# Shearing Capacity of Square Concrete-Filled Steel Tubular Columns

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## Abstract

Concrete-filled steel tubular (CFST) structures have been used extensively in buildings in the world, because the CFSTs combine steel tube and concrete to realize efficient and economical composite structural members. The inner concrete restrains local buckling of the steel tube while the steel tube provides longitudinal and transverse reinforcement of the concrete. The steel tube also provides formwork and shoring during construction, thus speeding construction and reducing costs. The inner concrete increases axial and flexural stiffness and load capacity, while permitting more slender elements. Slender columns are normally predicted to fail in buckling or flexure. The axial and flexural properties of CFSTs have been widely researched and reported in the literature but little research has been performed on the shear strength and behavior of CFST. In the few research for the shearing behavior of CFSTs, when the ratio of shear span $a$ by depth $D$ ($a/D$) of the CFST specimens became to less than 1.0, the specimens failed in shear.

A total of six square short column specimens has been tested under cyclic shearing forces and axial force. The depth of the square steel tube was 150mm. The $a/D$ of the specimens was 0.6. The yield strength of the steel tube was around 400MPa. The compressive strength of the inner concrete was 40MPa. The main test parameters were axial force levels and types of diaphragms which included inside type and outside type. All specimens showed the yielding at the center of the web of the steel tubes and did not attain to the flexural capacities of CFSTs. The authors judged that they failed in shear. The cyclic behavior of the CFSTs were enough stable to be used as damping devices in seismic regions.

The test results were compared with two different methods for predicting the shearing capacities of CFSTs. One was developed in U.S. (AISC 2010) and the other was developed in Japan (AIJ 2008). The test results were estimated conservatively by the American method which is neglecting the contributions of inner concrete and axial force. One the other hand, the Japanese method can predict precisely shearing capacities of our experimental results. The Japanese method has the difficulties to calculate the shearing capacities. It is necessary to develop the predicting method to estimate the capacities precisely with a simple expression.

***Key words** : Composite columns; Failure mode; Cyclic loading test; Axial force level; Types of diaphragms*

## 1. Introduction

An extensive amount of test data of Concrete-filled steel tubular (CFST) structures was accumulated in many papers in the world. On the bases of the experimental results that show efficient structural properties of CFST, the members are widely used in buildings in earthquake hazardous area. The feature of the CFSTs is brought from combination between steel tube and concrete. The inner concrete restrains local buckling of the steel tube while the steel tube provides longitudinal and transverse reinforcement of the concrete. The steel tube also provides formwork and shoring during construction, thus speeding construction and reducing costs. The inner concrete increases axial and flexural stiffness and load carrying capacity, while permitting more slender elements. Slender columns are normally predicted to fail in buckling or flexure. The axial and flexural properties of CFSTs have been widely researched and reported in the literature but little research has been performed on the shear strength and behavior of CFST. In Japan, the few research for the shearing behavior of CFSTs were repotetd by Sakino [1] and Nakahara [2]. In these resarches, the specimens of CFSTs were repoted that they failed in shear, when the ratio of shear span $a$ by depth $D$ ($a/D$) of the specimens became to less than 1.0. Sakino [1] tested square CFSTs and Nakahara [2] tested circulat CFSTs to estimate the shearing capacity and deformation behavior of CFSTs subjected to shear force under a constant axial force.

In U.S., an important research was reported by Roeder [3]. In the paper, the autohrs summerized test results by the researchers in U.S., Japan and China to estimate the shearing capacities of circular CFSTs.

In this study, in order to investigate the shearing behavior of square CFST columns with different typse of diaphragms, six specimens were tested with shear span ratio of 0.6.

