(44) A DISCUSSION ON RATIO OF AXIAL REINFORCEMENT IN RCFT COLUMNS

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It is clear from the former researches on reinforced concrete filled tubular steel (RCFT) structures that mechanical properties of RCFT differed from that of concrete filled tubular steel (CFT) structures due to the existence of the reinforcements. In order to clarify the effect of axial reinforcement on performance of RCFT, experimental and numerical investigations are performed with varying ratio of axial reinforcement under axial compression. Through a series of comparison and analysis, the effect of the axial reinforcement ratio is discussed, and following conclusions are drawn: reinforcement ratio has direct effect on performance of RCFT. Neither too many nor too small but proper ratio of axial reinforcement will make the RCFT possess better confined effect, ductility and toughness, and improve overall performance. After all, as a result, optimal ratios of axial reinforcement for RCFT are proposed.

Keywords: *RCFT; CFT; axial reinforcement; axial compression; ratio of axial reinforcement.*

1. INTRODUCTION

Reinforced concrete filled tubular steel (RCFT) structures are the composite structures which are mainly aimed at improving the shear resistibility of concrete filled tubular steel (CFT) structures by inserting the reinforcements into the core concrete.

The brittle-failure of CFT structures is concerned when it is considered to construct large-scaled structures[1)-4)], and then, RCFT structures which have high strength like CFT and can be adapted to large-scaled structures are developed and studied in the terms of practical utilization. **Fig.1** shows the model of CFT and RCFT.

Some research results until now[5)-9)] proved that the bearing capacity, toughness, ductility and anti-seismic performance of RCFT structures are increased compared with those of CFT. In other words, because of the existence of reinforcement, the performance of RCFT differed from that of CFT.

In this study, the axial compression tests of RCFT and CFT columns with varying ratios of axial reinforcement are carried out to examine whether the axial reinforcements affect the performance of the RCFT. After confirming the effects of axial reinforcements by the experiment, a numerical analysis is adopted to perform more detailed investigations. The numerical model is validated with the experimental results, and the validated model is applied to a plenty of numerical studies of RCFT columns. As a result, the effects of axial

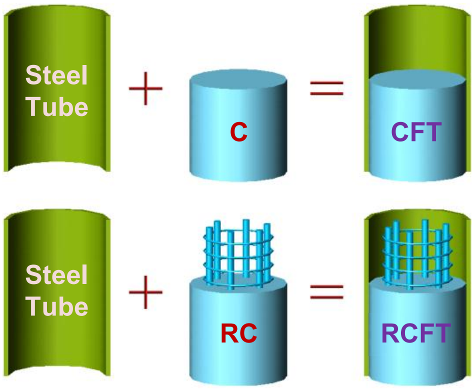


Fig.1 Model of CFT and RCFT

reinforcements on the mechanical properties of RCFT columns are clarified, and the optimal ratios of axial reinforcement which will put RCFT into better performance are proposed.

2. EXPERIMENTAL INVESTIGATIONS

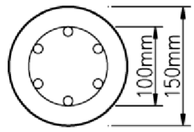
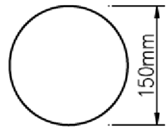
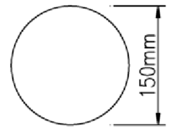
(1) Outline

RCFT, CFT and concrete specimens were prepared for the experimental investigations. The outer diameter D and height H of all specimens was D=150mm and H=450mm, respectively. Materials were selected from Japanese Industrial Standard (JIS). Concrete: desired strength was 40MPa; steel tube: material was SS400, thickness t was t=1.2mm, and made by welding; same lateral reinforcement was used for all specimens: material was SS400, diameter d_s was d_s=3mm, spacing was 28mm; axial reinforcement: material was SD295, ratio of reinforcement ρ was determined according to the diameters provided by JIS, detailed information are listed in the **Table 1**.

(2) Material test

Material test of 3 same steel plates whose size were 1.2×30×120mm and same material with steel tube(SS400) and 3 same reinforcement bar whose diameter was 10mm and same material with axial reinforcements(SD295) were carried out. Obtained ultimate results as follows: the yield strength of steel tube test piece is f_{sy}=323.0MPa and strain on start point of strain hardening is ε_{sy}=14800μm/m, the yield strength of reinforcement test piece is f_{ry}=355.0MPa and strain on start point of strain hardening is ε_{ry}=19100μm/m. The ultimate results are shown in **Fig.2**.

