RESEARCH ON CTF COLUMN SYSTEMS

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SUMMARY

` Concrete filled steel tubes (CFT) offer numerous advantages for seismic resistant design. CFT provides large axial stiffness and load capacity. The steel confines the concrete and significantly increases stiffness and resistance. The concrete fill restrains local buckling of the tube, and increases member ductility, while permitting more slender steel elements. Unfortunately, there also are severe limitations in the application of CFT, because the behavior of CFT elements is quite different than steel or concrete elements. Further, connections between CFT columns and steel members are also different than those used in ordinary steel construction. The US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures was started within this context, and CFT was one of 4 focus areas in this program. The goals of the research program were to develop practical guidelines so that structural engineers in both the US and Japan can understand and economically use CFT for seismic design. These goals were to be achieved through experimental and analytical research.

The Japanese research emphasized the strength, ductility and behavior of CFT members and the internal diaphragm connections. Japanese studies included development of a database of past research results and testing to evaluate 3-dimensional behavior and biaxial bending of CFT elements. However, the bulk of the Japanese research considered CFT columns under concentric and eccentric loading of both rectangular and circular tubes under a wide range of material properties and column slenderness ratios. US research emphasized connection details which are practical for US construction. In addition, studies of the resistance and ductility of CFT members and the bond stress transfer and composite action for CFT elements were completed. Several typical connection systems, which appear to be most practical for the US and which provide good seismic performance, are noted. Design guidelines are being developed in both countries. These are discussed, and the economic consequences of using CFT columns are noted. Some differences and similarities between the US and Japanese guidelines and results are explained

INTRODUCTION

Composite and hybrid structures offer many advantages for seismic design. They significantly increase the strength and stiffness of the building at little increase in cost. These systems require that dissimilar materials work together to fully develop these benefits. Many buildings constructed in the US and Japan have used various forms of composite and hybrid construction, but little research has been done to understand their performance. Further, building design standards and specifications provide little guidance to engineers using these forms of composite and hybrid construction. The US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures was started to address these research issues and to develop guidelines and recommendations for using these buildings in engineering practice. This was the 5th Phase of this international cooperative program.

Several planning meetings for this cooperative research program were held during 1992, and a comprehensive planning workshop was held in Berkeley, CA, in September of that year [Goel and Yamanouchi (1992).USJTCC

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(1992)]. Researchers and practicing engineers from the US and Japan discussed the state of existing knowledge and determined the questions that must be addressed if composite and hybrid systems are to be used more effectively in seismic design. A five year research program was planned about 4 major research groups. The groups were New Materials Elements and Systems, Concrete Filled Tube (CFT) Column Systems, Reinforced Concrete Column/Steel Beam (RC/S) Systems, and RC/SRC Wall Systems. This paper describes the efforts of the CFT group. Each group built its plans and efforts about a series of theme structures which focused the research on the questions that were important for seismic design of these systems.

Funding for the five year program started in Japan in 1993. A few isolated projects were funded in the US at a similar time, but the US research did not start formally until the summer of 1995. As a result, the Japanese program is complete, while the US program is not complete but is nearing completion.

OVERVIEW OF CFT PROGRAM

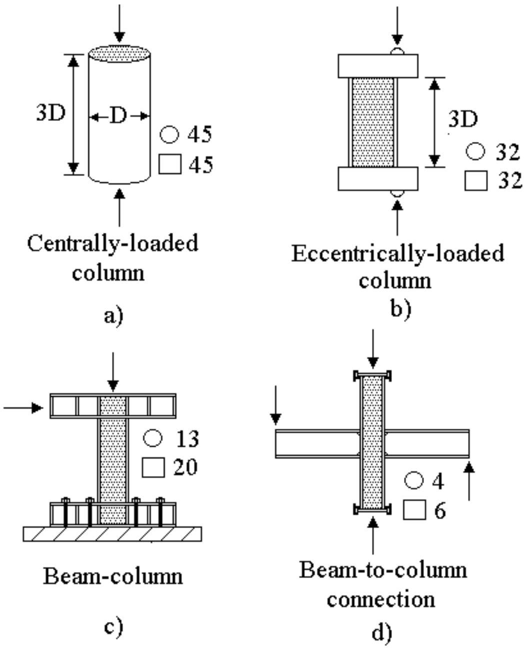
The research was coordinated through a US-Japan Joint Technical Coordinating Committee (JTCC). The US-Japan JTCC met every year to coordinate the US and Japanese efforts, to discuss progress and results on individual topics, and to plan research for subsequent years. The meetings lasted for 2 to 4 days, and alternated between sites in the US and Japan. Additional single country meetings were also held to coordinate each countries research efforts. A working group or subcommittee was established for each of the research groups, and these groups provided focus for the discussion at each US-Japan JTCC meeting. Each Working Group had a Japanese and US co-chair. The authors of this paper were the co-chairs for the CFT Working Group. All researchers with research topics related to that group participated in the group efforts. In addition, several practicing engineers from both countries worked with the group to assure that the research funding were well utilized and that the results were relevant to the engineering profession.