## 2. Specimen and test setup

### 2.1 Test specimen

Test matrix is shown in Table 1. There were six specimens. The main test parameter was types of diaphragms which included inside type and outside type. And the several axial force levels were set to investigate the influence to the strength enhancement by the axial compressive force. The average of compressive strengths of concrete $\sigma_c$ was around 35MPa. Yield stresses of steel tubes $\sigma_y$ of the specimens with inside type diaphragm and with outside type diaphragm were 385 MPa and 414 Mpa, respectively. The depth of the square steel tube was 150mm. The $a/D$ of the specimens was 0.6.

Table 1 – Test matrix

| Specimens | Loading Method | $D$[mm] | $t$[mm] | $D/t$ | $\sigma_y$[MPa] | $\sigma_c$[MPa] | $a/D$ | $N/N_0$ | Types of Diaphragms |
|---|---|---|---|---|---|---|---|---|---|
| SM3710 | Monotony | 150 | 4.31 | 34.8 | 353 | 37 | 0.60 | 0.10 | Inside Type |
| SC3720 | Cycle | | | | | | | 0.20 | |
| SC3726 | | | | | | | | 0.26 | |
| SM3620 | Monotony | | 4.11 | 36.5 | 414 | 36 | | 0.20 | Outside Type |
| SC3625 | Cycle | | | | | | | 0.25 | |
| SC3630 | | | | | | | | 0.30 | |

<Note>
$D$: width of steel tube, $t$: wall thickness of steel tube, $D/t$: width to thickness ratio
$\sigma_y$: yield stress of steel tube, $\sigma_c$: strength of concrete, $a/D$: shear span ratio
$N$: constant axial force applied, $N_0$: nominal axial force capacity

The shape of the test specimen is shown in Fig.1. The central part of the specimen was broken by the loading apparatus. A total of six square short column specimens had been subjected to cyclic shearing forces under a constant axial force.

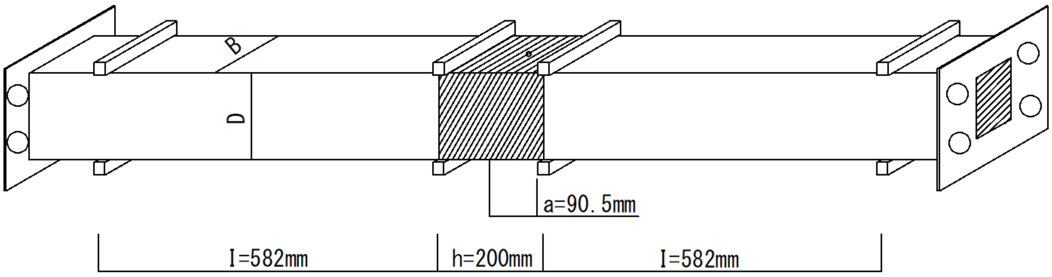


Fig. 1 – Test specimen

There were two type of diaphragms which were inside type and outside type. In the actual columns, inside type of diaphragm penetrates the steel tube and disturbs filling the concrete into steel tube. On the other hand, outside type of diaphragm was welded around the steel tube and keep easy casting of the concrete. It is generally said that the outside type of diaphragm is easier than the inside type of diaphragm from the point of view of the work for casting the concrete into steel tube. The appearances of the inside type of diaphragm and the outside type of diaphragm were shown in Fig.2 and in Fig.3, respectively.

