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Paper No. 1855. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

CONFINEMENT OF HIGH-STRENGTH CONCRETE COLUMNS FOR SEISMIC APPLICATIONS

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ABSTRACT

Strength and deformability of high-strength concrete columns were investigated experimentally. Fifteen full-size columns were tested under monotonically increasing concentric compression. The columns were confined by circular and rectilinear transverse reinforcement of different volumetric ratios, grades, spacings and arrangements. The results indicate that while the confinement steel requirements for high-strength concrete columns are more stringent than those for normal-strength concrete, it is possible to attain deformabilities that are usually expected of seismic resistant columns with concrete strength of 124 MPa. Higher grade transverse reinforcement may replace part of the high volumetric ratio required for proper confinement of high-strength concrete columns.

KEYWORDS

Confinement; concrete; concrete columns; ductility; high-strength concrete; earthquake resistant design; reinforced concrete columns; structural testing.

INTRODUCTION

Concrete strengths in excess of 100 MPa have been used in construction industry especially for lower story columns of multistory buildings. Although high-strength concrete has been accepted by the construction industry, many aspects of the material remain to be questionable. Among those is the inelastic deformability of earthquake resistant columns.

Strength and deformability of concrete is known to be inversely proportional. This raises serious concerns regarding the suitability of high-strength concrete for seismically active regions where inelastic deformability of structural components are relied on for the dissipation of earthquake induced energy. A comprehensive experimental and analytical investigation on behaviour of seismic resistant high-strength concrete columns are being conducted at the Structures Laboratory of the University of Ottawa. The research project includes tests of large scale columns under monotonically increasing concentric compression, as well as incrementally increasing lateral deformation reversals. The results of some of the square and circular columns with 124 MPa concrete, tested under concentric compression are presented and discussed in this paper.

EXPERIMENTAL PROGRAM

A total of 10 square and 5 circular columns with 124 MPa concrete were prepared and tested. The columns either had a 250 mm square section or a 250 mm diameter circular section. The square columns were confined with perimeter hoops with or without crossties or inner hoops, resulting in 4, 8 or 12-bar arrangements. The volumetric ratio of rectilinear transverse reinforcement varied between 0.99% and 3.33%. One column was tested without any reinforcement to establish the strength of plain concrete in columns. The circular columns were confined with spirals. The volumetric ratio of spiral reinforcement varied between 0.80% and 3.05%. The grade of confinement reinforcement in all columns varied between 400 MPa and 1000 MPa. Table 1 and Fig. 1 illustrate geometric and material properties of the test specimens.

Table 1. Properties of Column Specimens

Column	f'_c (MPa)	f_{yt} (MPa)	s (mm)	ρ_s (%)	Arrgmnt.*	P_{test} (kN)	P_0 (kN)	P_{test}/P_0	f_{test}/f'_{co}	$\varepsilon_{85}/\varepsilon_{01}$
CS-1	124	400	55	3.33	1	6040	6863	0.88	1.15	1.24
CS-2	124	570	55	2.16	2	6597	7139	0.92	1.15	2.69
CS-3	124	570	55	2.16	3	7402	7415	1.00	1.22	2.83
CS-4	124	1000	55	2.17	2	6631	7139	0.93	1.17	4.10
CS-5	124	1000	120	1.32	3	6849	7415	0.92	1.16	1.59
CS-6	124	400	85	1.05	2	6927	7139	0.97	1.10	1.59
CS-7	124	400	120	0.99	3	6910	7415	0.93	1.09	1.72
CS-8	124	400	85	3.24	2	6165	7139	0.86	1.12	3.21
CS-9	124	400	120	3.06	3	7177	7415	0.97	1.27	2.69
CS-10	124	Plain	Concrete		Column	6863	6588	1.04	1.04	-
CC-8	124	660	70	0.80	4	5354	5725	0.94	1.17	1.72
CC-9	124	400	135	1.35	4	5564	5725	0.97	1.22	N/A
CC-10	124	400	60	3.05	4	5076	5725	0.89	1.34	3.45
CC-11	124	660	60	0.93	4	5424	5725	0.95	1.32	1.83
CC-12	124	1000	60	1.32	4	5482	5725	0.96	1.21	3.45