The US research was funded by the National Science Foundation, and the Japanese research was funded by the Ministry of Construction and the other organizations listed in the acknowledgment. There are fundamental differences in the research done in the two countries, because the existing state of knowledge was different and the engineering practice are different. At the same time, both countries design for similar seismic loads, and there are similarities in their research and engineering practice. The CFT Working Group coordinated these efforts so that existing knowledge could be transferred from one country to the other, so both countries could effectively use the research completed in the other country, and so that there would not be excessive duplication of research efforts. A series of recommendations and resolutions were made at each JTCC Meeting to facilitate these goals

JAPANESE RESEARCH PROGRAM

The Japanese research program on CFT column system (composed of CFT columns and wide-flange beams) was carried out from 1993 to 1998 as a part of the 5th phase of U.S.-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures. The program included experimental investigation, development of database of test results, trial design of theme structures, and development of design guidelines for CFT column system. The results of the investigation has been partly presented elsewhere [Morino (1998), Sakino et.al. (1998)].

A wise range of experiments were performed to supplement past research results. The experimental investigations included four series of tests as shown in Fig. 1 on a) centrally-loaded stub columns, b) eccentrically-loaded stub columns, c) beam-columns, and d) beam-to-column connections. The objectives of these testing were to clarify the synergistic interaction between steel tube and the concrete fill, to better understand the stress transfer mechanism, and to derive methods to evaluate stiffness, strength and ductility of CFT elements and systems. Study parameters were as follows: i) tube shapes; ii) ultimate tensile strength of steel tube; iii) width B (diameter D)-to-thickness t ratio of steel tube; iv) design standard strength of concrete; v) axial load ratio; and vi) connection details. The number of specimens and the values of test parameters are shown in Fig. 1 and Table 1. 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 B(D)/t ratio, and some of the beam-column specimens were tested under the variable axial load. The steel tubes were cold-formed, and the value of B(D)/t ratio was controlled by changing the size of the tube.



Centrally-loaded column

a)

Eccentrically-loaded column

b)

Beam-column

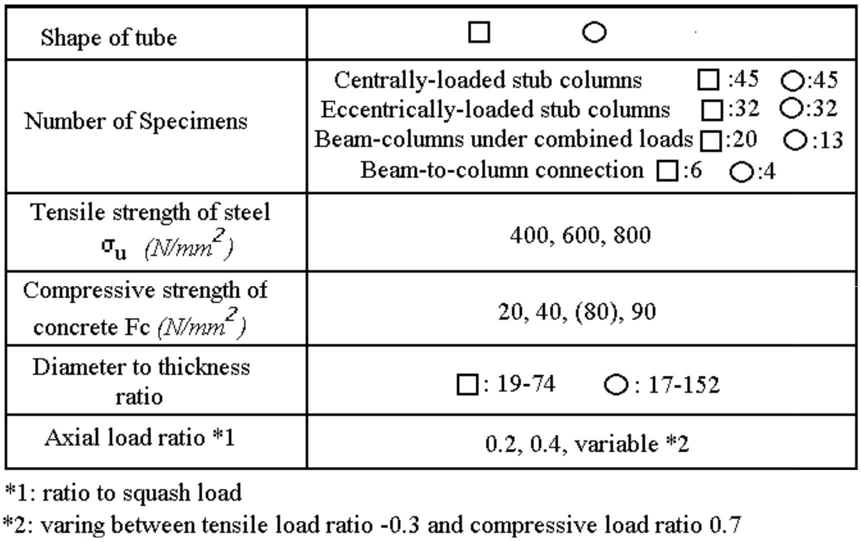
c)

Beam-to-column connection

d)

