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Experimental Study on Cyclic Behaviors and Restoring Force Characteristics of Concrete Filled Steel Tube Columns Using Ultra-high Strength Steel

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Abstract

H-SA700 is a type of new ultra-high-strength structural steel that is more environmentally friendly and more suitable for mass production than conventional high-strength steel. The objective of this paper is to contribute to the practical application of CFT columns using such ultra-high-strength as a means to provide a significant increase in the seismic capacity of building structures. In this paper, the cyclic behavior of concrete filled steel tubes (CFTs) using H-SA700 was investigated experimentally. H-SA700 offers an approximately three time higher yield strain than that of conventional steel, and therefore, the CFT columns using H-SA700 reached their elastic limit when the infilled concrete sustained compressive strength, while the steel tube remained elastic at the moment. In such a case, it is unsafe to evaluate the strength by using the current design formula based on the superposed strength method. Due to the relatively low ductility of H-SA700, steel is not allowed to yield in the design of CFT columns. Nevertheless, the experimental results revealed that, comparing with CFT columns using conventional steel, the CFT columns using H-SA700 exhibited a substantially large capacity of plastic deformation, smaller axial deformation associated with local buckling, and a similar capacity of energy dissipation.

Keywords: Ultra-high Strength Steel, H-SA700, CFT Column, Restoring Force Characteristic, Design Formula

1. Introduction

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

The study on steel structure members using H-SA700 has been published, for example [2-4]. In this paper, the cyclic behaviour of concrete filled steel tubes (CFTs) using H-SA700 was investigated experimentally. A total of five one-quarter-scaled CFT columns were tested under a combined axial and lateral load. Several design parameters of CFTs were investigated, including the grade of steel, the cross-section shape, and the axial load level. The effect of different parameters on column behavior, elastic deformation capacity, maximum strength and failure modes, were evaluated.

2. 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, sections where ultra-high strength steel is adopted is limited to the top portion of the tower (the gain tower).

As a structural member of the building, the columns of Abeno Harukas, which is the current tallest (300m, 60 stories) in Japan and opened in 2014, adopts the CFT member using the high strength steel SA440. The yield strength of SA440 is 440 to 540MPa, which is around 1.5 times that compared to conventional steel. H-SA700, which has an even higher strength than SA440, is expected to spread as the increasing choice of material.

The stress-strain curve of H-SA700 steel and conventional Japanese SM490 steel, which is equivalent to ASTM A992 in us, and EN-10025 S355JR in Eurocode 3, is depicted in Fig. 1, showing the results from coupon tests. By comparing these two curves, H-SA700 offers approximately two to three times higher yield strength than that of the conventional one and therefore, a higher elastic region. However, H-SA700 results in an increase on the ratio of the yield to ultimate tensile strength and a reduction in rupture elongation. In particular, rupture elongation is about half compared with conventional steel.

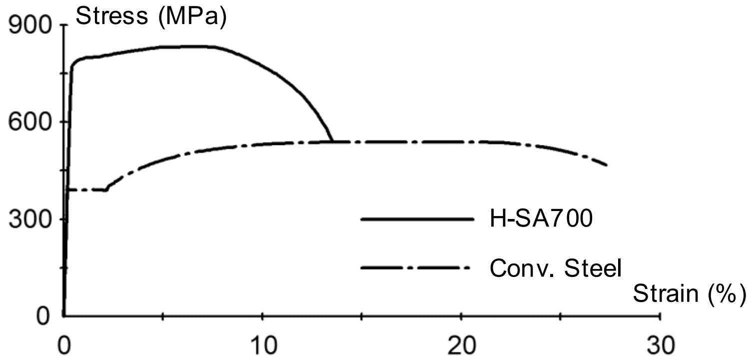


Fig. 1 – Stress-Strain Curve

3. Design Formula of a Composite Member

Japanese design standards of composite structured members are presented in [6] and [7]. In these standards, the elastic limit moment strength M_y and the ultimate moment strength M_u of a composite member subjected to axial force and bending is calculated based on the superposed strength theory.

H-SA700 offers an approximately two to three times higher yield strain than that of conventional steel, and therefore, the CFT columns using H-SA700 reached their elastic limit when the infilled concrete sustained compressive strength, while the steel tube remained elastic at the moment. In such a case, it is unsafe to evaluate the elastic limit moment strength M_y by using the current design formula based on the superposed strength method. In this paper, a new design formula that takes into account the elastic limit moment strength M_y of H-SA700 is proposed.

$$M_y = \frac{\eta \varepsilon_{y,c} - \varepsilon_n}{\varepsilon_{y,s} - \varepsilon_n} M_d \tag{1}$$

$$\eta = \frac{D}{D-t}$$

where: M_d is the elastic limit moment strength based on superposed strength method [7]; $\varepsilon_{y,c}$ is the yield strain of the concrete; $\varepsilon_{y,s}$ is the yield strain of the steel tube; ε_n is the axial strain caused by the compressive axial load; D is depth of steel tube; and t is thickness of steel tube.

