Design of Concrete Filled Steel Tube with High-Strength Materials

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Abstract
High-strength materials are now increasingly used for their economic and architectural advantages, and the need for sustainable construction. However, limited research data and design guidelines are available on the application of these materials. This paper presents significant findings from a comprehensive experimental investigation on the behavior of concrete filled steel tubes with high-strength materials at ambient and elevated temperatures, including high-strength material properties, stub columns, beams and slender beam-columns. High-strength materials include high-strength steel and ultra high-strength concrete. The test results were compared with predictions by extending the Eurocode 4 approach. It is found that it is feasible to use high-strength materials in high-rise construction and the current Eurocode 4 approach can be safely extended to such materials with minor modifications.

Keywords: Composite Member, Concrete Filled Steel Tube, Ultra High-Strength Material

Introduction
High-strength construction materials are now increasingly used due to their economic and architectural advantages, and the need for sustainable construction. The higher the material strength, the smaller the required member size. A lot of floor space can be saved and cost can be significantly reduced by using high-strength materials in tall building construction. However, there may be some problems. For example, brittleness may be a problem for structural members with high-strength concrete (HSC) and local buckling may be a problem for structural members with high-strength steel (HSS).

To overcome these problems, one solution is using composite structural members, especially concrete filled steel tubes (CFSTs) as columns, where the ductility and strength of the concrete core can be enhanced by the confinement effect provided by the steel tubes while the local buckling of the steel tube can be delayed or even prevented by the concrete core. In addition, the steel tube can serve as permanent formwork for concrete casting and thus eliminate the need for formwork and lead to fast track construction and economical design (Liew et al., 2008).

However, current design guidelines for composite columns may only be applicable for normal weight concrete and steel. For example, Eurocode 4 (2004) applies only for concrete cylinder strengths between 20MPa and 50MPa, the common thicknesses of steel and concrete layers for composite columns. AISC 360-10 (2010) is only applicable for concrete cylinder strengths between 23.5MPa and 69MPa. DBJ (2010) is only applicable for concrete cylinder strengths between 25MPa and 65MPa. Current design guidelines for composite columns will be discussed in the next section.

Abstract
高强度材料由于其经济性及建筑优势,以及可持续建设的需求,被越来越多地采用。然而,有关超高强度材料扩展应用的研究数据和设计准则却很有限。本文介绍了一个从综合试验研究所得的重大发现 -研究高强度材料混凝土填充钢管在环境温度和高温中的性能,包括高强度材料的特性、短柱、梁和长细比。高强度材料包括高强度钢材和超高强度混凝土。实验结果与按扩大欧洲规范4 (Eurocode 4) 方法所得的预测进行了比较分析。 结果表明在高层建筑施工中使用高强材料是可行的,而且对目前的Eurocode 4 方法作稍微修饰即可安全地扩展应用在此类材料上。

关键词: 复合构件、混凝土填充钢管、超高强材料
composite columns may be only applicable for normal strength concrete and steel. For example, Eurocode 4 (2004) applies to composite columns with normal weight concrete cylinder strength from 20MPa to 50MPa and steel yield strength from 235MPa to 460MPa, AISC 360-10 (2010) only applies to composite columns with normal weight concrete cylinder strength from 21MPa to 70MPa and steel yield strength up to 525MPa, and DBJ (2010) only applies to composite columns with normal weight concrete cylinder strength from 25MPa to 65MPa and steel yield strength from 235MPa to 430MPa. Therefore, sufficient work should be done to extend current design guidelines or propose new provisions for composite columns with HSC which is beyond C60/75, especially for ultra high-strength concrete (UHSC) which is beyond C120, and for HSS which is beyond S460.

Limited experimental investigations have been done on CFSTs with high-strength materials. Figures 1 and 2 show 1,948 test data samples collected from literature on CFSTs (including columns, beams and beam-columns) with non-slender (at least class 3) hollow steel sections subjected to static load, excluding the tests with stainless or aluminum steel tubes (Liew et al., 2012). The test results are compared with Eurocode 4 predictions by simply extending its limitations on material strengths to the test strengths reported in the literature. From Figures 1 and 2, it can be observed that many tests have been done on CFSTs with normal strength materials but only limited investigations have been done on CFSTs with high-strength materials. 19.10% of the test specimens have a concrete strength higher than 60MPa, 8.52% have a concrete strength higher than 80MPa, only 1.18% have a concrete strength higher than 120MPa, and only 7.49% test specimens have a steel yield strength higher than 460MPa. Most of the tests concentrate on normal strength materials and there are significant gaps in the range of high-strength materials.

