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Seismic Performance of CFT Column with Boxed I-Shaped Section

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Abstract

Nowadays, height, scale and shape of super high-rise building and structure with height over 450 meters have been successively renewed in the world. In order to meet the demands of the age and architectural design, mega-column with excellent seismic and wind-resistance performance is required to improve global stability of super high-rise building or structure. In this study, a novel concrete-filled steel tube (CFT) column with boxed I-shaped section is proposed. Quasi-static cyclic test of this kind of column specimen was carried out under constant axial force. The experimental results showed that the proposed CFT column specimen exhibited excellent seismic performance and the lateral load capacity of the proposed CFT column was bigger than that of the conventional SRC one. It is considered there is a possibility the proposed boxed I-shaped sectional CFT column can be applied to mega-column of super high-rise building in the future.

Keywords: Seismic performance; CFT column; Boxed I-shaped section

1. Introduction

Nowadays, height, scale and shape of super high-rise building and structure with height over 450 meters have been successively renewed in the world. In order to meet the demands of the age and architectural design, mega-column with excellent seismic and wind-resistance performance is required to improve global stability of super high-rise building or structure. Generally, the mega columns are expected to be located at the building perimeter, therefore they can sustain overturning moment efficiently and reduce the overturning moment in the core. Moreover, the mega columns can provide the vertical support and carry the building weight to the building perimeter effectively. For structural system of super high-rise building, mega-column is an important structural member. In a few super high-rise buildings, mega steel reinforced concrete columns (hereinafter referred to as "mega SRC columns") with each area of about 20 square meters have been used [1-3]. The cross-sectional details of one example are shown in Fig. 1. This mega SRC column has a rectangular cross-section with dimension of 5.3 m x 3.7 m. In this section, the encased steel part is built up of several steel plates by welding and it includes two closed rectangular elements and six T-shaped elements. A large number of reinforcement bars are set on the periphery of the encased steel skeleton and the whole section is filled with concrete. The steel ratio of this mega SRC column is 5%.

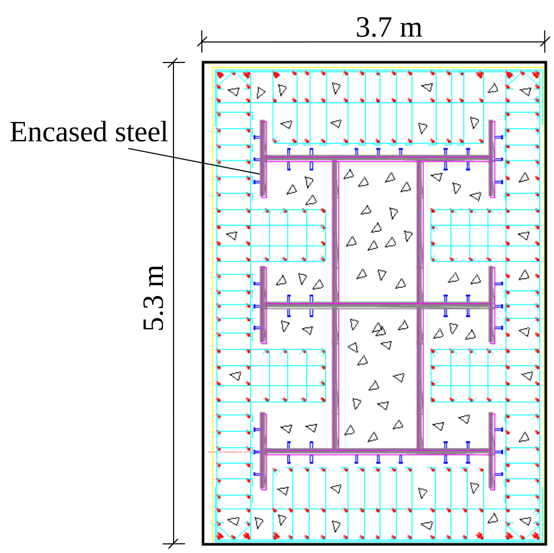


Fig. 1 – Steel skeleton section of super column for Shanghai Tower [2]

On the other hand, in the previous work, experimental research has shown that the SRC column with high steel ratio has good seismic performance and deformability [4]. It has also been clarified that the strength and ductility of the SRC column with high steel ratio are far superior to the normal SRC column [5]. And, in the practical design case of high-rise building, mega SRC column with multi-cavities and high structural steel ratio up to 30% has been used [6]. For each mega SRC column used in the actual projects, the reinforcement work is complicated and the construction is also hard.

