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Prediction of Compressive Behavior of CFCT Stub Columns on the Basis of Integrated Data Analysis

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SUMMARY

Using concrete fillings in structural steel tubes can vastly improve the compressive load-carrying capacities. This paper reports the investigations on the compressive behavior of concrete filled circular tubular (CFCT) stub columns under static loading. A correlation study deals with both test and analysis results. The effects of concrete to steel resistance ratios on the ultimate strength, as well as the deformation capacity and the axial stiffness are being discussed. An empirical formula for predicting the strength of confined concrete is proposed based on the data analysis. The comparison between the analytical predictions and test results show good correlation which suggests that the developed formula is useful for the practical designer.

INTRODUCTION

Seismic loading acts on a structure in all directions, but the main components are the horizontal with the vertical components. If the structural system doesn't have enough stiffening elements in the horizontal direction, there will be the danger of stability loss. Local buckling is usually followed by the total side sway of the whole thin walled steel column. High-rise commercial buildings are designed and built for the purpose of efficient use of a limited building site. After hollow structural steel sections became more available, engineers realized the advantages of filling the concrete. Concrete filled Tubular (CFT) members were studied continuously to adjust for tall buildings, especially those to be constructed in earthquake regions.

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Composite columns generally not only efficiently utilize the two materials but also produce fire-resistant structural members. Circular hollow sections have many advantages as structural members due to the fact that their properties are the same for all directions. This paper focuses on the prediction of compressive behavior of CFCT stub columns on the basis of integrated data analysis. Also experimental study was executed to make sure of the effect of filling the concrete. From the test results and the integrated data analysis, the correlation between the strength of material and the diameter to thickness ratio of the steel tube is assessed. This study will be useful to the engineer who is involved in the construction project using the CFCT columns and helpful to the understanding of their behaviors.

TEST PROGRAM

Tensile tests for steel tubes

The dimensions of steel tubes used in this study are Φ-76.3 x 2.4mm, Φ-88.5 x 2.4mm, Φ-101.6 x 4.0mm, and Φ-101.6 x 4.2mm and the diameter to thickness ratios of those specimens are ranged from 24 to 37. Coupon tests were carried out to investigate the material properties of steel tubes. The results are given in the Table 1 and Fig. 1. The 0.2% off-set method is also used for obtaining the yield strength in cases where it is difficult to obtain it.

Table 1. Test results of steel coupon

Specimen type	σ_y (MPa) yield strength	σ_u (MPa) ultimate strength	σ_y/σ_u yield ratio	ε_y (x10^{-6}) yield strain	Lo. (%) elongation
TC-1	315	364	0.83	1465	20.0
TC-2	310	360	0.89	1443	32.2
TC-3	344	396	0.79	1592	40.4
TC-4	364	419	0.87	1768	35.4

