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STRENGTH AND DUCTILITY OF CONFINED CONCRETE COLUMNS FOR SEISMIC DESIGN

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SUMMARY

An extensive experimental program, underway at the University of Houston, involves testing of confined concrete columns under concentric compression and under combined axial load and monotonic or cyclic flexure. The specimen size varied from 152 x 152 x 711 mm to 305 x 305 x 2740 mm. Normal weight and lightweight concrete with nominal strength ranging from 28 to 55 MPa was used. In this paper, results from a select group of specimens are presented. Effects of different variables on the behavior of confined concrete are evaluated. Confinement requirements of various building codes are discussed in the light of the test data.

INTRODUCTION

Seismic design of framed structures based on the ductility approach is allowed for most structures in various building codes (Refs. 1, 2, 3, 4, 5). Based on this philosophy, lateral loads significantly less than the elastic inertia loads are used to design the members for strength. The safety of the structure then depends on its ability to deform plastically while maintaining near maximum load-carrying capacity. Because of safety, practical, and economic considerations, it is preferable to dissipate seismic energy in beams, rather than in columns. Several building codes attempt to achieve this by limiting the ratio of sum of flexural strengths of the columns to that of the beams at a beam-column joint or by amplifying the column bending moments determined from elastic analysis. Realizing that these limitations may not be sufficient to avoid plastic hinging in the columns, most codes (Refs. 1, 3, 4, 5) specify lateral reinforcement in the critical regions of columns to confine concrete. Lateral reinforcement is also required to resist shear force. Requirements for lateral reinforcement for various levels of axial load are shown in Figure 1 for various design codes. Whereas, the U.S., Canadian, and New Zealand codes have detailed requirements for confinement steel, the Japanese code requires a minimum lateral reinforcement ratio of only 0.2%, primarily for shear. There are no specific requirements for confinement. The underlying assumption being that the columns designed according to the code provisions will not develop plastic hinging and the energy absorption will take place in beams.

Although confinement requirements (Refs. 1, 3, 5) are based on maintaining the axial strength of a column after cover concrete is spalled off, use of lateral reinforcement results in improved ductility of a section. The ductility of a section under flexure is strongly influenced by the level of axial load. Figure 2 shows the maximum loads allowed by various codes. It should be noted that large axial loads are permitted for columns designed for seismic resistance.

EXPERIMENTAL PROGRAM

In the test program carried out at the University of Houston, large-scale confined concrete column specimens (12" x 12" x 9' (305 x 305 x 2740 mm)) were tested to large inelastic monotonic or cyclic flexural deformations while simultaneously subjected to constant axial loads. The tests were terminated when the flexural loads dropped to zero or the axial loads could not be maintained. In some cases, the axial loads were up to about 10% higher than the allowable column capacity (Ref. 1). In a parallel test program, small-scale columns (6" x 6" x 28", 8" x 8" x 32" and 7" x 10" x 32" (152 x 152 x 711, 203 x 203 x 813 and 178 x 254 x 813 mm)) were tested under monotonic and cyclic concentric compression to evaluate the effects of different variables on the stress-strain behavior of confined concrete. Normal weight concrete with nominal cylinder strength ranging from 4 to 8 ksi (28 to 55 MPa) and lightweight concrete with strength in the range of 4 to 6 ksi (28 to 41 MPa) were used. The variables examined included longitudinal and lateral steel distribution, tie spacing, amount of lateral steel, precracking of specimens in the case of concentric compression and level of axial load for specimens under combined axial load and flexure. A total of 19 large and over 80 small specimens have been tested (Refs. 6, 7). The results from a select few specimens are shown here to describe the effects of different variables. The code requirements for confinements are evaluated in the light of these results.

RESULTS

Figure 3 shows the effects of steel configuration and the level of axial load on the moment-curvature behavior of three column sections. Comparison of Columns F-12 and A-16, in which the arrangement of ties is the only major difference, shows that at large displacements, crossties with 90° hooks are not as effective as the inner ties. It was observed during the tests that 90° hooks open out at large displacements when cover concrete is spalled off, thus resulting in a rapid loss of confinement and, hence, brittle behavior. The effect of axial load on column section can be evaluated by comparing Specimens A-11 and A-16. Although strength is not adversely affected by an increase in axial load from $0.6f_c'A_g$ to $0.74f_c'A_g$, ductility is reduced considerably. The amount of lateral reinforcement in each of the three columns was about one-half that required by the ACI code, Appendix A, but larger than that required for non-seismic design. None of these columns reached the theoretical moment capacity. It appears that at high axial loads, strength of concrete in the column is less than f_c' (standard cylinder strength) although in the analysis suggested by most building codes this strength is assumed to be equal to f_c' for all combinations of axial force and bending moment except for pure axial load. In the absence of the lateral reinforcement, the difference between the theoretical and experimental moment capacities is expected to be even higher than what is shown in Figure 3.

