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EFFECTS OF WALL THICKNESS OF STEEL TUBE ON THE BEHAVIOR OF SQUARE TUBED R/C COLUMNS

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ABSTRACT

Experimental work has been conducted to investigate effects of wall thickness of the steel tube on the axial and flexural behavior of reinforced concrete columns confined by square steel tubes. Eighteen short concrete columns were tested under concentric loading, and eight specimens were tested under cyclic lateral force simultaneously subjected to constant axial load. Test results indicated that effects of wall thickness of the steel tubes on the seismic behavior of R/C columns became more significant as the axial load applied was higher. It has also been observed that when the width-to-wall thickness ratio of square steel tube was beyond the range of 45 to 60, the confinement provided by the square steel tube was insufficient to prevent brittle failure modes of R/C columns, particularly of columns under relatively high axial load.

KEYWORDS

Wall Thickness of Steel Tube; Square Steel Tube; Confinement Effect; Axial Behavior; Flexural Behavior; Reinforced Concrete Column; Ultimate Lateral Load; Axial Load

INTRODUCTION

The 1995 Hyogoken-Nanbu earthquake has caused substantial damage to reinforced concrete bridge piers and building columns. Some of the major problems involved with the damaged reinforced concrete columns are inadequate shear strength and inadequate flexural ductility. In order to prevent loss to human life and property from future earthquake, method to enhance the shear strength and deformability of existing reinforced concrete columns, specially those designed by previous design codes has to be developed.

It has been well known that the use of steel tube can provide sufficient confinement to concrete core, hence results in enhanced shear strength and improved flexural ductility of columns. As compared with the ordinary transverse hoops, the steel tube has one more significant advantage of preventing the spalling of concrete shell, which is the main reason for the degradation of column's load-carrying capacity as well as the deterioration of bond at large deformation. Recently, confinement method utilizing the steel tubes has been increasingly used as retrofitting method for the existing damaged or nondamaged reinforced concrete columns.

As to the effectiveness of retrofitting method by steel tubes, some of the investigations have been reported (Tomii

Table 1 Details and Primary test results of specimens under concentric loading

Specimen	f_c' (MPa)	B/t	f_{yt} (MPa)	N_m (kN)	$\frac{N_m}{N_c}$	Specimen	f_c' (MPa)	B/t	f_{yt} (MPa)	N_m (kN)	$\frac{N_m}{N_c}$
L31-1	25.2	31	388	1169	1.73	L60-1	24.9	60	316	806	1.12
L31-2				1153	1.71	L60-2				814	1.13
L31-3				1212	1.79	L60-3				857	1.19
M31-1	42.9			1628	1.42	M60-1	48.3			1777	1.22
M31-2				1648	1.43	M60-2				1776	1.21
M31-3				1657	1.44	M60-3				1663	1.14
H31-1	68.0			2197	1.20	H60-1	66.7			2138	1.06
H31-2				2197	1.20	H60-2				2158	1.07
H31-3				2158	1.18	H60-3				2040	1.01

f_c' : compressive strength of concrete cylinder f_{yt} : yield strength of steel tube
N_m : experimental maximum load
N_c : nominal load capacity $= f_c'(B-2t)^2$

et al.,1987, Preistley *et al.*, 1991, Sun and Sakino, 1992). Those reports, however, were mainly concentrated on verification of confinement effectiveness of the steel tube. Problem associated with the relation between the confinement degree and wall thickness of steel tubes, which is very important from the viewpoint of economic design, has not yet been studied.

The objectives of this paper are 1) to experimentally investigate effects of wall thickness of the steel tubes on the axial and flexural behavior of concrete columns confined by square steel tubes (called as tubed column hereafter), and 2) to recommend appropriate wall thickness of the square steel tubes upon which both economic design and adequate confinement effectiveness can be achieved.

