Calculation on Bond Strength of High-Strength Concrete Filled Steel Tube

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Abstract. This paper describes a test study of the interface mechanical behavior of high-strength concrete filled steel tube. According to push-out tests of four specimens of high-strength concrete filled steel tube, the failure pattern and load-slip curves were analyzed. Test results show that the load-slip curves at the load end and free end are both a similarity for the stress-strain curves of steel with no apparent yield point. A reasonable calculation method for predicting the bond strength of high-strength concrete filled steel tube is presented based on the related theories and test results.

Introduction

With the improvement of concrete strength grade, the brittleness and deformation ability of high strength concrete reduces, which can affect the application scope in civil engineering. Thus, the concept of high-strength concrete filled steel tube is put forward, which is used in the lateral restraint of steel tube to overcome the brittleness of high strength concrete.

Several investigations by Cai (2003), Zhang (2004), Ellobody (2005), Zhong (2006) , Han (2007), Li (2009), Hoang (2011), Ke (2014), et al. have been performed to quantify the mechanical properties and bearing capacity of high-strength concrete filled steel tube at home and abroad. Some researches by Cai (2003), Yang (2006), Kang (2008), Gourley (2008), Xu(2013),et al. have been carried on the calculation of bond strength between steel and normal or recycled aggregate concrete. However, few studies were done on the interface bond properties and bond strength of high-strength concrete filled steel tube. Up till now, the bond strength calculation theory was established by the basis of normal strength concrete filled steel tube mostly, and this theory verified by more tests. Therefore, this paper designed four specimens of high-strength concrete filled steel tube for push-out test. It can be help for theoretical analysis, numerical simulation and application of high-strength concrete filled steel tube

Summary of Test

Design and Manufacture of Specimens.

Four specimens of high-strength concrete filled steel tube, considered the mainly parameters of concrete strength and steel tube bond length, were designed for push-out test to reveal the interface mechanical behavior between steel tube and high-strength concrete. The design parameters of specimens are shown in Table 1.

Table 1 Design parameters of specimens.

Labels	concrete strength	L/mm	d/mm	t/mm	L_e/mm
CST-1	C60	430	110	3	400
CST-2	C70	430	110	3	400
CST-3	C80	430	110	3	400
CST-4	C70	330	110	3	300

Notes: L is specimen length; d is the diameter of steel tube; t is the thickness of steel tube; L_e is bond length of steel tube.

High strength concrete was supplied by a commercial ready-mixed plant, i.e. 42.5 R brand ordinary Portland cement, sand, gravels with continuous gradation whose particle size ranged from 5 mm to 20 mm, tap water and AF-C poly hydroxy acid high efficiency water reducing agent. The design mix

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proportion and concrete cube compressive strength (f_{cu}) measured by Chinese Standard are shown in Table 2.

Circle steel tube use the straight welded steel tube with a diameter of 110 mm. The yield strength (f_y), ultimate tensile strength (f_u) and elastic modulus (E_s) are 398 MPa, 458 MPa, and 1.976×10^5 MPa respectively.

All empty steel tubes were accurately cut to the required length, and the bottom of steel tubes was sealed with plastic film for avoiding the leakage of any slurry. 30 mm distance without pouring concrete on the top of steel tubes was reserved to control bond length during pouring concrete. All specimens were vibrated by a vibration table, and placed indoor to 28 days' natural curing after pouring concrete.

Table 2 Design mix proportion and performance index of concrete.

concrete strength	Material /(kg. m-3)				slag /%	silica fume /%	water reducing agent /%	f_{cu} /MPa
	cement	Sand	gravel	water				
C60	408	576	1283	163	15	10	1.0	70.52
C70	482	664	1097	160	15	10	1.5	75.01
C80	533	745	1117	160	15	10	1.5	79.44

Test Loading and the Arrangement of Measuring Points

All specimens were performed on RMT-201 rocked and concrete compression machine, produced by Institute of Rock and Soil Mechanics Chinese Academic of Science and SIMENS Company. Test set-up is shown as in Figure1. In this test, It should be need that a 30 mm thickness steel plate, whose diameter is slightly smaller than the inner diameter of steel tube, was putted on the load end to ensure that loading can be transfer from core concrete to steel tube, and make the bond failure. Three dial indicators were distributed on the load end and free end to measure the relative slip between steel tube and core concrete.

