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Concrete-Filled Steel Tube Column System-Its Advantages

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Abstract

A concrete-filled steel tube (CFT) column system has many advantages compared with ordinary steel or reinforced concrete system. One of the main advantages is the interaction between steel tube and concrete: occurrence of the local buckling of steel tube is delayed by the restraint of concrete, and the strength of concrete is increased by the confining effect provided from the steel tube. Extensive research work has been done in Japan over the last 15 years, including "New Urban Housing Project" and "US-Japan Cooperative Earthquake Research Program, in addition to the work done by individual universities and industries, which has been presented at the annual meeting of Architectural Institute of Japan (AIJ). This paper introduces the merits, design provisions and recent construction trends of CFT column systems in Japan, and discusses the results of trial designs of CFT theme structures which have been carried out to look for the advantages in the performance and construction cost compared with other constructional system.

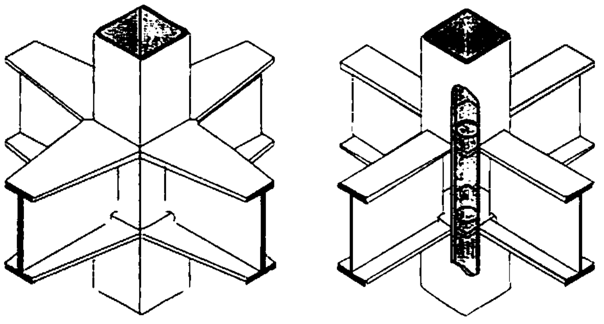
Key words : CFT, column, advantages, cost merits, US-Japan program

1. Introduction

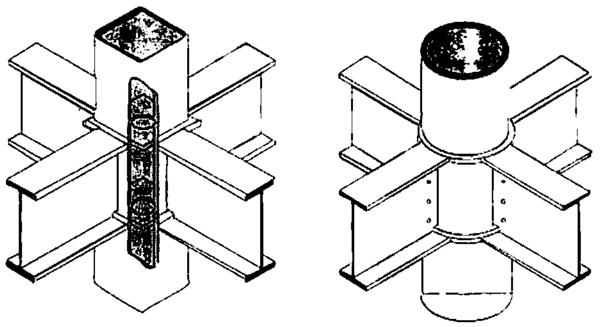
A framing system consisting of concrete-filled steel tube (CFT) columns and H-shaped beams has become very popular, of which typical connections between a CFT column and H-shaped beams often used in Japan are shown in Fig. 1. Beam-to-Column connections are all fabricated by shop welding, and the beams are bolted at site to the brackets. In the case of connections using inner and through-type diaphragms, the diaphragm plates are located inside the tube, and a hole is opened for concrete casting, while there is no object sticking inside the tube to interfere smooth casting of concrete, in the case of ring stiffener and outer diaphragm. Cast steel ring stiffener is used for a circular CFT column.

Bare and embedded type column bases shown in Fig. 2 are usually used in the CFT column system, and the structural reliability of the latter is much higher than that of the former. When the building has the basement stories, the CFT column section is converted to the concrete encased cross-H section at the first story of the basement as shown in Fig. 2 in cases.

This paper first describes the advantages in view of structural performance and constructional efficiency, then introduces the recent situation of research and construction, and finally discusses the cost merits of CFT column system.



Outer diaphragm Inner diaphragm



Through-type diaphragm Ring Stiffener

Figure 1. Beam-to-column connections.

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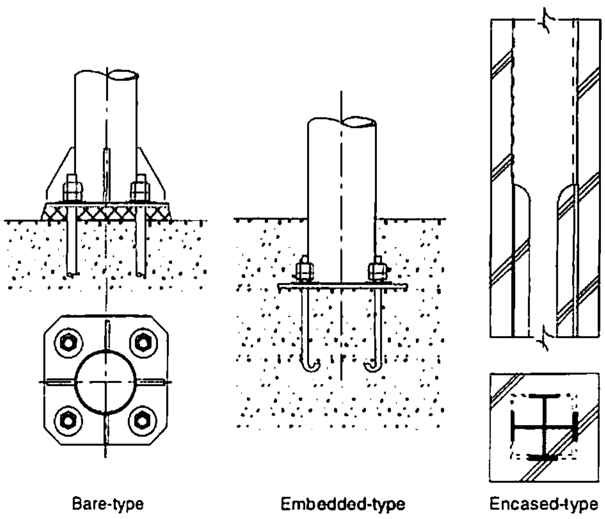


Figure 2. Column bases.

2. Advantages of CFT Column System

CFT column system has many advantages compared with ordinary steel or reinforced concrete system. The main advantages are listed below.

Interaction between steel tube and concrete:

i) The occurrence of the local buckling of the steel tube is delayed, and the strength deterioration after the local buckling is moderated, both due to the restraining effect of concrete.

ii) The strength of concrete is increased due to the confining effect provided from the steel tube, and the strength deterioration is not very severe, since the concrete spalding is prevented by the tube.

iii) Drying shrinkage and creep of concrete are much smaller than ordinary reinforced concrete.

Cross-sectional properties:

iv) The steel ratio in the CFT cross section is much larger than those in the reinforced concrete and concrete-encased steel cross sections.

v) Steel of the CFT section is well plastified under bending since it is located on the outside the section.

Construction efficiency:

vi) Forms and reinforcing bars are omitted, and concrete casting is done by tremie tube or pump-up method, which lead to savings of manpower and constructional cost and time.

vii) Constructional site remains clean.

Fire resistance:

viii) Concrete improves the fire resistance performance, and the amount of fireproof material can be reduced or its use can be omitted.

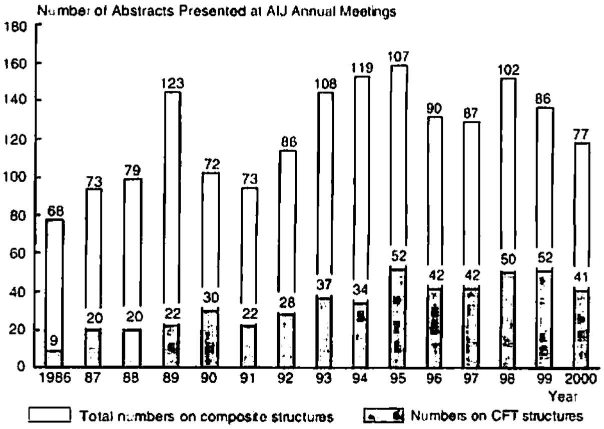


Figure 3. Number of abstracts presented at AIJ annual meetings.