Table 1 Detail of specimens

Labels		Axial reinforcement ρ (%)	Axial reinforcement d_s(mm)	Cross section
RCFT	RT11-1 RT11-2 RT11-3	1.11	6	
	RT25-1 RT25-2 RT25-3	2.50	10	
	RT44-1 RT44-2 RT44-3	4.44	13	
CFT	CFT-1 CFT-2 CFT-3	—	—	
C	C-1 C-2 C-3	—	—	

(3) Discussions on the experimental results

In the discussions, the following two indexes are used to evaluate the performance:

1) The toughness: toughness (signified with χ) is one of the important indexes to evaluate performance of a structure. In this study, toughness of the columns is determined by converting load-strain curves to stress-strain curves and taking the integral of that curves, upper limit for the integral is determined according to strain value by material test. The value of upper limit is selected as ε_f= 55000μm/m according to material test of steel tube (vertical dotted line in both **Fig.2** and **Fig.3**).

2) The confined effect: when concrete is subjected to laterally confining pressure, the uniaxial compressive strength and the corresponding strain are much higher than those of unconfined concrete. The concrete of RCFT is confined by both steel tube and reinforcement. According to JSSC[10],

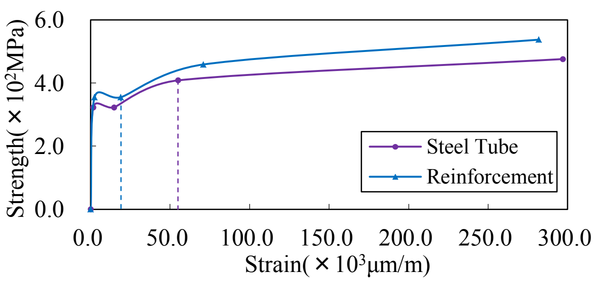


Fig.2 Material test for steel tube and reinforcement

Suzuki *et al.*[11], Murata *et al.*[12], Matsui *et al.*[13], Nakai *et al.*[14], Tang *et al.*[15], Fujimoto *et al.*[16], and Xu[17], in case of CFT structures, steel tube and concrete is completely bonded, meanwhile the effect of shrinkage and creep of concrete and local buckling of steel tube to the CFT structure can be neglected. If the same assumptions are applied to the steel tube and reinforcement of RCFT structures, the ultimate bearing capacity of RCFT columns under axial compression may be simply assumed as follows:

$$N_u = N_{so} + N_{ro} + k_c N_c \qquad (1a)$$

where the k_c represents the confined effect of steel tube and reinforcement to concrete of RCFT, and:

$$k_c = \frac{N_u - N_{so} - N_{ro}}{N_c} \qquad (1b)$$

where N_u is experimental ultimate strength of the RCFT and CFT specimens; N_c is experimental ultimate strength of concrete specimens; $N_{so}=A_{ss}f_{sy}$ and $N_{ro}=A_{rs}f_{ry}$ is uniaxial strength of steel tube and reinforcement in which A_{ss} and A_{sr} is cross-section area of steel tube and reinforcement, respectively.

a) Discussions on load and average strains

The results of the experiment are given in **Table 2** and the curves of axial force versus axial average strain for these columns are plotted in **Fig.3**. Through the comparison, the following discussions may be drawn:

1) In case of RCFT: obvious differences can be observed between curves of different ρ. The curve of RT44 drops rapidly after maximum load while the curve of RT11 and RT25 descends smoothly and gradually, and shape of its curve is similar to the curve of CFT, this may be understood as that: because better cooperation and balance between concrete and reinforcement are not achieved due to higher ρ, therefore, when it reaches at maximum load, the core concrete is failed in advance without exerting effect of reinforcement and promoted sudden strength decrease of all column, after this, all column keep its strength by steel tube, reinforcement and crushed concrete; All of RCFT columns have greater bearing capacity than CFT and concrete columns.

2) In case of CFT: The curve of CFT drops more rapidly after maximum load, this is also due to sudden rupture of the concrete, afterwards the column keep its strength by steel tube and crushed concrete, the failure is typical brittle-failure. Meanwhile, RT11 and RT25 tell that properly arranged reinforcement may prevent this kind of failure.

