



EXPERIMENTAL STUDIES OF CONFINED CONCRETE FILLED STEEL TUBULAR (CCFT) COLUMNS

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SUMMARY

This paper introduces an innovative concrete filled steel tubular (CFT) column structure for improved seismic design of steel and concrete composite structures. Based on fundamental mechanics, the design concept is aimed at controlling the local buckling of the steel tube and confining the concrete in the potential plastic hinge zones of a CFT column. To achieve this, several efficient details of transverse confinement have been examined through experimental testing. The new type of CFT column, named as CCFT, is expected to overcome many disadvantages of the conventional CFT column and to provide the ideal choice for structural design of tall buildings in seismic regions. Experimental tests validated the concept of the CCFT.

INTRODUCTION

The proposed new concrete filled tubular (CFT) column is conceived by the first author Xiao based on previous research on two steel tubular column structural systems: the CFT column and the tubed column. The two different but related systems are shown in Fig.1 and described below,

CFT column: In a conventional CFT column system, concrete is filled in steel tubes which typically continue throughout the full-height of a building (e.g. Moore and Gosain 1985; Viest et al. 1997). The steel tube is expected to carry stresses in longitudinal direction caused by axial loading and moments, as well as transverse stresses caused by shear and the internal passive pressure due to concrete deformation, i.e., the confining stress.

Tubed column: The concept of using steel tube as primarily transverse reinforcement for reinforced concrete (RC) columns was first studied by a research group lead by Tomii (Tomii, Sakino and Xiao, 1985, 1987; Xiao et al. 1986). The terminology of “tubed column” first adopted by Tomii et al. (1985), refers to the function of the tube as that of the hoops in a hooped RC column. In this regard, a tubed column defers from the conventional CFT column, where the steel tube is used as both longitudinal and

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transverse reinforcements. In other words, the composite action between the steel tube and concrete is primarily expected in transverse direction only for a tubed column, however, in both longitudinal and transverse directions for a conventional CFT column.

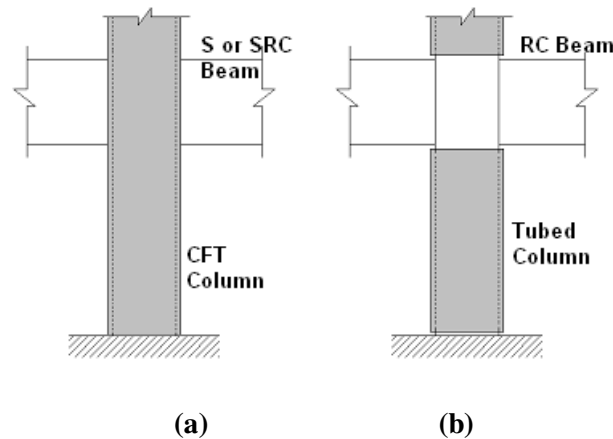


Fig.1. Two different tubular column systems: (a) CFT column; (b) tubed column

Advantages and Disadvantages of CFT Columns

In recent years, CFT structures become more widely accepted and used in tall buildings as well as arch bridges, particularly, in the far-east region, like China and Japan. The advantages of the conventional CFT column structure include:

- i. As a typical composite structural system, due to the composite effects, the advantages of the two materials can be utilized and their disadvantages can be avoided, thus forming a more rational system.
- ii. Compared with steel structures, the cost can be reduced by using composite or hybrid systems, since the reduced usage of steel and the increased stiffness as well as improved fire resistance.
- iii. The steel tubes can be used as the formwork for casting concrete and the shoring system in construction, thus CFT structures have much better constructability than concrete structures.