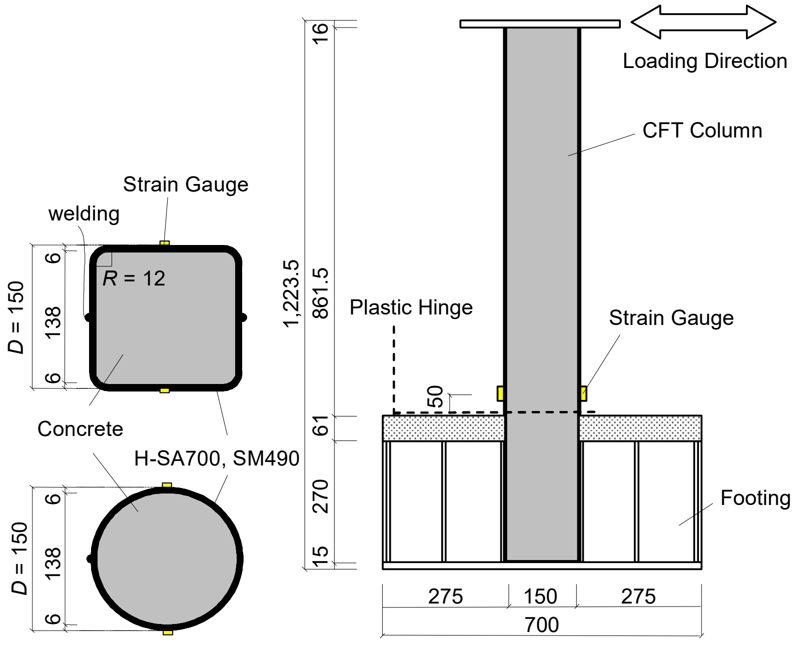
The ultimate moment strength M_u of a composite structural member is defined by the full plastic theory based on the superposed strength method in Japan. On the other hand, rupture elongation of H-SA700 is about half of that when compared to conventional steel. There is a need to verify whether a CFT member using H-SA700 has a plastic deformation capacity which can exert the full plastic moment M_u estimated by the cumulative strength theory.

4. Cyclic Loading Test

4.1 Specimens and Test Setup

Fig. 2 shows details for the configuration of specimens. The parameters of the five specimens are; the strength of the steel (H-SA700 and SM490), the shape of the cross section (circular and square) and the acting axial force ratio (n = 0.25, 0). 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 welded at one position. The steel tubes were filled with high strength concrete (f_c = 42.4 to 82.3MPa) using a pumper truck. The parameters of the specimens are listed in Table1.

The loading system in Fig.3 was adopted to provide a combined action of bending and compression to the column. The bottom side of the specimens was welded directly in this metal footing foundation consisting of a wide-flange which was fixed to the reaction floor. The top end of the specimens was connected to a 2,000kN vertical oil jack and a 200kN horizontal oil jack with a mechanical pin. Therefore, plastic hinge occurs in the position of the upper surface of the footing (show by the dashed line in fig.2).



(a) Cross Sections (b) Specimen

Fig. 2 – Configuration of specimens (Unit: mm)

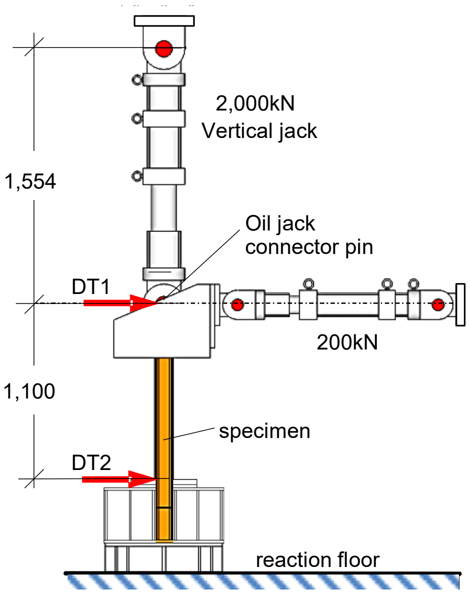


Fig. 3 – Loading system (Unit: mm)

Table 1 – Parameters of the specimens

Specimen	Section	Steel Tube				Concrete	Axial Force	
		Material	Yield Strength F_y (MPa)	Tensile Strength F_u (MPa)	Elongation (%)	Strength f_c (MPa)	Force N (kN)	Ratio n
HR-25	Square	H-SA700	788	837	14.5	77.1	1,025	0.25
CR-25	Square	SM490	387	488	28.4	74.5	694	0.25
HC-25	Circular	H-SA700	788	837	14.5	82.3	831	0.25
HC-0	Circular	H-SA700	788	837	14.5	42.4	0	0
CC-25	Circular	SM490	387	488	28.4	79.0	559	0.25

$n=N/N_0$, N_0 : The axial compressive yield strength of the cross-sectional area.

