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Research and Application of CFT Construction for Overseas Market

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Abstract:

In growing high-rise construction markets in Asia such as Vietnam and surrounding countries, the concrete construction is still dominant over the steel construction, and this market trend is also true to the high-rise buildings with around 30-stories. Considering this market trend, we had focused on Concrete Filled steel Tube (CFT) construction to promote structural steel in those markets; CFT is composed of both structural steel and concrete, and also maintains advantages of both steel and RC construction.

Compression tests of CFT short columns are carried out in Vietnam and the results are reviewed with respect to the design strength according to the international standards such as Eurocode and AIJ, which are widely recognized in those countries. To foresee the applicability in those markets, design studies by Eurocode are carried out for RC and CFT column, and mock-up test of CFT column was also carried out by J-Spiral Steel Pipe.

1. Introduction

The concrete filled steel tube (CFT) structure is a technical term for construction methods that use composite structural members consisting of hollow steel tubes filled with concrete, as illustrated in **Fig. 1**. Concrete has the weakness of brittle behavior in ultimate state, while steel members have the weakness of local buckling in thin-walled sections. CFT members realize excellent strength, rigidity and deformation performance by using a composite structure of these two materials to compensate for these mutual weaknesses[1–4]. The CFT structure is frequently used in combination with steel beams in the framework of buildings, and has been adopted in many high-rise buildings, as a short construction period similar to that of steel frame construction is possible. Due to the rationality and advantages of CFT construction from the viewpoints of both structural design and execution, CFT are widely used as main frame structures in Japan, North America and other regions where structural steel construction has high market penetration.

In Vietnam and other Asian countries, which are enjoying continuing stable economic growth, active development of urban facilities such as high-rise condominiums and office buildings with local or foreign capital is now underway, particularly in urban areas, following earlier improvement of urban infrastructure supported by ODA. However, in those markets, reinforced concrete (RC) construction is mainly selected as the construction method, even for high-rise buildings of around 30 stories. The relatively high cost of steel frame construction has been pointed out as a main reason for the dominant position of RC construction.

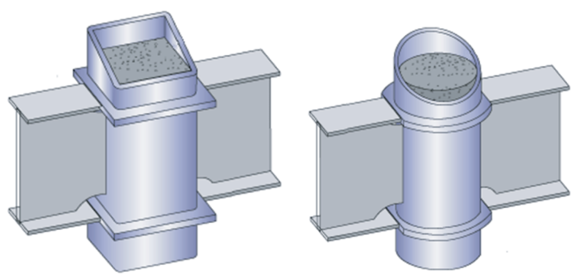

Fig. 1 CFT construction (H beam application)

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Because CFT construction is an intermediate method between concrete construction and steel construction in terms of both the materials used and the cost of those materials, high expectations are placed on CFT as a method that can contribute to rationalization of the structural design and construction of high-rise buildings in Asian markets.

In order to present clear picture of the strength advantages of CFT members, in this paper, the following chapter introduces the strength estimation equations for CFT members in international standards such as Eurocode, AIJ, etc., which are used in the various Asian countries. The results of a short column compression test of CFT that were prepared and tested locally in Vietnam, and the results of a verification of the applicability of the above-mentioned CFT strength estimation equations are also reported.

2. Strength Design Equations for CFT Members

The previous chapter introduced CFT members as a construction method that realizes excellent strength, rigidity and deformation performance by using concrete and steel materials to mutually compensate for the weaknesses of the two materials, particularly brittle fracture and buckling behavior. Since the mutual effect of concrete and steel materials is particularly remarkable in compression members, design equations have been constructed for those members on the assumption that brittle fracture and buckling behavior represent the limit state. The following introduces the design equations for the axial compression strength of CFT provided in various standards. In member design for actual structures, a design that considers overall buckling is generally required as well as ultimate strength of short column in axial compressive members. Here, however, we will focus on short columns, which show the correlation between material characteristics and member strength more clearly.