A novel concrete-filled steel tube (CFT) column with boxed I-shaped section (hereinafter referred to as "boxed I-shaped CFT column") shown in Fig. 2 is proposed in this study. This new type column is developed from the conventional CFT column. The side plate works as side web and serves as formwork in construction, therefore, labor and material costs can be decreased. In the direction subjected to bending moment, it is preferable to select the cross-section of boxed I-shaped CFT member as a rectangle one because its moment of inertia is biger than that of a square one under the same cross-sectional area. As shown in Fig. 2, in order to optimize the strength of the section, it is reasonable to thicken the flanges and keep them lie at the outer perimeter. At first, the flange elements are joined together with a steel plate in the center region which works as the web of I-shaped (or H-shaped) steel, meanwhile, the function of the I-shaped (or H-shaped) steel is ensured. Then, the built-up I-shaped (or H-shaped) steel is joined together with side plates which work as the outer webs and serve as formwork. However, for joining different elements of steel, butt welding is recommended in this study because strength equal to host material can be expected in this joining method. When the concrete is poured into these two steel tubes which are connected together, the steel-concrete composite member with boxed I-shaped will be made. After filling with the concrete, built-up I-shaped (or H-shaped) steel can be stiffened by the filled concrete; buckling of web can be prevented and buckling of the flanges can be delayed by the support offered by the concrete. Therefore, the built-up I-shaped (or H-shaped) steel can reach its full potential. Moreover, local buckling of the side plates can be delayed due to the stiffening effect of concrete. The side plate set in the direction subjected to bending moment will benefit the stress transmission due to the combined action of steel plates and concrete. When making a CFT member with boxed I-shaped (or H-shaped) section, the formwork for concrete placing can be omitted. However, while making a SRC member, the formwork cannot be saved. For the CFT member with boxed I-shaped (or H-shaped) section, it is considered that the flexural stiffness, axial stiffness, flexural strength and axial load carrying capacity can be expected.

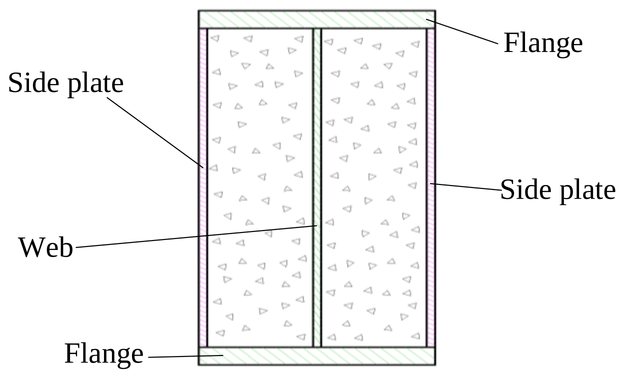


Fig. 2 – Proposed boxed I-shaped sectional CFT column

The main purpose of this study is to investigate the inelastic behavior of boxed I-shaped sectional CFT column subjected to reverse cyclic lateral loading together with constant axial force. Additionally, for comparison, a SRC column specimen with steel ratio equal to the boxed I-shaped sectional CFT column specimen was prepared. If the seismic performance of the boxed I-shaped sectional CFT column is equal to or better than that of the SRC column, a new column element will be discovered and it is considered that there is a possibility the proposed boxed I-shaped sectional CFT column can be applied to the mega-column of the super high-rise building in the future.

2. Test program

In this study, two specimens were planned based on the mega column located at the ground floor and at the building perimeter. One is a boxed I-shaped sectional CFT column specimen, 14-CFT-0.3, and the other is a SRC column specimen, 14-SRC-0.3. The mechanical properties of steel plates and reinforcing bars used in these two specimens are listed in Table 1. The experimental parameters of the specimens are summarized in Table 2. The dimensions and reinforcement properties of either specimen are illustrated in Fig. 3. Either specimen has a sectional dimension of 180 mm x 90 mm and clear height of 800 mm. The depth-to-width ratio of column cross section, D/B, was set as 2.0 in accordance with the upper limit value of reference [7] in case of the column.

In general, steel ratio of the SRC column ranges between 3% and 15% [8-15]. However, the high steel ratio was select in this study; and structural steel ratios of 14-CFT-0.3 and 14-SRC-0.3 were set as 19.6% which was markedly beyond the usual range of SRC column. For the steel skeleton of the column of 14-CFT-0.3, three pieces of SS400 plates with thickness of 3.2 mm (PL-3.2) and two pieces of SN400B plates with thickness of 9 mm (PL-9) were joined together by butt welding. For the steel skeleton of the column of 14-SRC-0.3, three pieces of SN400B plates with thickness of 12 mm (PL-12) were connected together by butt welding, too. The

