Proposal of a New Structural Member Using a Recently Developed High Strength Material

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***Abstract*—The ultra-high strength steel H-SA700 is a relatively new and environment-friendly structural steel with no requirement for intensive heat treatment during manufacturing. In this paper, the cyclic behavior of concrete-filled steel tubes (CFT) using ultra-high strength steel H-SA700 was investigated experimentally. Four column specimens were tested by subjecting them to combined axial and flexural loadings. Two CFT design parameters were investigated: the grade of steel (H-SA700 and conventional) used and the cross section shape (circular and square) of the column. CFT columns using H-SA700 have about twice the elastic deformation capacity of conventional members. They can exhibit performance that exceed the full plastic moment based on superposed strengths theory. They also have sufficient plastic deformation capacities until their strengths decrease due to fracture, and local buckling of the steel occur. These results show that CFT columns using H-SA700 steel can be used as building structural members.**

***Index Terms*—ultra-high strength steel, concrete-filled steel tube, column, seismic performance, maximum strength, experimental study**

I. Introduction

H-SA700 is an ultra-high strength steel that has been developed in recent years in Japan [1]. This steel has a specified yield strength in the range of 700 to 900MPa, and a specified tensile strength in the range of 780 to 1,000MPa, which is around two to three times greater than those of conventional steel used in ordinary buildings. Moreover, H-SA700 achieves very high strength without significantly altering its chemical composition (a lower increase in alloying elements) and without intensive heat treatment. Thus, the steel is more environmentally friendly and more suitable for mass production compared to other ultra-high strength steel.

Several studies have been published on steel structural members using H-SA700 [2]-[4]. In this study, our aim is to propose a new building structural member using H-SA700 steel: a concrete-filled steel tube (CFT) structural column, which is frequently used in high-rise buildings, and to verify its seismic performance.

This paper presents an experimental study of CFT column behavior subjected to combined constant axial force and cyclic lateral force in static loading tests. Four specimens were designed with two parameters: the strength of the steel material and the shape of the column cross section. The effect of these parameters on column behavior, elastic deformation capacity, maximum strength and failure modes were evaluated.

II. Material

An ultra-high strength steel with a yield strength of 700MPa was utilized in the construction of the Tokyo Skytree [5], which reached its full height of 634m in March 2011. As of 2015, the Tokyo Skytree is the tallest tower in the world, and the second tallest structure in the world after the Burj Khalifa (829.8 m). However, only the top portion of the tower, the gain tower, uses ultra-high strength steel as shown in Fig. 1 [6].

An example of a building using high strength steel in a structural member is the Abeno Harukas [7], which opened on March 7, 2014 and is currently the tallest building in Japan at a height of 300m in 60 stories, as shown in Fig. 2 [8]. Its columns are CFT columns using high strength steel SA440. The yield strength of SA440 is around 1.5 times that of conventional steel at 440 to 540MPa. However, H-SA700 has an even higher strength than SA440, and is expected to become the material of choice in building structural members in the future.

The stress-strain curve of H-SA700 steel and the conventional Japanese SM490 steel is depicted in Fig. 3, based on the results of coupon tests. Note that SM490 is equivalent to ASTM A992 in the U.S. and EN-10025 S355JR in Eurocode 3. Comparing these two curves, it

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can be seen that H-SA700 has approximately two times higher yield strength than conventional steel, and therefore, a higher elastic region. However, H-SA700 results in an increase of the ratio of yield to ultimate tensile strength and a reduction in rupture elongation. In particular, rupture elongation of H-SA700 is about half of that of conventional steel.

Figure 1. Tokyo Skytree [6]

Figure 2. Abeno Harukas building [8]

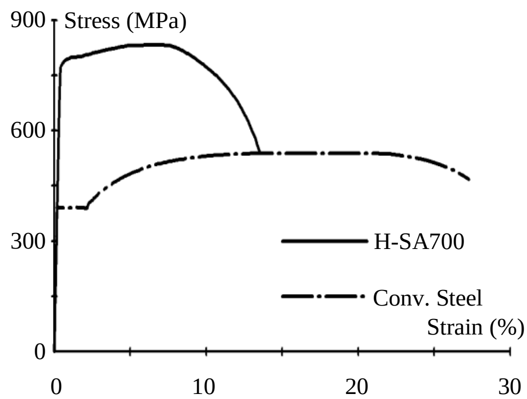


Figure 3. Stress-strain curve of H-SA700 and conventional steel

III. Design Formula of Composite Members

The Japanese design standards for building structural members with composite cross-sections are given in References [9] and [10]. In these standards, the horizontal load-carrying capacity of a composite member subjected to axial force and bending is calculated based on the superposed strengths theory. Equations (1) to (4) are the design formulas of a short CFT column member [10].

