) pitch.

Metric Equivalents:
1 kip = 4.45 kN
1 in. = 25.4 mm

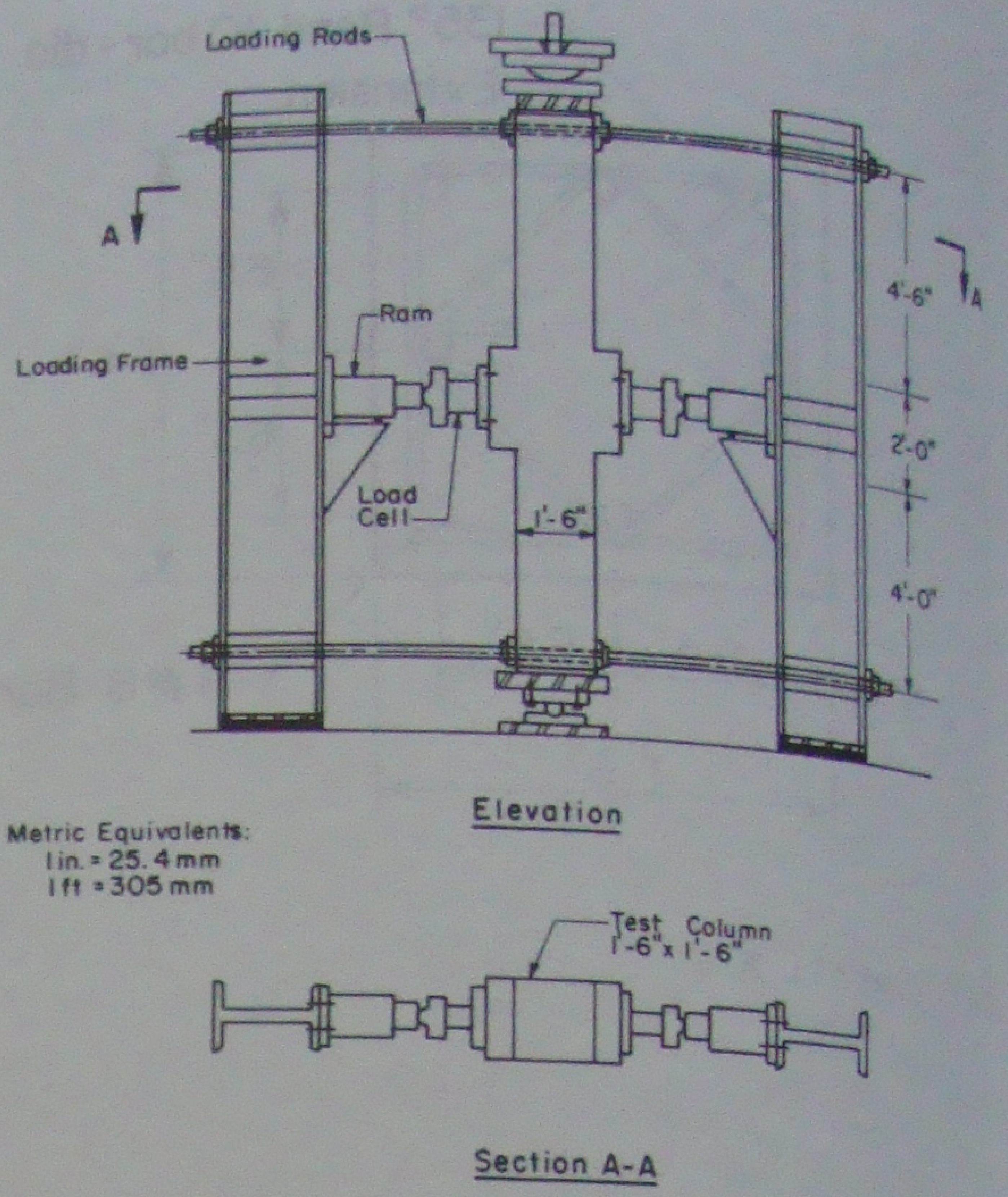


Figure 4. Test setup.

2.3 Test setup

Test setup and loading arrangement are shown schematically in Fig. 4 and 5. A one-million-lb (4448 kN) capacity testing machine was used to apply the vertical compressive force. Lateral load was applied with hydraulic rams pushing against reaction frames.

2.4 Instrumentation

Several types of instruments were required to obtain load-displacement, moment-curvature, vertical bar strain profiles, confining hoop strains, plastic hinge lengths, and maximum concrete compressive strains. External measurements were used to determine column axial and lateral loads, horizontal column displacements, column rotations, vertical reinforcement strains, and concrete strains. Internal measurements included strain on the vertical and transverse column reinforcement in the potential plastic hinge region.