SS400 as mentioned above is a kind of material type standing for structural steel with grade of 400, which is similar to AISI 1018. It is defined in JIS G 3101 standard, which is a Japanese material standard for hot Rolled steel plates, sheets, strips for general structural usage based on Japanese Industrial Standard. The SN400B is a kind of hot rolled steel product used for construction or building in the standard of JIS G3136. In specimen

Table 1 – Mechanical properties of reinforcement

Categories	***a*** **(mm^2)**	f_y **(MPa)**	ε_y **(%)**	E_s **(GPa)**	σ_u **(MPa)**	ε_u **(%)**
4ϕ	13	627		203	850	25.1
D10	71	378	0.181	208	540	24.4
PL-3.2		376	0.164	229	467	38.3
PL-9		335	0.144	233	496	44.9
PL-12		331	0.149	222	496	48.6

Note : a = cross-sectional area, f_y = yield strength of steel, ε_y = yield strain of steel, E_s = modulus of elasticity, σ_u = ultimate strength, ε_u = ultimate strain.

Table 2 – Experimental parameters of specimens

Specimens	η_0 **= 0.3**	σ_B **(MPa)**	p_g **(%)**	p_w **(%)**	p_s **(%)**	**Reinforcement**
14-CFT-0.3	$N/(A_{sp}\cdot f_{yp}+A_c\cdot\sigma_B)$	66.3			19.6	Boxed I-shaped steel
14-SRC-0.3	$N/(A_{sp}\cdot f_{yp}+A_c\cdot\sigma_B+A_{sl}\cdot f_{yl})$	66.6	2.64	0.85		Longitudinal reinforcement + hoops + encased H-shaped steel

Note : η_0 = axial force ratio, σ_B = compressive strength of concrete cylinder, p_g = longitudinal reinforcement ratio, p_w = transverse reinforcement ratio for column in loading direction, p_s = steel plate ratio, N = axial load on column, A_{sp} = area of steel plate in cross-section, A_c = area of concrete in cross-section, A_{sl} = area of longitudinal reinforcement in cross-section, f_{yp} = yield strength of steel plate, f_{yl} = yield strength of longitudinal reinforcement.

