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Compressive test on high-strength R/C columns and their analysis based on energy concept

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ABSTRACT: In this paper, the effects of longitudinal steel bars, spiral reinforcement and tie bars on the uniaxial compressive behaviors of high-strength reinforced concrete columns were clarified based on the test results and their analysis. A total of twenty-four columns were tested by monotonically axial compressive loading and the effects of tie bars as well as their hook extension length were confirmed. The analysis based on energy principle indicated that transverse reinforcement are more effective than longitudinal reinforcement due to their confining effect and excellent energy dissipation.

1 INTRODUCTION

In seismic design, ductility for reinforced concrete columns in plastic hinge regions needs to be provided with sufficient transverse reinforcement in the form of spirals or with rectangular arrangements of steel bars. The stress-strain relation for the compressed confined concrete need to be accurately evaluated in order to analyze moment-curvature relations of reinforced concrete columns with transverse reinforcement. However, the stress-strain relation for the confined concrete is highly influenced by a number of factors. To establish a more accurate theoretical model of the stress-strain relation for the confined concrete, the effects of those factors must be appropriately evaluated.

The purpose of this study is to define the stress-strain relationship of high-strength reinforced concrete columns. The effects of longitudinal and lateral reinforcement are clarified based on the test results and their analyses.

2 OUTLINE OF EXPERIMENTS

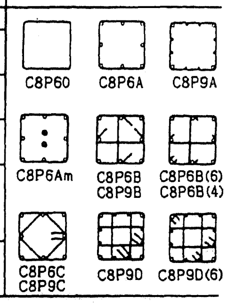
Uniaxial loading tests were carried out on nineteen 500-mm tall square columns and five 750-mm tall square columns until failure. The test specimens with 218mm square cross section were designed with respect to four

Table 1. Specimens.

Notation of specimen	Dimension (mm)	Longitudinal steel	Lateral steel	
		No.-Bar	Bar-spacing(mm)	ρ_s (%)
C8P0P-1 C8P0P-2		0	0	0
C8P60-1 C8P60-2	WIDTH B=218	0	D6-@40	1.51
C8P6A-1 C8P6A-2	TOTAL D=218	8-D13	D6-@40	1.51
C8P9A-1 C8P9A-2	TALL h=500	4-D13 +8-D10	D6-@27	2.26
C8P6Am		8-D13 +2-D25	D6-@40	1.51
C8P6B C8P6B(6) C8P6B(4)		8-D13	D6-@60	1.51

Notation of specimen	Dimension (mm)	Longitudinal steel	Lateral steel	
		No.-Bar	Bar-spacing(mm)	ρ_s (%)
C8P9B	WIDTH B=218 TOTAL D=218 TALL h=500	8-D13	D6-@40	2.26
C8P6C-1 C8P6C-2			D6-@70	1.51
C8P9C-1 C8P9C-2			D6-@47	2.26
C8P9D C8P9D(6)		4-D13 +8-D10	D6-@66	2.26
C8P0P3-1 C8P0P3-2 C8P0P3-3	WIDTH B=218 TOTAL D=218 TALL h=750	0	0	0
C8P6B3 C8P6B3(L)		8-D13	D6-@60	1.51

Reinforcement arrangement



Notes: 1. Reinforcing steel
Actual section area of bar D6mm bar, D10mm bar, D13mm bar band 25mm bar were 0.268cm2, 0.714cm2, 1.27cm2, and 5.07cm2, respectively.
2. ρ_s: Ratio of volume of lateral reinforcement to volume of core.

parameters, namely: (1)the volumetric ratio of lateral reinforcement;(2)arrangement of lateral reinforcement; (3)longitudinal reinforcement; and(4)hook tail length of lateral reinforcement. Details of column specimens are summarized on Table 1. Figure 1 shows dimensions and reinforcement arrangements of the specimens.

The high-strength longitudinal reinforcing deformed bar with 10-mm, 13-mm and 25-mm in diameter had the yield strength of 789MPa, 831MPa, 778MPa, respectively, while the high-strength lateral reinforcing deformed bars with 6-mm in diameter was 808MPa. Figure 2 shows their stress-strain curves. The compressive strength of the high-strength concrete was 74MPa.

