EARTHQUAKE-RESISTING PERFORMANCE OF R/C COLUMNS
CONFINED BY SQUARE STEEL TUBES

(Part 2 Effects of wall thickness of steel tube)

正方形鋼管横補強鉄筋コンクリート柱の耐震性能
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As the second part of an integrated theoretical and experimental study of earthquake-resisting performance of the reinforced concrete columns confined by square steel tube, this paper presents experimental results conducted over twelve reinforced concrete columns confined by square steel tubes having five kinds of wall thickness. The columns were tested under reversed cyclic lateral force while subjected to constant axial load to study the effect of wall thickness of the square steel tubes on the seismic performance of the columns. It is shown that the effect of wall thickness on the earthquake-resisting capacity of the confined columns depends on the applied axial load level; the higher the axial load was, the more significant the effect of wall thickness. Experimental results also indicate that strengthening the square steel tube with inner stiffeners in the potential failure regions of the column could enhance confinement effectiveness of the steel tube significantly. Even under high axial load with axial load ratio $n=0.67$, the column confined by strengthened square steel tube by inner stiffener with B/t ratio of 118 exhibited very stable response in a manner similar to the columns confined by much thicker square steel tube with B/t ratio of 43.

Keywords: earthquake-resisting performance, square steel tube confinement, width-to-wall thickness ratio of steel tube, confinement effect, ultimate deformation, axial load ratio
耐震性能、正方形鋼管横拘束、鋼管の幅厚比、拘束効果、終局変形能、軸力比

1. INTRODUCTION

It has been widely recognized that confinement of concrete by transverse reinforcement is effective in enhancing the earthquake-resistant capacity of reinforced concrete column. Since the steel tube, when used as transverse confiner, has a significant advantage over the conventional hoops of preventing spalling of the shell concrete, confinement by the steel tube has recently gained its increasing use in strengthening existing reinforced concrete columns as well as in improving ductility of high strength concrete (HSC) columns. While many investigators have experimentally verified confinement effectiveness of the steel tube as reviewed by authors [1], there is not yet a rational design method for the reinforced concrete column confined by the steel tube (referred to as tubed column hereafter), due to lack of knowledge on the following issues.

- 1) Seismic performance of the tubed column subjected to high axial compression.
- 2) Earthquake-resisting performance of the tubed column with large longitudinal reinforcement ratio.
- 3) Effect of wall thickness of the steel tubes on the earthquake-resisting performance of the tubed column
- 4) Effect of shear span ratio on the seismic performance of the tubed column.
- 5) Estimation method for the ultimate load-carrying and the deformation capacities of the tubed column.

To study these problems, the authors have conducted an integrated experimental and theoretical work with emphasis placed on the seismic behavior of the squarely tubed columns. As the first phase of this integrated study, the first two authors have experimentally investigated the first two issues listed above, and concluded that confinement by the steel tube with width-to-wall thickness ratio $B/t=31$ could assure sufficient flexural ductility to the column with longitudinal steel ratio of 7.68% even under such high axial load as the axial load ratio $n = 1.0$ [1].

This paper, as the second phase of the study, deals with effect of wall thickness of the steel tube on the seismic performance of the tubed columns. Twelve 250mm square and 1000mm high reinforced concrete columns were tested under reversed cyclic lateral force and constant axial load. Square steel tubes with B/t ratios varying from 28 through 118 were used as transverse confiner. In addition, to enhance the anticipated low confinement effectiveness of the thin square steel tube, three columns among the twelve specimens were tested with their steel tubes being strengthened by the inner stiffeners within the plastic hinge regions of the column.

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Table 1 Properties and main results of the tubed columns without inner stiffener

