Structural Engineering and Mechanics, Vol. 19, No. 6 (2005) 653-677
DOI: http://dx.doi.org/10.12989/sem.2005.19.6.653

Study on strength of reinforced concrete filled circular steel tubular columns

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(Received July 26, 2004, Accepted February 3, 2005)

Abstract. Concrete filled steel tubular columns (CFT) are widely used in civil engineering works, especially in large scale of works because of high strength, deformation, toughness and so on. On the other hand, as a kind of strengthening measure for seriously damaged reinforced concrete piers of viaduct in Hansin-Awaji earthquake of Japan in 1995, reinforced concrete piers were wrapped with steel plate. Then, a new kind of structure appeared, that is, reinforced concrete filled steel tubular column (RCFT). In this paper, compression test and bending-shearing test on RCFT are carried out. The main parameters of experiments are (1) strength of concrete, (2) steel tube with or without rib, (3) width-thickness ratio and (4) arrangement of reinforcing bars. According to the experimental results, the effect of parameters on mechanical characteristics of RCFT is analyzed clearly. At the same time, strength evaluation formula for RCFT column is proposed and tested by experimental results and existed recommendations (AIJ 1997). The strength calculated by the proposal formula is in good agreement with test result. As a result, the proposed evaluation formula can evaluate the strength of RCFT column properly.

Key words: reinforced concrete filled steel tubular column; compression test; bending-shearing test; load-carrying capacity; ductility ratio; strength; evaluation formula.

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1. Introduction

In recent years, CFT is widely used as a kind of composite structure in the field of engineering works and construction. A lot of theses on CFT have been presented up to now (JSSC 1998, Suzuki *et al*. 1997, Murata *et al.* 1998, Matsui *et al*. 1994, Nakai *et al*. 1999, Tang *et al.* 1996, Fujimoto *et al*. 1997). According to those results, CFT has better structural performance than that of bare steel tube or bare concrete: filled concrete controls the local buckling of steel tube, and steel tube can give play to own high mechanical performances; concrete strength, ductility and rigidity are improved greatly because filled concrete is confined by steel tube and it becomes triaxial stress condition. Moreover, concrete mould is unnecessary, so CFT possesses excellent workability such as saving labor and shortening term of works.

In 1995's Hansin-Awaji earthquake of Japan, many reinforced concrete (RC) piers and steel piers were heavily damaged (JSCE 1999). Most of RC piers were due to shear failure and most of steel piers were due to local buckling. As a reinforcement measure, steel plates were wrapped around the RC piers and RC was filled into the steel pipes. These reinforcement structures can be considered as RCFT structures.

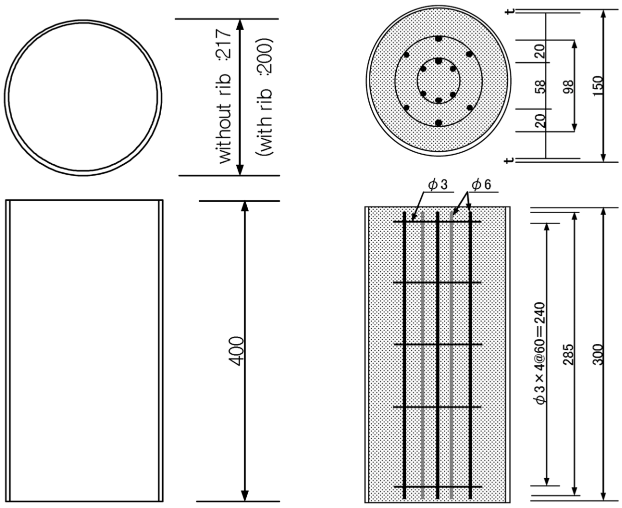
On the other hand, it is difficult to construct the large-scale structures that have excellent mechanical characteristics only using conventional steel and RC. Under such a situation, in order to correspond to large-scale civil engineering structures it is demanded to develop a structural element that excels bare steel or bare RC in strength, ductility, rigidity and the earthquake-resistant ability; and has the restoration performance and economical efficiency after an earthquake disaster. Then, in this paper, experiments of RCFT were carried out, and strength evaluation formula was proposed and tested. On the basis of author's research on RCFT until now (Wang *et al*. 1999, Endo *et al*. 2000, Wang *et al*. 2002, Wei *et al*. 2002), it is understood that filled concrete can be effective to shear force by inserting reinforcing bars and shear failure of filled concrete will not occur. Furthermore, if steel tube with rib is used, unification of steel and concrete will be promoted. Based on those results, it is thought that strength, rigidity and ductility of RCFT are improved; especially strength and ductility were improved after the peak of load-displacement curve (compression test) and moment-curvature curve (bending-shearing test) as compared with CFT.

In this paper, the outline of compression test, bending-shearing test, the experimental results and the obtained conclusions are described. Base on the experimental results, strength evaluation formula for RCFT is proposed; the strength calculated by the proposal formula is in good agreement with experimental results. As a result, the proposed evaluation formula can be used to evaluate the strength of the RCFT properly.

2. Outline of compression test

2.1 Test specimens and material properties

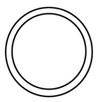
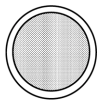
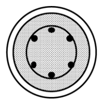
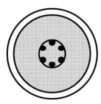
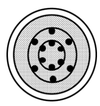
The section sizes and details of test specimens are presented in Fig. 1 and Table 1, respectively. In test A, 4 pieces of column specimens using normal steel tube (diameter: 217 mm, height: 400 mm) and 4 pieces of column specimens using ribbed steel tube (diameter: 200 mm, height: 400 mm) were made and tested. Among those there were hollow steel tubes and CFT specimens according to the filling situation. Furthermore, 3 pieces of concrete specimens the same as concrete filled in CFT



A test specimen B test specimen (unit: mm)

Fig. 1 Column specimens' size

Table 1 Details of test specimens

Types of specimens			Hollow steel tube	CFT	RCFT with thin cover	RCFT with thick cover	RCFT with double reinforcements
							
A Test	Specimen label	without rib with rib	SN1(SN2) SH1(SH2)	SN3(SN4) SH3(SH4)	---	---	---
B Test		without rib	SNC201 SNC202	SNC203 SNC204	SNC205 SNC206	SNC207 SNC208	SNC209 SNC210
		with rib	SHC201 SHC202	SHC203 SHC204	SHC205 SHC206	SHC207 SHC208	SHC209 SHC210

were made and tested to estimate the cumulative strength discussed later. Compressive strength of concrete at an age of 28 days was 27.4 kN/mm^2. The steel tubes were made of mild steel (STK400, Japanese Industrial Standards: JIS), with thickness of 6 mm. The yield strength and maximum strength of steel tubes were 354.3 N/mm^2 and 451.8 N/mm^2, respectively. The ribs are trapezoid with upper bottom of 3 mm, lower bottom of 7 mm and height of 4 mm, which are welded inside steel tubes in circumferential direction per 40 mm (see Fig. 2).

In test B, according to filling situation, 4 pieces of hollow steel tubes, 4 pieces of CFT and 12 pieces of RCFT specimens were made and tested. Furthermore, 12 pieces of concrete and RC specimens reinforced the same as CFT/RCFT specimens were tested in order to estimate the cumulative strength discussed later. The material properties are the same as test A except compressive strength

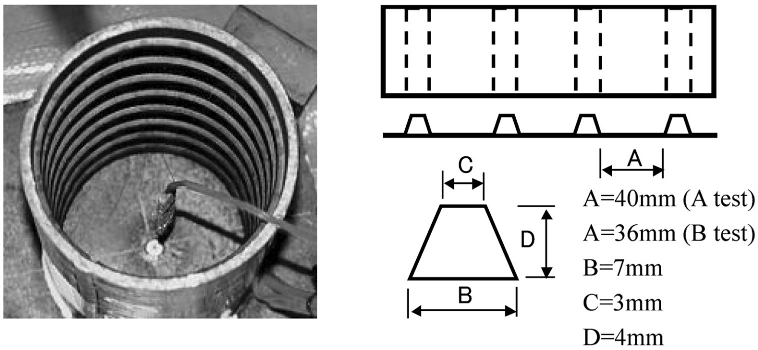
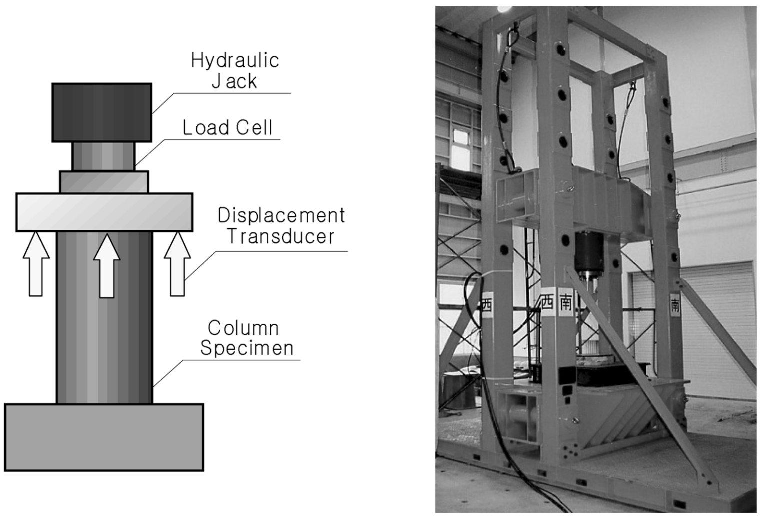


Fig. 2 Shape of the rib

of concrete (21.6 N/mm^2 in test B). The size of B specimens is 150 mm in the diameter, 300 mm in height, and 6 mm in the thickness of steel tube (see Fig. 1). The ribs' shape is the same as test A, only they are welded inside steel tubes in circumferential direction per 36 mm. Reinforcing bars were made of SR295 (in JIS). Sizes and arrangement of reinforcing bars are shown as Fig. 1 and Table 1, respectively.