Table 2 Test results

Labels	N_u (kN)	δ (mm)	χ (×10^{6}J/m^3)	N_{so} (kN)	N_{ro} (kN)	k_c
RT11	1218.8	2.64	20.3	181.2	67.5	1.35
RT25	1316.7	2.75	21.4	181.2	151.9	1.36
RT44	1365.9	2.36	26.3	181.2	269.9	1.27
CFT	968.0	2.44	19.8	181.2	__	1.04
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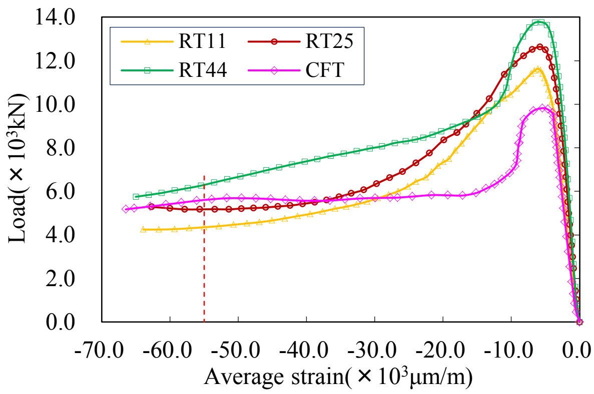

Fig.3 Load versus average strain

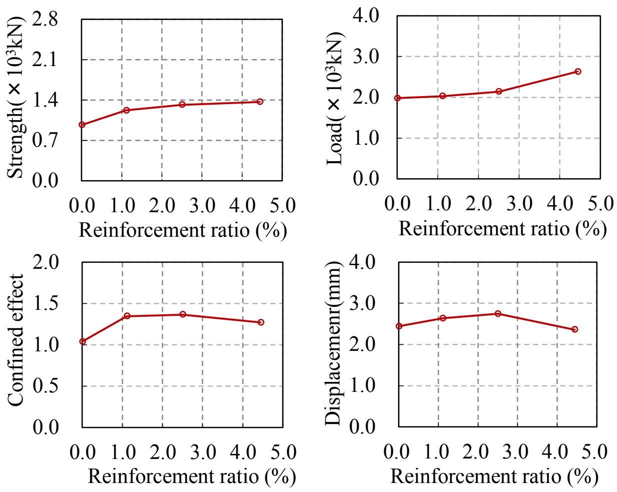

Fig.4 Effect of reinforcement ratio

d) Discussions on effects of reinforcement ratio

The effect of ρ on bearing capacity, toughness, displacement and confined effect of RCFT columns can be discussed from **Table 2** and **Fig.4** as follows:

1) RT44 have higher bearing capacity and toughness than RT11 and RT25, but compared with RT11, bearing capacity and toughness of RT44 only

increased 3.7% and 23. 4% while ρ increased 300%.

2) RT25 shows greater displacement at maximum load than both RT11 and RT44, and that of RT44 even smaller than that of CFT. This means RCFT will have better the ductility with proper ρ.

3) RT25 shows better confined effect than both RT11 and RT44, and all of RCFT have better confined effect than CFT. This means RCFT may have better performance than CFT due to its reinforcement, but increase of ρ not necessarily can increase confined effect of RCFT.

From the all of discussions above, it can be understood that RT25 showed better performance than all of other RCFT and CFT columns. This tells that the proper ratio of axial reinforcement can improve the performance of RCFT. In other words, there will be an optimal ratio of axial reinforcement which would put the RCFT into better performance.

In order to investigate the optimal ratio of axial reinforcement, more RCFT with more other ρ needs to be examined. This may be done with numerical simulations. To do this, a finite element method (FEM) software ADINA is employed in this study.

2. NUMERICAL INVESTIGATIONS

(1) FEM modeling

a) Concrete

The concrete of RCFT is in a multiaxial stress condition due to the confinement pressure by both steel tube and reinforcements. The key point on modeling the concrete is focuses on how to determine the multiaxial stress-strain relationship. Generally, the multiaxial stress-strain relations can be derived from uniaxial stress-strain relationship, shown as **Fig.5**, where σ_{co} is maximum uniaxial compressive stress, ε_{co} is uniaxial strain corresponding to σ_{co}, σ_{uo} is ultimate uniaxial compressive stress, ε_{uo} is ultimate uniaxial compressive strain corresponding to σ_{uo}, σ_{to} is uniaxial cut-off tensile strength, ε_{to} is uniaxial strain corresponding to σ_{to} , and all multiaxial parameters are identified with corresponding notations to uniaxial ones without "0" in subscript.