Figure 1. Tests of CFT Elements

Table 1. Study Parameters



Shape of tube	□ ○
Number of Specimens	Centrally-loaded stub columns □:45 ○:45 Eccentrically-loaded stub columns □:32 ○:32 Beam-columns under combined loads □:20 ○:13 Beam-to-column connection □:6 ○:4
Tensile strength of steel σ_u (N/mm^2)	400, 600, 800
Compressive strength of concrete Fc (N/mm^2)	20, 40, (80), 90
Diameter to thickness ratio	□: 19-74 ○: 17-152
Axial load ratio *1	0.2, 0.4, variable *2

*1: ratio to squash load

*2: varing between tensile load ratio -0.3 and compressive load ratio 0.7

A number of mathematical models, methods and formulas, were developed from the experimental results. Strength formula and stress-strain-relations for concrete and steel tube for a concentrically loaded CFT compression member were developed. These considered the effects of scale, confined concrete, triaxial state of stress and local buckling of steel tube. Strength formula, and method to calculate moment-curvature relation were developed for eccentrically-loaded stub columns, based on the stress-strain relations for the concrete and the steel tube. Strength formula, deformation capacity formula, method of analysis for cyclic behavior, and a model of restoring-force characteristics were developed for CFT beam-columns. Strength formula, stress-transfer mechanism, and a model of restoring-force characteristics were developed for CFT beam-to-column connections.

An extensive database of test information was compiled for analysis by engineers in both countries. Test data of CFT beam-columns and frames were collected from the Japanese literature published in 1972 through 1997, and a database was developed and maintained. A total of 353 test data (test specimens) of CFT beam-columns were found from 82 literature sources. The data included 242 square CFT and 111 circular CFT. A total of 236 test data (test specimens) of CFT beam-columns were found from 51 literature sources. These included 184 square CFT members and 52 circular CFT. The database contains the data for materials, dimensions and shapes of specimens, loading conditions and paths, strengths at maximum point and at points of drift angle equal to 1 and 2%, drift angles at points of maximum strength, strength reduced to 95% of the maximum strength, and stiffnesses at points of initial loading, strengths equal to 1/3 and 85% of the maximum strength. It also contains calculated data, such as B(D)/t ratio, squash load, and ultimate bending strength.

Two kinds of trial designs were performed for 10, 24 and 40 story building frames using CFT column system which have a common plan shown in Fig. 2. These designs examined the merits of employing the CFT system, by comparing constructional costs and structural performance with ordinary steel(S) and steel-reinforced concrete(SRC) systems. The first trial design was to see the elastic performance of 10, 24 and 40-story CFT and steel (S) frames, which were elastically designed, and analyzed against three recorded earthquake motions, which had a maximum ground velocity equal to 25 cm/sec. The analysis showed that the fundamental natural period was almost the same in both CFT and S frames, since CFT frame became stiffer but heavier than S frame. The total weight of steel of CFT frame was about 10% lighter than that of S frame, and the steel weight of column only of CFT frame was about 14 to 19% lighter than that of S frame. Construction cost was estimated to be about 5 to 7% smaller than that of S frame. The cost benefits of CFT increased with the height of the frame.

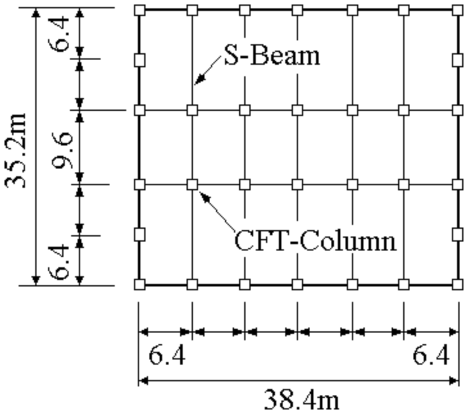


Figure 2. Plan of CFT Theme Structures

The second trial design followed current Japanese practice for 24-story CFT, S and SRC frames. That is, the buildings were designed by a dual design approach where the first step was an allowable stress at smaller seismic loads and the second step was an ultimate strength evaluation. The dynamic responses of the 3 buildings were checked against three recorded earthquake motions with the maximum velocity equal to 25 and 50 cm/sec. The analysis again showed that the fundamental natural period was almost the same in both CFT and S frames, and that of SRC frame was about 5% shorter than the former. The ratios of input earthquake load were - CFT : S : SRC = 1.00 : 0.91- 0.95 : 1.15 - 1.24. The ratio of total weight of steel were - CFT : S : SRC = 1.00 : 1.21 : 1.10, and the ratio of total estimated construction cost were - CFT : S : SRC = 1.00 : 1.16 : 1.15. The evaluation suggested that design allowing yielding in some of the columns in a story may be possible, since CFT columns possesses large ductility.

