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# Structural characteristics of welded built-up square CFT column-to-beam connections with external diaphragms

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**Abstract.** Generally, a box tube, which is used for an existing square CFT structure, is made by welding four plates. The manufacturing efficiency of this steel tube is poor, and it also needs special welding technology to weld its internal diaphragm and the through diaphragm. Therefore, an interior-anchor-type square steel tube was developed using the method of cold-forming thin plates to prevent welding of the stress concentration position, and to maximize the section efficiency. And, considering of the flow of beam flange load, the efficiency of erection and the weldability of the diaphragm to thin walled steel column, the external diaphragm connection was selected as the suitable type for the welded built-up square CFT column to beam connection. And, an analytical study and tests were conducted to evaluate the structural performance of the suggested connection details and to verify the suggested equations for the connection details. Through this study, the composite effect of the internal anchor to concrete, the resistance and stress distribution of the connections before and after the existing column is welded to the beam, the effective location of welding in connection were analyzed.

**Keywords:** welded built-up square CFT column; external diaphragm; weld throat thickness; inner anchor.

## 1. Introduction

Currently, due to the increase in material and labor costs and the development of high-strength materials, the need for using materials with high efficiency has been rising (Zhang *et al*. 2007). Furthermore, the CFT structure has been gaining attention as a method of increasing the efficiency of the use of steel materials for structures such as high-rise buildings that require high resistance. The CFT structure is being called "the fourth structure," as it was developed after the RC, S, and SRC structures. The CFT structure is a steel structure that is filled with concrete. By combining the merits of different materials such as the steel tube and concrete, it improves the efficiency of material use as a structural system with an excellent structural property. The steel tube that is currently being used is shown in Fig. 1.

Fig. 1 (a) is a box-type steel tube made with four welded plates. It is mostly the type of steel tube

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made with thick plates. The cold-formed square column in Fig. 1 (b) is a square column that is made by cold-forming either two channels or one steel plate and then welding them together, which makes the steel tube thinner. Previous cold-formed square columns had a larger width-to-thickness ratio because thin steel plates were used. The welded built-up square CFT columns that Lee *et al*. (2005) recently developed, however, actively used materials that combine the effect of a steel plate and concrete by placing an anchor inside. The effect of the residual stress caused by cold-forming the plate edges and the welding heat that occurred during the welding of the four plates has been minimized by placing the welding area at the center of the square column, as shown in Fig. 2. Also, the internal anchor can reduce the effective width-to-thickness ratio of the steel plates with excessive width-to-thickness ratios.

In general, internal diaphragms, through-type diaphragms (Choi *et al*.2005, 2006), external diaphragms (Cheng and Chung 2003), and other types of diaphragms(Morino *et al*.(2001), De Nardin and El Debs (2004), Wu *et al*.(2007), Kim *et al*.(2008)) are used for previous CFT connections. Regarding the internal and through-type diaphragms, the internal anchor can complicate the connection details, which is a characteristic of the welded built-up square CFT column. Thus, in this study, a connection with an external diaphragm was used.

The *Guidelines and Explanation of Steel Tube Structure Design and Construction* (1990) and *Design and Construction Guidelines for Concrete-filled Steel Tube Structures* (1997), which were published by the Architectural Institute of Japan, specify the design standards for CFT column-to-beam connections with external diaphragms. Currently, Fujita *et al*.(1999), Cheng and Chung(2003) conducted a research on localized deformation, which included elastic and plastic behaviors, by conducting a cross-cyclic test on column-to-beam connections with external diaphragms. Shin *et al*.(2004) conducted an

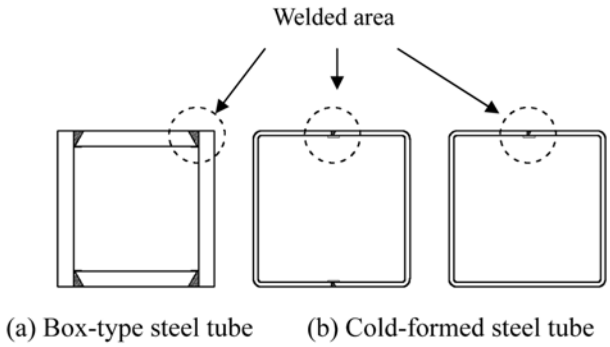



Fig. 1 Existing steel tube for CFT column

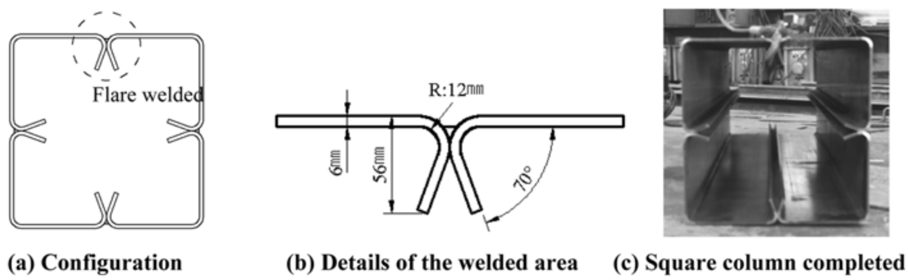



Fig. 2 Welded built-up square CFT column

experimental and analytical research of CFT column to H-section beam connections using vertical stiffener. Satish Kumar and Prasada Rao(2006) used C-shape channel as stiffener.

To apply these external diaphragms, this study suggests a design formula for deciding on the size of the external diaphragm connection area that suits the welded built-up square CFT column. Also, to minimize the effects of welding on steel tubes, which is characteristic of welded built-up square CFT columns that use thin plates, tests have been conducted by dividing the welding areas into the column-diaphragm and the column-beam flange, as shown in Fig. 3, and the effects of welding heat have been observed according to the extent of the welding.

The specimens were divided into the internal column of A and the external column of B, as shown in Fig. 4 (a), similar to the floor plan of a building, and it had four-way and three-way beam connections, as seen in Figs. 4 (b) and (c).

The test parameters included the welding of column to beam, the welding of column to diaphragm, the column-beam flange width ratio and the number of connected beam. In this study, considering of the flow of beam flange load, the efficiency of erection and the weldability of the diaphragm to thin walled steel column, the external diaphragm connection was selected as the suitable type for the welded built-up square CFT column to beam connection. And, an analytical study and tests were conducted to evaluate the structural performance of the suggested connection details and to verify the suggested equations for the connection details.

## 2. Resistance evaluation using a revised formula and FEM analysis

To decide on the details of the column to beam connection using the welded built-up square CFT column, a finite element analysis was performed with and without the use of column-beam flange welding and the extent of the welding of the column to the diaphragm as the variables. By analyzing the previous external diaphragm formula, the formula for the welded built-up square CFT column-beam diaphragm connection was suggested.

