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Effect Analysis of Expansion Agent on Interfacial Bond Behavior of Concrete Filled Steel Tubular

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Three concrete filled steel tube (CFST) push out specimens with different expansive agent (EA) content were made to investigate the effect of EA on interfacial bond behavior of CFST. Test results analysis show that the interfacial bond behavior of the CFST can be effectively improved, but in the aspect of changing the local maximum bonding stress of the interface, there is an optimum amount of expansion agent; the distribution curve of interfacial bond stress along the steel tube height *x* shows that the maximum bonding stress of the interface occurs at a certain position of the free end; the increasing effect of EA should be considered in calculating the interfacial bond stress.

1. Introduction

The CFST is widely used in the civil works due to its good bearing capacity and simple construction. As an important prerequisite, interfacial bond property must translate the internal force in the composition of CFST (Ji and Song, 2011). The findings suggest that there are several factors such as core concrete strength (Chen et al., 2015), section form interface smoothness which can produce great impact on the interfacial bond property. Xu Changwu et al (2015) explored a CFST self-stress with solar radiation by a simulation test. Results show that the self-stress can better improve the interfacial load properties of this composition under solar radiation conditions. Cao et al (2015) adopted the finite element analysis to simulate the push-out tests on the CFST under different self-stress conditions by heating up the core concrete in attempt to reveal its interfacial bond behavior and found that this behavior of the core concrete was improved as its self-stress increased. The self-stress of core concrete usually generates from expansion agent added in the concrete. The expansion products generated during the hydration, calcium hydroxide, ettringite compensate concrete shrinkage or cause it produce self-stress. Not only that, addition of expansion agent, however, also has the impacts on the hydration products and further on the concrete strength. It is certain that the expansion agent affects the interfacial bond behavior of this composition in many ways. Zhou et al., (2010) analyzed the impact of dosage of expansion agent on the mechanical properties of this composition. The results show that the optimal dosage of expansion agent in this composition falls within 10%~14%. Shakir-khalil (Sha-Khalil, 1993; Shakir-Khalil, 1993; Lu et al., 2018; Huang et al., 2009) carried out the interface-bond-slip test on the short concrete-filled steel tube pile by using different section forms, loading methods and support ways in attempt to drill down the interface bond properties of concrete-filled steel tube.The interfacial bond properties of concrete-filled steel tube can be tested by two ways, i.e. push-out and -off tests. In view of this, the paper investigates the interfacial bond properties of CFST with different dosages of expansion agent by push-out test (Jiang et al., 2000; Muciaccia et al., 2011).

2. Push-out test

2.1 Raw materials for test

The concrete strength grade is C60. The cement uses PO 52.5; Polycarboxylate water reducer; Calcium sulphoaluminate oxide expander; coarse aggregate cobblestone particle size 5mm~35mm; fine aggregate

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yellow sand, particle composition 2.7; steel pipe diameter 165mm; the height 495mm; wall thickness 3mm and the material Q235.

2.2 Specimen preparation and survey station collocation

A total of three tests are conducted with additives of EA at the dosages of 0%, 6%, and 12%, respectively. The concrete mix proportion is shown in Table 1. During the test, the core concrete slippage at the push-out end can be directly measured by a displacement sensor provided with a press. Before the concrete is poured into the steel tube, one end is sealed using a 2 mm thick steel plate smeared with glass sealant. The concrete is poured twice and vibrated for compaction. Strain and displacement survey station are shown in Fig. 1. The test apparatus and mechanical model are shown in Fig. 2.

Table 1: Mix proportion of common C60 concrete (kg/m^3)

Item	Cement	Gravel	Sand	Water	water reducer	EA volume	Water cement ratio
CFST0	500					0%	
CFST6	470	1100	625	165	8.25	6%	0.33
CFST12	440					12%	

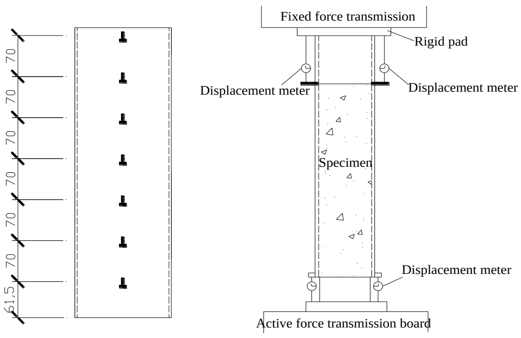

Figure 1: Layout of strain and displacement survey station

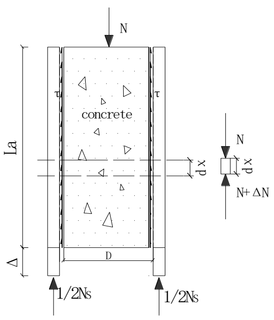

Figure 2: Test apparatus and mechanical model

2.3 Load control

At the initial stage of loading, the displacement load control is used at a rate of 0.02 mm/s. After a sharp inflection appears in the load slip curve, the force load control is performed at a rate of 0.4 kN/s. When the load slip curve starts to go down, the displacement load control is active instead, and at a rate of 0.02mm/s. The test is ended when the slippage is greater than 30mm.