Effect of the amount of lateral steel is shown in Figure 4 for a section in which all sixteen bars are supported by tie bends. For a section with well-distributed steel, amount of lateral reinforcement equal to about one-half of that required in the Appendix A of the ACI code provided reasonably ductile behavior, although the applied axial load exceeded the allowable limit set by the code. All the specimens discussed above were made of normal-weight concrete with nominal concrete strength of 4,000 psi (28 MPa).

Figure 5 compares the behavior of three columns (F-4, F-9, and F-9H) in which the amount and the arrangement of steel are identical. The main difference between the columns is axial load and concrete strength. The $P_e/f_c'A_g$ values which remained constant throughout the tests were 0.6, 0.77, and 0.65, for Columns F-4, F-9, and F9-H, respectively. The axial loads resulted in concrete stresses of approximately $0.46f_c'$, $0.60f_c'$, and $0.58f_c'$, respectively, in Columns F-4, F-9, and F-9H before the flexural loads were applied. The high-strength concrete column (F-9H) was tested under cyclic flexural load, whereas the normal-strength concrete columns were tested under monotonic flexure. For the same level of concrete stress, the high-strength concrete column behaved in a slightly more ductile manner compared with the normal strength concrete column (F-9 vs. F-9H), probably as a result of the incremental strain caused by the slow cyclic loading. If $P_e/f_c'A_g$ is used as an index (F-4 vs. F-9H), then the behavior of the high-strength concrete column was found to be less ductile than the column made of normal concrete. It would appear that concrete stress, rather than the average stress on the column, is a more appropriate parameter for the comparison of the column behavior. The effect of cyclic loading on the behavior of confined lightweight concrete is shown in Figure 6 which confirms the above conclusion that slow cyclic loading causes increased strains beyond peak.

Specimen 2A3-L1 was tested under monotonic concentric compression, while Specimen 2A3-L1R was tested under cyclic concentric compression. Similar slow strain rates were used for both tests. Unconfined concrete strength (f_c') in both columns was approximately 4,000 psi (27.6 MPa).

CONCLUSIONS

Concrete columns can demonstrate very ductile flexural behavior even under large axial loads if longitudinal and lateral reinforcements are distributed appropriately. The design of confining steel should be based on the performance expected of a column and the level of axial load. The confinement provisions of various building codes produce columns which may fail in an unacceptably brittle manner.

Crossties with 90° hooks, confine concrete effectively at small deformations, but at large deformations, confinement is lost suddenly due to the opening of 90° hooks which results in a brittle failure of the column. An increase in axial load causes a significant reduction in ductility, but the effect is less severe in columns with well-distributed steel. Behavior of a section under slow cyclic loading was found to be more ductile compared with that under monotonic loading due to the incremental damage caused in each cycle.

ACKNOWLEDGEMENTS

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NOTATIONS

- A total cross-sectional area of transverse reinforcement within spacing s
- A_g gross cross-sectional area of column
- b_w width of the section
- f_c' strength of concrete as measured from a standard cylinder
- h'' width of core in a section
- P_e axial load on the column
- s spacing of sets of ties
- v_i applied shear stress

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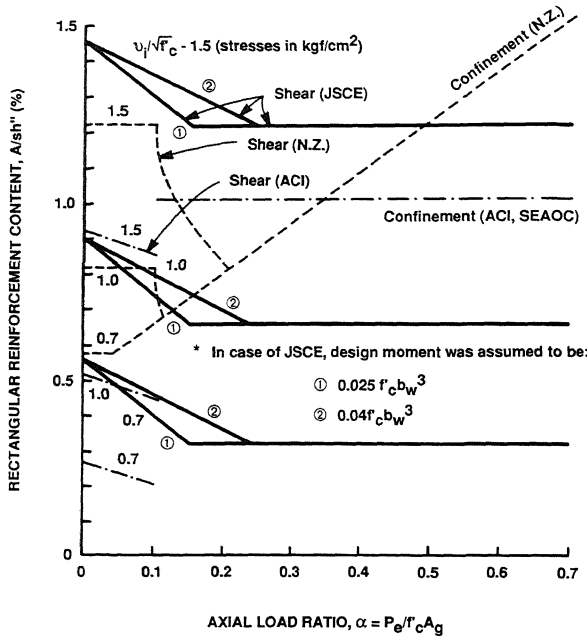

Fig. 1 Lateral reinforcement requirements according to different building codes.