### 2.1 Revised formula

According to the AIK(2004) and the AIJ(1990), the following equations, Eqs. (1) and (2) are being used for short- and long-term loads(Loading states to be considered in allowable stress design are categorized into either long-term or short term loading state according to loading period). The thickness ratio (ts/t),

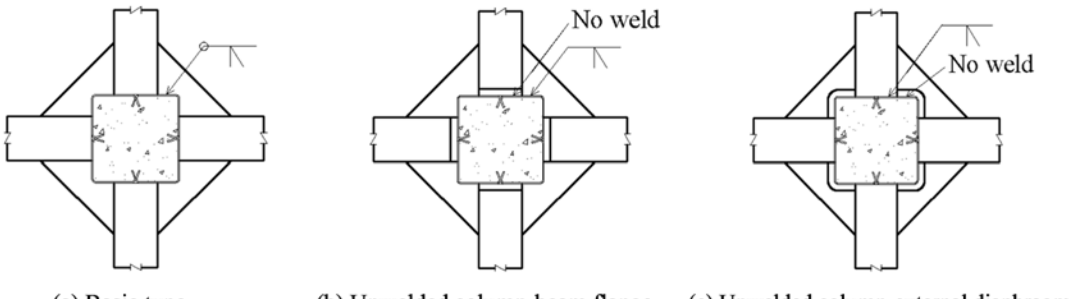



Fig. 3 Built-up square CFT column welded to external diaphragm connections

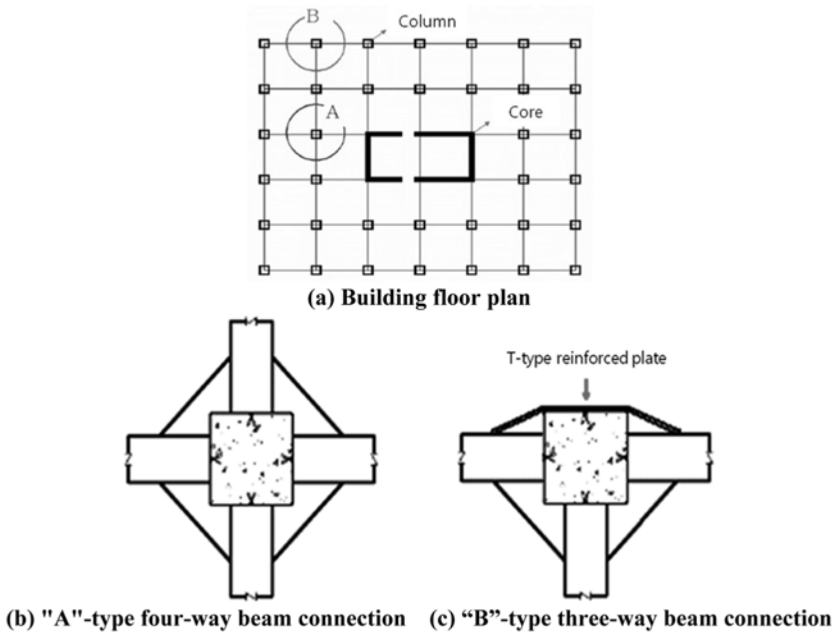



Fig. 4 External diaphragm column-beam connection details

however, of the diaphragm to the steel tube was 2.67 > 2 for the welded built-up square steel tube, which is beyond the acceptable range. Thus, the previous formula, as described below, should not be applied.

$$\text{Short-term loading state : Pa} = \frac{4}{\sqrt{3}} h_s t_s {}_s f_s + 2(4t + t_s) t_c f_t \tag{1}$$

$$\text{Long-term loading state : Pa} = 1.54 h_s t_s F_{df} + 1.33(4t + t_s) t F_{ct} \tag{2}$$

$$\text{Applicable range: } 20 \le B/t \le 50,\ 0.75 \le t_s/t \le 2.0,\ t_s \ge t_f$$

$$\text{Short-term: } h_s/B \ge 0.15 t_f/t_S,\ \text{Long-term: } h_s/B \ge 0.1 t_f/t_S$$

${}_s f_s$ : Allowable resistance of the beam flange, Allowable stress of the diaphragm
${}_c f_t$ : Allowable stress of the column steel tube,
$F_{dt}$ : Design yield strength of the diaphragm
$F_{cy}$ : Design yield strength of the column steel tube

Therefore, only a slight stress was transferred directly to the column made of thin plates. Thus, deleting the resistance transferred through the column side from Eq. (2) and using the formula only with the resistance of the diaphragm is more fail-safe. The revised resistance formula of the external diaphragm is the same as Eq. (3). Using the revised formula, hs was set as 135 mm for □ 400 × 6 welded built-up square CFT column and a PL 200 × 16 beam flange, and hs was set as 200 mm for □ 400 × 9 column and a PL 300 × 20 beam, as shown in Table 1.

$$\text{Long-term loading state : Pa} = 1.54 h_s t_s F_{dt} \tag{3}$$

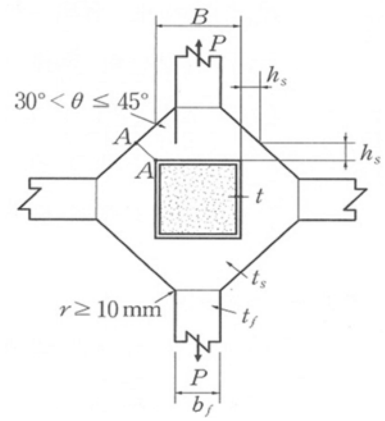



Fig. 5 External diaphragm shape configuration

### *2.2 Resistance Evaluation through FEM Analysis*

Welded built-up square CFT columns use thin plates with the same thicknesses or with thicknesses below 10.5 mm. Thus, depending on their thickness, they can be welded for more to a beam flange and a diaphragm that are thicker than they are. Since the diaphragm receives all the resistance of the beam flange in the revised formula in paragraph 2.1, however, it was decided that the welding of the steel tube to the beam flange and the steel tube diaphragm can be done via partial-penetration welding instead of full-penetration welding. To evaluate the effects of each variable before the structural testing, the structural analysis was performed with the universal finite element analysis program ANSYS 10.0.

#### *2.2.1 Analysis target*

For the target of the analysis, a □ 400 × 6 (SM490) steel tube and a PL 200 × 16 beam flange were used, and the diaphragm size (hs) was set at 135 mm. As seen in Fig. 4, this was done on the simple tension connection of the beam connected only in the four-way and three-way directions. The interpretation parameters were the welding of the column to the beam flange, the welding of the column to the diaphragm, and the T-type reinforced plate width.

#### *2.2.2 Interpretation model*

For the interpretation model, the Shell43 element with six degrees of freedom (displacement and rotation on the X, Y and Z axes) per joint for the steel material with four joints was used, as seen in Fig. 6. For the stress-strain characteristics of the steel, the yielding criteria of the Von Mises and Bi-linear Kinematic Hardening Model were used. The tangent modulus after the steel yielding was assumed as 1/100 of the modulus of elasticity. As seen in Table 2, the strength values of the general steel material were used.