Loading was conducted by displacement, and the displacement speed was 0.002 mm/s. When the slip value at the load end was about 6 mm, loading stopped.

Figure 1 Test set-up

Figure 2 Failure pattern

Test Results and Analysis.

Failure Pattern

When loading to a certain load, it appeared a tiny slip at the load end, accompanying with slight noise. The noise may be released from the chemical bond force failure between steel tube and concrete. With the increasing of loading, the slip value at the load end increased continuously, and the noise became frequently. Before bond failure, a small amount of concrete debris fell off at the load end, and steel tube did not appear bending failure. The typical failure pattern is shown in Figure 2.

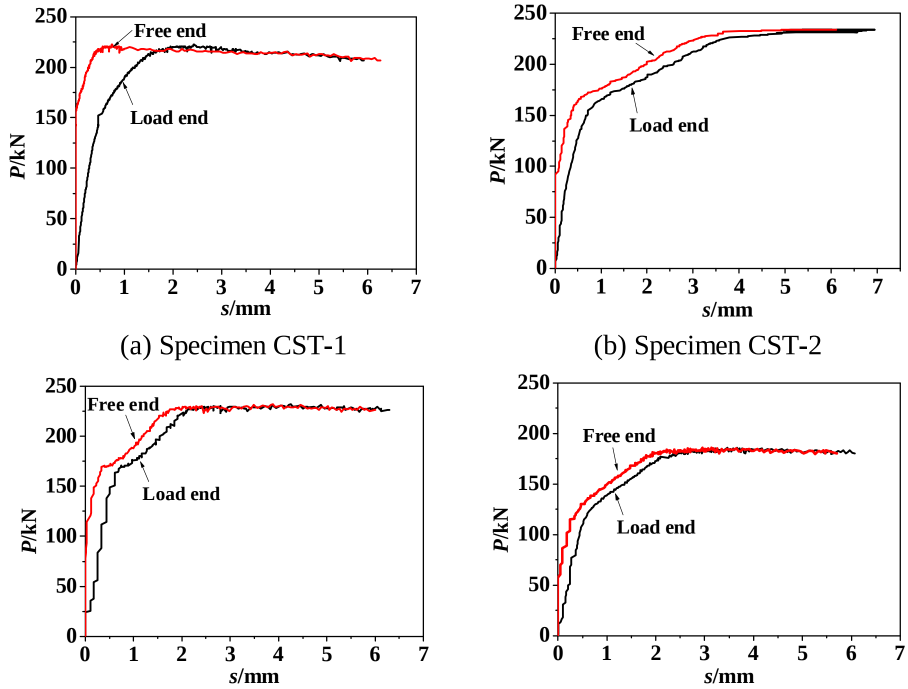
Load-slip Curve

The load-slip curves at the load end and free end are shown in Fig.3. It can be seen that the curve shape of all specimens is similar to the stress-strain curves of steel with no obvious yield point, and it generally posses the following characteristics:

a) The interface slip between steel tube and concrete can be divided into no slip, local slip and whole slid, which is a process of damage accumulation gradually.

b) The slip at the load end is the very early appearing, that is, the development of interface bond failure is from load end to free end.

c) After the peak load, the load-slip curve falls slowly, and the bearing capacity is more stable with the increasing of concrete strength and steel tube bond length.



(a) Specimen CST-1 (b) Specimen CST-2

(c) Specimen CST-3 (d) Specimen CST-4

Figure 3 Load-slip curves (*P*-*s*)

Nominal bond strength

On the basis of the assumption that the bond stress is evenly distributed along the interface between steel tube and concrete, the measured nominal bond strength of concrete filled steel tube can be calculated by using Equation 1.

$$t_u = \frac{P_u}{A} \tag{1}$$

Where τ_u is nominal bond strength; P_u is the bond failure load corresponding to the peak point or inflection point of load-slip curve; *A* is the effective contact area between steel tube and concrete. Table 3 shows the measured nominal bond strength of all specimens. It can be seen that the bond strength improves with the increasing of concrete strength and steel tube bond length on the whole.

Calculation Method of Bond Strength

On the basis of further researches about the interface bond performance of normal or recycled aggregate concrete filled steel tube at home and abroad, different methods for calculating bond strength between steel tube and concrete were put forward. To verify whether the existing theories are suitable for high-strength concrete filled steel tube, several practical calculation methods are discussed in this paper.