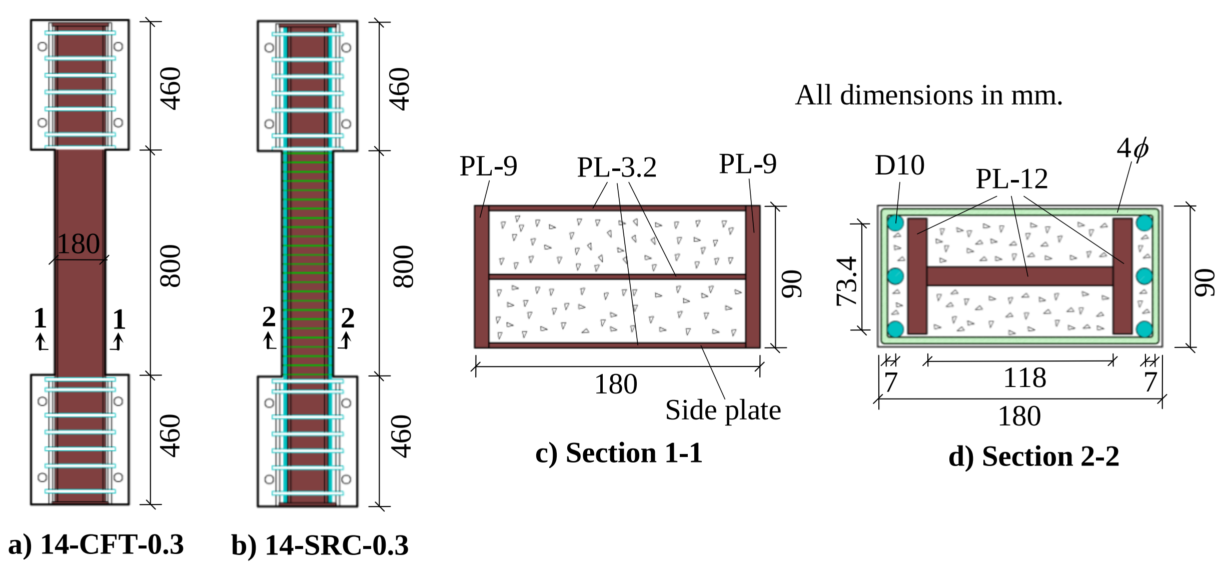


Fig. 3 – Dimensions and reinforcement properties of specimens

14-SRC-0.3, six D10 reinforcement bars (material type of SD295A) are used as longitudinal reinforcement with a longitudinal reinforcement ratio, p_g, of 2.63% based on reference [6]. In this specimen, transverse reinforcement bars consist of 4ϕ bars (material type of SUS304) spaced at 32.7 mm interval with transverse reinforcement ratio in loading direction, p_w, of 0.85%. Cyclic lateral displacements were applied to either specimen with fixed axial compressive force of 0.3N_u. The N_u is the axial compressive strength of the column, whose value is calculated based on the compressive strength of concrete cylinder and the yield strength of steel. However, the axial force ratio of 0.3 was determined based on the maximum axial force acting on the mega SRC column as shown in Fig. 1 for structural design [2].

