Experimental evaluation of high-strength concrete-filled steel rectangular tube columns under axial compression

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Abstract. This paper presents the effect of the high-strength concrete on the behavior and strength of concrete-filled steel tube (CFST) columns. To evaluate the structural performance, load-axial shortening responses, failure modes and axial load capacity are performed for ten high-strength concrete-filled steel tube (HSCFT) columns. All of the columns are 750 mm in height, and have compressive strength of 66 MPa. Test parameters included the wall thicknesses of the rectangular tube (3.0 mm, 4.5 mm and 6.0 mm) and three different of rectangular cross-sections (150x50 mm, 150x75 mm and 150x100 mm). From the experimental results, it is indicate that the load-axial shortening response of the columns have a linear behavior up to approximately 80-90% of their axial load capacity. Then, the behavior of the HSCFT columns is nonlinear with a very large deformation before failure. It is also shown that the axial load capacity and ductility of the HSCFT columns are increased significantly compared to the RC columns (reference columns), depending mainly on the wall thickness and cross-section of the hollow steel tube. Finally, by comparing the axial load capacity of the test results with those obtained from the AISC/LRFD design equation, the comparison results show that calculation formula in AISC/LRFD specification can be applied to compute the axial load capacity of HSCFT columns under axial compression.

1. Introduction

Concrete-filled steel tube (CFST) column is a structural member that uses a combination of concrete and cold-formed steel circular and rectangular tubes to provide adequate axial load capacity [1-2]. Concrete cores have the advantages of high compressive strength and stiffness, while thin-wall hollow tubes have the advantages of high strength and better ductility performance [3]. The steel tube serves as reinforcement and permanent formwork for the concrete fill. It is well known that the concrete core delays the inward buckling and temperature rise of steel tube, and significantly enhances resistance and inelastic deformation capacity in compression and combined loads. Also, CFST columns combine steel and concrete in one member resulting in a member that has the beneficial qualities of both materials, such as high ductility and large energy absorption for earthquake resistant properties, economical, reducing labor requirements and permitting rapid construction, when compared to traditional construction methods [4-8]. Although the use of high-strength concrete (HSC) in the construction sector provides significant economic benefits, the understanding of the behavior of high-strength concrete-filled steel tube (HSCFT) columns are still insufficient in comparison with normal strength CFST columns [9]. Consequently, there is a need to extensively investigate the structural performance of HSCFT columns.
under axial compression so that guidelines and recommendations can be developed for design. The purpose of this paper is to present the experimental results on HSCFT columns under concentric axial loading and to compare the obtained axial load capacity with the reference RC columns and the values predicted by AISC/LRFD specification [10].

2. Experimental procedures

2.1. Specimen details
An experimental study was made on 16 rectangular columns, including 10 HSCFT columns and 6 reference high-strength RC columns. All rectangular columns were 750 mm in height. The main parameters were the wall thicknesses of the rectangular tube (3.0 mm, 4.5 mm and 6.0 mm) and three different of rectangular cross-sections (150x50 mm, 150x75 mm and 150x100 mm). Two specimens of each set were tested to determine the average axial load capacity. A summary of the nominal dimensions of HSCFT columns are presented in Table 1. They were classified into 3 groups with \( H / B \) ratio. The column numbers were designated as RC(RS) - \( f'_c \cdot t \cdot H / B \), where “RC” or “RS” represents the reference high-strength RC columns and the HSCFT columns, respectively. For example, the column number RS-66-3.0-2.0 was the HSCFT columns, having \( f'_c = 66 \text{ MPa}, t = 3.0 \text{ mm} \) and \( H / B \) ratio of 2.0. Also, the average mechanical properties of the high-strength concrete at the age of 28 days and steel tube were tested according to ASTM procedures, and given in Table 1.

