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Bond strength in full-scale concrete-filled steel tubular columns

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ABSTRACT

This paper studies the bond strength between the steel tube and core concrete in full-scale concrete-filled steel tubes (CFST). A series of push-out tests were carried out to measure the bond stress versus slip curves of circular CFST specimens with a diameter of 400 mm and square CFST specimens with a width of 600 mm. The primary test parameters include steel type (stainless and carbon steels), concrete type (normal and expansive concretes), concrete age (28 days and about 3 years) and interface type (normal interface, interface with shear studs and interface with an internal ring). The experimental results indicate that CFST specimens with stainless steel tubes have lower bond strength compared with the CFST specimens with carbon steel tubes, and the bond strength decreases remarkably with increasing concrete age. It is also found that welding internal rings onto the inner surface of the steel tube is the most effective method in enhancing the bond strength in CFST specimens, followed by the method of welding shear studs onto the inner surface of the steel tube. Although using expansive concrete can also enhance the bond strength, this method is less reliable to be used in practice.

1. INTRODUCTION

Concrete-filled steel tubular (CFST) construction has received increasing interest from the research community and construction industry in recent years. For CFST columns, load transfer can sometimes occur between the steel tube and concrete. The load transfer needs to be ensured by enough bond strength between the steel tube and concrete (Tao et al. 2011). In the past few decades, numerous studies have been

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conducted to investigate the bond strength between the steel tube and concrete in concrete-filled carbon steel tubes (Abe et al. 1991; Shakir-Khalil 1993; Roeder et al. 1999; Parsley et al. 2000; Aly et al. 2010; Tao et al. 2011; Qu et al. 2013). But previous push-out tests were mainly conducted on specimens with a cross-sectional dimension smaller than 200 mm, where the measured bond strength did not represent that in real structures. Meanwhile, the majority of the push-out tests were conducted on specimens at a concrete age of less than 3 months. The influence of concrete age on the bond behaviour needs to be examined. Set against this background, a series of push-out tests were conducted on full-scale CFST specimens to investigate the effects of cross-sectional dimension and concrete age on the bond behaviour. Meanwhile, the effectiveness of different measures in enhancing the bond strength was also checked.

2. TEST PROGRAM

2.1 Specimen preparation

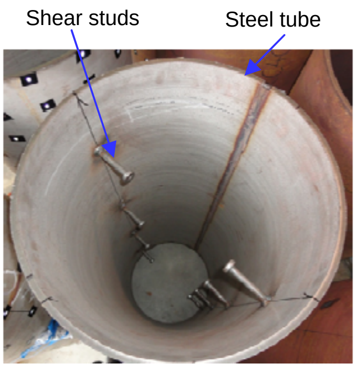
A total of 13 push-out tests on CFST specimens were conducted, including tests on 8 circular CFST specimens with a diameter of 400 mm and 5 square CFST specimens with a width of 600 mm. The main purpose of the test program was to investigate the bond behaviour between the steel tube and core concrete in full-scale CFST columns. The investigated parameters included steel type (carbon and stainless steels), concrete type (normal and expansive concretes), concrete age (28 days and 1163 days), and interface type between the steel tube and concrete (normal interface, interface with shear studs and interface with an internal ring). Table 1 provides a summary of the testing parameters for all specimens, in which D represents the diameter of the circular section or the width of the square section; t_s represents the thickness of the steel tube; L represents the length of the CFST specimen; and t_c represents the concrete age. The specimens were named according to the following rules: specimen labels starting with a “C” or “S” refer to specimens with circular or square cross-sections; the second character “C” or “S” in the specimen labels refers to the specimens with carbon steel or stainless steel tubes; “400” or “600” in the