It is known that the increase in strength of confined concrete is a result of the combination of lateral pressure and axial compression. In RCFT, the lateral pressure is provided by both steel tube and reinforcement. Whatever the confinement pressure, the strength of confined concrete may be expressed as the multiple of the strength of unconfined concrete, and the strength increase due to the confining stresses:

$$\sigma_c = k_c\sigma_{co} \tag{2}$$

The other parameters to define multiaxial stress-strain relationship may be presented by the same concept as following expressions:

$$\sigma_u = k_3\sigma_{uo}\ ;\ \varepsilon_c = (C_1k_c^2 + C_2k_c) \tag{3}$$

where the k_3 is defined as degradation parameter of material, C_1 and C_2 are coefficient , normally C_1=1.4 and C_2=-0.4[18].

Based on the study results of Hu *et al.*[19], Endo *et al.*[20], Nishida *et al.*[21], and Ito *et al.*[22], the ε_u can be ranged in:

$$1.2\varepsilon_c \le \varepsilon_u \le 11\varepsilon_c \tag{4}$$

Thus, the constants σ_c, σ_u, ε_c, ε_u can be employed instead of the uniaxial variables in order to establish, using the equations for uniaxial law by Saenz[23], the multiaxial stress-strain law (see region I and II in **Fig.5**).

For the strain states beyond ε_{uo} in compression (see region III after point P_o or P in **Fig.5**), it can be assumed that the stresses are linearly released to zero[18].

When the material is in tension (see Region IV in **Fig.5**), the stress-strain relation is linear with a constant initial tangent modulus E_o until tensile failure at ε_{to}. A post-crack tension hardening is considered by an unloading branch after ε_{to}, and assume that the tensile stress of the concrete is linearly released to zero at ε_{tm} [24)-25)].

A Kupfer model[26] is employed as failure criterion.

Throughout the section, some other constant parameters can be determined as follows: A

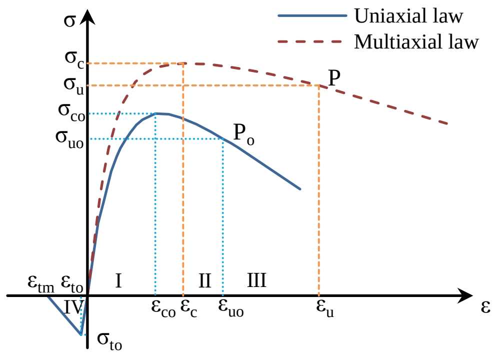

Fig.5 Constitutive law for concrete

representative value suggested by ACI Committee 318[27] for ε_{co} used in the analysis is ε_{co}=0.003. σ_t is determined by $\sigma_t=0.23(\sigma_c)^{2/3}$ according to JSCE [28]. E_o is highly correlated to its compressive strength and can be calculated with reasonable accuracy from the empirical equation $E_o = 4700\sqrt{\sigma_c}$ by ACI Committee 318[27]. With a representative value of 0.19 or 0.20[27], the Poisson's ratio v_c of concrete assumed to be v_c =0.2.

b) Steel tube and reinforcement

The response of the steel tube and reinforcement is modeled by an elastic-perfectly-plastic theory with associated flow rule. A von Mises yield criterion is employed as failure criterion and a bilinear stress-strain relationship without strain hardening is employed as constitutive law, as shown in **Fig.6,** where f_y is yield stress, ε_{sy} is yield strain, ε_{su} is maximum allowable plastic strain. Poisson's ratio v_s and Young's modulus E_s are set to $v_s=0.3$ and $E_s=200GPa$, respectively. These parameters will be determined by uniaxial material tests.

c) Contact modeling

Pre-calculations on RCFT columns were performed with and without friction between steel tube and concrete, and the results showed that there were no obvious differences between the analysis results of these two treatments, only the frictional treatment showed more time-consuming and convergence problem. Therefore, in this study, a constraint-function model with frictionless contact built in ADINA is employed.