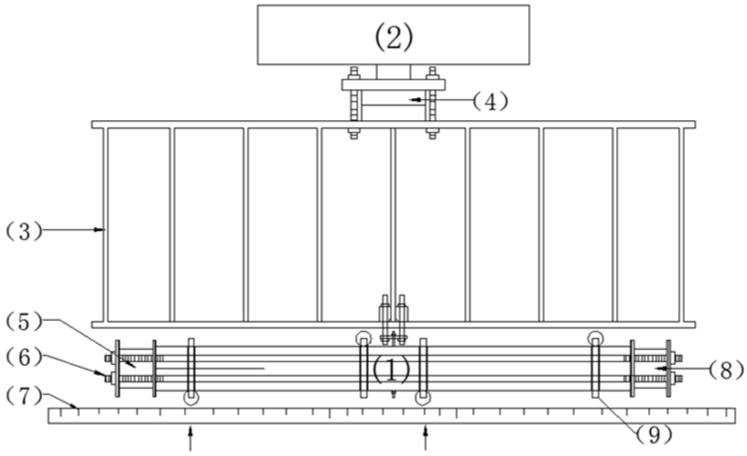
Fig. 2 – Inside type of diaphragm

Fig. 3 – Outside type of diaphragm

## 2.2 Test setup

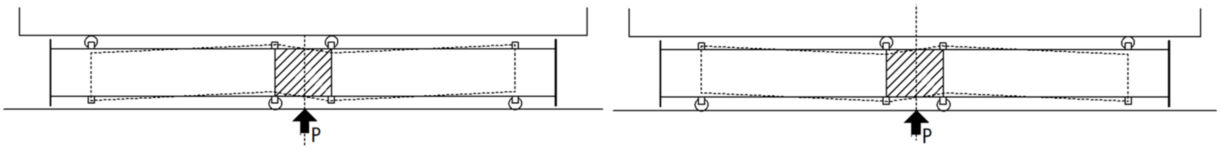
The loading apparatus is shown in Fig.4. The lateral force of the column was applied by using a 2MN loading device vertically. The axial force was introduced from the hydraulic jack useing the PC steel bar horizontally. Both of applied loads were measured by the load cell installed between the specimen and the loading apparatus.

The schematic drawing of deformations are shown in Fig.5. The shear force diagram and bending moment diagram of the test specimen are shown in Fig.6, where the alternate loading is conducted by switching the supoarting points.



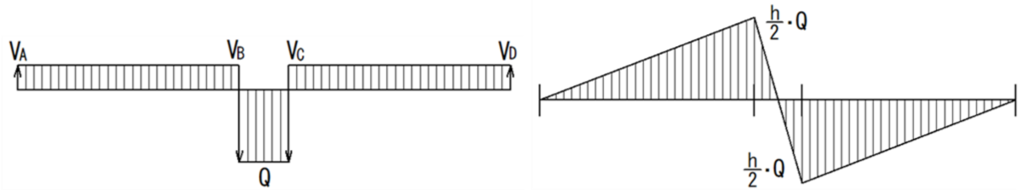
(1)Specimen (2)2MN Loading Machine (3)Loading Beam (4)Spherical Support
(5)Hydraulic Jack (6)PC Steel Bar (7)Test Bed (8)Load Cell (9)Flange

