

論文 Wall-Thickness Effect of Square Steel Tubed RC Columns on Their Seismic Behavior

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ABSTRACT: Eight 250x250x1000mm reinforced concrete columns confined in square steel tubes were fabricated and tested under reversed cyclic shear-bending type of loading in the presence of specified axial load levels. The main parameters were the wall-thickness ratio of the tubes, which varied from 28 to 117, and the axial load levels of 33 and 67% of the concrete's gross sectional capacity. The wall-thickness of the tubes did not show significant effect on the load-deflection curves of the columns at low axial load levels, but the effect was remarkable at high axial load levels. Stiffeners inside critical regions of tubes brought about large ductility.

KEYWORDS: reinforced concrete columns, square steel tube, wall-thickness of steel tube, earthquake-resistant columns, axial load.

1. INTRODUCTION

Recent major earthquakes in Japan and many other seismic-prone countries have attracted the attention of the engineering community to the vulnerability of many buildings and civil structures which once thought to be earthquake-resistant. Reinforced concrete structures sustained a considerable damage in this regard with column members initiating the collapse mechanism in most of the cases. Many of the damaged concrete columns designed prior to the adoption of the new seismic design provisions have low flexural ductility and low shear strength as reflected by the poor detailing of the transverse reinforcement. Recognizing the vital role that transverse reinforcement play in enhancing the flexural as well as the shear strengths of the column members, different techniques have been adopted to deal with the existing vulnerable structures. They included jacketing of RC columns for the purpose of repair or strengthening, depending on the state of the structure, by means of either additional reinforced concrete and/or steel jacketing plates or strips. However all this techniques could be thought of as an application of a more comprehensive method that was evolved more than a decade ago in Kyushu University and is known as the Transversely-Super-Reinforcing (TSR) method [1]. This method utilizes steel tubes to confine laterally the reinforced concrete columns, thereby replacing the conventional hoops and the cumbersome detailing and placement associated with them, with the tube detailed to avoid sustaining any direct axial load.

2. RESEARCH OBJECTIVE AND PARAMETERS

An ambitious multi-phase experimental research program was planned to investigate the effects of parameters that included the following: a) column's aspect ratio ($h/2B$), which includes 1, 1.5, and 2 resembling existing practical sizes and at the same time to distinguish the

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Table 1 Experimental parameters

Specimen notation	t (mm)	B/t	h (mm)	f _c (MPa)	Steel f _y (MPa)		n
					tube	rebars	
T2-33-4B	2.17	117	1000	32	322	318	0.33
T2-67-4B							0.67
T2-67-4BS							0.67
T3-33-4B	3.11	82			285		0.33
T3-67-4BS							0.67
T4-33-4B	4.29	60			292		0.33
T6-67-4B	6.09	43			305		0.67
T9-67-4B	9.46	28			279		0.67

Specimen notation : T2-67-4BS

T2 : Tubed specimen of 2mm nominal thickness.

67 : Percentage of axial load ratio.

4BS : Specimen's height as a multiple of its width B with  -shaped stiffeners at both ends of specimen.

B/t : Wall-thickness ratio

h : Specimen's clear height

n : Axial load ratio = N/B^2f_c N = axial load ; B^2f_c = gross-sectional capacity.

Table 2 Properties of material

a) Steel plates and rebars

Specimen		Stress (MPa)		Strain ϵ_{sh} (%)	E (GPa)	Elong. (%)
Notation	Thick.	f_y	f_u			
PL2	2.17	322	414	1.9	209	34.1
PL3	3.11	285*	451	0.7	213	34.2
PL4	4.29	292*	455	0.6	204	31.7
PL6	6.09	305	419	1.4	205	27.3
PL9	9.46	279	412	1.8	194	29.0
D13	13.0	318	507	1.8	190	19.4

* : taken at 0.2 % strain offset.

PL = plate

 ϵ_{sh} = strain-hardening threshold point.