2.2 Test setup and measurements

The compression test was performed on a 2940 kN capacity-testing machine given as Figs. 3(a), (b). The upper end of column is free, and the lower end is welded (four points) on the steel plate. The specimens were placed into the testing machine and the loads were applied on the specimens under load control with load speed of 5.88 kN/sec (0.6 tf/sec). The load increment was 196 kN



(a) (b)

Fig. 3(a) Test setup of the columns, (b) Photograph of test setup

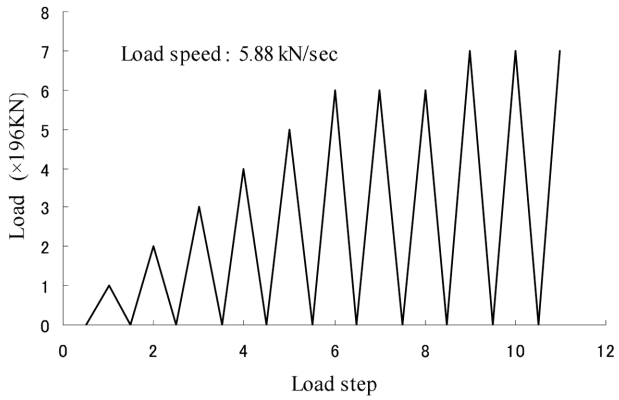
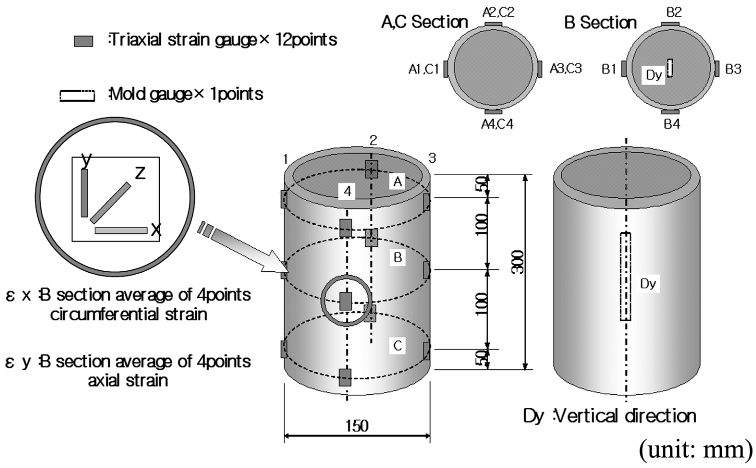


Fig. 4 Load step



(unit: mm)

Fig. 5 Details of stain gauges

(20 tf) and 3 times cyclic load was carried out from 1176 kN (120 tf) shown in Fig. 4. The axial deformation was measured for each specimen by 4 displacement transducers, and strains were measured by 12 strain gauges. To measure the compressive strain of filled concrete, a mold strain gauge was installed inside of concrete (see Fig. 5). After the load reached the maximum value, if the load fell to 80% of the maximum load or any displacement transducers indicated 40 mm, test would be terminated.

2.3 Test results

The maximum compressive strength, confined effect and ductility ratio obtained from the test are summarized in Tables 2(a), (b). The cumulative compressive strength, confined effect is explained as following formulas:

$$N_0 = N_c + N_s, \quad \alpha = N_u / N_0 \tag{1}$$

where N_0 is cumulative compressive strength, N_c, N_s and N_u is maximum compressive strength of concrete or RC specimen, hollow steel tube specimen and CFT or RCFT specimen, respectively. α is confined effect. The ductility ratio is given as following equation:

$$\mu = \delta_u / \delta_y \tag{2}$$

where μ is ductility ratio; δ_u is displacement at maximum compressive strength and δ_y is yield displacement.

It can be seen from Table 2 that the maximum compressive strength and confined effect of RCFT are higher than that of CFT; especially RCFT with double reinforcing bars shows the most excellent performances. It is considered that the integration between concrete and steel can be promoted by inserting reinforcing bars.

RCFT with double bars shows the highest ductility ratio. Specimens with ribs show higher ductility ratio than that without ribs. The average of ductility ratio of ribbed and non-ribbed specimens is 8.6 and 6.9, respectively in test B.

Table 2(a) Maximum compressive strength, confined effect and ductility ratio

	without rib									
	Types of specimens	Specimen label	Maximum compressive strength N_c' (kN)	Average N_c (kN)	Specimen label	Cumulative compressive strength N_0 (kN)	Maximum compressive strength N_u' (kN)	Average N_u (kN)	Confined effect α (N_u/N_0)	Ductility ratio μ δ_r/δ_y
A Test	Hollow steel tube				SN1		1278	1342		5.2
					SN2		1408			3.9
	CFT	CN1	858		SN3		2889			6.7
		CN2	975	937		2279		2886	1.27	
		CN3	974		SN4		2883			7.5
B Test	Hollow steel tube				SNC201		1136	1118		5.3
					SNC202		1100			5.9
	CFT	CNC201	498		SNC203		1702			7.1
		CNC202	391	463		1581		1728	1.09	
		CNC203	500		SNC204		1753			7.5
	RCFT with thin cover	CNC204	408		SNC205		1867			7.2
		CNC205	376	415		1533		1883	1.23	
		CNC206	462		SNC206		1898			5.6
	RCFT with thick cover	CNC207	497		SNC207		1822			6.3
		CNC208	483	475		1593		1847	1.16	
		CNC209	445		SNC208		1871			6.8
	RCFT with double reinforce-ments	CNC210	419		SNC209		1915			6.6
		CNC211	449	437		1555		1961	1.26	
		CNC212	442		SNC210		2007			8.4
	Average of B Test								1.19	6.9

Table 2(b) Maximum compressive strength, confined effect and ductility ratio

	with rib									
	Types of specimens	Specimen label	Maximum compressive strength N_c' (kN)	Average N_c (kN)	Specimen label	Cumulative compressive strength N_0 (kN)	Maximum compressive strength N_u' (kN)	Average N_u (kN)	Confined effect α (N_u/N_0)	Ductility ratio μ δ_r/δ_y
A Test	Hollow steel tube				SH1		1860	1879		6.3
					SH2		1896			5.6
	CFT	CN1	858		SH3		3147			
		CN2	975	937		2816		3206	1.14	
		CN3	974		SH4		3265			
B Test	Hollow steel tube				SHC201		1227	1228		6.4
					SHC202		1228			5.6
	CFT	CNC201	498		SHC203		1949			8.8
		CNC202	391	463		1690		1957	1.16	
		CNC203	500		SHC204		1964			8.2
	RCFT with thin cover	CNC204	408		SHC205		2096			8.4
		CNC205	376	415		1643		2109	1.28	
		CNC206	462		SHC206		2122			9.0
	RCFT with thick cover	CNC207	497		SHC207		2074			6.7
		CNC208	483	475		1702		2101	1.23	
		CNC209	445		SHC208		2127			9.1
	RCFT with double reinforcements	CNC210	419		SHC209		2146			8.0
		CNC211	449	437		1664		2224	1.34	
		CNC212	442		SHC210		2301			11.2
	Average of B Test								1.25	8.6

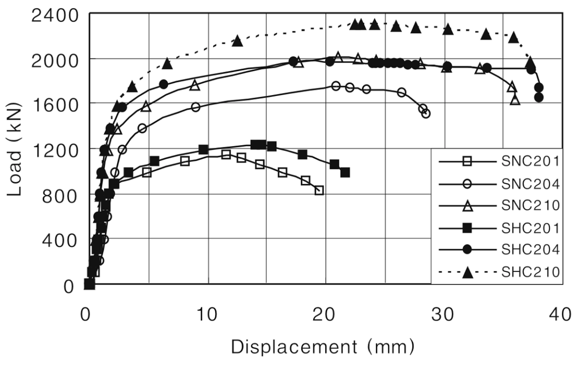
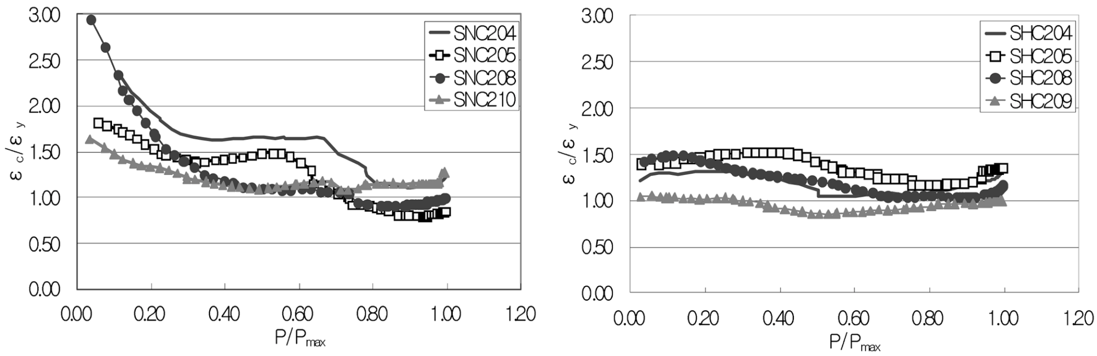


Fig. 6 Load-displacement envelope curves

The load-displacement envelope curves of typical specimens are shown in Fig. 6. It is understood that the compressive strength and deformation performance of RCFT are better than that of hollow steel tube and CFT specimens.



