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Summary

Confinement of concrete by transverse hoop or steel tube is effective in enhancing the ductility of reinforced concrete columns, especially columns under high axial load. Six specimens were tested under repeated lateral force to investigate seismic behavior of the confined columns. Test results of these specimens verified effectiveness of confinement by steel tube or high-strength hoop with rational configuration. The confined R/C columns exhibited very ductile performance even under axial compression force so high as the axial load ratio was 0.67.

1. Introduction

In Japan design standard for reinforced concrete structures, the upper limit of axial load ratio is recommended as 0.33 for column to ensure ductile seismic performance. However, columns at the lower stories of high-rise buildings usually have to sustain higher compression force when hit by a strong earthquake. It has been widely known that earthquake-resistant performance of the reinforced concrete columns under high axial load is very poor. Therefore, to promote the use of reinforced concrete structures in high-rise buildings located on seismic areas, a practical method is desirable to make the columns subjected to high axial load more ductile.

Confining reinforced concrete column by transverse reinforcements is one of the effective methods to enhance the earthquake-resistant capacity. This paper proposes two confining methods for square concrete columns under high axial load. The proposed methods are: 1) use of steel tube in lieu of conventional hoop or spiral, and 2) use of high-strength hoop, to confine columns. Using steel tube or high-strength hoop as confining material was for applying stronger lateral restraint to larger expansion of concrete in the column subjected to high axial force. Six specimens were tested under earthquake-simulated loading to investigate effectiveness of the proposed methods. This paper describes the experimental results of these tests.

2. Outlines of experiment

Six 250x250x1000 mm prismatic columns were fabricated. Longitudinal bars in each specimen consisted of twelve 13 mm diameter (D13) deformed bars uniformly distributed along the core perimeter. Among six specimens, four columns were confined by square steel tube, and the other

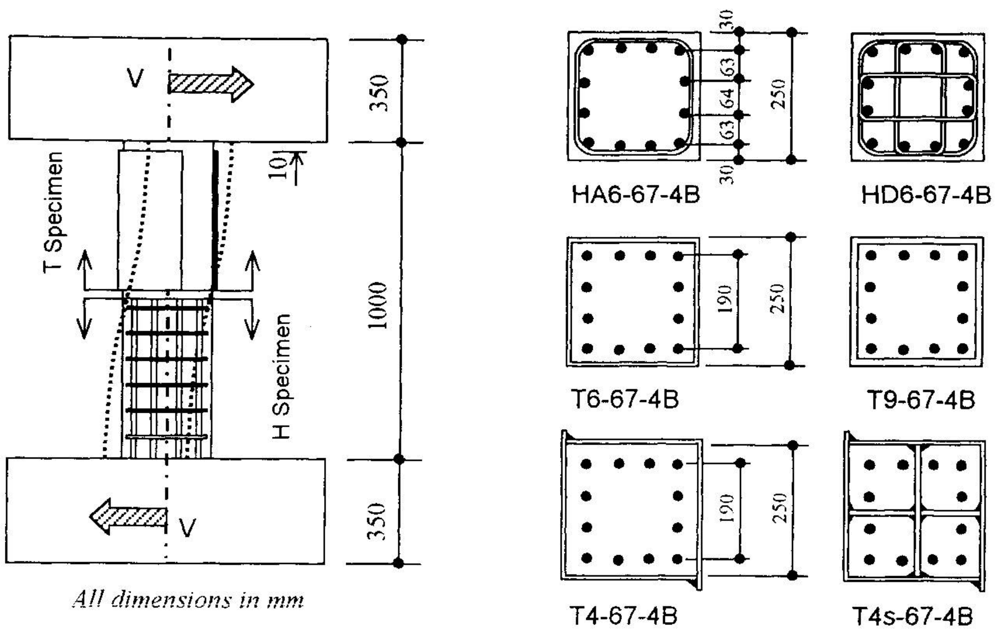

Fig. 1 Details of test specimens

twos confined by high-strength hoop having yield strength of 1026 MPa. For specimens confined by steel tubes, spaces of 10 mm were provided between loading stubs and steel tube at both ends of the columns. This was for ensuring that the steel tube provides a confining effect only, rather than a direct resistance to the axial stress due to the applied axial load and bending moment. Fig. 1 and Table 1 show sectional details and properties of the specimens, respectively.