AXIAL BEHAVIOR OF SQUARE TUBED COLUMNS

Test Specimens

The testing program described in this section was designed to study effects of wall thickness of the steel tubes on the axial behavior of concrete, since knowledge of the stress-strain behavior plays important role in assessing the flexural behavior of concrete columns. The experimental variables were (1) the wall thickness of square steel tube, expressed in terms of width to wall thickness, B/t, ratio and (2) the compressive strength of concrete. A total eighteen square concrete columns were constructed. The insides of steel tubes were coated with a thin grease layer to reduce the bond between the infilled concrete and steel tube. Table 1 summaries details of the test specimens along with the primary test results.

Square steel tubes with two kinds of B/t ratios, 31 and 60, were used to encase the concrete columns. The corresponding wall thicknesses were 5.63mm and 3.0mm, respectively. The square steel tubes with wall thickness of 3.0mm were made by bending thin steel sheets into L-shape, then welding them diagonally along the longitudinal direction. Yield strengths for the square steel tubes used are shown in Table 1. Three kinds of normal weight concrete with specified compressive strengths f_c', 25.0MPa, 45.5MPa, and 68.0MPa, were used for making specimens. Specimens were divided into six groups according to the values of B/t ratio and f_c'. Each group included three specimens with same condition to see the experimental scatter.

All specimens were loaded under a monotonic concentric loading through a universal testing machine of 5MN capacity. At both ends of specimens, steel blocks for loading were placed to ensure that the axial load be applied only to the infilled concrete (see Fig. 1(a)).

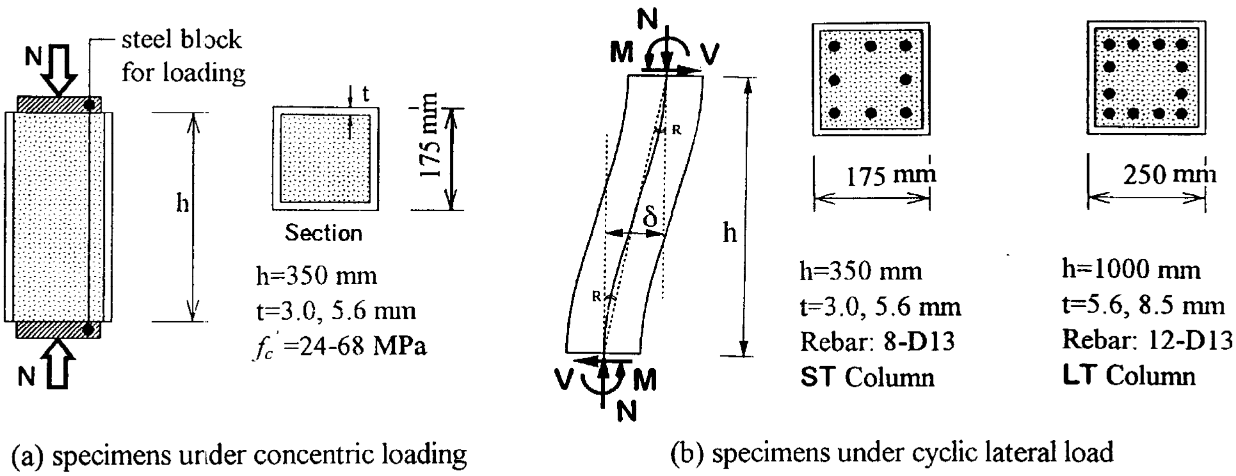


Fig. 1 Loading conditions and details of cross section

Test Results

Experimental relationships between axial load and axial shortening are plotted in Fig. 2 with respect to different B/t ratio. Only one curve for each group of specimens is shown in Fig. 2 since the difference among the test results of specimens under same condition was very small. It will be noted from Fig. 2 that the concrete columns exhibited higher load-carrying capacity than its' nominal axial load capacity when confined by square steel tubes. This can be attributed to the confinement of steel tubes which resulted in increased strength of concrete. Fig. 2 also indicates that the smaller the B/t ratio, the higher the strength and ductility of infilled concrete. On the other hand, it is quite clear that the steel tube with B/t ratio of 60 could not provide sufficient confinement to flatten the descending branch of the axial load versus axial shortening curve.