In all of the specimens, deformations were measured in the defined test region of the columns. Strains were measured in the longitudinal steel and ties bars. Figure 3 shows location of measurement in the test region of a column during testing. Longitudinal deformations in the test region of the columns were measured on all four sides of the columns using a displacement transducer. Four longitudinal bars were instrumented with electric strain gages, including two middle bars and two corner bars. All tie bars were instrumented in the test region of the columns with electric strain gages.

3 TEST RESULTS

The test results were listed in Table 2. The stress-strain curves of core concrete of each specimen are shown in Figs. 4 to 7. Where, the stress was calculated by subtracting the longitudinal steel contribution from the total applied load. In the figures, the average strain-longitudinal strain curves for transverse reinforcement are also shown.

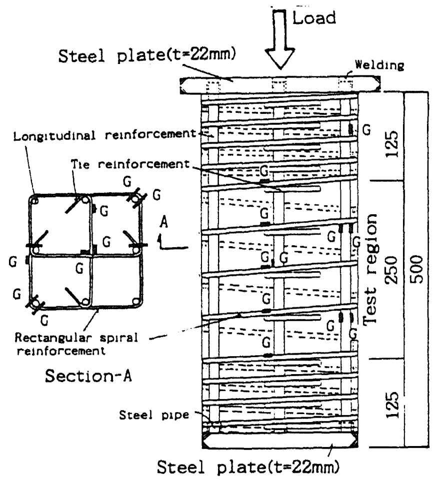
The results of experimental work were summarized as follows.

1. Tie bars tremendously enhanced the core concrete strength until failure.

2. Tie bars having 135 deg hooks with six-diameter extension length anchored in the core concrete were not effective compared to that with ten-diameter extension length.

3. The specimens with longitudinal reinforcement decreased in strength at smaller axial strain levels compared to that without longitudinal reinforcement, because longitudinal reinforcement caused fracture of spiral reinforcement, due to buckling effect.

4. The columns in which large increments in strain of the spiral reinforcement were occurred showed good performance.



Note:All dimensions in mm.
G:Electric strain gage

Fig. 1. Details of test specimen C8P6B.

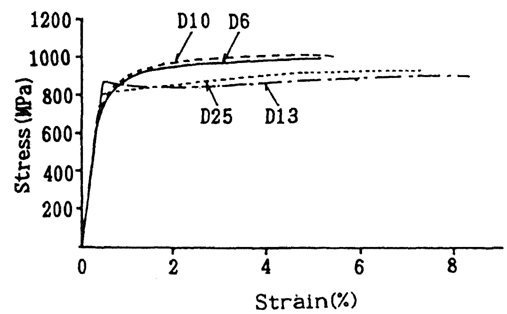


Fig. 2. Stress-strain curves of deformed bars.

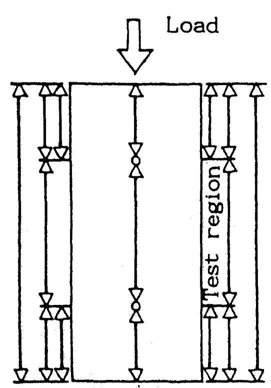


Fig. 3. Location of measurement insutrumentation.

Table 2. Test results.