4.2 Test Procedure and Instrumentation

Cyclic loading under a constant axial force was applied to all specimens. In all specimens, the acting axial force ratio was 0.25 or 0. The axial force ratio is defined as the ratio of the axial compressive force to the axial compressive yield strength of the cross sectional area.

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

The height of the column was taken as the distance from the upper surface of the footing to the centerline of the horizontal jack (1,100 mm). Two displacement transducers DT1 and DT2, were used to obtain the drift of the column, as shown in Fig.3. The longitudinal strain gauges were bonded to the steel tubes of the CFT specimens 50 mm above the upper surface of the footing.

5. Test Results

Fig.4 shows the bending moment versus the SDR relationship for each specimen. The bending moment is equal to the product of the lateral load and the height of the column, plus the product of the horizontal component of axial force and the height of the column, plus the product of the vertical component of axial force and the horizontal measured displacement (P-$\varDelta$ moment). In the figure, the symbol ○ denotes the elastic limit of the CFT columns based on the strain gauge values, △ denotes the local buckling of the steel tube, and the symbol □ denotes the first crack or fracture of the steel tube. The chain-dotted line is the elastic limit moment strength M_y estimated by equation (1), and the dotted line is the fully plastic moment M_u based on superposed strength theory. Photo 1 presents the final states of respective specimens. The dotted line in the photos indicate the locations where fracture occurred.

Based on Fig.5, all specimens indicated very stable behavior prior to the maximum strength limit, and local buckling and/or steel fracture did not occur. The new design formula (1) of the elastic limit moment strength M_y is capable of accurately evaluating the strength of the CFT columns using H-SA700. The maximum bending strength of all specimens is higher than the full plastic moment M_u indicated by dotted lines. On the other hand, the behavior at the region of post maximum strength is different depending on the shape of the cross section and the strength of the steel.

In square CFT specimens, local buckling occurred during the second cycle of SDR 4% for the specimen CR - 25(SM490) and during the second cycle of SDR it was 6% for HR-25 (H-SA700). In these two specimens, SDR local buckling occurs at around 1.8 times SDR when the maximum strength is applied (specimen CR-25 is 2.1%, HR-25 is 3.4%). After local buckling occurred, cyclic strength deterioration was then observed.