Horizontal displacements were measured at three locations along the height of the test specimen. The measurement taken at the top of the stub was considered representative of upper column displacement. Groups of linear potentiometers were used to measure column rotations over gage lengths above the beam stub. By considering a pair of potentiometers measuring

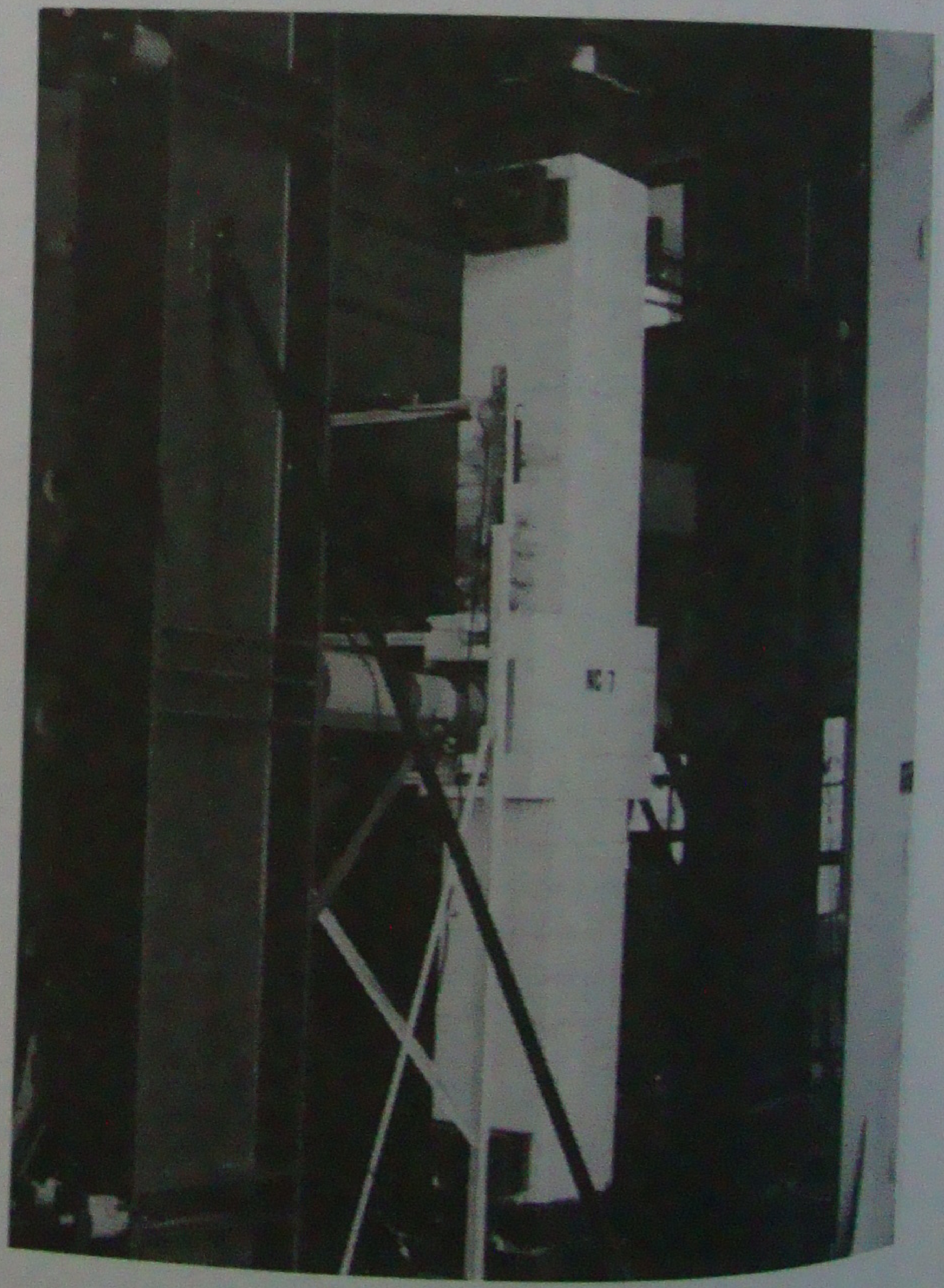
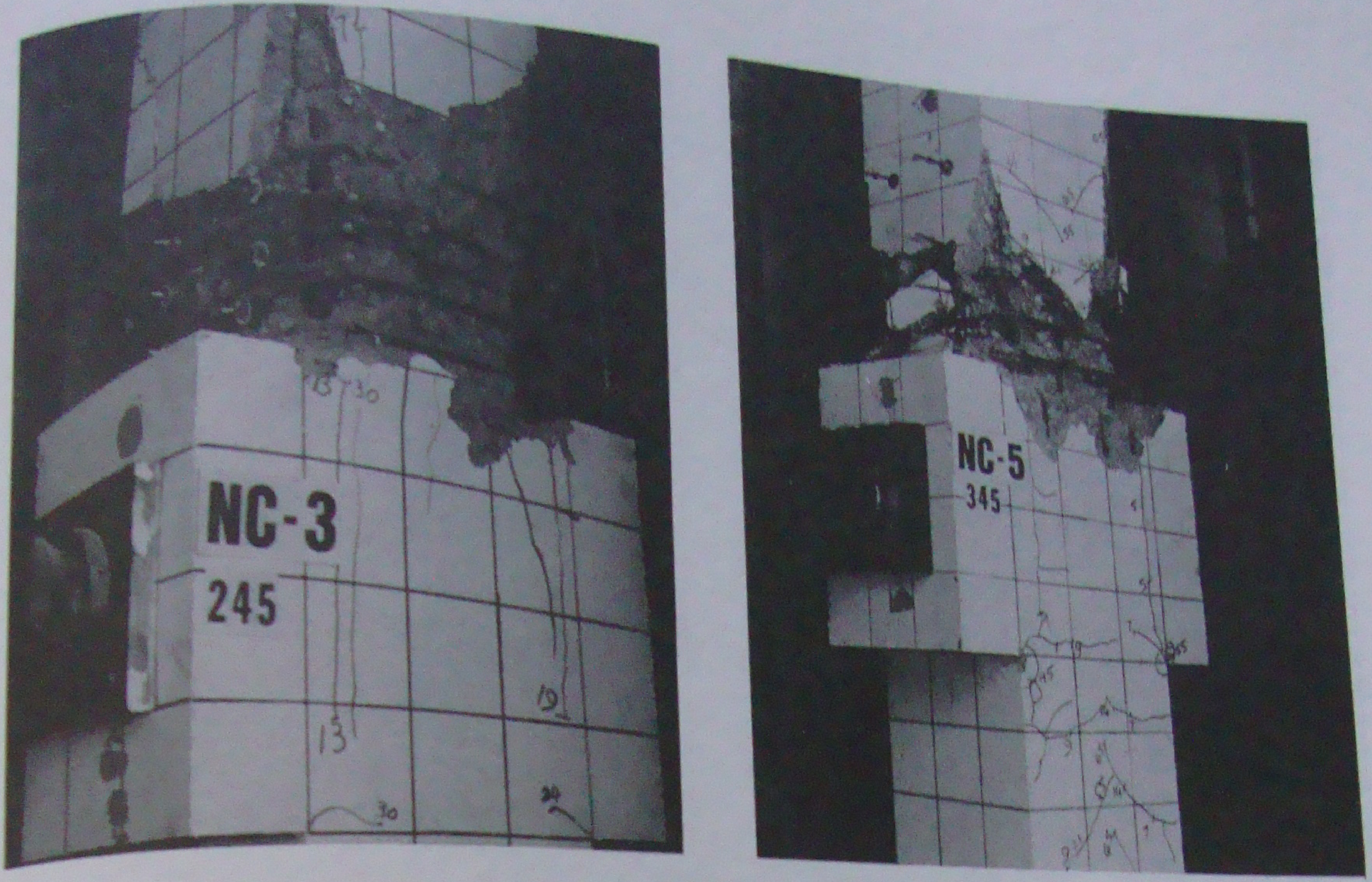
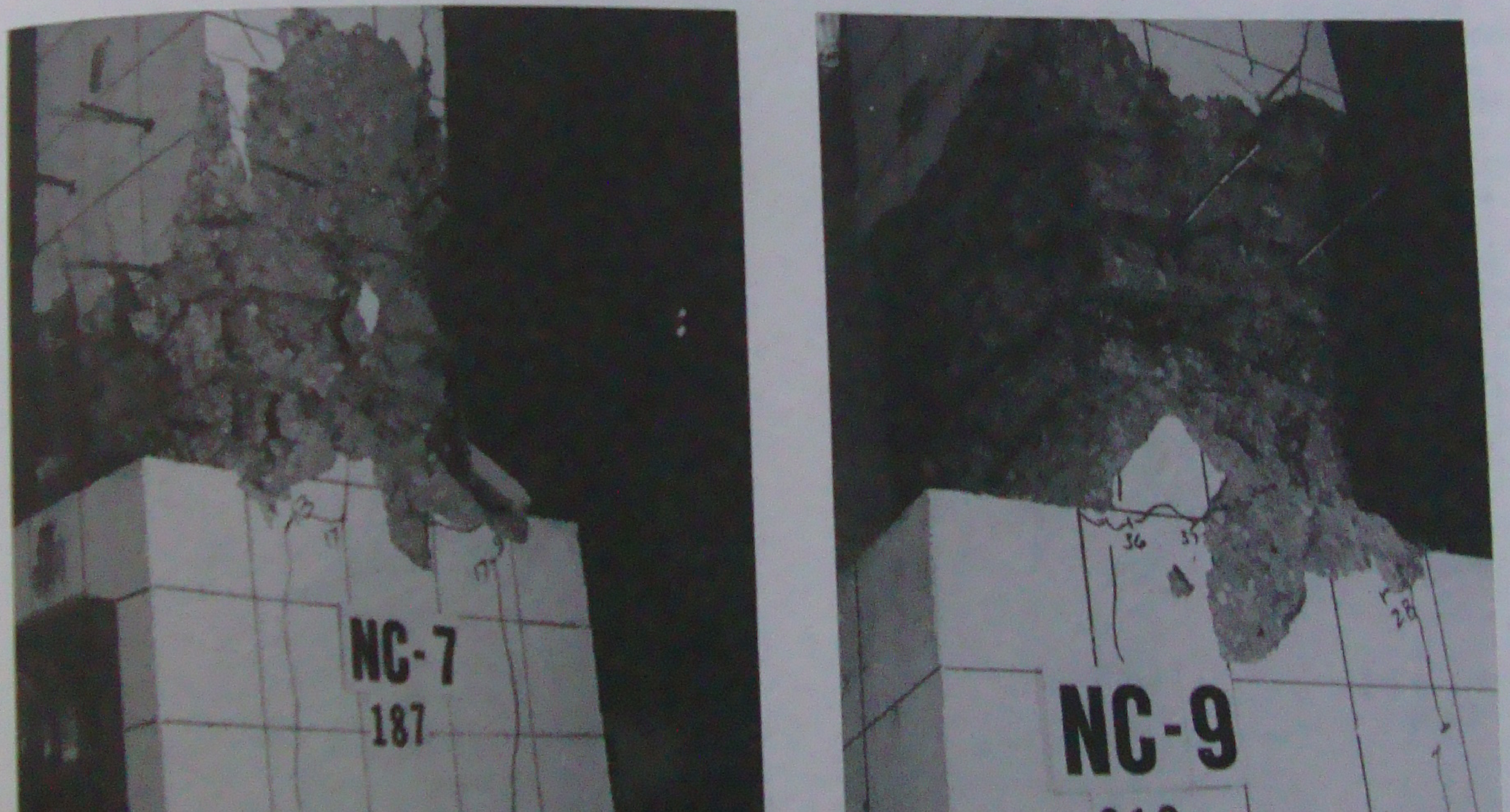