The following equations (1), (2) and (3) are the axial compressive strength design equations provided respectively in the standards of the Architectural Institute of Japan (AIJ)[5)], American Institute of Steel Construction (AISC)[6)] and Eurocode (EC4)[7)].

$$\text{(AIJ)}\ Pu = As \cdot Fy + (1+\xi) \cdot fc \cdot Ac \quad \text{(1)}$$

$$\text{(AISC)}\ Pu = As \cdot Fy + C_2 \cdot fc \cdot (Es/Ec) \cdot Ar + C_2 \cdot fc \cdot Ac \quad \text{(2)}$$

$$\text{(EC4)}\ Pu = \eta_{ao} \cdot As \cdot Fy + Fyr \cdot Ar + (1+\eta_{co} \cdot (t/d) \cdot (Fy/fc)) \cdot fc \cdot Ac \quad \text{(3)}$$

where,

Fy Design strength of CFT steel tube
Fyr Design strength of inserted steel reinforcement or steel frame
fc Design strength of concrete
Es Young's modulus of steel
Ec Young's modulus of concrete
As Cross-sectional area of CFT steel tube
Ar Cross-sectional area of inserted steel rebar or steel frame
Ac Cross-sectional area of infilling concrete
t Wall thickness of CFT steel tube
d Outer diameter of CFT steel tube
ξ Confinement effect (round steel tube: 0.27, square steel tube: 0.0)
C_2 Shape factor (round steel tube: 0.95, square steel tube: 0.85)

$\eta_{ao} = 0.25 \cdot (3+2 \cdot \lambda)$ [Round steel tube] EC4-eq.6.34
1.0 [Square steel tube]

$\eta_{co} = 4.9 - 18.5 \cdot \lambda + 17 \cdot \lambda^2$ [Round steel tube] EC4-eq.6.35
1.0 [Square steel tube]

$\lambda = \sqrt{N_{pl}/N_{cr}}$ EC4-eq.6.39

Here, the 2nd term in Eq. (1) and the 3rd terms in Eq. (2) and Eq. (3) correspond to the contribution of concrete to compressive strength. Normally, in compressive strength design equations for RC, SRC and other concrete-based members, application of the strength reduction factor 0.85 to the total value of compressive strength $fc \cdot Ac$ is a general rule common to all of the standards. In the case of CFT members, on the other hand, although the manner of expression is different in each standard, a reduction factor of 0.85 or more is applied. In particular, the higher values can be obtained for circular steel tubes, as the values in the respective standards are 1.27 (AIJ), 0.95 (AISC) and $1+\eta_{co} \cdot (t/d) \cdot (Fy/fc)$ (EC4).

Although the axial compressive strength design equations for CFT have been introduced above, it should be noted that higher concrete strength with conventional concrete-based structural systems can be achieved in CFT members by filling the concrete in steel tubes.

3. Short Column Compression test of CFT Column

3.1 CFT Column Test Specimens

Spiral steel pipe manufacturer (J-Spiral Steel Pipe) in Vietnam are currently producing and selling steel pipe piles, steel pipe sheet piles and other pipe products for the markets in Vietnam and other countries, mainly for use in civil infrastructure projects. However, in view of the active construction development in Vietnam in recent years, which includes high-rise buildings, demand for spiral pipes in the building construction

Table 1 CFT Specimen and test results

Specimen #	D (mm)	L (mm)	σc (N/mm^2)	σy (N/mm^2)	εy (%)	Pmax (kN)	εmid_ave (‰)	εmid_ave / εy
D20H501	200	500	Mean 59.98 STD 2.66 Max.64.1 Min.56.2	477	2.327	4 500	32.00	13.8
D20H502	200	500				4 380	29.54	12.7
D20H503	200	500				4 280	17.98	7.73
D25H500	250	500		470	2.293	6 300	29.11	12.7
D25H625	250	625				6 280	22.61	9.86
D25H750	250	750				6 090	11.70	5.10
D30H751	300	750		460	2.244	8 030	21.50	9.58
D30H752	300	750				8 320	18.52	8.25
D30H753	300	750				8 030	26.94	12.0

Remark) σc: Compressive cylinder strength, σy: Yielding tensile strength of steel pipe, εy: Yielding tensile strain of steel pipe
Pmax: Applied maximum force, εmid_ave: Averaged axial strain at mid-point of column height when Pmax loading

field is also expected in the future. Therefore, anticipating the upcoming demands of CFT construction, basic experiments of CFT members have been planned and carried out locally in Vietnam[8)].