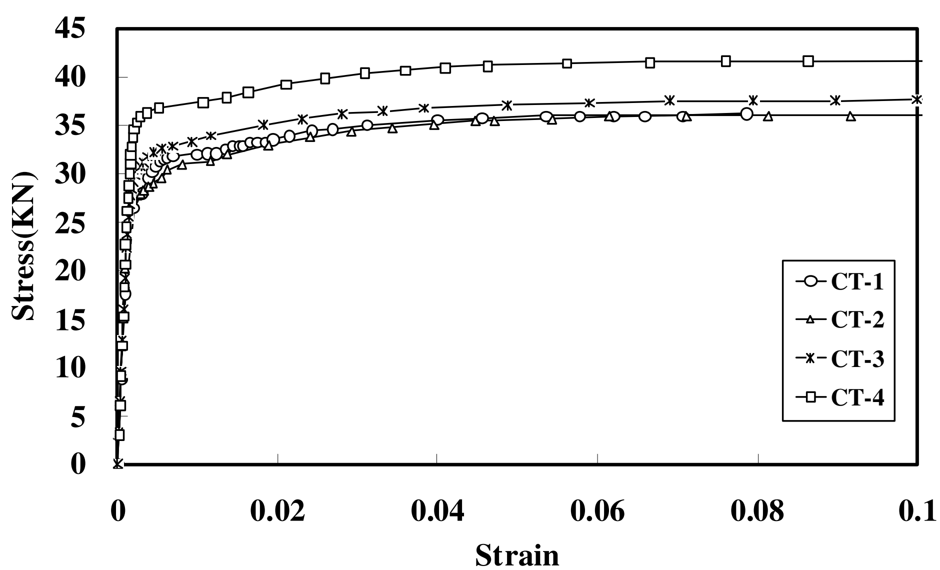


Fig. 1. Stress-strain curves of steel coupon

Concrete cylinder test

Table 2 shows the average compressive strength, f_c, at the time of testing and the average splitting tensile strength to be modified by the standard. The compressive strengths were obtained by testing cylinders having a diameter of 100mm and a height of 200mm. The concrete was poured into all the stub column specimens in the same manner and the compressive strength of concrete was measured to be 15MPa.

Table 2. Test results of concrete cylinders

f_c (MPa) compressive strength of concrete	ε_c (%) maximum strain	E_c (MPa) secant modulus	Slump (mm)
15	0.2	18	124

Test setup and instruments

The ends of the specimens were grouted to ensure a flat surface for axial load transfer. The axial load is applied to the steel and concrete simultaneously. Wire strain gauges and linear variable displacement transducers (LVDTs) were employed to measure the strains and displacements. The strains and displacements were monitored by a data logger having twenty channels. Before applying the main load, preliminary testing was conducted to make sure the monitoring system, was functioning.

Test Results

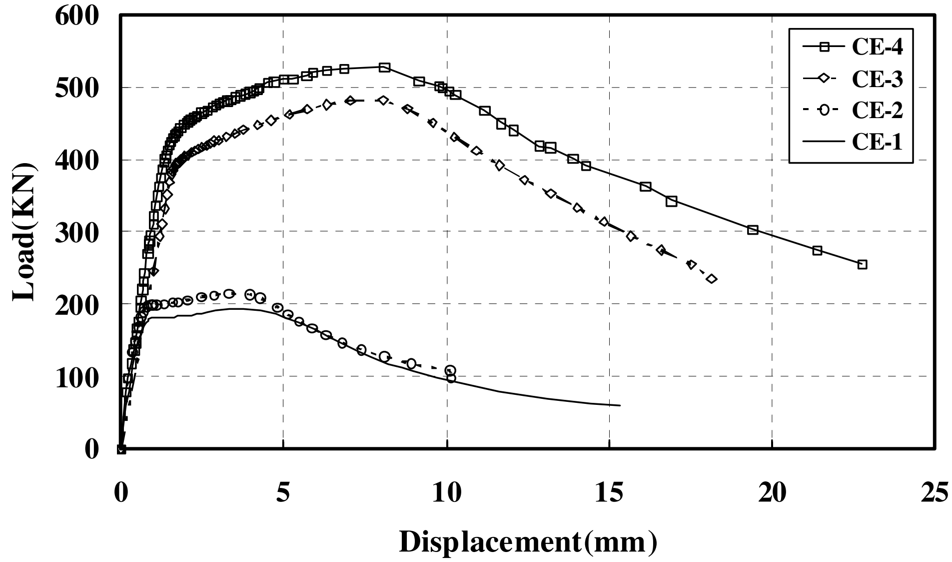
The results of tests are summarized as shown in Table 3. The relationships between applied load and axial strain to be measured at the middle of the tube through the height of the members are depicted in the Fig. 2. In Fig. 2(a) and (b), the hollow circles, diamonds, and squares represent the testing results of the hollow section specimens while the solid ones stand for the concrete filled specimens. The solid line represents specimen CE(F)-1, the dotted line with circles represents specimen CE(F)-2, the dashes and diamond-shapes represent CE(F)-3, and the solid line with squares represents CE (F)-4.

