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ASSESSMENT OF DIFFERENT TRANSVERSE REINFORCEMENT DETAIL IN EARTHQUAKE ENVIRONMENT

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SUMMARY

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 ductility reduces substantially. Reduction in the amount of transverse reinforcement results in lower ductility. Details of transverse reinforcement including hook bends and hook extensions can be further simplified.

INTRODUCTION

Columns in building frames are normally designed not to hinge, crush or otherwise lose their capacity to support the building during a moderate earthquake. However, columns in buildings subjected to an unexpectedly severe 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 (Refs. 1-3).

Inadequate transverse column reinforcement has resulted in severe damage to structures. Current code provisions (Refs. 4,5) for confining steel are based on providing confinement to increase concrete strain capacity. However, strain capacity 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, Inc. (CTL). square and circular test columns with differing amounts and details of transverse reinforcement and under different levels of axial load are subjected to horizontal force reversals at increasing inelastic deformations. In this paper, selected results of test columns are described, and a summary of the test results is presented.

EXPERIMENTAL PROGRAM

Dimensions and reinforcement details of a representative test specimen for columns with square cross sections are illustrated in Figs. 1 and 2. For the test specimen with circular cross section, test specimens differed in that the upper column had a circular cross section, 1'-6" in diameter. 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.

Test Specimens Eleven full-scale column specimens with square cross section and one column specimen with circular cross section have been tested. In the test specimen, the distance between the beam-column stub interface and the pivot point (see Fig. 5), in the lower and upper columns, represent the portion of a column in a building extending 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 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 1983 ACI Building Code requirements.

Reinforcement Details and Materials Transverse reinforcement details designated A, B, C, D, E, F, and G 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 1983 ACI Building Code. This required 135 degree hook bends with ten 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. As shown in Fig. 3(f), Specimen NC-12 used a No. 3 continuous square helix at 3-1/2-in. (89-mm) pitch with No. 3 crossties at 3-1/2-in. (89-mm) on center.

Transverse reinforcement for Specimen NC-11 consisted of 3/8-in. diameter continuous spiral reinforcement at a pitch of 2-1/4-in.

The length of column confined by transverse reinforcement was kept constant at 22-in. (0.56 m). The confined length for Specimen NC-11 was 34-in. Except for Specimens NC-8, NC-9, NC-10, and NC-12, hoops were spaced 4-in. (100-mm) on center in the confined region. Transverse reinforcement in the unconfined region of column was designed to carry maximum shear stress. Clear cover over vertical reinforcement was maintained at 1.5-in. (38-mm) in upper and lower columns.

Test Setup Test setup and loading arrangement are shown schematically in Figs. 4 and 5. A one-million lb (450 ton) capacity testing machine was used to apply the vertical compressive force. Lateral load was applied with hydraulic rams pushing against reaction frames.

Instrumentation Several types of instruments were used to obtain load-displacement, moment-curvature, vertical bar strain profiles, confining hoop strains, plastic hinge lengths, and maximum concrete compressive strains. 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 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.

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 at subsequent ductilities. Testing was stopped at a stage when the specimen could not sustain the vertical load under increasing lateral displacement.

TEST RESULTS

Behavior of Specimens Photographs of hinging regions of three specimens after testing are shown in Figs. 6-8. Observed length of hinging regions varied from approximately 10 to 16-in. (254 to 406-mm) for all specimens.

Hysteresis loops of lateral load versus horizontal displacement obtained for three tests are shown in Figs. 6-8. In these figures, the solid line parallel to the horizontal axis represents the theoretical ultimate lateral load, calculated using ACI 318-83 Code provisions, neglecting the P-Δ effect. However, if the P-Δ effect is included, the calculated maximum lateral load decreases as lateral displacement increases. The dashed lines in Figs. 6-8 represent the envelope of the calculated points corresponding to maximum lateral loads at increasing lateral displacement. For each displacement level, the maximum lateral load was calculated using ACI 318-83 Code provision. Maximum horizontal displacement ranged from five to nine times yield displacement.

Measured displacement ductility, calculated flexural strength, measured flexural strength and maximum core compressive strain values for all tests are listed in Table 2. Maximum core compressive strain for Specimens NC-1, NC-2, NC-3, NC-4, NC-5, NC-6 and NC-7 were approximated using the horizontal deflection of the stub and making the following assumptions: 1) plastic hinge was concentrated over a 10 in, length just above the stub column, and 2) depth of the neutral axis measured from the extreme compressive face at the ultimate load was 12 in. Fig. 9 shows the maximum core compressive strain for all specimens. The curve in Fig. 9 represents a lower bound to the test data.