Notation (1)	Details of specimen						Measured results				Predicted results					
	f'_c	N	n	t	B/t	f_{yt}	V_{max}	$\frac{V_{max}}{A_c f'_c}$	R_{max}	R_u	V_{mu}	$\frac{V_{max}}{V_{mu}}$	V_m	$\frac{V_{max}}{V_m}$	V_{un}	$\frac{V_{max}}{V_{un}}$
	(MPa)	(kN)	(=N/No)	(mm)		(MPa)	(kN)		(rad)	(rad)	(kN)		(kN)		(kN)	
T2-33-4D	32.8	702	0.342	2.17	117	323	211	0.103	0.010	0.024	203	1.04	187	1.13	171	1.23
T3-33-4D	30.6	657	0.344	3.11	82	285	210	0.110	0.013	0.030	197	1.07	182	1.15	165	1.27
T4-33-4D	30.8	661	0.343	4.29	60	292	211	0.110	0.013	0.040	201	1.05	186	1.13	165	1.28
T3-50-4D	50.9	1589	0.499	3.11	82	285	312	0.098	0.009	0.015	295	1.06	265	1.18	213	1.46
T6-50-4D	48.3	1510	0.500	6.09	43	305	321	0.106	0.014	0.022	310	1.04	282	1.14	206	1.56
T9-50-4D	47.9	1500	0.501	9.46	28	279	329	0.110	0.015	0.032	332	0.99	308	1.07	205	1.60
T4-67-4D	51.1	2128	0.666	4.29	60	292	316	0.099	0.010	0.013	300	1.05	254	1.24	178	1.78
T6-67-4D	33.4	1295	0.620	6.09	43	305	254	0.122	0.013	0.030	261	0.97	228	1.11	150	1.69
T9-67-4D	32.3	1364	0.676	9.46	28	279	272	0.135	0.018	0.040	299	0.91	266	1.02	137	1.99

 f'_c : compressive strength of concrete cylinder

N: axial load applied

B/t: width to wall thickness ratio of steel tube

No: nominal axial load strength of the concrete section ($=A_c f'_c$) V_{max} : measured maximum lateral force R_{max} : drift ratio of column at V_{max} R_u : drift ratio of column at which the lateral load dropped to 95% of the V_{max} V_{mu} : lateral load corresponding to the ultimate moment calculated by authors' method [4] V_m : lateral load corresponding to the ultimate moment calculated by taking only confinement effect of the steel tube into account [4] V_{un} : lateral load corresponding to the ultimate moment calculated by the ACI code [5]

2. EXPERIMENT FOR STUDYING THE EFFECT OF WALL THICKNESS OF STEEL TUBES

2.1 TEST SPECIMENS

Nine 250x250x1000mm prismatic columns were made and tested under reversed cyclic lateral load and constant axial compression to investigate effect of wall thickness of the steel tubes on the seismic performance of the tubed columns. These specimens, called as the T-series specimen hereafter, were confined by the square steel tubes having inner width of 250mm and five kinds of wall thickness, 2.17mm through 9.46mm. Longitudinal bars in each column consisted of twelve 12.7mm diameter deformed bars (D13) uniformly distributed around the column perimeter to give a steel ratio of 2.44%. Fig.1 shows reinforcement details along with the assumed deflection shape of the test column.

Fig.1 Reinforcement details and loading condition of the specimens

It can be seen from Fig. 1 that clearances of 10mm were provided between the loading stubs and the steel tube at both ends of the column.

This was done for ensuring that the steel tube provides only a confining effect to the concrete, rather than a direct resistance to the axial stress induced by the applied axial load as well as bending moment.

Experimental variables among the T-series specimens were: 1) wall thickness of the steel tube, expressed in terms of width-to-wall thickness ratio B/t , 2) concrete strength, and 3) magnitude of the axial load, represented in terms of axial load ratio $n(=NA_c f'_c)$, where N is the applied axial load, A_c is the concrete core area, and f'_c is the compressive strength of concrete cylinder. Table 1 lists outlines of the T-series specimens along with their primary measured and predicted results. The B/t ratios of the used steel tubes varied from 118 through 28, while the concrete had targeted compressive strength of 36MPa and 51MPa. Values of the axial load ratios were 0.33, 0.50, and 0.67. The axial load ratio of 0.33 corresponds to the upper limit axial load for the ordinary concrete column as recommended in the AIJ standards [2], and 0.67 equals to the upper limit axial load suggested in the AIJ design guidelines [3] for the well transversely confined concrete columns.

The ready-mixed concrete, with a slump of about 180mm and maximum aggregate size of 13mm, were used to construct the T-series specimens as well as the Ts-series specimens, whose details will be described in the next section. Compressive strength of concrete cylinder for each column at the testing stage is given in Table 1. Table 2 summarizes the mechanical properties of the steels used. Each value shown in Table 2 represents the average of three tests. Since the steel tubes with the targeted wall thickness were not available on the market, all of the steel tubes had been made from the steel plates

in laboratory, and the values shown in Table 2 actually express test results of the steel plates.