The variables among the four specimens confined by steel tube were wall thickness of tube as well as with or without inner stiffener. Variable for the two specimens confined by hoop was configuration type of the hoop. As shown in Fig. 1, hoop has two types of configuration. One consisted of one perimeter hoop only, and the other was of square perimeter hoop with two rectangular overlapping hoops. The level of applied axial load, expressed in terms of axial load ratio ($=N/A_g f_c'$), was 0.67 for all specimens, which is twice the upper axial load ratio recommended in the AIJ standards [1] for reinforced concrete column. Specimens T6-67-4B and T9-67-4B had little different axial load ratios, because the core sectional dimensions of them were different from the other specimens (see Table 1).

Two batches of ready-mixed concrete, with a slump of 180 mm and maximum aggregate size of 20 mm, were used to construct specimens. The first batch was used for making specimens T6-67-4B and T9-67-4B, and the second for the others. The target compressive strength of concrete was 41 MPa, and the concrete cylinder strengths at testing stage are given in Table 1.

All specimens were tested under reversed cyclic lateral load while subjected to constant axial load. After applying axial load with a 5 MN universal testing machine, cyclic lateral load was applied through one 500 kN hydraulic jack to deform specimen in a double curvature pattern. Loading pattern for lateral load was displacement-controlled type with alternating drift reversals. The peak drifts were increased stepwise from 0.005 rad to 0.03 rad with increment of 0.005 rad after three cycles at each drift level. The maximum drift was 0.05rad for specimen T4-67-4B and T4s-67-4B with one cycle at each drift level after 0.02 rad. For specimen HD6-67-4B, the first half cycle of loading in the positive (push) direction reached drift level of 0.01 rad due to miss of operation. From the subsequent cycle, scheduled loading program was applied. Applied lateral

Table 1 Properties of the test columns

Specimen	f_c' (MPa)	Axial load		Details of transverse reinforcement						Type
		N (kN)	$\frac{N}{A_g f_c'}$	ρ_h (%)	f_{yh} (MPa)	d_h (mm)	C (mm)	s (mm)	D_c (mm)	
T4-67-4B	51.1	2109	0.67	7.02	292	4.3	250	0	250	Tube
T4s-67-4B	47.9	1971	0.67	10.5	292	4.3	125	0	250	
T6-67-4B	40.5	1655	0.72	9.66	303	5.6	238	0	238	
T9-67-4B	40.5	1655	0.76	15.0	296	8.5	232	0	232	
HA6-67-4B	40.5	1655	0.67	2.21	1026	6.4	190	27	215	Hoop
HD6-67-4B	40.5	1655	0.67	2.21	1026	6.4	190	55	215	

Note: f_c' = strength of concrete cylinder, A_g = gross sectional
area ρ_h = volumetric ratio of hoop or steel tube f_{yh} = yield stress of transverse steel
d_h = nominal diameter or wall thickness of transverse steel s = hoop spacing
C = unsupported length of transverse steel D_c = dimension of confined core concrete

load was measured by calibrated load cell. Lateral deflection of column was recorded by two 100 mm displacement transducers.

3. Observed behavior and test results

Crack patterns of all specimens are shown in Fig. 2 along with hysteretic lateral load V – drift ratio R relationships. Crack patterns of the specimens confined by steel tubes were observed by cutting and removing steel tubes after the tests. The drift ratio R in Fig. 2 is defined as δ/H, where δ is the lateral deflection, and H is the clear height of column. The dashed line shown in the hysteresis loop of specimen HD6-67-4B represents the first half cycle of loading, which was out of the planned loading program.

Specimen T4-67-4B had the thinnest steel tube with width-to-wall thickness ratio B/t = 60 as its lateral confining material. The specimen showed rapid strength degradation during cycles of lateral loading at 0.015 rad drift level. During subsequent cycle of loading to the peak drift of 0.02 rad, axial shortening of the column due to high axial load became significant, and the steel tube touched the loading stubs and soon buckled. As the steel tube buckled, the specimen lost its axial and lateral load-carrying capacities. This result implies that steel tube with B/t = 60 cannot provide sufficient confinement to make the column ductile under high axial load.