Because the purposes of compression tests of CFT columns are to evaluate and confirm the fundamental properties of CFT members constructed at the site, and to verify the applicability of various strength design equations, these experiments were planned as short column compression experiments, which clearly show the correlation between material characteristics and member strength. The dimensions of the pipes for the CFT specimens were the three sizes of 200, 250 and 300 mm shown in **Table 1**. Concrete materials (aggregate, cement, etc.) procured domestically in Vietnam were applied in the fabrication of the specimens so as to represent the actual condition of CFT construction, assuming application of CFT structures in Vietnam.

The infilled concrete of the CFT columns was prepared from local materials corresponding to JIS A 5308 plain concrete (aimed strength: 60 N/mm^2) in terms of aggregate dimensions and slump flow. The maximum dimension of the aggregate material was 20 mm, and the unit water content was 194 kg/m^3. **Photo 1** shows the condition of the slump flow test. The measured value of slump flow was 50 to 60 cm, confirming that the concrete had sufficient workability for use as CFT infilled concrete.

A cylinder compression test was also conducted to confirm the strength development of the filled concrete on site. The specimens were seven cylindrical test pieces with a diameter 100 mm × height 200 mm conforming to ASTM C39, and the compression test was conducted 42 days after concrete casting. In comparison with the target strength of 60 N/mm^2, the test results σ_c for compressive strength were distributed from a minimum value of 56.2 N/mm^2 to a maximum value of 64.1 N/mm^2, as shown in Table 1, confirming sufficient strength.

Photo 1 Slump flow test of concrete

Photo 2 Tensile test specimen of CFT pipe

The base material of the CFT tubes was SM520B with a thickness of 6 mm. Specimens with the three outer diameters of 200, 250 and 300 mm were prepared. A full-thickness tensile test of three specimens of each tube size was carried out in accordance with ASTM E8. **Photo 2** shows the tensile test specimens after the loading test. The average values of the yielding strength σ_y measured in the tensile test are shown in Table 1.

3.2 CFT Short Column Compression Test Specimens and Outline of Test

The geometry of the CFT short column test specimens and the condition of loading and measurement