However, the conventional CFT system also has its own disadvantages, such as,

- i. The beam-to-column connections are complicated for CFT frame structures. In Japan, structural frames using CFT columns typically end up using steel or SRC beams with specially designed connections, thus increasing the construction cost. Practice in China tends to adopt more CFT column and RC beam system with using complicated connections (papers can be found in Xiao and Mahin ed. 2000). Such labor-intensive practice is apparently not suitable for the US construction industry.
- ii. Due to the fact that the steel tube is used as longitudinal reinforcement to resist axial force or moment, when the steel tube yields under excessive longitudinal stresses, its transverse confinement (particularly in terms of stiffness) to the internal concrete is drastically reduced. This may be considered as the fate of steel as an isotropic material.
- iii. As demonstrated in the cyclic loading tests of conventional CFT columns conducted by Sakino (Sakino and Tomii 1981; Council 1992), local plastic buckling may occur at the ends of the steel tube followed by the crushing of internal concrete. This type of failure is very difficult to repair if not impossible. Such failure mode also results in unstable hysteretic loading capacity, particularly for columns with higher axial load.

Development of Tuber RC Column

The tuber column system was developed to improve some of the disadvantages of the conventional CFT columns. A brief review is summarized below, from a more comprehensive discussion by the first author (Xiao 2001).

In Tomii et al.'s original studies, the tuber RC column concept was developed to prevent shear failure and to improve the ductility of short columns in RC frame structures or boundary columns of shear walls. The steel tubes are used to transversely confine concrete, whereas the ordinary longitudinal reinforcing bars are still needed for providing flexural strength of the columns. The tuber RC column can still be considered as RC structural system, thus, connection detailing and other design as well as construction methods used in conventional RC structures are applicable without significant modification.

One of the key features of a tuber RC column is to properly detail the tube to avoid or reduce direct transfer of the longitudinal stresses into the tube, which is designed primarily as transverse reinforcement. This is achieved by providing a gap between the tube and the beam or footing at the ends of a column, as shown in Fig.1(b). The concept of the tuber column was validated through testing model columns under constant axial load and cyclic shear in double-curvature condition (Tomii et al. 1985, 1988; Xiao et al. 1986, 1987).

Jacketing retrofit of existing deficient RC columns can also be considered as the application of tuber column concept. For most cases, the jacket is used to provide additional transverse reinforcement to increase the capacity and to improve the ductility of an existing column. This is achieved by welding steel plate shells to enclose an existing column to form a tuber system, same as that shown in Fig.1(b). Systematic studies on steel jacketing were carried out by Priestley et al. from late 80s (Priestley et al. 1994a and b). For circular columns, welded steel cylindrical shells are used, whereas for rectangular columns, an elliptical jacket is preferred to provide a continuous confinement. However, retrofitting rectangular columns using elliptical jacketing is typically not acceptable for building columns, for the reasons of architectural appearance and functional requirements. Two recent developments may have provided improved solutions for retrofitting rectangular or square columns using rectilinear steel jackets. Aboutaha et al. (1996) developed and tested a system which combined drilled cross-bolts with rectangular jacketing, showing enhanced confinement efficiency. Xiao and Wu (2003) developed a jacketing method to retrofit square columns using welded rectilinear steel jackets and stiffeners.

Significant research efforts have been recently carried out to explore fiber reinforced polymer (FRP) composites for retrofitting or strengthening RC structures (ACI 440R 1996; Teng et al. 2000; Xiao 2001). An FRP jacketed column can be categorized as the tuber system, from the fact that the FRP jacket, once installed, forms a tube to provide primarily additional transverse reinforcement to the original column.

CONFINED CFT COLUMN (CCFT)

A new CFT column system is conceived by the first author. In the new CFT column, additional transverse reinforcement is designed for the potential plastic hinge regions, as illustrated in Fig.2, to achieve improved seismic performance. Based on fundamental mechanics, the design concept is aimed at controlling the local buckling of the steel tube and more efficiently confining concrete in the critical regions of a CFT column. For this reason, the proposed new CFT column system can be named as confined CFT column system, and is referred to as CCFT hereafter.

