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Strength of circular concrete columns under concentric compression

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Abstract: An experimental study, in which six columns were loaded concentrically to investigate the behavior of reinforced normal strength and high strength circular columns under concentric compression, is described. The concrete strengths of the columns were 30 MPa and 60 MPa. The primary variables considered were the concrete strength and the amount of transverse reinforcement. Test results indicate that smaller hoop spacing provides higher column capacity and greater strength enhancement in a confined concrete core of columns. For the same lateral confinement, high strength concrete columns develop lower strength enhancement than normal strength concrete columns. Both the strength enhancement ratio (f'_{cc}/f'_{co}) and the column capacity ratio (P_{test}/P_o) were observed to show linear increase variations with $\rho_s f_{yt}/f'_c$ in circular columns.

Key words: columns; high strength concrete; hoop spacing; concentric loading

Investigations into the behavior of reinforced concrete columns have long been a popular interest to many researchers, since columns are one of the most widely used elements in structures. The differences between confined and unconfined concrete columns are well recognized[1-3] with the improvements in strength and ductility of confined columns. Common conclusions have been obtained that the behavior of confined columns depends greatly on the amount, spacing and strength of transverse reinforcement. Based on experimental programs, many investigators[2,4] have proposed empirical models in which both circular hoops or spirals and rectangular stirrups are covered. With the increasing use of high strength concrete (HSC), corresponding studies on the behavior of confined HSC columns have attracted the concern of researchers. It has been observed[1,3,5] that high strength concrete columns show less ductile behavior than normal strength concrete (NSC) columns, and that the confinement in columns is also greatly influenced by the strength of the concrete. However, the behavior of reinforced HSC columns is not yet fully understood. For example, what amount of confinement reinforcement is required for HSC columns to achieve ductile behavior? To date, the research on the confinement effects in columns has been mostly empirical, the conclusions and proposed equations obtained from particular test data may not be accurate if conditions are different.

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In this study, 3 NSC and 3 HSC circular columns were tested to investigate the effect of the amount or spacing of transverse reinforcement and concrete strength on the behavior of columns.

1 Experimental Program

Six circular columns were tested to failure under concentric compressive loading. The parameters varing in this investigation were the concrete strength and the spacing or the volumetric ratio of hoop steel. The test specimens were 250 mm in diameter, reinforced with eight 12 mm diameter hot-rolled deformed bars (Y12) longitudinally with a steel reinforcement ratio of 1.8% and yield strength of 440 MPa. Each column specimen consisted of a 250 mm × 1 000 mm circular central region and two 400 mm × 400 mm × 300 mm square capitals at the ends. A concrete cover of 15 mm was provided in all specimens. Half specimens were cast with target nominal concrete strength of 30 MPa; the other three with target nominal concrete strength of 60 MPa. The corresponding measured cylinder compressive strengths were 35.6 MPa and 59.1 MPa, respectively. The circular hoops consisted of 10 mm diameter hard-drawn wire (W10) having a yield strength of 470 MPa. The characteristics of reinforcement W10 and Y12 were determined by tension tests. The yield stress of W10 and Y12 was measured by means of 0.2% offset method. Three tie spacings used in the central region of the columns were 50 mm, 100 mm and 150 mm. To induce failure in the test region, the spacing of the hoop steel was reduced outside the middle 600 mm of the column. The specimens were fabricated and tested at the Randwick Heavy Structures Laboratory of the School of Civil and Environmental Engineering, the University of New South Wales, Australia.

The columns are denoted by Cxx-yy, where xx is the target nominal concrete strength and yy is the spacing of ties. For example, column C30-50 has a target nominal concrete strength of 30 MPa and hoop spacing of 50 mm. Fig.1 and Tab.1 provide geometric details and material properties for the test columns.