$$N_u = {}_cN_u + {}_sN_u \tag{1}$$

$$M_u = {}_cM_u + {}_sM_u \tag{2}$$

where

N_u is ultimate compressive strength of composite member

${}_cN_u$ is ultimate compressive strength of concrete portion

${}_sN_u$ is ultimate compressive strength of steel tube

M_u is ultimate bending strength of composite member

${}_cM_u$ is ultimate bending strength of concrete portion

${}_sM_u$ is ultimate bending strength of steel tube.

For a circular cross-section

$$ {}_cN_u = r_1^2\left(\theta - \sin\theta\cos\theta\right){}_cf_c \tag{3}$$

$$ {}_cM_u = \frac{2}{3} r_1^3 \sin\theta \cdot {}_cf_c$$

$$ {}_sN_u = 2r_2 t\left\{\beta_1\theta - \beta_2\left(\theta - \pi\right)\right\}F_y$$

$$ {}_sM_u = 2r_2^2 t\left(\beta_1 - \beta_2\right)\sin\theta \cdot F_y$$

where

D is depth of steel tube

${}_cD$ is depth of concrete portion

f_c is compressive strength of concrete

F_y is yield stress of steel tube

t is thickness of steel tube

x_n is distance between extreme compression fiber and neutral axis.

$$ {}_cf_c = f_c + 0.78\frac{2t}{D-2t}F_y$$

$$\theta = \cos^{-1}\left(1 - \frac{2x_n}{{}_cD}\right)$$

$$\beta_1 = 0.89, \qquad \beta_2 = -1.08$$

$$r_1 = \frac{{}_cD}{2}, \qquad r_2 = \frac{D-t}{2}$$

For a square cross-section

$$ {}_cN_u = x_n \cdot {}_cD \cdot f_c \tag{4}$$

$$ {}_cM_u = \frac{1}{2}\left({}_cD - x_n\right)x_n \cdot {}_cD \cdot f_c$$

$$ {}_sN_u = 2t\left(2x_n - {}_cD\right)F_y$$

$$ {}_sM_u = Dt\left(D-t\right)F_y + 2t\left({}_cD - x_n\right)x_n \cdot F_y$$

In Japan, the ultimate strength of a composite structural member is defined based on the full plastic theory. Therefore, for H-SA700 to be widely used commercially, the design formula of a structural member using this steel must allow for plastic behavior.

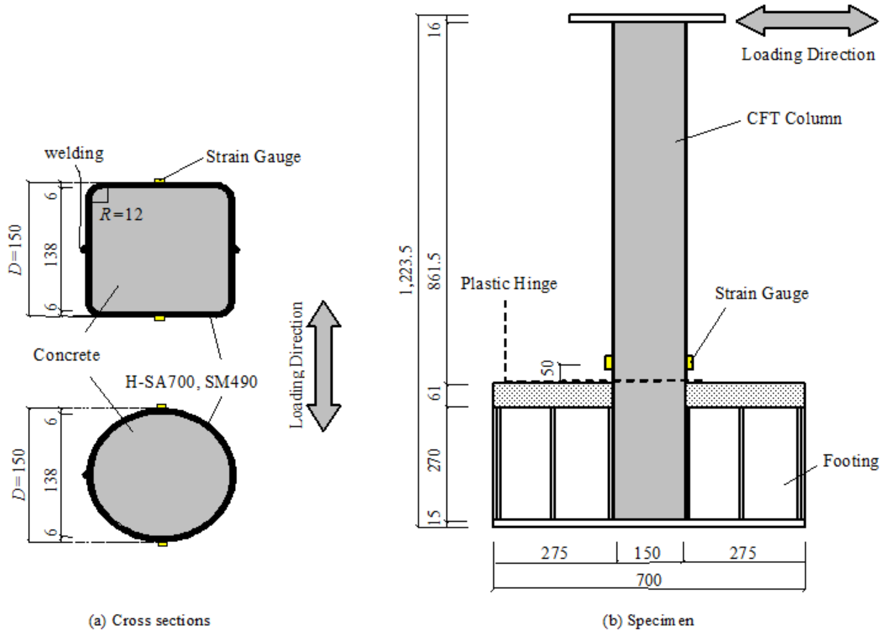


Figure 4. Configuration of specimens (unit: mm)