US RESEARCH PROGRAM

The US research effort was inherently less coordinated than the Japanese program, because individual research topics were funded based upon a competitive selection based in the individual merits of the study combined with a view of the program requirements. Theme structures were individually designed by each research team to fit the requirements of their research efforts. Prior to the 1990s, the only U.S. research regarding CFT were the testing of 52 short CFT columns under monotonic, eccentric loading at the University of Texas and a few inelastic cyclic tests of CFT braces at the University of Michigan. These were modest-size specimens, not reflective of the applications in high-rise construction in the U.S. It was known that extensive research on CFT member behavior had been completed in Japan. Therefore, most of the US research related to CFT member behavior consisted of analysis and evaluation [Hajjar and Gourley (1996)] of past experimental results with the aid of the database compiled by Japanese researchers.

The engineering practice and research from Japan are quite different from that of the U.S. In general, U.S. practice employs larger-diameter tubes with larger diameter-to-thickness (D/t) ratios. The U.S. practice has made extensive use of CFT columns in braced frames, but Japan has used and studied CFT columns nearly exclusively in moment-resisting frames and more modest-sized structures. Further, very high-strength concrete has been used to maximize the stiffness of CFT members in the U.S., but Japan has historically employed much lower-strength material.

Japanese engineers almost exclusively use the internal diaphragm connection illustrated in Fig. 3. U.S. engineers regard this connection as uneconomical since the column requires 4 complete penetration welds at every column-floor intersection. On the other hand, this diaphragm connection is known to perform well, and the internal diaphragm applies a blocking force to the concrete fill which helps the concrete and steel to work together at all load ranges. U.S. research has emphasized connection details, which are practical for U.S. construction. Rectangular CFT columns offer easier and more economical connections for US practice, and they are more suitable for modest sized buildings. Research at Lehigh University and the University of Texas show that T-stub connections with through, unbonded bolts as shown in Figures 4a and 4b offer considerable promise for seismic design. The research at the U. of Texas examined deformation of the panel zone of connections with rectangular CFT columns. At Lehigh, interior moment frame connections were tested with a number of different bolted connection variables. These tests showed that bolted connections with modest sized members were able to sustain plastic rotations of up to 0.05 radians. These connections used variations of the bolted Tee connection illustrated in Figs. 4a and 4b with or without web connections.

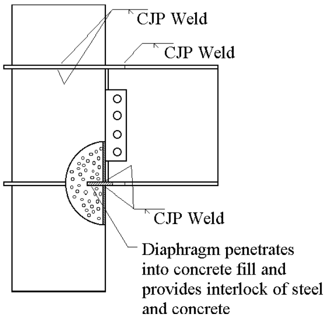


Figure 3. Typical Japanese Internal Diaphragm CFT Connection

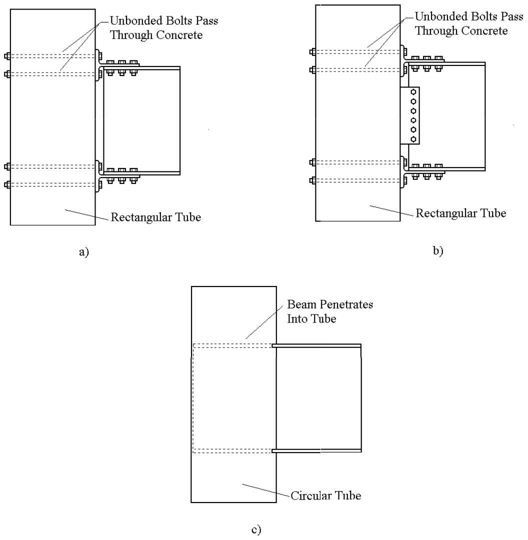


Figure 4. Schematic of CFT Moment Frame Connections Considered in US Research

Circular CFT columns are more suitable for bigger and taller buildings. Research at the Universities of Illinois [Schneider and Alostaz (1998)]] and Nebraska show that connections with the beam penetrating through the tube into the concrete core, as illustrated in Figure 4c. At the U. of Illinois, exterior connections, which were evaluated to be economical options for structural engineers were considered. Connections which have external steel to steel connections were viewed as very economical, but they did not provide good seismic performance. Penetrating connections such as illustrated in Fig. 4c can provide very good ductility while developing the full plastic capacity of the beam members. The U. of Nebraska test program followed the line of penetrating beam connections. These tests examined different failure modes possible for these connections, and models which address the relative strength of the beam and the column and various elements of the connection have been proposed.