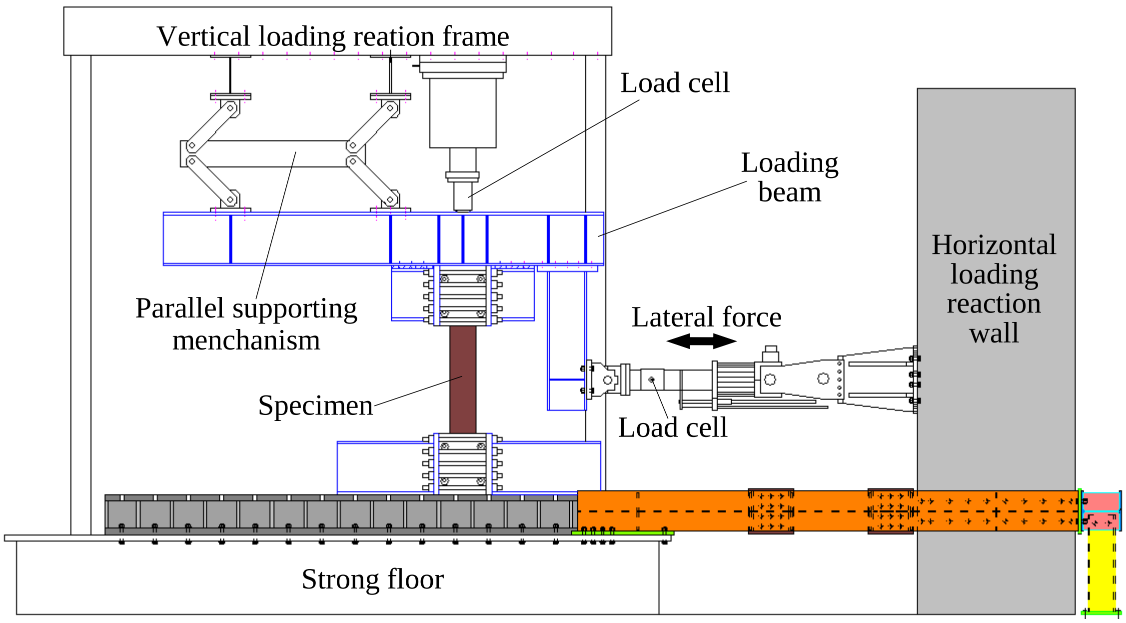


Fig. 4 – Details of test setup

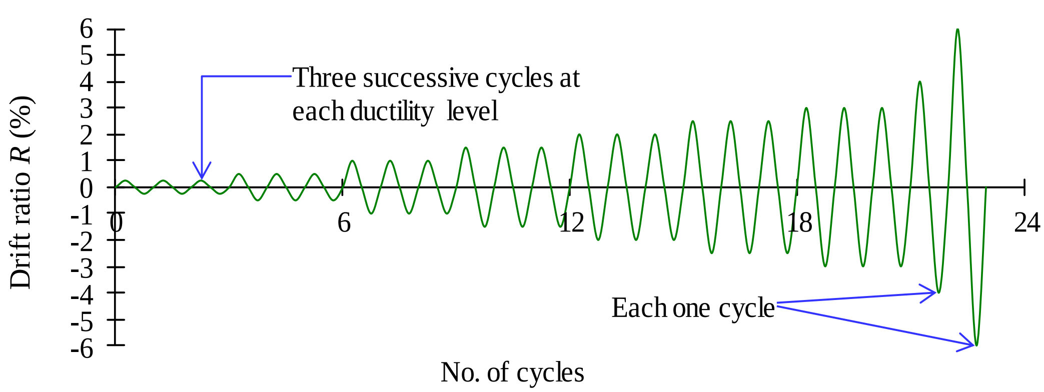


Fig. 5 – Loading program

The Ken-ken type test setup with parallel supporting mechanism developed by Japanese Building Research Institute is illustrated in Fig. 4. The parallel supporting mechanism maintained the horizontal loading beam to be parallel with strong floor and restrained the rotations of both top and bottom stubs of column specimen during the quasi-static cyclic tests. Lateral loading cycles under displacement control include three successive cycles at each drift ratio of R = 0.25, 0.5, 1.0, 1.5, 2.0, 3.0%. To investigate the behavior under the large deformations, the loading test is continued for R = 4.0% and 6.0% with one cycle for each as depicted in Fig. 5. The $R = \delta/h$ is the drift ratio of the column, where, δ is the story drift, and h is the clear height of the column.

3. Experimental results

The relationship between experimental lateral force, Q, and drift ratio, R, of each test specimen is shown in Fig. 6. In the Q-R curves, the dotted line represents the calculated flexural strength of the column based on the corresponding assumption of rectangular stress block as shown in Fig. 7 with yield strength of steel and compressive strength of concrete cylinder. First, the neutral axis of cross section is determined in term of the

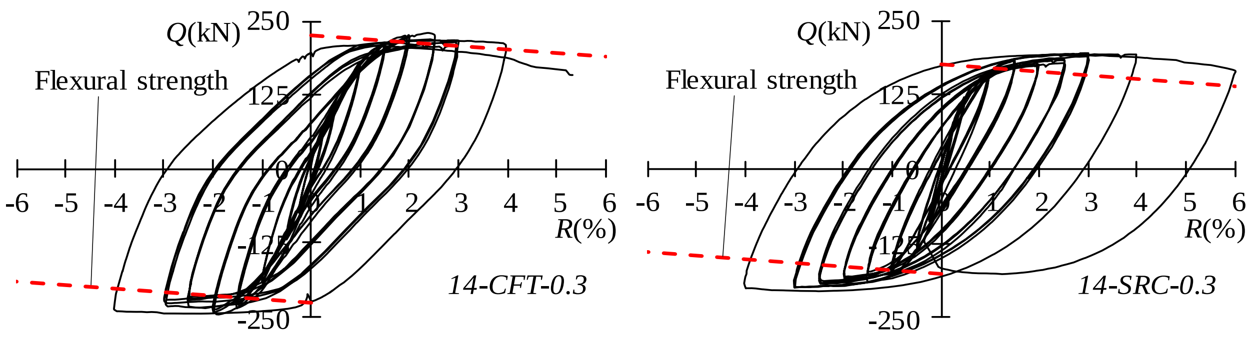
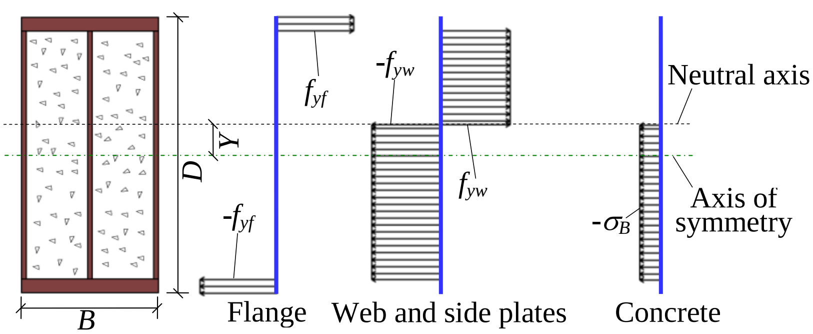
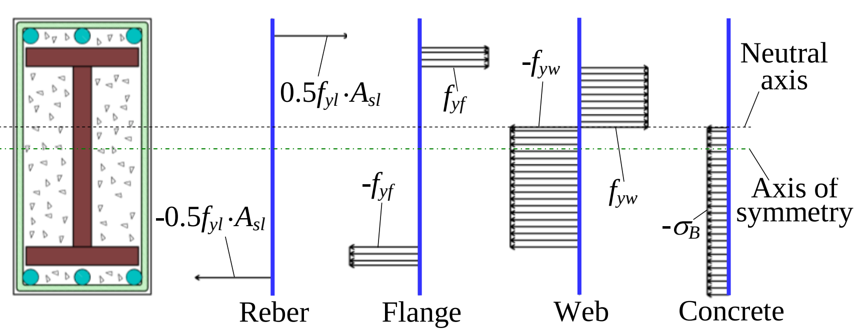