2.2 LOADING CONDITION AND INSTRUMENTATION

A loading apparatus with the same loading mechanism as the apparatus described in Ref. 1 was used to apply designed loading history to the columns. For each specimen, after the axial load being applied by means of an universal testing machine with 5MN capacity, the reversed cyclic lateral load was applied through one 500kN hydraulic jack to deform the column in a double curvature shape as shown in Fig. 1(b). The designed loading pattern for the lateral load was displacement-controlled type with alternating drift reversals. Fig. 2 illustrates the planned loading history for the lateral load. The drift ratio R was defined as ratio of the lateral displacement Δ to the clear height h ($=1000\text{mm}$) of the column. Peak drift ratios were increased stepwise from 0.005 rad to 0.02 rad with increment of 0.005 rad after three complete cycles at each drift ratio level. After then, the peak drift ratios were increased up to 0.05 rad or till failure with increment of 0.005 rad after one cycle at each drift ratio level. All specimens were loaded following the loading program described above with the exception of specimen T2-33-4D due to malfunction in instrumentation.

Deflections were measured by displacement transducers (D.T.). In addition to the lateral deflection measurements, the average axial deformation of each specimen was also measured. The measuring frame for the deflections was identical to that used in the tests described in Ref.1. Strains in the longitudinal bars as well as the confining steel tube were measured with strain gauges. All readings from both the strain gauges and the D.T. were fed into a computer-controlled data acquisition system, and stored into floppy-disk.

2.3 OBSERVED BEHAVIOR AND TEST RESULTS

Fig. 3 shows crack patterns of the T-series specimens. The crack patterns were observed by cutting and removing steel tube after the tests. Values of drift ratio given in Fig. 3 represent the peak drift experienced by each specimen. As can be seen from Fig.3, flexural cracks were dominant in all specimens, regardless of the axial load level. The damaged region tended to extend longer from the column end with the axial load level, and use of the thicker steel tube was really effective in preventing extension of the cracked zone.

The measured hysteretic lateral load V – drift ratio R relationships of the T-series specimens are plotted in Fig. 4. Solid circles shown in Fig. 4 express the testing stages when the confining steel tube contacted with the loading stubs due to accumulation of the axial shortening of the column at large deformation. In addition, the experimental maximum lateral load $V_{\max}$ as well as the corresponding drift ratio $R_{\max}$ were given in Table 1 along with the ultimate drift ratio R_u , where the lateral load dropped to 95% of the $V_{\max}$. The measured $V_{\max}$ in Table 1 represents the average of the maximum lateral forces measured in both the push direction and the pull direction.

Apparently, the axial load level influenced not only the seismic performance of the tubed column, but the confinement effectiveness of the steel tube as well. For the three specimens subjected to axial load with $n=0.33$, each specimen showed very ductile responses as seen in Fig. 4(a). While test of the specimen T2-33-4D was terminated at $R=0.025\text{rad}$ due to malfunction in instrumentation, the axial shortening of it was very small. Hence, it can be said that the steel tube with $B/t=118$ could assure sufficient ductility to the column, which implies that effect of wall thickness of the steel tube was not significant on the seismic performance of the tubed columns failing in flexure under relatively low axial load. However, as the axial load level increased, effect of the wall thickness became significant. When the axial load ratio increased to about 0.50, the steel tube with $B/t=82$ couldn't prevent strength degradation of the

Table 2 Mechanical properties of the steels

Notation	t (mm)	f_{yt} (MPa)	f_{ut} (MPa)	ϵ_{sh} (%)	E_s (GPa)	ϕ (%)
D13 bar	-	318	510	1.8	190	19.4
T2 plate	2.17	323	412	1.9	209	34.1
T3 plate	3.11	285*	453	-	213	34.2
T4 plate	4.29	292*	456	-	204	31.7
T6 plate	6.09	305	420	3.11	205	27.3
T9 plate	9.46	279	410	4.29	194	29.0

t : measured wall thickness of steel plate

f_{yt} : yield stress

f_{ut} : tensile strength

ϵ_{sh} : strain where strain-hardening begins

E_s : Young's modulus

ϕ : elongation ratio

*: 0.2% offset yield stress

Fig. 2 Loading program for the lateral force

Fig. 3 Crack patterns of the T-series specimens viewed from the web side

Fig. 4 The measured lateral load V - drift ratio R relationships of the T-series specimens

Fig. 5 Comparison of the envelop curves of the T-series specimens (effect of wall thickness)

tubed column commencing at the peak drift of 0.02 rad (see Fig. 4(b)). Furthermore, as obvious in Fig. 4(c), the steel tube with $B/t=60$ couldn't assure satisfactory seismic performance to the column under such high axial compression as $n=0.67$, either. This can be attributed to that higher axial load leads to more concrete in column section being compressed, hence requiring the use of the thicker steel tube.