Cost performance:

ix) Because of the merits listed above, a better cost performance is obtained by replacing a steel structure by a CFT structure.

Ecology:

x) Environmental burden can be reduced by omitting the form work, and by reusing steel tubes and high-quality concrete as recycled aggregates.

The cost advantage of CFT column system against other structural systems will be discussed later in more detail. One weak point of the CFT system is the compactness of concrete around the beam-to-column connection, especially in the case of inner and through-type diaphragms, in which the gap between concrete and steel may be produced by the bleeding of the concrete underneath the diaphragm. There is no way so far to assure the compactness and to repair the deficiency, and thus it is common construction practice to cast a high-quality concrete with low water-content and good workability by the use of a superplasticizer.

3. Research and Design Recommendations for CFT Column System

3.1. Activities in Architectural Institute of Japan

The number of abstracts of technical papers on CFT column system presented at the annual meeting of Architectural Institute of Japan (AIJ) has been increasing every year, and more than 40 abstracts have been presented recent years, as shown in Fig. 3. They have dealt with the following items: i) axial compressive stress-strain relations of concrete and steel tube, ii) moment-curvature relation, iii) ultimate strength, load-deformation relation and deformation capacity of a CFT beam-column, iv) buckling strength of a CFT compression member, v) bond strength between concrete and steel tube, vi) field tests of concrete casting, and vii) case study of CFT column systems. Table 1 indicates the research items in the categories of structural mechanics, constructional effi-

Table 1. Research items in abstracts at AIJ annual meeting.

Structural mechanics	Constructional efficiency	Fire resistance	Structural planning
Axial load carrying capacity Flexural strength Buckling strength Deformation capacity Stiffness Post-local buckling behavior Confining effect Stress transfer mechanism at beam-to-column connection	Compactness of concrete Concrete mixture Concrete casting method Reduction of construction time	Strength under fire Amount of fire-proof material	Application to high-rize building Application to long-span building

Table 2. Scope of research projects on CFT column system.

Project	New Urban Housing project	U.S.-Japan Cooperative project
Shape of tube	□ ○	□ ○
Number of specimens	Centrally-loaded stub columns □ : 24 ○ : 24 Beam-columns under combined load □ : 19 ○ : 19	Centrally-loaded stub columns □ : 45 ○ : 45 Eccentrically-loaded stub columns □ : 32 ○ : 32 Beam-columns under combined load □ : 20 ○ : 13 Beam-to-column connection □ : 6 ○ : 4
Tensile strength of steel σ_u (N/mm^2)	500, 600	400, 600, 800
Compressive strength of concrete F_c (N/mm^2)	26, 44, 62	20, 40, (80), 90
Diameter-thickness ratio	□ : 18-56 ○ : 15-67	□ : 19-74 ○ : 17-152
Axial load ratio*1	0.3, 0.5, 0.7	0.2, 0.4, variable*2

*1: ratio to squash load *2: varying between tensile load ratio-0.3 and compressive load ratio 0.7

ciency, fire resistance, and structural planning.

Provisions for the design of CFT structures have been included in SRC Standards of AIJ[1], and then CFT Recommendations[2] were published by AIJ in 1997, based on the recent research developments, which are characterized by covering following topics: i) special type of CFT members such as braces and truss members, in addition to compression members, beam-columns and connections, ii) formulas to evaluate deformation capacity of CFT columns and frames, iii) structural characteristics under fire, iv) manufacturing of steel tube and mixture of concrete, v) analysis of the behavior of CFT columns and frames, and vi) strength formulas used in the world. Confining effect on concrete is not considered in this recommendation.

3.2. New Urban Housing Project

In 1985, the Ministry of Construction, Japan, requested proposals for the structural system for urban type of apartment houses for the 21st century. The CFT column system was accepted, which was jointly proposed by 5 general contractors and a steel manufacturer. Since then, a series of experimental investigation, so-called "New Urban Housing Project (NUHP)", has been started by these industries and the Building Research Institute of the Ministry of Construction. This project covered the tests of centrally-loaded stub columns and beam-columns under combined axial force, bending and shear. Table 2 shows the number of specimens and test parameters.

The results of investigation carried under NUHP were published in CFT Reports[3], and it has been used for the design of CFT system. This report was the first document that allowed to count the strength increase of confined concrete of circular CFT's, and provided formulas to evaluate the deformation capacity. Evaluation of the deformation capacity of CFT columns is needed to calculate the structural characteristic factor D, used in seismic design. In 1996, those industries that originally joined NUHP established the Association of New Urban Housing Technology. The Association consists of more than 100 member companies that are related to the building construction, and authorizes the structural design of newly-planned CFT buildings according to the Association's CFT Recommendations[4].

3.3. U.S.-Japan Cooperative Earthquake Research Program

5-year research project on composite and hybrid structures started in 1993 as the 5th phase of the U.S.-Japan Cooperative Earthquake Research Program, and the program was organized into the following 4 groups: CFT column system; reinforced concrete column+steel beam system; hybrid wall system; and research for innovation of new materials, elements and systems. The program of the Japanese side for CFT system consists of the following topics. i) Experimental study: Centrally-loaded stub

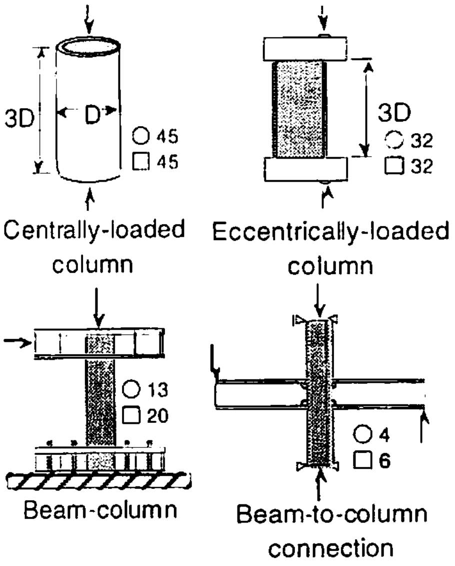


Figure 4. Tests of CFT elements.

columns, eccentrically loaded stub columns, beam-columns, and beam-to-column connections were tested to clarify the synergistic interaction between steel tube and concrete and stress transfer mechanism, and to derive methods to evaluate stiffness, strength and ductility of CFT elements and systems. The number of specimens and test parameters are shown in Fig. 4 and Table 2. The unique feature of this test program was that it covered the high-strength materials, such as 800 MPa steel and 90 MPa concrete, it covered large D/t ratio, and some of the beam-column specimens were tested under the variable axial load. ii) Database: Test data of CFT beam-columns and frames were collected from the Japanese literature published in 1971 through 1995, and a database was developed and maintained. A total of 589 test data (test specimens) were found: 353 beam-columns (242 square and 111 circular) and 236 frames (184 square and 52 circular). iii) Trial design: Trial designs were performed for 10, 24 and 40 story braced and unbraced building frames using CFT column system, to look for the merits of employing CFT system, by comparing constructional costs and structural performance with those of ordinary steel and reinforced concrete systems. iv) Design guidelines: Guidelines to the structural design of CFT column system were developed from the experimental investigation. The results of the CFT investigation were presented in Refs. [5-8], and an outline of the guidelines is given below.