To fill the gaps, a comprehensive investigation has been carried out on the behavior of concrete filled steel tubes with high-strength materials, including high-strength material properties, stub columns, beams and slender beam-columns. High-strength materials include UHSC with compressive strength up to 180MPa and HSS with yield strength up to 700MPa. For comparison, specimens with normal strength concrete and steel were also tested. In addition to the investigations at ambient temperature, studies were also carried out on material properties at elevated temperatures and fire resistance of slender beam-column specimens under ISO-834 standard fire. The parameters under investigation were a mix of proportion design of concrete, temperature, cross-section type, tube thickness, material strength, load level under fire, boundary conditions, thickness of fire protection, etc. The test results were compared with Eurocode 4 predictions by extending its limitations on material strengths to the test strengths reported herein.
Eurocode 4 Approach For Concrete Filled Steel Tubes

Generally, the cross-sectional resistance \( (N, M) \) of concrete filled steel tubes can be calculated by (see Figure 3)

\[
\begin{align*}
AC: & \quad N_c = N_{cr,ct} + M_{cr,ct}/f_{cr} = 1 \\
CD: & \quad N_c = 0.5N_{cr,ct} + M_{cr,ct}/M_{c,ct} = 1 \\
BD: & \quad N_c = 0.5N_{cr,ct} + M_{cr,ct}/M_{c,ct} = 1 \\
\end{align*}
\]

where \( N_{cr,ct} = A_f f_c \) is the cross-sectional plastic resistance under pure compression, \( M_{cr,ct} \) is the cross-sectional plastic moment resistance under pure bending, \( M_{c,ct} \) is the cross-sectional maximum moment resistance in the presence of a compressive normal force, and \( f_c \) is the yield strength of steel.

Design of Stub Column

Ultimate compressive resistance of stub CFST columns without reinforcement can be calculated by (Point A in Figure 3)

\[
N_c = N_{cp,ct} = A_f f_c + A_f f_a
\]

where \( A_f \) is the cross-section area of steel section, \( f_c \) is the yield strength of steel, \( f_a \) is the cross-section area of concrete, and \( f_a \) is the characteristic cylinder strength of concrete.

Confinement effect may be considered for concrete-filled circular tubes with non-dimensional slenderness ratio less than 0.5 and the ratio of eccentricity to diameter is less than 0.1 as

\[
N_c = N_{cp,ct} = \eta A_f f_c + A_f f_a \left( 1 + \eta \frac{f_a}{f_c} \right)
\]

where \( t \) is the wall thickness of the steel tube, \( d \) is the diameter of the steel tube, and \( \eta_c \) and \( \eta_t \) are two factors related to confinement effect, given by the following expressions for members without eccentricity:

\[
\eta_c = 0.25(3 + 2\lambda) \quad (\text{but} \leq 1.0)
\]

\[
\eta_t = 4.9 - 18.5\lambda + 17\lambda^2 \quad (\text{but} \leq 0)
\]

where \( \lambda \) is the non-dimensional slenderness ratio \( \lambda = \sqrt{N_{cp,ct}/N_c} \).

Design of Beam

Ultimate moment resistance of CFST beams without reinforcement can be calculated by (Point B in Figure 3).

\[
M_c = \alpha M_{pl,ct} = \alpha M \left[ (W_{pc} - W_{pf}) f_c + 0.5(W_{pf} - W_{pc}) f_a \right]
\]

where \( W_{pc} \) and \( W_{pf} \) are the plastic section moduli for the steel section and the concrete section respectively, and \( W_{pc} \) and \( W_{pf} \) are the plastic section moduli of the corresponding components within the range from 2h to the depth of the neutral axis from the middle line of the composite cross section where \( h \) is the depth of the neutral axis.

Design of Slender Beam-column

For concentrically and eccentrically compressed slender CFST beam-columns to consider the second-order effect, the moment resistance \( M_{Ed} \) in Equation (1) can be expressed as

\[
M_{Ed} = kN_{Ed} e
\]

where \( k = 1/(1 - N_{Ed}/N_{cr}) \) is a amplification factor considering member second-order effect due to axial load, is the critical load, \( N_{cr} = 0.9e(E_f f_a + 0.5E_I f_c) + E_c \) considering the member’s effective stiffness, and \( e = e_c + e_e \) where \( e_c \) is the eccentricity of loading at the member ends and \( e_e \) is the member imperfection taken as L/300 in Eurocode 4.