D = rebar

b) Concrete mix

Slump	18 cm
Air content (%)	4.9
W/C ratio	0.4
Material / cubic meter	
Cement	500 kg
Coarse aggregate*	1020 kg
Fine aggregate	607 kg
Admixture	1.25 kg

* Maximum size = 13mm

failure mode of the member; b) axial load ratio (n), ranging from 33% to 67% which correspond to the limits recommended by AIJ's design guidelines for normal and transversely well-reinforced RC columns, respectively; c) tube wall-thickness ratio (B/t), which includes five different thicknesses chosen from available plates to cover the potentially applicable ratios of 28~117. Phase-I of this investigation, reported here, is concerned with specimens having aspect ratio of two along with the rest of the parameters in b) and c). The main experimental parameters are listed in Table 1 along with the other relevant parameters of steel and concrete.

The objective of the present phase is to establish a clear understanding of the role that the tube wall-thickness ratio (B/t) plays on the seismic behavior of the tubed reinforced concrete columns of aspect ratio of two. And the reason for taking B/t as a main parameter is that previous studies [2,3] have not dealt with the effect of this parameter on the seismic behavior of RC column members. It is to be noted here that although it is unrealistic to use B/t of 28 (t=9mm), it is still needed to establish a practical design limit from a research point of view.

3. DETAILS OF SPECIMENS

A total of eight tubed columns 250x250x1000mm were fabricated using welded square tubes. Due to the unavailability of the desired sizes and thicknesses of steel tubes in the market, plates of five different thicknesses were used instead. They were JIS G3101 SS 400 steel plates having the mechanical characteristics listed in Table 2a. Two out of the eight tubes, namely 2mm and 3mm thick, were provided with additional cross-shaped stiffeners at their critical ends. The detail of the tubes and welds is shown in Figure 1. All the tubes were 20mm shorter than the height of the column specimen to provide some clearance between the tubes and the loading stubs and were also wiped with a thin layer of grease from the inside prior to casting

concrete, thereby insuring lateral confining action only. Two batches of concrete mix were used in casting the eight specimens with identical properties as shown in Table 2b, and the concrete strength f'_c listed in Table 1 is the average of three 10x20cm standard Japanese cylinders taken at the time of testing. The longitudinal bars consisted of twelve 13mm diameter (D13) deformed bars with a total ratio ρ_g equals to 2.44% of the gross concrete section. The mechanical properties of the reinforcement are also included in Table 2a, while the general details of the complete specimen are also shown in Figure 1.

4. MEASURING EQUIPMENT

Measurements were made possible via strain gauges mounted on two opposite reinforcement bars and on the tube surfaces as well. Strain gages on the flange and web sides of the tube were also distributed to monitor the axial strains, if any, induced on the tube as well as to follow the expansion of the tube while confining the concrete at different levels of the critical zones. Displacement transducers located on the web sides of the specimen were also used for axial shortening and horizontal displacement measurements.

5. LOADING ASSEMBLY

The loading assembly shown in Figure 2 was used to produce the desired pattern of loading. The axial load was applied through the upper part of the frame right above the center of the column specimen using a 5-MN universal testing machine. The lateral force was applied by means of a 50-ton double-acting hydraulic jack connected to the upper and lower parts of the loading frame. The loading history of all specimens is also shown in Figure 1. All the specimens were subjected to this loading history with the exception of specimen T2-33-4B that was terminated prematurely due to the malfunction of the lateral displacement transducer.