* Reinforcement arrangements are illustrated in Fig.1

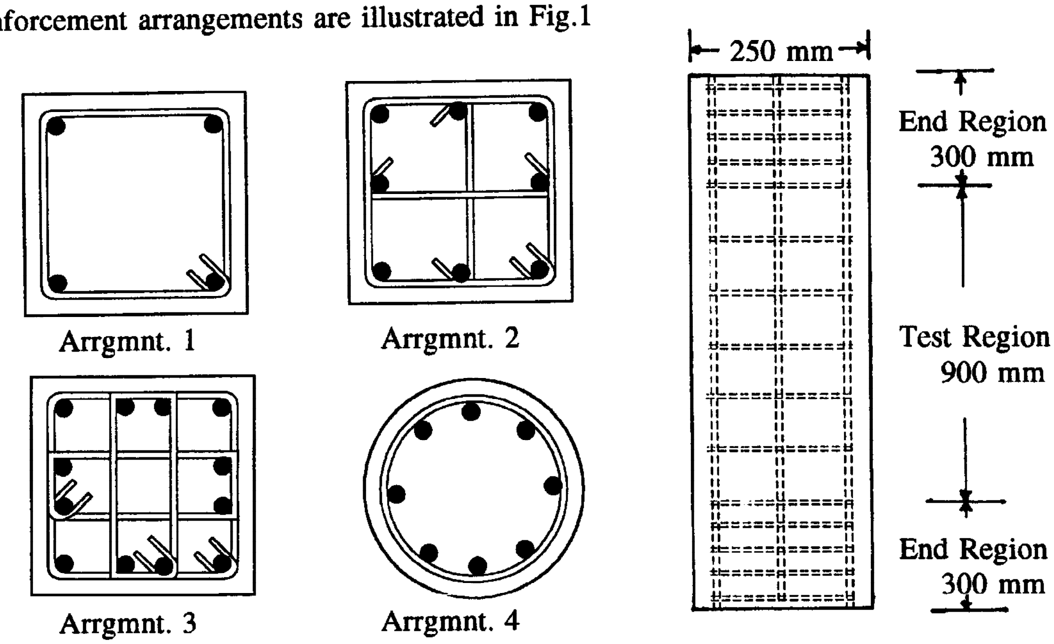

Fig. 1 Geometric properties of columns tested

Concrete mix design included 363 kg of Normal Portland Cement and 156 kg of slag per cubic metre of concrete. Silica fume was added in liquid form. The silica fume formed 10% of the cementitious material by weight. The water/cementitious material ratio was 0.2. The setting time and workability of the mix were controlled by 6 litres of superplasticizer and 1.6 litres of retarder per cubic metre of concrete. The strength was determined by testing 150 mm by 300 mm standard cylinders after griding the ends for uniform application of load. The 28-day strength was 102 MPa and the strength during the column test period was 124 MPa.

The specimens were instrumented with linear variable differential transducers to measure axial strains. Electric strain gauges were placed on reinforcement to monitor steel stress and strain. The load was measured by means of a pressure gauge. All the instrumentation was hooked up to a data acquisition system and a micro computer. A 10,000 kN (2000,000 lbs) testing machine was used to apply the load. The specimens were confined externally at the ends by steel brackets to prevent premature failure near the ends, outside the test region.

TEST RESULTS

All columns exhibited similar behaviour until the peak load. Premature spalling of cover concrete was observed prior to reaching the peak. Post peak behaviour depended on the amount of confinement provided for core concrete. Sudden drops of load were recorded at various stages of loading when the buckling of longitudinal reinforcement and fracture of hoop steel were observed. Fig. 2 illustrates a square and a circular column during testing.