Table 1 Details of test specimens

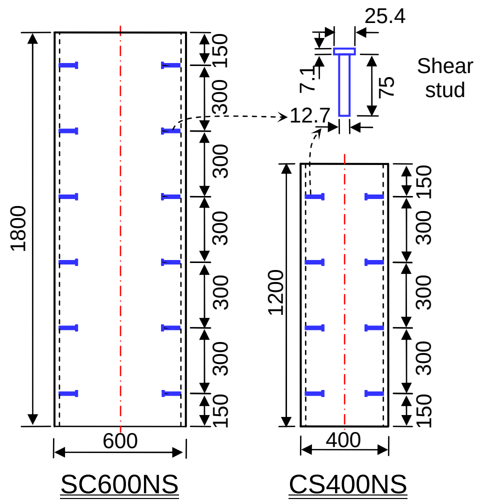
Specimen label	Section type	Steel type	$D \times t_s \times L$ (mm)	f_c' (MPa)	t_c (days)	f_y (MPa)	f_u (MPa)	E_s (GPa)	τ_u (MPa)	Remarks
CC400N1	Circular	Carbon	400×8×1200	42.0	28	372	515	209.2	0.59	
CC400N2				54.4	1163				0.04	
CC400E1				42.7	28				1.02	
CC400E2				55.8	1163				0.76	
CS400N1	Circular	Stainless	400×8×1200	42.0	28	359	647	178.2	0.21	
CS400E1				42.7	28				0.76	
CS400NS				42.0	28				1.26	Shear studs
CS400NR				54.4	1163				2.72	Internal ring
SC600N1	Square	Carbon	600×10×1800	54.4	1163	356	488	205.3	0.03	
SC600NS				54.4	1163				0.33	Shear studs
SC600NR				54.4	1163				1.58	Internal ring
SC600E1				55.8	1163				0.13	
SC600E2				55.8	1163				0.15	

specimens labels refers to the diameter or width of the cross-section; and the following “N” or “E” denotes a specimen with normal concrete or expansive concrete. If the last character of the label is “S” or “R”, it refers to a specimen with shear studs or an internal ring.

For the majority of the test specimens, no special measure was adopted to treat the inner surface of the steel tube after received from the mill. The corresponding interface between the steel tube and concrete is referred to as normal interface. For specimens CS400NS and SC600NS, two rows of shear studs were welded on the inner surface of the steel tube along the longitudinal direction of the specimen, as shown in Fig. 1(a). Detailed dimensions of the shear studs and welding locations are presented in Fig. 1(b). For specimens CS400NR and SC600NR, an internal ring was welded in the steel tube at 200 mm away from the top end of the specimen as shown in Fig. 2(a). The thicknesses of the internal rings are 8 mm and 10 mm for the circular and square sections, respectively. Other dimensions and the location of the steel ring are shown in Fig. 2(b).



(a) Shear studs in specimen CS400NS



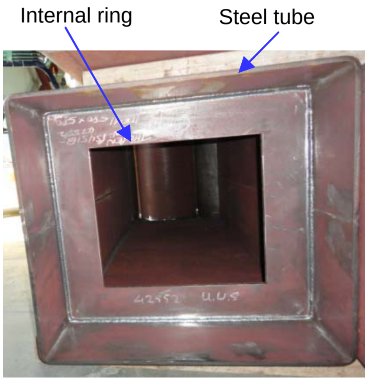
(b) Locations of shear studs

Fig. 1 Specimens with shear studs (unit: mm)

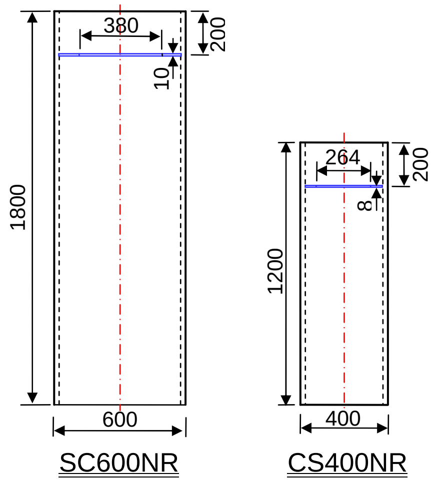
2.2 Material properties

Grade 350 carbon steel was used to fabricate the carbon steel tubes, and austenitic stainless steel Grade 304 specified in AS/NZS 4673:2001 (Standards Australia 2001) was used to fabricate the stainless steel tubes. Meanwhile, a series of coupon tests were conducted to measure the material properties of the carbon and stainless steels. The measured mechanical properties are given in Table 1, where f_y is the yield stress, f_u is the ultimate strength, and E_s is the Young’s modulus.