To more precisely study effect of the wall thickness, envelop curves of the V - R hysteresis loops in the push direction are compared in Fig. 5. The ratio of the average shear stress and the concrete cylinder strength was chose as vertical axis in Fig. 5 to eliminate influence due to different concrete strength. For the column subjected to high axial load with n larger than 0.50, not only the ductility but also the lateral load-carrying capacity were enhanced with wall thickness of the steel tubes. On the other hand, in the case of the column under relatively low axial compression, the strength enhancement due to use of the thicker steel tube was, if any, little.

Solid and linked lines superimposed on the measured V - R loops represent the theoretical ultimate lateral forces V_{mu} and V_{um} , respectively. The V_{mu} corresponds to the ultimate flexural strength calculated by the method proposed by the first two authors [4], and the V_{um} is based on the ACI ideal flexural strength [5]. As described in Ref. 4, authors' calculation method is different from the ACI method in that the proposed method can take into account not only confinement effect by the steel tube, but also extra confinement by the stiff loading stubs.

It is obvious from Fig. 4 that all the T-series specimens developed their ultimate strength as a confined column. Column (16) in Table 1 indicates

that the ACI ideal flexural strength led to very conservative evaluation of the ultimate lateral load of the tubed columns. Difference between the measured ultimate lateral loads V_{max} and the ACI loads V_{uni} increased as the axial load level increased, and over-strength of 23% - 99% of the ACI load was observed due mainly to ignorance of confinement effect of the steel tubes. On the other hand, by taking confinement effect by the steel tube and the stiff loading stubs into consideration, the proposed method predicted the ultimate lateral load fairly well. Ratios of the V_{max} and the V_{uni} has a mean value of 1.02 and a standard deviation of 0.05. For comparison, the theoretical strength V_m obtained by only considering the confinement effect of steel tube is also given in Table 1 (see columns (14) and (15)). The V_m conservatively predicted the test result only by 13% on average, while the V_{uni} underestimate the V_{max} by 54% on average. That is to say, confinement effect by the steel tubes accounts for about 80% of the over-strength, and confinement by the stiff loading stubs for about 20%. These observations indicate importance of taking confinement effect of the steel tube into account when evaluating the ultimate load of the tubed columns, particularly of the column subjected to high axial compression.

3. EXPERIMENT FOR STUDYING THE EFFECT OF INNER STIFFENER ON CONFINEMENT EFFECT OF STEEL TUBES

3.1 CONFINEMENT EFFECTIVENESS OF THE SQUARE STEEL TUBES

In order to find a practical method for enhancing the confinement effectiveness of the square steel tube, knowledge on confinement mechanism of the square steel tube is necessary. Fig. 6 shows concept of confinement mechanism by the square steel tube. When confining concrete, the square tube tends to bend the sides outward as concrete bears out. As a result, some of concrete can not be effectively contained, which results in decrease in confinement effectiveness of the square steel tube. To theoretically predict confinement effectiveness of the square steel tube, authors have developed a stress-strain model for the confined concrete [6]. In authors' confinement model, confinement effectiveness is expressed in terms of strength enhancement ratio K , which is the ratio of the confined concrete strength f_{cc}' to the unconfined concrete strength f_c' . According to the confinement model proposed by authors, the strength enhancement ratio K of the concrete confined by square steel tube can be predicted by Eq. (1).

$$K = \frac{f_{cc}'}{f_c'} = 1 + 11.5 \frac{\rho_h f_{yt}}{f_c'} \left(\frac{t}{C} \right) \quad (1)$$

where ρ_h is the volumetric ratio of the steel tube, B and t are the outside width and wall thickness of the steel tube, respectively, f_{yt} and f_c' are the yield stress of the steel tube and the concrete cylinder strength, respectively, and C is the unsupported length of the steel tube side (see Fig. 6).