Specimen T4s-67-4B was also confined by square steel tube having B/t = 60, but the steel tube was laterally strengthened by two crossed inner stiffeners provided along 250 mm end regions of the column (see Fig. 1). Having the same wall thickness as steel tube, inner stiffener greatly increased the lateral stiffness, hence confinement pressure, of the thin steel tube, and significant lateral expansion of the concrete was not observed. The specimen exhibited very ductile performance and sustained 90 percent of the peak load at large drift level up to 0.045 rad.

Specimen T6-67-4B had steel tube with B/t = 46 as its lateral confiner. The specimen showed relatively stable response until the drift ratio R = 0.02 rad. During the cycle of loading to the drift ratio of 0.025 rad, steel tube touched loading stub due to accumulation of the axial shortening. However, unlike specimen T4-67-4B, specimen T6-67-4B exhibited higher load-carrying capacity as shown by the dashed line in the V - R hysteresis loop after steel tube had touched the loading stub. Use of thicker steel tube apparently increased not only the confinement pressure, but the

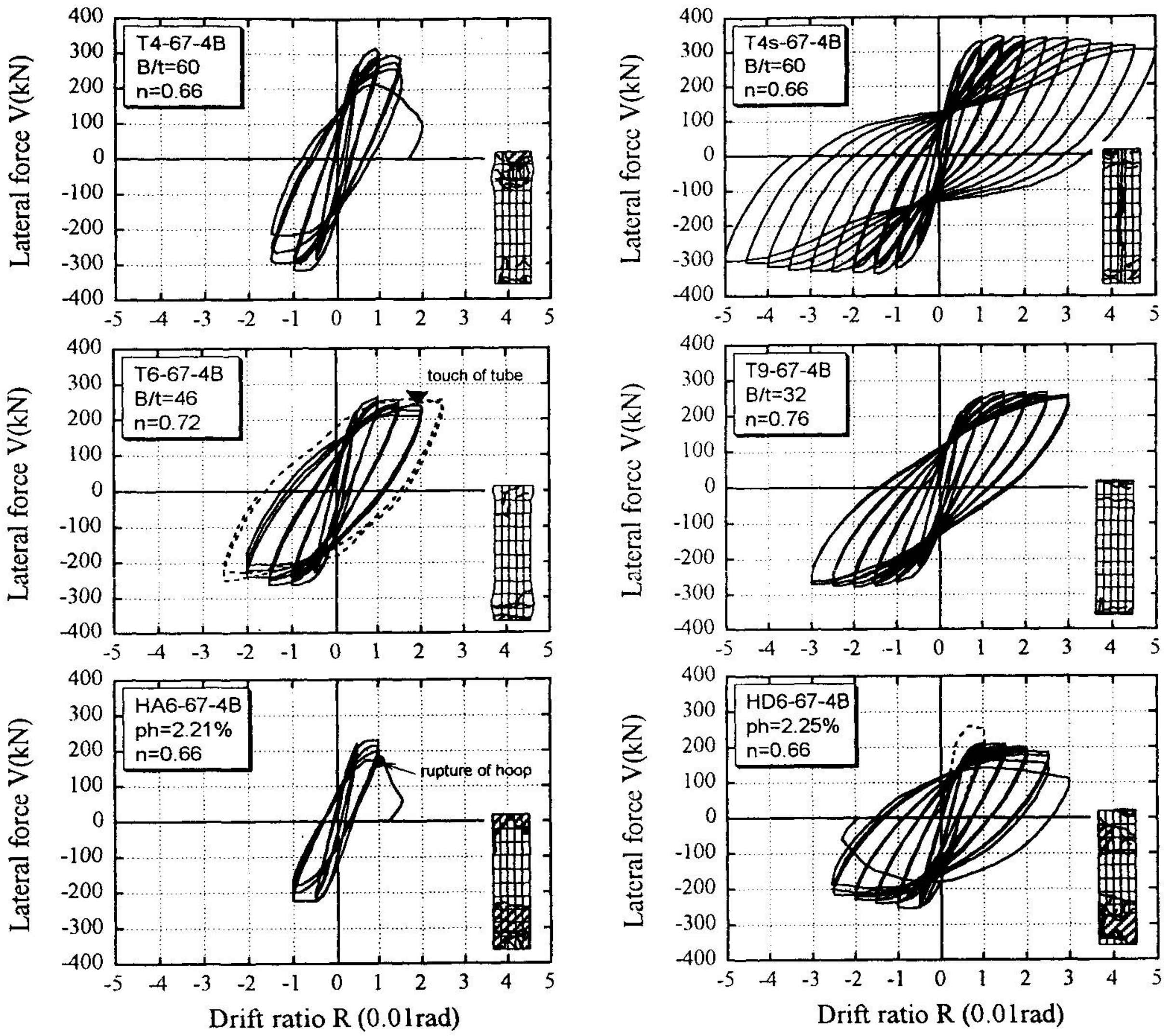

Fig. 2 Hysteretic response of specimens

axial buckling-resistant capacity of steel tube as well.

Specimen T9-67-4B was confined by the thickest steel tube with B/t = 32. The specimen showed very ductile behavior until end of test at drift ratio R = 0.03 rad. Damage was not observed, and the axial shortening was also very small.

Specimen HA6-67-4B was confined by high-strength conventional hoop. The amount of transverse hoop, expressed in terms of volumetric ratio of the hoop to the core concrete, was 2.21%, which is nearly equal to the maximum amount of hoop effective in resisting shear force [1] This specimen showed rapid