Fig. 6 – Measured Q-R relationships



a) 14-CFT-0.3



b) 14-SRC-0.3

where, B is the width of cross-section, D is the depth of cross-section, Y is the distance between the neutral axis and axis of symmetry, f_{yf} is the yield strength of flange, f_{yw} is the yield strength of web or side plate, σ_B is the compressive strength of concrete cylinder, f_{yl} is the yield strength of longitudinal reinforcement, and A_{sl} is the area of longitudinal reinforcement in cross-section.

Fig. 7 – Assumption of rectangular stress blocks for ultimate moment

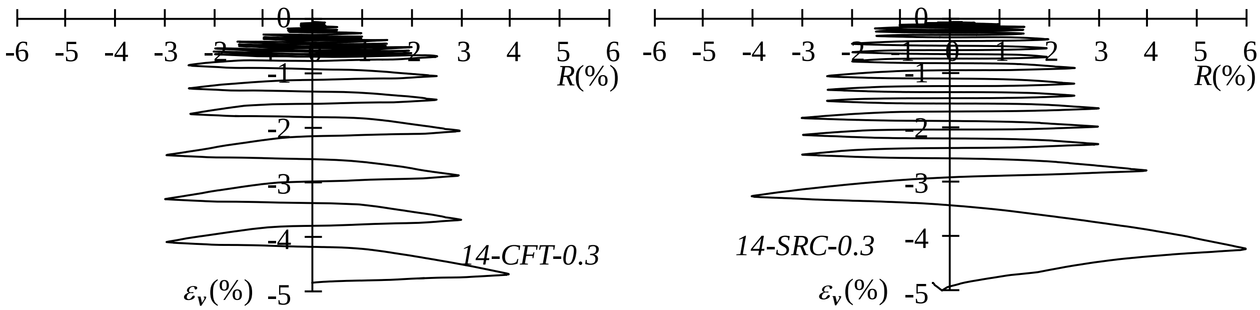
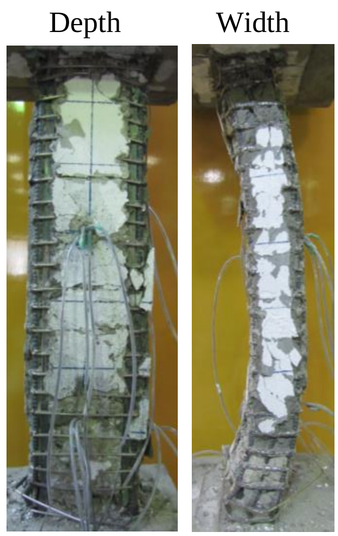


Fig. 8 – Measured ε_v-R relationships

a) 14-CFT-0.3



b) 14-SRC-0.3

c) Local buckling and crack of 14-CFT-0.3

d) Local buckling and broken hoops of 14-SRC-0.3

Fig. 9 – Photographs of specimens after tests

equilibrium condition of axial force on column. Second, ultimate moment of the cross section can be calculated depending on the determined neutral axis. Third, the flexural strength can be figured out based on the calculated ultimate moment. For either specimen, the experimental lateral load capacity exceeded the corresponding calculated flexural strength. The relationships between measured average axial strain, ε_v, and R of these two specimens are shown in Fig. 8. However, ε_v was measured until 5.0% due to capacity of displacement transducer. Failure pattern of specimens after tests are shown in Fig. 9.