As you can obviously see in Fig. 3, the deformation capacity of the CFT specimens was enhanced very much by filling them with concrete and it gradually increased to the maximum load. All the stub columns filled with concrete belong to failure mode 2 and the tests clearly showed the influence of the concrete filling on the behavior of the stub columns.

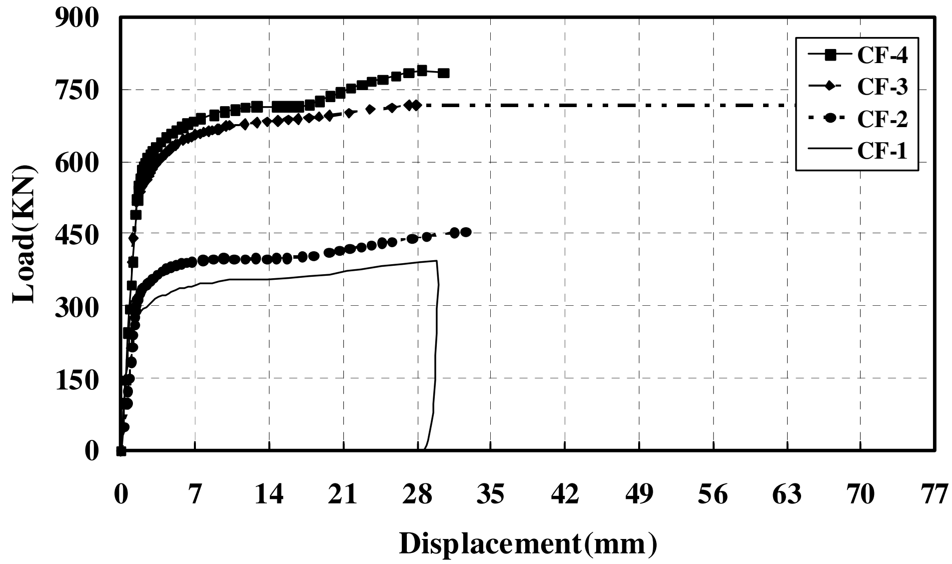
Table 4 and Fig. 4 shows the data for the yield load ratio, the maximum load ratio, and the initial stiffness ratio between the hollow and the filled specimens. The increasing rate of maximum load varies from 1.50 to 2.07 (mean value 1.78), the maximum displacement ratios lie between 3.18 and 8.80 (mean value 5.83), and the initial stiffness ratios vary from 1.13 to 1.75 (mean value 1.79). The rate of ultimate load between hollow and filled specimen is increased in proportion to the diameter to thickness ratio.

Table 3. Test results of stub columns.

Specimens type	${}_s\sigma_y$ (MPa)	${}_eP_y$ (KN)	${}_e\delta_y$ (mm)	${}_eP_{max}$ (KN)	${}_e\delta_{max}$ (mm)	Failure Mode
CE-1	326	180	1.11	192	3.85	1
CF-1		260	1.03	394	29.80	2
CE-2	302	199	1.31	215	3.70	1
CF-2		335	1.95	445	32.46	2
CE-3	321	404	2.54	472	10.26	1
CF-3		564	1.83	717	27.18	2
CE-4	344	441	2.26	525	7.87	1
CF-4		608	1.78	790	28.45	2