(2) Implementation program

As described in previous section, σ_c, σ_u, ε_c and ε_u should be provided in order to completely define the multiaxial stress-strain relation for core concrete. Consequently, their appropriate values are determined by matching the numerical results with experimental results via parametric study.

For each column, the calibration process is: 1) Start the calculation with σ_{co}, σ_{uo}, ε_{co} and ε_{uo}; 2) Perform calculations by adjusting σ_c with Eq.(2) until the differences N_{err} of experimental bearing capacity N_u^T against analytical bearing capacity N_u^A satisfies$N_{err} \leq 3.0\%$; 3) At the starting of this stage, a k_c is already achieved. Continue calculations by using Eq.(3) and Eq.(4) and adjusting σ_u and ε_u until the differences δ_{err} of experimental displacement δ^T (corresponding to N_u^T) against analytical

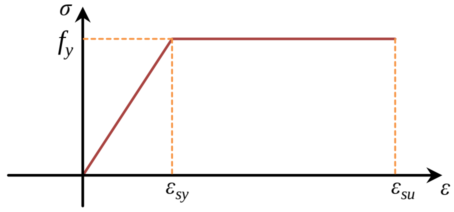

Fig.6 Constitutive law for steel

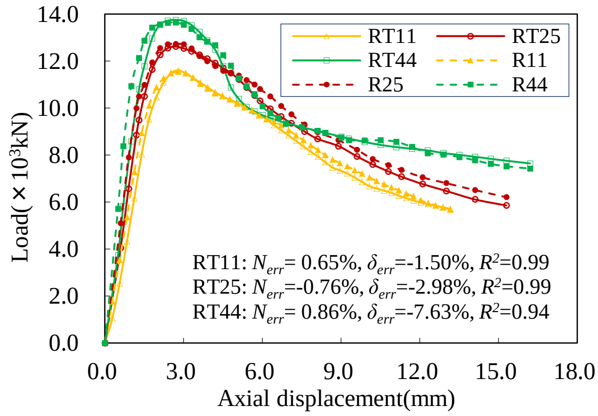

Fig.7 Validation of the numerical results

displacement δ^A (corresponding to N_u^T) satisfies $\delta_{err} \leq 10.0\%$, and the correlation coefficient R^2 between experimental and analytical load-displacement curves satisfies $R^2 \geq 0.9$; 4) Stop calculations if N_{err}, δ_{err} and R^2 satisfied $N_{err} \leq 3.0\%$, $\delta_{err} \leq 10.0\%$, and $R^2 \geq 0.9$, respectively.

The calibrated results of numerical analysis are drawn in **Fig.7**, where R11, R25 and R44 are the numerical results corresponding to RT11, RT25 and RT44, respectively. Generally, the numerical results showed very good agreement with experimental results.

Thus, based on the reliable results of numerical analysis above, in order to clarify the optimal ρ, numerical analysis with other varying ρ can be performed by only changing the ρ in one of the R11, R25 and R44.

In this study, the varying ρ for RCFT is determined based on the specifications of JSCE code on the range of ρ for RC columns, namely, 0.8%≤ρ≤6.0%, and other two smaller values than 0.8% are also used considering extra small ρ for RCFT. The determined 13 values for ρ and the corresponding labels for numerical analysis are list in **Table 3**, besides , all other parameters same with that of experiments.

(3) Discussions on analytical results

The curves of load versus average strains for the reinforcements of 13 RCFT columns are plotted in **Fig.8**. It can be clearly observed from the **Fig.8** that the degradation in strength of the reinforcements is happening, and its amount is varying with varying ρ and strains.

It can be noticed in the material test of reinforcement (**Fig.2**) that the relationship between ε_{ry} and the yield strain ε_e is $\varepsilon_{ry}\approx 8\varepsilon_e$ (where ε_e=7500μm/m). Thus, to evaluate the amount of the degradation, three strain points are defined, namely, $\varepsilon_1=4\varepsilon_e$=-10000μm/m, $\varepsilon_2=\varepsilon_{ry}$=-19100μm/m and $\varepsilon_3=12\varepsilon_e$=-30000μm/m, and marked with vertical dotted lines in **Fig.8**. Then, the ratio of degradation ΔN can be calculated for these three strain points by:

$$\Delta N = (N_u^r - N_\varepsilon^r)/N_u^r \tag{5}$$

where N_u^r is maximum load, N_ε^r is load corresponding to ε_1 , ε_2 and ε_3.