(a) Specimen without rib (b) Specimen with rib

Fig. 7 Relationship between axial strains of steel tube and filled concrete

The relationship between the axial strain of steel tube ε_y and filled concrete ε_c is shown in Fig. 7. As for non-ribbed specimens, $\varepsilon_c/\varepsilon_y$ indicate 1.5-3.0 at the beginning, concrete and steel tube of non-ribbed specimens do not behave as a unified one yet. When normalized load $P/P_{\max}$ reached about 0.3-0.4, correspondingly, $\varepsilon_c/\varepsilon_y$ is 1.0-1.5, and at this time it is considered that concrete and steel tube approximately behave as a unified one. On the other hand, $\varepsilon_c/\varepsilon_y$ of ribbed specimens indicated 1.0-1.5 from beginning to end. Comparing Fig. 7(a) to Fig. 7(b), it is obvious that ribs can improve combination of steel tube and concrete. For ribbed specimens, ε_c at maximum axial load is approximately 8-9%, it is higher than that of non-ribbed specimens. From the results discussed above, it was proved that ribs have the function to enhance strength and ductility of CFT and RCFT.

Figs. 8(a), (b) show the failure mode of hollow steel tube, CFT and RCFT specimens without or

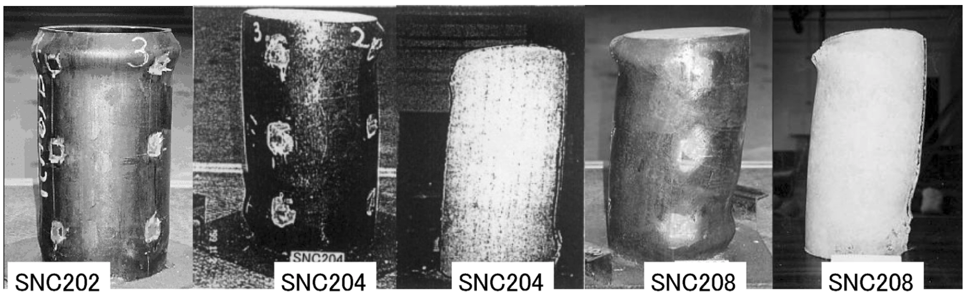


Fig. 8 (a) Failure mode of hollow steel tube, CFT and RCFT specimens without rib

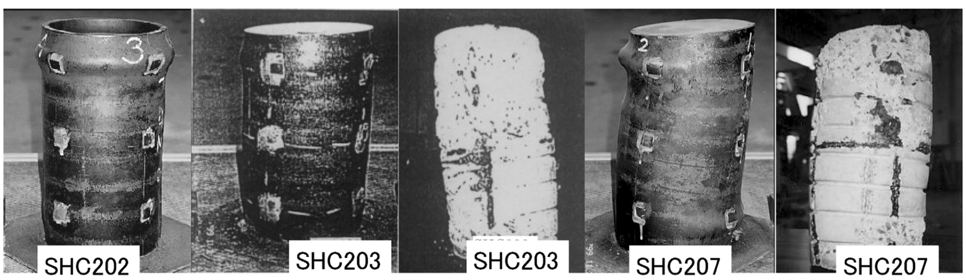


Fig. 8 (b) Failure mode of hollow steel tube, CFT and RCFT specimens with rib with rib, respectively. Local buckling was observed at upper end of column in hollow steel tube specimens. In the case of CFT and RCFT specimens, local buckling occurred at both upper and lower end. After testing, steel tube of typical specimens were cut and removed to make sure of the failure mode of filled concrete. As for CFT and RCFT specimens without rib, concrete were crushed at the part of steel tube occurred local buckling. In the case of CFT and RCFT specimens with rib, the phenomenon that the coating of the surface of steel tube flaked off in the rib pattern was seen.

3. The proposal of compressive strength evaluation formula for RCFT column

3.1 Analysis model and assumption

Based on the experimental results, following assumptions are supposed when trying to evaluate the strength of RCFT column.

(1) There is no gap between steel tube and filled concrete, and they are unification until ultimate strength generating.

(2) Since filled concrete is subjected to the confinement pressure σ_r from steel tube and it becomes a 3-dimension stress state, the concrete strength σ_{cb} increases compared with concrete cylinder. σ_{cb} is given by the following formula:

$$\sigma_{cb} = \sigma_c + k\sigma_r \tag{3}$$

in which σ_{cb} is compressive strength of concrete subjected to the confinement pressure σ_r; σ_c is uniaxial compressive strength of concrete; and k is committed coefficient.

(3) Steel tube is in a complete plastic state and follows the Mises yield criterion.

(4) The strength of reinforcing bars fully plays the role by the restraint of filling concrete.

3.2 The proposal of compressive strength evaluation formula for RCFT column

3.2.1 Discussion of steel tube in a 2-dimension stress state

Normalized load-vertical strain relationships of a hollow steel tube and a steel tube filled with concrete are shown in Fig. 9. The strain of steel tube filled with concrete is almost the same as that of hollow steel tube at the maximum load. Steel tube is in 2-dimension stress state by lateral action of filled concrete. Therefore, as the yield condition of steel tube, the yield criterion of Mises in 2-dimension stress state is used.

$$\sigma_{sz}^2 - \sigma_{sz} \cdot \sigma_{s\theta} + \sigma_{s\theta}^2 = \sigma_{sy}^2 \tag{4}$$

where σ_{sz} is axial stress of steel tube, $\sigma_{s\theta}$ is circumferential stress of steel tube, and σ_{sy} is yield strength of steel tube.

Since the width-thickness ratio of steel tube is large, if steel tube is approximately assumed to be a plane stress state, the following formula will be appropriate to the axial stress and circumferential stress of steel tube. Moreover, axial stress of steel in uniaxial stress state is $\sigma_{sy} = E_s\varepsilon_z$.

$$\sigma_{sz} = \frac{E_s(\varepsilon_z + \nu_s\varepsilon_\theta)}{(1-\nu_s^2)} \tag{5}$$

$$\sigma_{s\theta} = \frac{E_s(\varepsilon_\theta + \nu_s\varepsilon_z)}{(1-\nu_s^2)} \tag{6}$$

where ε_z, ε_θ is axial and circumferential strain of steel tube, E_s is Young's modulus of steel pipe, and ν_s is Poisson's ratio of steel, and here, it is referred to 0.3.

Consequently, reduce factor of axial stress for steel tube β in 2-dimension stress state can be given by

$$\beta = \frac{\sigma_{sz}}{\sigma_{sy}} = \frac{E_s(\varepsilon_z + \nu_s\xi\varepsilon_z)}{E_s(1-\nu_s^2)\varepsilon_z} = \frac{1+\nu_s\xi}{1-\nu_s^2} \tag{7}$$

in which $\xi = \varepsilon_\theta/\varepsilon_z$.

According to experimental results, relationship between normalized load and ξ is shown in Fig. 10. The label SHCS and SNCS respectively express the average value of hollow steel tube specimens with and without rib; the label SHS+C and SNS+C express the average value of CFT, RCFT with and without rib respectively in Fig. 10. It can be seen that P/P_{max} is about 0.8 when steel pipes reach yield state from Fig. 9. Therefore, it is considered that P/P_{max} is about 0.8 when specimens reach yield district in Fig. 10. After steel tube enters into yield state, the absolute value of ξ increases with the increase of load, and the load bore by steel tube decreases. Moreover, the axial strength of steel tube with rib is higher than that of rib-less steel tube because rib can control circumferential distortion effectively.

In order to compare with reference (AIJ 1997), when expressed $\alpha = \sigma_{s\theta}/\sigma_{sy}$, formula (4) can be expressed:

$$\beta^2 - \beta\times\alpha + \alpha^2 = 1 \tag{8}$$

from formula (8), α can be calculated. The relationship of ξ, α and β is given as Table 3.