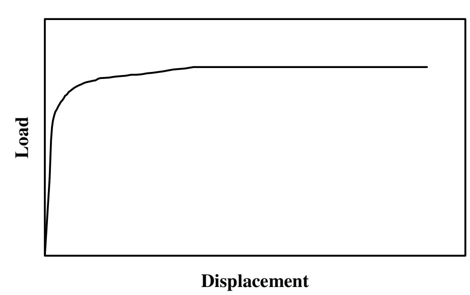
(a) Hollow section specimens



(b) Concrete filled specimens

Fig. 2. Load versus displacement response for test specimens

(a) Mode 1



(b) Mode 2

Fig. 3. Failure modes of test specimens

Table 4. Comparison between hollow section and concrete filled specimens

Specimens	δ_{F_max} / δ_{H_max}	$_eP_y$ (MPa)	P_{F_y} / P_{H_y}	$_eP_{max}$ (MPa)	P_{F_max} / P_{H_max}	K_i (kN/mm)	K_{F_i} / K_{H_i}
CE-1	7.73	180	1.44	192	2.05	163	1.55
CF-1		260		394		253	
CE-2	8.80	199	1.68	215	2.07	152	1.13
CF-2		335		445		172	
CE-3	3.18	404	1.40	472	1.52	231	1.60
CF-3		564		717		371	
CE-4	3.61	441	1.38	525	1.50	195	1.75
CF-4		608		790		341	

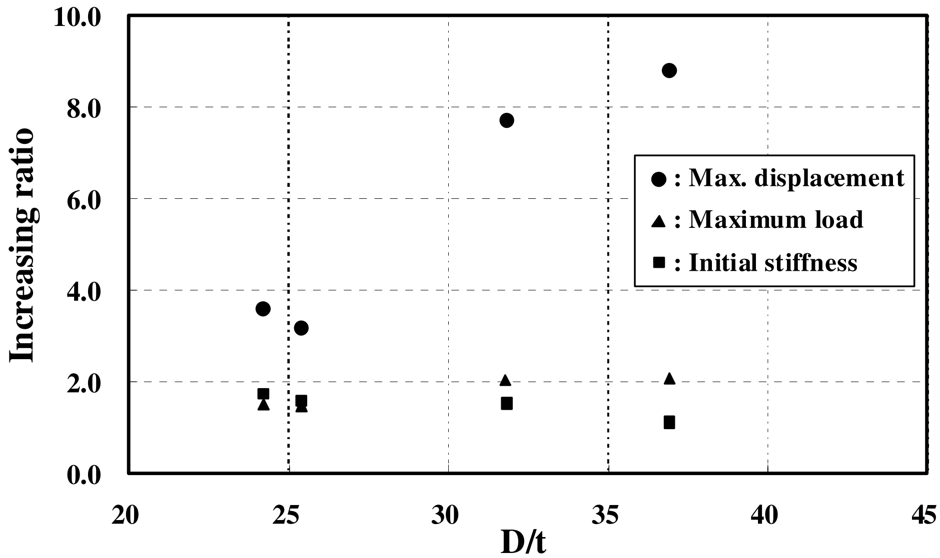


Fig. 4. Comparison of increasing ratio due to filling the concrete and D/t

DISSCUSION

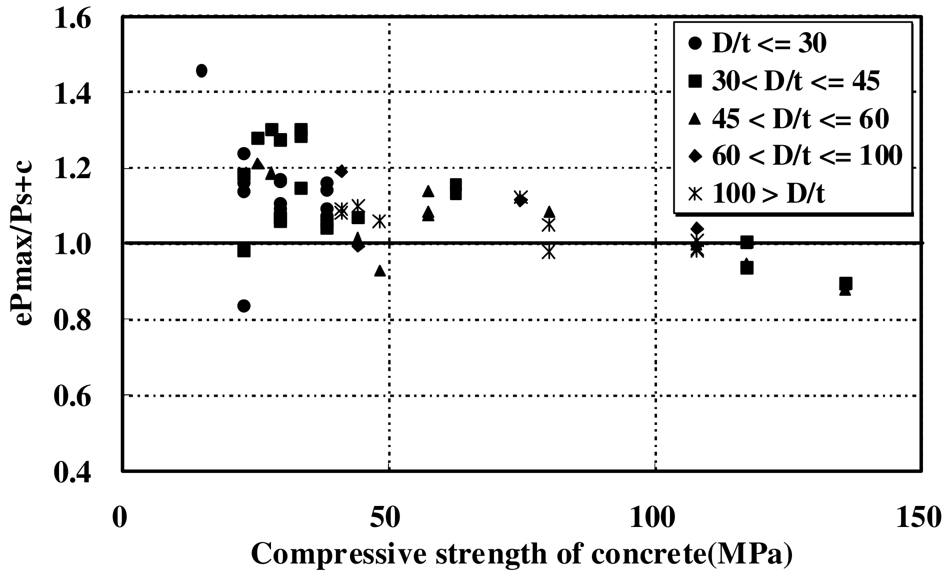
It is evident that the several parameters influence the ultimate strength of the stub columns, both from the results of this study and the other researcher's test results. The strength of concrete to be used in this analysis is from 15MPa to 136MPa, yield strength of steel tube is from 210MPa to 463MPa.

