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Behaviour of steel tubular members infilled with ultra high strength concrete

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ABSTRACT

This study is motivated by increasingly prevalent use of high strength steel and concrete materials in high-rise buildings to achieve better structural performance with less material usage. Previous studies and many modern design codes place some limits on the strength of steel and concrete for designing steel-concrete composite members, attributed to insufficient test data and design experience on their applications in construction. With this research gap being identified, an experimental program has been carried out to investigate the composite behaviour of concrete filled steel tubes (CFST) employing high tensile strength steel (HTS) and ultra-high strength concrete (UHSC). Both concentric and eccentric compression loads were applied to evaluate the overall buckling resistances and moment-axial force interaction with second-order effect considered. The yield strength of HTS under the investigation was about 800 N/mm^2 and the concrete compressive cylinder strength was up to 200 N/mm^2. To examine the test results, the rotational stiffness of semi-rigid end supports was analytically derived and the stress-strain models of HTS and UHSC were properly calibrated to predict the composite behaviour through finite element analysis. The Eurocode 4 approach was then checked regarding its applicability to the said high- and ultra-high strength construction materials for composite design. A new database including 1160 test data was established to further study the reliability of the use of HTS and UHSC, and suggestions were made to extend the Eurocode 4 design approach.

1. Introduction

Concrete filled steel tubes (CFSTs) are the most widely used composite members in high-rise construction, taking the full advantages of the characteristic behaviour of steel and concrete. It is well known that the local buckling and temperature rise of steel tube are delayed by the core concrete, in turn, the strength and ductility of core concrete could be enhanced by the steel tube. The CFSTs generally have circular, square and rectangular sections, whereas elliptical and polygonal sections could be adopted catering for the architectural aesthetics or functional requirements. Plain concrete can be infilled into the hollow tubes without the need of any formwork. Polymer or steel fibres may be added into the concrete to enhance ductility and fire performance. In such cases, the workability/flowability of the concrete should be carefully examined to avoid clogging if it is pumped into the tubes. Steel reinforcements are sometimes used to improve the fire resistance as they are capable of resisting loads when the steel tube is softened under fire. The steel reinforcements could also be replaced by an inner tube to improve not only the fire resistance but also the compressive resistance and ductility due to the higher confinement provided. Other steel sections, such as solid steel sections, H-sections, etc., could be inserted into the concrete to further improve the compressive resistance and thus reduce the member sizes. Nevertheless, steel reinforcements and inner sections are seldom used in practice due to some construction difficulties, for instance, they could lead to congestion at the concrete casting area, obstruction with the inner diaphragm plates at beam-column joints, etc.

With the development of concrete technology and availability of various high performance materials such as silica fume and high-range water-reducing admixtures, it is possible to produce ultra-high strength concrete (UHSC) with a compressive strength higher than 120 MPa nowadays. However, the UHSC has been limited to some special applications such as offshore or marine structures, industrial floors, pavements, and security barriers, etc. It has not been widely used in building structures due to concerns on its brittleness and compatibility with normal strength steels. To solve these problems, the UHSC may be confined by the steel tubes. As the UHSC is more brittle than normal strength concrete (NSC, $f_{ck} \leq 50$ N/mm^2) and high strength concrete (HSC, $f_{ck} \leq 90$ N/mm^2), high tensile strength steel (HTS, $f_y > 460$ N/mm^2) tubes may be used to provide the higher confinement. The production of HTS with a tensile strength around 800 MPa becomes possible nowadays with the development of metallurgical technology and availability of a variety of alloy elements. However, the HTS are mostly used in

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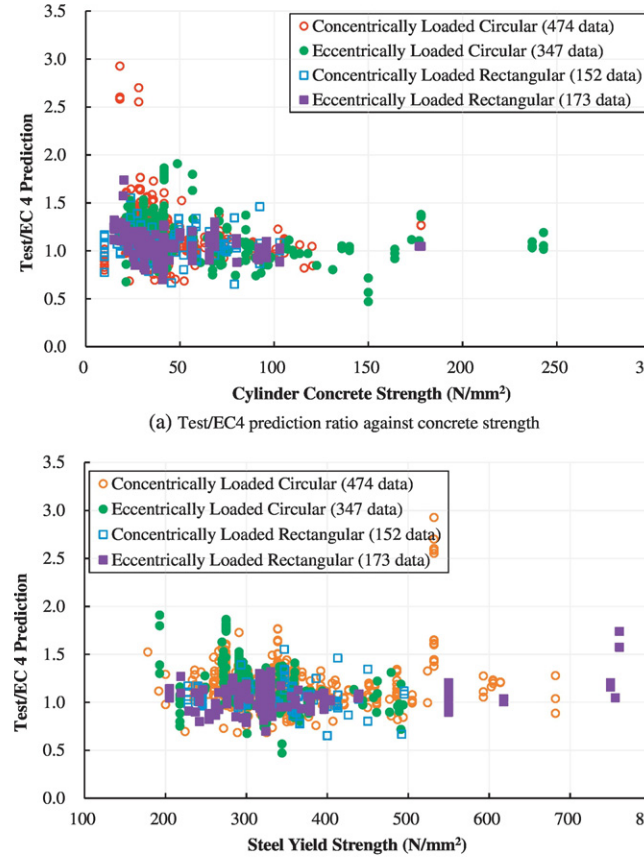
cars, trucks, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of stress or need a high strength-to-weight ratio. The HTSs are rarely used in high-rise buildings as there are limitations for their use in many of the modern design codes (Chinese code: GB 50936 [1]; US code: AISC 360-10 [2]; Japanese code: AIJ 1997 [3]; Eurocode 2: EN 1992-1-1 [4]; Eurocode 3: EN 1993-1-1 [5] & EN 1993-1-12 [6]; Eurocode 4: EN 1994-1-1 [7]), as summarized in Table 1.