For specimens with rib, by the time of steel tube filled with concrete yielding, the average value

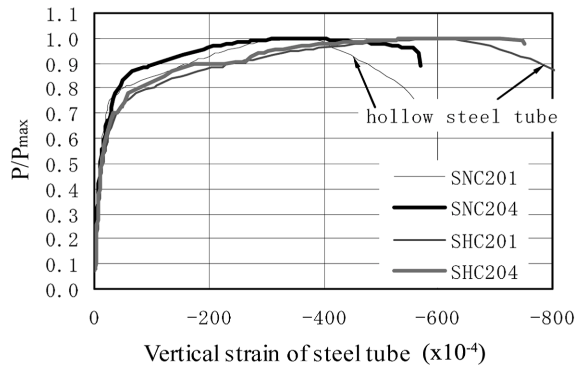


Fig. 9 Normalized load-vertical strain relationship of hollow steel tube and concrete filling steel tube

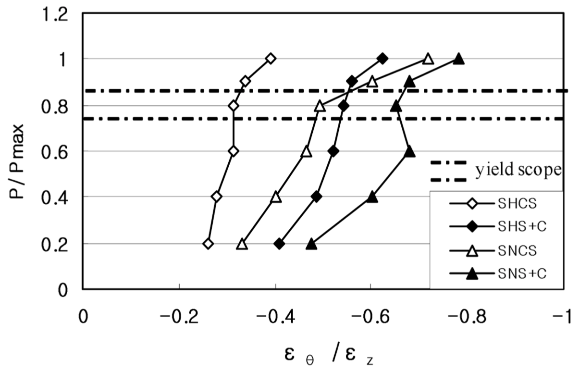


Fig. 10 Normalized load-ξ relationship

Table 3 Reduce factors in the circle and axial direction

$\xi = \varepsilon_\theta/\varepsilon_z$	$\beta = \sigma_{sz}/\sigma_{sy}$	α by the terms of Mises
–0.350	0.984	–0.032
–0.400	0.967	–0.063
–0.450	0.951	–0.092
–0.500	0.934	–0.121
–0.540	0.921	–0.143
–0.550	0.918	–0.148
–0.600	0.901	–0.175
–0.610	0.898	–0.180
–0.630	0.891	–0.190
–0.647	0.886	–0.199
–0.680	0.875	–0.215

of ξ is –0.54, corresponding β is 0.92, and α is –0.14. On the other hand, for rib-less specimens, ξ is –0.65, corresponding β is 0.89, and α is –0.20. In AIJ (1997), α is –0.19, and β is 0.89.

3.2.2 Discussion of filled concrete in a 3-dimension stress state

The filled concrete will be in a 3-dimension compressive stress state by lateral restraint of steel tube. Fig. 11 shows the stress state of a synthetic section of RC filled steel tube column subjected to axial compressive load.

From the equilibrium of Y direction, $\Sigma Y = 0$, namely, $-\int_{-\frac{\theta}{2}}^{\frac{\theta}{2}} \sigma_r \bullet \cos\alpha \bullet r d\alpha + 2\sigma_{s\theta} t \sin\frac{\theta}{2} = 0$, the relational expression of the main stress between the radial and circumferential direction is given by

$$\frac{\sigma_r}{\sigma_{s\theta}} = \frac{t}{r} \tag{9}$$

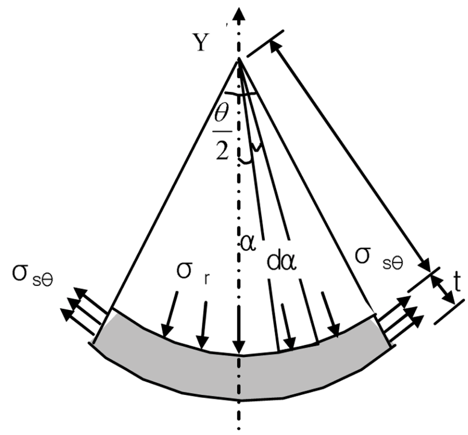


Fig. 11 Stress state of synthetic cross section

The filled concrete receives two equal main stresses in radial and circumferential direction and it becomes a 3-dimension stress state, the strength σ_{cb} is given by formula (3). Moreover, the circumferential stress of steel tube is given by the following formula:

$$\sigma_{s\theta} = \alpha\sigma_{sy} \tag{10}$$

Consequently, the strength σ_{cb} is given by

$$\sigma_{cb} = \sigma_c + \alpha k\frac{t}{r}\sigma_{sy} \tag{11}$$

if $(\sigma_{cb} - \sigma_c)/\sigma_c$ is defined as the rate of increase of filled concrete strength, formula (11) can be turned into the following formula:

$$\frac{\sigma_{cb} - \sigma_c}{\sigma_c} = \alpha k\frac{t}{r}\frac{\sigma_{sy}}{\sigma_c} \tag{12}$$

where σ_{cb} is compressive strength of concrete under the confinement pressure σ_r, σ_{sy} is yield strength of steel, σ_c is uniaxial compressive strength of concrete, r/t is radius-thickness ratio of steel tube, and α, k is coefficient.

k is a coefficient by the Richart experiment which carried out the triaxial compression test of the concrete by the lateral static water pressure, and it is about 3-4. It is referred to 4.1 in RDC. However, in this paper it is considered that the effect of a horizontal restraint changes with size of steel tube, so suppose k is the function of t/r.

3.2.3 The proposal of compressive strength evaluation formula for RCFT column

According to discussion above, taking account of axial reduction of steel tube strength and the increase of filled concrete strength, the compressive strength for RCFT column is proposed as follows:

$$P_y = P_{st} + P_{sr} + P_c = \beta A_{st}\sigma_{sty} + A_{sr}\sigma_{sry} + R_{cu}A_c\sigma_{cb} \tag{13}$$

in which P_{st}, P_{sr}, P_c is the load on section of steel tube, axial reinforcing bars and concrete, A_{st}, A_{sr}, A_c is cross section area of steel tube, reinforcing bars and concrete, σ_{sty}, σ_{sry} is yield strength of steel tube and reinforcing bars, respectively. In this research, in order to prevent the influence of strength rise by strain hardening, the maximum strength was used instead of the yield strength of steel tube. R_{cu} is reduction factor of concrete under the confinement pressure σ_r, β is reduction coefficient reflected the variation of degree of yield stress for steel tube; it is 0.89 for rib less steel tube and 0.92 for ribbed steel tube.

Substituting experimental data P_y into Eq. (13), σ_{cb} can be inversely calculated, and then substituting σ_{cb} into Eq. (12), αk can be approximate expressed as Eq. (14):

$$\alpha k = 8.47 \times t/r + 0.18 \tag{14}$$

The relation of αk and t/r is shown in Fig. 12. Substituting Eq. (14) into Eqs. (11), (12), the concrete compressive strength and the increase rate of the concrete strength under the confinement pressure can be expressed as follows:

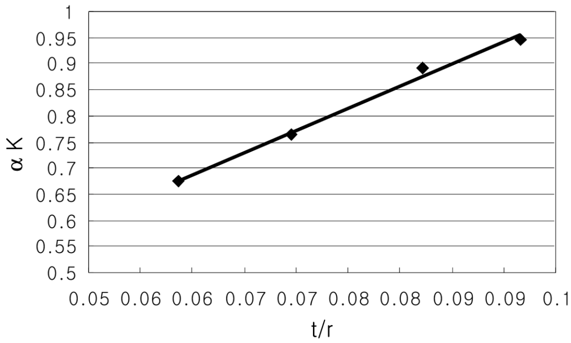


Fig. 12 Relationship of αk and t/r

$$\sigma_{cb} = \sigma_c + \left(8.47 \times \frac{t}{r} + 0.18\right)\frac{t}{r}\sigma_{sy} \tag{15}$$

$$\frac{\sigma_{cb} - \sigma_c}{\sigma_c} = \left(8.47 \times \frac{t}{r} + 0.18\right)\frac{t}{r}\frac{\sigma_{sy}}{\sigma_c} \tag{16}$$

According to Eq. (16), it is understood that the increase rate of filled concrete strength is a quadratic function of *t/r* (thickness-radius ratio) of steel tube, and it is in proportion to yield strength of steel tube and is in inverse proportion to concrete strength. Therefore, the compressive strength evaluation formula for RCFT column is proposed as follows:

$$P_y = \beta A_{st}\sigma_{sty} + A_{sr}\sigma_{sry} + R_{cu}A_c\left(\sigma_c + \left(8.47 \times \frac{t}{r} + 0.18\right)\frac{t}{r}\sigma_{sty}\right) \tag{17}$$

4. Outline of bending-shearing test

4.1 Test specimens and material properties

A total 21 pieces of test specimens including RC, CFT and RCFT twin-column piers were made; bending-shearing test was carried out. According to the type of steel tubes and reinforcing bars, thickness of steel tubes, and strength of filled concrete, 4 pieces of hollow steel tube, 8 pieces of CFT and 6 pieces of RCFT were made in this test. Furthermore, 3 pieces of RC specimens reinforced the same as RCFT specimens were used in order to estimate the cumulative strength discussed later. The details of test specimens are shown in Table 4. The sectional form is listed in Fig. 13. The diameter of specimen is 200 mm, and the length of it is 1900 mm. The steel tubes were made of mild steel (in JIS); thickness of steel tube is 3.2 mm, 4.5 mm and 6.0 mm. Yield strength and tensile strength are 291.2 MPa and 456.8 MPa, respectively. The ribs are trapezoid with lower bottom of 3 mm, upper bottom of 7 mm and height of 4 mm; which are welded inside of steel tubes in circumference direction per 36 mm. Reinforcing bars used in specimens are SR235, φ6 (in JIS) and used in footing are SD295A, φ13. The size of coarse aggregates is about 15 mm; 28 days compressive strength for footing, low and high strength concrete is 19.8 MPa, 23.6 MPa, and 46.8 MPa, respectively. The concrete was filled in layers and was vibrated by a poker vibrator. The specimens were placed upright to air-dry until testing.