The theoretical K values are shown in Fig. 7 for the T-series specimens as well as the Ts-specimens, which will be described later. Because of its weak flexural stiffness, confinement effectiveness provided by the thin square steel tube with B/t ratio larger than 60 is very low. On the other hand, the flexural stiffness of the tube sides can be significantly upgraded when the steel tube is strengthened by the crossed inner stiffeners. One can see from Fig. 7 that use of the inner stiffener theoretically can bring about 200% increment in confinement effectiveness of the square steel tube without increasing its thickness. Therefore, it is reasonable to expect that strengthening by the inner stiffener could make it possible for the thin square steel tube to effectively confine the RC column subjected to high axial compression and/or the HSC column, both of which need strong confinement.

3.2 TEST SPECIMENS

In order to validate the above mentioned theoretical observation, three specimens were fabricated and tested under the same loading condition as of the T-series specimens. As shown in Fig. 1, in these three specimens, which will be referred to as the Ts-series specimen hereafter, the crossed inner stiffeners were welded to the square steel tube within the potential plastic hinge regions of about $1.0D$ (D = depth of the concrete section) adjacent to the loading stubs. The experimental variable among the Ts-series specimens was wall thickness of the steel tubes only. The inner stiffener had the same thickness as the perimeter tube. Table 3 gives details of the Ts-series specimens along with the primary results.

All the three specimens were subjected to high axial load with a designed axial load ratio $n=0.67$. The testing conditions for the Ts-series columns, such as materials properties, loading apparatus as well as instrumentation, were the same as for the T-series specimens.

Fig. 6 Confinement by the square steel tubes

Fig. 7 Examples of the predicted K values

Fig. 8 Crack patterns of the Ts-series specimens

Table 3 Properties and main results of the tubed columns with inner stiffener

Notation (1)	Details of specimen						Measured results				Predicted results					
	f'_c	N	n	t	B/t	f_{yt}	V_{max}	$\frac{V_{max}}{A_g f'_c}$	R_{max}	R_u	V_{mu}	$\frac{V_{max}}{V_{mu}}$	V_m	$\frac{V_{max}}{V_m}$	V_{un}	$\frac{V_{max}}{V_{un}}$
	(MPa)	(kN)	(=N/No)	(mm)		(MPa)	(kN)		(rad)	(rad)	(kN)		(kN)		(kN)	
Ts2-67-4D	31.3	1295	0.662	2.17	117	323	217	0.111	0.010	0.018	227	0.96	192	1.13	138	1.57
Ts3-67-4D	31.1	1295	0.666	3.11	82	285	246	0.127	0.015	0.041	243	1.01	206	1.19	136	1.81
Ts4-67-4D	47.9	1991	0.665	4.29	60	292	339	0.113	0.015	0.039	340	1.00	292	1.16	172	1.97

Fig. 9 The measured lateral load V - drift ratio R relationships of the Ts-series specimens

3.3 TEST RESULTS AND INVESTIGATION

The crack patterns, observed after the tests, are shown in Fig. 8. Use of the inner stiffeners caused some splitting cracks extended between the ends of stiffeners, but these cracks were very subtle and the flexural cracks were dominant within the end regions with length of less than 1.0D. Range of the damaged regions shortened as the wall thickness increased. In addition, by comparing the crack pattern of specimen Ts2-67-4D with that of specimen T4-67-4D, one can see that strengthening by the inner stiffeners could upgrade constraint effect of the thin steel tube to the axial deformation higher than the steel tube twice its wall thickness.

The experimental V - R hysteresis response for the Ts-series specimens are shown in Fig. 9. The solid and linked lines superimposed on Fig. 9 have the same meaning as those in Fig. 4. As apparent in Fig. 9, existence of the inner stiffeners brought the column confined by thin steel tube very large deformation capacity. All specimens exhibited very stable performance until drift ratio of 0.05rad in spite of the high axial load and reached its theoretical ultimate lateral load V_{mu} . While gradual strength degradation occurred in the specimen Ts2-67-4D, this degradation was mainly caused by the $N - \Delta$ effect and the column still withstood 80% of the maximum experienced lateral load at $R = 0.05$ rad without losing its gravity-sustaining capacity. The theoretical ultimate strength V_{mu} obtained by authors' method agreed satisfactorily well with the measured load V_{max} . The ratio of the V_{max} and the V_{mu} had a mean value of 0.99 and a standard deviation of 0.03.