Two types of concrete, including normal concrete and expansive concrete, were used to fill the steel tube. Standard concrete cylinders (100×200 mm) were cast and cured in similar conditions as the specimens, and the corresponding concrete compressive tests were conducted on the same day when the push-out test was conducted. The average measured cylinder compressive strength (f_c') for each specimen is given in Table 1.



(a) Internal ring in specimen SC600NR

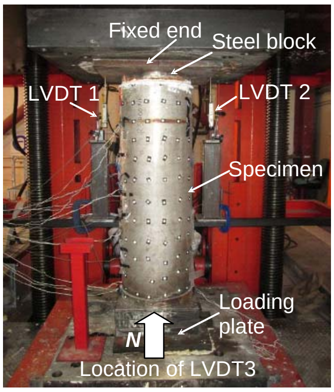


(b) Location of the internal ring

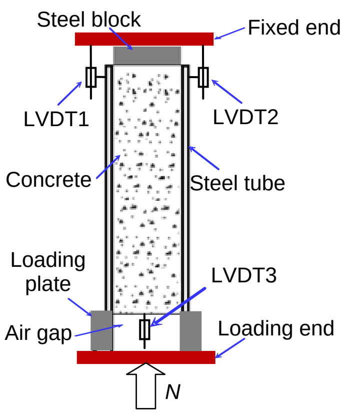
Fig. 2 Specimens with an internal ring (unit: mm)

2.3 Test setup

The test setup used to carry out the push-out tests is shown in Fig. 3. The specimen was set up in the testing machine in a vertical position with an air gap at the bottom. A loading plate was placed on the bottom of the steel tube, and the push force (*N*) was applied to the steel tube through the loading plate during the test. Meanwhile, a steel block was placed on the top of the core concrete. The steel block had a cross-section which was slightly smaller than that of the concrete core (a clearance of 2 mm on each side). This assured the load to be applied only on the concrete core and allowed the steel tube to be pushed upward when testing. A total of 3 linear variable displacement transducers (LVDT) were used to measure the slip between the steel tube and core concrete, where two of them (LVDT1 and LVDT2) were located at the top of the specimen as shown in Fig. 3(a), and the third one (LVDT3) was located at the bottom of the specimen [not visible in Fig. 3(a)].



(a)



(b)

Fig. 3 Push-out test setup

3. TEST RESULTS

3.1 Failure modes

The failure mode of a specimen was determined by its interface type. For specimens with normal interface and shear studs, no visible change in appearance of the steel tube was observed except the slip between the steel tube and concrete. However, for the specimens with an internal ring (CS400NR and SC600NR), outward local buckling of the steel tube was observed. For the square specimen SC600NR, significant local buckling occurred at the location of the internal ring, as shown in Fig. 4(a). On the other hand, for the circular specimen CS400NR, as shown in Fig. 4(b), the local buckling occurred at the bottom of the steel tube near the air gap. It indicates that the internal ring was very effective in resisting the push-out force and the increased force caused the local buckling of the steel tube.