Table 4 Details of test specimens

Types of specimens	Hollow steel tube	CFT		RCFT		
		Low strength	High strength	Thick cover	Thin cover	Double bars
3.2 mm	N32CH	N32LM	N32HM	-	-	-
4.5 mm	N45CH	N45LM	N45HM	-	-	-
6.0 mm	N60CH	N60LM	N60HM	N60LS	N60LB	N60LW
6.0 mm (rib)	R60CH	R60LM	R60HM	R60LS	R60LB	R60LW

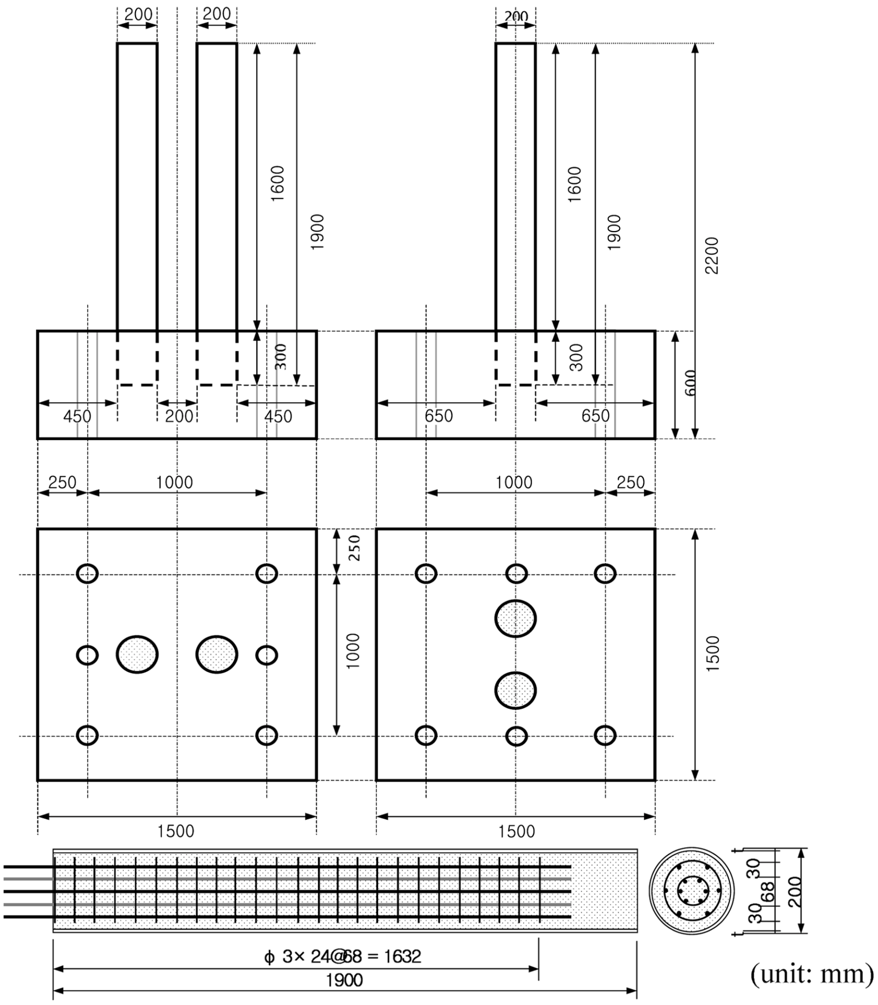
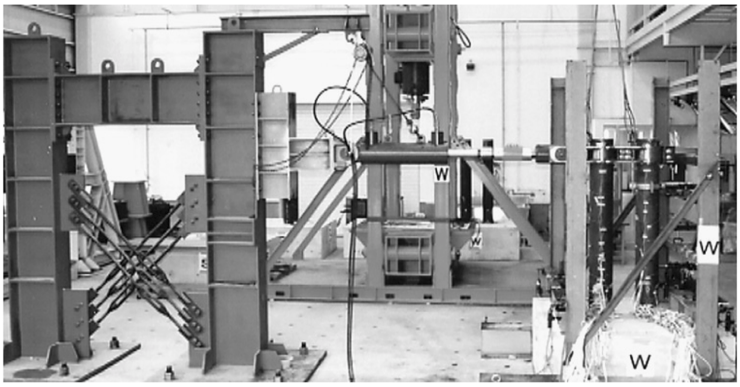


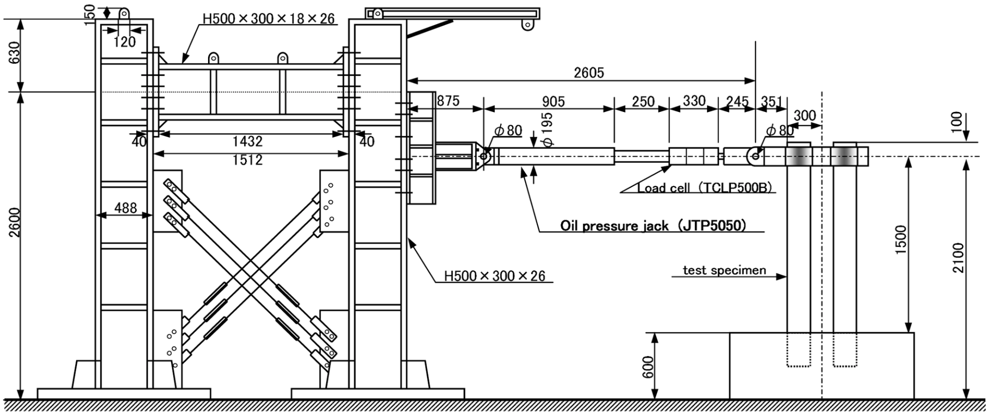
Fig. 13 Cross section of test specimens

4.2 Test setup and measurements

All the specimens were loaded under horizontal cyclic load through the test device shown in Figs. 14(a), (b). The oil pressure jack is fixed by reactive force frame, and its maximum load



(a) Photograph of test setup



(unit: mm)

(b) Test setup

Fig. 14 (a) Photograph of test setup, (b) Test setup

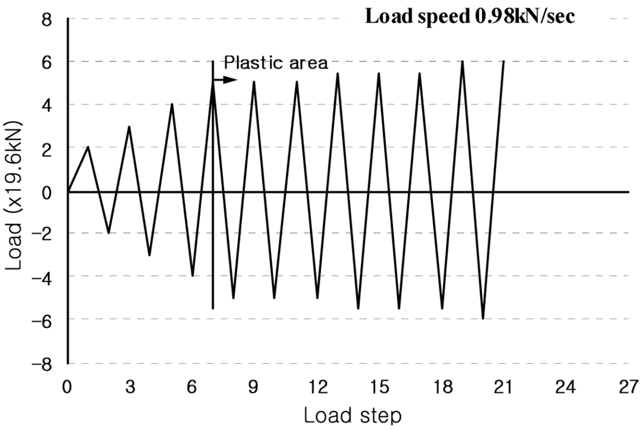


Fig. 15 Load step

capacity is 500 kN. All specimens are fixed to the 720 mm thick RC floor by high strength bolts. Horizontal positive and negative loads alternately were applied to specimens via a connecting steel beam. The loading mode is given as Fig. 15; loading speed is 0.49 kN/sec for RC specimens and 0.98 kN/sec for CFT and RCFT specimens. Considering different load-carrying capacity, load increment is 4.9 kN for RC types, 9.8 kN for hollow steel tube types and 19.6 kN for other specimens, respectively. After the specimens entering into plastic area, cycling load was carried out three times at per load stage. If the maximum displacement reached 200 mm or the test were in dangerous state by distinguishing, test would be terminated.

The measurement items given in Fig. 16 include horizontal load; horizontal and vertical displacement of specimens and footing; strains in surface of steel tubes, and strains of reinforcing bars. The strains of filled concrete were also measured by mold strain gages. All data were recorded automatically by date-log system.