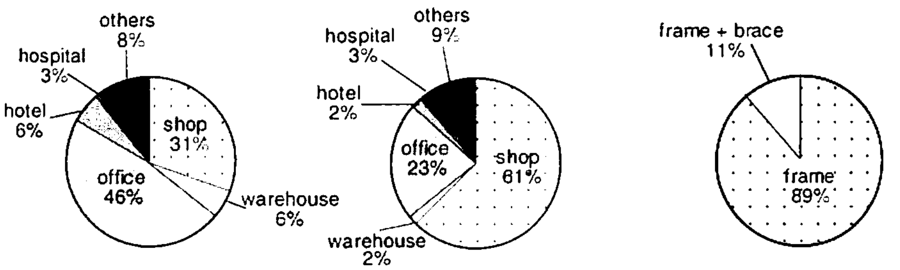
CFT investigation carried in the 5th phase of the U.S.-Japan Cooperative Earthquake Research Program produced CFT Guidelines[9]. In Chap. 2, the scope of the guidelines is shown together with the flow charts for the seismic design, based on the conventional method using the structural characteristic factor D_s, and performance-based design method which is specified in the recent revision of the Building Standard Law of Japan. Chapter 3 presents the constitutive laws for concrete and steel tube derived from the test results of centrally-loaded stub columns, method of analysis for the moment-curvature relation, method of analysis for the load-deformation of a beam-column under combined axial force, bending and shear, and model for the restoring-force characteristics of a beam-column which may be used in the analysis of an overall CFT frame. This chapter also provides the formulas to evaluate the stiffness, ultimate strength and deformation capacity of CFT beam-columns. These formulas are newly developed, and the ultimate strength formulas take into account the confining effect on concrete, triaxial state of stress in the steel tube, and local buckling of the steel tube. First two sections of Chapter 4 deal with the connection between a CFT column and an H-shaped steel beam, in which the structural behavior of the connection is discussed in view of the test results, and the design considerations are shown especially on the stress transfer mechanism around the connection. The strength formulas for the shear panel are based on a framing action consisting of tube walls and diaphragms, and diagonal strut of concrete. The connection between a brace and a CFT frame and the column base were not included in the program of investigation, and thus only the design considerations and details usually used in the practice in Japan are described in the last two sections of Chapter 4. Chapter 5 describes material, manufacturing and fabrication of steel tube, concrete mixture and casting. As indicated before, it is most important to cast the concrete with low water-content and high workability in the CFT construction. Chapter 6 shows a design example for an 11-story office building, written for the beginners of designing the CFT column system. Two appendices show the results of the investigation by the trial design of CFT column system, and a reference list of the name of the specimens and test parameters.

4. Recent Construction of CFT Column System

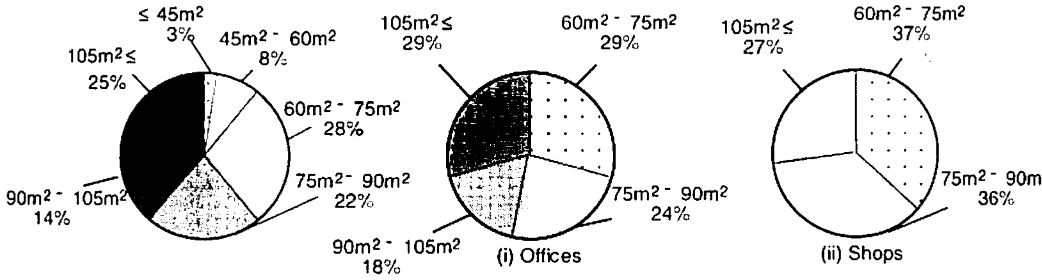
4.1. Questionnaire Investigation on the Construction of CFT Column System

An investigation on the design and construction of CFT column systems was carried out in 1990 by questionnaires sent to general contractors, engineering offices, fabricators and steel manufacturers[10]. This investigation is a little old, but the situation is still almost the same. The results of the investigation by questionnaires are as follows.

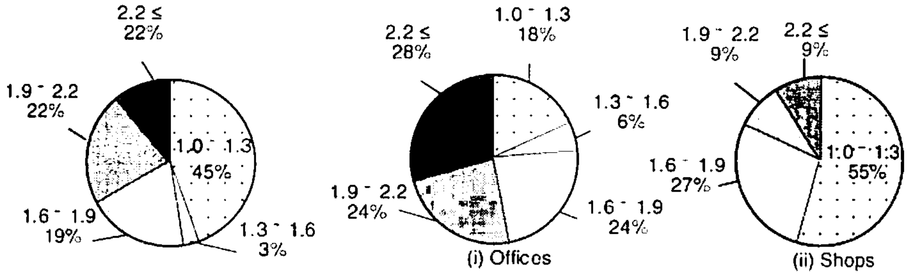
The use of concrete-encased-and-filled steel tubular columns was very few. The use of CFT structures was not limited, but they were mainly used for office and hotel construction. It was not very common to use a structural wall in CFT structures. The merits of CFT structures compared with other structural systems were applicability to high-rise and long-span structures, improvement of stiffness, and construction efficiency, that is the savings of construction cost, time and man-



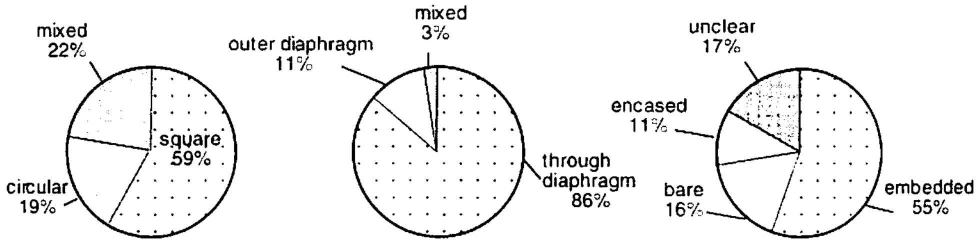
(a) Number of Constructions and Use (b) Total Floor Area and Use (c) Type of Structural Frames