Table 1 Deciding width (hs) of the external diaphragm

| Column | Beam Flange | B/t | ts/t | hs/B | Diaphragm (mm) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Width (hs) | | Thicknessts |
| | | | | | Prev. | Appl. | |
| □ 400×6 | PL 200×16 | 67 | 2.67 | 0.33 | 120 | 135 | 16 |
| □ 400×9 | PL 300×20 | 44 | 2.22 | 0.50 | 180 | 200 | 20 |

### 2.2.3 Interpretation results

(1) Column-beam flange and column-diaphragm welding

Fig. 7 shows the load-displacement relations of the column and beam flange welding and the column and diaphragm welding. Moreover, the Von Mises stress distribution of the beam flange yielding load is shown in Fig. 8. The interpretation results show that the welding of the column to the beam flange had no effect on the resistance and strength of the connection, but the welding of the column to the diaphragm significantly affected the strength and resistance of the column to beam connection. Also, even if the load of the beam flange was entirely transferred to the opposite beam flange through the diaphragm, it was seen that the welding of the diaphragm to the column was definitely required.

(2) T-type reinforced plate

The preliminary interpretation of the basic type of beam flange that was connected in a four-way

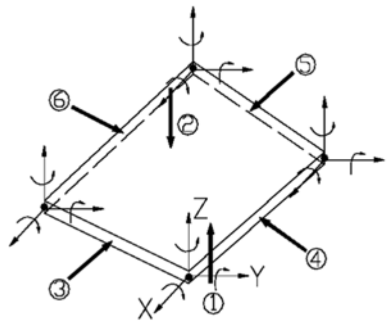



Fig. 6 Shell 43 factor

Table 2 Material characteristics of simple tension interpretation model factors

| Category | Steel Type | Fy (MPa) | Elast. Mod. (GPa) | Tangent Mod. (GPa) | Poisson Rate |
|---|---|---|---|---|---|
| Steel tube | SM490 | 330 | 210 | 2.1 | 0.3 |
| Diaphragm<br>Beam flange | SS400 | 240 | | | |

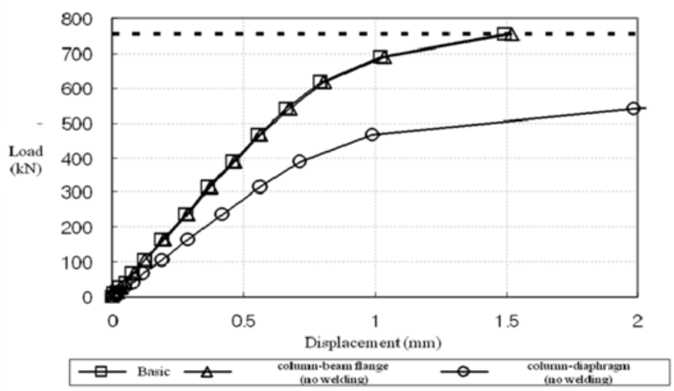
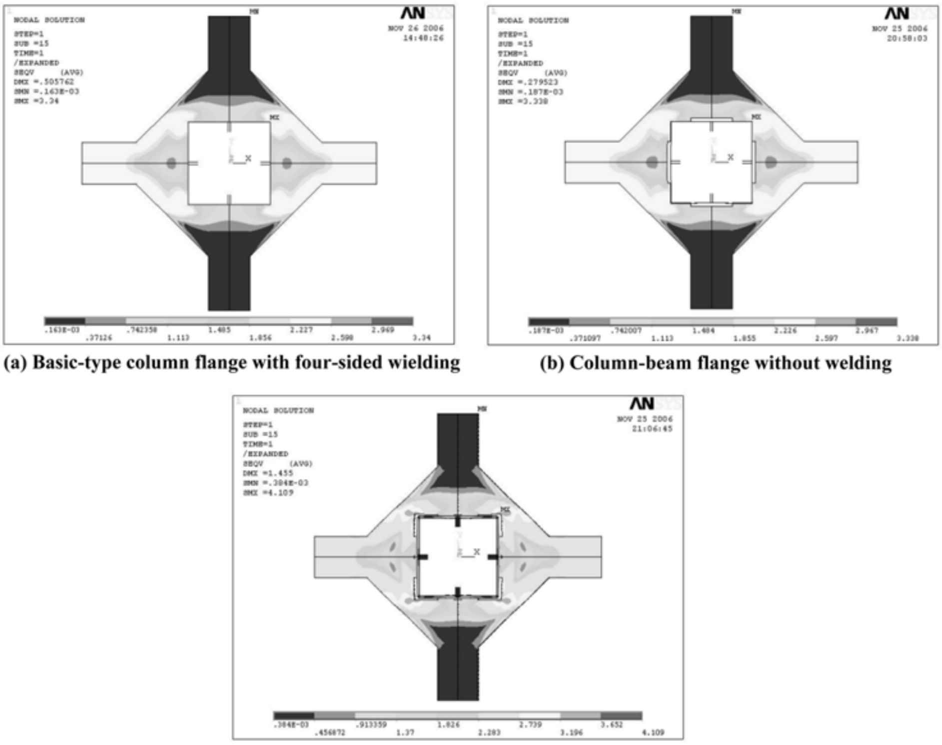



Fig. 7 Load-displacement relations according to the column-beam flange and the column-diaphragm welding



**(a) Basic-type column flange with four-sided wielding** **(b) Column-beam flange without welding**

**(c) Column-diaphragm without welding**

Fig. 8 Stress distribution according to the column-beam flange and the column-diaphragm welding

direction and of the T-type reinforced plate simple tension connection that was connected to the beam flange in a three-way direction showed a stable structure behavior, similar to the basic type when the width of the T-type reinforced plate was 60% larger than the width of the beam flange. Fig. 9 shows the load-displacement relationship of the simple tension connection of the T-type reinforced plate with a width of 60%. Moreover, the Von Mises stress distribution on the beam flange yielding load is shown in Fig. 10.