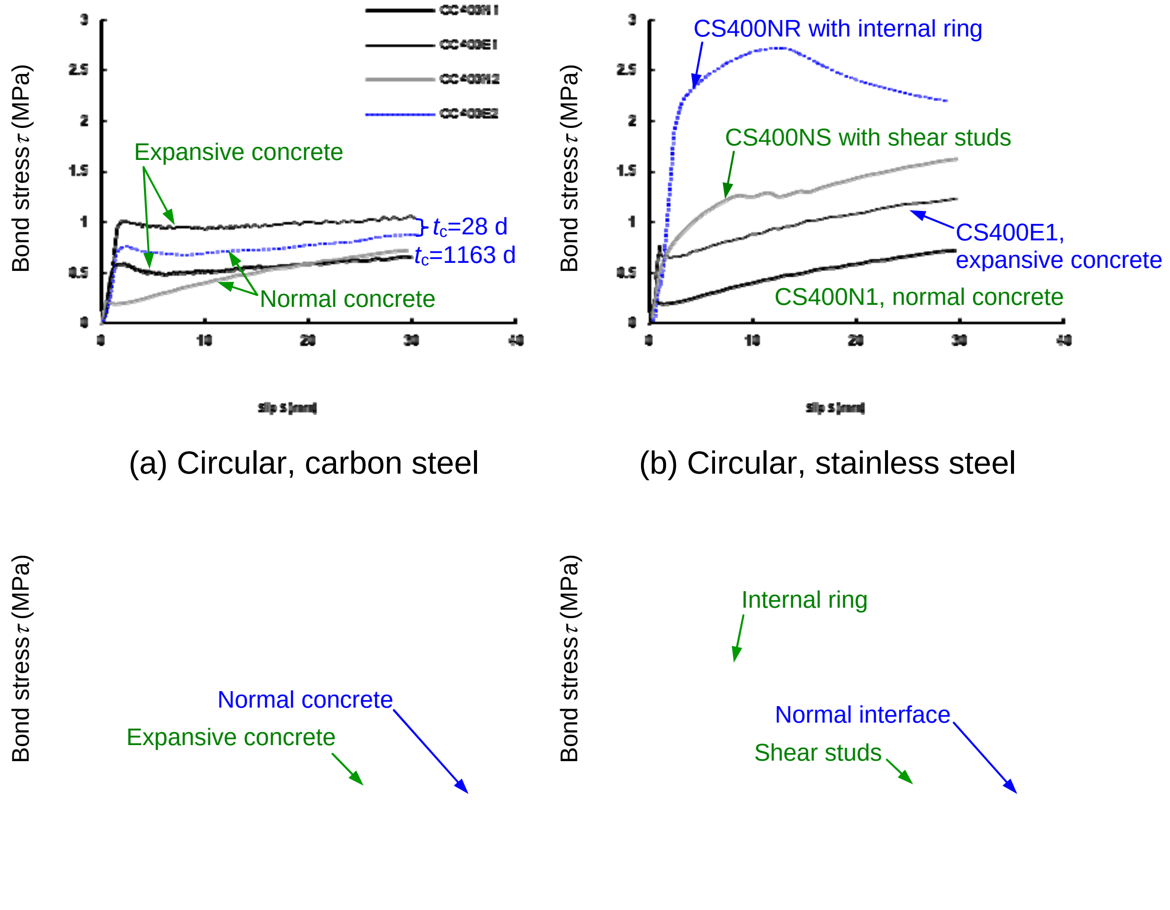
(a) SC600NR, square (b) CS400NR, circular

Fig. 4 Failure mode of specimens with an internal ring

3.2 Bond stress versus slip relation

The bond behaviour between the steel tube and concrete in this paper is evaluated by the average bond stress (τ), which is the axial push load (N) divided by the area of the contact interface. In the initial loading stage, the slip measured at the top (fixed end) is slightly smaller than that measured at the bottom (loading end). After reaching the ultimate bond strength, the difference is negligible. This is consistent with the observation reported by Tao et al. (2011). In this paper, the relative slip (S) measured by the one LVDT at the bottom end of the specimen is used to derive the bond stress versus slip relationship. Fig. 5 shows the bond stress (τ) versus slip (S) curves of all the CFST specimens. The measured ultimate bond strength (τ_u) for each specimen are presented in Table 1, where τ_u is the average bond stress calculated from the first peak load in this paper.

Two identical specimens SC600E1 and SC600E2 have been prepared to conduct push-out tests. The agreement between them is very good in terms of ultimate bond strength and τ-S curve as shown in Fig. 5(c). The measured τ_u-values for the two specimens are 0.13 MPa and 0.15 MPa, respectively.