Table 1. Dimensions and mechanical properties of column specimens.

| Specimen | \( t \) (mm) | \( H \) (mm) | \( B \) (mm) | \( H / B \) | \( H / t \) | Concrete | Steel Tube | Number |
|----------|--------------|--------------|--------------|-------------|-----------|----------|------------|--------|
|          |              |              |              |             |           |          |            |        |
| RC-66-0-1.5 | -           | 150         | 100         | 1.5         | -         | 14,548   | 66.2       | -       | -       | 2       |
| RS-66-3.0-1.5 | 3.0       | 150         | 100         | 1.5         | 50        | 13,467   | 66.2       | 1,533   | 382.2   | 2       |
| RC-66-0-2.0 | -           | 150         | 75          | 2.0         | -         | 10,798   | 66.2       | -       | -       | 2       |
| RS-66-3.0-2.0 | 3.0       | 150         | 75          | 2.0         | 50        | 9,959    | 66.2       | 1,291   | 384.5   | 2       |
| RS-66-4.5-2.0 | 4.5       | 150         | 75          | 2.0         | 33.3      | 9,358    | 66.2       | 1,892   | 388.2   | 2       |
| RS-66-6.0-2.0 | 6.0       | 150         | 75          | 2.0         | 25        | 8,787    | 66.2       | 2,463   | 395.4   | 2       |
| RC-66-0-3.0 | -           | 150         | 50          | 3.0         | -         | 7,048    | 66.2       | -       | -       | 2       |
| RS-66-3.0-3.0 | 3.0       | 150         | 50          | 3.0         | 50        | 6,209    | 66.2       | 1,141   | 380.8   | 2       |

Figure 1. Typical HSCFT column details and test setup.
2.2. Test setup and instrumentations
Depending on the axial load capacities of each column, axial compressive test of the column specimens were performed by a 2,000 kN TINIUS OLESEN Universal Testing Machine. The axial compressive load was applied to entire section through the bearing plates (applied load to the concrete and steel tube section). The load arrangement and test setup can be seen in Figure 1. Two linear variable differential transducers (LVDT) were used to monitor overall axial shortening. Before the beginning of each test, a preload of approximately 20% of the predicted axial load capacity of the columns was applied in order to reduce the friction between the steel bearing plates and the columns, and to balance the uneven top and bottom surfaces. The specimens were loaded at a very slow rate, was increased at a constant rate up to axial load capacity, such that the axial load, the axial shortening of the columns were automatically recorded by a KYOWA EDX-10 Series data acquisition unit. Additionally, the local tube wall buckling and the axial load capacity were carefully observed.

3. Results and discussion
3.1. Behavior and failure mode
In this paper, the term “short column” refers to a compression member which can attain its axial load capacity, known as the squash loads ($P_{\text{test}}$), without buckling of the columns. The typical structural behavior of the tested reference high-strength RC column and HSCFT column are represented in Figure 2 by relations between the axial load and axial shortening. From Figure 2, it can be seen that the HSCFT column showed a linear elastic behavior up to 80-90% of their axial load capacity. In elastic stage, the deformation of HSCFT column was too small and invisible. After that, as the load continued to increase and reached ultimate load, the curves are gradually becoming nonlinear due to the start of the cracking of the concrete underneath the applied load and the local yielding of the steel tube. Then, it is seen that nonlinear behavior of the columns is the strain-softening type, in which the load began to decrease and the axial shortening increased rapidly. Finally, the outward local wall buckling of the steel tube in the areas near the ends of the columns are investigated and the axial load capacity is recorded. Figure 3 shows a typical failure mode of the HSCFT column. The failure mechanism of the columns was identified as the crushing of concrete core and the yielding of steel tube. This indicates that the concrete core in these locations was contained by the steel tube, in turn providing large axial deformability to the columns. Hence, the HSCFT column represented well post-yield behaviour.

![Figure 2. Axial load versus axial shortening](image)

![Figure 3. Failure modes of HSCFT column](image)
3.2. Axial load capacity and comparison with AISC/LRFD

Figure 4 presents the comparisons of the obtained axial load capacity \( P_{\text{test}} \) of the HSCFT column. It can be seen from the ratio of the axial load capacity of the HSCFT column to the axial load capacity of the reference high-strength RC column \( P_{\text{test,ref}} \) or \( P_{\text{test}} / P_{\text{test,ref}} \) ratio that the HSCFT column with \( t = 3.0 \text{ mm}, 4.5 \text{ mm and 6.0 mm} \) have larger \( P_{\text{test}} \) than the \( P_{\text{test,ref}} \) of the reference CLC column by 37\%, 64\% and 89\%, respectively. This indicates that the axial load capacity increased with the increase of thickness [11].