strength degradation when the cover concrete commenced spalling at the drift ratio of 0.01 rad. Cover concrete of the column completely spalled off at the end of loading cycles of 0.01 rad. During the subsequent cycle of loading to R = 0.015 rad, transverse hoop was broken, and the specimen lost its sustaining capacity to axial load and failed.

Specimen HD6-67-4B had the same quantity of transverse hoop as specimen HA6-67-4B. The difference between them was hoop configuration as shown in Fig. 1. The specimen HD6-67-4B

Table 2 Experimental and calculated results

Specimen	V_{max} (kN)	R_{max} (10^{-2}rad)	R_u (10^{-2}rad)	M_{exp} (kN-m)	M_{cal} (kN-m)	M_u (kN-m)	M_{ACI} (kN-m)	$\frac{M_{exp}}{M_u}$	$\frac{M_{exp}}{M_{ACI}}$
T4-67-4B	317	0.90	1.52	168	128	155	90	1.08	1.87
T4s-67-4B	338	1.38	4.50	183	147	176	87	1.04	2.10
T6-67-4B	264	1.00	2.01	140	114	142	69	0.99	2.03
T9-67-4B	274	1.50	5.40	149	129	163	62	0.91	2.40
HA6-67-4B	226	0.85	1.05	120	101	121	83	0.99	1.45
HD6-67-4B	254	1.28	2.45	138	101	139*	83	0.99	1.66

Note: V_{max} = maximum experimental lateral force R_{max} = drift ratio corresponding to V_{max}
R_u = drift ratio where the lateral load dropped to 90% of the V_{max}
M_{exp} = experimental ultimate moment M_{cal} = theoretical ultimate moment [2,3]
M_u = enhanced ultimate moment by Eq.1 M_{ACI} = the ACI moment [4]
*: n=0.884 for core section has been used to calculate the enhanced ultimate moment by Eq. 1

responded in a stable manner and sustained 90 percent of its peak load up to the peak drift of 0.025 rad. The cover concrete completely spalled off at drift ratio R = 0.01 rad, but spalling of cover concrete had little negative influence on the seismic performance of the column. This can be attributed to the use of supplementary hoops, which enhanced confinement force of hoop.