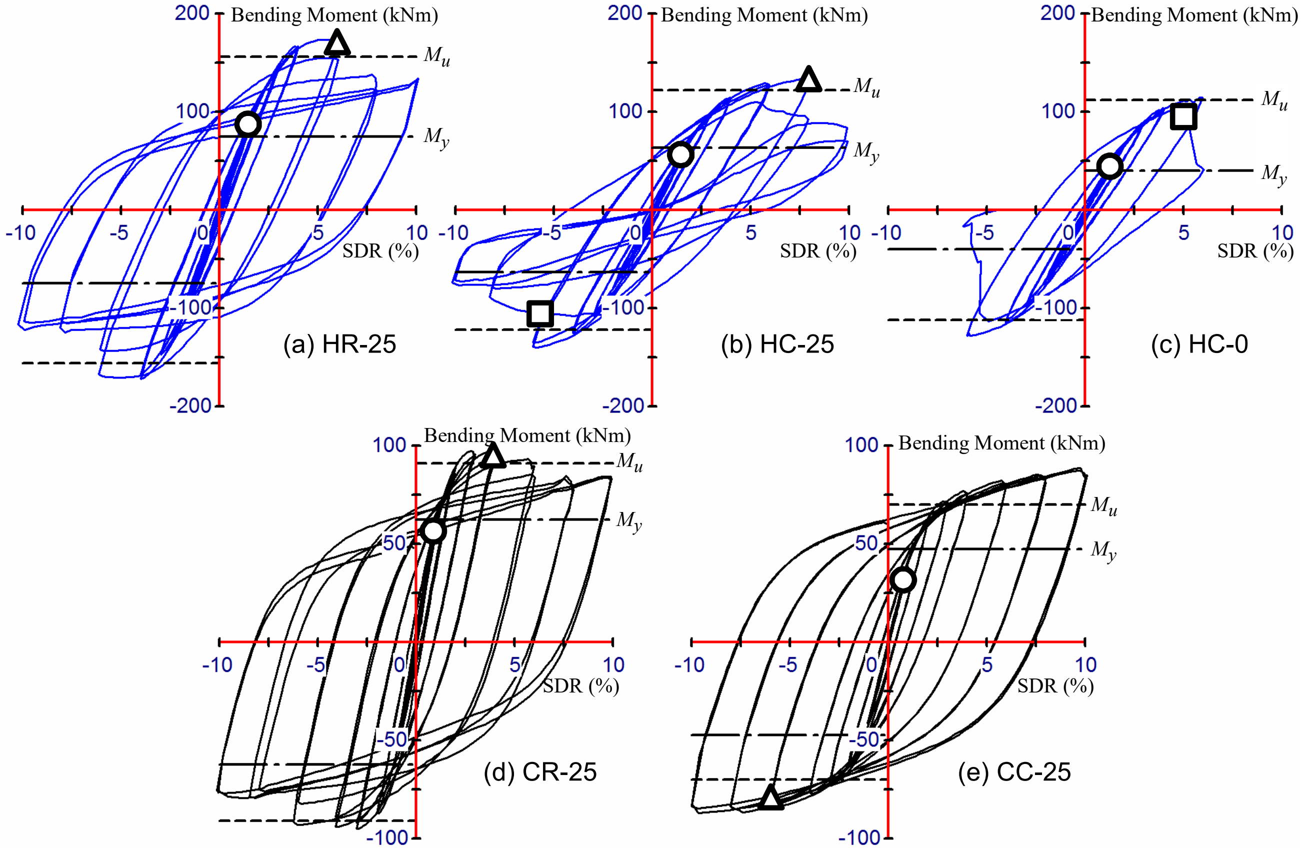
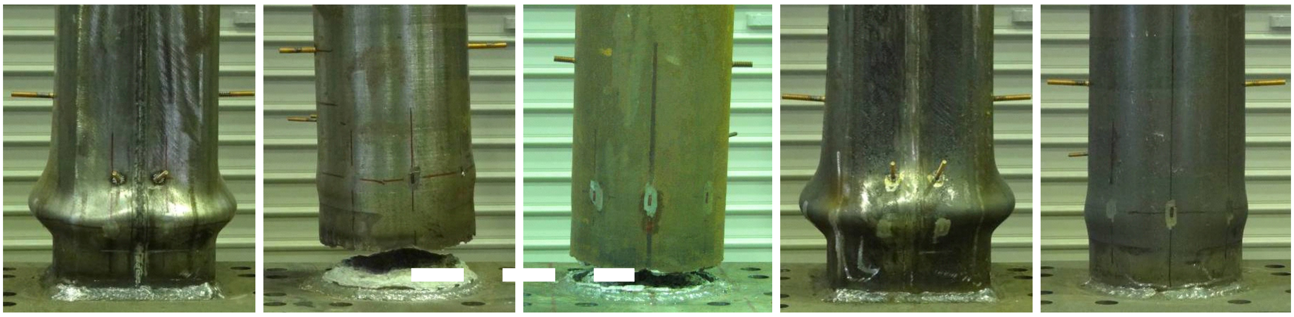


Fig. 4 – Bending Moment - SDR Relationship



(a) HR-25 (b) HC-25 (c) HC-0 (d) CR-25 (e) CC-25

Photo 1 – The final states of respective specimens

However, cracking or fracturing of the steel tubes was not observed, and the buckling shape was similar [Photo 1(a), (d)]. The strength reduction of both specimens after local buckling occurs is gradual, finally retaining more than 70% of their maximum strength.

In circular specimens, the SDR at the full plastic moment was 2.6% for specimen CC-25, 4.9% for specimen HC-25 and 4.0% for specimen HC-0. Local buckling for circular cross section specimens was less serene than for the square cross section [Photo 1]. 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 SDR 8% in the specimen HC-25 and SDR 6% in the specimen HC-0 using H-SA700. However, the SDR fracture occurring when the full plastic moment applies is 1.5 to 1.6 times story drift angle.

Due to the relatively low ductility of H-SA700, this steel grade is not allowed to yield in the design of CFT columns. Nevertheless, the experimental results revealed that, when comparing with CFT columns using conventional steel, the CFT columns using H-SA700 exhibited a substantially large capacity of plastic deformation. A design guideline was proposed for the estimation of ductility of CFT columns using ultra-high strength steel.

6. Conclusion

H-SA700 steel, which has been developed in recent years in Japan, is a new material that achieves an ultra-high strength and offers a low cost. However, its rupture elongation is lower than that of conventional steel. The proposed design formula of the elastic limit moment strength is capable of accurately evaluating the strength of the CFT columns using H-SA700. It can exhibit performance that exceeds the full plastic moment based on the superposed strength theory. Prior to the maximum strength being applied, the hysteresis loop indicates a very stable behaviour where local buckling and steel fracturing do not occur. Furthermore, until the strength decreases due to fracture and local buckling of the steel, it possesses sufficient plastic deformation capacity. Accordingly, CFT Columns using H-SA700 steel can be utilized as building structural members.

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