The calculated ΔN values, maximum load (N_u) and corresponding displacement (δ_u) and toughness of core concrete (χ_c) corresponding to ε_2 for every ρ are listed in **Table 3**. It is clear from the table that the ΔN, N_u, δ and χ_c are varying with varying ρ.

The CFT shows the smallest bearing capacity, and bearing capacity of RCFT is increasing with the increase of ρ.

The ductility ratio μ of RCFT can be the ratio of δ_u against yield displacement δ_y of the column. Thus, the relationship between μ and ρ, and the relationship between χ_c and ρ are plotted in **Fig.9**.

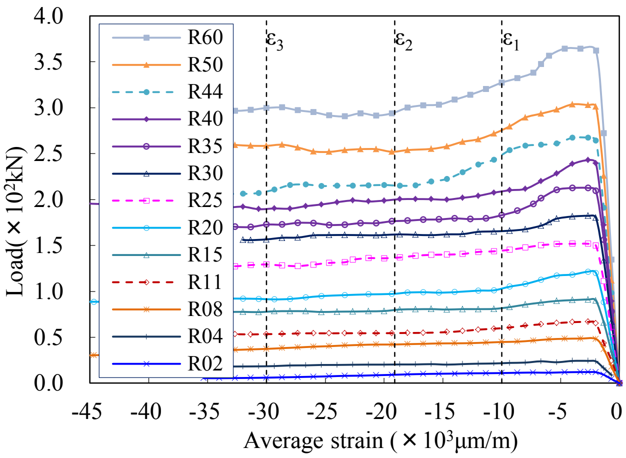

Fig.8 Load-strain curves of axial reinforcement

Again, the relationships between ΔN and ρ corresponding to those three stain points are plotted in **Fig.10.** Through the general considerations with **Fig.9**, **Fig.10** and **Table 3**, the following discussions are drawn: the μ, χ_c and ΔN are not proportional to ρ. The larger μ and χ_c are happening in the range of 1.1%≤ρ≤3.0% and decreasing with smaller and larger ρ. On the contrary, the smaller ΔN is happening in the same range for all three strain points and increasing with smaller and larger ρ. In other words, the ductility and toughness of RCFT are increasing with smaller strength degradation ratio of axial reinforcement. Therefore, it can be concluded that the smaller degradation in strength of axial reinforcement will be the better performance will be achieved with RCFT columns.

Based on the conclusion above, according to **Table 3** and **Fig.10**, the optimal ratios ρ_o for axial reinforcement in RCFT columns will be 1.5%≤ρ_o≤3.0%.

Table 3 Results of numerical analysis

Labels	ρ (%)	N_u^r (kN)	ε_1		ε_2		ε_3		N_u (kN)	δ_u (mm)	χ_c (×10⁶J/m³)
			$N_{\varepsilon1}^r$	$\Delta N_{\varepsilon1}$	$N_{\varepsilon2}^r$	$\Delta N_{\varepsilon2}$	$N_{\varepsilon3}^r$	$\Delta N_{\varepsilon3}$			
CFT	0.0	-	-	-	-	-	-	-	1039.2	2.19	0.70
R02	0.2	12.1	10.7	0.12	9.1	0.25	5.9	0.52	1080.3	2.12	0.76
R04	0.4	24.3	22.0	0.09	19.5	0.20	13.6	0.44	1103.2	2.13	0.81
R08	0.8	48.6	44.2	0.09	40.8	0.16	35.1	0.28	1121.2	2.48	0.82
R11	1.1	66.8	61.3	0.08	56.8	0.15	52.7	0.21	1154.8	2.82	0.84
R15	**1.5**	**91.1**	**83.9**	**0.08**	**78.6**	**0.14**	**75.4**	**0.17**	**1168.6**	**2.74**	**0.85**
R20	**2.0**	**121.5**	**112.1**	**0.08**	**105.8**	**0.13**	**101.8**	**0.16**	**1181.0**	**2.76**	**0.86**
R25	**2.5**	**151.8**	**141.0**	**0.07**	**131.7**	**0.13**	**127.0**	**0.16**	**1254.7**	**2.77**	**0.83**
R30	**3.0**	**182.2**	**165.4**	**0.09**	**156.3**	**0.14**	**150.8**	**0.17**	**1260.9**	**2.52**	**0.83**
R35	3.5	212.6	183.0	0.14	173.6	0.18	169.1	0.20	1291.4	2.43	0.82
R40	4.0	243.0	203.7	0.16	194.0	0.20	189.0	0.22	1305.0	2.43	0.81
R44	4.4	267.3	221.6	0.17	213.4	0.20	206.2	0.23	1364.7	2.54	0.82
R50	5.0	303.7	249.6	0.18	241.9	0.20	233.6	0.23	1391.5	2.11	0.79
R60	6.0	364.4	296.4	0.19	291.5	0.20	296.7	0.19	1454.5	2.21	0.78