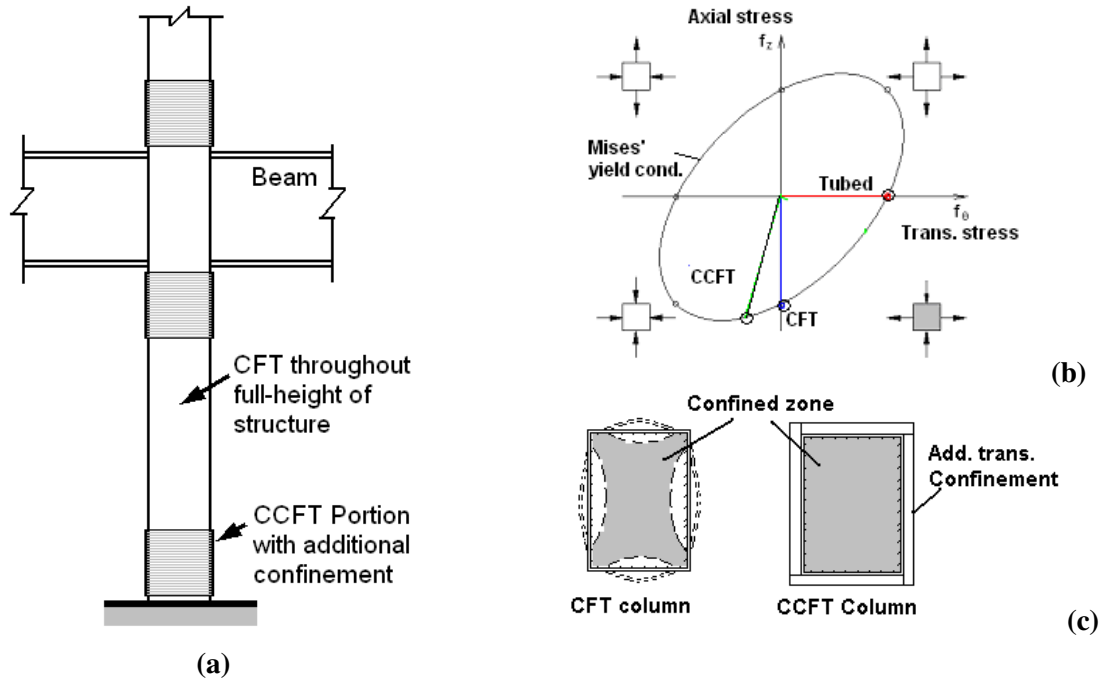


Fig.2. Proposed CCFT column system: (a) elevation view of a frame portion; (b) different transverse confinement effects in CFT and CCFT; (c) stress states in different tubes

The CCFT column is expected to overcome many disadvantages of the conventional CFT column and to provide the ideal choice for structural design of tall buildings or bridges, particularly for seismic regions. The followings are several expected merits of CCFT column system as compared with the conventional CFT structures.

- i. In a CCFT column the functions of the through-tube (similar to the tube in a conventional CFT column) and the additional transverse reinforcement are separated, with the former mainly resists longitudinal stresses caused by axial load and moment as well as shear in the middle portion of the column, whereas the additional reinforcement mainly enhances the potential plastic hinge regions.
- ii. The additional transverse reinforcement can effectively prevent or delay the local buckling of the through-tube in the plastic hinge regions of a CFT column, thus improving its seismic performance with stable load carrying capacity and ductility.
- iii. The concrete in the column plastic hinge regions can be more efficiently confined by the additional transverse reinforcement, and as a consequence, the ductility of the column can be assured.
- iv. Due to the additional transverse confinement, the through-tube in the compression zone of the plastic hinge region is subjected to biaxial compressive stress state (strictly speaking, should be triaxial compression), shown as the third quadrant in Fig.2 (c). This is a more efficient working state for steel tube as compared with the combination of axial compression and transverse tension (fourth quadrant in Fig.2(c)), which is the working stress state of the tube in compression zones of a conventional CFT column.
- v. In a conventional CFT column, in order to prevent the local buckling of the steel tube in the plastic hinge regions, relatively thicker steel tube is required, and typically such thickness is provided throughout the length of the column, particularly for columns with a rectangular section. On the other hand, in a CCFT column, the through-tube is designed mainly as longitudinal reinforcement to resist axial load and moment, and is enhanced transversely by the additional transverse reinforcements in the potential plastic hinge regions. The secondary function of the through-tube is to resist shear in the middle portion of the column, and this can typically be achieved by using the same thickness of the

through-tube. Thus, it is expected that even with the addition of the transverse reinforcement for the potential hinge regions, the total amount of steel usage in a CCFT column may be less than the identical CFT column.