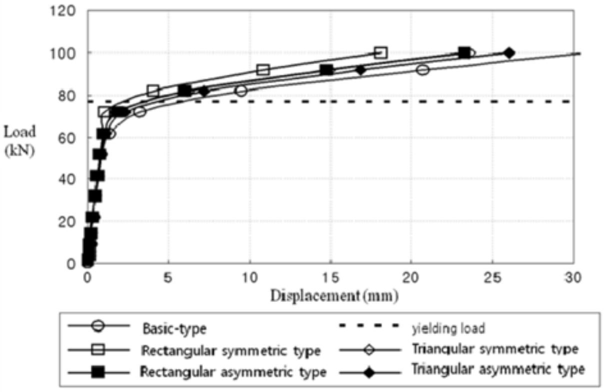
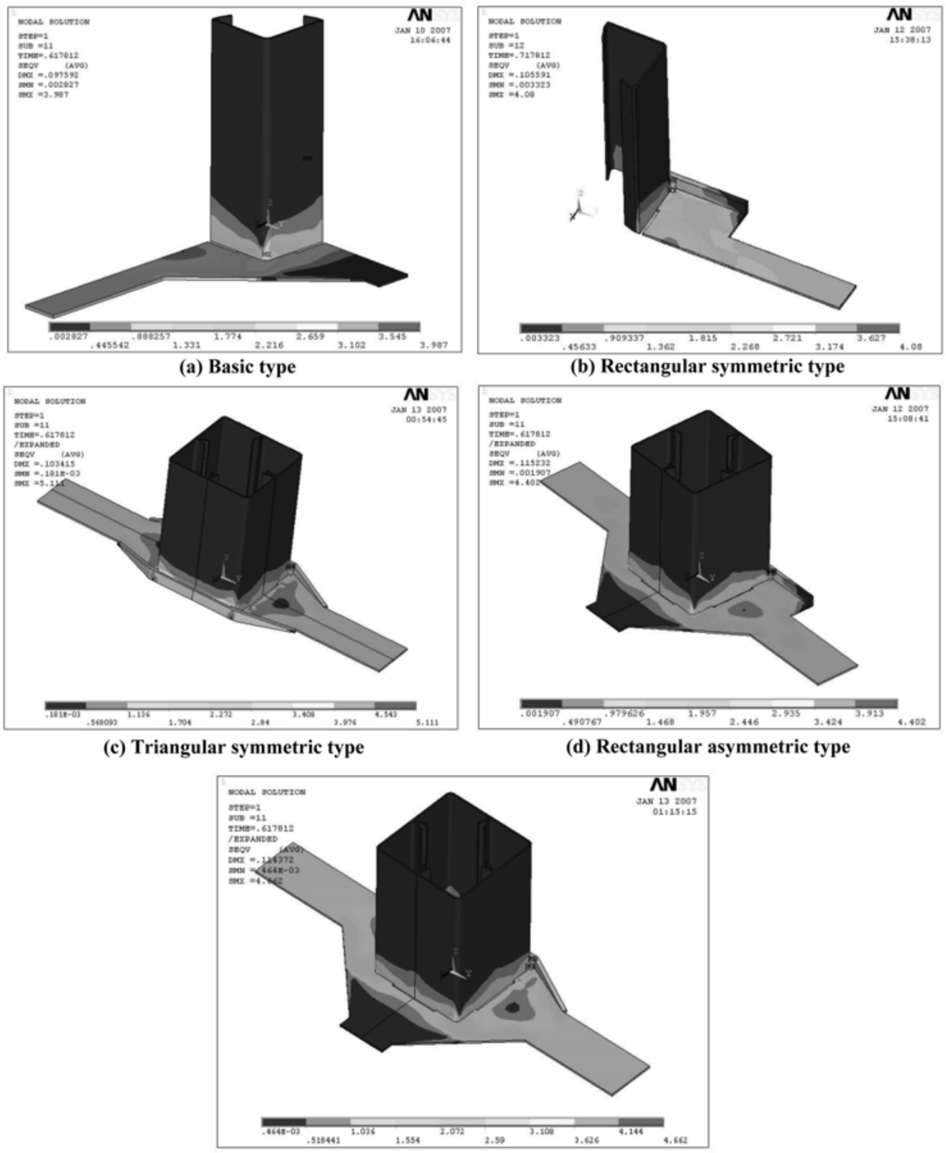



Fig. 9 Load-displacement relations according to the diaphragm type

## 3. Simple tension-type testing

To decide on the details of the welded built-up square CFT column-beam external diaphragm connection, its structural behavior was evaluated by choosing specimens with different variables in terms of the column-beam flange welding, the column-diaphragm welding extent, the column and beam flange width ratio, the three-way column to beam connection structural resistance evaluation, and the external diaphragm.



(a) Basic type

(b) Rectangular symmetric type

(c) Triangular symmetric type

(d) Rectangular asymmetric type

(e) Triangular asymmetric type

Fig. 10 Stress distribution according to the diaphragm shape

### *3.1 Testing plan*

For this research, a total of nine simple tension specimens were made to evaluate the structural characteristics of the T-type reinforced plate installation of the welded built-up square CFT column connection for cases of column-beam flange welding use or non-use, column-diaphragm welding extent, and when the beam was connected in a three-way direction.

The specimen types are shown in Table 3, and the horizontal and cross-section views of each subject are shown in Fig. 11 with detailed measurements. Except for specimen No. 7, for which the CFT column without anchor was used, the welded built-up square CFT columns were used for the rest of the columns. The size of the used column was SM490 □ -400 × 400 × 6, except for the No. 5 specimen, the size of which was SM490 □ -400×400×9. Regarding the beam flange, SS400 1050×200×16 was used for all the specimens, except for specimen No. 5, for which SS400 1050×300×20 was used.

The formula suggested in paragraph 2.1 was used so that each specimen's hs became 200 mm or 135 mm. For the strength of the concrete-filled steel tube, a 28 day compression strength of 30 MPa was planned. Comparing the specimens in terms of their variables, HT-1 and HT-2 were planned for application to the use or non-use of welding for the column-beam flange, and HT-2 and HT-3 were planned for application to the determination of the column-diaphragm welding extent. Also as an unfilled specimen, HT-4 was planned for use in comparing and analyzing the anchor effect that took place in the concrete-filled HT-2 and the rib. HT-5 was planned for use in evaluating the appropriateness of the diaphragm strength by increasing the beam flange and diaphragm thickness. HT-6 and HT-7 were planned for use in evaluating the resistance of the welded-form square column and the CFT column without anchor when the diaphragm was not installed therein. Lastly, HT-8 and HT-9 were planned for connection with beams from three-directions. In Fig.11(e), which is a detail of specimen, It is considered for design that the thickness(16 mm for HT-8 and HT-9)and the width of the T-type reinforce plate are the same thickness of beam flange and 60%(120 mm for HT-8 and HT-9) of the beam flange width, respectively.

Table 3 Specimen types

| Specimen Num. | Column (SM490) □ -400×6 | Beam Flange (SS400) | | Diaphragm (SS400) | | Flange Welding | Column and Diaphragm Welding (): Welding thickness <>: T-type reinforced plate width | 30 MPa Filled Concrete |
|---|---|---|---|---|---|---|---|---|
| | | Wdth (mm) | Thck (mm) | Wdth (mm) | Thck (mm) | | | |
| HT-1 | Welded built-up square CFT column | 200 | 16 | 135 | 16 | ○ | 1(6 mm) | ○ |
| HT-2 | | 200 | 16 | 135 | 16 | × | 1(6 mm) | ○ |
| HT-3 | | 200 | 16 | 135 | 16 | × | 1/2(3 mm) | ○ |
| HT-4 | | 200 | 16 | 135 | 16 | × | 1(6 mm) | × |
| HT-5 | | 300 | 20 | 200 | 20 | × | 1(6 mm) | ○ |
| HT-6 | | 200 | 16 | - | - | ○ | - | ○ |
| HT-7 | CFT column without anchor | 200 | 16 | - | - | ○ | - | ○ |
| HT-8 | Welded built-square CFT column | 200 | 16 | 135 | 16 | × | 1 (6 mm) <120> | × |
| HT-9 | | 200 | 16 | 135 | 16 | × | 1 (6 mm) <120> | ○ |