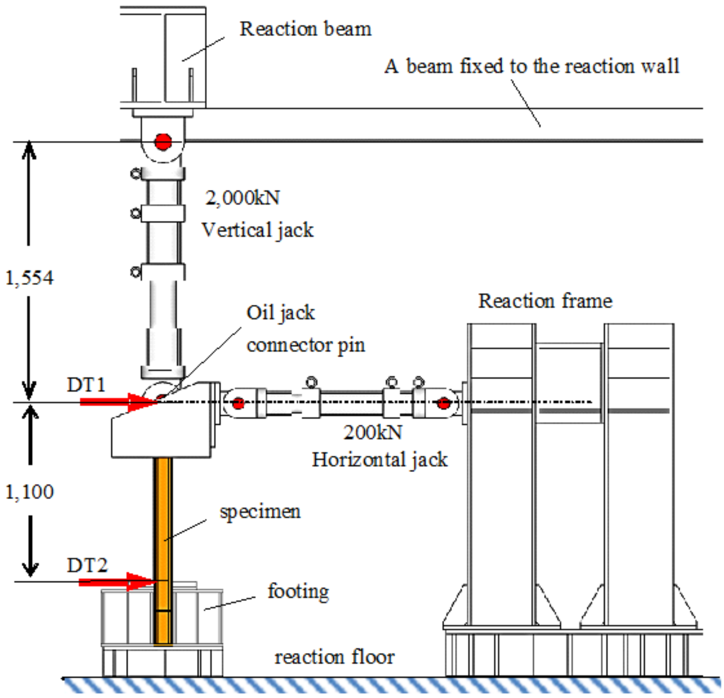


Figure 5. Loading system (unit: mm)

IV. Cyclic Loading Test

A. Specimens and Test Setup

Fig. 4 shows details of the specimen configurations. The parameters of the four specimens are (1) the strength of the steel material (H-SA700 and SM490) and (2) the shape of the column cross section (circular and square). The square steel tubes were fabricated by welding two pieces of cold formed channel sections together. The circular steel tubes were cold formed by a press bending machine and were welded at one point in the cross section. The steel tubes were filled with high strength concrete (f_c = 74.5 to 82.3MPa) using a pumper truck. The specimens and their parameters are listed in Table I.

The loading system shown in Fig. 5 was adopted to provide a combined action of bending and compression to the column. The bottom of the specimens were welded directly into the metal footing foundation consisting of a wide-flange that was fixed to the reaction floor. On the other hand, the top end of the specimens were connected to a 2,000kN vertical oil jack and a 200kN horizontal oil jack by a mechanical pin. Therefore, plastic hinging will occur on the upper surface of the footing at the location shown by the dashed line in Fig. 4.

B. Test Procedure and Instrumentation

Cyclic loading under a constant axial force was applied to all specimens. The acting axial force ratio used in in all specimens was 0.25. Here, the axial force ratio is the ratio of axial compressive force to axial compressive yield strength of the cross sectional area.

The loading protocol used for the lateral drift of the column was as follows: two cycles for each story drift ratio (called as SDR hereafter) of ±0.25, ±0.5, ±1s, ±2, ±3, ±4, ±6, ±8, ±10%. Story drift ratio here is the ratio of lateral drift to column height. Fig. 6 shows a specimen loaded at SDR = 10%.

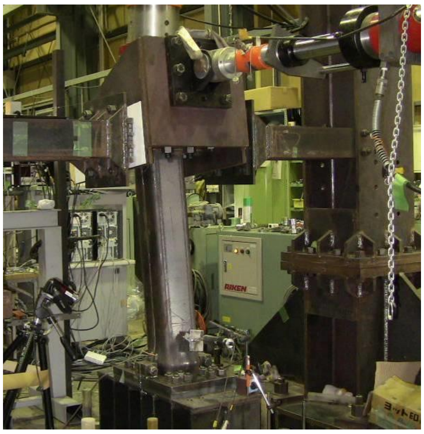
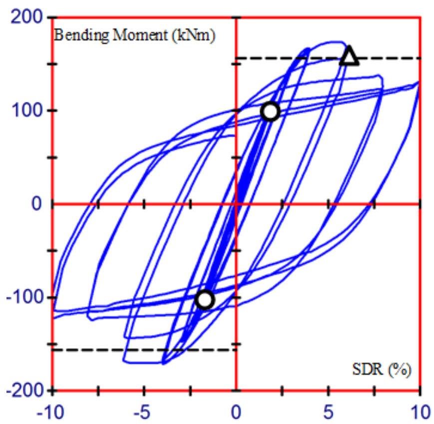