Fig. 4 – Loading apparatus



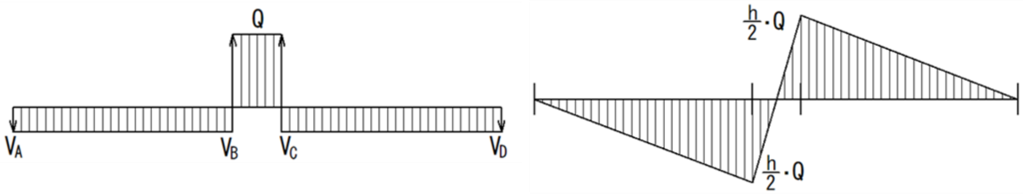
i) Positive side ii) Negative side

Fig. 5 – Schematic drawing of deformations



a) Shear force diagram b) Bending moment diagram

i) Positive side



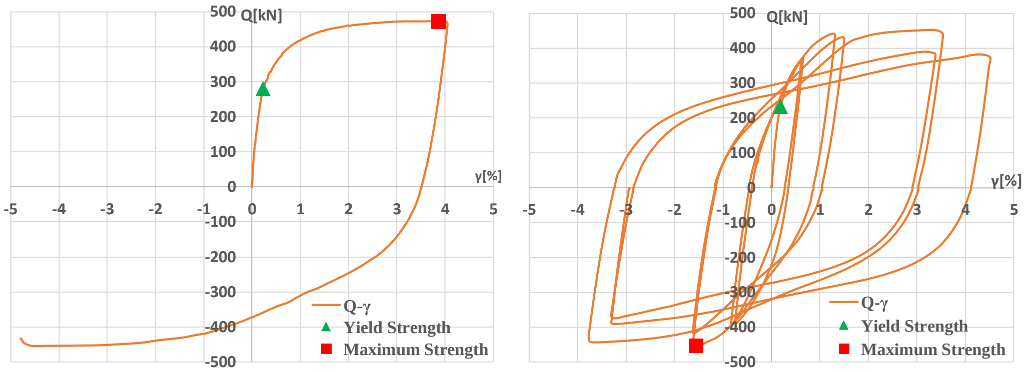
a) Shear force diagram b) Bending moment diagram

ii) Negative side

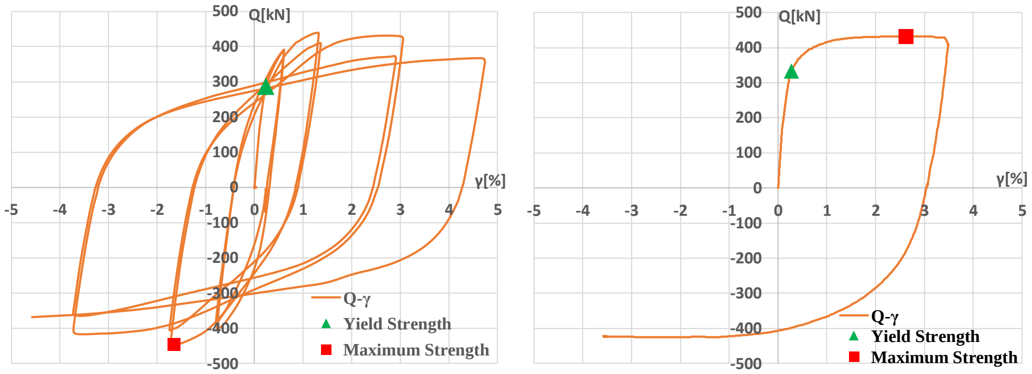
Fig. 6 – Cross sectional forces

## 3. Experimental result

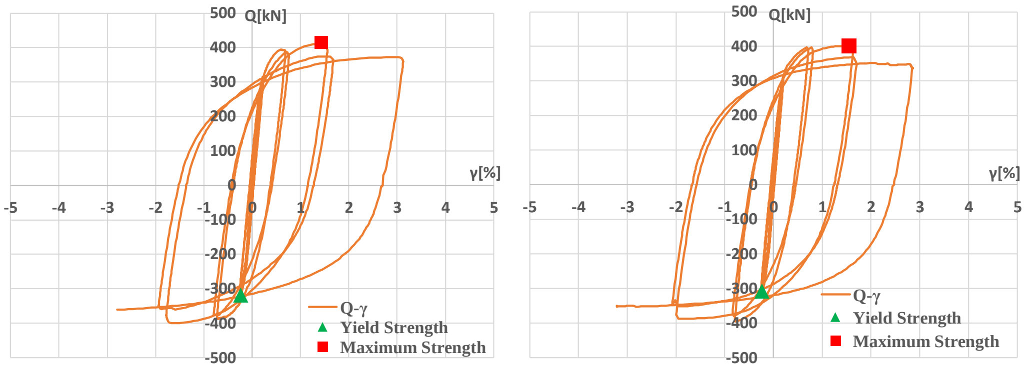
The experimental results are summarized in this section. The relations between shearing force *Q* and shear strain γ are shown in Fig.7. The shear strains γ are measrued at the cectral part of the specimen by wire strain gauges. The relations between shearing force *Q* and shear drift angle *R* are shown in Fig.8. The mark of ▲ denoted the occurrence of yielding of the web of the steel tuber and the mark of ■ denoted the maximum strength of the CFSTs. All specimens showed the yielding at the web of the steel tubes and attained to the shearing capacities finally. We judged they failed in shear. SM series specimens showed stable manner after the maximum strength. SC series specimens showed strength deteriorating behavior slightly due to the effect of cycle loading. The CFSTs which failed in shear were enough stable to be used as damping devices in seismic regions.