Figure 5. Loading arrangement.



(a) Specimen NC-3

(b) Specimen NC-5



(c) Specimen NC-7

(d) Specimen NC-9

Figure 6. Column specimens after test.

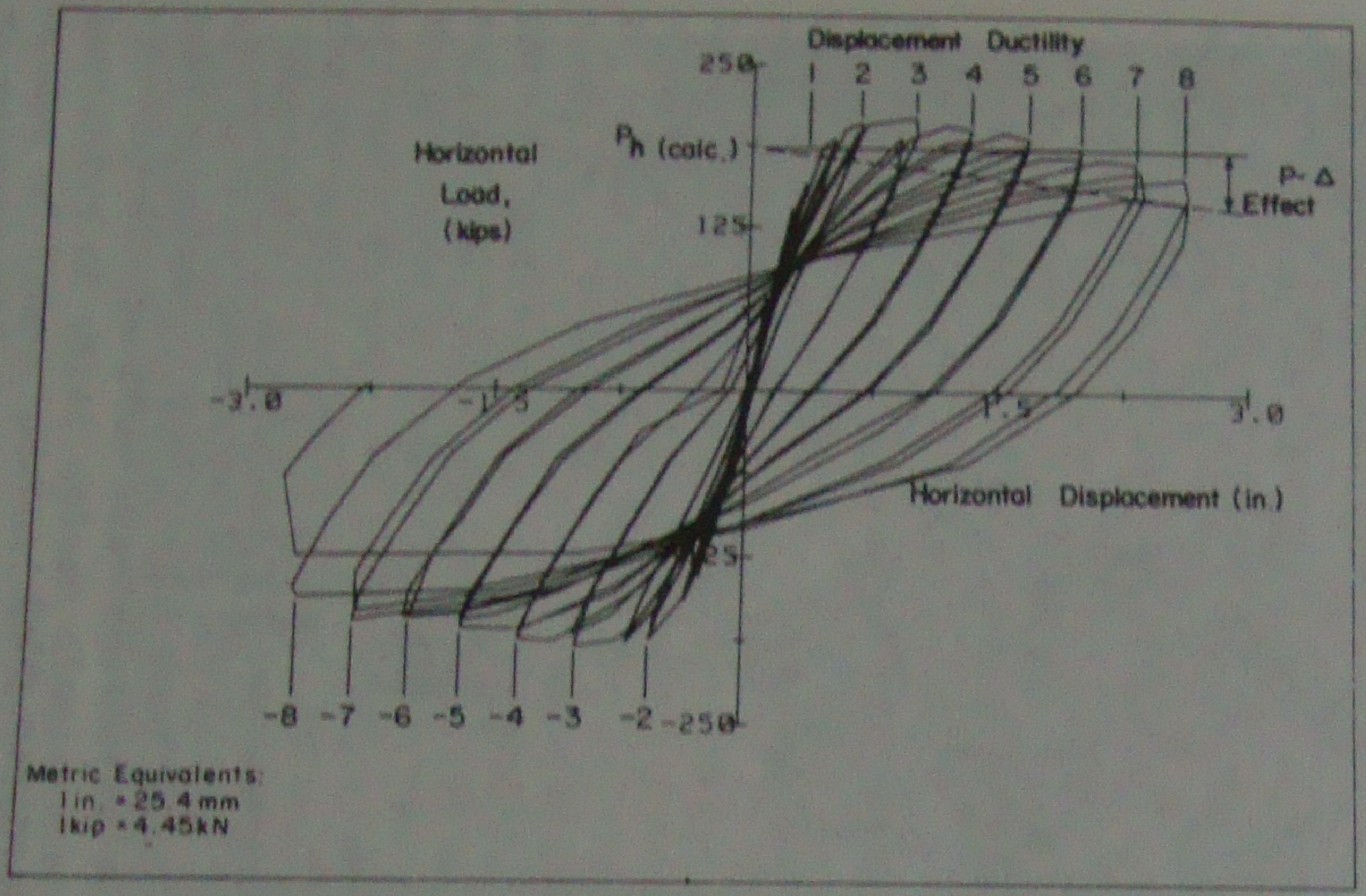


Figure 7. Horizontal Load versus Displacement for Specimen NC-2

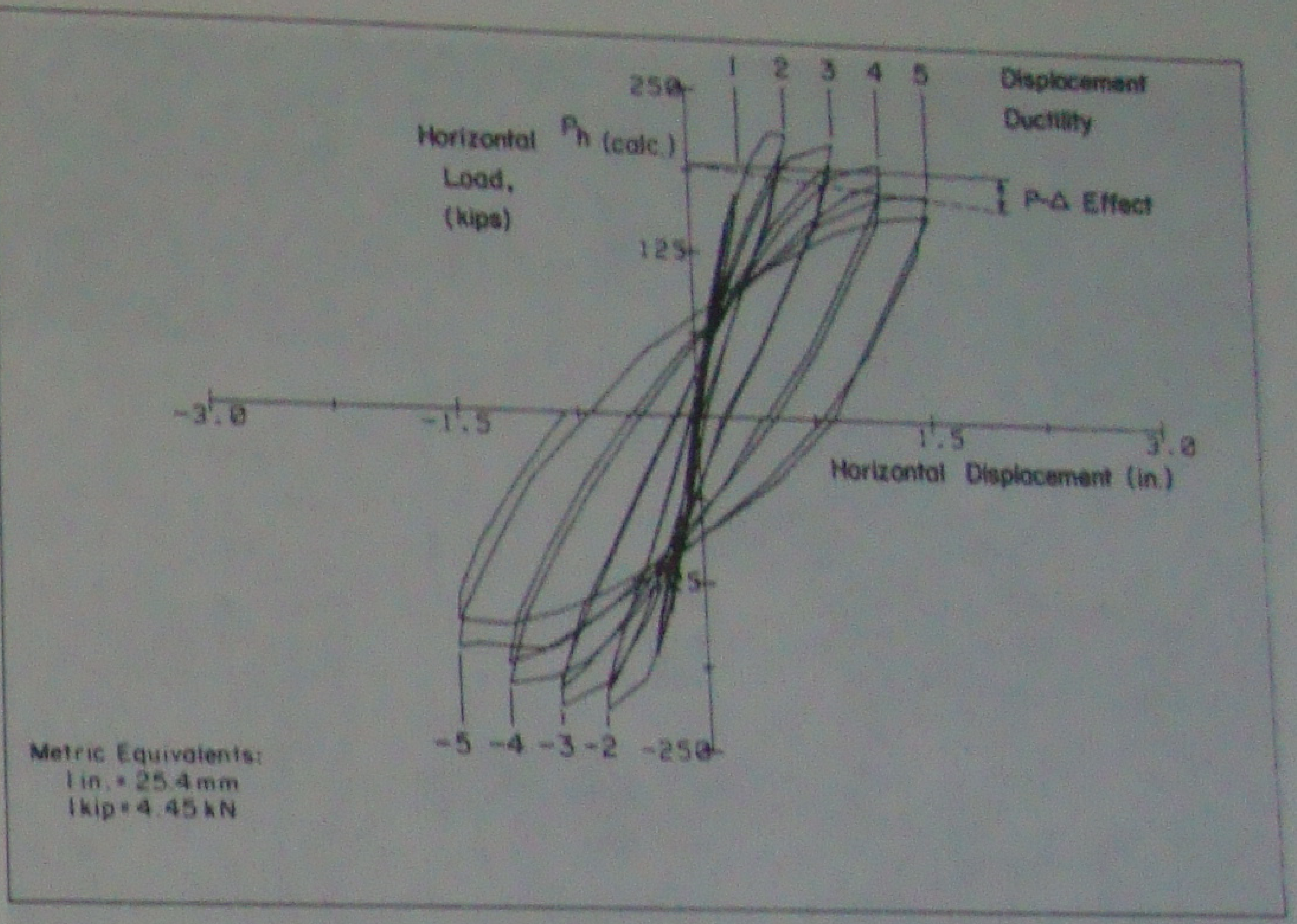