CONCLUSIONS AND RECOMMENDATIONS

From comparison of the test results following conclusions are drawn with regard to each variable investigated.

Axial Load For a constant amount of confinement, flexural capacity of a column increases with axial load, but ductility is reduced substantially.

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 Fig. 3(e) as indicated by a comparison of results from Specimens NC-4 and NC-7. Comparison of test results from specimens NC-1 and NC-8 indicates that staggering the inner and peripheral hoops in vertical direction decreased the flexural strength while it has no effect on ultimate displacement ductility.

A qualitative comparison of the behavior of Specimens NC-9, NC-10, and NC-12 with other specimens utilizing discrete type transverse reinforcement indicates that the continuous square helix reinforcement provided the same level of ductility ratio and was able to enclose the core concrete more efficiently at test conclusion.

A qualitative comparison of the behavior of Specimens NC-9, NC-10, and NC-12 with NC-11 indicate that continuous square helix transverse reinforcement is not as effective as the circular spiral reinforcement. This can be attributed to the mechanism by which the circular spiral and square helix transverse reinforcement provide confinement for core concrete. Circular spiral reinforcement is primarily subject to uniform tension, whereas square helix reinforcement is subjected to both bending and axial tension.

Area of Transverse Reinforcement Although the area of provided lateral reinforcement for all test specimens was less than the ACI 318-83 requirement (i.e., 46 to 97 percent of ACI 318-83), the resulting displacement ductilities exceeded or were equal to those implied by the Code. For columns tested UBC implied displacement ductility ratio is approximately 5. A comparison of results from Specimen NC-1 with those of NC-4 and NC-7 indicates that the use of almost 50% less transverse reinforcement in these two specimens resulted in only slightly lower ductility. Strength maintained was also generally lower at all load stages. It should be noted, however, that the measured ductility in Specimens NC-4 and NC-7 were equal to that generally implied by codes.

Hook Bends of Inner Hoops All specimens except NC-1 used 90° hooked bends for inner hoops. Behavior of these specimens indicated that a standard 90° hook on inner hoops did not reduce ductility.

Hook Extensions Test results indicate that a ten bar-diameter extension as required by Section A.1 of the 1983 ACI Building Code is not needed. Six bar-diameter extensions used in all specimens except NC-1 produced displacement ductilities exceeding or equal to those generally assumed in design.

Limiting Strain Test results indicate that the limiting strain is well above the 0.003 in./in. generally assumed in design, and that Corley's equation gives a very conservative estimate of the limiting strain. Under the loading conditions considered, use of a higher valve of limiting strain appears to be appropriate.

ACKNOWLEDGMENTS

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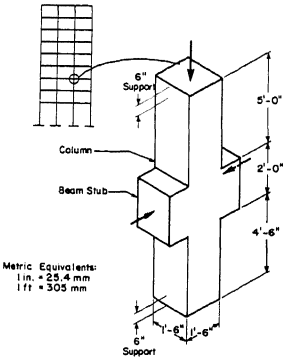
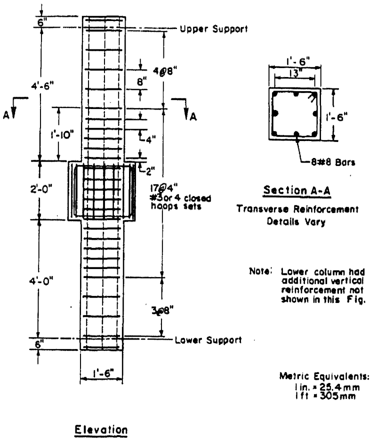


Metric Equivalents:
1 in. = 25.4 mm
1 ft = 305 mm

FIG. 1 TEST SPECIMEN



Elevation

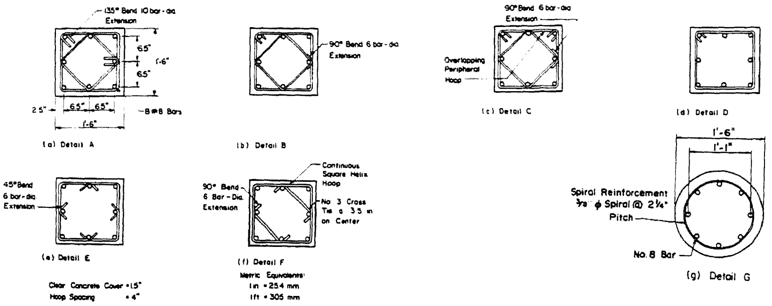
Section A-A

Transverse Reinforcement Details Vary

Note: Lower column had additional vertical reinforcement not shown in this Fig.