一般关于，混凝土填充钢管的横截面承载力 \( (N, M) \) 可按下列公式计算 (见图3)

\[
\begin{align*}
AC: & \quad N_c = N_{cr,ct} + M_{cr,ct}/f_{cr} = 1 \\
CD: & \quad N_c = 0.5N_{cr,ct} + M_{cr,ct}/M_{c,ct} = 1 \\
BD: & \quad N_c = 0.5N_{cr,ct} + M_{cr,ct}/M_{c,ct} = 1 \\
\end{align*}
\]

where \( N_{cr,ct} = A_f f_c \) 是纯受压状态下横截面塑性承载力，\( M_{cr,ct} \) 是纯受弯状态下横截面塑性弯矩承载力，\( M_{c,ct} \) 是横截面在压缩正交力存在时的最大弯矩承载力，\( f_c \) 是混凝土筒芯强度。
By incorporating Equation (5), Equation (1) can be expressed for concentrically and eccentrically compressed slender CFST beam-columns as

\[ N_c = \frac{N_x - N_{pm,ri}}{N_{pm,ri} - N_{pm,ei}} \cdot \frac{kN_e / (\mu - M_{pl,ri} / \lambda)}{M_{pm,ri}} = 1 \]

Alternatively, for slender CFST beam-columns under concentric compression, the overall buckling resistance may be evaluated as

\[ N_c = \chi N_{pm,ri} \]

where \( \chi \) is the reduction factor expressed as

\[ \chi = \left( \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda^2}} \right) \text{ but } \lambda \leq 1 \]

where \( \Phi = 0.5\left[1 + \alpha(\lambda - 0.2) + \lambda^2\right] \) and \( \alpha = 0.21 \) is the imperfection factor for concrete filled sections without reinforcement. For slenderness \( \lambda \leq 0.2 \), the overall buckling effects may be ignored and only cross sectional resistance checks apply.

**Experimental Investigations On Concrete Filled Steel Tubes**

**Material Properties**

The basic mechanical properties of the high-strength materials used in the study will be presented in this section.

- **Ultra high-strength concrete**
  
  UHSC is very brittle under compression, as shown in Figure 4 for the typical uniaxial stress-strain curve of UHSC cylinder under compression. Once cracked, the UHSC cylinders were instantly crushed into pieces and the pieces flew out in all directions. Therefore, a descending part could not be obtained. The Poisson's ratio is about 0.23 and the modulus of elasticity is about 65GPa.

  Different strengths of UHSC can be obtained by adding different proportions of ordinary coarse aggregates, as shown in Figure 5 for compressive strength of cylinder with dimension of 100mm(D)×200mm(H) at curing ages of 3, 7, 28 and 91 days.

  The residual strength of UHSC after being exposed to elevated temperatures is shown in Figure 6 for residual compressive cylinder strength, compared with normal strength concrete. Different proportions of polypropylene fiber were added to prevent UHSC from spalling at elevated temperatures, and for UHSC without polypropylene fiber the spalling occurred at about 500°C. For these residual strength tests, no coarse aggregates were added to the UHSC.

- **High tensile strength steel**

  The uniaxial stress-strain relationship for the high tensile strength steel used in the study is shown in Figure 7. as opposed to hot finished steel sections with mild steel, there is no significant yielding plateau or hardening effect. The reduction in strength at elevated temperatures was tested as shown in Figure 8, compared with the reduction values recommended in Eurocode 3 for normal strength steel. Both steady and transient states were considered. The reduction in strength for high tensile strength steel is more than normal strength steel.
Tests on Stub Column Specimens

For stub column tests, there were 35 circular specimens with mild steel, 5 square specimens with mild steel, and 16 square specimens with high tensile strength steel, including 7 hollow single-tube specimens, 31 UHSC filled single-tube specimens, 14 UHSC filled double-tube specimens, 2 normal strength concrete filled single-tube specimens, and 2 normal strength concrete filled double-tube specimens (Liew & Xiong, 2010).