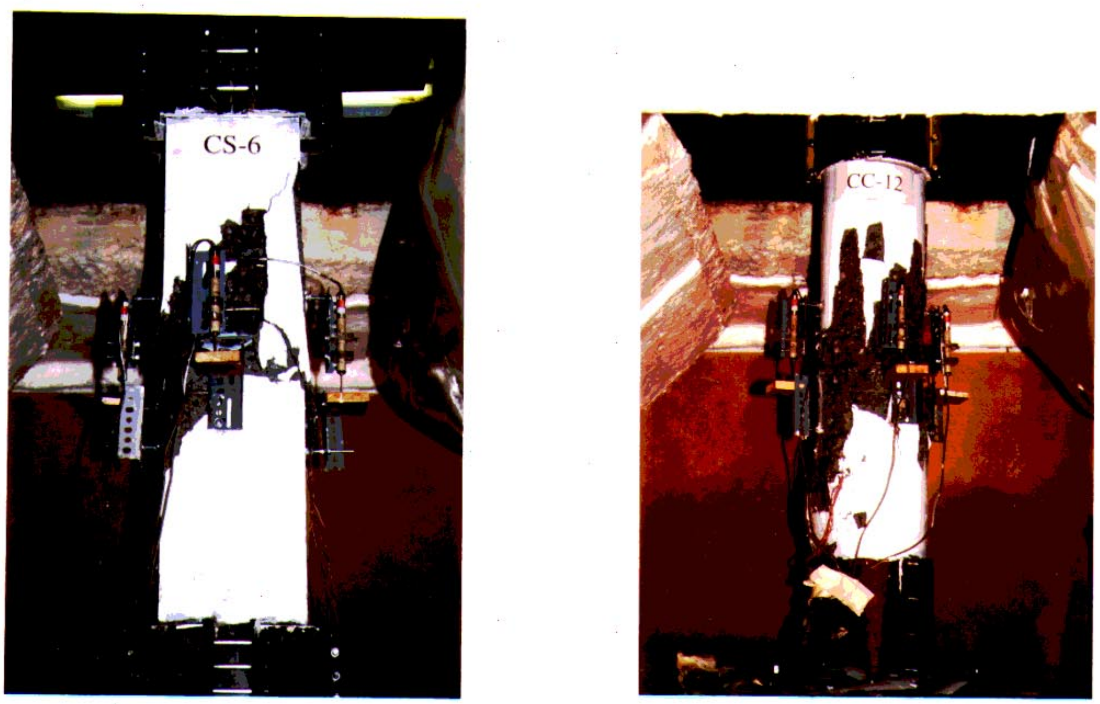

Fig. 2 A square and a circular column during testing

Column Strength

Column strength was attained after the spalling of core concrete. The load resistance at this stage was provided by confined core concrete and longitudinal reinforcement. The columns developed capacities approaching to those computed based on gross cross-sectional area and unconfined in-place strength of concrete. The majority of the columns showed slightly lower capacities that those corresponding to unconfined capacities computed on the basis of the current ACI-318 building code (1995) as specified in

Eq. 1. This was attributed to the instability of shell concrete under high compressive stresses required to test such high-strength columns. The recorded strain values indicated that the spalling of cover concrete occurred much before the development of crushing strain observed in cylinder and plain column tests. The

$$P_0 = 0.85 f'_c (A_g - A_s) + A_s f_y \tag{1}$$

strength of unconfined concrete in the plain column specimen was recorded to be $0.89f'_c$, indicating slightly higher value of in-place strength of concrete in columns as compared to $0.85f'_c$ commonly believed to represent normal-strength concrete. Table 1 gives experimentally recorded strength values for all specimens. The results indicate up to 28% increase in the strength of confined concrete. The comparison of recorded and computed strength values is depicted in Fig. 3.

Deformability of Columns

Deformability of columns was investigated by examining the stress-strain characteristics of core concrete. The stress-strain relationship of core concrete was established by subtracting the contribution of longitudinal reinforcement from recorded column resistance and by assuming gradual spalling of cover concrete between 0.15% and 0.25% axial strains. Axial strain ductility ratio was used to quantify the deformability of confined concrete. The strain ductility ratio was computed as the ratio of post peak strain at 85% of confined strength to strain at unconfined peak stress ($\varepsilon_{85}/\varepsilon_{01}$). Table 1 contains the strain ductility ratios of columns.