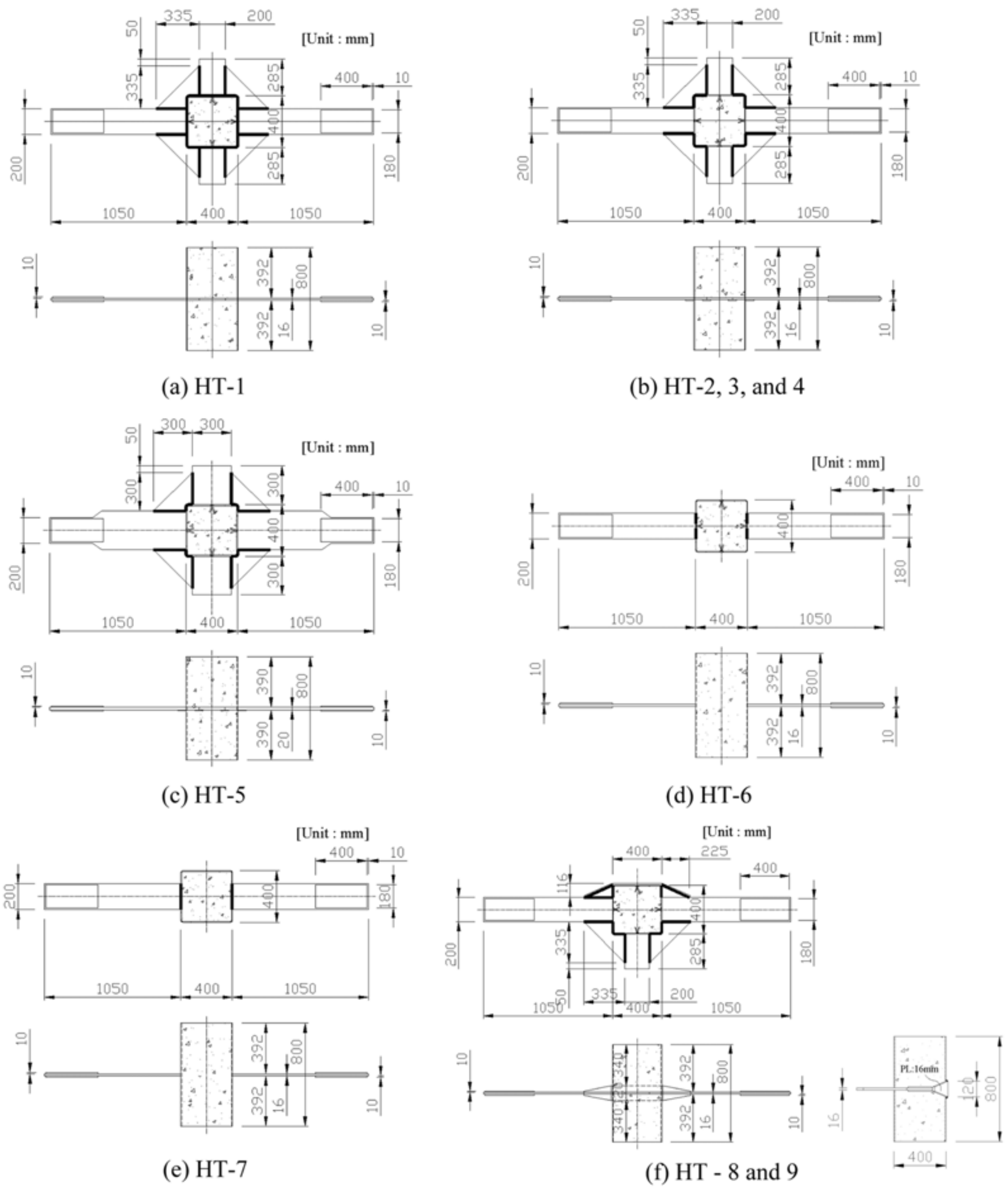



Fig. 11 Horizontal and cross-section views of the specimen

## 3.2 Testing plan

### 3.2.1 Displacement and strain measurement plan

To measure the displacement, the gauge length was set at 1,200 mm, as seen in Fig. 12 (b). Moreover, using a stud bolt, a L-shape thin plate was installed on the upper-lower beam flange, and a 100 mm LVDT was installed on the upper and lower parts, after which the axial displacement was measured.

Also, to evaluate the beam flange and external diaphragm strain changes according to the loading, 5-

11 strain gauges (W.S.G) were installed per specimen, as seen in Fig. 13, three on the beam flange, two to three on the diaphragm, four on the T-type reinforced plate, etc. In the areas where the gauge was installed, the outer layer was first removed with a sand grinder, after which it was further ground smoothly with sandpaper and wiped free of dust using alcohol.

For the beam flange, two gauges were placed 350 mm to the left and right sides of the column, and one gauge was placed at the center. The same process was applied to all the specimens. Two gauges were installed when the diaphragm width was 135 mm in the diagonal direction on the upper part of the diaphragm, and three gauges were installed when the diaphragm width was 200 mm. For the T-type