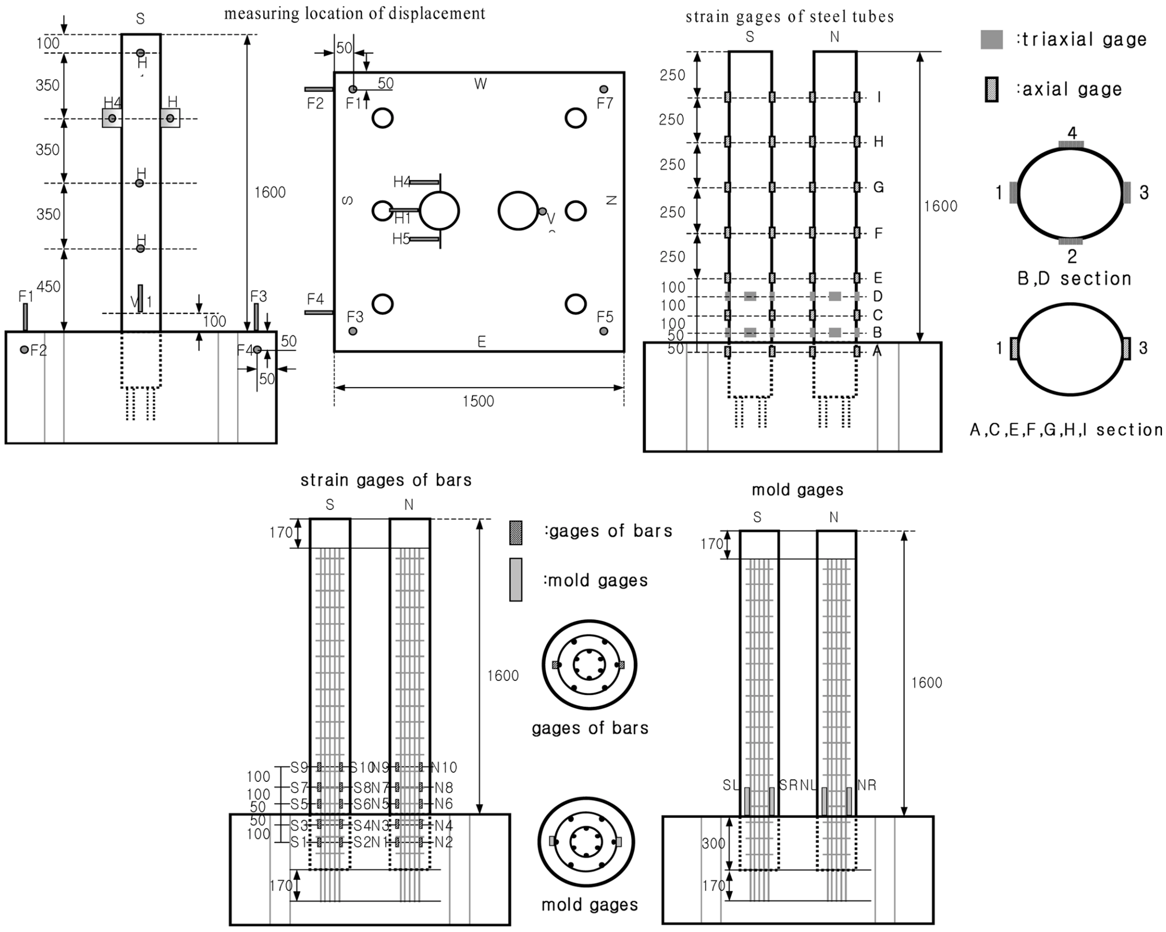


Fig. 16 Measurement items

4.3 Test results

4.3.1 Moment-Curvature curve relationship

Fig. 17 gives Moment-Curvature curve relationship of hollow steel tube, CFT and RCFT specimens. Structural ductility is usually measured by the amount of energy absorption capacity of the structure. This energy absorption capacity in each hysteresis loop is determined based on the area enclosed by moment-curvature curve. The larger the area surrounded by the hysteresis loop, the greater the energy absorption would be achieved, the higher the ductility of structure would be got. From these figures, it is understood that RCFT test specimens show more excellent energy absorption capacity as compared with hollow steel tube and CFT test specimens. The bending strength of CFT filled with high strength concrete is high, and is approximately equal to RCFT with double reinforcing bars filled with low strength concrete, but its area surrounded by the hysteresis loop is smaller than that of RCFT. Therefore, it is said that RCFT filled with low strength concrete shows better deformation performance than CFT filled with high strength concrete. Fig. 18 shows the moment-curvature envelope curve of test specimens. Obviously, the bending strength of RCFT/CFT is higher than that of hollow steel tube. By filling concrete or RC into steel tube, the resistance against bending moment can increase greatly. The thinner the thickness of steel tube, the higher increase rate of strength of specimens would be achieved. The reason is that thin steel tube is low resistance against local buckling, but concrete filled in steel tube can restrain the local buckling effectively. The bending strength of CFT filled with high strength concrete is approximately equal to RCFT with thin cover or RCFT with double reinforcing bars filled with low strength concrete. Furthermore, by reinforced with ribs, specimens can obtain higher resistance against bending moment.

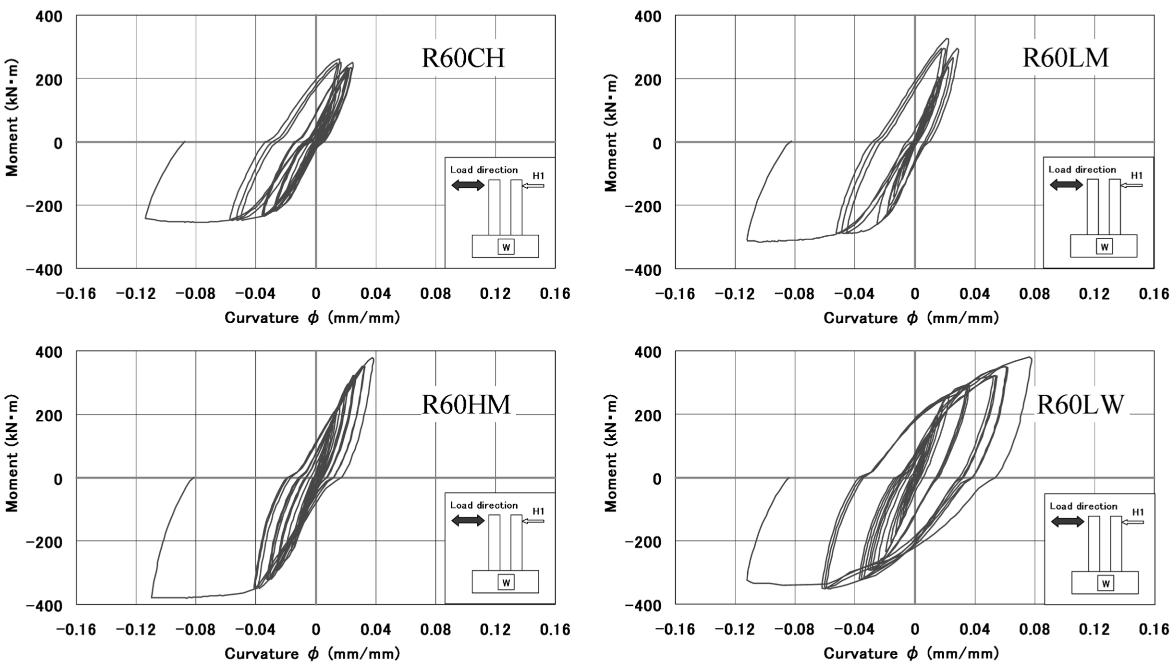


Fig. 17 Moment-Curvature relationship

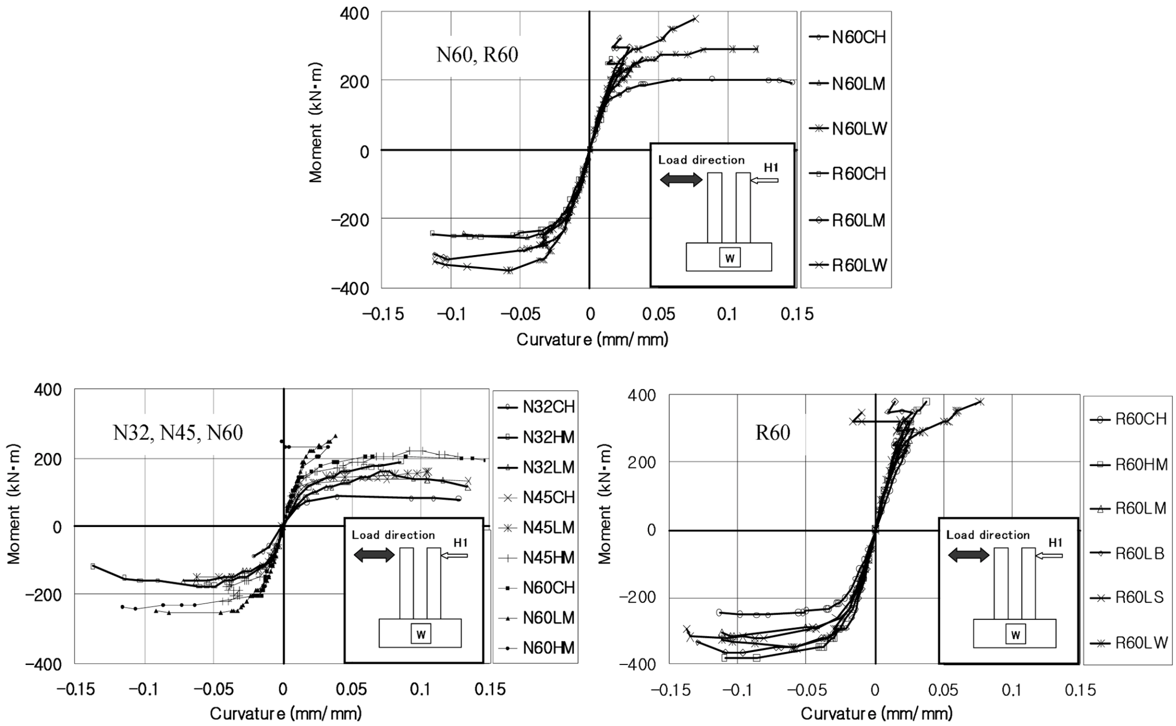


Fig. 18 Moment-Curvature envelope curves

4.3.2 Strain distribution in the section

Fig. 19 shows the strain distribution in the B and C section of RCFT with ribs in elastic range. Transverse axis shows the distance from the center of specimens to strains measured, and longitudinal axis shows axial strains. According to results measured, the strains of reinforcing bars, filled concrete and outside of steel tube in elastic range are shown on the same straight line. It is said that the steel tube and concrete filled into RCFT are unified.