Effects of the material strength on the ultimate strength

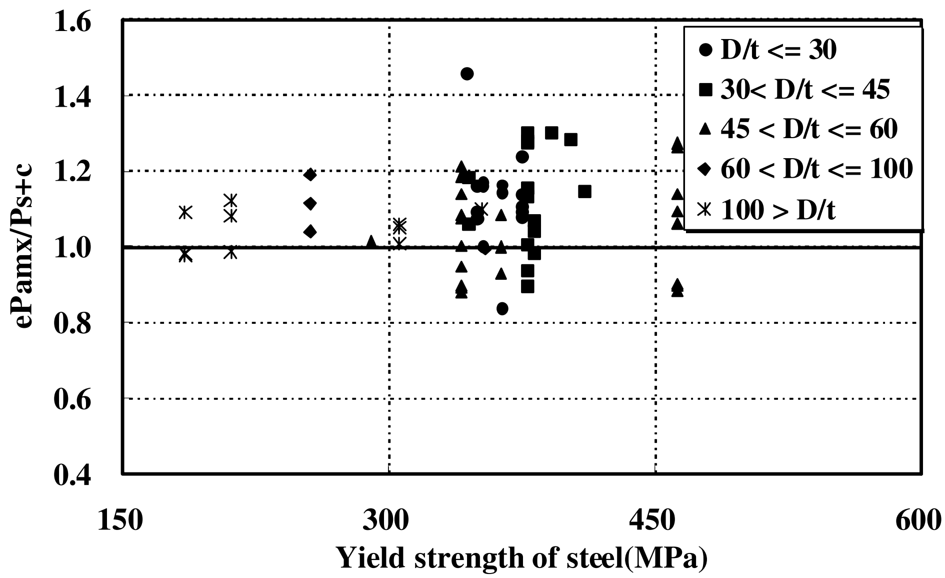
Table 5 shows the strength limit both for concrete and steel suggested in several countries. The shape of the compressive testing mould of concrete in the United Kingdom and China is cubic while that of the other counties is cylindrical. As you can see in Table 5, the strength limits of the two materials were selected within wider ranges in Japan. Some specimens that have a diameter to thickness ratio ranging from 30 to 60 and yield strength between 343MPa and 392MPa are shown to be less than 1.0 as you can see in Fig. 5(a). (Kim [1], Park [2], Russel [3], Saishi [4], Matsui[5])

Table 5. Strength limits both of concrete and steel Unit : MPa

	Japan (AIJ)	China (CASCCS)	USA (AISC)	Canada (CISC)	Europe (EC4)	England (BS5400)
Concrete	18-85	Above 20	21-56	Above 20	21-50	Above 16
Steel	279-833	235-392	Under 379	248-700	235-353	274-353



(a)



(b)

Fig. 5. Relationship between non-dimensional load and material strengths

Limits of diameter to thickness ratio

Many countries have suggested a limit for the diameter to thickness ratio that can carry ultimate compressive load without the local buckling of the steel tube as shown in Table 6. The limit value for a composite axial compressive member using mild steel is a 150% larger value than the hollow section members in Japan. Canada suggests the second largest value among the countries shown in Table 6. As you can see in Fig. 6, the vertical axis represents the non-dimensional load obtained by using a simplified cumulative method ($P_{s+c}=f_cA_c+\sigma_yA_s$), while, on the other hand, the horizontal axis shows the non-dimensional diameter to thickness ratio ($\alpha= (D/t)(\sigma_y/E_s)$). Young's modulus ($E_s$) is assumed to be a value of 206GPa. In some specimens made of normal strength steel tube (SPS400) and high strength concrete over 108MPa, the ratio of non-dimensional strength is less than 1.0. One of the reasons to be considered is the lower Poisson's ratio of high strength concrete compared to normal strength concrete. When high strength concrete used, the volumetric expansion was reduced and, when axial load was applied, the concrete cracked immediately emitting an explosive sound.