Metric Equivalents:
1 in. = 25.4mm
1 ft = 305mm

FIG. 2 REPRESENTATIVE REINFORCEMENT DETAILS



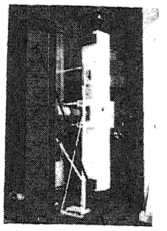


FIG. 4 LOADING ARRANGEMENT

FIG. 3 DETAILS OF TRANSVERSE REINFORCEMENT

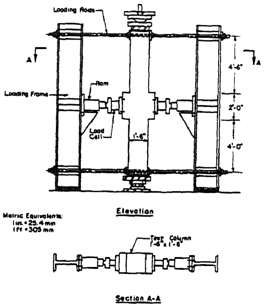


FIG. 5 TEST SETUP

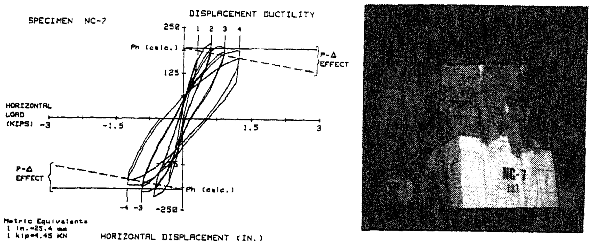


FIG. 6 HORIZONTAL LOAD VERSUS DISPLACEMENT FOR SPECIMEN NC-7

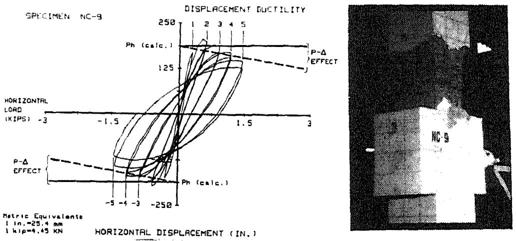


FIG. 7 HORIZONTAL LOAD VERSUS DISPLACEMENT FOR SPECIMEN NC-9

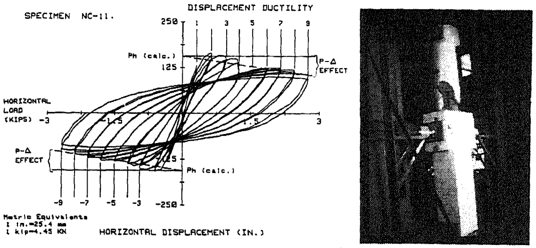


FIG. 8 HORIZONTAL LOAD VERSUS DISPLACEMENT FOR SPECIMEN NC-11

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	F**	0.40	1.29
NC-10	0.30	550	F+	0.22	1.29
NC-11	0.30	460	G	-	1.29
NC-12	0.30	554	F	0.30	1.29

*Detail B modified by staggering inner and peripheral hoops.

**Detail F with no crosstie and No. 4 continuous square helix at 4-in. (100-mm) pitch.

+Detail F with no cross tie and 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

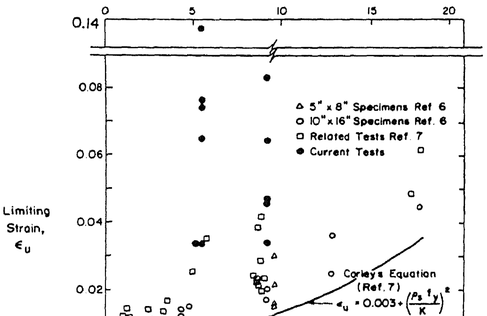


TABLE 2 TEST RESULTS

Specimen Designation	Measured Displacement Ductility	Flexural Strength, kip-in.		$\frac{M_2}{M_1}$	ϵ_u
		Calculated, M_1	Measured, M_2		
NC-1	6	5184	6102	1.18	0.04
NC-2	8	4814	5773	1.20	0.063
NC-3	5	5198	6514	1.25	0.036
NC-4	5	5268	6152	1.17	0.036
NC-5	7	5226	6365	1.22	0.047
NC-6	5	4800	3651	.76	0.036
NC-7	5	4950	5873	1.19	0.036
NC-8	6	5100	5351	1.05	0.085
NC-9	5	4810	5591	1.16	0.076
NC-10	5	4970	5379	1.08	0.065
NC-11	9	4000	4543	1.14	0.134
NC-12	5	5000	5389	1.08	0.074

FIG. 9 EFFECT OF TRANSVERSE HOOP REINFORCEMENT ON LIMITING STRAIN CAPACITY OF CONCRETE