(d) Floor Area Carried by One Column (e) Floor Area Carried by One Column of Offices and Shops



(f) Aspect Ratio of Span Grid (g) Aspect Ratio of Span Grid of Offices and Shops



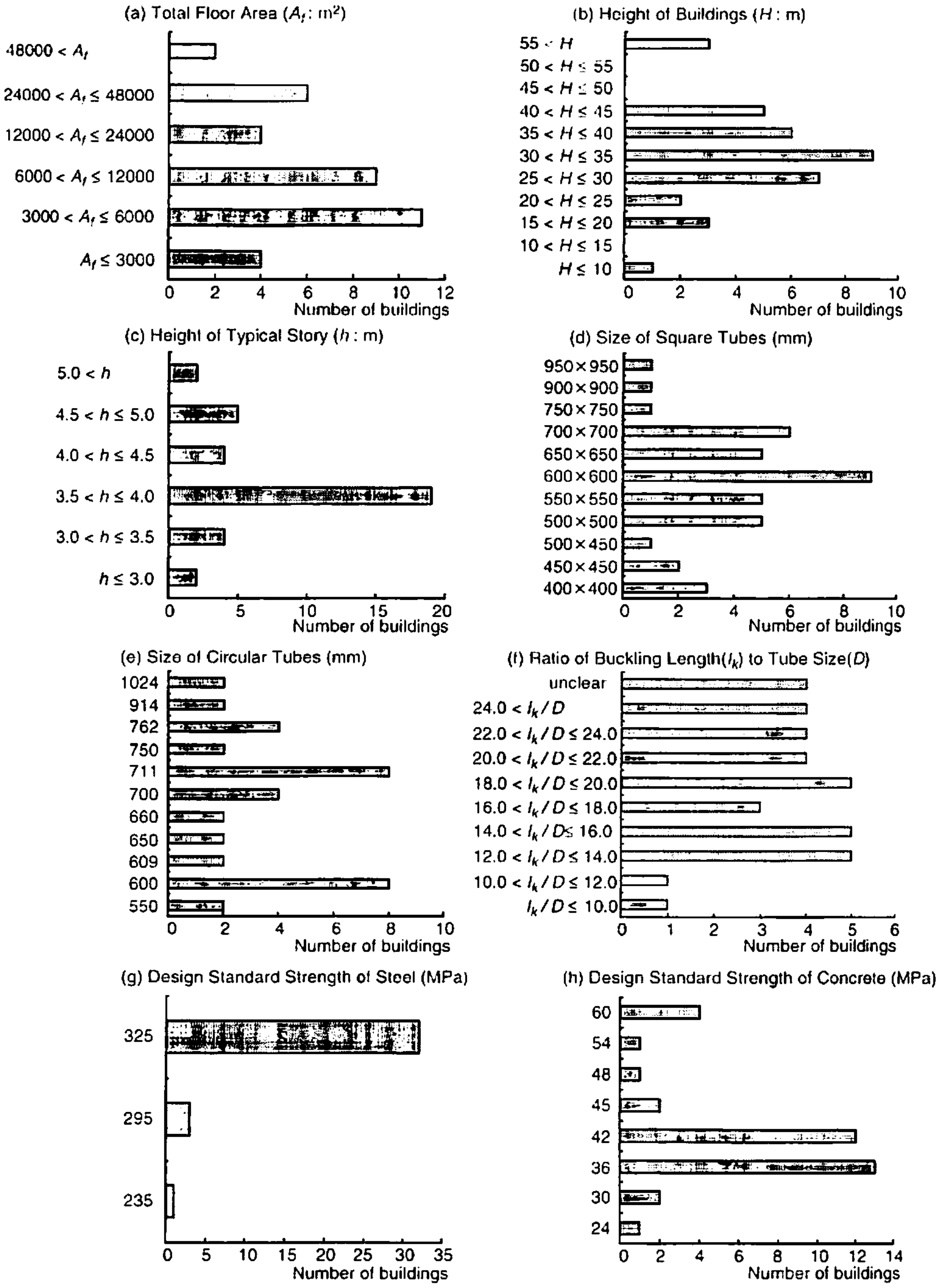
(h) Shape of Steel Tubes (i) Type of Beam-to-Column Connections (j) Type of Column Bases

Figure 5. Construction data in 1999: structural planning.

power. Stiffness and strength of CFT column and strength of beam-to-column connection were evaluated by the method of superposition according to SRC Standards[1] in most cases. Increase of concrete strength due to confining effect and deformation capacity of CFT column were counted according to CFT Report[3]. In some cases, the concrete was counted only for the stiffness. The structural performance of CFT structures was evaluated by SRC Standards[1] in most cases.

Square and circular tubes were evenly used for CFT structures. Circular tubes (diameter of 450 to 1000 mm, diameter-thickness ratio of 17 to 65) were used for the building with irregular plan grid, and square and rectangular tubes (width of 400 to 900 mm, width-thickness ratio of 10 to 54) were used for the case of regular plan. Most tubes were cold-formed, which were inexpensive and widely available in the market. Box sections built-up by welding were used when the plate became thick and/or large ductility was required. Cast-steel tube was used to simplify the beam-to-column connection. Annealing to remove residual stresses were rarely done in Japan.

The types of diaphragm of the beam-to-column connection are shown in Fig. 1, and seemed to be determined according to plate thickness of the column and the beam: through-type diaphragm was often employed when the beam plate was thicker than the column plates, and otherwise inner diaphragm was employed. This tendency led to the use of through-type diaphragm for cold-formed tubes, and inner diaphragm for built-up tubes. Outer diaphragm was used as an easy solution to assure



(a) Total Floor Area (A_f: m^2)

(b) Height of Buildings (H: m)

(c) Height of Typical Story (h: m)

(d) Size of Square Tubes (mm)

(e) Size of Circular Tubes (mm)

(f) Ratio of Buckling Length(l_k) to Tube Size(D)

(g) Design Standard Strength of Steel (MPa)

(h) Design Standard Strength of Concrete (MPa)

Figure 6. Construction data in 1999: properties of CFT columns.

concrete compactness of CFT. Through-type usually had an opening with diameter of 200 to 300 mm for concrete casting, with several small holes for air passage. Beam-to-column connections were built-up by welding flanges and welding or bolting webs.