Table 6. Limits on diameter to thickness ratio for CFCT column

	Equation	SPS400	SPS490	Unit
Japan(AIJ)	$1.5\times240/F_y$	150	100	$tonf/cm^2$
China(CASCCS)	$85\sqrt{(235/F_y)}$	85	69	N/mm^2
U.S.A.(AISC)	$\sqrt{(8Es/F_y)}$	83	67	ksi
Europe(EC4)	$90\sqrt{(235/F_y)}$	90	70	N/mm^2
U.K.(BS5400)	$\sqrt{(8Es/F_y)}$	83	67	ksi
Canada(CISC))	$28000/F_y$	113	86	MPa
Korea(KSSC)	$240/F_y$	100	67	$tonf/cm^2$

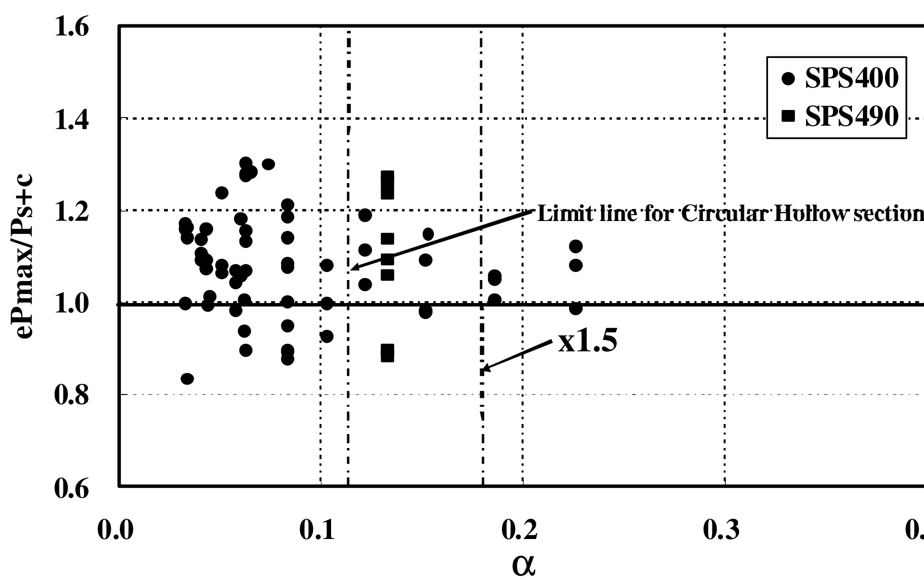


Fig. 6. Relationship between non-dimensional load and α

Relationship between axial stiffness ratio and diameter to thickness ratio

In the elastic range of two materials, the axial stiffness of composite column was assumed as follows:

$$(EA)_{CFT}=E_sA_s+E_cA_c \tag{1}$$

where, E_s=206GPa, $E_c=0.043w_c^{1.5}\sqrt{f_c}$ for normal strength concrete (MPa, ACI 318), and $E_c=3320\sqrt{f_c}$ +6900 for high strength concrete (MPa, ACI 363)

Fig. 7 illustrates the relationship between the axial stiffness ratio and the diameter to thickness ratio. As illustrated in Fig. 7, the axial stiffness of the specimen filled with high strength concrete having a compressive strength of 108MPa was 3.5 times as great as that of the hollow section specimens. In the case of the specimen filled with normal concrete with a compressive strength of 29.4MPa, the ratio of axial stiffness was 2.5.