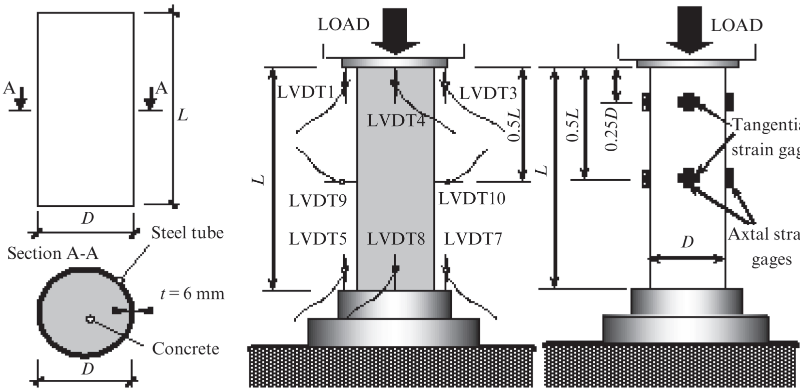


Fig. 2 CFT Test specimen and measurements in compression loading test

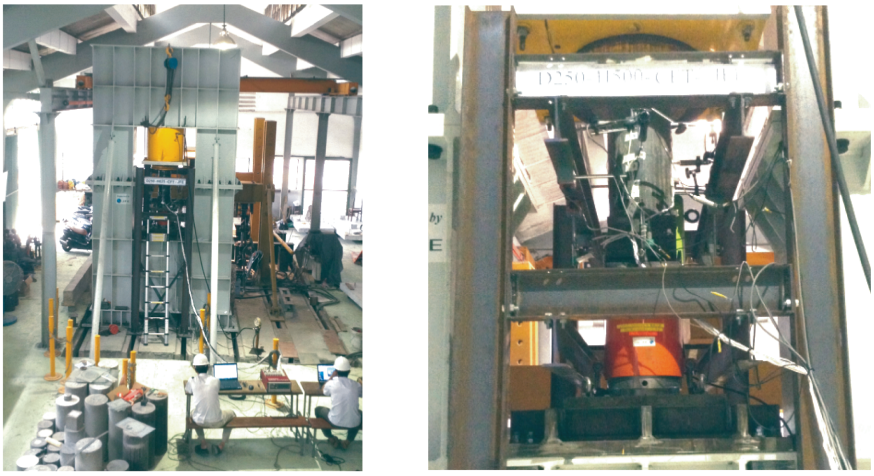


Photo 3 Compression loading test setup

are shown in **Fig. 2**. The test group consists of the nine specimens shown in Table 1. Specimens with three outer diameters, 200, 250 and 300 mm, and a standard diameter/height ratio of 2.5 were tested. Besides, in case of the outer diameter of 250 mm, three diameter/height ratios of 2.0, 2.5 and 3.0 were used. For loading, flatness of contact surface was maintained by grinding the top and bottom surfaces of all specimens.

The loading device used in the compression test and a test specimen set in the test device are shown in **Photo 3**. Loading was applied continuously at a loading rate of 100 kN/min using a 1 500 ton hydraulic jack until collapse occurred. The measurement items in the test were load, displacement and strain of the steel tube. The vertical displacements of the specimens were measured with displacement sensors (LVDT: linear variable displacement transducer) at four points each on the top and bottom faces of the specimens, and horizontal displacements were measured with the same type of LVDT at three points at the specimen center. As the axial strain of the steel tubes, as shown in Fig. 2, the circumferential strains at four points in each measurement cross section were measured at two cross sections, one in the mid-point of the column (0.5 *L*) and the other near the top end (0.25 *D*).

3.3 Test Results

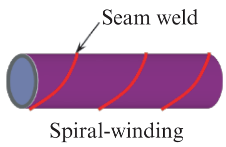
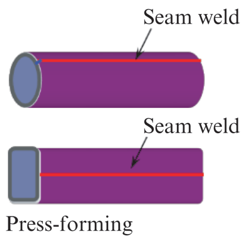
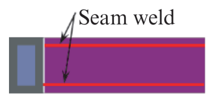
Here, the applied maximum force *P*max, the averaged axial strain εmax_mid at the mid-point of column height under *P*max and the ductility ratio (εmax_mid/εy) under *P*max are presented in Table 1. **Photo 4** shows specimens D20, D25 and D30 after completion

Photo 4 CFT specimen (collapsed)

Table 2 Applied maximum Load (Pmax) and estimated strength according to AIJ, AISC & EC4

Specimen #	*D* (mm)	*L* (mm)	*P*max (kN)	AIJ		AISC		EC4	
				*P*u	*P*max/*P*u	*P*u	*P*max/*P*u	*P*u	*P*max/*P*u
D20H501	200	500	4 500	3 881	1.16	3 327	1.35	4 197	1.07
D20H502	200	500	4 380	3 881	1.13	3 327	1.32	4 197	1.04
D20H503	200	500	4 280	3 881	1.10	3 327	1.29	4 197	1.02
D25H500	250	500	6 300	5 415	1.16	4 697	1.34	5 976	1.05
D25H625	250	625	6 280	5 415	1.16	4 697	1.34	5 821	1.08
D25H750	250	750	6 090	5 415	1.12	4 697	1.30	5 661	1.08
D30H751	300	750	8 030	7 146	1.12	6 262	1.28	7 639	1.05
D30H752	300	750	8 320	7 146	1.16	6 262	1.33	7 639	1.09
D30H753	300	750	8 030	7 146	1.12	6 262	1.28	7 639	1.05

Table 3 Typical line-ups of hollow structural steels and those materials standards & dimensions

Type of product	Spiral-wounded pipe	Press-formed pipe	Welded box
Profile and weld seam			
Material source	Hot-coil	Plate	Plate
Applicable material	JIS G 3444-STK400/490 EN 10219-S355NH etc.	MDCR0003-BCP235/325# EN 10219-S355NH etc.	JIS G 3106-SM490/570 EN 10025-4-S355/S460M etc.
Thickness*	6-25 mm	12-40 mm	19-100 mm
Outer-dimension*	600-2 500 mm	400-1 000 mm	1 000-1 500 mm

* Typical values or specifications, not necessarily represents the market available products.
#MDCR0003-BCP235/325 is a construction material standard established by Japan Iron and Steel Federation.

of the test. Appearance of local buckling on the surface of the steel tube was observed in all test specimens, as shown in Photo 4, and the results confirmed that the ductility ratio under maximum loading exceeded 5 in all specimens, thus confirming stable load-bearing performance.