For the design of the additional transverse reinforcement, the followings are considered but not limited as potential options and are examined in the research program:

- i. Additional steel plates or tubes welded to the potential plastic hinge regions of the through-tube, shown in Fig.2;
- ii. Angles, small tubes or pipes, etc., which have larger transverse stiffness and resistance can be used, similar as those proved to be effective to enhance the retrofitting efficiency of rectangular jacketing by the first author (Xiao and Wu 2003).
- iii. Fiber-reinforced plastics (FRP) can also be considered to create the new composite system;
- iv. Reinforced concrete shells that can also serve as the fire proof for the steel tube.

Apparently, since the additional transverse reinforcement is only provided for the potential plastic hinge regions of the columns, the structural system using CCFT columns remains the same as the CFT structure. Thus, design details such as connections developed for conventional CFT structures are still applicable to the proposed CCFT system.

BASIC MECHANICS VALIDATION OF CCFT CONCEPT

In order to validate the basic mechanical concepts of CCFT columns, 13 cylinder specimens were tested under monotonic axial compression, shown in Fig.3. Three plain concrete cylinders with a diameter of 152 mm were first tested to provide the compressive strength of the concrete used in all the specimens. One hollow steel tube and one conventional CFT specimens were tested to provide the benchmark behavior data. Eight CCFT specimens with CFRP confinement were tested. Testing parameters for the CCFT specimens were the number of layers of CFRP wraps and with or without the gap between the steel tube and the CFRP confinement. The gap was made with 1 mm thick soft foam tapes affixed on the surface of the steel tube to provide a kind of cushion effect. Such cushion effect was designed to delay the participation of the CFRP wraps for possibly maximizing the deformability while minimizing the unnecessary strength enhancement.



Fig.3. Axial compression test setup.

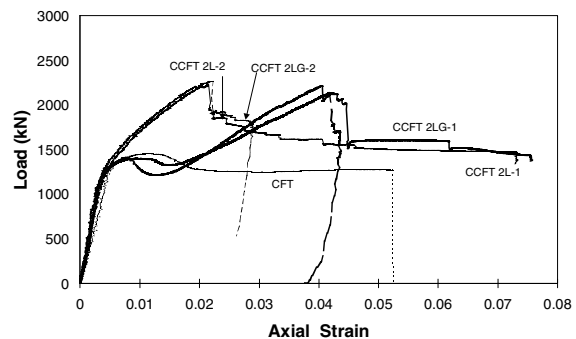


Fig.4. Axial load – strain relationships for CFT cylinder and CFRP Confined CFT cylinders.

As an example, Fig.4 compares the axial load and strain relationships for CFT cylinder and the CFRP confined CFT cylinders with or without the gap. As demonstrated in Fig.4, the use of additional confinement in the CCFT cylinders significantly improved the mechanical behavior of CFT cylinders. The

CCFT cylinders without cushion gap, CCFT-2L-1 and CCFT-2L-2 showed a bilinear feature similar to CFRP confined concrete (Xiao and Wu 2000), prior to the rupture of the CFRP jacket. Due to the existence of the cushion gap between the steel tube and the CFRP jacket, specimens CCFT-2LG-1 and CCFT-2LG-2 had an identical behavior as that of the CFT specimen up to an axial strain of 0.015, where plastic local buckling of the steel tube became apparent. Measurement of the transverse strain of the CCFT-2LG specimens showed that the CFRP jacket confinement was activated after this stage, and as the consequence, the load carrying capacities of the CCFT-2LG specimens increased again until the rupture of the jacket. Comparing with the CCFT-2L specimens, providing the cushion gap in the CCFT-2LG specimens significantly increased the axial deformability at the CFRP jacket rupture. It is also noticed that though a sudden drop of the load carrying capacity followed the rupture of the CFRP jacket, a capacity slightly higher than that of the CFT specimen can be maintained by the CCFT specimens until large axial strains.