(a) Circular, carbon steel (b) Circular, stainless steel

(c) Square, carbon steel (d) Square, carbon steel

Fig. 5 Measured τ-S curves of CFST specimens

In general, all τ-S curves have an initial linear portion before reaching the ultimate bond strength τ_u. When no shear studs or internal rings are provided, the ultimate slip S_u corresponding to τ_u are usually smaller than 2 mm. At the presence of the shear studs, S_u-value increases to about 7 mm. When an internal ring is provided, S_u-value further increases to about 12 mm. After reaching τ_u, no obvious declining portion is observed when no shear studs or internal rings are provided. This is because the surface irregularities provide mechanical interlocking between the steel tube and concrete in this stage (Tao et al. 2011). When an internal ring is welded in the steel tube, the push-out force decreases slowly due to the local buckling of the steel tube. But for specimens with shear studs, the square specimen SC600NS has a declining portion, whilst the circular specimen CS400NS does not have. As reported by Shakir-Khalil (1993) and Tao et al. (2011), during the push-out process, friction forms uniformly around the perimeter of a circular tube, but forms mainly in the vicinity of the corners of a square tube. After the shearing off of the headed studs, the weld remaining around the stud periphery continues to resist the push load in the circular specimen CS400NS. But this effect is negligible in the square specimen SC600NS since the studs were welded along the central line of the steel plate. Despite this, the residual bond strength of SC600NS is still higher than that of the reference specimen SC600N1 without the presence of shear studs, as shown in Fig. 5(d). To improve the residual bond strength in a square CFST column, shear studs may be welded near the corners of the square tube. Further research is required to confirm this.

4. EFFECT OF DIFFERENT PARAMETERS ON τ_u

4.1 Steel type

The effect of steel type on τ_u is shown in Fig. 6(a). For circular CFST specimens with normal concrete, the bond strength of carbon steel specimen CC400N1 is around 3 times that of stainless steel specimen CS400N1. For circular specimens with expansive concrete, the influence of steel type on τ_u is less significant. But compared with CC400E1, a decrease in τ_u by 25% is still observed for the stainless steel specimen CS400E1. In most cases, the inner surface of a stainless steel tube is smoother than that of a carbon steel tube because stainless steel is usually free of rust. The smoother the initial surface condition of the steel tube, the lower the bond strength