Table 2 shows the ultimate strength (*P*u) predicted by the AIJ, AISC and EC4 strength design equations, which are presented together with the test results. Here, in designing ultimate strength by the respective design equations, the design strengths of the concrete and steel (*f*c, *F*y) were calculated using the material test results (σc, σy). Table 2 also shows the ratio (*P*max/*P*u) of the experimental and estimated values. As shown in the table, the results for all specimens confirmed that the maximum load exceeded the design value of predicted strength according to the above-mentioned three standards. It may also be noted that the EC4 gives a higher estimated strength than the other standards, because EC4 considers the confinement effect (ηao, ηco) corresponding to the width/thickness ratio of the steel tube. However, even in this case, the experimental values exceeded the estimated values, confirming appropriate strength development in concrete and steel.

4. Design Study of CFT Columns

This chapter examines the suitable products and standards for local use in Vietnam from the viewpoint of availability of CFT steel tube materials. Focusing on columns as the object of study, the following introduces the results of a design study of RC construction, which is currently the dominant method in Vietnam, and CFT construction as the object of comparison.

Table 3 shows examples of the hollow structural steels that can be applied as CFT steel tubes. Because the base material and the range of outer dimension sizes and thicknesses are different for each product, it is necessary to select a product suitable for the intended application. On the other hand, since product standards are also closely related to availability, it is impor-

Table 4 EC4 design study of CFT vs. RC column

	RC column	CFT column (Square)	CFT column (Circular)
Column profile (rebar)	1 600×1 600 mm (60−$D$32/$SD$345)	1 080×1 080 mm Fire protect & finish (50 mm)	D = 1 100 mm Fire protect & finish (50 mm)
Steel profile	-	BOX-980×980×26 mm/Fy = 440	ϕ-1 000×25 mm/Fy = 440
Concrete	C30/37	C30/37	C30/37
Partial factor γ	γc = 1.5/γs = 1.15/γk = 1.0	→	→
Design strength	(Axial) 57 200 kN	(Axial) 60 900 kN	(Axial) 57 500 kN ※Assuming λ = 0.2
Occupied area	2.56 m^2	1.17 m^2(Area saving 1.39 m^2) ⇒ [Rent increase] 1.39×15USD×12×10yr≒$2 500	0.95 m^2(Area saving 1.61 m^2) ⇒ [Rent increase] 1.61×15USD×12×10yr≒$3 000
Steel amount	379 kg/m	779 kg/m (+400 kg)	601 kg/m (+222 kg)

tant to check the standards that can actually be supplied by the vendor (manufacturer). In particular in Vietnam, the availability of spiral pipes (Spiral-wounded Pipe) and square box-shaped pipes is good, as manufacturers have already set up local production operations.

The following presents an example of a design study comparing an RC column and CFT columns using the above-mentioned spiral pipes and square box pipes as the pipe materials. Taking an RC column with outside dimensions of 1 600 mm × 1 600 mm as an example, **Table 4** shows the results of a trial calculation for two types of CFT columns (Square box, Spiral pipe) for which equivalent axial compressive strength could be confirmed. For consistency in the designs compared here, the Eurocode standard was applied to both the RC column and the CFT columns. EC2[9] was applied to the RC column, and EC4 (Eq. 1.3) was applied to the CFT columns. As assumptions of the trial calculation, concrete strength of C30/37, SD345 rebars and Fy = 440 N/mm^2 class steel (EN-10025-4-S460M, SM570, etc.) were applied. In the outer diameter dimensions (Column profile) of the CFT columns in the table, the trial calculation considered a surface fire protection covering layer with a thickness of 50 mm. The table shows the calculated occupied area or cross-sectional area (depending on the column). As shown in table, it can be understood that the cross-sectional areas of the CFT columns are less than 1/2 that of the RC column.