Design standard strength of concrete was between 20.6 and 26.5 MPa (210 and 270 kgf/cm^2) in most cases, which may be because SRC Standards[1] limit the concrete strength at 26.5 MPa, and it is required to obtain an administrative permission for the construction if the concrete strength exceeds 35.3 MPa (360 kgf/cm^2). The maximum strength found in the answers to the questionnaire was 85.3 MPa (870 kgf/cm^2), of which concrete was compacted by the centrifugal method and cured by autoclave. Special consideration was given to the mix proportion of concrete in 80% of the cases answered: Air entraining high-range water reducing agent was often used to obtain good workability of concrete with low water content. Concrete was cast by pumping-up method or by the use of tremie tube in most cases, and the casting height was about 30 m in the former case and about 10 m in the latter. In about 50% of the cases answered, the efficiency of the casting method was confirmed by the experiments. The construction technique is well established with real construction experiences of high-rise buildings taller than 100 m.

Structural characteristic factor D_s was determined according to the rank of beams, since the frame was usually proportioned so that the frame would fail with plastic hinges forming in beams prior to columns. However, the engineers thought that D_s should be determined according to the overall characteristics of the frame. The restoring-force characteristics for the dynamic analysis of the frame were assumed to be a tri-linear type, which modeled the load-deformation relation obtained from the incremental analysis assuming bi-linear characteristics for CFT columns and steel beams. Viscous damping was often assumed to be proportional to the frequencies, and the critical damping ratio was taken equal to 2%. Design criteria were usually set as follows: elastic response and story drift angle not greater than 1/200 under the seismic input of level 1 which corresponds to a moderate level of earthquake; and story drift angle neither greater than 1/100 nor greater than 2 times the elastic limit under the seismic input of level 2 which corresponds to a severe earthquake.

4.2. Construction Data in 1999

As indicated in Section 3.2, the Association of New Urban Housing Technology (ANUHT) was established in 1996. Since then, the Association has been inspecting the structural design, including fire resistance, of newly planned CFT structures, and authorizing the construction of those structures. In addition to these inspection works, the Association provides CFT construction technology concerning structural design and construction at site, educates the companies that are newly joined to the Association, and promotes the research on the CFT system. The construction data in 1999 given below has been provided by the Association.

A total of 36 CFT buildings were inspected by the Association in 1999, and their statistical details are shown in Figs. 5 and 6. The following observations are made from the data:

i) Among 36 buildings, 13(36%) are shops and warehouses (Fig. 5(a), (b)). Application of CFT to those buildings has increased in comparison with the results of questionnaire investigation in 1990. This indicates building designer's recognition to the spannability of the CFT system. The CFT system is quite often applied to the buildings of rather large scale (Fig. 6(a)~(c)).

ii) CFT system is not very often applied to braced frame type buildings. It may not be necessary to use the braces, since the tube section has identical strength and stiffness in both x- and y-directions (Fig. 5(c)).

iii) The floor area carried by one column is much larger than that in the ordinary reinforced concrete or pure steel buildings. Particularly in the case of about 30 % of office and shop buildings, the floor area exceeds 105 m^2, which emphasizes the application of CFT system to the long-span buildings (Fig. 5(d), (e)).

iv) Variety of the aspect ratio of span grid indicates the CFT's possibility of free planning about the span grid (Fig. 5(f), (g)). The aspect ratio here indicates the ratio of the longer distance between two columns to the shorter one in x- and y-directions of a floor plan.

v) Both square and circular column sections are mixedly used in a number of buildings (Fig. 5(h)). The size of tube section often used is between 500 and 700 mm in the case of square CFT's (Fig. 6(d)), and 600 and 711 mm in the case of circular CFT's (Fig. 6(e)). The value of diameter or width -to-thickness ratio scatters between 16 and 50 in the case of square tubes, and 19 and 57 in circular tubes.

vi) Through-type diaphragms are used for the beam-to-column connection in most cases (Fig. 5(i)).

vii) Embedded-type column bases are most popularly used, which is the best in view of the structural reliability (Fig. 5(j)).

viii) Ratio of the effective column length l_k to the tube size D of the CFT column is much larger than that in ordinary reinforced concrete or pure steel buildings (Fig. 6(f)). This indicates CFT's large bearing capacity for the axial load.

ix) Design standard strength of concrete often used is 36 and 42 MPa, and that of steel is 325 MPa (Fig. 6(g), (h)).

5. Trial Design of CFT Column System

5.1. Theme Structures and Trial Design

Theme Structures

In order to look for the merits of CFT column system, trial designs were performed for unbraced building frames using this system. Theme structures treated here are 10, 24 and 40-story unbraced building frames made of CFT or Steel (S) system, as shown in Fig. 7. A typical floor plan is shown in Fig. 8, which is common for all six theme structures designed. CFT or S is used for columns and H-shaped steel is used for beams. All beam-to-column connections are designed as moment connections, and thus moment resisting frames are used for both inte-

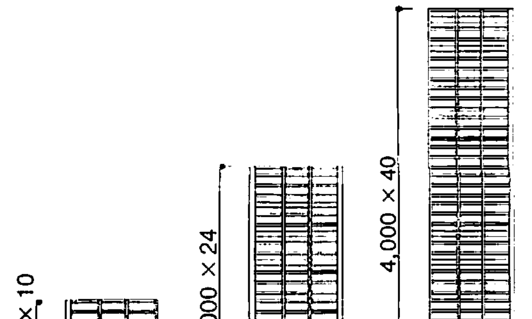


Figure 7. Framing elevations.