Figure 8. Horizontal Load versus Displacement for Specimen NC-4

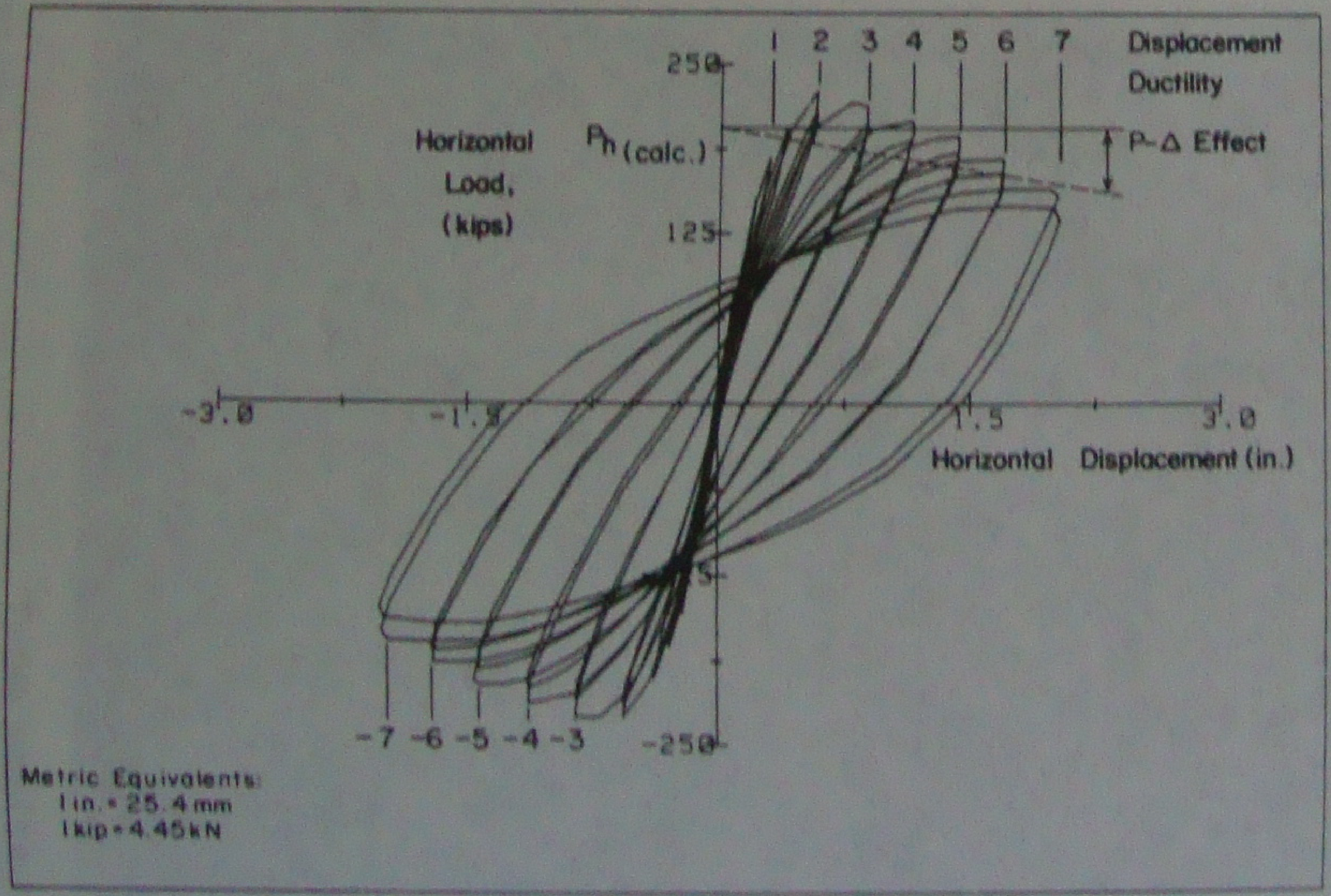


Figure 9. Horizontal Load versus Displacement for Specimen NC-5

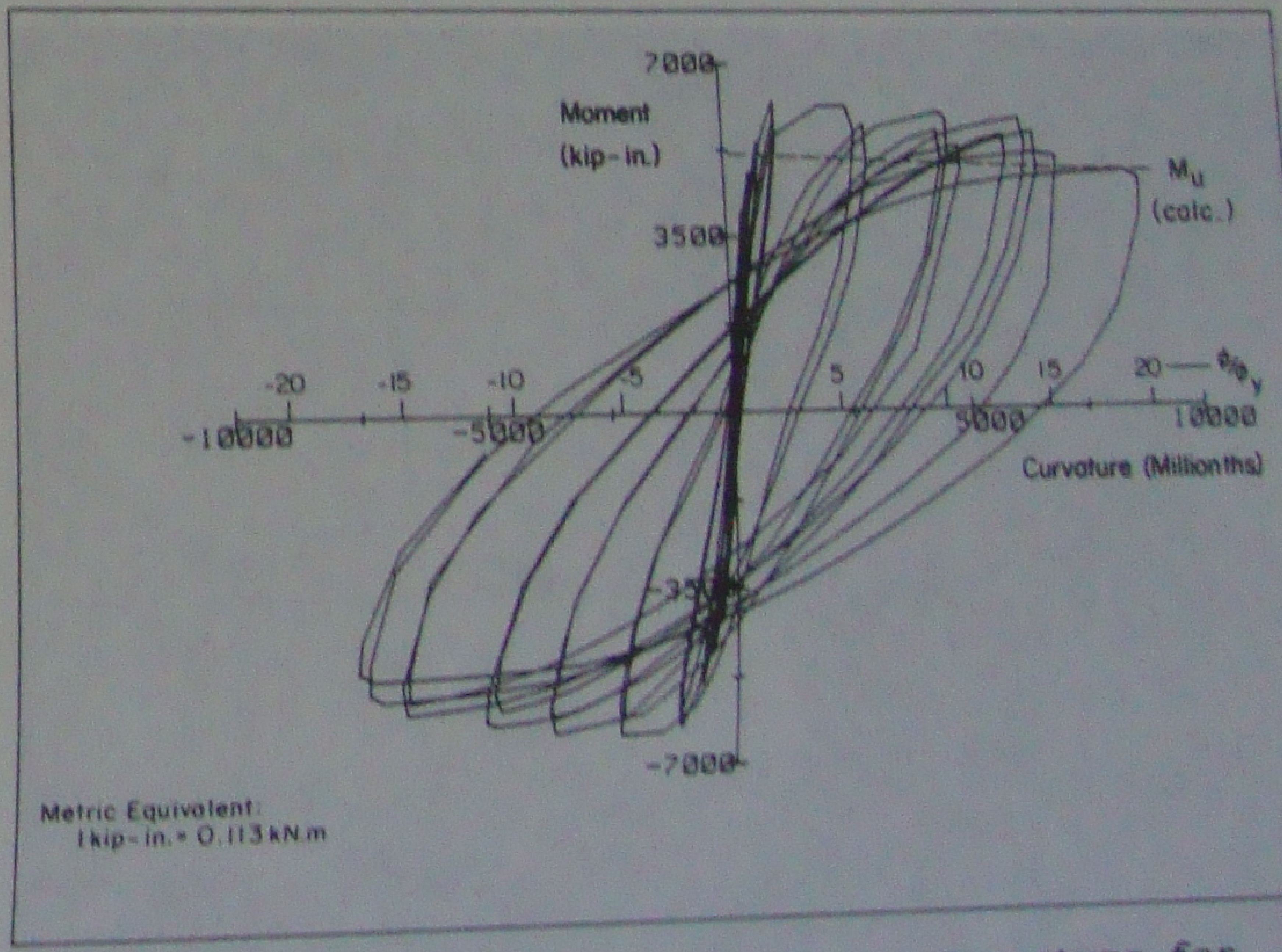


Figure 10. Moment versus Curvature for Specimen NC-5

longitudinal displacement over the same height on each side of the column, and knowing the distance between them, a strain distribution across the column section can be obtained. Determination of the neutral axis depth from the strain gradient allows curvatures to be determined. Electric resistance strain gages were used to obtain reinforcing steel strain profiles.