i)SM3710 ii)SC3720

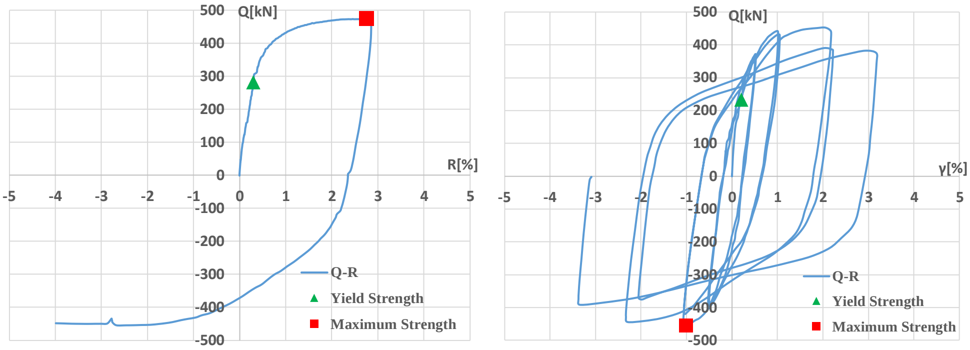


iii)SC3726 iv)SM3620

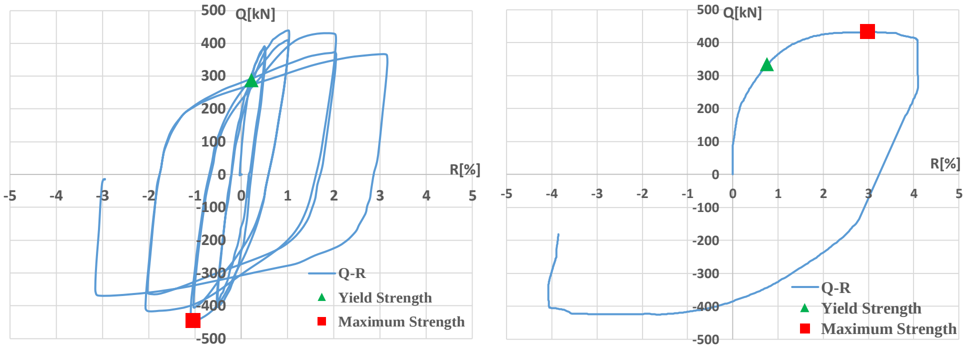


v)SC3625 vi)SC3630

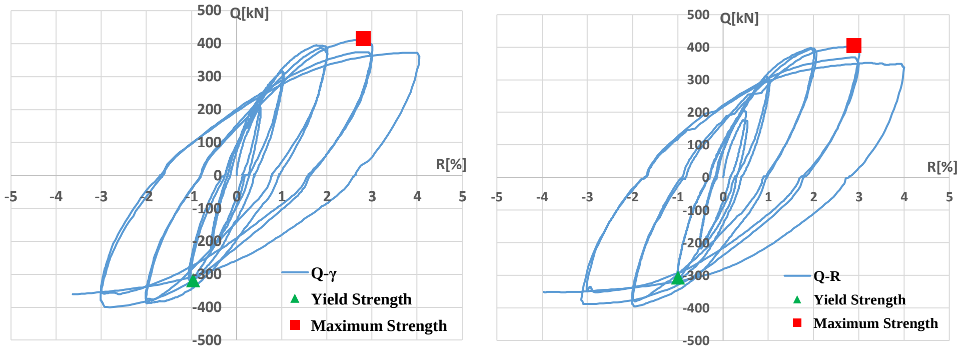
Fig. 7 – Relations between shearing force *Q* and shear strain *γ*