In addition, AISC Load and Resistance Factor Design (LRFD) is the most completed specification in composite members [3], and covers composite columns, including the CFST column. From the analytical results, the comparison of axial load capacity between the test values and the LRFD design equation are presented in Figure 5. The comparison of results shows that LRFD closely predicts with a difference of 5-21\%. This indicates that the LRFD design equation can adequately predict the axial load capacity of the HSCFT column.

![Figure 4. Ratio of \( P_{\text{test}} / P_{\text{test,ref}} \) of test columns](image)

![Figure 5. Comparison of the axial load capacity obtained from experiments and AISC/LRFD Eq.](image)

4. Conclusions

The conclusions from the experimental studies are summarized as follows.

1) The structural performance of HSCFT column have a linear elastic behavior up to 80-90\% of their axial load capacity. Then, the behavior of the columns is gradually becoming nonlinear with the strain-softening type. Failure mechanism of the columns is identified as the crushing of concrete core and the localized buckling of steel tube.

2) The typical failure mode of the HSCFT column is progressive mode with a very high axial deformability.

3) The encasing effect is more effective for the HSCFT column with thicker wall thickness than those with thinner wall thickness.

4) Good agreement is evaluated between the predicted axial load capacity using the AISC/LRFD design equation and the experimental results.

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References

[1] Han, L.H., Li, W. and Bjorhovde, R. (2014). Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members. Journal of Constructional Steel Research, 100: 211-228.

[2] Thumrongvut, J. and Tiwjantuk, P. (2018). Strength and axial behavior of cellular lightweight concrete-filled steel rectangular tube columns under axial compression. Materials Science Forum, 941: 2417-2422.

[3] Saw, H.S. and Liew, J.Y.R. (2000). Assessment of current methods for the design of composite columns in buildings. Journal of Constructional Steel Research, 53(2): 121-147.

[4] Seangatith, S. and Thumrongvut, J. (2011). Behaviors of square thin-walled steel tubed RC columns under direct axial compression on RC core. Procedia Engineering, 14: 513-520.

[5] Ananthi, B.G. and Knight, S. (2014). Experimental and theoretical study on cold-formed steel box stub columns under uniaxial compression. Arabian Journal for Science and Engineering, 39(10): 6983-6993.

[6] Lu, Y., Li, N., Li, S. and Liang, H. (2015). Behavior of steel fiber reinforced concrete-filled steel tube columns under axial compression. Construction and Building Materials, 95: 74-85.

[7] Ding, F., Lu, D., Bai, Y., Zhou, Q., Ni, M., Yu, Z. and Jiang, G. (2016). Comparative study of square stirrup-confined concrete-filled steel tubular stub columns under axial loading. Thin-Walled Structures, 98(B): 443-453.

[8] Thumrongvut, J., Seangatith, S., Siriparinyanan, T. and Wangrakklung, S. (2016). An experimental behaviour of cellular lightweight concrete-filled steel square tube columns under axial compression. Materials Science Forum, 860: 121-124.

[9] Liu, D., Gho, W.M. and Yuan, J. (2003). Ultimate capacity of high-strength rectangular concrete-filled steel hollow section stub columns. Journal of Constructional Steel Research, 59(12): 1499-1515.

[10] ANSI/AISC 360-10. (2010). Specification for structural steel buildings. American Institute of Steel Construction, Chicago, IL.

[11] Thumrongvut, J. and Seangatith, S. (2016). Axial load capacity of cellular lightweight concrete-filled steel square tube columns. Central Europe Towards Sustainable Building (CESB 2016), Czech Republic, 22-24 June 2016: 1312-1319.