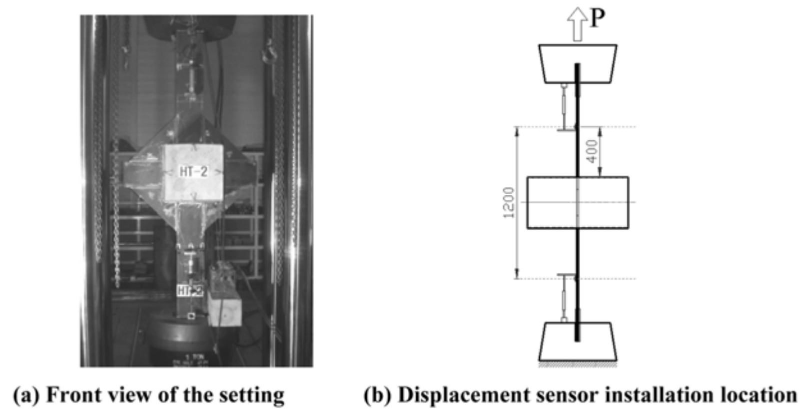



Fig. 12 Specimen setting

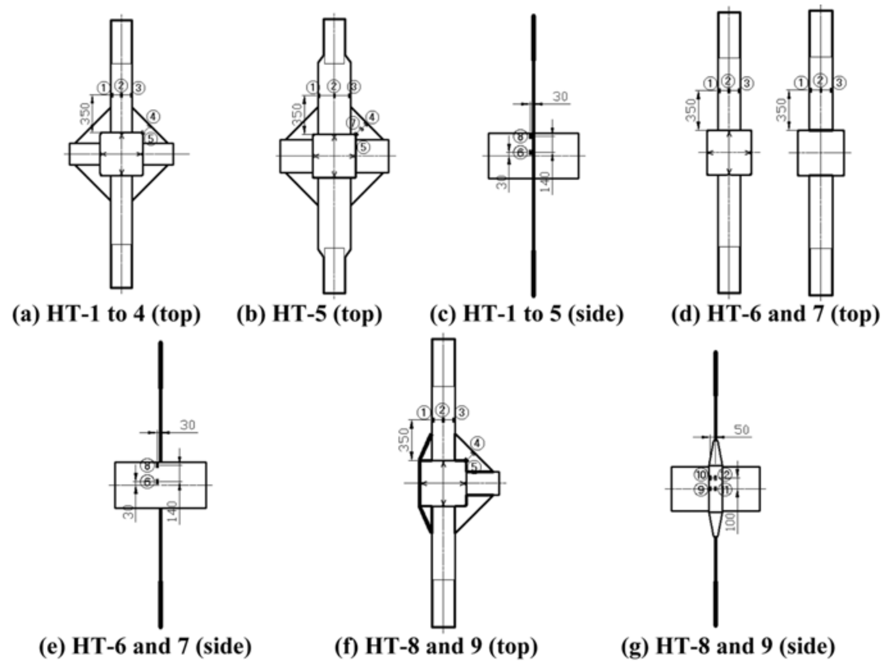



Fig. 13 Strain sensor gauge installation location

specimen, a total of four gauges were added, with one installed at the center and one at the upper area of the horizontal plate.

Note: Strain gauge installation location
1-3: Beam flange
4,5,7: External diaphragm
6,8: Steel tube
9-12: T-type reinforced plate

### 3.2.2 Loading

For the loading, tension force was applied using the position control at a loading speed of 0.015 mm/sec until the checking failure mode, after the maximum load was passed, using the 3,000 kN hydraulic test machine (U.T.M.) of the Research Institute for Information Science and Technology (RIST).

## 3.3 Material testing

To find out the mechanical properties of the steel materials used in this test, a tension test was performed on three specimens, using the KS B 0802 standard method. The results are shown in Table 4. Also, the compression strength test result on the concrete was 22.06 MPa, which was lower than the expected 30 MPa, as shown in Table 5. The effect of the concrete strength was neglected, however, because the purpose of the research was to evaluate the behavior of the simple tension connection that was transferred only via the resistance of the outer diaphragm of the beam flange loading.

## 3.4 Test result

The test results on the nine specimens are as follows. Only the beam flange was idealized and considered affected by the tension strength on the welded built-up square CFT column to beam connection.

### 3.4.1 Load-displacement curve

The Py value of 832 kN was the beam-flange yielding resistance of all the specimens, except for HT-5

Table 4 Tested mechanics of materials

| Category | Steel Type | Thickness (mm) | Yielding Stress Fy (MPa) | Ultimate Tension Stress Fu (MPa) | Overstrength Factor Fy /Fu(%) | Strain (%) |
|---|---|---|---|---|---|---|
| Steel tube | SM490 | 6 | 414 | 535 | 78.5 | 27.7 |
| | | 9 | 383 | 492 | 77.8 | 28.8 |
| Beam flange<br>Diaphragm<br>Vertical plate | SS400 | 16 | 260 | 423 | 61.4 | 31.5 |
| Beam flange<br>Diaphragm | | 20 | 261 | 432 | 60.4 | 29.9 |

Table 5 Compression strength of concrete

| Concrete specimen | 7 Days (MPa) | 14 Days (MPa) | 28 Days (MPa) |
|---|---|---|---|
| Ave. | 13.70 | 17.05 | 22.05 |

(20 t). The value was a result of the multiplication of the yield strength of 260MPa, which was the test result of the 16t specimen, by the size of the cross-section area of the beam flange. Fig. 15 shows the loading displacement relationship of the welded built-up square CFT column subject in the simple tension test.

In Fig. 14, the HT-1 to HT-4 and the HT-8 and HT-9 specimen showed similar types of loading-displacement relationships but differed in their maximum load and ductility according to the variables. Because the beam flange size of HT-5 was larger, it was able to accommodate a greater load than the other 16t specimens, but it showed less ductility. HT-6 and HT-7, which did not have an external diaphragm, showed much lower strength and resistance than the external diaphragm specimens.

### 3.4.2 Resistance and failure types

The initial stiffness, designed resistance, maximum resistance, maximum displacement, and connection failure types of the simple tension specimens are shown in Table 6. Fig.15 shows the tangential method for the decision of the yield load(Py) of specimens. In Fig.15, the initial stiffness is a gradient between 0 to 1/3Py and the yield load(Py) is where initial stiffness(K) of load-displacement curve is met with the

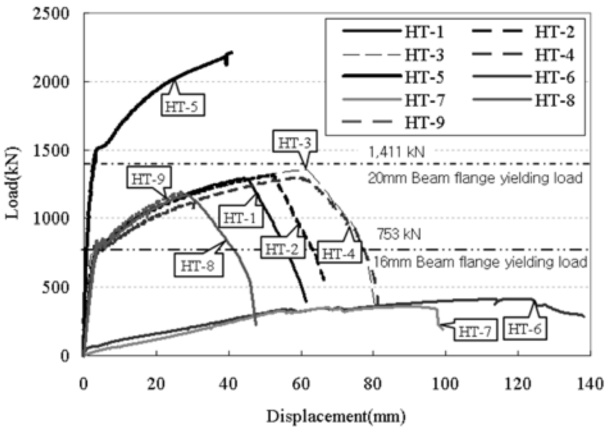



Fig. 14 Load-displacement curve of the simple tension specimens

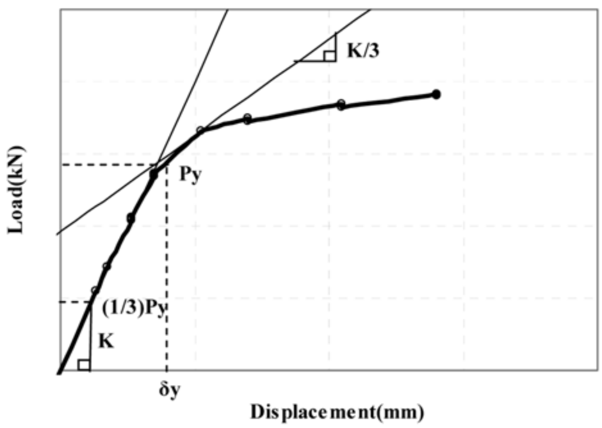



Fig. 15 Yield resistance(Py) by a tangential method

tangent line with the gradient of K/3.

And, Fig.16 shows the pictures of the failures of specimens. All the external diaphragm specimens showed fractures on their beam flange, whereas the simple column-beam flange without an external diaphragm showed a failure after the yielding on the column-beam flange connection. For HSS connections a connecting face deformation of 1% of the main member width (B) has generally been used as a serviceability deformation limit, as given by IIW ~1989. Therefore, the yield strengths of HT-6 and HT-7 was calculated using IIW(1989) and represented in Table 6.