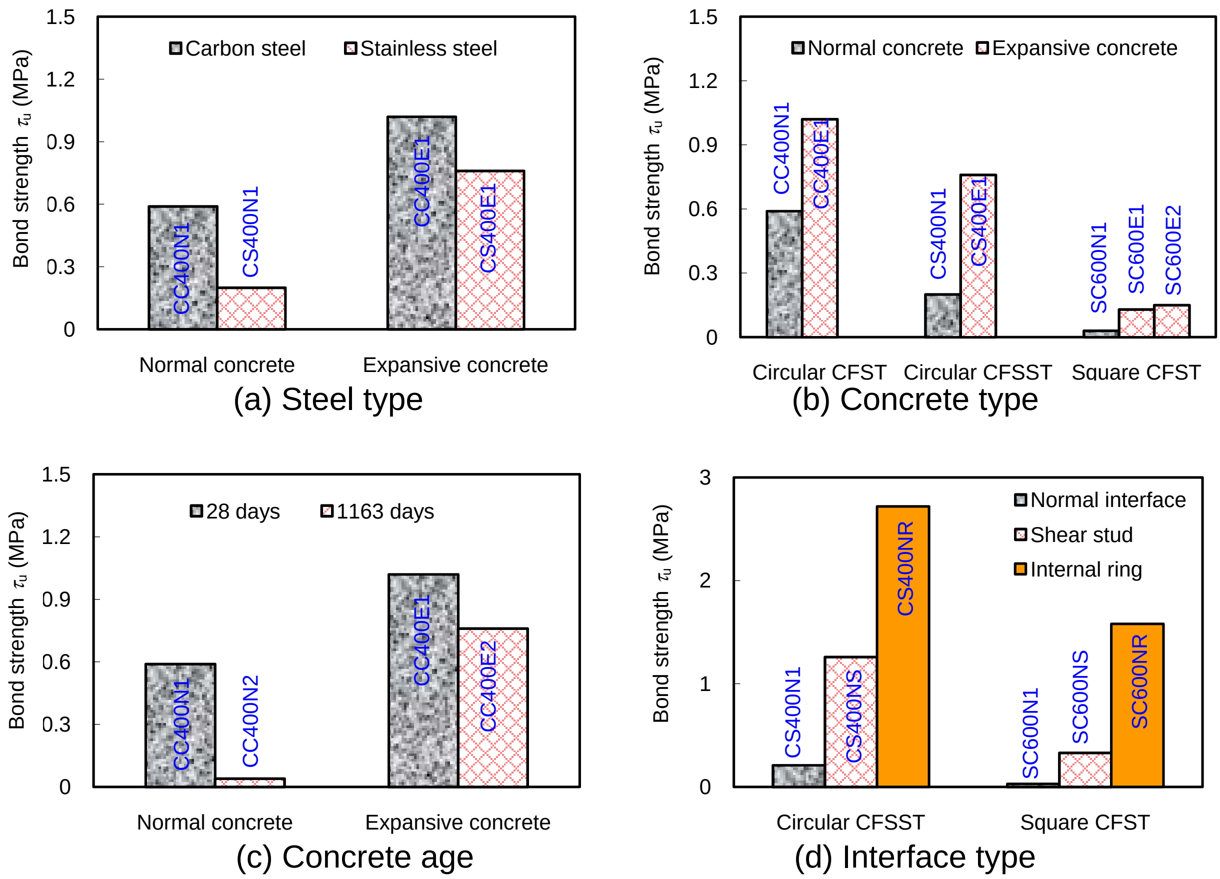


Fig. 6 Effects of different parameters on τ_u between the steel tube and concrete.

4.2 Concrete type

The influence of concrete type on the bond strength is illustrated in Fig. 6(b). It seems that expansive concrete is very effective in improving the bond strength in circular CFST columns, but less effective for square CFST columns. For circular carbon steel specimens tested at 28 days, τ_u increased from 0.59 MPa to 1.02 MPa when normal concrete was replaced by expansive concrete. The effect is more significant for circular concrete-filled stainless steel tubular (CFSST) specimens tested at around 3 years. In this case, τ_u-values are 0.21 MPa and 0.76 MPa when normal and expansive concretes were used, respectively. For square carbon steel CFST columns tested at around 3 years, τ_u increased from 0.03 MPa to 0.14 MPa when normal concrete was replaced by expansive concrete. The beneficial influence of using expansive concrete can be attributed to the enhanced interaction between the steel tube and concrete. When expansive agent is added to the concrete, the concrete develops lateral expansion, which is restrained by the steel tube. For early age concrete, the lateral expansion leads to the formation of pressure between the steel tube and concrete; this directly contributes to the bond strength increase. When concrete shrinkage occurs, the prestress built in the steel tube can be released. The steel tube springs back radially inward; thus prevents the formation or reduces the size of the gap between the steel tube and concrete. This can also help to retain the bond strength for mature concrete.

4.3 Concrete age

Fig. 6(c) shows the influence of concrete age on τ_u. The bond strength of CFST specimens decreases with increasing concrete age. This is due to the influence of concrete shrinkage which increases with concrete age. When normal concrete was used, a clear gap was formed between the steel tube and concrete around almost the entire perimeter in the first few weeks and the gap size increased with increasing concrete age. For circular CFST columns with normal concrete, τ_u decreased from 0.59 MPa to a very small value of 0.04 MPa when the concrete age increased from 28 days to 1163 days. When expansive concrete was used, no visible gap was observed in the first few months and a very small gap formed at a later stage. For this reason, when expansive concrete was used in circular CFST columns, τ_u only decreased slightly from 1.02 MPa to 0.76 MPa when the concrete age increased from 28 days to 1163 days. Despite this, the measured bond strength at 1163 days for specimen CC400E2 with expansive concrete was still 28.8% higher than that of specimen CC400N1 with normal concrete tested at 28 days.

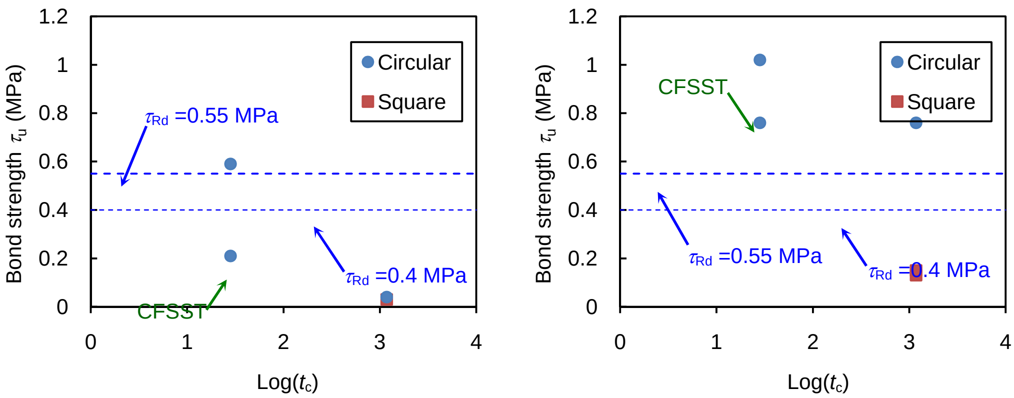
4.4 Interface type between the steel tube and concrete