In addition, it can be noticed in **Table 3** and **Fig.10** that the reinforcement with smaller ratio (e.g. ρ=0.2%) showed significant degradation in strength in all strain points, this may be assumed that the reinforcements will be yielded prior to the failure of the concrete due to its smaller amount, and its behavior is easily controlled by the behavior of the concrete.

3. CONCLUSIONS

From the discussions above, conclusions may be drawn as follows:

1) Ratio of axial reinforcement has direct effect on the performance of RCFT. Over arranged reinforcement will cause the failure of the concrete prior to the yield of reinforcement without exerting its strength, and not only may cause brittle-failure or lower performance of the structure, but also cause the increase of construction cost. On the contrary, too small ratio of reinforcement will result in yield of reinforcement prior to the failure of the concrete. All of those will be not conductive to better performance of RCFT.

2) The proper ratio of reinforcement can make the RCFT possess better confined effect, ductility and toughness, and improve overall performance.

3) Optimal ratios for axial reinforcement proposed in this study may have applicable means in the design or construction of RCFT structures.

4) It is also proved in this study that the RCFT has better performance than CFT, especially possesses more brittle-failure resistance than CFT.

In this study, the optimal ratios only for axial reinforcements are obtained only with one type of concrete strength and steel tube thickness. It is necessary to carry out further studies on optimal ratios for both axial and lateral reinforcement with varying concrete strength and steel tube thickness, and propose an evaluating method suitable for various RCFT.

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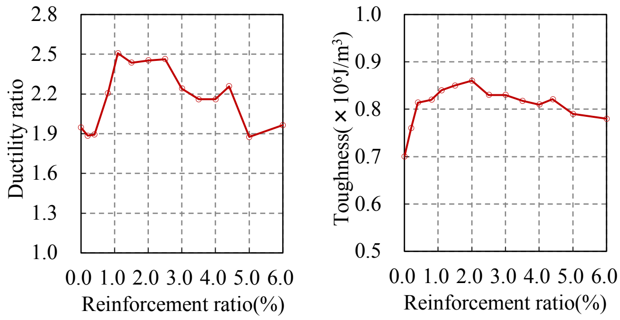

Fig.9 Ductility ratio of RCFT and toughness of concrete

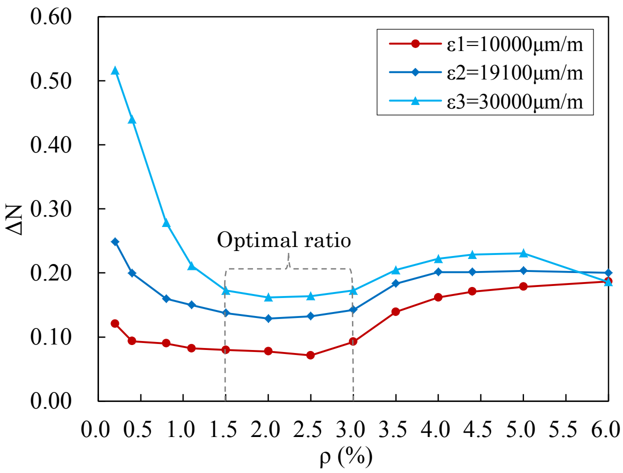

Fig.10 Optimal ratio of axial reinforcements

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