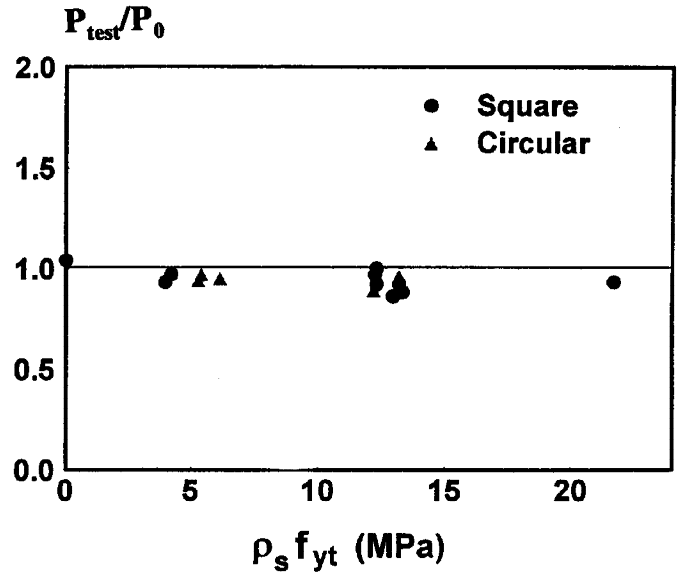

Fig. 3 Comparison of computed and recorded column strengths

Effect of Volumetric Ratio of Transverse Reinforcement. The effect of the amount of confinement reinforcement, expressed in terms of volumetric ratio, ρ_s is illustrated in Fig. 4 for both square and circular columns. While columns with approximately 1% volumetric ratio of Grade 400 steel showed a sudden strength loss at about 0.3% strain, those with approximately 3% volumetric ratio were able to sustain at least 0.6% strain prior to strength decay. This observation is consistent with those made on normal-strength concrete. An increase in the amount of confinement reinforcement, within the range considered here, translates into an equivalent increase in passive confinement pressure and results in strength and ductility enhancements.

Effect of Yield Strength of Transverse Reinforcement. The effect of steel grade was investigated by testing companion columns with different grades of transverse reinforcement. Fig. 5(a) illustrates stress-strain relationships of core concretes confined with grades 570 MPa and 1000 MPa. The results indicate improved ductility of concrete confined with higher grade reinforcement. Fig. 5(b) illustrates a comparison of two circular columns with grades 400 MPa and 1000 MPa reinforcement. These specimens were designed to provide similar confinement pressures as indicated by product $\rho_s f_{yt}$ while having different grades and volumetric ratios of lateral reinforcement. The behaviour shown in Fig. 5(b) indicates that the detrimental effects of reducing the volumetric ratio could be offset in these columns by a proportional increase in the grade of steel. However, additional data obtained by the authors on other columns indicate that this observation is limited to columns with efficient arrangements of reinforcements (Razvi and Saatcioglu, 1995). High grade reinforcement may not be effective in columns with widely spaced longitudinal and transverse reinforcement .