i)SM3710 ii)SC3720



iii)SC3726 iv)SM3620



v)SC3625 vi)SC3630

Fig. 8 – Relations between shearing force *Q* and drift angle *R*

## 4. Compaisons between test and calculation of shearing capacity

The shearing capacity $Q_u$ of CFST obtained by the test was compared with the predictions by some methods. One was developed in Japan by Architectural Institute of Japan (AIJ 2008) [4] and another was developed in U.S. by American Institute of Steel Construction (AISC 2010) [5].

### 4.1 Calculating method in Japan

Japanese method is general summation of the shear strength of the steel tube and the inner concrete, which are varied by the axial force as shown in Eq. (1).

$$Q_u = {}_sQ_u + {}_cQ_u \tag{1}$$

Here ${}_sQ_u$ is the shear strength of the steel tube and ${}_cQ_u$ is shear strength of the inner concrete. They are calculated by using the shear span ratio of the steel tube ${}_s\bar{a}\left(=a/D\right)$ and the shear span ratio of the inner concrete ${}_c\bar{a} = a/{}_cD$, where ${}_cD$ is the depth of the inner concrete.

In the CFST Recomendation in Japan, the shear strength of concrete is estimated under the asumption of the stress states of inner concrete shown in Fig.9. The shear strength of concrete ${}_cQ_u$ is calculated in Eq. (2).

$${}_cQ_u = \sqrt{{}_cN({}_cN_0 - {}_cN) + {}_c\bar{a}^2 \cdot {}_cN_0^{\,2}} - {}_c\bar{a} \cdot {}_cN_0 \tag{2}$$

Here ${}_cN$ is axial force of concrete, ${}_cN_0$ is compressive strength of concrete $(= {}_cA \cdot \sigma_c)$, ${}_cA$ is cross sectional area of the inner concrete.

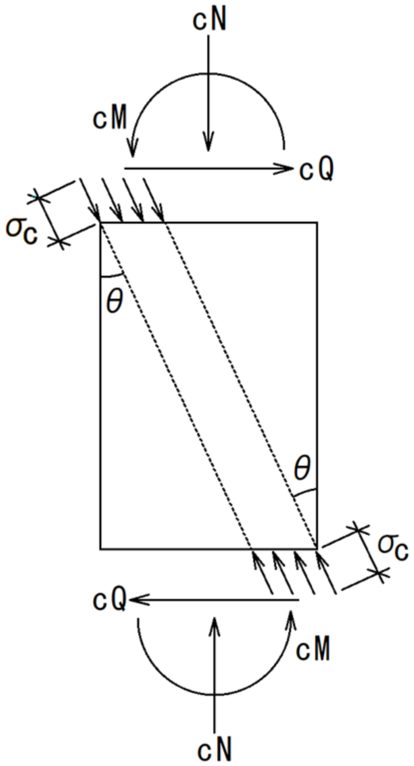


Fig. 9 – Stress state of inner concrete

In the CFST Recomendation in Japan, the shear strength of steel tube is estimated under the asumption of the stress states of the steel tube shown in Fig.10. The shear strength of ${}_sQ_u$ was expressed as follows;

i) when the web of steel tube sustains only shear force,

$$2\,{}_sN + 4\,{}_s\bar{a}\cdot{}_sQ_u \le {}_sN_0$$

$${}_sQ_u = \frac{{}_sN_0}{2\sqrt{3}} \tag{3}$$

ii) when web of steel tube sustains shear force and axial force,

$$4\,{}_s\bar{a}\cdot{}_sQ_u \le {}_sN_0 \le 2\,{}_sN + 4\,{}_s\bar{a}\cdot{}_sQ_u$$