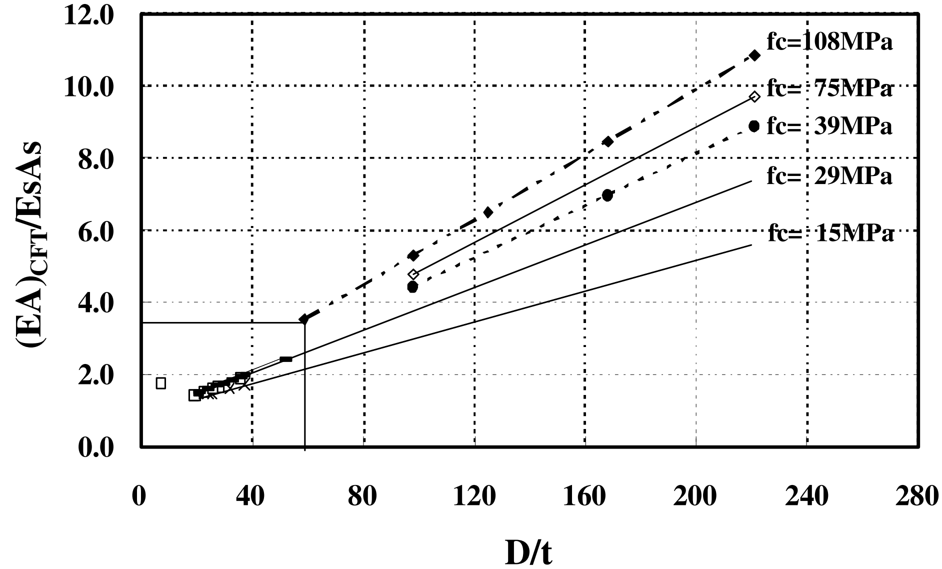


Fig. 7 Relationship between the ratio of axial stiffness and D/t

Coefficient with respect to the confining effect of concrete

The confining effect of concrete is assumed to be the following equation:

$$G_c=[P_{max}-A_s\sigma_y]/[A_cf_c] \quad (2)$$

As shown in Fig. 8, the range of its value is very wide from 0.2 to 3.6. The mean value obtained by using the sixty-six specimens is 1.3. The parameters influencing the confining effect of concrete are the local buckling of the steel tube wall, the strain hardening of the steel tube and the different value of the Poisson ratio according to the concrete compressive strength