3. Test results and analysis

3.1 Load-slip curve

Load-slip curve obtained from the test is shown in Fig. 3. Most obviously, the bond failure at the interface of the CFST starts from the load end and then gradually extends toward the free end. Limit load is proportional to the dosage of the expansion agent. The up-leg of the curve is basically consistent at each dosage of expansion agent, but the down-leg has a big difference. After the load hit upon the top point A, the chemical adhesion force is completely lost, and the mechanical occlusion effect gradually wear off. Curve after passing through the peak displays the partial down-leg inversely proportional to the dosage of expansion agent. The leading reason why the analysis is done is that the core concrete expands due to the incorporation of the expansion agent and gets denser externally due to the clamp restraint effect on the steel pipe. The interface defect is also reduced. Mechanical occlusion force between the interfaces weakens. There is basically no down-leg in the curve when the dosage of expansion agent reaches 12%. As the loads increase continuously, the up-leg curve appears again mainly because the interface concrete material is completely destroyed. As the slippage increases, the damaged concrete will deposit at the interface. As a result, the local normal force grows up, and the up-leg curve appears.

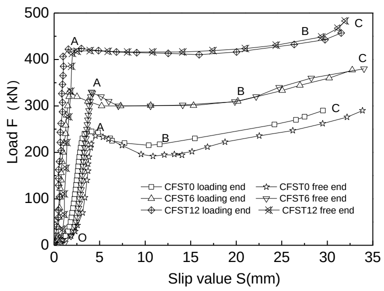

Figure 3: Load-slip curve

3.2 Surface stress of steel tube

The vertical strain on the surface of the specimen obtained by the test is shown in Fig. 4. It is obvious that at the initial stage of loading, the load is lower, and the interfacial bond mainly shows a chemical adhesion force. As load increases, the chemical adhesion force at the load end is gradually destroyed, and the interfacial bond force is gradually delivered to the free end. The curve shows that the strain at the load end grows more slowly, whereas free-end strain increases rapidly. Compared with the steel tube under the equal load, the surface strain of specimens added with the expansion agent is greater than that of those without the expansion agent, so does the surface stress of the steel tube.

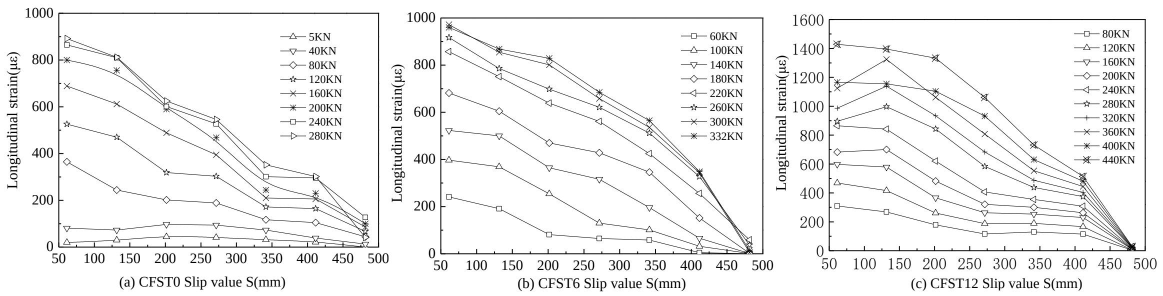

Figure 4: Longitudinal strain distribution on the surface of specimen

Hoop strain on the surface of the specimen obtained by the test is shown in Fig. 5. It is obvious that the stress at the free end is far greater than that at the load end in the case of any dosage of expansion agent. It is because that the slippage starts from the load end and an embolization effect will form at the free end. When the load is lower, the hoop stress curve in each middle section is smooth, but as the load gradually increases, the trend of the broken line gets obvious. It is because that the local deposit of the crushed concrete material at the interface leads to overhigh compression stress in the local part, but the trend of broken lines in the case of the high dosage of expansion agent is obviously weaker than that in the case of low dosage of it. It turns out that the incorporation of expansion agent improves the quality of core concrete.