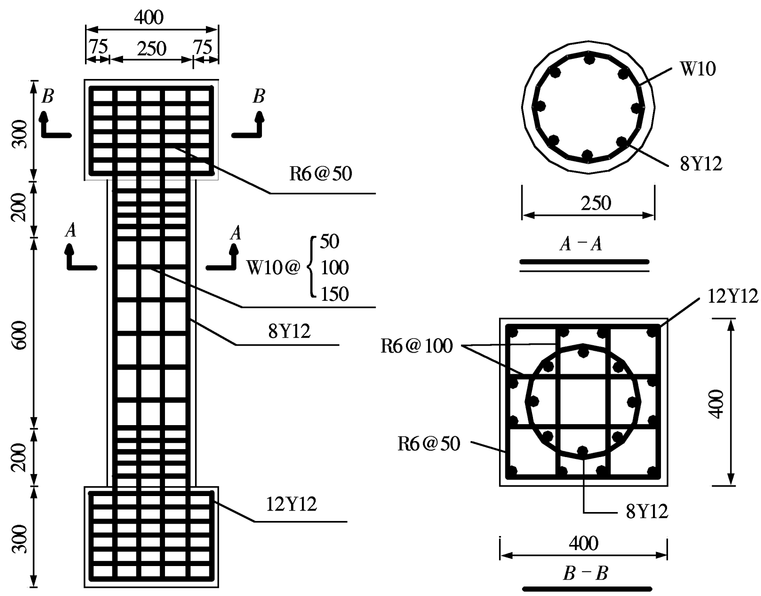

Fig.1 Geometric details of test columns (unit: mm)

Tab.1 Column properties and test results

Column	f'_c/MPa	P_{test}/kN	f_{yt}/MPa	s/mm	ρ_s/%	P_o/kN	P_{test}/P_o	$\rho_s f_{yt}/f'_c$	$f'_{cc}/(0.85f'_c)$
C30-50	35.6	2 233	470	50	2.99	1 856	1.20	0.40	1.75
C30-100	35.6	1 828	470	100	1.50	1 856	0.98	0.20	1.36
C30-150	35.6	1 708	470	150	1.00	1 856	0.92	0.13	1.25
C60-50	59.1	2 967	470	50	2.99	2 819	1.05	0.24	1.48
C60-100	59.1	2 463	470	100	1.50	2 819	0.87	0.12	1.19
C60-150	59.1	2 303	470	150	1.00	2 819	0.82	0.08	1.09

Note: f'_c is the compressive strength of plain concrete obtained from a standard cylinder test; P_{test} is the maximum compressive load resisted by a column in the test; s is the hoop spacing; ρ_s is the volumetric ratio of transverse reinforcement; P_o is the nominal concentric column capacity, defined in Eq.(1); f_{yt} is the yield strength of transverse reinforcement; f'_{cc} is the in-place compressive strength of confined core concrete in each column.

The specimens were tested horizontally in a stiff testing frame. Electrical resistance strain gauges were used to measure strains in the longitudinal and transverse reinforcement, and linear variable differential transducers (LVDTs) were instrumented to measure the axial strains of the columns. Each test was conducted over 30 to 90 min. Loading was applied via a 5 MN capacity hydraulic jack and the load was measured using an electronic load cell. For well-confined specimens, the postpeak behavior could be obtained up to the point where the hoop ruptured. After the rupture of the hoops, the columns failed suddenly and no further data was collected. For poorly confined specimens, failure occurred at, or shortly after, the peak loads due to the limitation of the testing system. The tests were terminated at the rupture of lateral reinforcement, the crushing of core concrete, or the buckling of longitudinal bars.

2 Test Results

The results of the tests are presented in Tab.1 and Fig.2 and Fig.3. All of the six columns failed in compression, either with an inclined shear failure plane or by crushing of the tied concrete core, accompanied by the buckling of longitudinal bars and the rupture of the hoop steel. Failure of the specimens was initiated by fracture of the hoop steel at the welds. Once the ties failed the stiffness of the testing frame was inadequate to obtain any more of the descending curve.

The load versus axial strain relationships for columns is provided in Fig.2 and Fig.3. In columns

C30-50 and C60-50, after the spalling of cover, a slightly higher second peak in the load capacity of the column was recorded due to the well confinement in the concrete core. The cover spalling in columns with better confinement (C30-50, C30-100 and C60-50) took place before the peak load was reached. Considerable ductility was also observed in these specimens. Specimens C30-150, C60-100 and C60-150 showed limited ductility and failure occurred suddenly in an explosive manner with the crushing of concrete between the ties, before any concrete crack or concrete spalling was observed. For the 60 MPa columns, failure occurred in a more brittle way due to their higher strength. At the maximum load, yielding of the critical circular hoops generally occurred except for columns with 150 mm hoop spacing. The longitudinal bars were yielded or close to yielding at the failure load.