$$(3+4\,{}_s\bar{a}^{2})\,{}_sQ_u^2 + 4\,{}_s\bar{a}\cdot{}_sN\cdot{}_sQ_u - 2\,{}_s\bar{a}\cdot{}_sQ_u\cdot{}_sN_0 - {}_sN\cdot{}_sN_0 + {}_sN^2 = 0 \tag{4}$$

iii) when web of steel tube sustains shear force, bending moment and axial force,

$${}_sN_0 \le 4\,{}_s\bar{a}\cdot{}_sQ_u$$

$$(3+16\,{}_s\bar{a}^{2})\,{}_sQ_u^2 - 8\,{}_s\bar{a}\cdot{}_sQ_u\cdot{}_sN_0 + {}_sN^2 + \frac{3}{4}\,{}_sN_0^2 = 0 \tag{5}$$

Here ${}_sN$ is axial force of steel tube, ${}_sN_0$ is compressive strength of steel tube ($= {}_sA\cdot\sigma_y$), ${}_sA$ is cross sectional area of the steel tube.

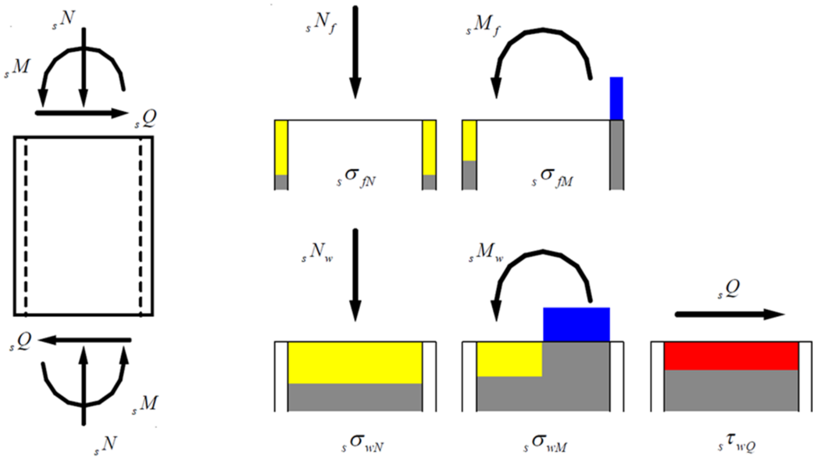


Fig. 10 – Stress state of steel tube

## 4.2 Caluculating method in U.S.

A metnod for calculating the shearing capacity of CFST is shown in Specification for Structural Steel Building by AISC as follows.

$$Q_u = 0.5A_s\cdot 0.6\sigma_y \tag{6}$$

This equation is simple expression because of the concept that only the steel tube is dominat to the shearing capacity of CFST. The above method tends to underestimate the experimental capacities. The pricise prediction was proposed by Roeder [3]. Roeder improved the AISC method as the Eq. (7) considering the strength of the inner concrete.

$$Q_u = 2\cdot 0.5\,{}_sA\cdot 0.6\sigma_y + 3\cdot {}_cA\cdot 0.0316\sqrt{\sigma_c}\ \text{(ksi units)} \tag{7}$$

## 4.3 Accracy of the predicting methods of the shearing capacities

The test results of the of maximum strength in this test were compared by the calculated shearing capacities by Japanese method, American method and Roeder's method. They were summerized in Table 2. The test results were estimated conservatively by the American method which is neglecting the contributions of inner concrete and axial force. One the other hand, the Japanese method can predict precisely shearing capacities of our experimental results. The Japanese method has the difficulties to calculate the shearing capacities. It is necessary to develop the predicting method to estimate the capacities precisely with a simple expression.

When we observe that there are not big differences due to the variations of the level of axial force, it seemns to be usefull to predict the experimental results by the Roeder'method which is considering the contributions of both of steel tube and inner concrete. The test results by us were overestimated by Eq. (7). The authors will study to develop a simple equaiton to predict the shearing capacitiy of CFST with as good as the accuarcy by the Japanese method.