## 4. Analysis and consideration

In this research, a total of nine real-scale loading simple tension specimens were made, and the structure test results were analyzed to suggest connection details for welded built-up square CFT column-beam external diaphragms with the following variables: the column-beam flange welding, the extent of welding of the column to the diaphragm, the effect of the column to the beam flange width ratio, the three-way column to beam connection, the use or non-use of an external diaphragm, and the filling and non-filling with concrete.

### 4.1 Column and beam flange welding

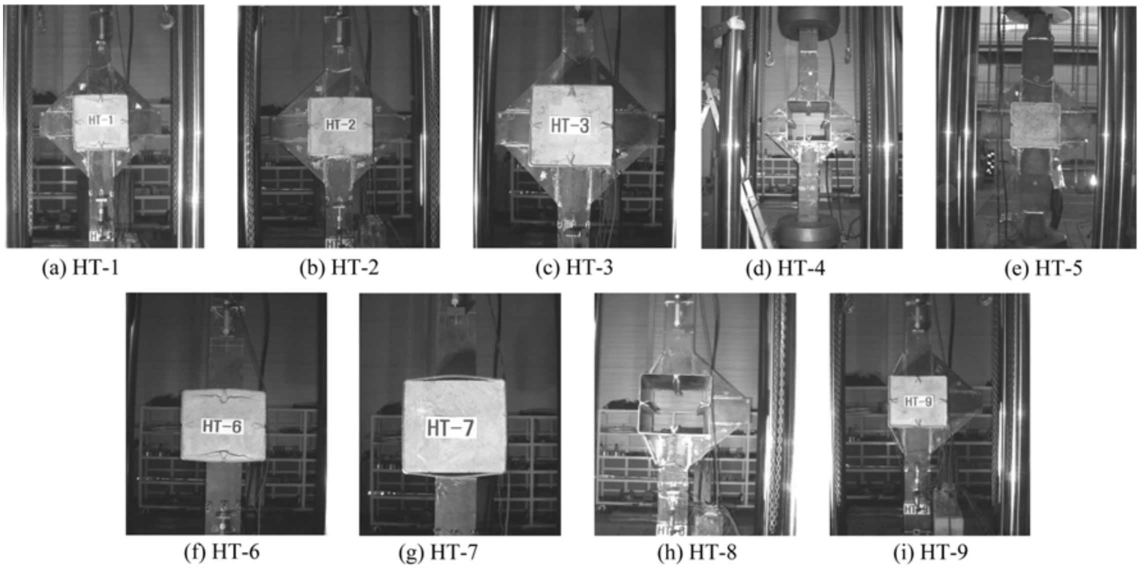
As seen in Table 7, HT-1, which had a welded column-beam flange, showed 13% higher initial stiffness than HT-2. HT-1 and HT-2 showed almost identical resistance values in their yielding load and their maximum resistance, though. Thus, it was decided that the welding of the column to the beam flange could be omitted when considering the yielding load and the maximum resistance.

### 4.2 Extent of welding of the diaphragm to the column

Between the specimens with a welding extent of 1 (welding thickness: 6 mm) and the specimens with a welding extent of 1/2, the initial stiffness was 18% higher in the subjects with a welding thickness of 1/2, whereas there were no significant differences between their yielding load and their maximum resistance. Thus, with respect to the connection that was designed to withstand the full weight of the beam flange, it was seen that the welding thickness could be reduced to ½ (3 mm) without a significant difference.

Table 6 Test results

| Specimen | Initial Stiffness (kN/mm) | Loading (kN) | | | Failure Type |
|---|---|---|---|---|---|
| | | Design Res. | Yield Res. | Max. Res. | |
| HT-1 | 333 | 753 | 803 | 1,291 | Beam flange fracture |
| HT-2 | 290 | 753 | 799 | 1,311 | Beam flange fracture |
| HT-3 | 341 | 753 | 819 | 1,355 | Beam flange fracture |
| HT-4 | 268 | 753 | 805 | 1,300 | Beam flange fracture |
| HT-5 | 518 | 1,411 | 1,515 | 2,210 | Beam flange fracture |
| HT-6 | 131 | 753 | 71 | 414 | Column fracture |
| HT-7 | 9 | 753 | 36 | 357 | Column fracture |
| HT-8 | 251 | 753 | 818 | 1,172 | Beam flange fracture |
| HT-9 | 278 | 753 | 836 | 1,191 | Beam flange fracture |



(a) HT-1 (b) HT-2 (c) HT-3 (d) HT-4 (e) HT-5
(f) HT-6 (g) HT-7 (h) HT-8 (i) HT-9

Fig. 16 Pictures of the specimen failures

### *4.3 Connection resistance before/after concrete filling*

#### *4.3.1 Initial stiffness and resistance comparison*

The specimens HT-4 that was not filled with concrete showed 8% less initial stiffness than the concrete-filled test material HT-2, but their yield resistance and maximum resistance were almost identical. Therefore, it was seen that the connection could adequately transfer the beam flange resistance when the connection was unfilled with concrete and that the infill concrete of columns has no effect on the strength of the specimens.

#### *4.3.2 Strain ratio comparison of steel tubes*

To determine the effects of the filling and non-filling of the connections with concrete, the values of the strain gauges installed on the sides of HT-2 and HT-4 were compared and analyzed. As seen in Fig. 17, the maximum strain ratio of HT-2 was $270 \times 10^{-6}$, and that of HT-4 was $1{,}101 \times 10^{-6}$, which was four times higher. HT-4 also showed a strain ratio that was more than twice HT-2's maximum strain. From

Table 7 An effect of welding between column and beam flange

| Specimen | Init. Stiffness (kN/mm) | Init. Strength Ratio (%) | Yield Load (kN) | Yield Load Ratio (%) | Max. Resist. (kN) | Max. Resist. Ratio (%) |
|---|---|---|---|---|---|---|
| HT-1 | 333 | 100 | 803 | 100 | 1,291 | 100 |
| HT-2 | 290 | 89 | 799 | 99 | 1,311 | 102 |

Table 8 An effect of welding between column and diaphragm

| Specimen | Initial Stiff. (kN/mm) | Initial Stiff. Ratio (%) | Yielding Load (kN) | Yield. Load Ratio (%) | Max. Resist. (kN) | Max. Resist. Ratio (%) |
|---|---|---|---|---|---|---|
| HT-2 | 290 | 100 | 799 | 100 | 1,311 | 100 |
| HT-3 | 341 | 118 | 819 | 103 | 1,355 | 103 |

Table 9 An effect of concrete filling

| Specimen | Initial Stiffness (kN/mm) | Initial Stiff. Ratio (%) | Yielding Load (kN) | Yield. Load Ratio (%) | Max. Resist. (kN) | Max. Resist. Ratio (%) |
|---|---|---|---|---|---|---|
| HT-2 | 290 | 100 | 799 | 100 | 1,311 | 100 |
| HT-4 | 268 | 92 | 805 | 101 | 1,300 | 99 |

these results, it was seen that since HT-4 was empty, it could not restrain the strain of the steel tube, which resulted in more strain on the steel tube than with HT-2. The beam flange load effect on the steel tube was considered small, however, even when it was unfilled with concrete, because the steel tube's strain ratio did not reach the yielding strain rate of $2,000 \times 10^{-6}$.