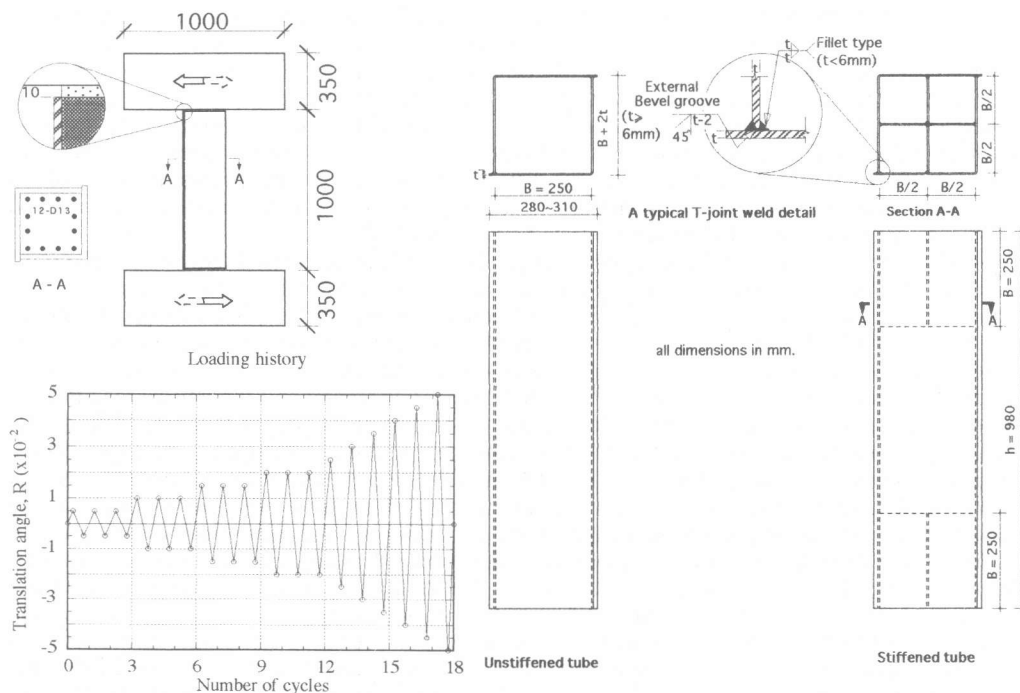


Figure 1 Specimen and tube details

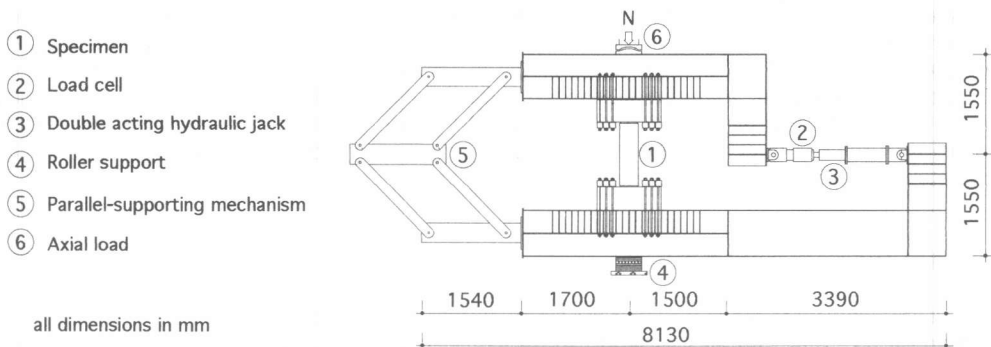


Figure 2 Loading assembly

6. EXPERIMENTAL RESULTS

The original cyclic responses are presented in the form of V-R relationships, where V is the lateral force and R is the translation or drift angle defined as δ/h . δ here represents the lateral deflection and h is the clear height of the column specimen. The results are shown in Figure 3 and the dotted mechanism lines represent the theoretical lateral capacities as dominated by the flexural strengths that will be referred to later. In general, it can be said that all the specimens behaved in a satisfactory and stable manner as far as the overall seismic behavior is concerned even with axial load levels as high as 67%. The lateral load capacities have far exceeded the theoretical, and the deflection ductilities, excluding specimen T2-33-4B, went as far as expected and were only limited by the capacities of the measuring equipment and/or by the tube getting into contact with the loading stubs. For the sake of easy comparison, the envelope curves, as represented by the forward loading portion of the cyclic responses, were generated and presented in Figure 4. From the figure, it can be seen that at an axial load of 33%, there is no significant effect of the wall-thickness ratio on the lateral load capacities of the specimens having B/t of 117, 82, and 60; however, there is some effect on the deformation capacity beyond $R=2\%$ and the trend is an increase with the increase of the wall thickness. On the other hand, at a higher axial load level of 67%, the difference was clear on the gradual increase of the lateral load capacity, and the deformation capacity as well, with the increase of the wall thickness, or the decrease of the B/t ratio, i.e. 117, 43, and 28.