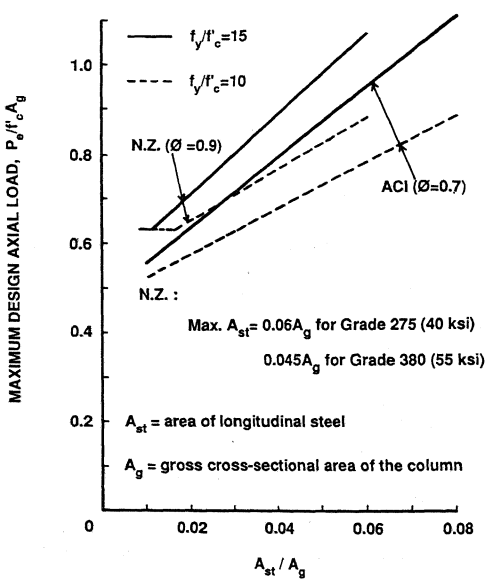

Fig. 2 Maximum design axial loads according to different building codes.

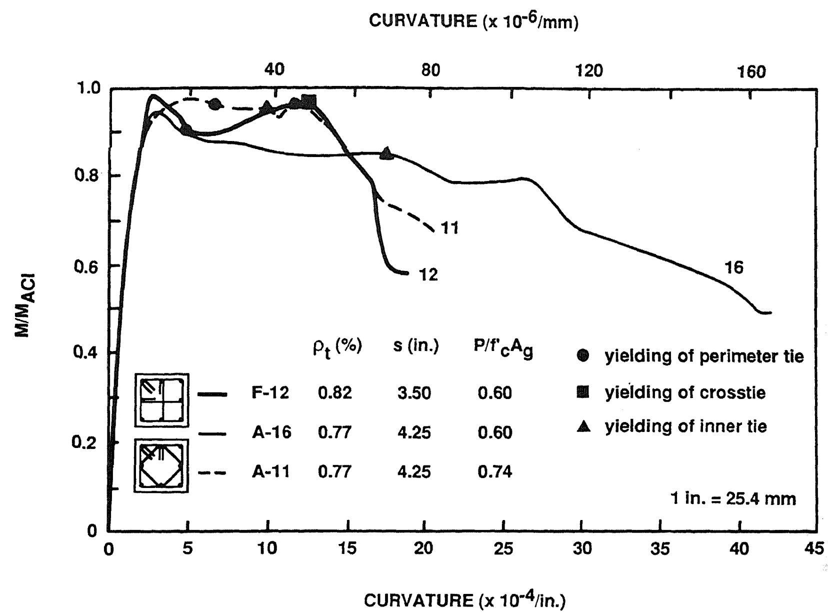

Fig. 3 Effect of steel configuration and axial load.