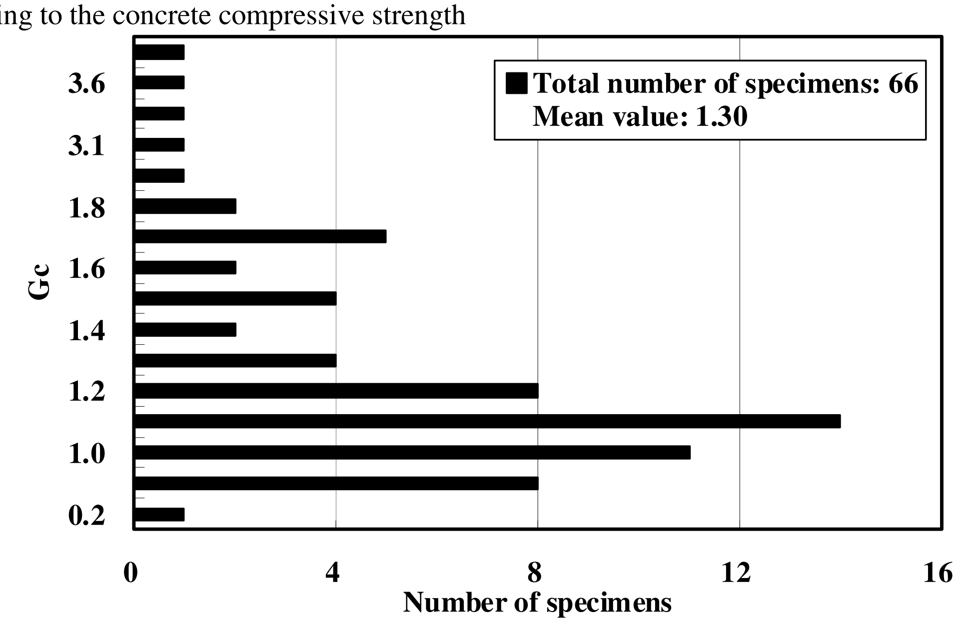


Fig. 8. Relationship between G_c and number of specimens

Estimate of the compressive strength of confined concrete

The compressive strength of confined concrete was defined by the following equation because it is considered to be the stress of concrete at the time when the load-carrying capacity of the CFCT stub column reaches its maximum value.

$$f_{ce}=[P_{max}-(\sigma_u/\sqrt{3})/A_s]/A_c \quad (3)$$

In the Fig. 9, the vertical axis represents the ratio between the compressive strength of confined concrete calculated by equation (3) and that of concrete to be obtained by testing. Using the regressive method, the resulting equation for the confined concrete incased in the steel tube was found to be as follows:

$$f_{ce}=(1.576\rho^{-0.441}) \times f_c, \; R^2=0.9675 \quad (4)$$

where, $\rho = f_c A_c/\sigma_u A_c$, the strength ratio between the steel tube and the concrete.

The above equation can be of wide application to estimate the compressive strength of confined concrete.

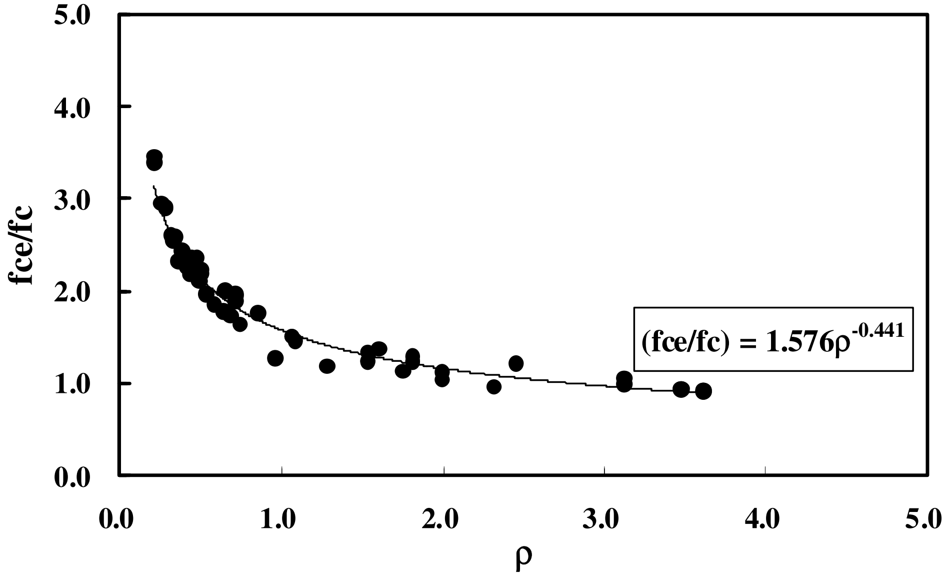


Fig. 9. Non-dimensional compressive load of confined concrete versus ρ

CONCLUSIONS

The following conclusions were drawn from the results of the experimental and analytical study:

1. Maximum load of test specimens both hollow section and filled with concrete was decided by the local buckling of steel tube. In case of the filled specimens, it was not shown a steep declining of load after being reached the maximum point on the load-displacement curves.

2. As the increasing of diameter to thickness ratio, the ratio of initial stiffness was decreased, while both the ratios of ultimate strength and that of maximum strain were increased.

3. From the result of data analysis, the compressive strength of confined concrete can be predicted by the following equation: $f_{ce}=(1.576\rho^{-0.441}) \times f_c$, $R^2=0.9675$

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