Similar behavior was observed from all the tests (see Figure 9) for typical loading-shortening curves of two UHSC filled steel tube specimens, compared with one normal strength concrete filled steel tube specimen. The steel contribution ratio of Specimen 1 was 0.40, higher than that of Specimen 2 which was 0.23, close to the lower limit value of 0.2 as recommended in Eurocode 4. Due to the brittleness of the UHSC core, very loud cracking/crushing noise was heard around the first peak load during the testing for most of the UHSC filled steel tube specimens. A steep drop in the load-displacement curves was observed right after the peak load. Soon after the load drop, visual inspection was carried out on the specimens and no visible deformation was observed. Therefore, the noise was thought to be originated from the crushing of the UHSC core. For Specimen 1 with higher steel contribution ratio, the second peak load is higher than 70% of the first peak load; for Specimen 2 with lower steel contribution ratio, the second peak load is lower than 50% of the first peak load. For plastic design, the second peak load should be greater than 70% of the first peak load. Therefore, the lower limit of steel contribution ratio as recommended in Eurocode 4 should be increased from 0.2 to 0.3 (Liew & Xiong, 2010). In addition, the crushing of UHSC core occurred almost in the elastic range before significant confinement.
effect had been developed. Therefore, confinement effect should not be considered for UHSC filled steel tubes, and Equation (2) but not Equation (3) should be used to predict the cross-sectional resistance under compression. For the normal strength concrete filled steel tube specimen, the post-buckling behavior was sufficient ductile for plastic design.

Compared with the predictions by using Equation (2) as recommended in Eurocode 4, the average value of the ratios of test results to predictions is 1.095 and the standard deviation is 0.089. Therefore, conservative predictions are provided by Eurocode 4.

Tests on Beam Specimens

For beam tests, there were 3 circular specimens with mild steel, 1 square specimen with mild steel, and 4 square specimens with high tensile strength steel (Liew & Xiong, 2012). As opposed to the brittle behavior observed from stub column tests as shown in Figure 9, very ductile behavior was observed from beam specimen tests as shown in Figure 10.

Compared with the predictions by using Equation (5) as recommended in Eurocode 4, the average value of the ratios of test results to predictions is 1.262 and the standard deviation is 0.028. Therefore, very conservative predictions are provided by Eurocode 4. The value of $\alpha_M$ is taken as 0.8 for high tensile strength steel used in the study.

Tests on Slender Beam-column Specimens

For concentrically and eccentrically loaded slender beam-column specimen tests with L/D ratio ranging from 18 to 20, there were 9 circular specimens with mild steel, 1 square specimen with mild steel, and 4 square specimens with high tensile strength steel (Liew, Xiong & Yu, 2012). Typical load-deflection curves are shown in Figure 11 for three specimens with different values of eccentricity. The load-deflection curves after reaching the peak load were also recorded and the results indicated that strength degradation was gradual without brittle or sudden failure as observed from stub column tests shown in Figure 9, especially for specimens with larger value of eccentricity.

Compared with the predictions by using Equation (7) for eccentrically loaded tests and Equation (8) for concentrically loaded tests as recommended in Eurocode 4, the average value of the ratios of test results to predictions is 1.169 and the standard deviation is 0.096. Quite conservative predictions are provided by Eurocode 4.

All the test results from the investigation are shown in Figure 12, together with the test data collected from literatures. The research has filled a large gap in the knowledge of high-strength concrete filled steel tubes. To completely fill the gap, more investigations should be carried out in the future.

Figure 10. Typical loading-shortening curves for stub columns

Figure 11. Typical load-deflection curves for slender beam-column specimens

Figure 12. All test results compared with the predictions by Eurocode 4
Conclusions
The following conclusions can be drawn from the experimental investigations:

- Eurocode 4 limitation on concrete strength can be extended to C180 concrete;
- Eurocode 4 limitation on steel grade can be further extended to high-strength steel up to 780MPa. If αM = 0.8 is adopted for S700 steel, the predictions are conservative compared to the test results reported in this paper;
- The overall buckling behaviour of stub UHSC filled steel tube columns with low steel contribution ratio may be very brittle. The lower limit as recommended in Eurocode 4 should be increased from 0.2 to 0.3.
- The overall behaviour of UHSC filled steel tube beams is very ductile.
- The overall buckling behaviour of slender UHSC filled steel tube columns is quite ductile with smooth unloading from the peak load. There is no sudden failure due to the brittle failure of ultra-high-strength concrete as observed in the short column tests.
- Concrete filled boxed columns with ultra-high-strength concrete (180MPa) and high-strength steel (780 MPa) are capable of resisting high compression static loads. The test results show that they are feasible for use in multi-storey buildings and especially in high-rise construction, with reduced column size.

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