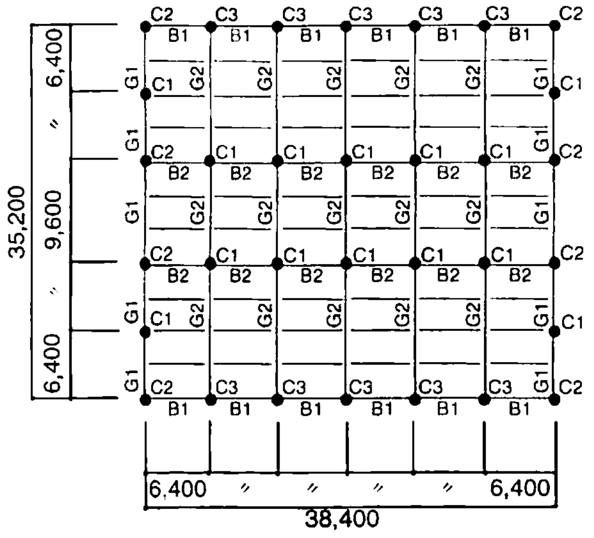


Figure 8. Framing floor plan.

rior and exterior frames. The structural design was mainly based on the design provisions in Structural Requirements of Building Center of Japan (BCJ)[11] and CFT Guidelines[9]. All frames were first designed by the allowable stress design against the seismic shear force under moderate earthquake, and the ultimate horizontal strength was calculated by the pushover analysis, and it was verified that the strength of each story exceeded the required value. In the course of design, each member was proportioned in such a way that the plastic hinges mainly formed in beams, and the columns remained elastic until the mechanism state was reached, except for a few cases such as the column bases in the 1st story.

Load Conditions

Table 3 shows the intensities of gravity loads, which are normally employed in the design practice of a typical office building in Japan, and Table 4 shows the intensity of gravity load calculated for each story indicated, which is used for the seismic design, and the shear force acting in each story Q determined from the Japanese regulations[11].

Design Conditions

In a conventional seismic design of a building structure, the concept of weak beam and strong column has been adopted to avoid energy concentration to a specific story. Thus, the following design conditions were adopted in this study: i) The ratio of the stress in the column caused by the design load to the allowable stress was kept as near to 0.8 as possible, and that of the beam as near to 1.0 as possible; ii) Story drift angles were kept within about 1/200 under the design load in the allowable stress design; and iii) The collapse mechanism at the ultimate state was the overall frame mechanism in which the plastic hinges formed only in beams, and all columns remained elastic except for the specific part such as the bottom ends of columns in the 1st story.

Member Proportions

Table 5 shows the list of members for 40-story frames proportioned by the design conditions described above. The material strength employed were as follows: yield strength of steel=325 MPa, compressive strength of concrete=36 MPa for 10-story building, and 72 MPa for 24- and 40-story buildings, respectively.

5.2. Characteristics of Designed CFT and Steel Frames

Push-Over Analysis

In order to check the structural characteristics of the designed frames, the elasto-plastic pushover analysis was

Table 3. Design loads.

	Gravity load			Seismic load	
	Dead load (N/m^2)	Live load (N/m^2)		Fram	Base shear coefficient
		For vertical	For seismic	10-story fram	0.20
Roof	5190	1270	590	24-story fram	0.12
Office	2940	1760	780	40-story fram	0.10

Table 4. Gravity and seismic loada of 40-story frames.

Floor	CFT-40					S-40				
	W	W/A	ΣW	C	Q	W	W/A	ΣW	C	Q
40F	11.2	8.3	12.5	0.480	6.0	9.6	7.1	11.8	0.469	5.5
30F	11.5	8.5	125.1	0.204	25.5	10.1	7.5	109.5	0.205	22.5
20F	11.8	8.7	241.5	0.155	37.4	10.4	7.7	212.1	0.156	33.0
10F	12.0	8.9	360.6	0.123	44.5	10.7	7.9	318.3	0.124	39.4
2F	12.2	9.0	470.0	0.100	47.0	11.1	8.2	417.7	0.100	41.8

W: Gravity load of each story (MN), W/A: Gravity load per unit floor area (kN/m^2), ΣW: Total gravity load supported by the story (MN), C: Shear coefficient in each story, Q: Shear force in each story (MN), Q= CΣW

Table 5. List of members of 40-story frames.

(a) List of beams

	Beam list for CFT-40		Beam list for S-40	
Floor	B1	B2	B1	B2
R-34F	BH-800x250x16x28	BH-800x250x16x28	BH-800x250x16x28	BH-800x250x16x28
33-26F	BH-900x300x16x36	BH-900x300x16x36	BH-900x300x16x36	BH-900x300x16x36
25-2F	BH-900x450x16x36	BH-900x400x16x36	BH-900x400x16x36	BH-900x400x16x36
	G1	G2	G1	G2
R-34F	BH-800x300x16x28	BH-800x300x16x28	BH-800x300x16x28	BH-800x300x16x28
33-26F	BH-900x350x16x36	BH-900x350x16x36	BH-900x350x16x36	BH-900x350x16x36
25-2F	BH-900x400x16x40	BH-900x400x16x40	BH-900x400x16x40	BH-900x400x16x40

(b) List of columns

	Column list for CFT-40			Column list for S-40		
Story	C1	C2	C3	C1	C2	C3
40-33th	ϕ900x19	ϕ900x19	ϕ900x19	ϕ900x25	ϕ900x25	ϕ900x25
32-25th	ϕ900x22	ϕ900x22	ϕ900x22	ϕ900x32	ϕ900x32	ϕ900x32
24-17th	ϕ900x25	ϕ900x25	ϕ900x25	ϕ900x36	ϕ900x36	ϕ900x36
16-9th	ϕ900x28	ϕ900x50	ϕ900x40	ϕ900x40	ϕ900x60	ϕ900x50
8-1th	ϕ900x32	ϕ900x70	ϕ900x60	ϕ900x45	ϕ900x90	ϕ900x70

performed for each frame with the following treatments and assumptions: i) bending and shear deformations were considered for all members, and axial deformations for columns, in addition; ii) floor of each story was assumed as a rigid horizontal diaphragm; iii) stiffness of CFT columns was calculated as a simple sum of stiffness of steel and concrete; iv) moment-rotation relation assumed for beam-ends was normal bi-linear, which changed the stiffness at the full plastic moment, having the second stiffness equal to 1/100 of the first; and v) moment-rotation relation assumed for column-ends was normal tri-linear[9], which changed the stiffness at yield moment and at the full plastic moment. 3-dimensional analysis by stiffness matrix method was used.

Weight and Stiffness

Weight and stiffness of 40-story frames are shown in Table 6, which reveal the following characteristics: i)

Table 6. Weight and stiffness of 40-story frames.