Figure 6. Specimen loaded at SDR = 10%

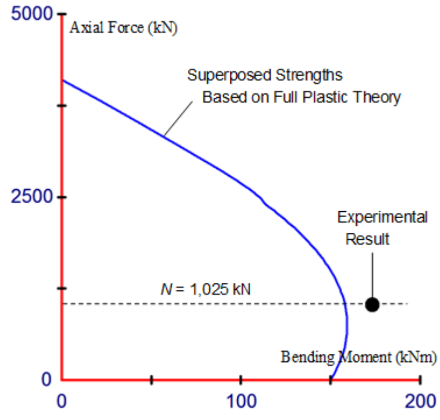
The height of the column was taken as the distance from the upper surface of the footing to the centerline of the horizontal jack, equal to 1,100 mm. Two displacement transducers DT1 and DT2, were used to obtain the drift of the column, as shown in Fig. 5. Longitudinal strain gauges were bonded to the steel tubes 50 mm above the upper surface of the footing.

V. Test Results

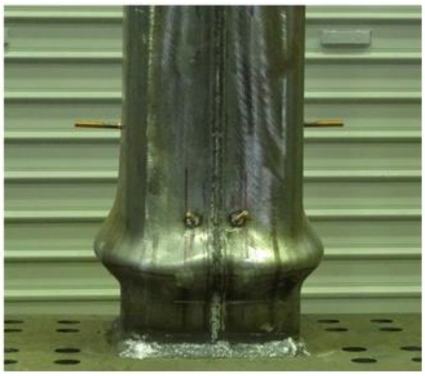
Fig. 7 to Fig. 10 show the test results for each specimen. Fig. (a) for each specimen plots the relationship between bending moment versus cyclic rotation, in terms of SDR.



(a) Bending Moment - SDR relationship

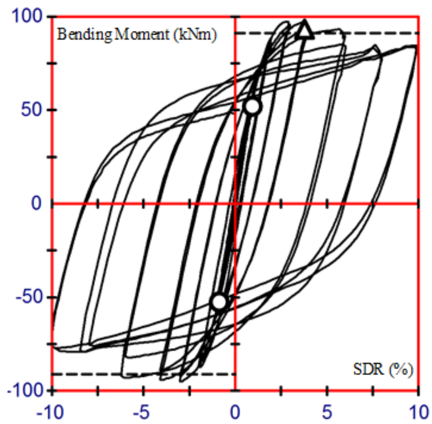


(b) Axial Force N - Bending Moment M relationship

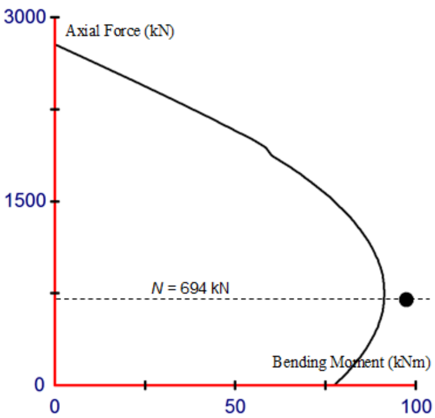


(c) Final state of local buckling

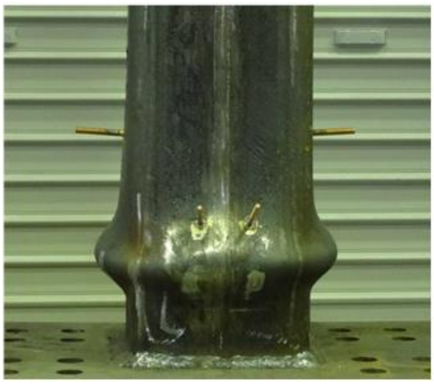
Figure 7. Results for specimen HR (square, H-SA700)



