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# Experimental and numerical behaviour of eccentrically loaded high strength concrete filled high strength square steel tube stub columns

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Using high strength materials in concrete filled steel tube (CFST) columns is expected to achieve better structural performance and fulfil the requirements of sustainable construction. To study the mechanical behaviour of eccentrically loaded high strength concrete filled high strength square steel tube (HCFHSST) stub columns, this paper describes 12 tests with different eccentricity ratios and steel ratios. The cubic strength of high strength concrete under investigation was 110.5 MPa, and the yield strength of the high strength steel was about 434 MPa. Curves of load-lateral deformation were presented, along with values of ductility index, and the minimum ductility index based on the steel ratio of columns was suggested. Finite element analysis (FEA) software ABAQUS was applied to simulate HCFHSSTs. The analytical results were in good agreement with the experimental ones. The load-lateral deformation curve was divided into four stages: elastic, elastic-plastic, plastic hardening and descending. The confinement effect of steel tube at various stages was analysed. The parametric studies were carried out to evaluate the influences of the eccentricity ratio, concrete compressive strength, steel yield strength and steel ratio on the strength reduction factor (SRF), concrete contribution ratio (CCR), $P$-$M$ and $P/P_u$-$M/M_u$ interaction curves of the HCFHSST members. The bending moments at balanced points of $P/P_u$-$M/M_u$ curves calculated by the plastic stress distribution models (PSDM) and FEA models were compared. The ultimate bearing capacities obtained from the tests and the values calculated from the AISC 360, GB 50936 and CECS 28: 90 design codes were compared. Finally, the formulas were proposed to predict the $P/P_u$-$M/M_u$ curves for the HCFHSST stub columns subjected to eccentric load. The proposed formulas' predictions agreed well with the test results.

## 1. Introduction

Applying high strength steel can increase the bearing capacity of the structure and reduce the section size and weight of the structure. As a result, the needs for building long-span bridges and high-rise buildings can be satisfied. Besides, high compressive strength, high elastic modulus, good durability and small creep are the important factors for high strength concrete's adoption in engineering. For the concrete filled steel tube (CFST) columns with high strength concrete and steel tube, high strength concrete infill effectively delays the local buckling of the steel tube. Due to the confinement effect of high strength steel, the compressive strength and ductility of high strength concrete can be improved effectively. During earthquakes, the columns usually bear the vertical load and the bending moment. Hence, the study on the behaviour of eccentrically loaded CFST columns with high strength materials is of great significance.

Previous research mainly focused on three aspects: (a) high strength concrete filled normal strength steel tubes; (b) normal strength concrete filled high strength steel tubes; (c) high strength concrete filled high strength steel tubes.

### 1.1. High strength concrete filled normal strength steel tubes

Lam et al. [1] studied 18 CFST stub columns under axial load with $f_y$ = 289–400 MPa and $f_{cu}$ = 30.8–98.9 MPa. The predicted axial bearing capacities, according to ACI 318 [2] code and Australian standards AS 3600 [3] and AS 4100 [4], were generally lower than the test results. De Oliveira et al. [5] conducted tests on 16 CFST columns with circular cross-section under axial load ($f_y$ = 287.33 MPa and $f_c'$ = 32.7, 58.7, 88.8, 105.5 MPa). The results showed that the Brazilian code NBR 8800 [6] was the most conservative, and it was closest in code EC4 [7] predictions. Ekmekyapar et al. [8] investigated the behaviour of 18 axially loaded circular CFST columns with $f_y$ = 235–355 MPa and $f_c'$ = 56.2–107.2 MPa. The results showed that the code EC4 [7]

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predictions agreed well with the test results, while the code AISC 360 [9] prediction was conservative. Portolés et al. [10] conducted tests on 37 circular CFST slender columns ($f_y$ = 320–325 MPa and $f_{ck}$ = 32.7–107.33 MPa) under eccentric load. Test results showed that it was not significantly useful for the slender columns with a high eccentricity ratio to increase the strength of the concrete too much, because the peak-load was not greatly improved (compared with the 70–90 MPa's).