Story	System	Section	For unit column			For story		
							Shear stiffness	
			Weight (kN)	EA (kN)	EI (kN · cm^2)	Weight (MN)	X (kN/cm)	Y (kN/cm)
33th	CFT	ϕ900x19	68.8	3.13E+07	2.00E+10	11.2	1.07E+04	1.03E+04
	S	ϕ900x25	21.2	1.41E+07	1.35E+10	9.7	8.33E+03	8.11E+03
	CFT/S		3.25	2.21	1.48	1.16	1.29	1.27
25th	CFT	ϕ900x22	70.6	3.27E+07	2.13E+10	11.5	1.63E+04	1.55E+04
	S	ϕ900x32	26.9	1.80E+07	1.69E+10	10.1	1.33E+04	1.28E+04
	CFT/S		2.63	1.82	1.26	1.14	1.23	1.21
17th	CFT	ϕ900x25	72.3	3.41E+07	2.25E+10	11.8	2.04E+04	1.91E+04
	S	ϕ900x36	30.1	2.01E+07	1.88E+10	10.4	2.24E+04	1.66E+04
	CFT/S		2.4	1.69	1.2	1.13	1.16	1.15
9th	CFT	ϕ900x28	74.1	3.54E+07	2.38E+10	12	2.44E+04	2.26E+04
	S	ϕ900x40	33.2	2.22E+07	2.06E+10	10.7	2.24E+04	2.08E+04
	CFT/S		2.23	1.59	1.15	1.12	1.09	1.09
1st	CFT	ϕ900x32	76.3	3.72E+07	2.54E+10	12.2	3.32E+04	3.26E+04
	S	ϕ900x45	37.2	2.49E+07	2.28E+10	11.1	3.11E+04	3.06E+04
	CFT/S		2.05	1.5	1.11	1.1	1.07	1.07

EA: axial stiffness, EI: bending stiffness

Table 7. Story drift angle of 40-story frame under the design load (%).

Story	CFT		S		CFT/S	
	X	Y	X	Y	X	Y
40th	0.283	0.290	0.340	0.343	0.83	0.84
30th	0.443	0.460	0.488	0.500	0.91	0.92
20th	0.478	0.505	0.498	0.523	0.96	0.97
10th	0.460	0.498	0.448	0.480	1.03	1.03
1st	0.353	0.360	0.335	0.340	1.05	1.06

weight of CFT columns: CFT/S=2.1~3.3; ii) cross-sectional axial stiffness: CFT/S=1.5~2.2; iii) cross-sectional bending stiffness: CFT/S=1.1~1.5; iv) story weight: CFT/S=1.1~1.16; and v) story shear stiffness: CFT/S=1.1~1.3.

Story Drift

Story drifts of 40-story frames under the design load are shown in Table 7. Story drifts of CFT frame in lower stories are larger than those of S frame, while the former becomes smaller than the latter in upper stories. Figure 9 shows each story displacement of CFT frames and components caused by the bending and shear deformations of beams and the bending, shear and axial deformations of columns. It is observed from Fig. 9 that 60 to 70% of the total story displacement is caused by the beam deformation and the rest is caused by the column deformations in all cases of 3 frames analyzed. The proportion of axial deformation of the column to the total story displacement increases as the number of story increases, and it becomes as large as 30% in the case of 40-story frame.

Table 8. 1st natural period.

Frame	Systen	Tx (sec)	Ty (sec)
10-story frame	CFT	1.37	1.42
	S	1.39	1.43
	CFT/S	0.99	0.99
24-story frame	CFT	2.64	2.71
	S	2.70	2.75
	CFT/S	0.98	0.98
40-story frame	CFT	3.73	3.80
	S	3.72	3.80
	CFT/S	1.00	1.00

Table 9. Absorbed energy.

Story	Systen	Ex (MJ)	Ey (MJ)
9th	CFT	1.87	1.79
	S	1.76	1.66
	CFT/S	1.06	1.08
2nd	CFT	2.15	2.10
	S	2.08	2.03
	CFT/S	1.04	1.04

Natural Period

Natural periods were calculated by the elastic eigenvalue analysis of the lumped mass model with 3 degrees of freedom, which modeled the designed frame. The stiffness in each story was determined from the full stiffness matrix in the elastic range obtained in the pushover analysis. Table 8 shows the 1st natural period of vibration. There is only 2 % difference between CFT and S systems. This is because the weight ratio and the lateral stiffness ratio between CFT and S systems are almost the same.

Absorbed Energy

Figure 10 shows the relations between the story shear Q and the story drift δ at 2nd and 9th stories of 40-story frames. Table 9 shows the energy absorbed until the drift angle reaches 1/100, which is the area enveloped by the Q-δ curve, the horizontal axis and the vertical line at the drift angle of 1/100. The following observations are

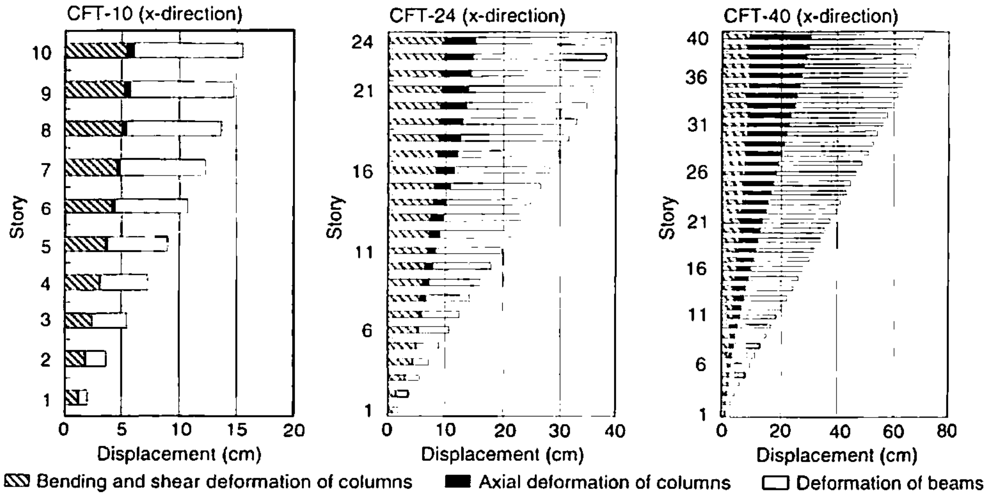


Fig 9. Proportions of each story displacement caused by beam and column deformations.