SEISMIC TESTING PROGRAM

Specimen Design

Eleven large-scale model CFT columns were designed to simulate typical columns in multi-story buildings in seismic regions, as shown in Table-1. The basic details of the CFT columns are illustrated in Fig.5. Seven specimens were circular with a diameter of 325 mm and two specimens were 350 mm by 350 mm square cross-section. Height of the columns was 1,500 mm from the point of lateral loading to the top of the footing. Thickness of steel tube was 3 mm for five circular ones and 6 mm for the others. There was no any special confinement for model columns C1-CFT3, C6-CFT6 and SQ1-CFT6 for providing benchmark data of conventional CFT columns. CFRP and other methods were used to provide additional confinement to the potential plastic hinge regions of CCFT columns. The length of the confined zone was 300 mm, close to the section diameter. The specimens were designed and constructed with a stiff stub footing of 2000 mm x 700 mm x 420 mm. The stub footings were heavily reinforced to eliminate any premature failure during testing.

Table-1 Seismic loading test matrix

| Specimen | Section Shape | Steel Tube Thickness (mm) | Steel Tube D/t ratio | Steel Yield Strength F_y (MPa) | Confinement | Concrete Strength f'_c (MPa) |
|-----------|------------------------------|---------------------------|------------------------|----------------------------------|-----------------|--------------------------------|
| C1-CFT3 | Circular $D=336\text{mm}$ | 3.0 | 112 | 303 | — | 39.1 |
| C2-CCFT3 | | | | | CFRP* | 39.1 |
| C3-CCFT3 | | | | | GFRP | 39.1 |
| C4-CCFT3 | | | | | Steel collars | 39.1 |
| C5-CCFT3 | | | | | RC cover | 39.1 |
| C6-CFT6 | Circular $D=325\text{mm}$ | 6.0 | 54 | 312 | — | 28.0 |
| C7-CCFT6 | | | | | CFRP* | 28.0 |
| SQ1-CFT6 | Square $D=B=350\text{mm}$ | 6.0 | 58 | 312 | — | 40.0 |
| SQ2-CCFT6 | | | | | Steel plate ** | 40.0 |
| SQ3-CCFT6 | | | | | Steel strips ** | 40.0 |
| SQ4-CCFT6 | | | | | Steel angles** | 40.0 |

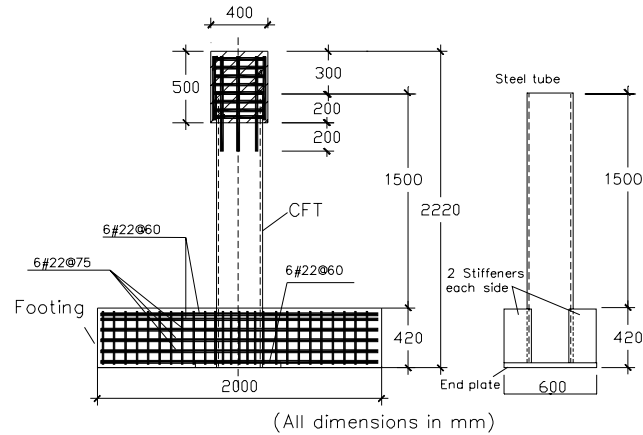


Fig.5. CFT specimen details

Material Properties

Material properties for all specimens are summarized in Table 1. The mixture proportions per cubic meter concrete were 190 kg water; 425 kg cement; 1211 kg coarse aggregates; and 570 kg fine aggregates. The water-to-cementitious materials ratio was 0.45. The maximum dimension of the coarse aggregates was about 20 mm. The concrete compressive strength values shown in Table 1 are based on compression tests on concrete cubes, however converged to the cylinder strength by a factor of 0.8. The Chinese standard Q235 grade steel with average yield strength of 235 MPa was used for steel tube in all the columns. The stub head and footing were longitudinally reinforced with Grade III steel with average yield strength of 345 MPa and transversely reinforced with Grade II steel with average yield strength of 215 MPa. The tensile strength and the modulus of the unidirectional carbon fiber reinforced plastic (CFRP) sheets used for confining the two circular CCFT columns were 2,500 MPa, and 210 GPa, respectively, based on 0.22 mm/layer thick flat coupon tests.