Evaluation of the Confinement Effect of Square Steel Tubes

As observed in Fig. 2, in addition to the B/t ratio of steel tubes, compressive strength of concrete is as well one of the main factor influencing the confinement degree of steel tubes. The first two authors have proposed a formula to evaluate the confinement effect of rectilinear transverse reinforcement including both conventional hoops and square steel tubes (Sakino and Sun, 1994). According to this confinement model, strength of concrete confined by the square steel tubes, f_{cc}', can be obtained as follow:

$$f_{cc}' = f_c' + 11.5 f_{re} = f_c' + 11.5 \rho_h f_{hs} \frac{t}{B-2t} \tag{1}$$

Where f_c'=strength of concrete cylinder; ρ_h=volumetric ratio of the steel tube defined by $[B/(B-2t)]^2-1$; B=width of the square steel tube; t=wall thickness of square steel tube. After obtaining confined concrete strength f_{cc}' by Eq. (1), the stress-strain curve for confined concrete can be defined by the following equation.

$$\frac{f_c}{f_{cc}'} = \frac{AX + (D-1)X^2}{1 + (A-2)X + DX^2} \tag{2}$$

in which, $X=\varepsilon_c/\varepsilon_{co}$; f_c and ε_c are the stress and strain; f_{cc}' and ε_{co} are the stress and strain at the peak; $A=E_c/E_{sec}$; $E_c=(0.69+0.332(f_c')^{1/2})x10^4$ is the Young's modulus of elasticity of concrete in MPa (Martinez *et al*, 1984); $E_{sec}=f_{cc}' / \varepsilon_{co}$ is the secant modulus at the peak point; and D is the parameter mainly governing the slope of descending