### 4.4. Stiffness and resistance of the three-way connection

Comparing the basic four-way beam connection specimen HT-1 with HT-8 and HT-9, HT-1 had a 17-25% lower initial stiffness and an 8-9% maximum resistance but showed 2-4% higher maximum resistance in its yielding load. Likewise, the three-way beam connection specimens had a weak axis when such was reinforced with the T-type reinforced plate, and showed the same or a higher yielding load as or than the four-way column to beam connection that had identical shapes on its four sides. Thus, it was concluded that the three-way connection could be used. On the other hand, the fracture behavior of the HT-8 and HT-9 specimens that had a T-type reinforced plate width that was 60% of the beam flange width resulted in beam flange failure. Thus, it was deemed that increasing the width and thickness of the T-type reinforced plate would not significantly increase its stiffness and resistance. Also, the three-way beam connection specimen that was unfilled with concrete showed a yielding load and a maximum resistance that were similar to those of the concrete-filled specimens. Thus, it was seen that the resistance of the beam flange could be adequately transferred when it is not filled with concrete.

### 4.5 Sharing resistance of the internal anchor and the external diaphragm

To evaluate the performance of the internal anchor of the welded built-up square CFT column, the test results of HT-6 and HT-7 were analyzed. HT-7s initial stiffness was only 6.9% of that of HT-6, and

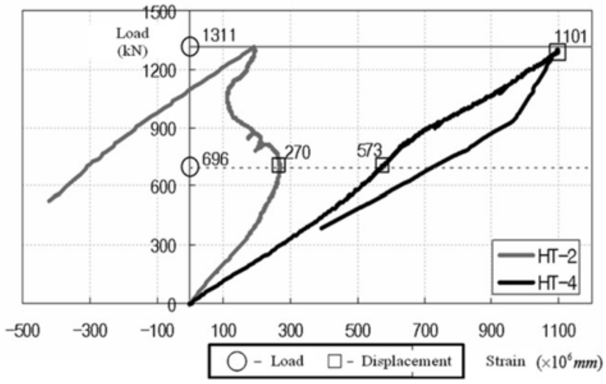



Fig. 17 Comparison of the column strain ratios

Table 10 Comparison of connections with four-way and three-way beam

| specimen | Init. Stiff. (kN/mm) | Init. Stiff. Ratio (%) | | Yield. Load (kN) | Yield. Load Ratio (%) | | Max. Resist. (kN) | Max. Resist. Ratio (%) | |
|---|---|---|---|---|---|---|---|---|---|
| HT-1 | 333 | - | 100 | 803 | - | 100 | 1,291 | - | 100 |
| HT-8 | 251 | 91 | 76 | 818 | 98 | 102 | 1,172 | 98 | 91 |
| HT-9 | 278 | 100 | 83 | 836 | 100 | 104 | 1,191 | 100 | 92 |

HT-6 showed a 14% larger resistance in its maximum resistance. Comparing HT-1 to HT-6 and HT-7, which had no external diaphragms, HT-6 showed a initial stiffness of 39% and a maximum resistance of 32% compared with HT-1. These results show that the external diaphragm had a major role in increasing the resistance, and it was deemed that for connections without external diaphragms, the steel tube's resistance range must be maintained.

### 4.6 Width ratio effect of the column/ beam flange

By comparing the specimen HT-2 with the column-to-beam-flange width ratio of 50% and the extended-type specimen HT-5 with the ratio of 75%, the effect of the column-to-beam-flange width ratio was analyzed and is stated in Table 12. Table 12 shows that the rate of the yielding load on the design yield resistance of the specimens with different width ratios of 50% and 75% resulted in an 106%-107%. Thus, it was deemed that the width ratio effect on the transferring load of the beam flange was small.

### 4.7 Verification of the plausibility of the revised formula

The results of the application of the design formula to the decided width of the CFT column external diaphragm using the thin steel tube that was suggested in this research show that all the beam flanges were fractured on the external diaphragm specimens. Thus, the suggested design formula for deciding on the external diaphragm width, ($Pa = 1.54h_st_sF_{dt}$), was shown to be fail-safe. It is also concluded that the suggested design formula can be used for welded built-up square CFT column to beam connections.

## 5. Conclusions

In this study, considering of the flow of beam flange load, the efficiency of erection and the weldability of the diaphragm to thin walled steel column, the external diaphragm connection was

Table 11 The performance of the internal anchor

| specimen | Init. Stiff. (kN/mm) | Init. Stiff. Ratio (%) | | Yield. Load (kN) | Yield. Load Ratio (%) | Max. Resist. (kN) | Max. Resist. Ratio (%) | |
|---|---|---|---|---|---|---|---|---|
| HT-1 | 333 | - | 100 | 803 | 100 | 1,291 | - | 100 |
| HT-6 | 131 | 100 | 39 | - | - | 414 | 100 | 32 |
| HT-7 | 9 | 7 | 3 | - | - | 357 | 86 | 28 |

Table 12 An effect of the width ratio between column and beam flange

| Specimen | Design Yield. Load (kN) [A] | Yield. Load (kN) [B] | Yield Load Ratio |
|---|---|---|---|
| HT-2 | 753 | 799 | 1.06 |
| HT-5 | 1,411 | 1,515 | 1.07 |

Table 13 Decision on the external diaphragm width (hs)

| Column | Beam Flange | B/t | ts/t | hs/B | Diaphragm (mm) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Width ($h_s$) | | Thick. ts |
| | | | | | Prev. | Appl. | |
| □ 400×6 | PL 200×16 | 67 | 2.67 | 0.33 | 120 | 135 | 16 |
| □ 400×9 | PL 300×20 | 44 | 2.22 | 0.50 | 180 | 200 | 20 |

selected as the suitable type for the welded built-up square CFT column to beam connection. And, an analytical study and tests were conducted to evaluate the structural performance of the suggested connection details and to verify the suggested equations for the connection details. The obtained results in this research as follows.

In the welded built-up square CFT column to beam connection using the external diaphragm, to reduce the effect by welding heat on steel tube, the welding of the column to the beam flange could be omitted and the welding thickness of the diaphragm to the column could be reduced. And, the T-type connection with the height of reinforced plate, which is 60% of the beam flange width, showed almost identical resistance. Therefore, the T-type connection could be used for three-way connections. For the welding of the column-beam flange without an external diaphragm, the internal anchor seems to contribute to increasing the stiffness and resistance. And, it is considered that the formula for deciding on the suggested external diaphragm width would be fail-safe and can be used to decide on the external diaphragm width of welded built-up square CFT column to beam connections. Hereafter, for the application to on-site, the full scale tests on column-to-beam connection using the external diaphragm are needed.

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