Notation of specimen	At peak load				Notation of specimen	At peak load			
	Pmax	ε_{Pmax}	Lateral steel (μ)			Pmax	ε_{Pmax}	Lateral steel (μ)	
	kN	(%) a)	Perimeter b)	Tie c)		kN	(%) a)	Perimeter b)	Tie c)
C8P0P-1	28.2	0.391	—	—	C8P9B	52.4	1.407	5838	5030
C8P0P-2	26.5	0.406	—	—	C8P6C-1	46.2	1.113	4131	4772
C8P60-1	37.8	0.614	2180	—	C8P6C-2	45.9	1.420	5035	4865
C8P60-2	33.5	0.713	1720	—	C8P9C-1	50.6	1.280	6261	8103
C8P6A-1	43.6	0.440	1686	—	C8P9C-2	51.0	1.389	5498	6490
C8P6A-2	44.9	0.515	2506	—	C8P9D	52.4	1.117	4110	5186
C8P9A-1	45.7	0.537	2231	—	C8P9D(6)	49.7	1.201	5205	6101
C8P9A-2	44.7	0.484	2238	—	C8P0P3-1	23.7	0.281	—	—
C8P6A■	52.6	0.611	2863	—	C8P0P3-2	24.1	0.258	—	—
C8P6B	45.3	0.738	2978	3797	C8P0P3-3	25.9	0.292	—	—
C8P6B(6)	46.1	0.797	3337	3867	C8P6B3	43.1	0.541	2897	2752
C8P6B(4)	45.6	0.732	3204	3538	C8P6B3(L)	42.1	0.563	2586	2971

a)Average longitudinal strain of test region. b)Average strain of perimeter steel bars of test region. c)Average strain of tie steel bars of test region.

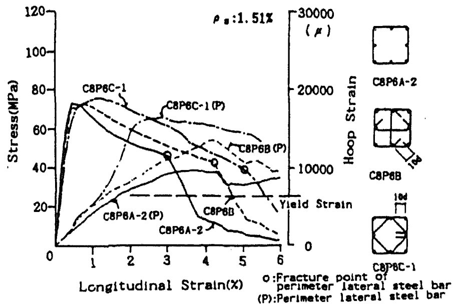


Fig. 4. Effect of lateral reinforcement configuration: ρ s=0.0151.

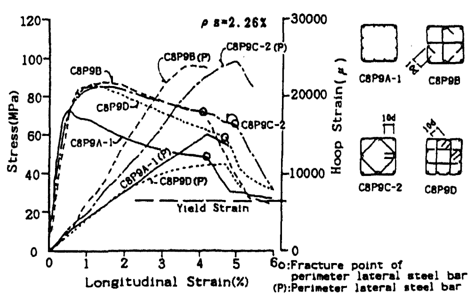


Fig. 5. Effect of lateral reinforcement configuration: ρ s=0.0226.

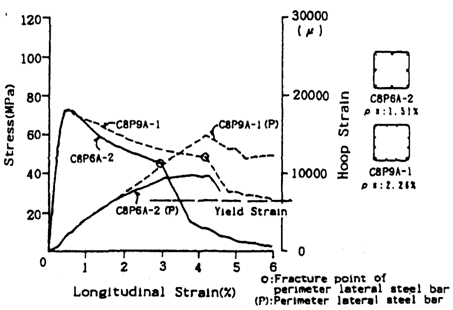


Fig. 6. Effect of amount of lateral reinforcement.

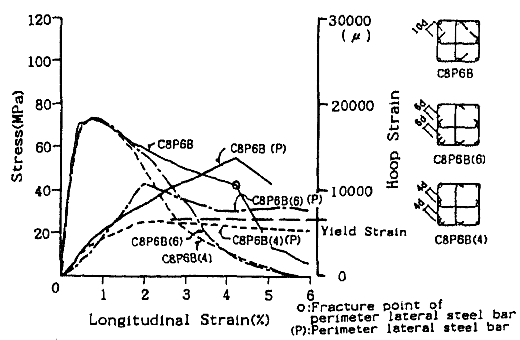


Fig. 7. Effect of hook extension length of lateral reinforcement.

4 EQUIVALENT AXIAL STRESS

In order to clarify the effects of core concrete, longitudinal reinforcement, and lateral reinforcement consisting of confined concrete columns, analytical method based on energy principle is proposed.

The increment of strain energy of each element was calculated on the following five assumptions, namely:(1)the strain at the test region of the columns is uniform; (2)the average strains in all the lateral reinforcement steel bars of the test region are the strain value measured; (3)the strain in the longitudinal steel bars at the test region is equal to the strain at the test region of the columns; (4)the stresses of longitudinal and lateral reinforcement steel bars are obtained from the stress-strain relations of their tension tests; (5)the work by axial load is the product of axial load by the increment of deformation in the test region.