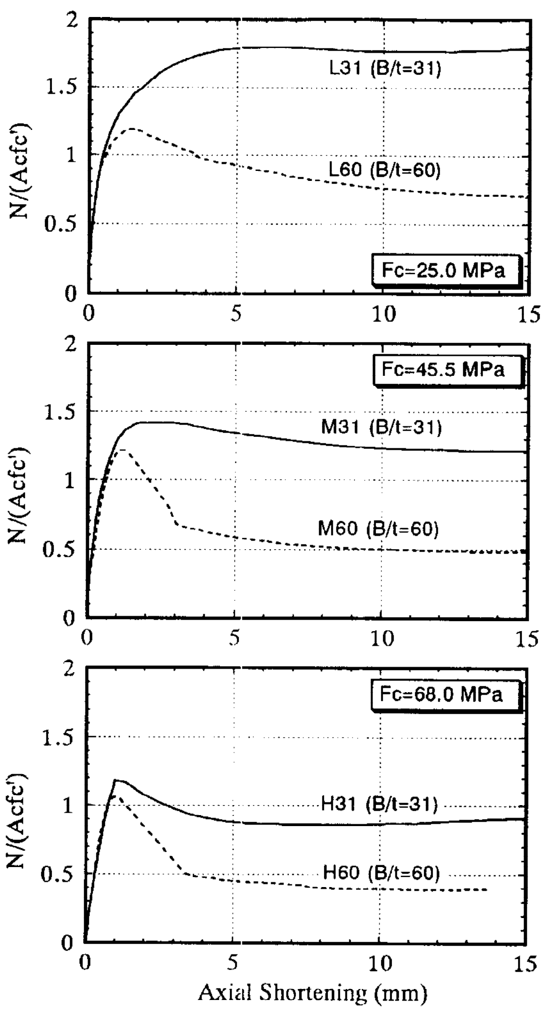


Fig. 2 Experimental relationships between the axial load and axial shortening

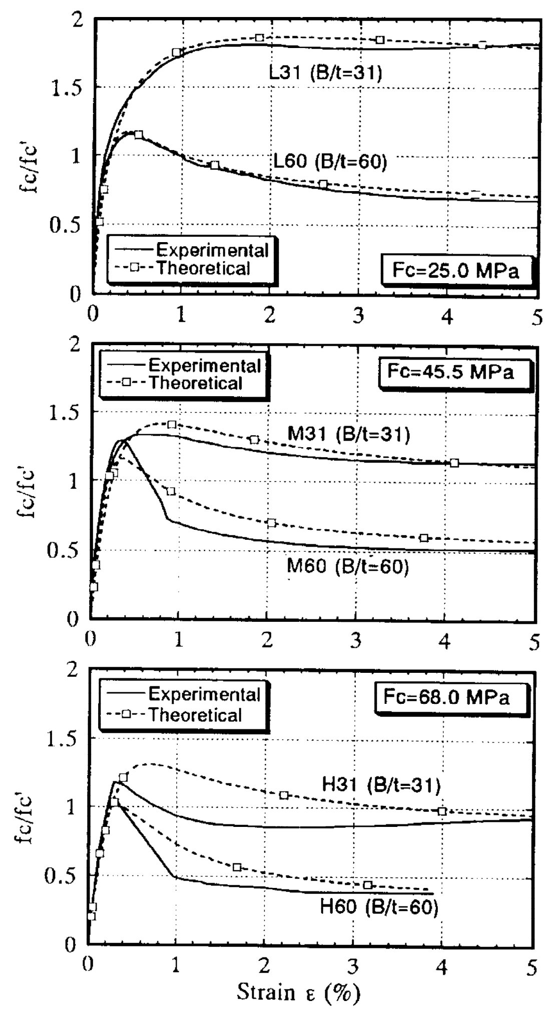


Fig. 3 Comparison between the experimental and analytica. stress-strain curves of concrete

portion of the stress-strain curve. Expressions for calculating the peak strain ε_{co} and the parameter D are given in the forms of

$$\frac{\varepsilon_{co}}{\varepsilon_o} = \begin{cases} 1 + 4.7(K-1), & K \le 1.5 \\ 3.35 + 20(K-1.5), & K > 1.5 \end{cases} \quad (3)$$

$$D = 1.5 - 1.7 \times 10^{-2} f_c' + 2.4\sqrt{(K-1)f_c' / 23} \quad (4)$$

where $\varepsilon_o = 0.94(f_c')^{1/4} x 10^{-3}$ is peak strain for unconfined concrete (Popovics, 1973), and $K = f_{cc}'/f_c'$ is the strength enhancement ratio of confined concrete.

Analytical stress-strain curves of confined concrete obtained by Eqs. (1)-(3) are compared with measured results in Fig. 3. For the peak stress, peak strain, and stress-strain curve up to large strain, good agreement between the analytical and experimental results was apparent. Difference between the predicted and measured results of specimens of H31 group was observed. The reason is that when using Eq. (1) to calculate the strength of confined concrete, the yield strength of steel tube f_{yt} was used for simplicity instead of the actual lateral stress in steel tube f_{hs}, though the measured f_{hs} was lower than f_{yt}. The above observations imply that effects of wall thickness of the square steel tubes on the axial behavior of concrete can be quite well predicted by Sakino and Sun's model (1994).