To assess the influence of strengthening by the inner stiffeners, three pairs of specimens (Ts2-67-4D and T4-67-4D, Ts3-67-4D and T6-67-4D, and Ts4-67-4D and T4-67-4D) are compared in Figs. 10 and 11. All of these columns were under same axial compression with $n = 0.67$.

The envelop curves of the V - R hysteresis loops in the push direction are compared in Fig. 10. It can be observed from Fig. 10 that strengthening thin steel tube with inner stiffeners has a great effect on the seismic performance of the tubed column. The Ts specimens Ts2-67-4D and Ts3-67-4D showed higher ductility than the T specimens T4-67-4D and T6-67-4D, though wall thickness of the Ts specimens is only half of that of the T specimens. Further comparing specimen Ts4-67-4D with T4-67-4D one can see that for the tubed column made of high strength concrete, use of the inner stiffener can greatly enhance not only ductility but also ultimate lateral load-carrying capacity. Effectiveness of the inner stiffeners can be more clearly observed from comparison of the axial deformation (elongation is taken as positive) of these specimens. As indicated in Fig. 11, strengthened by the inner stiffener, the thin steel tube with $B/t = 118$ provided the tubed column nearly the same resistance to the axial shortening as the steel tube with $B/t = 43$.

The above test results imply that strengthening the square steel tube with the crossed inner stiffener enables the use of thinner steel tube in the column made of HSC and the column subjected to high axial load, hence economical design of the square tubed columns.

Fig. 10 Comparison of the envelop curves (effect of inner stiffener)

4 CONCLUDING REMARKS

As the second phase of a systematic study on the seismic performance of reinforced concrete column confined by square steel tube, twelve square columns were made and tested under reversed cyclic lateral load and constant axial compression. These specimens were confined by square steel tubes with five kinds of width-to-wall thickness ratios, 28 through 118 in this study, to provide experimental information about the effect of wall thickness of the tube and inner stiffener on the earthquake-resisting capacity of the square tubed columns. The following conclusions can be drawn from the test results.

1) Earthquake-resistant capacities of the tubed columns increased with the wall thickness of the tubes used, but effectiveness of the wall thickness was greatly dependant upon the axial compression level. For a reinforced concrete column subjected to the axial load with $n = 0.33$, increasing wall thickness could enhance ductility of the tubed column, and the thin steel tube having $B/t=118$ could make the column sufficiently ductile. On the other hand, the increment in the ultimate strength due to use of thicker steel tube was, if any, very small.

2) For the columns subjected to higher axial load with n larger than 0.50, however, not only the ductility but also the ultimate strength of the tubed column would be significantly influenced by the wall thickness. To assure sufficient deformation capacity to the tubed column under such high axial load level as n is larger than 0.50, use of the steel tube with B/t less than 43 was necessary.

3) Strengthening the square steel tube by inner stiffener only within the potential plastic regions of the tubed column was very effective in upgrading the confinement effectiveness of the steel tube. The constraint effect provided by the inner stiffener to the axial shortening of the column under high axial compression was particularly significant. When strengthened by the inner stiffener, the steel tube with $B/t=118$ could make the tubed column under high axial load with $n = 0.67$ behave in the same ductile manner as the column confined by much thicker tube with $B/t=43$ but without inner stiffener. For the HSC column with $f'_c = 51\text{MPa}$, within the test range described in this paper, strengthening the steel tube having $B/t=60$ by the inner stiffener brought the tubed column 200% gain in ductility and 15% increment in ultimate strength. Note that the inner stiffeners used in this experiment had the same thickness as the perimeter tube. As to effect of use of thinner stiffener than the perimeter tube remains to be experimentally verified.

4) The confinement model and calculation method proposed by the first two authors in Ref. 1 could account for the ultimate strength gain due to confinement effect by the square steel tubes with or without being strengthened by the inner stiffener. For all specimens, the ratios of the measured ultimate lateral loads and the theoretical predictions had a mean value of 1.14 and a standard deviation of 0.06. By further taking into account the extra confinement effect from the stiff loading stubs, these values are improved to 1.01 and 0.05, respectively.