Calculation Method by Cai Shaohuai

A typical calculation formula for bond strength of concrete filled steel tube in China, applied to concrete strength grade ranging from C40 to C80, is proposed by Cai Shaohuai.

$$t_{\mathrm{u}} = 0.1 f_{\mathrm{cu}}^{0.4} \tag{2}$$

Where f_{cu} is the cubic compressive strength of concrete

Calculation Method by Kang Xiliang

Through the regressive analysis of experimental data, Kang Xiliang put forward a calculation formula for bond strength of concrete filled steel tube, shown as follows.

$$t_{\mathrm{u}} = \frac{1}{g} k f_{\mathrm{t}} [-0.00028(4L_{\mathrm{e}}/d) + 0.11121 d/t + 29.09049a + 0.03439q - 7.36037] \tag{3}$$

Where: γ is the correction coefficient with the influence of uncertain factors, and γ=0.96 is suggested; f_t is the tensile strength of concrete; k is the influence coefficient of steel tube's surface condition, and k =1.3 is suggested without rust; θ is the confinement coefficient ($\theta=\alpha f_y/f_c$), in which the ratio of steel tube $\alpha=A_s/A_c$, f_y is the yield strength of steel tube, f_c is the axial compressive strength of concrete, A_s, A_c are the area of steel tube and concrete, respectively.

Calculation Method by Gourley

Gourley holds that the diameter-thick ratio is the key factor which influences the bond strength of concrete filled steel tube, and it should be considered for calculating bond strength of concrete filled steel tube. According to the regressive analysis of test results, the bond strength between concrete and steel tube can be calculated by using Equation 5.

$$t_u = 2.109 - 0.026(d/t) \tag{4}$$

Where: d is the outer diameter of steel tube; t is the wall thickness of steel tube.

Calculation Method by Chen Zongping

On the basic of push-out test, Chen Zongping proposes the following calculation formula, which can consider simultaneously the influence of replacement rate of recycled coarse aggregate, concrete strength grade and length-diameter of ratio on bond strength of recycled aggregate concrete filled steel tube.

$$t_u = [0.0336 + 0.0141d - 0.0028(L_e/d)]f_{cu} \tag{5}$$

Where: δ is the replacement rate of recycled coarse aggregate; L_e/d is the length-diameter ratio.

Predicted bond strength of high-strength concrete filled steel tube using different methods is compared with test results (τ_u) in Table 3. Results in Table 4 show that bond strength calculated by Equation 3 is about 1/3 of test results, and calculation results by Equation 4 and 5 are about 2/3 of test results. Therefore, the first three calculation methods are conservative for predicted bond strength, and give a safe prediction. The results calculated by Equation 6 are in a good agreement with test results, and the mean value of their ratio is 1.0. This represents that the calculation method proposed by Chen is the best predictor to predict the bond strength of high-strength concrete filled steel tube.

Table 3 Bond strength calculated by different calculation methods.

Labels	P_u/kN	τ_u /MPa	$\tau_{u.2}$/MPa	$\tau_{u.2}/\tau_u$	$\tau_{u.3}$/MPa	τ_{u3}/τ_u	$\tau_{u.4}$/MPa	$\tau_{u.4}/\tau_u$	$\tau_{u.5}$/MPa	τ_{u5}/τ_u
CST-1	220.31	1.69	0.55	0.33	1.22	0.72	1.16	0.69	1.65	0.98
CST-2	240.34	1.84	0.56	0.31	1.26	0.68	1.16	0.63	1.76	0.95
CST-3	235.46	1.80	0.58	0.32	1.30	0.72	1.16	0.64	1.86	1.03
CST-4	183.98	1.88	0.56	0.30	1.26	0.67	1.16	0.62	1.95	1.04

Notes: τ_u is the measured nominal bond strength; $\tau_{u.2}$, $\tau_{u.3}$, τ_{u4}, $\tau_{u.5}$ are corresponding to the results calculated by the Equation 2~5.

Summary

1) The load-slip curves at the load end and free end are both similar to the stress-strain curves of steel with no obvious yield point, the slip at the load end is the very early appearing.
2) The bond strength of high-strength concrete filled steel tube improves with the increasing of concrete strength and steel tube bond length on the whole.
3) Comparing with the specification regulated data, the measured bond strength is far greater. According to the existing theories, a reasonable calculation method is put forward to predict the interface bond strength of high-strength concrete filled steel tube.

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