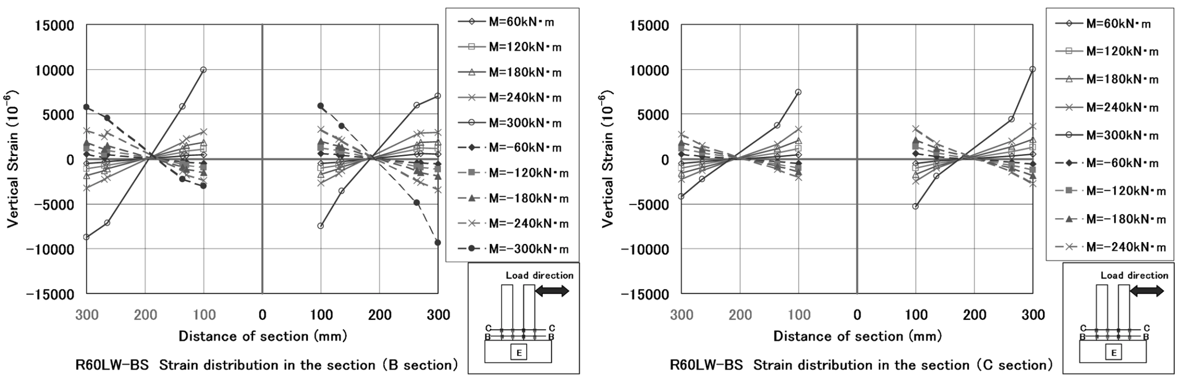


Fig. 19 R60LW strain distribution in B and C section

Table 5 Maximum bending strength, confined effect and ductility ratio

Types of specimens		Specimen label	Maximum bending strength M_u (kN · m)	Strength increase ratio M_{up}	Cumulative bending strength M_0(kN · m)	Confined effect $\alpha(M_u/M_0)$	Ductility ration μ_N δ_u/δ_y	Ductility ration μ_D δ_{max}/δ_y
Hollow steel tube		N32CH	87.3	-	-	-	1.9	11.6
		N45CH	140.7	-	-	-	5.7	13.4
		N60CH	204.6	-	-	-	7.1	12.2
		R60CH	262.4	-	-	-	4.5	6.6
CFT	High strength	N32HM	188.8	2.16	-	-	7.7	7.7
		N45HM	219.6	1.56	-	-	11.3	14.1
		N60HM	262.0	1.28	-	-	8.2	8.8
		R60HM	379.9	1.45	-	-	6.4	8.2
	Low strength	N32LM	160.6	1.84	-	-	6.5	8.4
		N45LM	158.3	1.13	-	-	8.8	8.8
		N60LM	263.2	1.29	-	-	3.2	7.8
		R60LM	325.1	1.24	-	-	1.4	7.2
RCFT	Thin cover	N60LB	-	-	-	-	-	-
		R60LB	379.1	1.44	279.9	1.35	6.9	8.7
	Thick cover	N60LS	-	-	-	-	-	-
		R60LS	349.5	1.33	283.2	1.23	4.9	8.2
	Double reinforcements	N60LW	293.0	1.43	239.9	1.22	6.9	8.7
		R60LW	380.0	1.45	297.8	1.28	5.0	7.4

4.3.3 Bending strength and confined effect

The maximum bending strength, increase rate of bending strength to hollow steel tube, cumulative bending strength and confined effect are shown in Table 5. The cumulative bending strength, confined effect and strength increase rate of bending strength are explained respectively as following formulas:

$$M_0 = M_c + M_s, \quad \alpha = M_u / M_0, \quad M_{up} = M_u / M_s \tag{18}$$

where M_0 is cumulative bending strength, M_c is strength of RC specimens (concrete specimens same as CFT specimens were not produced and tested.), M_s is strength of hollow steel tube specimens, M_u is maximum bending strength, α is confined effect and M_{up} is increase rate of bending strength to hollow steel tube specimens. The thinner the thickness of steel tube, the higher increase rate of bending strength would be. The reason is that thin steel tube is low resistance against local buckling; filled concrete or RC can generate replenishing effect. Compared with CFT column filled with low strength concrete, the bending strength and increase rate of it for CFT column filled with high strength concrete is more excellent, approximately the same as that of RCFT column filled with low strength concrete. The confined effect and increase rate of bending strength of RCFT column with thin concrete cover (thin concrete cover/double reinforcing bars) were remarkably high because the damage of concrete was restrained along with local buckling of steel tube. The bending strength, confined effect and increase rate of bending strength for specimens with ribs were higher than those without ribs.

4.3.4 Ductility ratio

The ductility ratio of test specimens is also shown in Table 5. For some specimens, there is deviation of deformation because of plastic deformation. The load direction at maximum bending strength is different from that at maximum displacement. Therefore ductility ratios at maximum bending strength and at maximum displacement are used to discuss, and the bending strength at maximum displacement is 90% of the maximum bending strength. The two ductility ratios are given as following equations:

$$\mu_N = \delta_u / \delta_y, \quad \mu_D = \delta_{\max} / \delta_y \tag{19}$$

in which μ_N and μ_D are the ductility ratio at maximum bending strength and at maximum displacement, respectively, δ_u is displacement at maximum bending strength, δ_y is yield displacement and $\delta_{\max}$ is maximum displacement.

Experimental results are scattered because of deviation of deformation. For the specimens with ribs, the ductility ratio at maximum displacement of RCFT is better than that of CFT. It is understood that the shearing damage of filled concrete is restrained by reinforcing bars, so its deformation characteristic is improved.

According to the width-thickness ratio, large change of ductility ratio is not found. The ductility ratio of test specimens with ribs is worse than that without ribs. It is understood that cracks generate along with ribs and ductility ratio is declined. It is necessary to held further discussion on it considering deformation deviation of test specimens.

5. The proposal of bending strength evaluation formula for RCFT column

5.1 Assumption

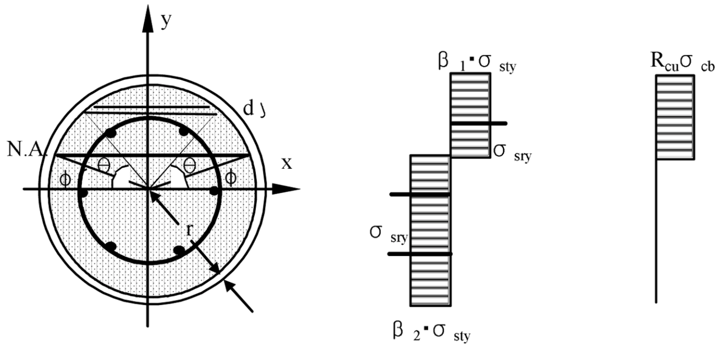
Based on the experimental results, following assumptions are supposed when trying to evaluate the bending strength of RCFT column.

(1) There is no slippage between steel tube and filled concrete or RC. They are unified until ultimate bending strength generate.

(2) Since the crack has occurred to the concrete on the side of tension when bending strength generating, tensile stress of concrete is ignored.

(3) Since the concrete on the side of compression receives confinement pressure σ_r from steel tube and it becomes a 3-dimension stress state, the compressive strength σ_{cb} of concrete is expressed by formula (12).

(4) Steel tube shall be in complete plastic state, and shall follow the Mises yield criterion. Steel tube on the tensile side is in a 2-dimension stress state, and the degree of yield stress of axial direction can be regarded as $\beta_2 \cdot \sigma_{sty}$. On the other hand, steel tube on the compressive side is in 2 dimensions tensile and compressive stress state, and the degree of yield stress of axial direction can be regarded as $\beta_1 \cdot \sigma_{sty}$. Here, β_1 and β_2 are the variation coefficients of the degree of yield stress of steel tube, which is decided by experimental result.



(a) Cross section (b) Stress of steel (c) Stress of concrete

Fig. 20 Stress distribution of steel tube and filled concrete

(5) The strength of reinforcing bars fully plays the role by the restraint of filling concrete.
(6) The stress distribution of a beam section is assumed as shown in Fig. 20.

5.2 Neutral axis of cross section

The neutral axis of cross section is calculated by equilibrium of cross-sectional stress of axial direction. It is considered that the compressive force of section is based on the compressive force of steel tube, concrete and reinforcing bars on compressive side. Tensile force is based on tensile force of steel tube and reinforcing bars on tensile side. Therefore, the following formula is materialized:

$$\beta_1\sigma_{sty}A_{s1} + \sigma_{cb}A_c + \sum\sigma_{sry}A_{r1} = \beta_2\sigma_{sty}A_{s2} + \sum\sigma_{sry}A_{r1} \tag{20}$$

$$\theta = \frac{\pi}{2}\cdot\frac{(\beta_1-\beta_2)\sigma_{sty}tr + 0.5r^2\sigma_{cb}}{(\beta_1+\beta_2)\sigma_{sty}tr + r^2\sigma_{cb}} \tag{21}$$

in which $\beta_1 = 0.89$, $\beta_2 = 1.05$, σ_{sty}, σ_{sry} is yield strength of steel tube and reinforcing bar, σ_{cb} is strength of concrete on compressive side and $\sigma_{cb} = \sigma_c + (8.47 \times t/r + 0.18)\ t/r \cdot \sigma_{sty}$, A_c is area of compressed concrete and $A_c = 0.5r^2(\pi - 2\theta - \sin 2\theta)$, A_{s1} is area of steel tube subjected to compressive stress and $A_{s1} = tr(\pi - 2\theta)$, A_{s2} is area of steel tube subjected to tensile stress and $A_{s2} = tr(\pi + 2\theta)$, A_{r1}, A_{r2} is area of reinforcing bars subjected to compressive stress and tensile stress, respectively.