The virtual work principle shown by Eq.(1) holds for increment of energy in every loading steps.

$$\Delta W_{con} + \Delta W_{ls} + \Delta W_{ws} + \Delta W_{wt} = \Delta W_{ext} \quad (1)$$

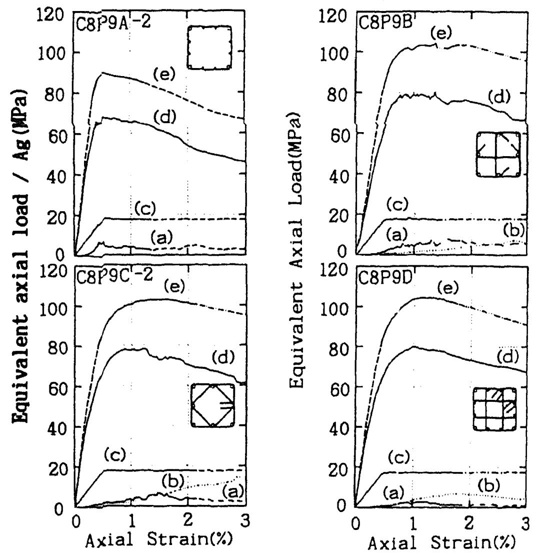
where on the left side, △Wcon, △Wls, △Wws and △Wwt represent the increment of strain energy by concrete, longitudinal steel bars, spiral reinforcement and tie bars, respectively. On the right side, △Wext is the increment of work by axial load. Dividing each △Wcon, △Wls, △Wws, △Wwt and △Wext by △δaxi, which is the increment of axial shortening, equivalent axial loads from energy absorption viewpoint, carried by each element was derived. The corresponding axial stresses of each elements were calculated by considering their volumes.

Figures 8 and 9 illustrate the calculated results. Figure 8 shows the relation between equivalent axial load and longitudinal strain. Figure 9 shows the relation between equivalent axial stress and longitudinal strain.

The following results were derived from Figs. 8 and 9.

1. The lateral reinforcement does not only enhance the axial load carrying capacity of core concrete due to its confining effect, but also absorbs similar energy to that of longitudinal reinforcement.

2. The strength enhancement of confined concrete produced by longitudinal reinforcement was much smaller compared to that by lateral reinforcement, if the volumes of the reinforcements are the same.



(a):Spiral Reinforcement
(b):Tie Bar
(c):Longitudinal Reinforcement
(d):Concrete(Confined)
(e):Sum of Them

Fig. 8. Equivalent axial strss divided by cross sectional area (Ag) of specimen.

5 CONCLUSION

The effects of longitudinal and lateral reinforcement on the compressive behaviors of high-strength R/C columns were clearly evaluated by the experimental results as well as the analyses based on the energy concept.

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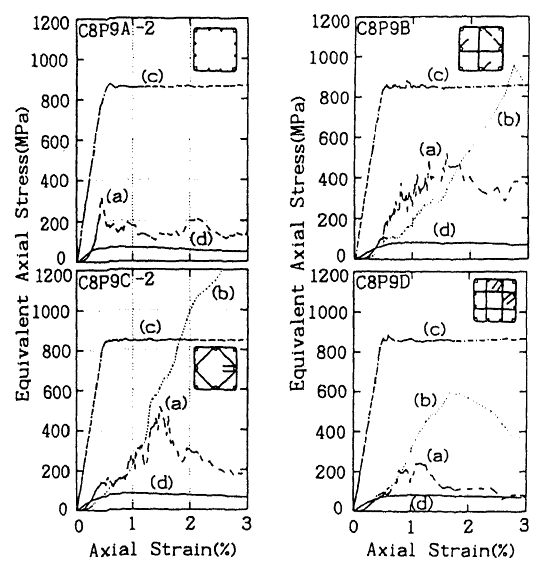

(a):Spiral Reinforcement
(b):Tie Bar
(c):Longitudinal Reinforcement
(d):Concrete(Confined)

Fig. 9. Equivalent axial strss divided by equivalent cross sectional area (Ai) of element considered (Ai=Equivalent axial load / (Volume of element / height) in test region).