Fig. 6(d) demonstrates the influence of interface type on the bond strength. Clearly, welding shear studs or internal ring onto the inner surface of the steel tube can significantly increase the bond strength. Take the circular CFST specimens as examples, τ_u of CS400NS with shear studs is 6 times that of CS400N1 with normal interface, whilst τ_u of CS400NR with an internal ring is 13 times that of CS400N1 with normal interface. In the current research, the bond strength of the specimen with shear studs is smaller than that of the corresponding specimen with an internal ring. Although it is possible to weld more shear studs to further improve the bond strength, less welding time is required for installing the internal ring. Therefore, welding internal rings can be considered as the most effective method in enhancing the bond behaviour between the steel tube and concrete.

5. Comparison with existing design codes

Due to the numerous influencing parameters and their uncertainties, it is still not possible to provide reliable equations to predict bond strength in CFST columns. Instead, some design codes specify design bond strengths (τ_{Rd}) for CFST columns based on test data. In Australia standard (Standards Australia 2004), and American standard (ANSI/AISC 360-10 2010), the specified design bond strength for CFST columns is 0.4 MPa. In contrast, the specified τ_{Rd}-values in Eurocode 4 (2004) are 0.55 MPa and 0.4 MPa for circular and rectangular CFST columns, respectively. Since the specified τ_{Rd}-values were proposed only based on existing test results of small size columns usually tested at a concrete age of less than 3 months, there is a need to check the validity of the specifications.

For the current tests, when normal concrete is used, τ_u of the circular specimen with carbon steel at 28 days exceeds 0.55 MPa, but that of the counterpart with stainless steel is lower than 0.4 MPa, as shown in Fig. 7(a). When the concrete age exceeds 3 years, the τ_u-values of both the circular and square specimens (only 0.04 MPa and 0.03 MPa) are negligible. This indicates that the current specified τ_{Rd} values are not safe for real CFST columns. When expansive concrete is used, the τ_u-value of the circular CFST column exceeds 0.55 MPa at a concrete age of over 3 years. But the corresponding τ_u-value of 0.14 MPa for the square CFST column is much smaller than 0.4 MPa. It concludes that expansive concrete can be effectively used to ensure the bond strength of circular CFST columns with a diameter of 400 mm or less. Further research is required to confirm the effectiveness of expansive concrete in improving the bond strength for circular CFST columns with a diameter over 400 mm. For large size square CFST columns, however, expansive concrete should not be considered in ensuring the bond strength although some improvement can still be expected. Instead, shear studs or internal rings should be used to achieve this purpose.



(a) Normal concrete (b) Expansive concrete

Fig. 7 Comparison between measured τ_u and specified τ_{Rd}

6. CONCLUSIONS

An experimental investigation has been carried out to investigate the bond behaviour between the steel tube and concrete in full-scale concrete-filled steel tubular specimens. It was found that the use of stainless steel leads to a decrease in bond strength compared with the carbon steel specimen. Meanwhile, the bond strength decreases remarkably with increasing concrete age and the bond strength can drop to a negligible value. Therefore, the specified design bond strengths in current codes are not safe for real CFST columns. To ensure the bond strength in circular CFST columns, expansive concrete can be used to fill the concrete. Alternatively, shear studs or internal rings can be welded onto the inner surface of the steel tube. Further research, however, is required to confirm the effectiveness of expansive concrete in improving the bond strength of circular CFST columns with a diameter of over 400 mm. For square CFST columns, only welding shear studs or internal ring is recommended to enhance the bond strength.

7. ACKNOWLEDGMENTS

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