## 4.4 Effect on the difference of the types of diaphragms

There is noteworthy result of comparisons affected by the difference of the type of the diaphragm. The shear strengths of CFSTs with outside type diaphragm were smaller than those of the CFSTs with inside type diaphragm. The authors think that this is because the angle of compressive strut appeared in inner concrete of CFSTs. In the case of the inside type diaphragm, some parts of the diaphragm protruded to inside of the steel tube. The inner part of the steel plates sometimes prevent to the casting work of filling in the concrete, but this part works as the stopper against the pushing out of inner concrete under the shearing deformations. On the other hand, the outside type diaphragm does not prevent to the casting work. There is no stpper at the inside of the steel tube, the inner concrete does not resist the shearing force effectivly than the inner concerte with steel stoppers. The image drawing of concrete strut under shearing deformation is shown in Fig.11. The authors predict that the compressive strut of concrete with inside type of diaphragm must exist steeper than that with outside type of diaphragm. The difference of the strength demonstrating mechanism of the inner concrete will be cleared by FEM analysis. The investigation about this will be presented in our next paper in near future.

Table 2 ― Comparisons between test and three caluculating method

| Specimens | $Q_{MAX}$ [kN] | Japanese Method | | American Method | | Roeder's Method | |
|---|---|---|---|---|---|---|---|
| | | $Q_{AIJ}$ [kN] | $Q_{MAX}/Q_{AIJ}$ | $Q_{AISC}$ [kN] | $Q_{MAX}/Q_{AISC}$ | $Q_{Rroeder}$[kN] | $Q_{MAX}/Q_{Roeder}$ |
| SM3710 | 474 | 377 | 1.26 | 266 | 1.78 | 562 | 0.84 |
| SC3720 | 453 | 384 | 1.18 | 266 | 1.70 | 562 | 0.81 |
| SC3726 | 445 | 384 | 1.16 | 266 | 1.67 | 562 | 0.79 |
| SM3620 | 433 | 430 | 1.01 | 318 | 1.36 | 666 | 0.65 |
| SC3625 | 413 | 429 | 0.96 | 318 | 1.30 | 666 | 0.62 |
| SC3630 | 402 | 426 | 0.94 | 318 | 1.26 | 666 | 0.60 |

i) Inside type of diaphragm ii) Outside type of diaphragm

Fig. 11 – The image drawing of angle of compressive strut appeared in the inner concrete

## 5. Conclusions

The shearing capacities and behaviors of short square CFST columns were experimentally investigated. Six specimens with $a/D$ of 0.6 were subjected to cyclic shearing force under a constant axial force. The conclusions were listed as below.

1. All specimens failed in shear in the loading test.
2. The shearing capacities of our experimental results were predicted by the calculating method of AIJ recommendations precisely.
3. The shear strengths with outside type diaphragm were smaller than those with inside type diaphragm.

## 6. Acknowledgements

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## 7. References

[1] Sakino K, Ishibashi, H (1985): Experimental Studies on Concrete Filled Square Steel Tubular Short Columns Subjected to Cyclic Shearing Force and Constant Axial Force. Journal of Structural and Construction Engineering, AIJ, **353**, 81-91, Tokyo, Japan.

[2] Nakahara H, Tokuda, S (2012): Shearing Behavior of Circular CFT Short Columns. Proc. of the 10th Intl. Conf. on Advances in Steel Concrete Composite and Hybrid Structures, 362-369, Singapore.

[3] Roeder C, Lehman D, Heid A, Maki T (2016): Shear Design Expressions for Concrete Filled Steel Tube and Reinforced Concrete Filled Tube Components, WSDOT Research Report, Seattle, Washington.

[4] Architectural Institute of Japan (2008): Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures, 54-62, Tokyo, Japan (in Japanese).

[5] American Institute of Steel Construction (2010): Specification for Structural Steel Buildings. AISC, Chicago, Il.