Composite structural members are deemed to exhibit the better ductility and the higher buckling resistance compared with individual steel or reinforced concrete members. However it can be seen from Table 1 that, Eurocode 4 (design of composite steel and concrete structures) gives narrower range of material strength for steel and concrete compared with Eurocode 2 (design of concrete structures) and Eurocode 3 (design of steel structures). This implies that the material strength range in Eurocode 4 could be further extended to match those in Eurocodes 2 and 3. However, there are limited test data and design experience, thus more work should be done for this extension. Set against this background, this study, focusing on the structural behaviour of CFST beam-columns with the UHSC and HTS based on experimental work, was motivated.

There are many researches on CFST columns using normal strength materials as reviewing the available literature [8–13]. However, there is very limited research on the CFST beam-columns using the UHSC or HTS. Among which, Varma et al. [14] experimentally investigated the structural behaviour of high strength square concrete-filled steel tube beam-columns, made from either conventional (A500 Grade-B) or high strength (A500 Grade-80) steel, and infilled with high strength concrete (110 MPa). It was concluded that the moment resistance of the said CFST beam-columns can be predicted with reasonable accuracy using the current ACI code provisions for composite columns. Liu [15] conducted an experimental study on 12 high strength rectangular CFSTs subjected to eccentric loading. High strength concrete was used and the steel yield strength reached 550 MPa. Comparisons showed that Eurocode 4 overestimated the ultimate resistance of the columns approximately by 3%, whereas ACI and AISC conservatively predicted the failure loads by 11% and 25%, respectively. Portolés et al. [16] and Romero et al. [17] experimentally investigated the influence of UHSC infill on slender CFST single-tube and double-tube columns. The compressive strength of the UHSC reached 130 MPa. It was found that the UHSC infill is more useful for concentrically loaded tubes than for eccentrically loaded ones. The Eurocode 4 could be used to predict the resistance of eccentrically loaded single-tube columns. However, for concentrically loaded CFSTs and double-tube CFSTs, the predictions might not be safe.

The foresaid studies have provided significant contributions to the research progress in developing guideline to determine the beam-column resistance of the CFSTs using the high strength materials. However, the work is still insufficient for CFST members with combined UHSC of compressive strength higher than 120 MPa and HTS of yield strength >460 MPa as shown in Fig. 1, where 1146 test data in total for the CFST beam-columns were collected from the available literature (not including the test data introduced in this article). Besides, the authors have studied the axial and flexural behaviours of composite members using the UHSC and HTS in previous work [18,19]. As a continuous work, this research is expected to enrich the existing database and complete the previous work. A total of 14 CFSTs made from the HTS and UHSC were physically tested under concentric or eccentric axial forces. The yield strength of HTS approached 800 MPa and the compressive strength of UHSC approximated 200 MPa. Eurocode 4 simple calculation method and finite element method were employed to predict the overall buckling resistance and M-N interactive resistance of the tested elements. The applicability of Eurocode 4 approach for designing the CFST beam-columns with the said HTS and UHSC is then examined.



(a) Test/EC4 prediction ratio against concrete strength

(b) Test/EC4 prediction ratio against steel strength

Fig. 1. Test results compared with EC4 predictions.

Table 1
Limits on steel and concrete strengths in modern design codes.

Codes	Yield strength of steel (N/mm^2)	Cylinder compressive strength of concrete (N/mm^2)
GB 50936 [1]	235–420	25–67
AISC 360-10 [2]	≤525	21–70
Architectural Institute of Japan [3]	235–440	18–90
EN 1992-1-1 [4]	–	12–90
EN 1993-1-1 [5], EN 1993-1-12 [6]	235–700	–
EN 1994-1-1 [7]	235–460	20–50

2. Eurocode 4 approach for concrete filled steel tubes

In general, CFST beam-columns can be designed according to the resistance interaction curve for combined compression and bending shown in Fig. 2 and the ultimate axial resistance (N_u) can be calculated by

$$\begin{cases} AC: \dfrac{N_u - N_{pm,Rk}}{N_{pl,Rk} - N_{pm,Rk}} + \dfrac{kN_u e/\alpha_M}{M_{pl,Rk}} = 1 \\ CD: \dfrac{N_u - 0.5N_{pm,Rk}}{N_{pm,Rk} - 0.5N_{pm,Rk}} + \dfrac{kN_u e/\alpha_M - M_{pl,Rk}}{M_{max,Rk} - M_{pl,Rk}} = 1 \\ BD: \dfrac{N_u}{0.5N_{pm,Rk}} + \dfrac{kN_u e/\alpha_M - M_{max,Rk}}{M_{pl,Rk} - M_{max,Rk}} = 1 \end{cases} \quad (1)$$

where $N_{pm,Rk} = A_c f_{ck}$, $N_{pl,Rk}$ is the cross-sectional plastic resistance under pure compression, $M_{pl,Rk}$ is the cross-sectional plastic moment resistance under pure bending, $M_{max,Rk}$ is the cross-sectional maximum moment resistance in the presence of a compressive normal force, and α_M is a coefficient taken as 0.9 for S235 and S355 steel inclusive and 0.8 for steel grades S420 and S460. The factor of $k = 1/(1 - N_u/N_{cr,eff})$ is an amplification factor considering member second-order effect due to the existence