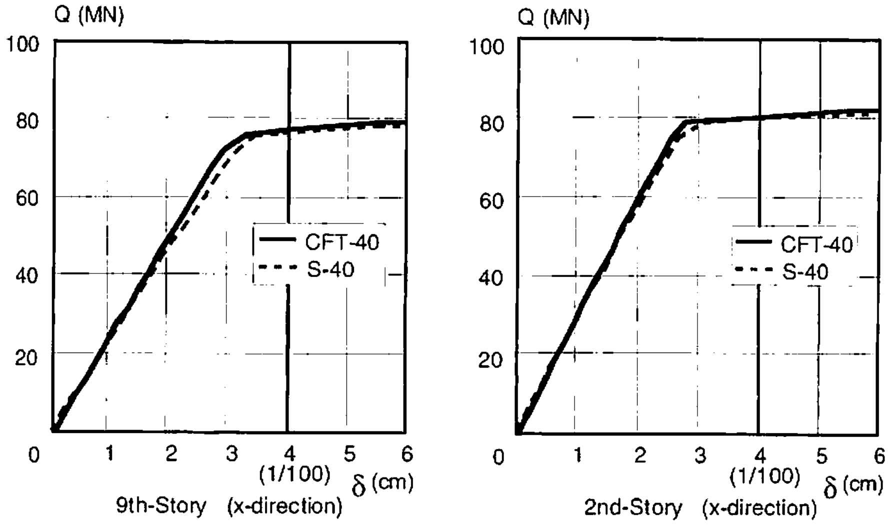


Figure 10. Load-deflection relations of 40-story frames.

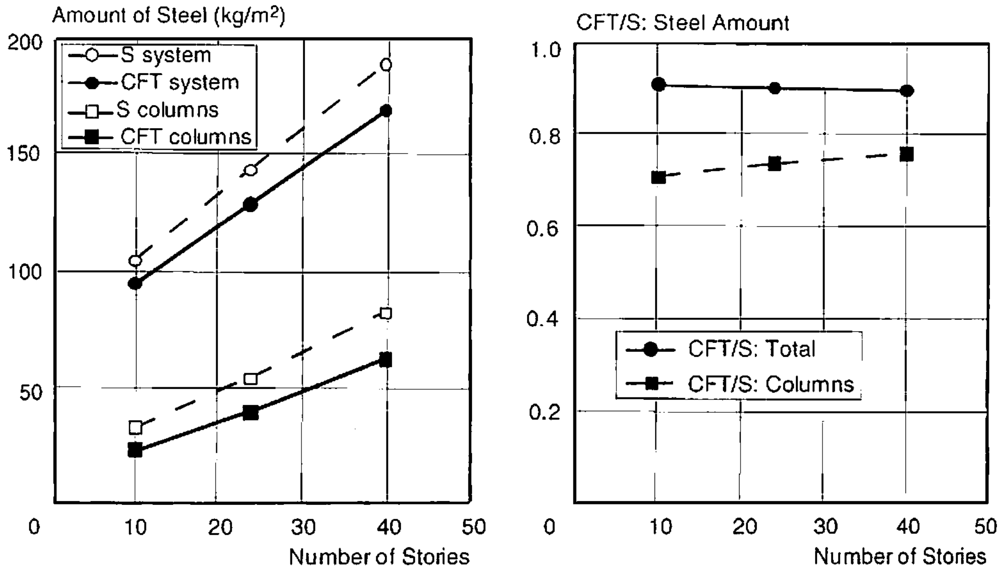


Figure 11. Comparison of steel amount between CFT and steel frames.

made: i) Yielding story shear forces of CFT and S systems are almost the same, because the overall frame mechanism with beam hinges was adopted; and ii) Energy absorbed in one story of the CFT system at drift angle 1/100 is larger by 4 to 8% than that of the S system.

5.3. Amount of Steel and Cost Estimation

Amount of Steel

Figure 11 shows the comparison of steel amount per unit floor area used for the CFT and S systems, and its ratio. Total steel amount includes steel used for the columns, beams and sub-beams for entire building. Plates and bolts for connections and reinforcing bars for floor slabs, foundation beams and footings are not included, which may be almost the same in both the CFT and S systems. The following results were obtained: i) total steel amounts per unit floor area of the S frames were 105 kg/m^2 for the 10-story frame, 143 kg/m^2 for the 24-story frame and 189 kg/m^2 for the 40-story frame. These numbers are within a reasonable comparable range compared with those in the existing buildings; ii) steel amount of CFT columns is less by about 25% than that of S columns, and the total steel amount of the CFT system is less by about 10% than that of the S system.

Cost Estimation

Table 10 shows a cost estimation of main frames including columns, beams and sub-beams. The unit cost was assumed to be 250,000 Japanese yen per ton for steel, and 35,000 yen per cubic meters for concrete. These unit costs include materials, fabrications, transportation, and constructions. The cost merits provided from the savings in the construction time and manpower were not precisely considered, but it is observed that: i) cost of the CFT main frames is lower by 5 to 7% than that of the S frames; ii)

Table 10. Cost estimation of main frames.

Frame	Systen	Amount of steel (t)	Amount of concrete (m^3)	cost (Japanese yen)
10-story frame	CFT	1283	454	336,640,000
	S	1414	0	353,500,000
	CFT/S	0.91	-	0.95
24-story frame	CFT	4186	1379	1,094,765,000
	S	4653	0	1,163,250,000
	CFT/S	0.9	-	0.94
40-story frame	CFT	9148	2905	2,388,675,000
	S	10221	0	2,555,250,000
	CFT/S	0.9	-	0.93

total building cost for the CFT system would be lower by 1 % than that of the S system, if the cost of main frame structure is assumed to occupy 15% of the total building cost; and iii) as the number of stories increases, the cost merit of the CFT system becomes larger.

6. Concluding Remarks

Rational design method for the CFT column system has been established through extensive research done by Architectural Institute of Japan, New Urban Housing Project and U.S.-Japan Cooperative Earthquake Research Program, and several design standards, recommendations and guidelines are available. However, a review of recent developments on the research, design and construction of the CFT column system has revealed that the experimental study on the behavior of brace-to-CFT frame connection, column base, and braced and unbraced CFT frames are still needed, of which results will refine the design provisions. The overall behavior of the CFT system must be assured by the frame tests.

Recently, more than 40 CFT buildings have been constructed every year in Japan, and it has been known that the CFT structures are mainly used for office, hotel and shop constructions, and the merits of CFT structures compared with other structural systems were applicability to high-rise and long-span structures, improvement of strength and stiffness, and construction efficiency that is the savings of construction cost, time and manpower.

Comparison of CFT and S systems based on the results of trial designs showed that the structural characteristics of both systems were almost the same, but the total steel consumption of the CFT system for entire building was about 10% less than that of the S system, which lead to more advantageous cost performance of the CFT than S systems. However, these trial designs have been done only for the case of CFT application to unbraced frames. It is needed to investigate the performance of other type of structural system, such as the combination of CFT column system with reinforced-concrete structural shear wall, which may provide more merit.

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