Specimen Construction

The 3 mm thick circular steel tubes were made by a local pressured container manufacturer with rolling steel plate to cylindrical shells and then welding the seam. The 6 mm thick circular steel tubes were standard pipe products with spiral weld seams. The square tubes were made by welding two L-shape folded steel plates. The tubes were first welded with an end plate and stiffeners for the bottom end to ensure a strong connection with the stub footing. The tubes were then shipped to the Structural Laboratory of the Hunan University for preparing the steel caging for the footing and top stub as well as casting concrete. Two specimens were typically cast together with concrete produced in the laboratory using a forced mixer.

The additional transverse confinement for the CCFT columns was made carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP), steel or reinforced concrete around the potential hinge region. For FRP confinement, prior to applying the CFRP wrapping, a layer of 1 mm thick foam tapes were affixed to the surface of the tube to yield a cushion effect based on the basic mechanical testing studies. Fig.6 shows the process of applying the CFRP wrapping to the potential plastic hinge region of model column C7-CCFT6. Patents for the technique are currently under filing process. For the square CCFT specimen, thick steel plates, strips and angles were welded in the potential plastic hinge region to

provide additional confinement. The design followed the procedure proposed by the first author (Xiao and Wu 2003).

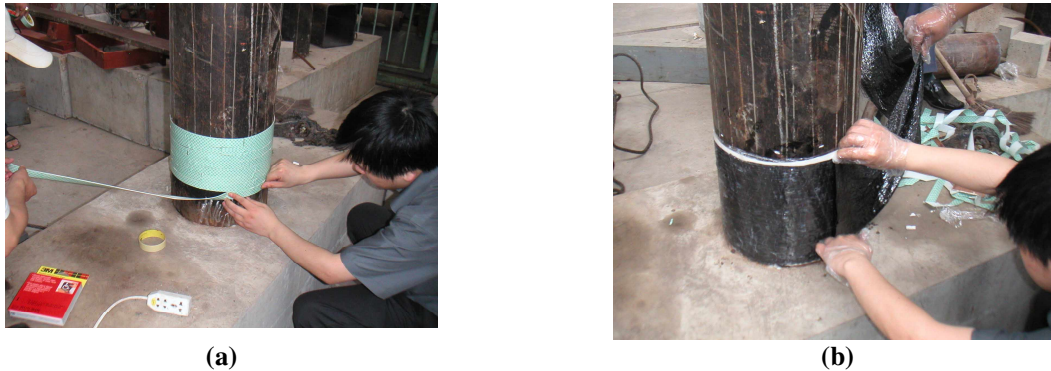


Fig.6. CFRP Wrapping: (a) applying foam tape; (b) applying CFRP wrapping.

Test Setup and Loading Method

All the model columns were tested using the test setup shown in Fig.7. The test setup, designed by the first and the second authors, can apply lateral loading using a pseudo controlled hydraulic actuator to large-scale model column in a condition of vertical cantilever. A constant of axial load of 2,000 kN was applied to the column through post-tensioning two 50 mm diameter high-strength steel rods using two 1,500 kN capacity hydraulic hollow jacks. The forces of the rods were transferred to the model column by a cross beam mounted on top of the load stub. In order to eliminate the bending of the high-strength rods, a specially designed pin device was connected to the lower end of each rod.

The axial load applied to the column was measured by a set of strain gauges affixed on the high-strength rods. The imposed lateral displacement was measured by both the displace transducer of the actuator and a separate linear potentiometer. The corresponding lateral force was recorded by the load cell of the actuator. Electrical resistance strain gauges were affixed on the surfaces of the steel tube and the additional confinement CFRP.