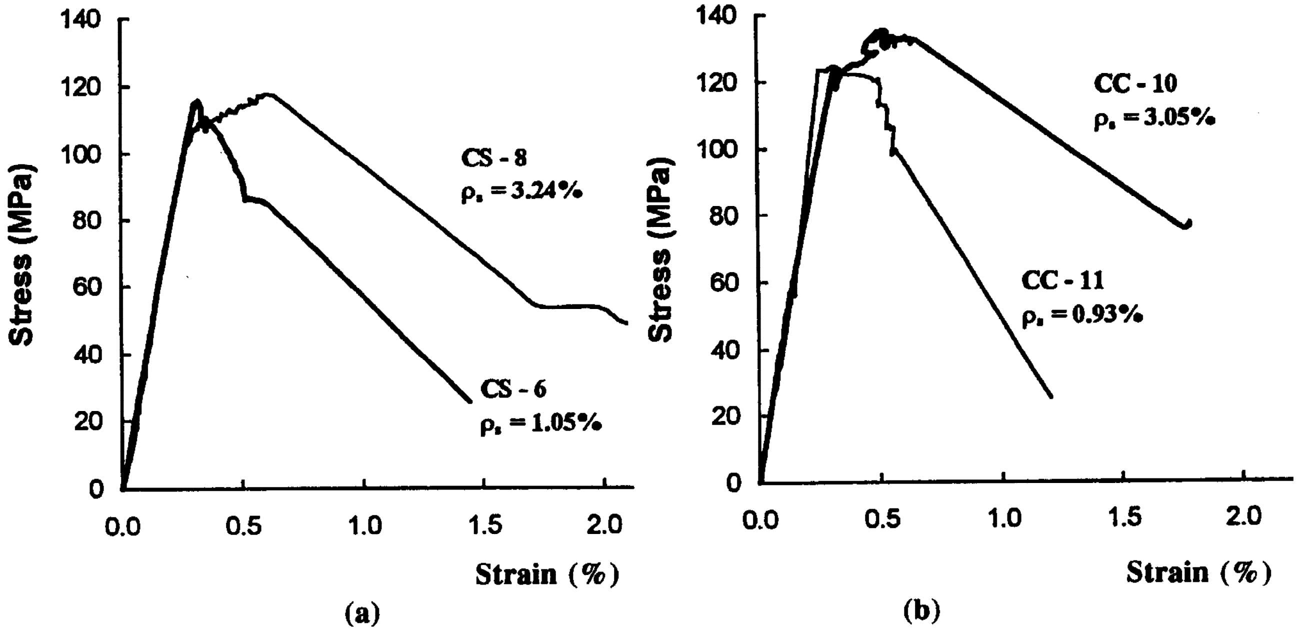

Fig. 4 Effect of volumetric ratio

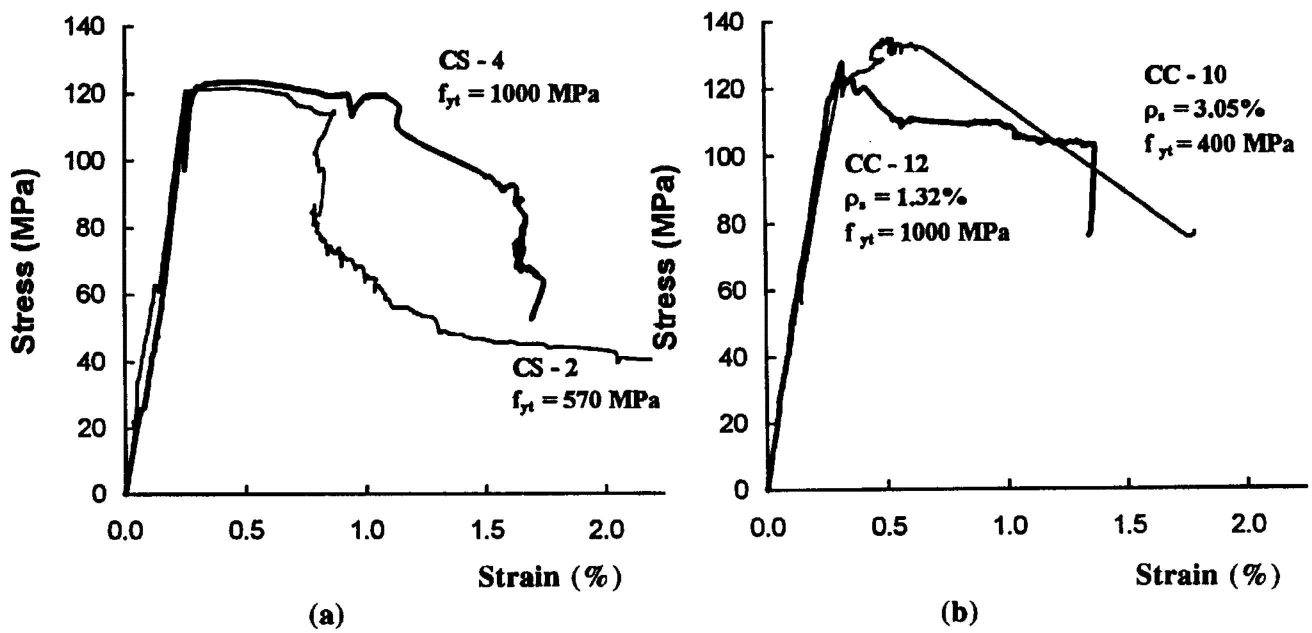

Fig. 5 Effect of transverse steel strength

Effect of Tie Spacing. Tie spacing is a parameter that affects the distribution of confinement pressure. As the spacing of tie reinforcement decreases the efficiency of confinement pressure increases, potentially reducing the need to have high volumetric ratios. Behaviour of columns with different tie spacings is shown in Fig. 6. In each case the volumetric ratio of transverse reinforcement is adjusted so as to produce approximately the same behaviour. The comparisons of stress-strain relationships indicate that the detrimental effect of increased tie spacing may be offset by an increase in the volumetric ratio. Conversely, columns with closely spaced ties do not require high volumetric ratios of transverse steel to attain similar behaviour. However, this observation is limited to the tie spacings considered in the test program. As the tie spacing becomes excessively high, the increase in volumetric ratio looses its effectiveness in confining concrete (Razvi and Saatcioglu, 1995).

Effect of Reinforcement Arrangement. Tie arrangement is another parameter that affects the distribution of confinement pressure. The efficiency of confinement pressure improves as the distribution of laterally supported longitudinal reinforcement improves (Saatcioglu and Razvi 1992). Fig. 7 illustrates stress-strain relationships of core concretes confined with 4, 8, and 12 bar arrangements. The figure indicates improvements in deformability with reduced spacing of tie legs in the cross-sectional plane. Column CS-1, with perimeter hoops only, showed an extremely brittle response with a sudden failure at approximately 0.25% strain, as opposed to 8-bar and 12-bar arrangements that developed 0.75% strain with little or no strength decay, with gradual strength loss in Column CS-3 with 12-bar arrangement.