In the specimen 14-CFT-0.3, at an early stage, the measured lateral force increased with the increase of drift ratio, and the hysteresis loops were almost overlapping together. When the drift ratio shifted from 0.25% to 0.5%, the strain of flanges at both top and bottom region of the column reached the yield strain. After the drift ratio of 2.0%, local buckling of the side plates at the top and bottom region of the column began to occur. As a result, the rapid increase of ε_v in the negative side was measured and lateral force decreased gradually. However, hysteretic curve showed stable flexural behavior before R reached 4.0%. While the drift ratio shifted from 4.0% to 6.0%, a crack near the welding joint of flange and side plate was observed at bottom end of the column (see Fig. 9 c)). After that, the experimental test was stopped since measurement for the drift ratio was not available.

On the other hand, in the specimen 14-SRC-0.3, the measured lateral force increased with the increase of drift ratio and the hysteresis loops were almost overlapping together at an early stage. This behavior was the same as the specimen 14-CFT-0.3. When the drift ratio was near 0.25%, rebars around critical section of bottom end of the column yielded, and strain of flanges at bottom region of the column approached the yield strain too. At the drift ratio of 1.0%, eye-catching bond cracks developed at boundary regions between the flanges of H-shaped steel and concrete. After the drift ratio of 1.5%, in the vicinity of formed bond cracks, the spalling of concrete began to occur and longitudinal reinforcement could be observed. Afterward, the in-plane deformation of hoops was observed at the drift ratio of 2.0%; the out-of-plane bending deformation of hoops occurred at the drift ratio of 2.5%; and buckling of longitudinal reinforcement, broken hoops and shear failure of the column were observed at bottom region of the column while the drift ratio was near 3.0%. However, there was no degradation of lateral load capacity at those time points due to contribution of encased H-shaped steel. Subsequently, local buckling of the flange at the bottom end of the column was also observed. Consequently, lateral force of 14-SRC-0.3 decreased gradually while the drift ratio shifted from 4.0% to 6.0%. After that, buckling of this specimen suddenly took place in the out-of-plate direction (see Fig. 9 b)) and instability phenomenon occurred during unloading. The lateral load capacity of 14-SRC-0.3 was lower than that of 14-CFT-0.3. But the progress of ε_v in the negative side (shortening of column axial length) for 14-SRC-0.3 was slower than that of 14-CFT-0.3.

According to the experimental result, lateral load capacity of boxed I-shaped sectional CFT column specimen 14-CFT-0.3 whose steel elements were set at the outer perimeter as much as possible was bigger than that of the conventional SRC column specimen 14-SRC-0.3. Furthermore, the calculated flexural strength of 14-CFT-0.3 is higher than that of 14-SRC-0.3. It was verified that the proposed boxed I-shaped sectional CFT column specimen shows better response than the conventional SRC column specimen, by focusing on the experimental lateral load capacity and calculated flexural strength. As a consequence, it can also be concluded that the seismic performance of the proposed boxed I-shaped sectional CFT column is better than or equal to that of the conventional SRC column. And, it is considered that there is a possibility the proposed boxed I-shaped sectional CFT column can be applied to the mega-column of super high-rise building in the future.

4. Conclusions

The conventional SRC column specimen and the proposed boxed I-shaped sectional CFT column specimen were tested under the reversed cyclic lateral force and constant axial force ratio at 0.3. The experimental results lead to the following conclusions:

(1) The proposed boxed I-shaped sectional CFT column specimen exhibited excellent seismic performance.

(2) The seismic performance of proposed boxed I-shaped sectional CFT column is better than or equal to that of conventional SRC column.

(3) It is considered that there is a possibility the proposed boxed I-shaped sectional CFT column can be applied to the mega-column of super high-rise building in the future.

(4) For conventional SRC column with depth-to-width ratio of 2.0 for column cross section which is subjected to larger drift ratio, the buckling of the column can occur also in the out-of-plate direction, even during unloading.

5. Acknowledgements

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