(a) Bending Moment - SDR relationship

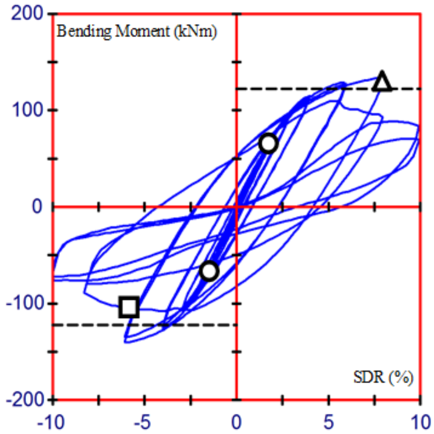


(b) Axial Force N - Bending Moment M relationship

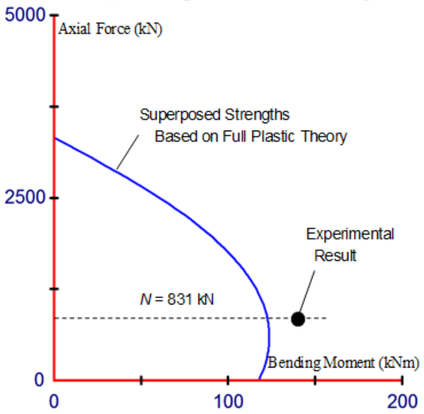


(c) Final state of local buckling

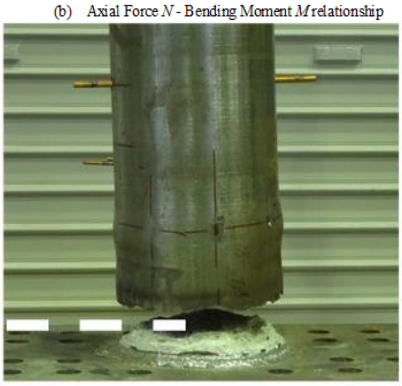
Figure 8. Results for specimen CR (square, SM490)



(a) Bending Moment - SDR relationship

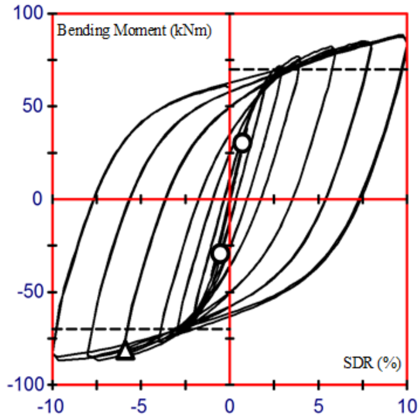


(b) Axial Force N - Bending Moment M relationship

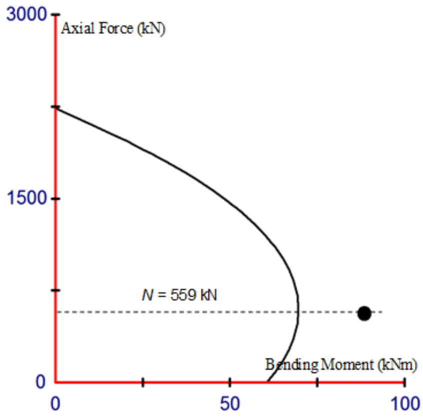


(c) Final state of local buckling

Figure 9. Results for specimen HC (circular, H-SA700)



(a) Bending Moment - SDR relationship



(b) Axial Force N - Bending Moment M relationship

(c) Final state of local buckling

Figure 10. Results for specimen CC (circular, SM490)

Note that the bending moment is calculated as the product of the lateral load and height of the column, plus the product of the horizontal component of axial force and height of the column, plus the product of the vertical component of axial force and horizontal measured displacement (P-Δ moment). In the figures, the experimental results are shown by the solid line, while the dotted line is the fully plastic moment based on superposed strengths theory. The symbol ○ denotes the elastic limit of the steel tube, △ denotes the local buckling of the steel tube and □ denotes the first crack or fracture of the steel tube.

Fig. 7(b) to 10(b) shows the axial force N versus bending moment M relationship, which compares the maximum strength from experimental results with the full plastic moment for the specimen cross section. In the figure, the solid line is the superposed strengths based on full plastic theory, while the symbol ● denotes the maximum strength from experimental results. Fig. 7(c) to 10(c) shows the photo of the final state of each specimen after loading. The dotted line in Fig. 9(c) indicates the location where the fracture occurred.