4. Ultimate moment capacity and deformation

Experimental moments of all specimens are given in Table 2. The experimental moments were measured as the maximum column end moment at the positive loading within drift ratio of 0.02 rad, including the N-δ moment. The ultimate drift ratios shown in Table 2 were measured as drift ratio where the lateral force dropped to 90% of the peak load. For specimens whose tests were terminated at drift ratio of 0.03 rad, the ultimate drift ratios were determined by extrapolation of the envelop curves. Theoretical moment M_{cal} and M_{ACI} were obtained by using two stress blocks proposed by authors [2,3] and in the ACI codes [4], respectively. confinement effect of steel tube has been taken into consideration in the stress block proposed by authors.

As is obvious in Table 2, the ACI ultimate moments are 45% to 140% conservative due to ignorance of confinement effect of steel tube. By taking confinement effect of steel tube into consideration, the moments predicted by authors method show good agreement with experimental moments. Experimental moments M_{exp} exceeded theoretical moments M_{cal} by 25% on average mainly because of existence of stiff loading stubs at the ends of column, which would apply extra confinement to the compressed concrete at critical end regions of column. To account for the effect of extra confinement from loading stub, authors have developed an empirical formula for the moment enhancement above the predicted moment M_{cal}, of the form [3]

$$\frac{M_u}{M_{cal}} = \begin{cases} 1.10, & n \le 0.3 \\ 1.10 + 0.8(n-0.3)^2, & n > 0.3 \end{cases} \qquad (1)$$

where M_u is the ultimate design moment, and n is the axial load ratio. From Table 2, very good agreement can be observed between the experimental moments and ultimate design moments calculated by Eq. 1. The ratio of M_{exp} to M_u has mean value of 1.00 and standard deviation of 0.06. These results show importance of taking confinement effect of steel tube into account when calculating the ultimate capacity of confined concrete columns.

The experimental ultimate drift ratios are plotted in Fig. 3. The linked horizontal line superimposed in Fig. 3 presents the permissible ultimate drift ratio for well-confined concrete columns recommended in the AIJ guideline [5]. When confined by steel tube, columns show higher ultimate deformation as wall thickness of steel tube is thicker. In addition, use of inner stiffener is very effective in enhancing confinement effect of thin steel tube, hence ultimate moment and deformation capacity of the column. On the other hand, hoop configuration provided by one perimeter hoop only cannot make column ductile enough to satisfy the requirement of AIJ guideline. So, to fully utilize advantage of high-strength hoop, hoop should be used with rational configuration.

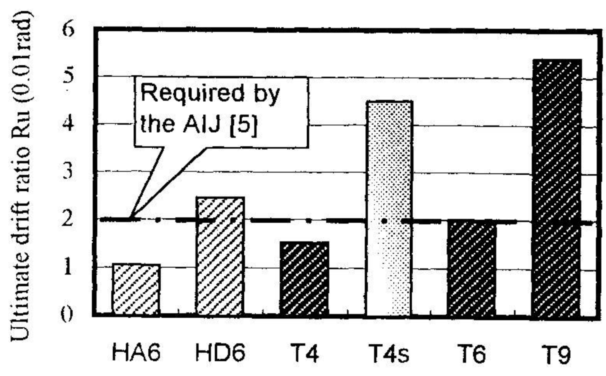

Fig. 3 Ultimate deformation

5. Conclusions

To make concrete column in high-rise buildings more ductile, this paper proposed two confining methods that involve use of square steel tube and high-strength hoop. The following conclusions can be drawn from the tests reported in this paper on the effectiveness of the proposed methods.

(1) Confinement of concrete by square steel tubes was effective in enhancing the ductility of reinforced concrete columns under high axial load, but too thin steel tube could not provide sufficient confinement to the column because of its weak lateral stiffness. For concrete column under high axial load to have the ultimate drift ratio of 0.02 rad, one should use steel tube with B/t <46 to confine the column. However, if strengthened with inner stiffener, the thin steel tube having B/t=60 could make column to be able to sustain 90% of the peak load at R = 0.045 rad.

(2) One single perimeter hoop cannot prevent column under high axial load from brittle crushing failure, even a large amount of high-strength hoops were used. However, use of supplementary hoop could increase confinement effect of hoop, and the column confined by hoop with rational configuration showed very ductile performance at large deformation up to R = 0.025 rad.

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