With regard to the end-stiffened specimens, a remarkable increase in ductility over the non-stiffened ones was observed especially for specimen having B/t = 117, which gives a very promising indication of the benefit of using additional stiffeners at the plastic hinge regions of columns having high wall-thickness ratios. The slope of the descending part is influenced, to some extent, by the thickness of the confining tube and indicates the thicker the tube the more flat the descending part of the curve. Table 3 lists the experimental and theoretical results with some comparisons, included in the table also are the lateral drifts ($R_{0.9}$) taken at 90% of the lateral load capacities as indicators of the deformation capacities developed by the specimens. Specimens T9-67-4B, T4-33-4B and T3-67-4BS had developed large deformation capacities as far as 5% $R_{0.9}$ in this regard. As expected, all the specimens have failed in flexure and the theoretical lateral load capacities were calculated accordingly. The analytical model used in calculating the flexural capacities is the Sakino-Sun model [4] along with an empirical equation [5] for the prediction of the moment-enhancement due to the effects of the moment gradient and the extra confinement from the loading stubs as well. Comparable results were secured by the model, and taking the extra enhancement into consideration produced more agreement between the experimental and analytical flexural strengths, with the exception of specimen T2-67-4B. The need for further research and refinement on the part of the model is recommended in view of the little variation seen between the experimental and theoretical values of some specimens.