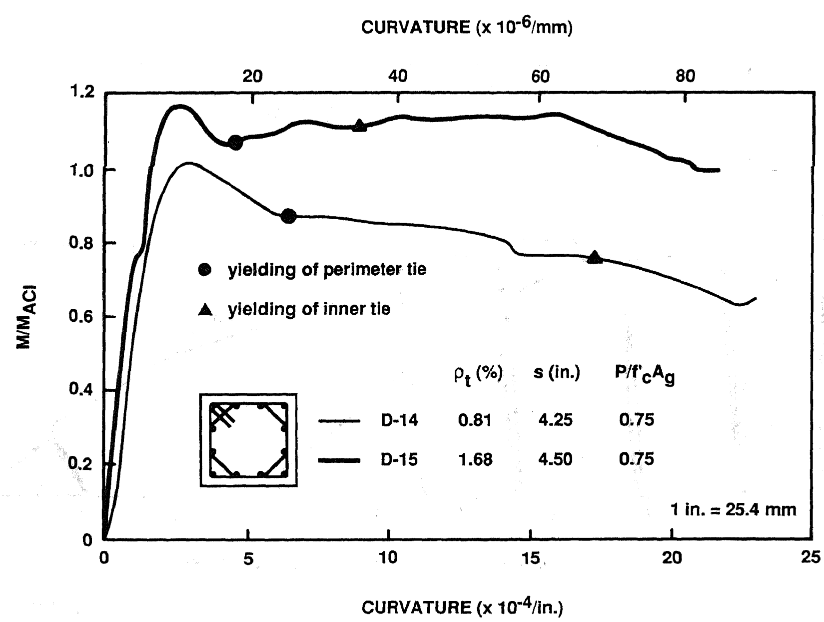

Fig. 4 Effect of amount of lateral steel

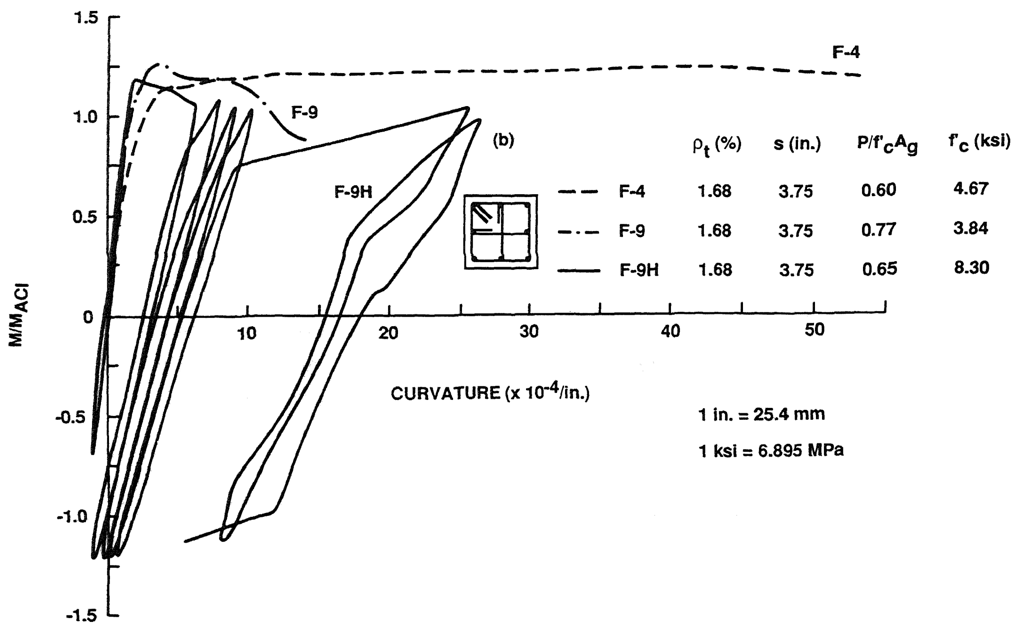

Fig. 5 Effect of axial load and concrete strength.

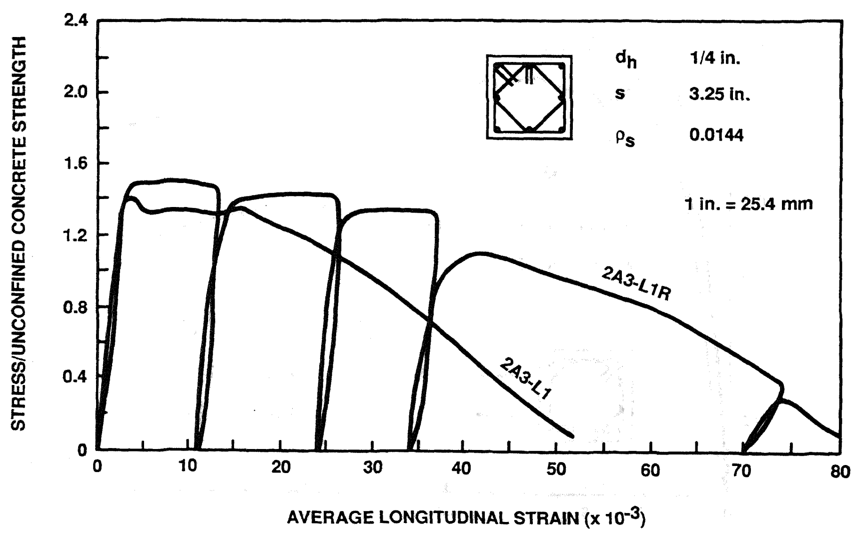

Fig. 6 Effect of cyclic loading on confined concrete behavior.