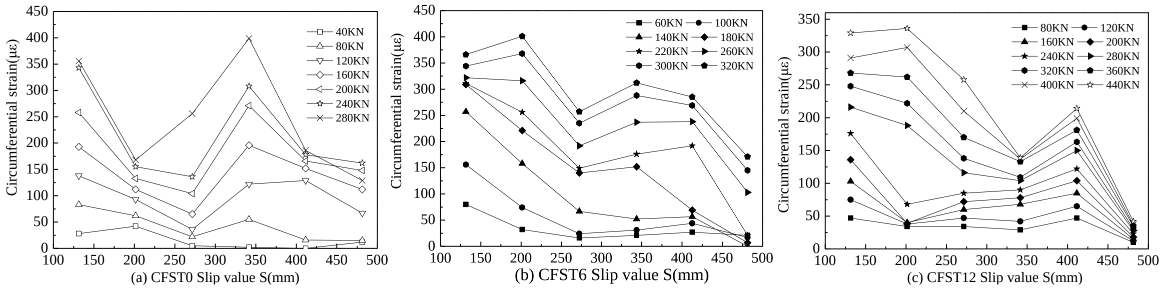

Figure 5: Circumferential strain distribution on the surface of specimen

3.4 Interfacial bond strength

Bond strength between steel pipe and core concrete is referred to as the average bond strength τ_u. The literature (Gourley et al., 2008) provides various models for the interfacial bond strength calculation, as shown in Table 2. Table 3 lists the test eigenvalues and the results of the corresponding interfacial ultimate bond strengths obtained by each theoretical calculation formula. As shown in the Table 3, the incorporation of the expansion agent can improve the interfacial bond properties of the CFST. Results in literature and deviate a lot from test; those in the literature (Gourley et al., 2008) are close to that of the test CFST0, but the deviation widens with the increase of the dosage of expansion agent because the calculation model does not allow for the impact of the expansion agent on the interfacial bond behavior. While the addition of the expansion agent will cause the core concrete to generate self-stress, increasing the normal force between the steel tube and the core concrete, thus further improving the interfacial bond property.

Table 2: Theoretical calculation formula for interfacial bond strength

Interfacial bond strength	Theoretical calculation formula	Remarks
τ_u	$\tau_u = F_u/A$	*F*F_u-pull-out load; A-Contact surface area
$\tau_{u[11]}$	$\tau_u = 0.1f_{cu}^{0.4}$	F_{cu}-Concrete cubic compressive strength
$\tau_{u[12]}$	$\tau_u = k\left[\left(-0.00028\left(\frac{4L_e}{d}\right) + 0.11121\left(\frac{d}{t}\right) + 29.09049\alpha + 0.034390\theta - 7.36037\right)f_c\right]/\gamma$	γ-correction factor, Can take 0.95; *k*-The roughness coefficient of the inner wall of the steel tube, Can take 1.3; α-Steel content; θ-Hoop coefficient, f_c- Concrete axial compression strength
$\tau_{u[13]}$	$\tau_u = 2.109 - 0.26(D/t)$	*D*-Outer diameter of the steel tube; *t*-Wall thickness of the steel tube

Table 3: Test eigenvalues and interfacial ultimate bond strength

Item	Limit slip (mm)	Failure displacement (mm)	Limit load (kN)	τ_u(MPa)	τ_u[11](MPa)	τ_u[12](MPa)	τ_u[13](MPa)
CFST0	3.866	35.51	245.0	1.10	0.50	0.75	1.0365
CFST6	3.993	28.24	334.6	1.51	0.52	0.71	1.0365
CFST12	2.549	29.75	417.7	1.88	0.52	0.69	1.0365

According to the above analysis, given the dosage of expansion agent, the interfacial bond stress between the steel tube and the core concrete can be corrected by the formula given in literature (Gourley et al., 2008). Given the effect that the expansion agent improves the interfacial bond stress, the coefficients α and β are introduced. The interface stress can be expressed by the following formula (1), where γ represents the percentage of the expansion agent. The linear regression analysis of the test results derive $\alpha = 0.0675, \beta = 6.5$, substituted into correction formula (2), see Fig. 6 for comparison between the corrections and the test value. It can be seen that the curve is better fitted.

$$\tau_u = 2.109 - 0.026(D / t) + (\alpha + \beta\gamma) \quad (1)$$

$$\tau_u = 2.109 - 0.026(D / t) + (0.0657 + 6.5\gamma) \quad (2)$$

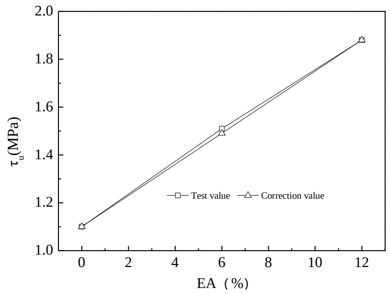

Figure 6: Comparative curve between correction and test values

3.5 Bond stress distribution with height *x*

The study in the literature (Shakir-Khalil, 1991) finds that the relationship between the strain on the surface of the steel tube and the length of the specimen during the push-out test can be expressed by an exponential function. For this purpose, the longitudinal strain on the surface of the steel pipe is fitted with an exponential function along the length of the specimen. A functional expression of the surface strain of the steel tube as a function of the height *x* at all levels of load is available. Fitting correlation coefficients all exceed 0.9. According to the mechanical model in Fig. 2, Eq. (3) can be deduced. Based on the above fitting results, we can assume that the longitudinal strain on the surface of the steel tube is subjected to change with the height *x* of the specimen, and the variation rule satisfies the function formula (4). Then, according to Eq. (5), we can obtain a functional Eq. (6) that the interfacial bond force varies with height *x*. The relationship between the interfacial bond strength and the height of the specimen calculated from Eq. (6) is shown in Fig. 7.