In the course of calculation of neutral axis, comparing with the area of steel tube, area of reinforcing bars here is minute, so it is disregarded.

5.3 The proposal of bending strength evaluation formula for RCFT column

Based on above discussion, considering axial reduction of steel tube strength and the increase of filled concrete strength, the bending strength is proposed as follows:

$$M_y = 2r^3 R_{cu}\sigma_{cb}\int_{\phi}^{\pi/2}\sin\theta\cos^2\theta d\theta + 2r^2 t\left(\int_{\phi}^{\pi/2}\beta_1\sigma_{sty}\sin\theta d\theta - \int_{-\pi/2}^{\phi}\beta_2\sigma_{sty}\sin\theta d\theta\right) + \sum\sigma_{sry}A_{sr}Z_r$$

$$= \frac{2}{3}r^3 R_{cu}\left[\sigma_c + \left(8.47\times\frac{t}{r} + 0.18\right)\frac{t}{r}\sigma_{sty}\right]\cos^3\phi + 2r^2 t\sigma_{sty}(\beta_1 + \beta_2)\cos\phi + \sum\sigma_{sry}A_{sr}Z_r \quad (22)$$

where, M_y is yield bending moment of cross section, t, r is thickness and inner radius of steel tube, A_{sr} is area of reinforcing bars in axial direction, Z_r is distance from figure center to neutral axis, σ_{sty}, σ_{sry} is yield strength of steel tube and reinforcing bar, respectively, σ_c is compressive strength of concrete, R_{cu} is reduction coefficient of concrete, here is 0.85, and φ is angle which shows the position of neutral axis.

6. Verification of proposal evaluation formula for RCFT column

In order to verify the validity of proposal formula, comparisons are made with the experimental results and the calculation results based on RDC1997 (Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures).

6.1 Verification of proposal compressive strength formula

Based on RDC1997, yield strength evaluation formula for CFT column is:

$$N_u = \left(\beta - \frac{(D-2t)}{2(D-t)}\kappa\alpha\right)A_{st}\sigma_{sty} + A_c\sigma_c \quad (23)$$

In this study, bars reinforce RCFT specimens, so formula (23) can be expressed as:

$$N_u = \left(\beta - \frac{(D-2t)}{2(D-t)}\kappa\alpha\right)A_{st}\sigma_{sty} + A_c\sigma_c + \sum A_{sr}\sigma_{sry} \quad (24)$$

in which A_{st}, A_c, A_{sr} is cross section area of steel tube, concrete, and reinforcing bars, σ_{sty}, σ_{sry} is yield strength of steel tube and reinforcing bar, respectively, σ_c is compressive strength of concrete, α, β is coefficient reflected variation of yield strength of steel tube in circumferential and axial direction, and here, $\alpha = -0.19$, $\beta = 0.89$ (for steel tube without rib), $\beta = 0.92$ (for steel tube with rib) t, D is thickness and diameter of steel tube, and k is restraint coefficient, here it is 4.1.

Yield strengths calculated by the proposal formula (17), by experimental data, and by RDC1997 (24) are shown in Table 6.

According to comparison result, the yield strength by RDC1997 is 4.7%-19.8% larger than that by experiment. On the other hand, the difference between calculated value by the proposal formula (17) and by experimental value is 1.5%-10.4%. It is smaller than the difference between calculated value by RDC1997 and by experiment, and calculated values by the proposal formula are in good agreement with experimental results. This is due to the increase parameter αk of the compressive strength of concrete in the 3-dimension stress state is considered to be the function of t/r in this proposal, but it is a constant in RDC1997. Moreover, in this proposal, β applied to steel tube with and without ribs is defined, respectively.

Table 6 Verification of proposed compressive strength formula

Specimen label			Yield compressive strength (kN)	Average value (kN)	Calculated value by RDC 1997		Calculated value by proposed formula	
					Calculated value (kN)	Difference with experimental result (%)	Calculated value (kN)	Difference with experimental result (%)
A Test	without rib	SN3	2207.3					
		SN4	2355.0	2281.1	2733.1	19.8	2447.1	7.3
	with rib	SH3	2454.5					
		SH4	2358.4	2406.5	2572.9	6.9	2369.6	-1.5
B Test	without rib	SNC203	1281.8					
		SNC204	1268.3	1275.1	1434.9	12.5	1378.4	8.1
		SNC205	1274.1					
		SNC206	1474.7	1374.4	1491.9	8.5	1432.2	4.2
		SNC207	1281.0					
		SNC208	1379.5	1330.2	1491.9	12.2	1432.2	7.7
		SNC209	1138.0					
		SNC210	1429.3	1429.3	1548.9	8.4	1485.9	4.0
	with rib	SHC203	1439.1					
		SHC204	1531.0	1485.1	1610.4	8.4	1604.9	8.1
		SHC205	1476.5					
		SHC206	1525.6	1501.0	1666.6	11.0	1657.2	10.4
		SHC207	1564.7					
		SHC208	1517.0	1540.9	1666.6	8.2	1657.2	7.6
		SHC209	1568.8					
		SHC210	1721.2	1645.0	1722.9	4.7	1709.6	3.9

6.2 Verification of proposal bending strength formula

According to RDC1997, bending strength of CFT specimens can be expressed by the following formula

$$M_u = \frac{(D-t)^2}{2} t(\beta_1 + \beta_2)\sin\phi\sigma_{sty} + \frac{2}{3} r^3 \sin^3\phi\left(\sigma_c + \frac{2\kappa\alpha t}{(D-2t)}\sigma_{sty}\right) \tag{25}$$

In this study, bars reinforce RCFT specimens, so formula (25) can be expressed as:

$$M_u = \frac{(D-t)^2}{2} t(\beta_1 + \beta_2)\sin\phi\sigma_{sty} + \frac{2}{3} r^3 \sin^3\phi\left(\sigma_c + \frac{2\kappa\alpha t}{(D-2t)}\sigma_{sty}\right) + \sum A_{sr}\sigma_{sry}Z_r \tag{26}$$

where t, r, D is thickness, inner radius and diameter of steel tube, A_r is area of reinforcing bars in axial direction, Z_r is distance from figure center to neutral axis, σ_{sty}, σ_{sry} is yield strength of steel

Table 7 Verification of proposed bending strength formula

Specimen label			Yield bending strength (kN · m)	Calculated value by RDC 1997		Calculated value by proposed formula	
				Calculated value (kN · m)	Difference with experimental result (%)	Calculated value (kN · m)	Difference with experimental result (%)
CFT	Low strength	N32LM	40.85	43.08	5.5	39.36	–3.6
		N45LM	-	58.09	-	53.46	-
		N60LM	67.31	73.27	8.9	67.84	0.8
		R60LM	83.32	85.16	2.2	79.20	–4.9
	High strength	N32HM	47.98	47.62	–0.8	42.91	–10.6
		N45HM	55.98	62.73	12.1	56.99	1.8
		N60HM	66.97	78.07	16.6	71.40	6.6
		R60HM	97.11	90.06	–7.3	82.75	–14.8
RCFT	Thin cover	N60LB	-	-	-	-	-
		R60LB	97.15	89.58	–7.8	87.17	–10.3
	Thick cover	N60LS	-	-	-	-	-
		R60LS	89.58	90.39	0.9	87.98	–1.8
	Double bars	N60LW	74.94	82.22	9.7	80.34	7.2
		R60LW	97.37	94.11	–3.3	91.69	–5.8

tube and reinforcing bar, respectively, σ_c is compressive strength of concrete, φ is angle which shows the position of neutral axis.

Yield bending strengths calculated by the proposal formula (22), by experimental data, and by RDC1997 (26) are shown in Table 7. According to comparison result, the difference (absolute value) between calculated value by RDC1997 and by experiment is 0.8%-16.6%; On the other hand, the difference (absolute value) between calculated value by the proposal formula (22) and by experimental value is 0.2%-14.8%. It is smaller than the difference between calculated value by RDC1997 and by experiment, and calculated value by the proposal formula is in good agreement with experimental results. The reason is the same as that of proposal compressive strength formula.

7. Conclusions

In this study, rib-less steel pipes and ribbed steel pipes were used; compression test and bending-shearing test were carried out. Taking into consideration the influence of concrete strength, steel strength, rib, width-thickness ratio, the formula which can evaluate strength of RCFT were proposed, and the validity was verified as compared with experimental result and evaluation formula of RDC1997. The conclusions can be drawn as follows.

(1) RCFT columns have higher strength than hollow steel tube and CFT columns by a confined effect of steel and concrete, especially strength and ductility are largely improved after the

peak of load-displacement curve. When ribbed pipes are used, integration of steel and concrete is promoted and a greater confined effect is created.

(2) For CFT/RCFT column, the confined effect is considered that strength of concrete can be improved sharply in response to a strong horizontal restraint of steel pipe.

(3) Considering the influence of concrete strength, steel strength, rib and width-thickness ratio, evaluation formula of the strength for a RCFT column have been proposed and verified, and it is in good agreement with results from the experiment and prior to the evaluation formula of RDC1997. As a result, the proposed evaluation formula can evaluate the strength of RCFT properly.

Acknowledgements

We appreciate to Japan Society for the Promotion of Science (Grant-in-Aid for Scientific) and China State Education Ministry (Scientific Research Foundation for the Returned Overseas Chinese Scholars).

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