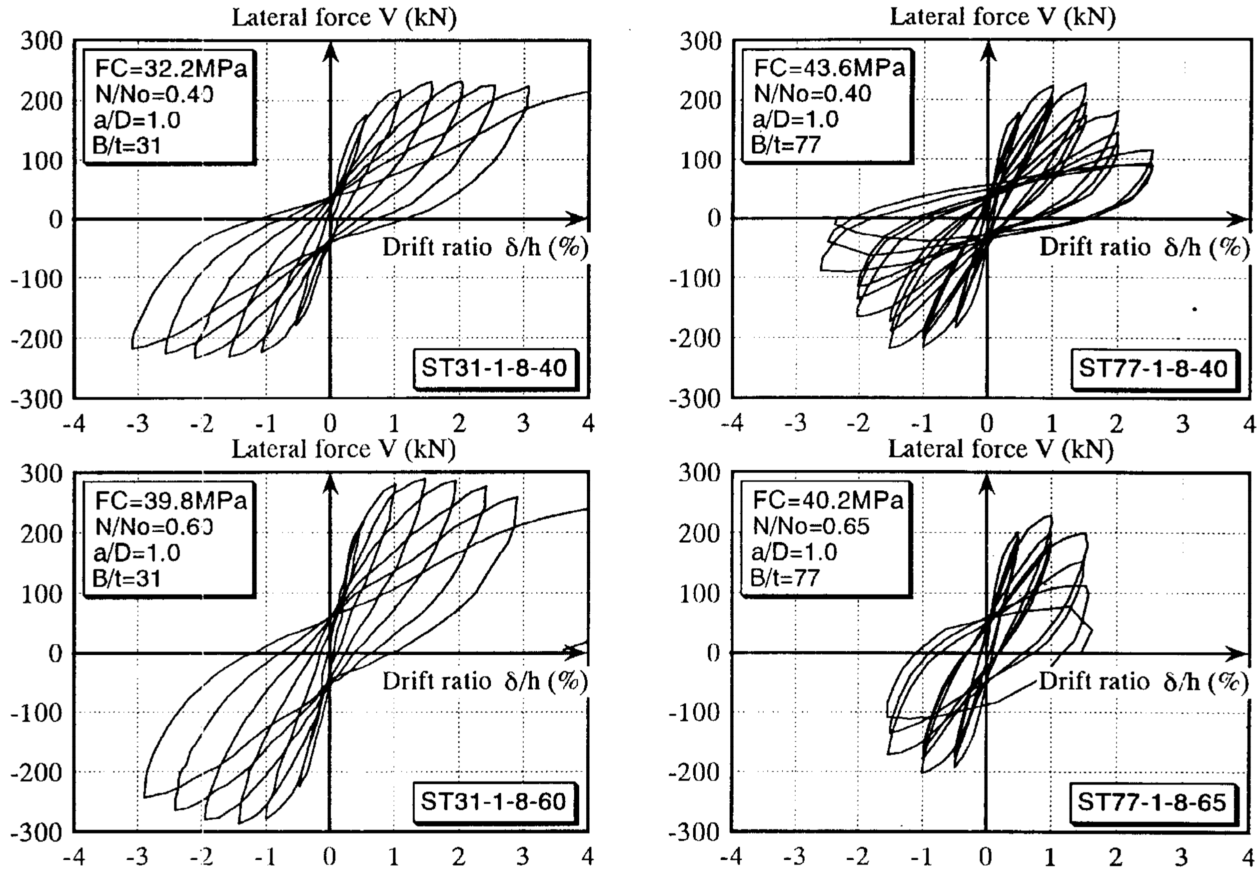


Fig. 4 Measured lateral load - drift ratio relationships of ST columns

FLEXURAL BEHAVIOR OF SQUARE TUBED COLUMNS

Testing Program

In order to investigate effects of wall thickness of the square steel tubes on the flexural behavior of tubed columns, eight concrete columns confined by square steel tubes were fabricated. Test columns were divided into two groups according to the shear span ratios, 1.0 and 2.0 in this experiment, of columns. These two groups of specimens are referred to as ST (Short Tubed) column and LT (Longer Tubed) column, respectively.