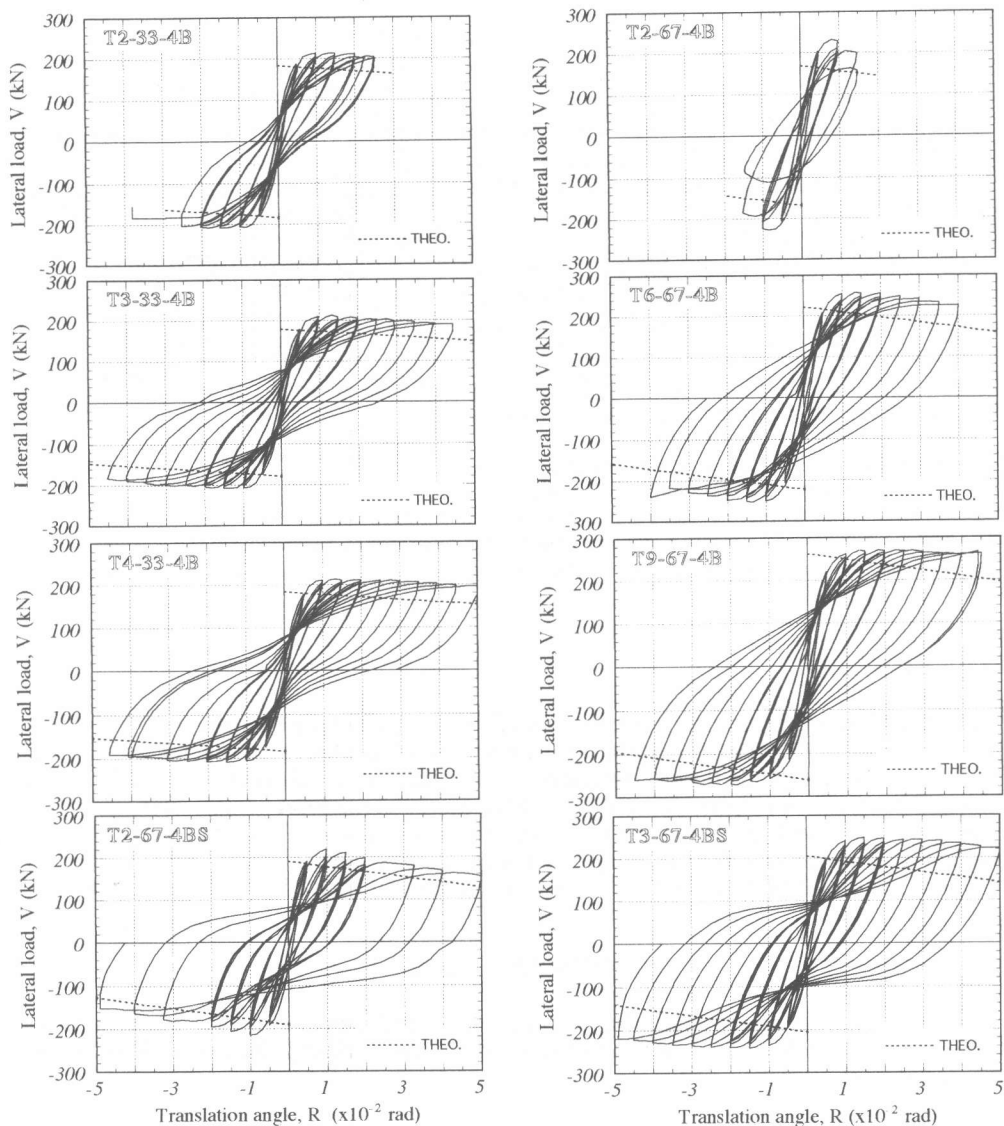


Figure 3 Experimental cyclic responses

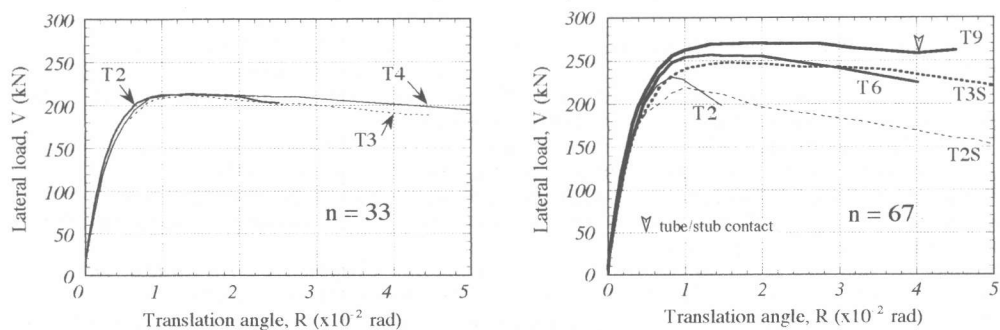


Figure 4 Effect of wall-thickness

Table 3 Experimental and theoretical results

Specimen	f'_c	Axial load	Experimental				Analytical				Comparisons		
			R_x	V_x	M_x	$R_{0.9}$	V_{aci}	V_{ara}	V_a	M_a	V_x/V_a	M_x/M_a	M_x/M_e
T2-33-4B	32.8	702	1.00	211	112	3.00	292	234	184	92	1.15	1.22	1.11
T2-67-4B	30.5	1295	0.82	229	121	1.30	333	276	168	84	1.36	1.44	1.19
T2-67-4BS	31.3	1295	1.00	217	116	2.10	341	298	191	96	1.14	1.21	1.00
T3-33-4B	30.6	657	1.33	210	110	4.10	281	239	179	89	1.17	1.24	1.12
T3-67-4BS	31.1	1295	1.50	246	143	5.00	339	313	205	103	1.20	1.39	1.15
T4-33-4B	30.8	661	1.34	211	111	5.00	282	261	184	92	1.15	1.21	1.10
T6-67-4B	33.4	1295	1.30	254	140	3.80	365	332	226	113	1.12	1.24	1.04
T9-67-4B	32.3	1364	1.84	272	162	5.00	352	377	262	131	1.04	1.24	1.02

Remarks: Units are : (MPa) for stress; (kN) for axial and shear loads; (kN-m) for the moments.

R_x : drift angle in percent radians at lateral load capacity.

V_x : experimental lateral load capacity.

$R_{0.9}$: drift angle in percent radians at 90% lateral load capacity.

V_{aci} : predicted shear strength according to ACI method.

V_{ara} : predicted shear strength according to Arakawa's (AIJ modified) equation.

V_a : analytical lateral load capacity as dominated by flexure calculated by Sakino-Sun model.

M_a, M_e : analytical, and enhanced analytical flexural strength .

$$\frac{M_x}{M_e} = \begin{cases} 1.1 & n \leq 0.3 \\ 1.1 + 0.8(n - 0.3)^2 & n > 0.3 \end{cases}$$

M_x : experimental flexural strength .

7. CONCLUSIONS

The following remarks can be made in view of the experimental investigation;

- 1) At low axial load levels, the lateral load capacities were almost unaffected by the wall thickness of tubes, while the effect became more prominent at high axial load levels and the thicker the wall is the higher the capacity and the more flat the descending part is.
- 2) The lower the axial load level is the better the deformation capacity, and the thicker the tube is the higher the deformation capacity for a given axial load level.
- 3) Columns with stiffeners inside the critical zones of tubes displayed significant ductility.

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