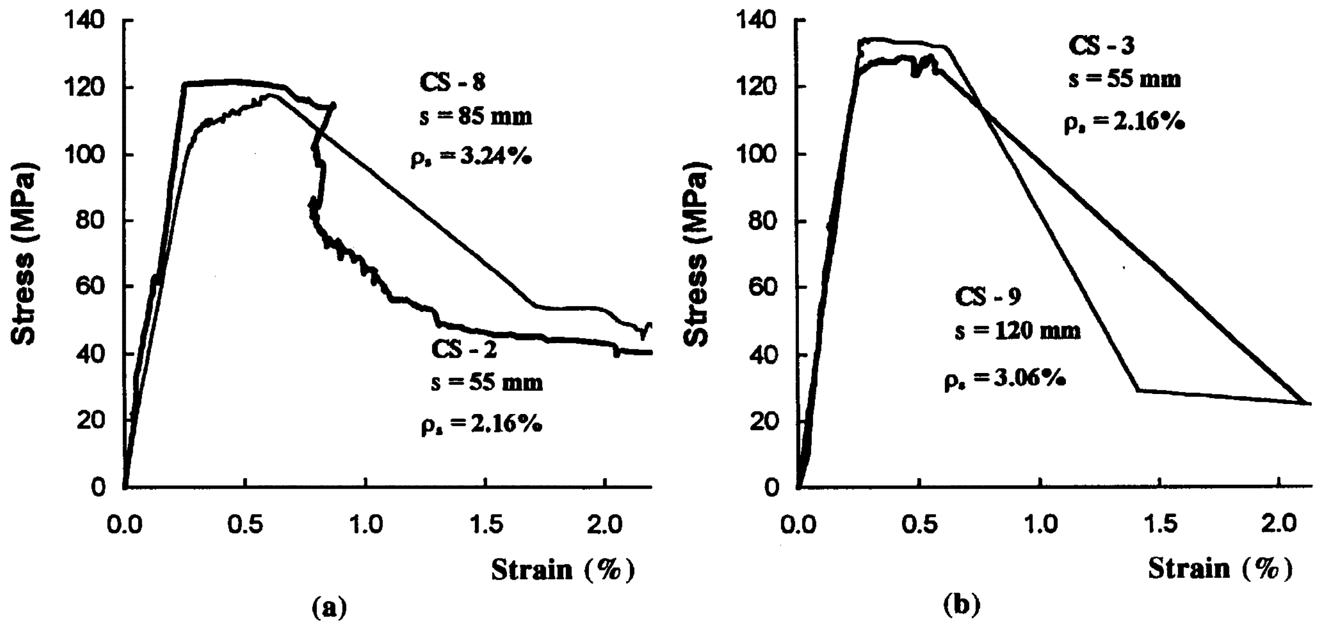

Fig. 6 Effect of tie spacing

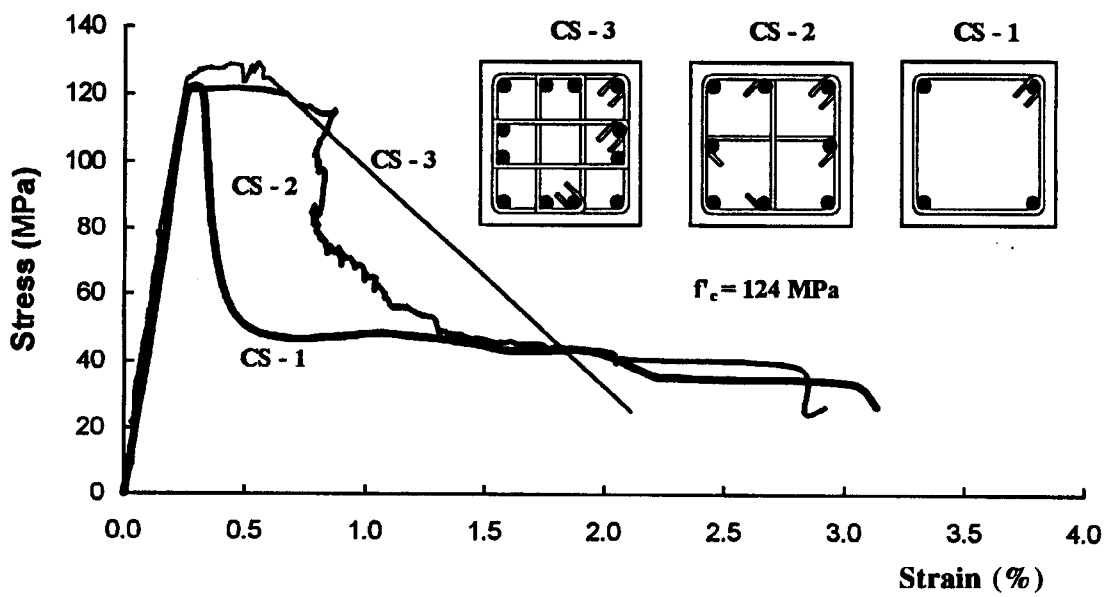

Fig. 7 Effect of tie arrangement

Effect of Section Geometry. Spirally reinforced circular columns develop near uniform lateral pressure resulting from hoop tension, producing the most efficient distribution of confinement pressure. Square columns with rectilinear reinforcement develop lateral pressure peaks at locations of transverse tie legs with reduced confinement pressure between them (Saatcioglu and Razvi, 1992). The effect of section geometry and corresponding reinforcement arrangement is illustrated in Fig. 8(a) where a spirally reinforced circular column shows a distinctly superior behaviour as compared to a square column with only perimeter ties. However, it is possible to improve the efficiency of lateral pressure through a better reinforcement arrangement even in square columns. Fig. 8(b) includes the comparison of a square section with a 12-bar arrangement and a spirally reinforced circular column. The results show almost identical behaviour between the two, underlining the importance of reinforcement arrangement once again on the efficiency of confinement pressure and resulting improvements in strength and deformability of confined high-strength concrete.