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Fig. 11 Comparison of the axial deformation (effect of inner stiffener)

和文要約

1. 序

鋼管横補強法の有効性については実験的に明らかにされているが¹⁾、鋼管横補強法を合理的に遂行するためには以下の問題点を明らかにする必要がある。

- 1) 高軸力を受ける鋼管横補強柱の耐震性能
- 2) 大量の主筋を有する鋼管横補強柱の耐震性能
- 3) 鋼管横補強柱の耐震性能に及ぼす鋼管板厚の影響
- 4) 鋼管横補強柱の耐震性能に及ぼす柱のせん断スパン比の影響
- 5) 鋼管横補強柱の終局耐力および変形能力の評価法

本研究の第1報においては、上述した問題の内1)と2)の問題について検討した。本報においては、3)の問題を取上げ、12体の試験体(せん断スパン比2.0)を用いて実験的に検討する。

2. 鋼管板厚の影響に関する実験

2.1 試験体

本章で述べる実験をTシリーズと呼ぶことにする。鋼管の内径は250mmで板厚は2.17mmから9.46mmの間の5種類である。図1に試験体の詳細と、試験体に与えた応力と変形を示す。Tシリーズにおける実験変数は、1) 鋼管幅厚比(B/t :28~118)、2) コンクリート強度(設計強度:36MPaと51MPa)、3) 軸力比(0.33~0.67)である。Tシリーズ試験体の一覧を表1に示す。コンクリートの圧縮強度を表1に示す。鋼材の力学的性質を表2に示す。薄肉鋼管は市販されていなかったことから、実験に用いた鋼管はすべて鋼板を加工して製作した。

2.2 加力および測定

試験体には図1(b)に示すような逆対称の変形を与えた。載荷プログラムは図2に示す変位制御型で、正負の繰り返し変形を与えた。

2.3 加力および測定

図3にTシリーズ試験体のひび割れ図を示す。図3から分るように、ひび割れは軸力の大きさに拘らず、すべての試験体において曲げひび割れが支配的である。破壊領域は、軸力が大きくなるほど材端より広がる傾向がある。また、鋼管厚を増すことは、破壊領域の広がりを押えるのに非常に効果的であることが分かる。

図4に繰返し水平力V-部材角R関係を示す。各試験体の最大水平力 V_{max} 、その時の部材角 R_{max} 、および水平力が V_{max} の95%に低下した時の部材角 R_u を表1に示す。図4より、軸力の大きさは、鋼管横補強柱の耐震性能にだけでなく、鋼管の拘束効果の発現度合にも影響を及ぼすことが分る。軸力比が0.33の試験体に関して言えば、いずれの試験体も靱性に富む挙動を示しており、最も大きい幅厚比である $B/t=118$ の鋼管でも柱に十分な変形能力を与える事が出来る。すなわち、軸力がそれほど大きくない柱で曲げ破壊が先行するような場合は、横補強用の鋼管厚は補強効果にそれほど影響を与えない。一方、柱の軸力比が大きくなると、鋼管厚の影響が顕著になる。軸力比が0.50と0.67と高くなると、それぞれ $B/t=82$ と $B/t=60$ の薄肉鋼管による横補強では柱に十分な靱性を保証できるとは言えなくなってくる。

鋼管厚の影響をより詳しく検討するために、V-R関係の正荷重時包絡線の比較を図5に示す。軸力比が0.5以上の高軸力を受ける柱の場合、鋼管厚が増すと、靱性のみならず耐力も上昇している事が分る。

また、図4のV-R関係に描かれている実線と一点鎖線は、水平耐力計算値である V_{mu} と V_{un} をそれぞれ示している。 V_{mu} は著者等の提案式⁴⁾により求めた曲げ耐力計算値に対応する水平耐力で、 V_{un} はACI規準⁵⁾による曲げ耐力に対応している。著者等の提案式とACI規準の算定法との違いは、前者が鋼管および加力スタップの拘束効果を考慮に入れている点である。図4から明らかなようにTシリーズの試験体は全て、拘束効果を考慮に入れた水平耐力を発揮しており、拘束効果を考慮していないACI規準による耐力は非常に安全側の評価となっている。一方、鋼管と加力スタップ両方の拘束効果を考慮に入れている著者等の提案式は実験値を精度良く評価しており、両者の比は平均値1.02で標準偏差は0.05である。