The parameters varied among specimens of each group were the magnitude of axial load applied and the wall thickness of steel tubes. The magnitude of axial load is expressed by the axial load ratio $n=N/Af_c'$, where N is the applied axial load, A is the confined concrete area, and f_c' is the compressive strength of concrete cylinder. The values of axial load ratio were 0.4 and 0.6 for ST columns, 0.33 and 0.67 for LT columns, respectively. Specimens of ST group were confined by 175x175mm square steel tubes with wall thicknesses of 2.2mm and 5.6mm, while LT columns were encased in 250x250mm square steel tubes with wall thicknesses of 5.6mm and 8.5mm. Eight 12.7mm diameter deformed bars called D13 were used as longitudinal bars in each ST columns. For LT columns, the longitudinal bars consisted of twelve D13 bars. Normal weight concrete, having target compressive strength of 40.0MPa, was used for making specimens.

Clearances between the loading stubs and the steel tubes at both ends of specimens were provided with length of 5mm and 10mm for ST columns and LT columns, respectively. This was for ensuring that the steel tubes only provided a confinement effect, rather than directly sustained the axial stress.

All specimens were subjected to cyclic lateral load simultaneously under constant axial load and deformed in a dou-

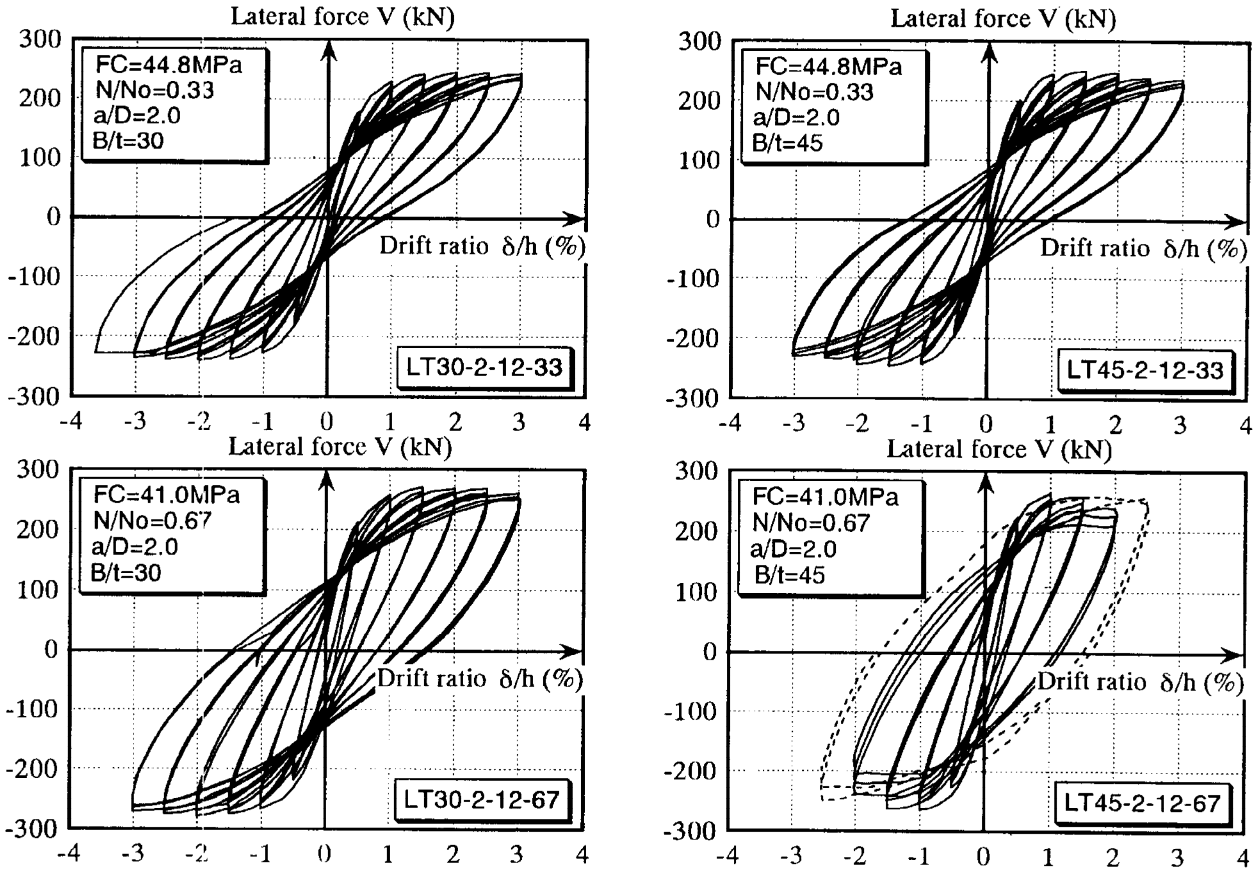


Fig. 5 Measured lateral load - drift ratio relationships of LT columns

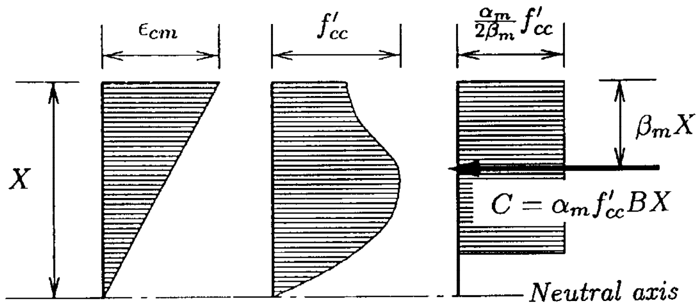
ble curvature pattern. The loading condition is shown in Fig. 1(b) along with the cross-sectional details of specimens. Loading arrangement described in Tomii *et al* (1987) was used to applied the lateral load as well as the constant axial load. The loading pattern for lateral load was displacement-controlled type with alternating drift reversals. The peak drifts were increased from 0.005h, where h is the clear height of columns, to 0.03h with increment of 0.005h after three complete cycles at each drift level.

Test Results