Hassanein et al. [11] presented the finite element analysis (FEA) investigations to study the behaviour of large diameter octagonal CFST short columns ($f_c'$ up to 100 MPa) under axial load. Based on three design strength models, a new ultimate bearing capacity calculation formula was proposed, where the extensive series of $D/t$ values were considered. Javed et al. [12] carried out numerical investigations to study the flexural behaviour of normal strength and high strength concrete ($f_c'$ up to 100 MPa) filled square and rectangular steel tubes. It was found that the shear span-to-depth ratio and concrete strength have little effects on the ultimate bearing capacity of CFST beams.

### 1.2. Normal strength concrete filled high strength steel tubes

Uy [13] performed tests on CFST specimens subjected to axial and pure bending loads ($f_y$ = 750 MPa and $f_c'$ = 30 MPa). Mursi and Uy [14] conducted tests on four stubs and four slender CFST columns using high strength square steel tubes of $f_y$ = 761 MPa and normal strength concrete of $f_c'$ = 20 MPa. The results showed that the rigid plastic model in code EC4 [7] was unconservative, and therefore a modified model (elastic-plastic) was proposed. Aslani et al. [15] conducted tests on 12 square CFST columns and four hollow columns under axial load with $f_y$ = 701 MPa and $f_c'$ = 21–54.5 MPa. The results showed that the AS 5100 code [16] got the most accurate prediction compared with EC4 [7] and AISC 360 [9] codes. Zhu et al. [17] presented tests on three large diameter CFST stub columns under axial load. The steel tubes were made of grade Q550 ($f_y$ = 546 MPa) and filled with C30 concrete ($f_{cu}$ = 31.7 MPa). The EC4 design code [7] gave the most accurate estimations, at less than 4% discrepancies. The results from CECS 28: 90 [18] and BS 5400 [19] codes were relatively conservative, with an underestimation of less than 7%. Du et al. [20] conducted tests on 17 rectangular CFSTs ($f_y$ = 514.5 MPa and $f_{cu}$ = 43.2–55.3 MPa) and six hollow columns under eccentric load. The load-moment formulas were presented to design the strength of rectangular CFST beam-columns, and were conservative.

Al-Ani [21] conducted the FEA investigations to study the effects of several parameters ($f_y$ = 200–800 MPa, etc.) on the enhancement of $f_c'$ ($\Delta f_c'$). The results showed that $\Delta f_c'$ is associated with the value of the confinement factor. Despite the confinement factor increases with the increase in $f_y$ and steel ratio ($\alpha$), the greater values of $\Delta f_c'$ were achieved mainly by increasing $\alpha$.

### 1.3. High strength concrete filled high strength steel tubes

Sakino et al. [22] reported 114 experimental investigations on hollow and CFST stub columns (circular and square) under axial load, where $f_y$ = 262–853 MPa and $f_c'$ = 25.4–91.1 MPa. Based on the experimental results, a stress-strain model was proposed to simulate the behaviour of the square steel tubes. Liu [23,24] investigated behaviour of CFST columns ($f_y$ = 495 MPa and $f_c'$ = 60, 89 MPa) subjected to axial and eccentrical loads. Results showed that for the members under axial load, AISC 360 [9], ACI 318 [2] and EC4 [7] codes gave conservative predictions. For the members under eccentric load, the AISC 360 [9] and ACI 318 [2] codes underestimated the ultimate bearing capacity by 24% and 14%, respectively. In contrast, code EC4 [7] overestimated the ultimate bearing capacity by 4%.

Liew et al. [25] tested axially and eccentrically loaded CFST columns using high strength steel of $f_y$ up to 779 MPa and ultra-high strength concrete (UHSC) of $f_{ck}$ up to 193.3 MPa. The design guide of compatibility between steel and concrete materials was proposed for CFST members for steel with yield strength up to 550 MPa and concrete with compressive strength up to 190 MPa.