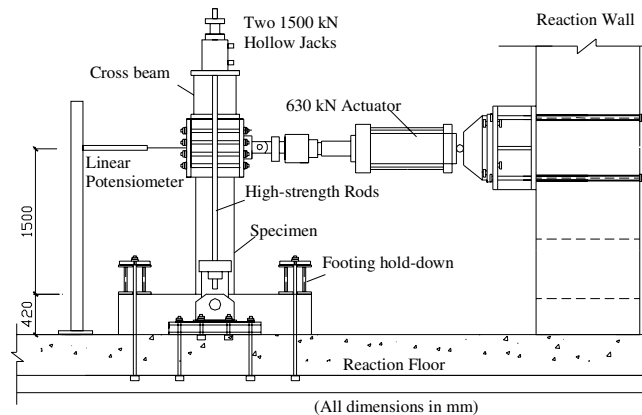


Fig.7. Test setup

During testing, the axial load was maintained constant by the hydraulic system, whereas the lateral force was cycled under lateral displacement control condition. Three single cycles were initially applied corresponding to an increment of 0.25% peak drift ratio, D/L , here D is the lateral displacement and L is

the clear length of the model column measure between the bottom end and the application point of lateral force. Then, three repetitive loading cycles were applied for each of the peak drift ratios, $D/L=1\%$, 1.5% , 2% , 3% , 4% , 6% , 8% and 10% . Such standard loading procedure was attempted until the stage where the model column was judged as unsuitable for further loading.

Test Results

Examples of the hysteretic responses of the column end moment and drift ratio for the model columns are shown in Fig.8 and Fig.9. The calculation of the column end moment included the effects contributed by the axial loading system.

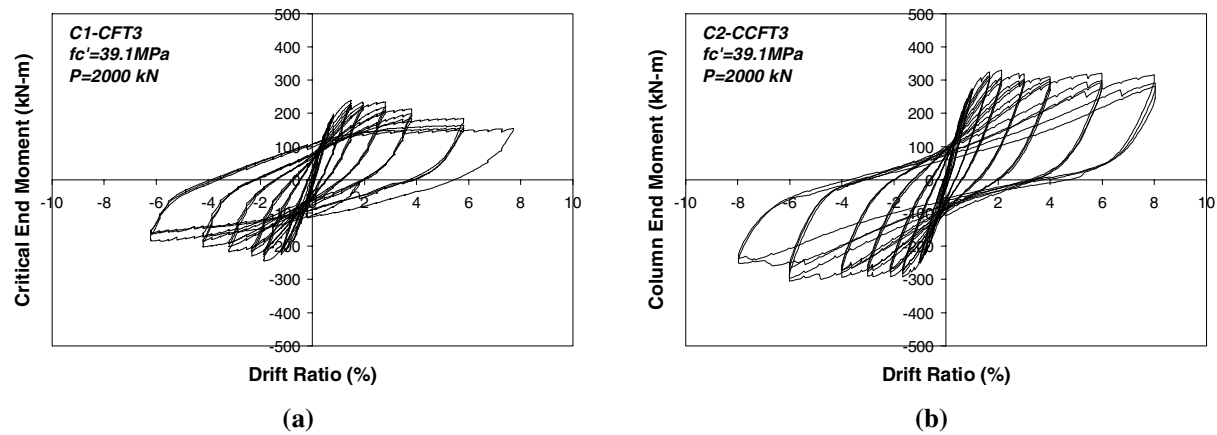


Fig. 8. Test results of circular specimens with 3mm thick steel tube: (a) CFT column; (b) CCFT column with CFRP.