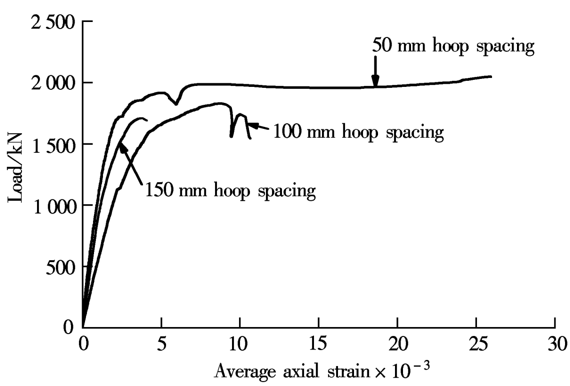

Fig.2 Load versus axial strain curves for 30 MPa columns

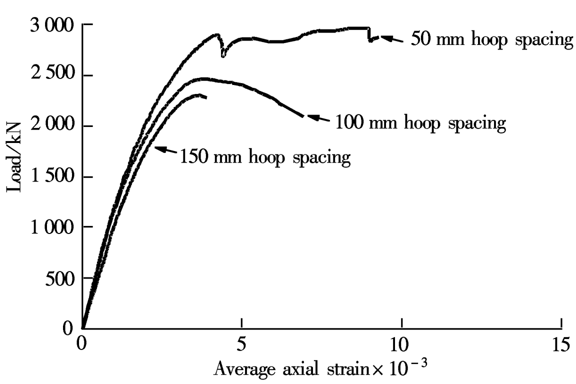

Fig.3 Load versus axial strain curves for 60 MPa columns

3 Analysis of Test Results

3.1 Evaluation of column strength

Experimentally recorded column strengths are listed in Tab.1. The nominal concentric capacities P_o for each specimen are computed on the basis of Eq. (1), which reflects the ACI building code provision. Test results showed that, except for columns with 50 mm hoop spacing, the load-carrying capacities for other columns were all smaller than the unconfined column capacities P_o, indicating that the losses of strength resulting from the cover spalling in these columns were not compensated by the strength enhancement in core concrete due to confinement. Tests proved that considerable strengths were achieved for columns C30-50 and C60-50, satisfying the requirement in ACI, code for minimum volumetric ratio for tie reinforcement (which is 1.67% for 30 MPa columns and 2.77% for 60 MPa columns), since the ratios of maximum axial strength P_{test} to the nominal concentric capacity P_o for them are greater than 1.0. Similar conclusions were also obtained from tests by Razvi and Saatcioglu[1]. Tests by Razvi and Saatcioglu[1] showed that for HSC columns Eq. (1) can also be applicable, that is, the unconfined in-place strengths of HSC columns can conservatively be taken as 0.85 f'_c. However, test data in Tab.1 indicates that the application of Eq.(1) should be based on the condition that the tie reinforcement in columns satisfies the ACI requirement, otherwise overestimated column strengths can be obtained from Eq.(1).

$$P_o = 0.85f'_c(A_g - A_s) + f_{sy}A_s \qquad (1)$$

where A_g is the gross area of column section; A_s is the area of longitudinal reinforcement; f_{sy} is the yield strength of longitudinal reinforcement.

3.2 Effect of test variables

Fig.4 illustrates the relationship between the hoop spacing and the strength enhancement in columns. The strength enhancement due to confinement was established by comparing strengths of confined core f'_{cc} with unconfined concretes (f'_{co} = 0.85 f'_c). The core capacity was calculated by subtracting the contribution of longitudinal reinforcement from the recorded column capacity. Ratios of confined to unconfined concrete strengths are listed in Tab.1. These ratios range from 1.09 to 1.75. The increase in strength of up to 75% was obtained for NSC and as high as 48% for HSC columns, indicating that decreasing the spacing of transverse reinforcement resulted in the strength enhancement of both NSC and HSC columns. Fig.4 illustrates that the strength enhancement ratio f'_{cc}/f'_{co} decreases with the increase in hoop spacing. Thus, it is obvious that, given all other conditions remaining the same, for the same confinement HSC columns developed lower strength enhancement than NSC columns.