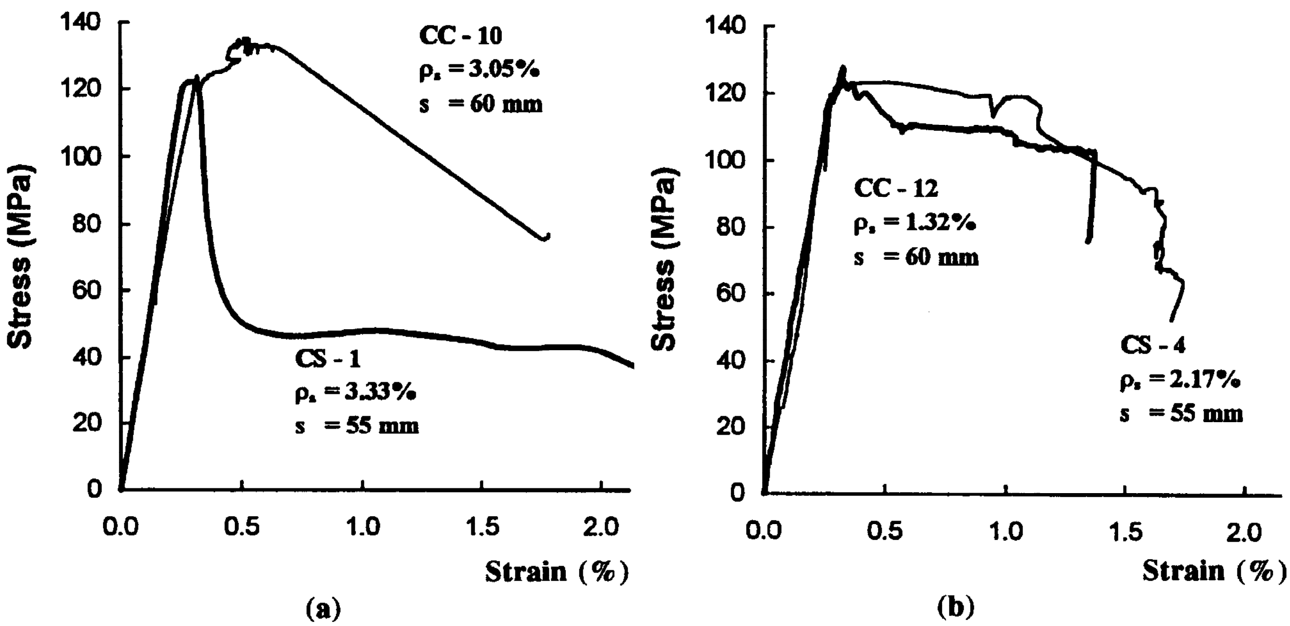

Fig. 8 Effect of section geometry

CONCLUSIONS

The following conclusions may be drawn from the experimental investigation reported in this paper.

- Reinforced concrete columns with 124 MPa concrete can be confined to develop inelastic deformabilities that are expected of seismic resistant columns. This can be achieved by using an efficient tie arrangement and a corresponding value of average confinement pressure as reflected by product $\rho_s f_{yt}$.
- The volumetric ratio of transverse reinforcement required for proper confinement of high-strength concrete columns vary with the arrangement and grade of lateral steel. For the square columns tested in this investigation, $\rho_s f_{yt} \geq 12.0$ MPa resulted in sufficient confinement when reinforcement grade f_{yt} was limited to 1000 MPa and the column was confined with at least 8 laterally supported longitudinal reinforcement and ties with a spacing not exceeding one quarter of the column dimension. Similarly, spirally reinforced circular columns with a pitch not exceeding one quarter of the column dimension performed well when designed to have $\rho_s f_{yt} \geq 12.0$ MPa with steel grade f_{yt} limited to 1000 MPa.
- Columns with 124 MPa concrete may develop premature spalling of cover concrete, in the form of instability of the shell, prior to the attainment of concrete crushing strain. While this may result in a slight reduction in column concentric capacity, this observation should be viewed with caution since most columns in practice are subjected to significant strain gradient which may alter the behavior of cover concrete near failure.

ACKNOWLEDGEMENTS

This research project was jointly funded by the Portland Cement Association and the Natural Sciences and Engineering Research Council of Canada. Their contributions are gratefully acknowledged.

NOTATIONS

A_g : Gross cross-sectional area.
A_s : Area of longitudinal reinforcement.
f'_c : Strength of concrete determined by testing standard cylinders.
f'_{co} : Strength of unconfined concrete in column, taken as $0.85f'_c$.
f_y : Yield strength of longitudinal reinforcement.
f_{yt} : Yield strength of transverse reinforcement.
f'_{test} : Confined concrete strength in column core obtained by test.
P_o : Concentric capacity of column as computed from Eq. 1.
P_{test} : Maximum axial force recorded during test.
s : Centre-to-centre spacing of transverse reinforcement.
ε_{01} : Concrete strain corresponding to peak unconfined strength.
ε_{85} : Confined concrete strain at 85% of peak strength within the descending region.
ρ_s : Volumetric ratio of transverse reinforcement, computed as the volume of steel divided by volume of core concrete between centre-to-centre of perimeter hoop.

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