Studies presented by Xiong et al. [26–28] focused on the axial, flexural and eccentrical behaviour of CFST specimens with $f_y$ = 300–779 MPa and $f_c'$ = 51.6–193.3 MPa. For the CFST stub columns using the UHSC, the ultimate bearing capacity can be achieved at a very small axial strain before any significant confinement on core material can be developed due to the brittleness of the UHSC. Design recommendations were also provided, so that code EC4 [7] could be safely extended to determine the flexural strength of CFST members with high strength steel and UHSC.

Gho and Liu [29] studied the flexural behaviour of 12 rectangular CFST specimens ($f_y$ = 409, 438, 495 MPa and $f_c'$ = 56.3–90.9 MPa). It was found that the flexural strength of the specimens was significantly underestimated (about 18%) by AISC 360 [9] code. Chung et al. [30] performed experimental studies on six CFST specimens under flexural load. The CFST specimens consist of high strength steel tubes ($f_y$ = 325, 555 and 901 MPa) and high strength concrete ($f_{ck}$ = 82.5 and 119.7 MPa). It was found that the AISC 360 [9] design formula was conservative with underestimation more than 26% in their prediction of the maximum moment.

Fujimoto et al. [31] conducted tests on 33 circular ($f_y$ = 283–835 MPa, $f_c'$ = 24.5–77.6 MPa) and 32 square CFST columns ($f_y$ = 262–835 MPa and $f_c'$ = 25.4–80.3 MPa) under eccentric load. The results showed that the ductility of the columns decreased as the concrete strength increased. However, the ductility behaviour can be improved as the concrete is confined by the high strength steel tube or the $D/t$ value of the steel tube is small. Lee et al. [32] presented eccentric compression tests on eight circular CFST columns involving high strength steel ($f_y$ = 468–517 MPa) and normal strength concrete ($f_{ck}$ = 31.5 MPa), three specimens involving high strength steel ($f_y$ = 468–498 MPa) and high strength concrete ($f_{ck}$ = 59 MPa). It was found that AISC 360 [9] code showed good agreement for the circular CFST columns under eccentric load. Kim et al. [33] conducted tests on two CFST columns without longitudinal rebars ($f_y$ = 913 and 806 MPa, $f_c'$ = 94 and 113 MPa, $e/B$ = 0.86) under eccentric load. It was found that the plastic stress distribution model (PSDM) from the EC4 [7] and AIJ [34] codes accurately predicted the test results. Lee et al. [35] performed an experimental investigation on rectangular CFST columns ($f_y$ = 301, 746 MPa and $f_c'$ = 70.5, 83.6 MPa) under eccentric load. A design method of vertical stiffener was put forward to design the rectangular CFST columns with high strength materials. Choi et al. [36] investigated the mechanical behaviour of three rectangular CFST columns with different steel grades ($f_y$ = 351, 425, 703 MPa) and concrete compressive strength (61.5 and 99.6 MPa) under eccentric load. The results showed that the predictions by current design codes in the ultimate bearing capacity of the specimens were conservative.

Patel et al. and Liang et al. [37–40] presented nonlinear analysis investigations on behaviour of CFST columns ($f_y$ up to 690 MPa and $f_c'$ up to 120 MPa) under axial, eccentric and bi-axial eccentric loads. The constitutive model of concrete considering the confinement effects was suggested and indicated that the confinement effect on the ultimate bearing capacity of circular CFST slender columns under eccentric load is insignificant when the column slenderness ratio is greater than 70. Thai et al. [41] carried out the extensive numerical studies on the axial behaviour of CFST columns with high strength materials ($f_y$ = 300–800 MPa and $f_c'$ = 20–190 MPa). Dilation angle $\psi = 40^\circ$ was used for the concrete in their studies and proved to be accurate to simulate the behaviour of high strength concrete filled high strength square steel tube (HCFHSST) columns under axial load. Ouyang et al. [42] adopted FEA models to analyse the behaviour of square CFST columns ($f_y$ = 262–835 MPa and $f_c'$ = 24–110 MPa) under axial load. Results showed that the confinement effect of the steel tube increases dramatically from the pre-peak stage to the post-peak stage. Ouyang et al. [43] also investigated the behaviour of eccentrically loaded