Based on Fig. 7(a) to Fig. 10(a), all the specimens exhibited very stable behavior prior to the maximum strength limit. Local buckling and steel fracture did not occur. According to strain gauge measurements, the SDR at elastic limits (denoted by **O** in the figures) of H-SA700 specimens (1.8% for HR, 2.2% for HC) were about two times greater than those of conventional steel specimens (1.0% for CR, 0.7% for CC). Moreover, the maximum bending strengths of all specimens are higher than the full plastic moments indicated by dotted lines in Fig. 7(a) to 10(a). However, the post-maximum strength behavior is different depending on the shape of the cross section and the strength of the steel.

A. Square CFT Specimens

In the square specimens, local buckling occurred during the second cycle of 4% SDR for specimen CR (SM490) and during the second cycle of 6% SDR for specimen HR (H-SA700), as indicated by **Δ** in the figures. In these two specimens, the SDR when local buckling occurred was around 1.6 times the SDR when maximum strength was applied (2.5% for CR, 5.1% for HR). After local buckling occurred, cyclic strength deterioration was then observed. However, cracking or fracturing of steel tubes were not observed and the shape of the buckling were similar in Figs. 7(c) and 8(c). Strength reduction of both specimens after local buckling occurred gradually, with the members finally retaining more than 70% of their maximum strength.

B. Circular CFT Specimens

In the circular specimens, the SDR at full plastic moment was 2.5% for specimen CC and 5.1% for specimen HC. Local buckling of circular cross section specimens were significantly smaller than the square specimens, which can be observed in Figs. 9(c) and 10(c). Moreover, strength reduction due to local buckling did not occur in the circular cross section specimens. On the other hand, a fracture in the steel tube occurred during the second cycle of 8% SDR in specimen HC using H-SA700. The SDR when fracture occurred was 1.6 times the SDR when full plastic moment was applied. However, post fracture behavior of the specimen showed that more than 50% of its ultimate strength was retained.

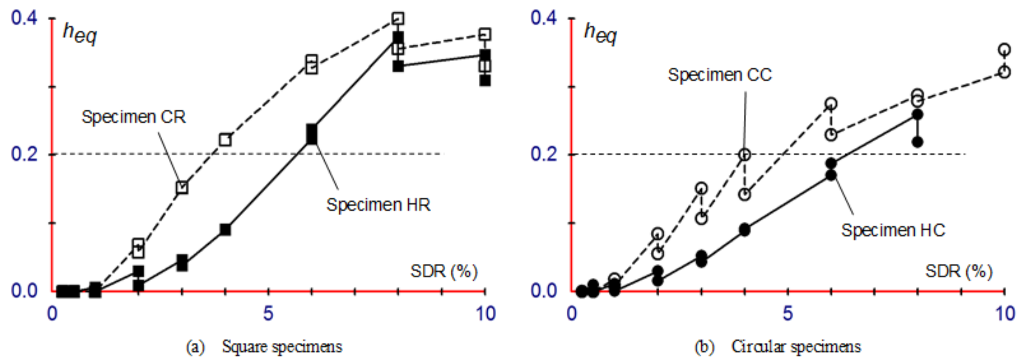


Figure 11. Equivalent damping ratio with respect to SDR for all specimens

C. Equivalent Damping Ratio

The equivalent damping ratios h_{eq} with respect to SDR of each specimen are shown in Fig. 11. h_{eq} is calculated based on the following equation [11].

$$h_{eq} = \frac{1}{4\pi} \frac{\Delta W}{W} \tag{5}$$

where

ΔW is the dissipation energy of a hysteretic loop.

W is potential energy of each story drift ratio.

From the figure, it can be seen that HR and HC using H-SA700 steel have smaller h_{eq} than CR and CC using conventional steel at the range of 0.25 to 6% SDR. This is because the elastic deformation region of H-SA700 steel is greater than conventional steel. At 8% SDR, the h_{eq} are approximately equal for both square and circular specimens, with all the values exceeding 0.2. These results show that CFT columns using H-SA700 have sufficient damping.

VI. Conclusion

H-SA700 steel has been recently developed in Japan as a new material that achieves ultra-high strength at a low price. However, its rupture elongation is lower than conventional steel.

Based on the results of the experiment conducted for this paper, CFT columns using H-SA700 have about two times the elastic deformation capacity of conventional members. They can exhibit performance that exceed the full plastic moment based on superposed strengths theory.

Prior to the application of maximum strength, their hysteresis loops indicate very stable behavior where local buckling and steel fracturing do not occur. Furthermore, until their strengths decrease due to fracture and local buckling of the steel, they possess sufficient plastic deformation capacities.

The above results indicate that CFT columns using H-SA700 steel has the potential to be utilized as building structural members.

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