3. 鋼管の拘束効果に及ぼす内スチフナの影響に関する実験

3.1 正方形鋼管の拘束効果

図6に鋼管による拘束効果のメカニズムを示している。著者等は鋼管の拘束効果を考慮に入れた拘束コンクリートの応力-ひずみ関係モデルを提案している⁶⁾。著者等のモデルにおいては、鋼管の拘束効果は拘束コンクリートの強度 f_{cc} と無拘束コンクリートの強度 f_c の比である強度上昇係数Kにより評価されるが、Kの算定式は本文(1)式により与えられる。Tシリーズの鋼管と後述する内スチフナを設けたTsシリーズの鋼管について、(1)式で求めたKの値を図7に示す。内スチフナを設ければ鋼管厚を増すことなく、拘束効果を約200%増大させ得る事が図7より分る。したがって、内スチフナを設けることは非常に効果的であることが予測される。

3.2 試験体

上述した予測の妥当性を検証するために、Tsシリーズと名づけた3体の試験体についてTシリーズと同様な載荷条件で実験を行った。これらの3体の試験体においては、材端より材せい(1.0D)だけの長さを有する塑性ヒンジ領域の鋼管に内スチフナを溶接により取付けた。Tsシリーズの試験体間のパラメーターは鋼管厚で、スチフナに用いた鋼板の厚さは取付ける鋼管厚と同じであった。表3にTsシリーズ試験体の一覧とおもな実験結果を示す。

3.3 実験結果と考察

ひび割れ状況を図8に示す。支配的なひび割れは材端から材せいの長さ以下の領域内に生じた曲げひび割れである。これらの曲げひび割れが生じる領域の長さは鋼管壁が厚くなるほど小さくなる。

Tsシリーズ試験体のV-R関係を図9に示す。図9より分るように、内スチフナを設けることにより薄肉鋼管の拘束効果を飛躍的に高めることが出来る。また、図10より分るように、Tsシリーズの試験体であるTs2-67-4DとTs3-67-4Dは、Tシリーズの試験体であるT4-67-4DとT6-67-4Dと比較して、鋼管厚が半分であるにも拘らず靱性に富む挙動を示す。更に、試験体Ts4-67-4Dと試験体T4-67-4Dを比較すると、内スチフナを設ける事により、靱性のみならず水平耐力も上昇させる事が分る。また、内スチフナは柱の軸方向縮みを抑制する点でも効果的である。図11に示すように、内スチフナを設けた幅厚比118の鋼管で横補強した試験体の軸方向縮み量は、幅厚比43の鋼管で横補強した試験体のそれと同程度にまで抑制する事が出来る。

4. 結論

正方形鋼管横補強法に関する研究の第2報として、鋼管の径厚比(B/t が28~118)を実験変数に取り、せん断スパン比2.0の鋼管横補強柱について、一定軸力下における繰返し曲げせん断実験を行った結果、以下の結論が得られた。

- 1) 鋼管横補強柱の耐震性能は、鋼管厚を増す事により上昇するが、その上昇の程度は柱の軸力の大きさに強く依存する。すなわち、軸力比が0.33の場合は、鋼管厚を増しても柱の靱性の上昇は僅かで水平耐力の上昇は殆ど無く、 B/t が118の薄肉鋼管でも十分な補強効果が期待できると言える。
- 2) 柱の軸力比が0.5以上の場合は、鋼管厚は柱の靱性のみならず、水平耐力にも影響を及ぼすようになる。このような高軸力を受ける柱の場合は、 B/t が43以下の鋼管により横補強する事が必要となる。
- 3) 塑性ヒンジ領域内の鋼管内部にスチフナを設ける事は、鋼管の拘束効果を高める上において非常に有効で、特に高軸力を受ける柱の軸方向縮みの抑制に効果的である。例えば、内部にスチフナを設けた幅厚比 $B/t=118$ の鋼管で横補強した柱は、軸力比にして0.67という高軸力下においても、 $B/t=43$ の鋼管で横補強した柱と同程度に靱性的な挙動を示す。
- 4) 著者等が提案した曲げ耐力算定式を用いれば、鋼管横補強により水平耐力が上昇する現象を、スチフナが無い場合と有る場合の違いも含めて、評価する事が出来た。水平耐力実験値と鋼管の拘束効果を考慮に入れた提案式による計算値の比は、全試験体に対する平均値で1.14、標準偏差が0.06であった。さらに、著者等が提案する方法によりスタップの拘束効果の影響も考慮に入れた算定式の精度は、平均値で1.01、標準偏差が0.05に改善される。

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