Lateral load V versus drift ratio δ/h hysteresis loops are presented in Fig. 4 and Fig. 5 for ST columns and LT columns, respectively. The dashed line shown in the hysteresis loop of specimen LT45-2-12-67 represents the loading cycles where the steel tube was observed having touched into the loading stub and begun to sustain the axial stress.

It will be noted from Fig. 4 that for ST columns, ductile flexural behavior can be expected even under high axial load if the column was confined by square steel tubes with B/t ratio of 31. On the other hand, columns confined by steel tubes with B/t ratio of 77 behaved in a very brittle manner. Therefore, it can be concluded that the confinement provided by square steel tube with B/t ratio of 77 was insufficient to prevent reinforced concrete column under relatively high axial load from failing in a brittle mode.

In the case of LT columns, all test specimens exhibited very stable hysteresis loop without serious strength degradation. Columns confined by square steel tubes with B/t ratio of 30 showed higher ductility than columns confined by steel tubes with B/t ratio of 45, and the effect of wall thickness of steel tubes on the flexural behavior of tubed columns became significant as the applied axial load increased. But columns confined by square steel tubes with B/t ratio of 45 also maintained over 80 percent of their peak loads up to the end of cycles at δ/h=0.02 even under



$$\frac{\epsilon_{cm}}{\epsilon_{co}} = 1.375 + 0.108K - 0.102K^{-4}\left(\frac{f'_c}{42}\right)$$
$$\alpha_m = 0.724 + 0.107K - \frac{0.037}{K - 0.007}\left(\frac{f'_c}{42}\right)$$
$$\beta_m = 0.383 + 0.046K - \frac{0.019}{K + 0.387}\left(\frac{f'_c}{42}\right)$$

(a) distribution of strain (b) actual stress (c) stress block (d) details of stress block parameters

Fig. 6 Idealisation of equivalent stress block proposed by Sun and Sakino (1992)

high axial load. This observation means that the square steel tube having B/t ratio of 45 is able to provide sufficient confinement to the concrete column under such high axial load as the axial load ratio is 0.67.