$$\tau_x = \frac{A_s}{\pi D_0} \cdot \frac{d\sigma_s}{d_x} = \frac{1}{4} D_0 \cdot \frac{A_s}{A_c} \cdot E \frac{d\varepsilon_s}{d_x} \quad (3) \qquad \varepsilon = \lambda e^{kx} + C \quad (4)$$

$$\frac{A_s}{A_c} = [\frac{1}{4}\pi(D_0 + 2t)^2 - \frac{1}{4}\pi D_0^2)] / (\frac{1}{4}\pi D_0^2) = \frac{4t}{D_0} + 4(\frac{t}{D_0})^2 \approx \frac{4t}{D_0} \quad (5)$$

$$\tau_x = \frac{A_s}{\pi D_0} \cdot \frac{d\sigma_s}{d_x} = \frac{1}{4} D_0 \cdot \frac{A_s}{A_c} \frac{d\sigma_s}{d_x} = E_s t \frac{d\varepsilon_s}{d_x} = \lambda k E_s t e^{kx} \quad (6)$$

Where, l_s is the circumference of the inner wall of the steel pipe; A_c is the cross-section area of the core concrete; *D* is the diameter of the outer wall of the steel pipe; *t* is the wall thickness of the steel pipe. *x* represents different positions; E_c, A_c represent the elastic modulus and interface area of core concrete, respectively; E_s, A_s represent the elastic modulus and interface area of the steel tube, respectively; ε_s represents the longitudinal strain of the steel tube.

As shown in Fig. 7, at all levels of loads, the interfacial bond stress reaches peak at 70mm ~ 80mm from the free end. Before the ultimate load is applied, the bond stress increases a little along the interface length with the increase of the load, but a lot at the free end. The most obvious reason is that during the loading test, the destruction of the bond force starts from the load end where the core concrete first generates a slight slip. During this process, the interface bond stress will be redistributed. Due to the slippage at the load end, the bond force shows a friction force but not obvious during the pushing-out test, so that the bond stress in the slip area increases slowly. Compared with the maximum interface bond stress, it is found that the maximum interface bond stress keeps at about 3.0 MPa when the dosages of expansion agent are 6% and 12%, which suggests that there is an optimal dosage of expansion agent that can improve the interface bond properties of the CFST.

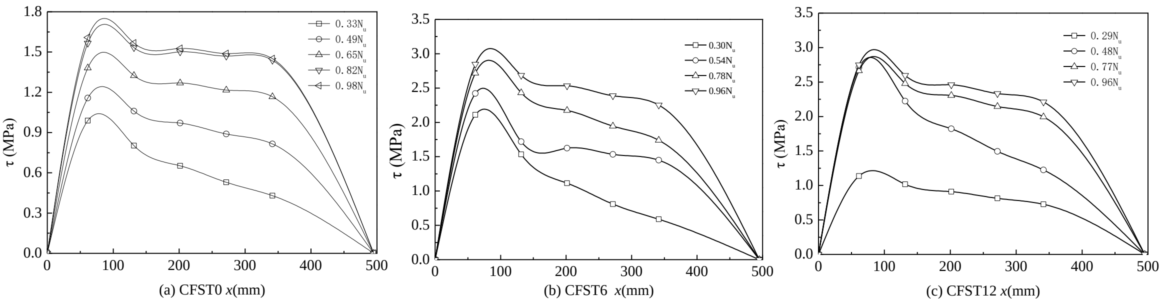

Figure 7: Curve of interfacial bond stress as a function of specimen height x

4. Conclusion

The conclusions of the push-out test for the CFST in the case that expansion agent is added at different dosages are drawn as follows: The incorporation of expansion agent can increase the push-out ultimate load, reduce the mechanical occlusion between steel tube and core concrete interface, raise the normal pressure stress, and improve the interfacial bond stress of the CFST. An optimal dosage of expansion agent, however, exists for the maximum interface bond stress; the magnified effect of expansion agent must be considered when calculating the interfacial bond stress between steel tube and core concrete; the maximum bond stress at the interface between both should appear at a certain distance near the free end.

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