2.5 Test procedure

Each test was started by applying vertical load to the column. During a test, this load was kept constant at a predetermined level. Horizontal force was applied in increments alternately first in one direction and then in the opposite direction. The specimen was loaded to initial yielding in about three increments of horizontal force. Subsequent to initial yielding, loading was controlled by deflection increments.

Basic loading cycles were generally applied as follows: two cycles before yield, one cycle at yield, one cycle at ductility between 1 and 2, two cycles each at ductility 2, and subsequent ductilities. Testing was stopped at a stage when the specimen could not sustain the vertical load under increasing lateral displacement.

3 SUMMARY OF TEST RESULTS

3.1 Behavior of specimens

Photographs of hinging regions of four specimens after testing are shown in Fig. 6. Observed length of hinging regions varied from approximately 10 to 16 in. (254 to 406 mm) for the ten specimens. Hysteresis loops of lateral load versus horizontal displacement obtained for three tests are shown in Figs. 7 through 9. A downward sloping line indicating maximum theoretical horizontal load, P_h, obtained from the calculated moment capacity is also shown in these figures. The downward slope indicates additional moment due to the P-Δ effect. Maximum horizontal displacement ranged from five to eight times yield displacement.

A representative plot of moment versus curvature for Specimen NC-5 is shown in Fig. 10. This plot includes total moment at the upper column-stub interface versus curvature obtained over the first 4 in. (100 mm) from the beam stub. The calculated moment capacity, M_u, indicated in this figure, was determined using provisions of the ACI Building Code. Capacity reduction factor, ϕ, was taken as 1.0. For a displacement ductility of seven in Specimen NC-5, maximum curvature ductility exceeded 20 as shown in Fig. 10. Measured displacement ductility, calculated flexural strength, and measured flexural strength values are listed in Table 2.

3.2 Effect of variables

1. Axial load - A comparison of results from Specimens NC-2 and NC-3 indicates that the flexural capacity of the column increased with axial load but ductility reduced substantially. Plastic hinge length increased with axial load.
2. Amount of transverse reinforcement - A comparison of results from Specimen NC-1 with those of NC-4, NC-6, and NC-7 indicates that the use of almost 50% less transverse reinforcement in these three specimens resulted in slightly lower ductility. Maintained strength was also generally lower at all load stages. It should be noted, however, that the measured ductility in Specimens NC-4, NC-6, and NC-7 exceeded that generally implied by codes.
3. Details of transverse reinforcement - A comparison of test results from Specimens NC-1 and NC-5 indicates that the flexural capacity and ductility of Specimen NC-5 was not reduced by the use of overlapping peripheral hoops. Also, flexural capacity and ductility were not reduced by the use of special hoops shown in Figure 3(e) as indicated by a comparison of results from Specimens NC-4 and NC-7. However, the use of single peripheral hoops in Specimen NC-6 resulted in lower flexural strength. Use of continuous square helixes in Specimens NC-9 and NC-10 improved flexural strength.

Table 2. Test results.

Specimen Desig-nation	Measured Displacement Ductility	Flexural Strength, kip-in.		$\frac{M_2}{M_1}$
		Calculated, M_1	Measured, M_2	
NC-1	6	5184	6102	1.18
NC-2	8	4814	5773	1.20
NC-3	5	5198	6514	1.25
NC-4	5	5268	6152	1.17
NC-5	7	5226	6365	1.22
NC-6	5	4800	3651	0.76
NC-7	5	4950	5873	1.19
NC-8	6	5100	5351	1.05
NC-9	5	4810	5591	1.16
NC-10	5	4970	5379	1.08

Metric Equivalent:
1 kip-in. = 0.113 kN•m

4. Hook bends of inner hoops - All specimens except NC-1 used 90 degree hook bends for inner hoops. Behavior of these specimens indicated that a standard 90 degree hook on inner hoops did not reduce ductility.

5. Hook extensions - Test results indicate that a ten bar-diameter extension as required by Section A.1 of the ACI Building Code is not needed. Six bar-diameter extensions used in all specimens produced displacement ductilities exceeding those generally assumed in design.

ACKNOWLEDGMENTS

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