Next, the following shows the results of a study of the column size reduction effect from the viewpoint of economic rationality. Since substituting CFT columns for RC columns has the effect of reducing the column section, in other words, increasing the effective floor area, the economic effect can be evaluated based on the rent per unit area. Table 4 shows an example of a trial calculation assuming the rent per unit area is US$15/m^2/month and the effect continues for 10 years. The results show that the rent increase is $2 500/column with the square box column and $3 000/column with the spiral pipe column. As a cost increase factor, the increased amount of steel makes a large contribution to increased costs when CFT is used; the increase of the steel amount in this trial calculation was considered to be approximately 200 to 400 kg/m/column.

For simplicity, the preceding discussion focused only on the loaded axial force and axial compressive strength. However, in high-rise buildings, there is also a design trend toward larger girder spans, and in such cases, the additional bending force transferred from the girders becomes a critical factor in designing the member section. Substituting CFT for conventional RC columns has a large effect in increasing strength, particularly for bending strength, and as a result, the cross section reduction effect of CFT becomes even larger, and a higher effect of substituting CFT can be achieved.

In this section, a comparative design study of an RC column and CFT columns was conducted and the results were discussed. However, as described above, the advantages of adopting CFT can be clearly realized by confirming the design conditions (e.g., design geometry and bearing load of members) in each project, and selecting and judging the most effective locations for adoption of CFT, for example, use in the lower stories or in columns surrounding an atrium.

5. Conclusion

Because the CFT structure is simpler and faster in execution of construction work and has higher member strength, recently adoption of CFT has been studied from the viewpoint of total cost of construction in various projects in Asia where a large number of high-rise condominium and office buildings has been developed and constructed rapidly. Among those, CFT columns tends to be actually adopted particularly in projects in

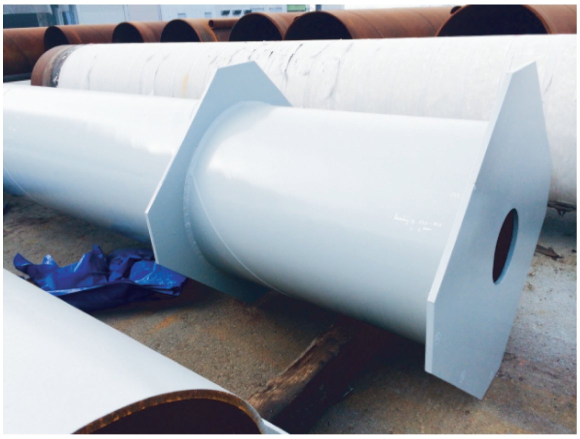


Photo 5　CFT Mock-up fabricated by J-Spiral Steel Pipe

which columns have excessively large outer profiles so as to fit the profile into the design and planning requirements. On the other hand, there are also issues from the viewpoint of popularization of CFT construction, as design engineers generally lack technical information related to the design and execution of CFT structures.

Recently, J-Spiral Steel Pipe Co., Ltd., a spiral pipe manufacturer in Ho Chi Minh City with capital participation by JFE Steel Corporation, had studied application of CFT columns in an airport terminal in Vietnam to which the company's products were adopted. **Photo 5** shows a CFT mock-up fabricated by J-Spiral Steel Pipe for verification of buildability. Lastly, in order to contribute to rationalize the construction of high-rise buildings in the Asian countries, and to realize wider application of CFT and steel frame constructions in the future, JFE Steel shall ever continue to promote CFT structures, and add more supply records and application patterns of CFT.

Acknowledgements

The structural performance verification of the CFT columns described herein was conducted as joint research with Prof. Ngo-Huu Cuong of Vietnam National University, Ho Chi Minh City — University of Technology. Mr. Yasushi Wakiya, the former General Director of J-Spiral Steel Pipe, also provided valuable cooperation in the fabrication of the CFT column steel frames. We wish to take this opportunity to express our deepest appreciation to all those concerned.

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