The strength enhancement ratio f'_{cc}/f'_{co} and the column capacity ratio P_{test}/P_o are plotted against the

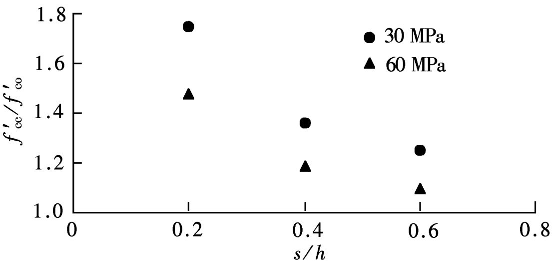

Fig.4 Relationship between hoop spacing and strength enhancement (h is the diameter of columns and equals 250 mm)

confinement ratio $\rho_s f_{yt}/f'_c$ in Fig.5 and Fig.6, respectively. Razvi and Saatcioglu[4] reported that improvements in strength and ductility were achieved in columns with higher value of $\rho_s f_{yt}/f'_c$, and if $\rho_s f_{yt}/f'_c$ is kept constant, it is possible to achieve similar levels of ductility in HSC columns as in NSC columns. Sugano et al.[6] recommended that $\rho_s f_{yt}/f'_c$ should not be less than 0.2 for ductile behavior of columns. Fig.5 and Fig.6 correlate well with their observations. For columns with lower confinement ratios (smaller than or equal to 0.2), the column capacity ratios (P_{test}/P_o) were all less than 1.0, indicating little confinement effect and lower-than-design strength development. Linear increase trends were obtained for both the strength enhancement ratio f'_{cc}/f'_{co} in Fig.5 and the column capacity ratio P_{test}/P_o in Fig.6, which are consistent with the conclusions proposed by Razvi and Saatcioglu[1,4]. Highly similar linear relationships were observed for HSC columns compared to NSC columns, either in Fig.5 or Fig.6. It is recommended that the

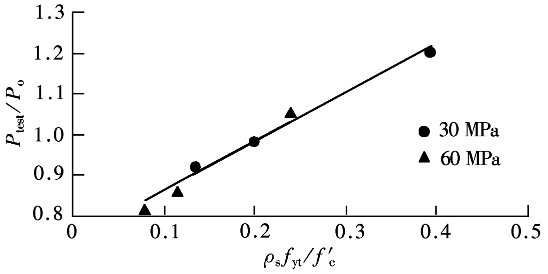

Fig.5 Relationship between column capacity ratio and $\rho_s f_{yt}/f'_c$

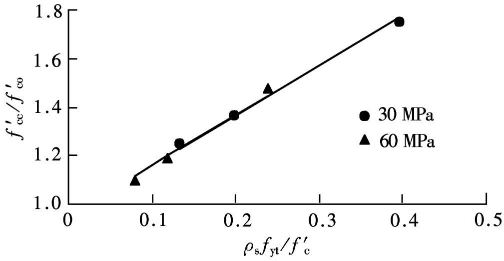

Fig.6 Relationship between strength enhancement and $\rho_s f_{yt}/f'_c$

values of $\rho_s f_{yt}/f'_c$ for NSC and HSC columns be at least equal to 0.22 to prove the column capacity ratio is no less than 1.0 and the strength enhancement is no less than 40%, together with ductile behavior.

4 Conclusions

The experimental program reported in this paper consists of 6 circular columns tested under concentric loading. The main variables considered were the concrete strength and the amount or spacing of lateral reinforcement. The dimensions of the columns were kept constant to enable a direct comparison between the test results. The specimens were detailed with the aim of obtaining failure in the center of the column with additional transverse reinforcement provided outside of the test region.

The following conclusions are drawn:

1) For the same confinement, HSC columns developed lower strength enhancement than NSC columns.

2) Reducing the spacing of transverse reinforcement improved the strengths of both NSC and HSC columns.

3) When the amount or spacing of lateral steel is low (such as for specimens C30-150 and C60-150), few benefits are observed by the use of confining reinforcement for both the NSC and HSC columns.

4) Both the strength enhancement ratio f'_{cc}/f'_{co} and the column capacity ratio P_{test}/P_o show linear increase variations with $\rho_s f_{yt}/f'_c$ in circular columns.

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圆柱体钢筋混凝土柱的轴压强度

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摘 要 通过对6根圆柱体钢筋混凝土柱的轴压试验,研究普通及高强混凝土柱的轴向受压性能.柱的混凝土强度为30 MPa和60 MPa.所考虑的主要因素为混凝土强度和箍筋用量.试验结果表明,箍筋间距越小,则柱承载能力越高,混凝土核心约束强度提高幅度越大.在相同的侧向约束下,高强混凝土柱的核心强度提高幅度低于普通混凝土柱.混凝土核心约束强度与非约束强度比率(f'_{cc}/f'_{co})及柱承载能力试验值与理论值之比(P_{test}/P_o)均与约束率 $\rho_s/f_{yt}/f'_c$ 成正比.

关键词 柱; 高强混凝土; 箍筋间距; 轴向荷载

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