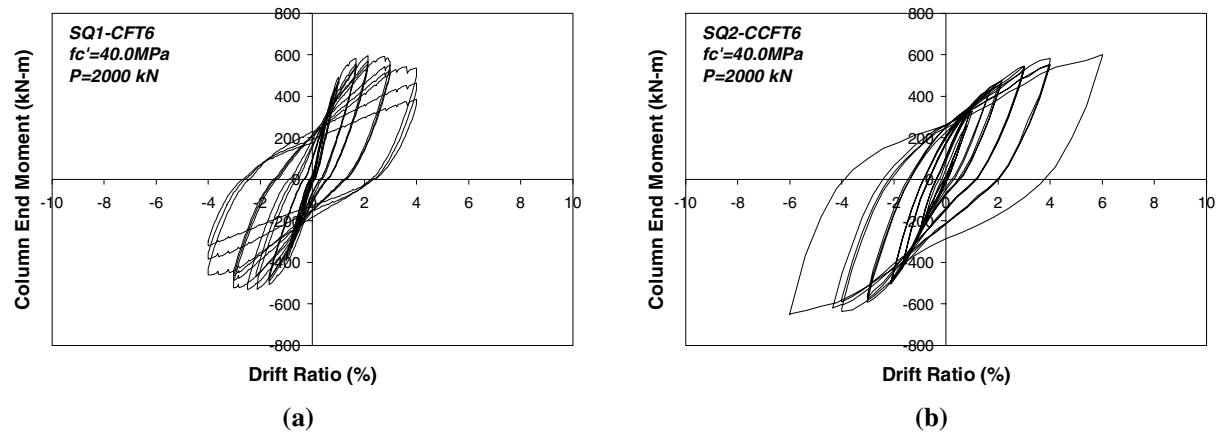


Fig. 9 Test results of square specimens with 6mm thick steel tube: (a) CFT column; (b) CCFT column with steel plate.

Circular CFT columns: As shown in Fig.8 (a), circular CFT model column C1-CFT3 with a D/t ratio of 112 had a stable behavior only until cycles corresponding to a peak drift ratio of 2% in the push direction where as 1.5% in the pull direction. At these stages, the so-called “elephant foot” type local buckling of

the steel tube was observed at the position about 20 mm to the bottom end of the column. In the subsequent loading cycles, the local buckling of the steel tube severed, forming several cripples in the column end region with a length approximately equal to the diameter. During the loading cycles corresponding to a peak drift ratio exceeding 3%, the column sections within the end region expanded drastically indicating the insufficient lateral confinement of the thin steel tube. The moment carrying capacity degraded below 80% of the maximum value at 4% peak drift ratio in the pull loading direction. The loading was continued until the loss of the axial loading capacity during the first cycle at 8%. The final condition of this CFT specimen is shown in Fig.10(a).

Circular CCFT columns: Drastically improved behavior can be seen from Fig.8 (b) for CCFT model column C2-CCFT3. The additional CFRP jacket wrapped in the potential plastic hinge region effectively restrained the local buckling of the steel tube and provided better confinement to the section. As the consequence, the CCFT column was able to develop a ductile and stable hysteretic behavior until a peak drift ratio of 8%, where the test was terminated. Rupture of the CFRP jacket near the column end was observed during the cycles corresponding to a drift ratio of 6%. The first rupture was initiated in the compression side of the column at a height of about 30 mm from the bottom end. The rupture of CFRP then formed a ring of about 20 mm wide where the steel tube was exposed and subsequently squeezed out due to the “elephant foot” type local buckling. Local buckling was also observed above the CFRP jacket. As shown in Fig.10(b).

Square CFT column: As shown in Fig. 9(a), square CFT column SQ1-CFT6 exhibited a premature behavior with significant capacity degradation after drift ratios exceeding 3%. Local out-of-plane buckling of the square tube was observed for its compression face near column end at a loading stage as early as 1% peak drift ratio. The severed local buckling caused the tube to rupture along the welded corners during the loading cycles corresponding to peak drift ratio 4%.

Square CCFT column: The use of welded additional steel plates to confine the potential plastic hinge region of a CFT column was demonstrated successfully by the model column SQ2-CCFT6, as shown by its excellent hysteresis loops in Fig.9(b). Local buckling was completely prevented within the confined region and was forced to form above the confined region at a larger lateral displacement. This significantly enhanced the stiffness and increased the load carrying capacity as shown in Fig.9(b). The test was terminated after successfully completing the first loading cycle corresponding to peak drift ratio 6%, for saving the specimen.



(a)



(b)

Fig.10. Final conditions of (a) CFT specimen C1-CFT3; and (b) CCFT specimen C2-CCFT3

CONCLUSIONS

The paper presented a new CFT column system, named as confined CFT, or CCFT, in which additional confinement is provided to improve seismic performance. The proposed CCFT columns combine the advantages of conventional CFT column and tubed RC column systems. Axial compression tests and seismic loading tests described in this paper successfully validated the author's concept.

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