Ultimate Lateral Load of Square Tubed Columns

Comparison between experimental and analytical ultimate lateral loads of specimens is shown in Table 2. The analytical ultimate loads were based on the ultimate moments calculated by two methods. One is the method recommended in ACI code (ACI, 1989), and the other is that proposed by the first two authors (Sun and Sakino, 1992). In both methods, equivalent stress block of the compressed concrete was utilized to simplify the calculation procedure. Details of the ACI block can be found in ACI code and will not be given here.

Idealization and details of the stress block utilized in authors' method are shown in Fig. 6. The stress block parameters as well as the ultimate strain for the compressed concrete given in Fig. 6 were derived using the stress-strain curve model of confined concrete Proposed by Sakino and Sun (1994). In expressions of stress block parameters and ultimate strain proposed by authors, confinement of concrete by the square steel tubes is expressed by the term K, defined as ratio of confined concrete strength to unconfined concrete strength.

As is evident in Table 2, ultimate moment capacities based on the ACI block led to very conservative estimate of the ultimate lateral loads. The discrepancies between measured loads and ACI loads increase as the increase of axial load applied. Overstrengths of up to 114% of the ACI value occurred. This is mainly due to ignorance of confinement effect of the steel tubes and conservative extreme fiber concrete strain of 0.003 in ACI stress block. On the other hand, it is obvious from Table 2 that the ultimate moments obtained by authors' stress block predict very well the ultimate lateral loads. These results show the importance of taking confinement effect of the steel tubes into account when the axial load is high, since the higher axial load leads more concrete section compressed and the ultimate moment of section depends more upon the capacity carried by the compressed concrete.

CONCLUSIONS

Experiments were conducted on reinforced concrete columns confined by square steel tubes. Two kinds of loading was applied, concentric loading as well as combined axial load and cyclic lateral load. Effects of wall thickness of the square steel tubes on the axial and flexural behavior of tubed columns were investigated. The following conclusions have been drawn.

1) Confinement degree by the square steel tubes decreased as the B/t ratio of steel tubes and concrete strength increased. Effects of wall thickness of the square steel tubes on the flexural behavior of tubed columns became more significant as the applied axial load was higher.

Table 2 Ultimate lateral loads of specimens under cyclic lateral laod

Specimen	f'_c (MPa)	B/t	f_{yt} (MPa)	N (kN)	V_{exp} (kN)	V_f (kN)	$\frac{V_{exp}}{V_f}$	V_{ACI} (kN)	$\frac{V_{exp}}{V_{ACI}}$
ST77-1-8-40	43.6	77	277	479	226	232	0.97	206	1.10
ST77-1-8-60	40.2			715	228	231	0.99	165	1.38
ST31-1-8-40	32.2	31	330	368	234	232	1.01	175	1.34
ST31-1-8-60	39.8			608	291	265	1.10	170	1.71
LT45-2-12-33	44.8	45	303	926	251	232	1.08	199	1.26
LT45-2-12-67	41.2			1655	264	228	1.16	139	1.90
LT30-2-12-33	44.8	30	296	926	246	242	1.02	191	1.29
LT30-2-12-67	41.2			1655	270	260	1.04	126	2.14

f'_c : compressive strength of concrete cylinder f_{yt} : yield strength of steel tube

V_{exp} : experimental ultimate lateral load

V_f : analytical ultimate lateral load based on authors' stress block

V_{ACI} : analytical ultimate lateral load based on the ACI stress block

2) The appropriate wall thickness for square steel tubes, expressed by B/t ratio, was in the range of 45-60. Having B/t ratio beyond this range, the square steel tubes could not provide adequate confinement to prevent brittle failure modes of reinforced concrete columns, particularly of columns under relatively high axial load.

3) Effects of wall thickness of the square steel tubes on the axial and flexural behavior of tubed columns can be quantitatively evaluated by the stress-strain curve model, Eqs. (1)-(2), proposed by Sakino and Sun (1994), since good agreement has been observed between the experimental response and theoretical result obtained using this model.

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