To obtain the full benefit of composite action in CFT, shear stresses must be transferred between the steel and concrete. Most US connection details do not provide the blocking action provided by the Japanese internal diaphragm connection, and so this transfer must be achieved by natural bond or mechanical means. Mechanical shear connectors on the inside of the tube add cost to CFT construction and they are often difficult to install. A study at the University of Washington [Roeder et.al (1999)] examined bond stress transfer between the steel-and-concrete and shear connector requirements for CFT columns. This work has shown that larger diameter tubes and tubes with larger D/t ratios are more likely to require mechanical shear transfer than smaller diameter tubes or tubes with small D/t ratios. Shrinkage was shown to cause severe deterioration of the natural bond capacity. The shear transfer requirements also are localized and depend upon the forces transferred and the structural system. Another basic study at the State University of New York at Buffalo examined the interfacial conditions at CFT with consideration of axial and torsional loading and the interaction between confinement of the concrete and stress at the steel concrete interface.

While most US research on CFT has focused on connections and interaction at the steel concrete interface, a few studies have considered member behavior with emphasis on the issues that most closely relate to US practice. A study at Lehigh University considered the behavior of rectangular CFT members manufactured from high performance materials. These tests considered CFT member behavior with steel with 317 MPa or 552 MPa and concrete strength of 104 Mpa. The tubes are relatively stocky members with B/t ratios of 32 and 48.

The US portion of the US-Japan program was not complete, when this paper was prepared. Work will continue for at least one more year, but significant progress can already be noted.

APPLICATION OF RESEARCH RESULTS TO ENGINEERING PRACTICE

A major goal of this research program is the development of design recommendations from the research results. The Japanese research has been nearly complete for more than one year, and significant progress has been made in translating the research results into practice. Guidelines for the Structural Design of CFT Column System (Draft) were developed from the experimental investigation. Table 2 illustrates the table of contents of this draft document. In Chap. 2, the scope of the guidelines is shown together with the flowcharts for the seismic design, based on the conventional method using the structural characteristic factor Ds, 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-deflection relation 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 shows the formulas to evaluate the stiffness, ultimate strength and deformation capacity of CFT beam-columns. The first two sections of Chap. 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 strength formulas are derived, based on the stress transfer mechanism around the connection. 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. 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 using an 11-story office building, written for the beginners of the CFT design. Two appendices show the results of the investigation by the trial design of CFT column system, and the list of the names of the specimens and test parameters for the reference.

Similar efforts for the development of design guidelines are planned for the US, but little progress has been made to date. The final year of research funding was about to start as this paper was written, and it is expected that further developments along this line will proceed in the near future. Development of detailed design guidelines for US practice are planned, but work on this has not started yet.

Table 2. Guidelines for the Structural Design of CFT Column System (Draft): Table of Contents

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CONCLUSIONS

CFT columns are increasingly used for seismic design in the US, Japan, and other Pacific Rim countries. While the system is known to be economical and offer a number of practical advantages, the limited understanding of the behavior of these systems has inhibited their use. Research programs such as the U.S.-Japan program provide valuable insight into the behavior of CFT and other composite systems. This program has developed models for predicting the strength and stiffness of CFT members, and it has examined connections which are economical and viable for the two countries construction practice. The research has improved the understanding of stress transfer between the steel and concrete, and the local behavior within connections and members. However, gaps in our knowledge still remain. Some of the more pressing gaps which affect the ability of structural engineers to use CFT to its full potential are:

Better models are needed for estimating the axial shortening and composite stiffness of CFT columns.

Better models and recommendations are needed for using elements such as link beams and outrigger walls and trusses with these composite systems.

Braced frames are an ideal use for CFT columns in the US because of their large axial strength and stiffness, but there has been no research on braced-frame connections. The connections used in U.S. high-rise construction have been quite variable and complex, and the complexity may reduce the economy of this valuable structure.

These are only a few of the questions facing structural designers. As more experience is gained and more research is accomplished, we will all learn how to more effectively and efficiently design buildings using CFT construction.

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